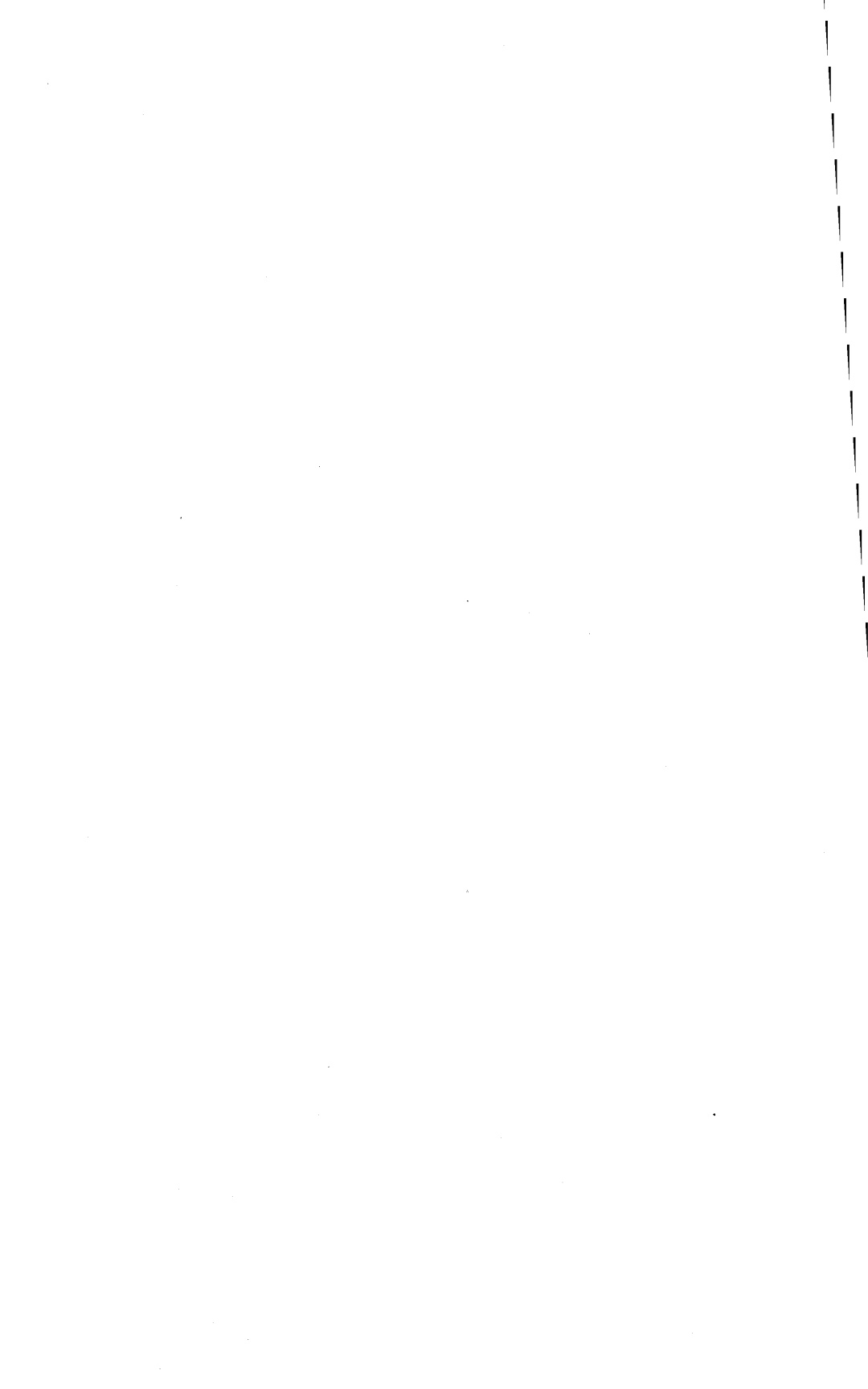


# Telecommunications Transmission Engineering

Volume 2  
Facilities



**Telecommunications  
Transmission  
Engineering**



# Telecommunications Transmission Engineering

Volume 2—Facilities

First Edition

Technical Personnel  
American Telephone and Telegraph Company,  
Bell Telephone Companies,  
and  
Bell Telephone Laboratories



Bell System Center for Technical Education

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**Telecommunications  
Transmission  
Engineering**

*Introduction*

Communication Engineering is concerned with the planning, design, implementation, and operation of the network of channels, switching machines, and user terminals required to provide communication between distant points. Transmission Engineering is the part of Communication Engineering which deals with the channels, the transmission systems which carry the channels, and the combinations of the many types of channels and systems which form the network of facilities. It is a discipline which combines many skills from science and technology with an understanding of economics, human factors, and system operations.

This three-volume book is written for the practicing Transmission Engineer and for the student of transmission engineering in an undergraduate curriculum. The material was planned and organized to make it useful to anyone concerned with the many facets of Communication Engineering. Of necessity, it represents a view of the status of communications technology at a specific time. The reader should be constantly aware of the dynamic nature of the subject.

Volume 1, *Principles*, covers the transmission engineering principles that apply to communication systems. It defines the characteristics of various types of signals, describes signal impairments arising in practical channels, provides the basis for understanding the relationships between a communication network and its components, and provides an appreciation of how transmission objectives and achievable performance are interrelated.

Volume 2, *Facilities*, emphasizes the application of the principles of Volume 1 to the design, implementation, and operation of transmission systems and facilities which form the telecommunications

network. The descriptions are illustrated by examples taken from modern types of facilities most of which represent equipment of Bell Laboratories design and Western Electric manufacture; these examples are used because they are familiar to the authors.

Volume 3, *Networks and Services*, shows how the principles of Volume 1 are applied to the facilities described in Volume 2 to provide a variety of public and private telecommunication services. This volume reflects a strong Bell System operations viewpoint in its consideration of the problems of providing suitable facilities to meet customer needs and expectations at reasonable cost.

The material has been prepared and reviewed by a large number of technical personnel of the American Telephone and Telegraph Company, Bell Telephone Companies, and Bell Telephone Laboratories. Editorial support has been provided by the Technical Publications Organization of the Western Electric Company. Thus, the book represents the cooperative efforts of many people in every major organization of the Bell System and it is difficult to recognize individual contributions. One exception must be made, however. The material in Volume 1 and most of Volume 2 has been prepared by Mr. Robert H. Klie of the Bell Telephone Laboratories, who was associated in this endeavor with the Bell System Center for Technical Education. Mr. Klie also coordinated the preparation of Volume 3.

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## Volume 2 — Facilities

### *Preface*

The Bell System transmission facilities network is made up of a large number of transmission systems, media, terminal equipment units, and items of apparatus that have been designed and constructed to operate efficiently and economically as an integrated communications system. The network has grown rapidly in recent years and has changed remarkably with the increasingly sophisticated technological designs and processes that have emerged over the same period.

The network has evolved as one capable of providing high-quality telecommunications services economically. In addition, it is composed of facilities and equipment that give it flexibility and adaptability in the face of a wide range of environmental factors that include rural and metropolitan areas, hot and cold climates, residential and business communities, and many more. Furthermore, the entire network has proven to be adaptable to transmitting signals of a constantly changing character that have resulted from the provision of new and expanded services.

Volume 2 is devoted to descriptions of the major facilities, systems, circuits, equipment, and apparatus designed and used by the Bell System to provide the required wide range of communications services. The text is organized in seven sections devoted to descriptions and discussions of (1) the network and the principal transmission media, (2) local plant facilities, (3) the major analog carrier systems



that utilize metallic media, (4) analog microwave radio systems, (5) a wide range of digital systems, (6) transmission maintenance systems and equipment, and (7) how all these elements are brought together into an integrated communications system that serves this nation and interconnects with the facilities network of the entire world.

Section 1 provides a general description of the facility network and discusses briefly the manner in which it has evolved. A summary is also given of the characteristics of transmission media. Section 2 presents descriptions of loops and station sets, voice-frequency network trunk and data facilities, and wideband facilities. The section also includes discussions of the transmission aspects of central office and customer premises switching equipment generically called Business Communications Systems.

In the third section, descriptions of analog carrier systems utilizing metallic media are presented. The section begins with a chapter in which the frequency division multiplex equipment is described. Basic design features of analog transmission systems are then discussed after which descriptions of systems based on wire-pair cable and coaxial cable utilization are given. Section 4 covers analog microwave radio systems. Basic design features, systems engineering, and protection switching systems are first described. These general discussions are followed by descriptions of the features of short-haul and long-haul radio systems. Domestic satellite transmission and miscellaneous radio systems and services, principally mobile communications services and radio paging services, are also described.

Section 5 contains descriptions of digital transmission systems. The general design features of such systems are discussed and it is shown how they differ from analog carrier systems. Digital system terminal and multiplex equipment, digital transmission lines, and digital microwave radio systems are treated in succeeding chapters.

Section 6 is devoted to a discussion of transmission maintenance. New maintenance systems, which are currently playing such a prominent role in the field of transmission maintenance, are computer-controlled and are being utilized to fulfill significant functions in record keeping, operations control, and force management. Descriptions of more conventional types of test equipment and the important functions still fulfilled by such equipment in transmission maintenance are also presented.

An overall view of the facilities network and how the parts fit together is presented in Section 7. Some of the limitations imposed upon system use because of interferences introduced into one system by another are first described. Finally, the methods of interconnecting the parts and ensuring compatibility are covered. In addition to system interconnection, the design and operation of some common-equipment designs are also discussed.



## Contents

<i>Introduction</i> .....	iii
<i>Preface</i> .....	v
<b>SECTION 1 THE FACILITY NETWORK</b> .....	<b>1</b>
<b>Chapter 1. The Evolution of the Facility Network</b> .....	<b>2</b>
1-1 Voice-Frequency Transmission Facilities .....	3
1-2 Carrier Transmission Facilities .....	4
Analog Cable Carrier Systems .....	4
Radio Transmission Systems .....	7
Pulse Transmission Systems .....	10
1-3 Video Transmission .....	11
1-4 Maintenance and Reliability .....	13
1-5 Facility Selection and Application .....	15
Growth Factors .....	15
Facility Forecasts .....	19
1-6 Engineering Considerations .....	20
Economics .....	20
Technology .....	22
<b>Chapter 2. Transmission Media</b> .....	<b>26</b>
2-1 Open Wire .....	27
2-2 Loop and Local Trunk Cables .....	27
Physical Characteristics .....	28
Transmission Characteristics .....	31

2-3	Toll Trunk Cables .....	40
	Cable Pairs .....	40
	Coaxial Cables .....	44
2-4	Microwave Radio Transmission .....	46
	Propagation Paths .....	46
	Antennas .....	51
	Waveguides .....	56
2-5	Mobile Radio Transmission .....	57
<b>SECTION 2 LOCAL PLANT FACILITIES .....</b>		<b>61</b>
<b>Chapter 3. Loops and Station Sets .....</b>		<b>63</b>
3-1	Loop Baseband Facilities .....	64
	Loop Design Plans .....	65
	Voice-Frequency Electronic Equipment .....	68
	Bridge Lifters .....	78
	Concentrators .....	80
	Program Facilities .....	80
3-2	Loop Carrier Facilities .....	81
	Analog Systems .....	81
	Digital Systems .....	85
3-3	Telephone Station Equipment .....	89
	The 500-Type Telephone Station Set .....	89
	Other Station Set Types .....	93
	Ringing Considerations .....	93
<b>Chapter 4. Voice-Frequency Trunk Facilities .....</b>		<b>102</b>
4-1	Transmission Considerations .....	103
4-2	Negative Impedance Repeaters .....	104
	Repeater Design .....	105
	Gain .....	106
	Impedance Relationships .....	108
	Disablers .....	109
	Applications .....	109
4-3	Four-Wire V-Type Repeaters .....	109
	Equipment Arrangements .....	111
	Amplifiers .....	113
	Equalizers .....	115
	Four-Wire Terminating Sets .....	118
	Four-Wire Extension Networks .....	119
	Low-Pass Filter .....	120

# Contents

xi

4-4	Metallic Facility Terminals	120
	Equipment Features	121
	Transmission Features	122
4-5	Voice-Frequency Equipment Comparisons	123
	Bandwidth and Stability	123
	Return Loss and Echo	124
	Losses and Transmission Level Points	124
	Signalling	125
4-6	Echo Suppressors	126
	Operation	126
	Types	128
	Enablers and Disablers	131
<b>Chapter 5. Voice-Frequency Data Facilities</b>		<b>133</b>
5-1	Transmission Channels	134
	Access Facilities	134
	Interoffice Facilities	137
5-2	Transmission Performance	138
	Objectives	138
	Impairments	140
5-3	Voiceband Data Stations	141
	Data Sets	142
	Analog Interface	143
5-4	The 208-Type DATA-PHONE Data Set	144
	Description	144
	Electrical Characteristics	148
<b>Chapter 6. Wideband Facilities</b>		<b>153</b>
6-1	Wideband Data Facilities	153
	Wideband Data Station	154
	Access Facilities	157
	Central Office and Carrier System Equipment	161
6-2	Local Plant Facilities for DDS	166
	Customer Premises Equipment	167
	Access Facilities	168
6-3	Baseband Television Facilities	170
	The A2-Type Video Transmission Systems	170
	The A4 Video Transmission System	174
<b>Chapter 7. Central Office Equipment</b>		<b>177</b>
7-1	Central Office Transmission Paths	178
	Intraoffice Wiring	178
	Switching Networks	179

7-2	Terminating and Ancillary Circuits .....	183
	Line Circuits .....	184
	Trunk Circuits .....	185
7-3	Transmission-Related Switching Operations .....	195
	Call Sequencing .....	196
	Switched Transmission Operations .....	196
7-4	Digital Switching Interfaces .....	197
	Digroup Terminal .....	198
	Voiceband Interface Units .....	198
7-5	Television Equipment .....	199
7-6	Sources and Control of Impairments .....	200
	Noise .....	200
	Crosstalk .....	201
	Coupling Circuits .....	202
	Loss and Return Loss .....	202
	Battery Voltage .....	202
<b>Chapter 8. Business Communications Systems .....</b>		<b>204</b>
8-1	Key Telephone Systems .....	206
8-2	Equipment for PBX and Centrex Services .....	209
	Station Lines and Tie Trunks .....	209
	PBX Types and Services .....	210
	Transmission Considerations .....	214
8-3	Call Distributors and Telephone Answering Systems .....	216
<b>SECTION 3 ANALOG CARRIER SYSTEMS ON METALLIC MEDIA ...</b>		<b>221</b>
<b>Chapter 9. Frequency Division Multiplex .....</b>		<b>223</b>
9-1	The FDM Hierarchy .....	224
	Channel Banks .....	226
	Group and Supergroup Banks .....	229
	The Mastergroup Multiplex .....	236
	Multimastergroup Multiplex Equipment .....	241
9-2	Design Considerations .....	246
	Efficiency Factors .....	247
	Transmission .....	250
	Reliability .....	253
9-3	Special Multiplex Equipment Designs .....	254
	Program Terminals .....	254
	Wideband Data Terminals .....	255

<b>Chapter 10. System Design Features</b> .....	<b>257</b>
10-1 The Design Process .....	258
Design Relationships .....	259
Design Implementation .....	263
10-2 Equalization .....	268
Functions and Objectives .....	268
Design Types .....	270
Equalization Strategy .....	272
10-3 Ancillary Designs .....	274
Power .....	274
Maintenance and Reliability .....	275
Terminal Arrangements .....	275
 <b>Chapter 11. Wire Pair Carrier Systems</b> .....	 <b>277</b>
11-1 O-Type Systems .....	278
O-Type Terminals .....	278
Line Repeaters .....	286
11-2 N-Type Repeatered Lines .....	288
Transmission Plan .....	289
N1 Repeaters .....	291
N1A Repeaters .....	297
N2 Repeatered Line .....	298
11-3 N-Type Terminals .....	302
The N1 Terminal .....	303
ON Junctions and Terminals .....	305
N2 Terminal .....	308
N3 Terminal .....	311
 <b>Chapter 12. Coaxial Carrier Systems</b> .....	 <b>317</b>
12-1 Coaxial Systems Engineering .....	318
Transmission Media .....	318
Survey of Systems .....	320
Route Engineering .....	324
12-2 The L5 Coaxial Carrier System .....	326
Transmission Design and Layout .....	327
Maintenance and Reliability .....	338
Power System .....	344
12-3 Undersea Cable Systems .....	344
System Comparisons .....	346
Design Features .....	347



<b>SECTION 4 ANALOG RADIO SYSTEMS</b> .....	<b>351</b>
<b>Chapter 13. Microwave Radio System Design Features</b> .....	<b>353</b>
13-1 The Transmission Medium .....	354
Transmission Medium Impairments .....	355
Continuity of Service .....	356
13-2 Repeaters and Terminals .....	358
Baseband System Repeaters .....	358
Intermediate-Frequency Repeaters .....	360
FM Terminals .....	360
13-3 Entrance Facilities .....	362
Signal Sources .....	363
Wire-Line Entrance Links .....	364
13-4 Signal-to-Noise Considerations .....	368
<b>Chapter 14. Microwave System Engineering</b> .....	<b>371</b>
14-1 Operating Frequencies and System Characteristics .....	371
The 2-GHz Band .....	372
The 4-GHz Band .....	372
The 6-GHz Band .....	372
The 11-GHz Band .....	373
The 18-GHz Band .....	373
14-2 Choice of System .....	374
14-3 Route Selection and Layout .....	376
Site Selection .....	376
Path Transmission Characteristics .....	380
Interference Studies .....	388
Governmental Jurisdictions .....	393
<b>Chapter 15. Protection Switching</b> .....	<b>396</b>
15-1 Continuity of Service .....	398
15-2 Frequency Diversity Switching in Long-Haul Systems .....	399
The 400A System .....	400
The 100A System .....	405
The TDAS System .....	410
The THAS System .....	414
15-3 Frequency Diversity Switching of Short-Haul Systems .....	415
The 400B Protection Switching System .....	416
401-Type Systems .....	417
15-4 Space Diversity and Hot Standby Switching .....	418

# Contents

xv

15-5	Entrance Link and FM Terminal Switching .....	421
	The 200A Protection Switching System .....	422
	The 200B System .....	423
<b>Chapter 16. Short-Haul Systems .....</b>		<b>424</b>
16-1	The TJ, TL-Type, and TM-1 Systems .....	425
	The TJ System .....	425
	The TL-1 System .....	426
	The TM-1/TL-2 System .....	426
16-2	The TM-2 Systems .....	427
	Frequency Plans .....	428
	Repeaters .....	429
16-3	The TN-1 System .....	435
	Frequency Plans .....	435
	Equipment Layouts .....	439
	Transmission Performance .....	443
	The 5A FM Terminal .....	444
<b>Chapter 17. Long-Haul Systems .....</b>		<b>446</b>
17-1	The TD-Type Systems .....	447
	Frequency Plan .....	448
	System Layout .....	450
	Repeaters .....	452
17-2	The TH-3 System .....	460
	System Considerations .....	461
	Intermediate Repeater .....	464
	Main Station Repeater .....	468
17-3	The TH-1 System .....	469
	System Considerations .....	470
	Repeaters .....	472
<b>Chapter 18. Domestic Satellite Communications .....</b>		<b>477</b>
18-1	International and Domestic Regulation .....	478
18-2	Space Vehicle Considerations .....	481
	Satellite Stabilization .....	481
	Station Keeping .....	482
	Satellite Lifetime .....	483
	Launch Vehicles .....	483
18-3	Satellite Transmission Equipment .....	484
	Major Equipment Items .....	484
	Comstar Satellite Design .....	486

18-4	Earth Station Equipment .....	489
	Frequency Coordination .....	489
	Earth Station Transmission Equipment .....	489
18-5	Transmission System Considerations .....	494
	Link Transmission Characteristics .....	494
	Message Circuit Noise .....	499
	Transmission Delay .....	502
<b>Chapter 19. Supplementary Radio Communications .....</b>		<b>504</b>
19-1	Land-Mobile Communications .....	504
	System Layout .....	506
	Channel Frequencies and Uses .....	506
	Method of Operation .....	508
	Channel Loading .....	511
19-2	Personal Paging Services .....	512
	Mode of Operation .....	512
	Control Terminal .....	513
	Transmitter .....	514
	Receiver .....	515
19-3	Marine, Aircraft, and Railroad Customer Services .....	516
	Marine Services .....	516
	Aircraft and Railroad Services .....	517
19-4	Supplementary Long-Haul Radio Facilities .....	518
	Tropospheric Transmission Beyond Line of Sight .....	518
	Overseas Radio Facilities .....	519
<b>SECTION 5 DIGITAL SYSTEMS .....</b>		<b>522</b>
<b>Chapter 20. Cable System Design Features .....</b>		<b>524</b>
20-1	Digital Terminal Signal Processing .....	525
	Sampling, Quantizing, and Companding .....	526
	Coding .....	530
	Multiplexing .....	533
20-2	Digital Transmission Line .....	535
	Signal Characteristics .....	536
	Transmission Line Signal Impairments .....	537
	Repeater Characteristics .....	542
	Transmission Line Layout .....	546
20-3	Maintenance .....	547

<b>Chapter 21. Digital Terminal and Multiplex Equipment</b> .....	<b>549</b>
21-1 The Digital Multiplex Hierarchy .....	550
The 24-Channel DS1 Signal .....	552
The DS1C Signal .....	553
The DS2 Signal .....	556
The DS3 Signal .....	558
The DS4 Signal .....	561
The Digital Data System .....	563
21-2 Digital Multiplex Equipment .....	563
Signal Characteristic Specifications .....	564
Line Rates and Codes .....	564
Synchronization .....	565
Elastic Stores .....	565
Pulse Parameters .....	566
Multiplex and Cross-Connect Operations .....	568
21-3 PCM Channel Banks .....	569
Channel Units .....	570
The D1 Channel Banks .....	571
The D2 Channel Bank .....	581
The D3 Channel Bank .....	583
The D4 Channel Bank .....	584
Special Purpose Terminal Arrangements .....	586
<b>Chapter 22. Digital Transmission Lines</b> .....	<b>589</b>
22-1 The T1 Digital Transmission System .....	589
Transmission Media .....	590
Regenerative Line Repeater .....	591
Line Layout .....	597
Maintenance Considerations .....	598
The T1 Outstate Digital Transmission System .....	600
22-2 The T1C Digital Transmission System .....	601
Transmission Media .....	602
Regenerative Repeater .....	602
Line Layout .....	603
22-3 The T2 Digital Transmission System .....	603
Signal Format .....	604
Transmission Media .....	604
Regenerative Repeater .....	605
Line Layout .....	605
Maintenance .....	606
22-4 The T4M Digital Transmission System .....	606
Signal Format .....	607
Transmission Medium .....	608
Regenerative Repeater .....	608
Line Layout .....	609
Maintenance .....	610

<b>Chapter 23. Digital Transmission on Radio Systems</b> .....	<b>612</b>
23-1 The 1A Radio Digital System .....	613
Terminal Equipment .....	613
System Layout .....	615
Engineering .....	618
23-2 The 3A Radio Digital System .....	619
Terminal Equipment .....	620
System Layout .....	625
Maintenance .....	627
23-3 The DR 18A Digital Radio System .....	627
Terminal and Repeater Arrangements .....	628
System Engineering and Layout .....	634
Maintenance .....	638
<b>SECTION 6 TRANSMISSION MAINTENANCE</b> .....	<b>639</b>
<b>Chapter 24. Maintenance Systems</b> .....	<b>640</b>
24-1 Network Effects on Maintenance .....	641
Surveillance .....	642
Test Procedures .....	642
Test Equipment .....	643
Preventive Maintenance .....	644
Trouble Identification and Location .....	644
Operating Centers .....	644
24-2 Facility Maintenance Systems .....	645
System-Integrated Maintenance Arrangements .....	645
System-Independent Maintenance Arrangements .....	653
24-3 Circuit Maintenance Systems .....	656
Loop Maintenance .....	656
Trunk Maintenance .....	658
Special Services Circuit Maintenance .....	661
24-4 Maintenance Support .....	662
Access for Maintenance .....	663
Communications for Maintenance .....	663
Service Protection .....	665
<b>Chapter 25. Test Equipment</b> .....	<b>668</b>
25-1 Voiceband Loss and Delay Measuring Equipment .....	670
Test Signal Generators .....	670
Test Signal Measuring Instruments .....	671
Combined Signal Generator and Measuring Instruments .....	672

25-2	Noise Measuring Equipment .....	673
	The 3C Noise Measuring Set .....	675
	The 7A Carrier-Frequency Noise Measuring Set .....	676
	The 6-Type Noise Measuring Sets .....	677
25-3	Impedance-Related Measuring Equipment .....	678
	Return Loss Measurement .....	679
	Balance Testing .....	680
	Level Tracers .....	681
	Measurement of Line Impedance .....	682
25-4	High-Frequency Measuring Equipment .....	683
	Test Sets for Analog Channel Measurements .....	683
	General Purpose Test Equipment .....	684
	System-Related Test Sets .....	688
	Test Sets for T1-Carrier Systems .....	689
25-5	Data Set and Data Loop Test Equipment .....	690
	The 911NA Data Test Set .....	690
	The 914C Data Test Set .....	691
	The 921A Data Test Set .....	691
	Data Test Sets For the DDS .....	692
<b>SECTION 7 TRANSMISSION SYSTEM INTEGRATION .....</b>		<b>694</b>
<b>Chapter 26. System Compatibility and Coordination .....</b>		<b>695</b>
26-1	Coupling Considerations .....	696
26-2	Coordination in the Loop Plant .....	697
	Inductive Coordination .....	697
	Transmission Level Point Coordination .....	699
	Data Loops .....	700
	Loop Carrier Systems .....	700
26-3	Coordination in the Trunk Plant .....	701
	Short-Haul Carrier Systems .....	701
	Frequency Coordination .....	703
<b>Chapter 27. Common System Facilities .....</b>		<b>705</b>
27-1	Circuit and System Interconnection .....	706
	Voice-Frequency Interconnections .....	706
	Analog Carrier Systems .....	707
	Digital Systems .....	718
	Digital-Analog Interfaces .....	718
27-2	Common Systems Equipment .....	719
	Synchronization .....	719
	Pilots and Carrier Supplies .....	723
	Restoration .....	724
<i>Index</i> .....		726



# Telecommunications Transmission Engineering

## *Section 1*

### *The Facility Network*

The public and private switched message networks and the many special services circuits share a nationwide network of telecommunications facilities. These facilities include transmission media, voice-frequency and carrier systems and equipment, a wide variety of terminating circuits, channelizing equipment, signalling and switching equipment, power supplies, and outside plant items of many descriptions. In short, the facility network comprises the telecommunications plant.

High-quality transmission is provided over this network by careful design of all of these facilities and by paying particular attention to the interactions at the interfaces. Each of the categories of facilities mentioned above has some effect on transmission. However, those having the largest and most direct effects are transmission systems and the transmission media.

Chapter 1 briefly reviews the evolution of transmission systems from the single-wire, ground-return circuits that were initially leased from telegraph service suppliers through the alphabetically designated analog cable carrier and microwave radio systems to the modern digital transmission systems. Video signal transmission is also covered. The rapidly changing fields of maintenance and reliability are discussed and all of these factors are related to the importance of controlling the dynamic network changes by adequate planning and by the application of engineering principles.

Every connection established for electrical communications between two points requires some form of transmission medium. Chapter 2 describes the media most commonly used. These include open-wire lines, loaded and nonloaded multipair cables, coaxial cables, and the atmosphere, which provides the medium for a large number of different types of radio transmission systems. Transmission over waveguide is also briefly discussed.



## Chapter 1

# The Evolution of the Facility Network

Transmission facilities include transmission media, assemblies of equipment required to make up transmission systems, and the channels derived from these systems. A network of such facilities exists to provide a wide variety of telecommunications services. Included are many types of transmission systems and subsystems which have evolved with advancing technology and with increasing demands for more and different types of services.

As it becomes necessary to expand facilities and to replace portions that become obsolete, various criteria must be used in order to accomplish the expansion in an orderly and economic manner. Selection of new facilities and the manner in which they are applied are dependent on many factors. The rate of growth and development of a geographic area, shifts of population and business activities, and the interaction of such factors in their influence on community of interests must all be taken into account. Separate consideration of these factors must be given to urban, suburban, and rural environments and accurate forecasts of loop and trunk facility needs must also be separately made.

In all these aspects of the facility network evolution, engineering control has been and must be exercised so that new plant is compatible with the existing plant. Engineering economy studies must be made to assure that growth is efficient and that short and long range objectives are satisfied wherever possible. New technology and innovations must be carefully evaluated and applied to assure the satisfaction of customer demands for improved performance and new services.

## 1-1 VOICE-FREQUENCY TRANSMISSION FACILITIES

The transmission media used during the years following the invention of the telephone were single, iron-wire conductors rented from suppliers of telegraph service. These circuits operated on the principle of ground return circuit completion and, as a result, were subject to many types of impairments. The advantages of paired copper conductors, primarily lower transmission loss and lower susceptibility to noise, were recognized very early and by 1900, virtually all existing telephone communication was over paired copper conductors. The transition from iron to copper conductors was accelerated by the development during the late nineteenth century of the hard drawing process for copper wire. Also by 1900, some cables had been manufactured and the technique of inductive loading had been invented and was being used. These advances permitted telephone communications over longer and longer distances.

With the introduction of electron tube amplifiers, transmission of telephone signals from coast to coast was accomplished in 1915. Nearly all transcontinental circuits during those early years were open-wire lines. These were used for long distance telephony because large gauge conductors were necessary to obtain the required low line loss.

As the toll plant grew in size and complexity, problems were recognized and solved one by one. In terms of transmission performance, these problems included the need to reduce circuit loss and noise and, as transmission paths increased in length, to control or suppress echoes. Losses were first reduced by increasing the size of conductors. Later, inductive loading was applied and, with the invention of the electron tube, amplification was provided. Noise performance was improved by using balanced pairs, transposition (or frogging) of pairs, staggered twisting of cable conductors, and quadded cable. Four-wire transmission, impedance matching, controlled losses, and echo suppressors were used to improve echo performance of the network. In addition, economics and operational considerations led to the adoption of common battery operation, the development of multichannel carrier systems, and the introduction of machine switching of local and toll traffic.

In the local plant, the transition from open-wire lines to cable and the application of inductive loading techniques permitted the development of economical subscriber loops and local trunks. Central office

equipment expanded from simple manual switchboards to large cord-type switchboards with A-board and B-board arrangements, the A-board for outgoing calls and the B-board for incoming calls. This was followed by the first switching machines such as step-by-step and panel. In the manual and early machine switching systems, the status of telephone set development and signalling requirements placed limitations on wire gauge selection in the loop and trunk plant.

The use of smaller wire gauges in the local plant was initially made possible by the application of inductive loading. Later, the invention of electron tubes and solid-state devices and improvements in circuit components of all types provided further important advances in voice-frequency transmission performance. These new devices and improved components have made possible the development of a wide range of amplifiers, repeaters, bridge lifters, hybrid coil transformers, impedance matching devices, noise balancing circuits, and filters. They have also led to improvements in frequency response, antisidetone features, and loop current equalization of telephone station sets. These improvements together with the development of circuits to increase loop signalling ranges have made possible the use of smaller wire gauges in the loop plant.

## 1-2 CARRIER TRANSMISSION FACILITIES

The history of carrier systems really begins in the early years of the 20th century and progress in all areas has been rapid. Carrier modes of transmission increase the efficiency of utilization of transmission media by combining (multiplexing) a large number of message signals into a single composite signal. Nearly all types of carrier modulation have been used but three are now predominant. Single- and double-sideband *amplitude modulation* with frequency division multiplexing of signals are commonly used to form a broadband signal for transmission over analog cable carrier systems. *Frequency modulation* of a microwave carrier is used to transmit this broadband signal over microwave radio systems. Various forms of *pulse modulation*, notably pulse code modulation, are used with time division multiplex techniques for transmitting signals over digital (regenerative repeater) facilities. Many other combinations of these techniques are possible and some are being developed.

### Analog Cable Carrier Systems

The application of electron tubes and solid-state devices and continuing improvements in passive components have made it possible

to develop carrier systems providing ever wider bandwidths, thus substantially reducing the per-unit line cost of circuits. However, the distance between terminals, among other factors, does affect the point at which the use of electronics becomes more attractive than voice-frequency cable circuits.

In addition to the economic advantages of carrier systems, a number of performance improvements are realized. The velocity of propagation at carrier frequencies in any cable circuit is substantially higher than at voice frequencies. This is especially true when carrier circuits are compared with loaded cable pairs. The higher velocity offers advantages in respect to control of echoes and favors some types of signal transmission where absolute delay is important. Some form of four-wire transmission is necessary in broadband carrier systems; as a result, impedances are better controlled thus permitting the operation of circuits at lower losses yet with satisfactory stability and echo performance.

The development of the A-type system in 1917 was followed by a succession of carrier systems identified by alphabetical designations. These systems were at first developed for use on open-wire transmission lines. Most of these early systems, designated A through J, provided four-wire or equivalent four-wire transmission in a frequency band above a voice-frequency channel which could simultaneously be provided on the open-wire pair. Two exceptions should be noted. The E-type system provided transmission for one single-sideband channel on power lines. The same band was used for both directions of transmission, a mode that was made possible by voice-frequency switching so that only one direction of transmission occurred at any one time. Only three such systems were placed in service, those during the middle 1920s. The other exception was the G1 system, placed in service in 1935. It provided a single channel above a voice-frequency channel on a single pair of wires in a double-sideband transmitted carrier mode and was the only carrier system which employed true two-wire transmission.

The J-type system provided transmission for twelve single-sideband suppressed carrier channels on an open-wire pair in the equivalent four-wire mode. A voice-frequency channel and a C-type carrier system, which had a frequency allocation between the voice-band and the J-carrier band, could be operated simultaneously on the same pair. A number of different frequency allocations were used for J carrier but all involved a first step of modulation into a group band

covering the spectrum from 60 to 108 kHz. Thus, the *basic group* was formed to become the foundation of the entire modern frequency division multiplex (FDM) system, during the 1930s. The K-carrier systems, developed at about the same time as the J-type, provided twelve single-sideband message channels for four-wire transmission on cable pairs rather than on open-wire lines. This was the first system in which the transmission medium was not shared with a voice-frequency channel or with another type carrier system. Due to crosstalk effects, separate cables were normally used for the two directions of transmission. However, a single cable could be used when pairs were carefully shielded from one another.

Terminal equipment for both J- and K-carrier systems used the same basic group frequencies. Both J- and K-type systems were manufactured and installed in quantity before, during, and after World War II. Manufacture of these systems has now been discontinued although a number of both types are still in service.

While the J- and K-type systems filled long-haul needs, short-haul analog systems were also developed. In 1950, the first N-type system was placed in service to provide twelve double-sideband transmitted carrier channels over nonloaded cable pairs for distances up to about 200 miles. The initial designs utilized electron tubes throughout. However, the system was redesigned during the 1960s to exploit solid-state technology. The terminal equipment was again redesigned to permit the transmission of 24 single-sideband channels.

The N-type systems were originally designed for four-wire transmission in two frequency bands which were alternated in succeeding repeater sections by a modulation process at each repeater (frequency frogging). This technique partially equalizes the attenuation/frequency characteristic and minimizes the crosstalk coupling between the two directions of transmission. Another version of line design also uses the alternation of frequency positions at each repeater but utilizes the equivalent four-wire mode of transmission.

The O-type systems, made available during the same era and similar in many respects to the N-type systems, provide short-haul carrier transmission on open-wire facilities. These systems, many of which are still in service, utilize electron tubes. The equivalent four-wire mode of transmission is used and frequency frogging is employed at each repeater. In addition, the open-wire pairs must be transposed in accordance with a plan developed for carrier frequencies.

The O-type system can provide a maximum of 16 4-kHz single-sideband channels which are multiplexed in groups of four channels. Each of the two pairs of channels in a four-channel group is transmitted on a common carrier frequency, one channel as an upper sideband and the other as a lower sideband. This arrangement is called twin-channel operation.

Certain O-type terminal arrangements have been adapted for use with N-type lines. This combination of O-type terminals and N-type lines is called an ON system. Up to 24 channels can be provided by this method. An ON junction is available to permit convenient interconnection of cable and open-wire facilities. In addition, ON-type system signals can be multiplexed by standard arrangements to provide for the transmission of 96 channels on microwave radio systems.

In 1929, the initial patent for a coaxial cable transmission system was granted. Cable and system development work continued from that time until 1941 when the L1 coaxial system was placed in service. Initially, the L1 system provided transmission for 480 (later expanded to 600) 4-kHz message channels using separate coaxial units for each direction of transmission. The continuing development of coaxial systems has produced the 1860-channel L3 system (1953), the 3600-channel L4 system (1967), and the 10,800-channel L5 system (1974). The L5 system is currently being expanded to a capacity of 22 600-channel mastergroups (13,200 channels).

Design improvements in active devices, components, and systems have been paralleled by improvements in the performance and capabilities of the transmission media. From open wire, progress has been made in conductor, insulation, and sheath designs of cables and numerous advances have been made in all aspects of coaxial cable design.

## Radio Transmission Systems

Early theoretical studies pointed to the possibility of using the earth's atmosphere as a transmission medium. The invention and development of the electron tube opened the way not only to cable carrier system development but also to the exploitation of the atmosphere for radio transmission methods.

In 1915, significant experimentation in communication by radio was started. One of the principal objectives, at first, was to provide a means for communications between the United States and Europe. By 1923, the basic feasibility had been established and intensive work was underway [1]. The first transatlantic commercial telephone service was established in 1927 when a long-wave (57-kHz) system was put into service between the United States and Great Britain. This system employed single sideband transmission with suppressed carrier [2]. In 1928, short-wave systems were installed to operate in the 3- to 30-MHz range and service was expanded to all parts of the world. In the 1950s, overseas service was largely taken over by submarine cable transmission systems [3, 4].

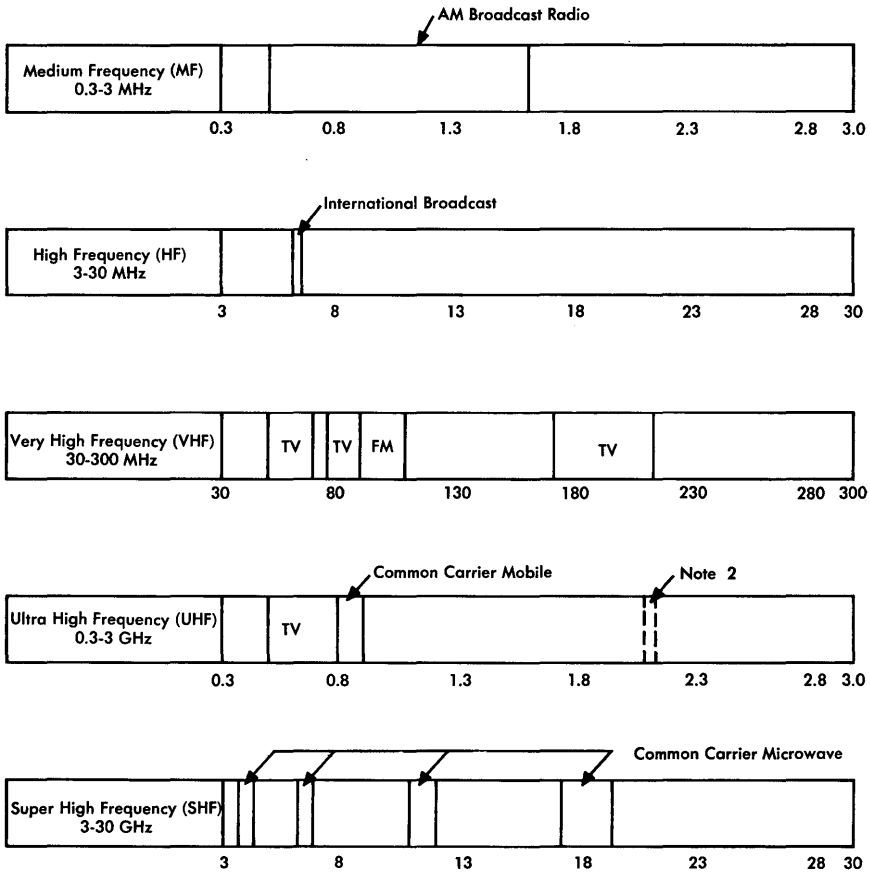
During this period, radio transmission capability was also developed for a number of mobile services. These included high-seas ship-to-shore communication, coastal-harbor service (ship-to-ship and ship-to-shore), and mobile radio telephony to moving vehicles including automobiles, trains, and aircraft. Most important, from the point of view of modern communications, was the development of microwave radio systems.

Microwave system development was stimulated significantly by World War II developments of radar and microwave components. There was some microwave transmission system work done for military applications and in preparation for the tremendous growth in communications services anticipated for the early post-war years. This growth quickly materialized; it was stimulated by the pent-up demand for services that could not be satisfied during the war and by the introduction and rapid growth of television. The first experimental microwave radio system, called TDX, was installed between New York and Boston and service was begun in May, 1948. This system was manufactured commercially as the TD-2 System [5]. It is now the most widely used long-haul transmission system in the United States.

Many microwave systems have been developed to fill service needs in long-haul and short-haul applications. These have been designed to operate in a number of frequency bands specified for common carrier use. Since the medium must be shared by many users of communication services, the allocation of frequency bands and the design and use of radio transmission equipment in the United States are subject to licensing and control by the Federal Communications Commission. The frequency bands allocated for various types of services must con-

form to agreements made by member nations of the International Telecommunication Union through its World Administrative Radio Conferences. Figure 1-1 shows the principal bands and some of the services allocated to various portions of the bands [6, 7].

Microwave radio systems have successfully filled a growing need for telecommunications circuits. They presently carry all of the inter-urban broadcast network television signals and a majority of the



- Notes:
1. The very low (VLF), low (LF), and extremely high frequency (EHF) allocations are not shown.
  2. Common carrier microwave and space telecommand signals share allocations in the bands from 2.110 to 2.130 and from 2.160 to 2.180 GHz.

Figure 1-1. Some radio-frequency spectrum allocations.



telephone, data, and other signals in the long-haul toll plant. Long repeater spacing, typically 25 miles, and ease of growth have given such systems substantial economic advantages over other types. Some limitations on this form of communication may be brought about by crowding of the radio frequency spectrum and the increased concentration of circuits but, as will be seen in subsequent chapters, considerable further growth of microwave radio may still be expected through improved techniques and more efficient use of the medium.

### Pulse Transmission Systems

Some of the earliest attempts to transmit speech and music signals electrically involved efforts to code the signals into a pulse format and then to transmit the signal by telegraph [8]. These attempts were thwarted by the primitive technology of the times. Furthermore, devices were not available to facilitate advanced experimentation with coding techniques. Digital modes of transmission and digital processing of analog signals were delayed until more recent times although digital data signals were often transmitted over analog systems.

While the evolving electron tube technology permitted some advances in digital techniques [9], the most significant event leading to the application of pulse code modulation (PCM) techniques was the invention of the transistor in 1948. The operating speed, size, low power dissipation, and low cost of transistors and other solid-state devices facilitated the design of practical and economical circuits for the digital mode of transmission.

In the Bell System, progress in pulse code modulation and regenerative repeatered transmission line operation has advanced steadily since the transistor became a practical reality. During the late 1950s, an experimental 1.544-megabit-per-second system was designed [10]. This system, later designated the T1 Carrier System, was capable of transmitting simultaneously 24 voice signals which had been processed by pulse coding and time division multiplexing [11]. It was put in service in 1961 and now provides much of the circuit growth in typical metropolitan areas. As system costs have been reduced, T1 has proven to be economical at shorter and shorter trunk lengths relative to other types of facilities.

Work on digital modes of transmission has expanded to higher capacity systems capable of transmitting over longer distances. In 1972, the T2 Carrier System was introduced and provided 96 channels of toll quality on a 6.3 megabit-per-second pulse stream [12]. In 1975,

the T4M system was installed as the first high-speed system to operate on coaxial cable. The T4M, designed for use in metropolitan areas, can carry 168 T1 system line signals, thus providing 4032 voice-grade channels. Systems that operate at even higher rates appear to be feasible and are under study [13].

The development of coding and multiplexing equipment for use with multimegabit transmission systems has kept pace with development of the line equipment. One example is that of the D2 channel bank which processes 96 individual voiceband signals into four 1.544 Mb/s bit streams [14]. These signals, designated DS-1 in the digital hierarchy, may be transmitted separately over four T1-type systems. In addition, any combination of four DS-1 signals may be combined by an M12 multiplexer into a single 6.3 Mb/s bit stream to form a DS-2 signal.

Digital transmission systems have proven to be effective for the transmission of analog signals that have been converted to a digital format. Although PCM systems are not as efficient as analog FDM systems for a given bandwidth, they tend to be more economical than the analog FDM systems on paired cable facilities due to lower terminal and line costs and substantially lower cost of providing signalling. Furthermore, regenerative repeatered line noise is low and virtually independent of line length; hence, PCM idle circuit noise is usually lower than that of analog FDM circuits. This has been especially beneficial in the noisy local plant environment. Regenerative repeatered lines are also more efficient for transmitting most forms of digital data signals.

Digital signals are being adapted for transmission over analog facilities and to provide rural service. The introduction of the time division No. 4 ESS has given added impetus to the need for economical analog-digital interface arrangements.

### 1-3 VIDEO TRANSMISSION

Transmission of pictorial matter by electrical means was the subject of research for many years before practical systems evolved. Proposed methods of converting picture information to electrical signals and electrical signals to pictures included a large number of electromechanical and electrochemical processes. Much research was spent on light sensitive materials that could be used in these processes and in the use of ink and photographic processes for use in the re-

ceiving equipment. Synchronization and scanning were recognized as important ingredients of the overall problem and solutions were sought in the applications of tuning forks and pendulums to these processes [15].

Many of the transmission means that were proposed in the early investigations were made to work, some of them quite well. However, development of the first economically feasible system for general commercial application had to await the invention and development of electron tubes. Telephotograph transmission of commercially acceptable still pictures was begun in the United States in 1925. Demonstrations of the new system were given by transmitting pictures of the 1924 Democratic and Republican National Conventions and large-scale demonstrations were given in early 1925 when pictures of President Coolidge's inauguration were transmitted successfully from Washington to New York, Chicago, and San Francisco [16].

As work progressed toward the successful transmission of still pictures, research was going forward to achieve true television transmission, that is, the direct conversion of a live action scene to an electrical signal format and its reproduction at a remote location. Success in these efforts came with the invention of the cathode ray tube. The first public demonstration of television signal transmission took place in 1927 [17] but commercial possibilities did not emerge until the early 1940s.

Continued development of these possibilities was essentially halted during the years of World War II but in the immediate post-war era, television came into its own. With improved camera and viewing equipment, the quality of received pictures became quite acceptable and new emphasis had to be placed on methods of signal transmission over long distances. Concurrently, picture standards had to be established and, particularly with the anticipated introduction of color signal transmission, an industry-wide National Television System Committee (NTSC) was formed to control the evolving signal format [18].

Systems have been developed for the transmission of baseband monochrome and color television signals over intracity wire facilities. These systems were initially designed to use electron tubes but have since been redesigned to use solid-state components. Shielded conductor pairs are used in lieu of the more expensive coaxial cable conductors. Portable microwave radio systems are also used in some instances.

The local distribution by the Bell System of television program signals has assumed high importance to the television industry. The availability of baseband transmission systems and facilities for switching, monitoring, and operating local television networks has made operations much more economical than would be possible if the industry had to furnish these facilities.

Experimental long distance service over microwave radio began in November 1947 on the New York-to-Boston TDX system. This service is now provided over a nationwide network of microwave systems. Baseband signals are delivered by a baseband system from the broadcaster directly to the microwave radio transmitter and are returned to the broadcaster at the receiving end by a baseband system connected at the output of the radio receiver. Sometimes the baseband signals are switched at a television operating center (TOC) where network configurations may be changed to satisfy broadcaster needs or to make more efficient use of transmission facilities.

The L1 and L3 coaxial transmission systems were initially designed to permit television signal transmission but, with one exception, are no longer used for this purpose. Transmission performance is superior on microwave radio systems and costs are lower.

Telephotograph and a variety of facsimile services are provided over voiceband circuits. Except for special equalization of some circuits, the Bell System provides little equipment that is especially devoted to these services.

PICTUREPHONE® signal transmission is in its infancy. A transmission plan for this new service has been proposed and many elements of a network have been developed [19]. However, it is difficult to predict when final characteristics that satisfy the needs of the public will be determined.

#### 1-4 MAINTENANCE AND RELIABILITY

By modern standards, early transmission facilities were simple in concept and simple to operate. The problems of providing adequate maintenance and reliability were correspondingly simple and straightforward. As the plant has become more complex, it has been necessary to think of maintenance and reliability in terms of their being integrated into the overall plant and into the design, operation, and installation of specific systems. The impact of growth alone has had

serious repercussions on maintenance and reliability. Disastrous troubles can affect great numbers of circuits and because of complex system interrelationships, the effects of such troubles may become very widespread. The introduction of machine switching and direct distance dialing have to a large extent removed the operator, an important monitor of transmission performance, from the network. As a result, when performance is below par on a connection, it is difficult to determine the source of trouble since the connection is lost when the call is terminated. Thus, there is a need for routine trunk testing that is most efficiently filled by various forms of automated testing. Some automated loop testing has also been introduced in order to reduce manpower requirements for maintenance operations.

As analog and digital carrier systems have increased in capacity, complexity, and design sophistication, the need for improved and simplified facility maintenance and reliability has also increased. For example, a fully equipped (18 mastergroups) L5 coaxial system carries 180 supergroup pilots, 900 group pilots, 18 mastergroup pilots, 3 multimastergroup pilots, and several line pilots to control the gain regulation of the line and associated multiplex equipment. In addition, other single-frequency signals are used for L5 line maintenance features. These multiple maintenance and control features may interact in ways that would make manual methods of measurement and analysis very difficult. Therefore, most modern systems contain automatic equipment which aids maintenance personnel in identifying, isolating, and repairing troubles. Most new transmission system equipment is designed in the form of plug-in units and test procedures and equipment are designed to identify defective units. Thus, new pretested units may be quickly and easily substituted in order to restore circuits to service most expeditiously.

Many special bays and special designs of equipment have been developed to provide test access to switched network and special services circuits through plugs and jacks or by switching arrangements. Among these special arrangements are emergency broadband restoration centers which permit the interconnection of broadband carrier facilities in such a way that service from failed systems can be restored by patching or switching to protection line facilities.

The entire field of maintenance operations and reliability procedures is supplemented by maintenance support systems and equipment. These include special systems for communications (speech or

data) among maintenance personnel. Alarm functions are provided in all operating systems and provision is made to transmit alarms from remote unattended stations to central maintenance locations for analysis and action. Trunk processing circuits are provided so that, in the event of failure, the failed trunks are taken out of service, made busy so they cannot be seized, processed so that unwarranted charges are not made for calls affected by the failure, and then restored to service when the trouble condition is eliminated.

## 1-5 FACILITY SELECTION AND APPLICATION

In planning for the introduction or installation of new transmission facilities, a choice must be made from among a number of alternatives. As a general rule, the available choices have been designed for use in a particular field of application such as the loop plant or the trunk plant. These fields of application tend to overlap and the choice must usually be based on an analysis of many criteria.

One feature that often influences the choice of facilities is the steady growth and expansion of the plant. Inevitably, when new installations are under consideration, plant growth and expansion and the resulting interactions between the new plant and the old must be considered. The growth may be due to an increase in traffic caused by expansion of population centers or industrial park areas. Growth may also be strongly influenced by changes in technology, by increased service offerings, by a lower rate structure, or by shifts in the economic status of an area. These factors all interact and it is virtually impossible to consider any one without considering the impact of the others.

### Growth Factors

Population density and distribution and related community-of-interest factors have a major effect on the way in which the telephone plant is organized and, therefore, on the selection of transmission facilities that must be provided. In addition to these geographical factors which influence the organization and growth, other factors that affect the facility network relate to the scope and diversity of services.

**Population Effects.** Figure 1-2 shows a medium size city,  $C_a$ , with a number of surrounding suburban towns,  $S_1$  to  $S_8$ , all located within a radius of about 25 miles. Each suburb is assumed to be large enough

to be served by a separate switching machine. Examination shows that any of the suburban communities may be interconnected by no more than two tandem trunks through the hub at  $C_a$ . In addition, some of these suburbs have a community of interest great enough to justify direct trunks as shown between  $S_1$  and  $S_2$ ,  $S_3$  and  $S_6$ ,  $S_4$  and  $S_6$ ,  $S_5$  and  $S_6$ , and  $S_7$  and  $S_8$ .

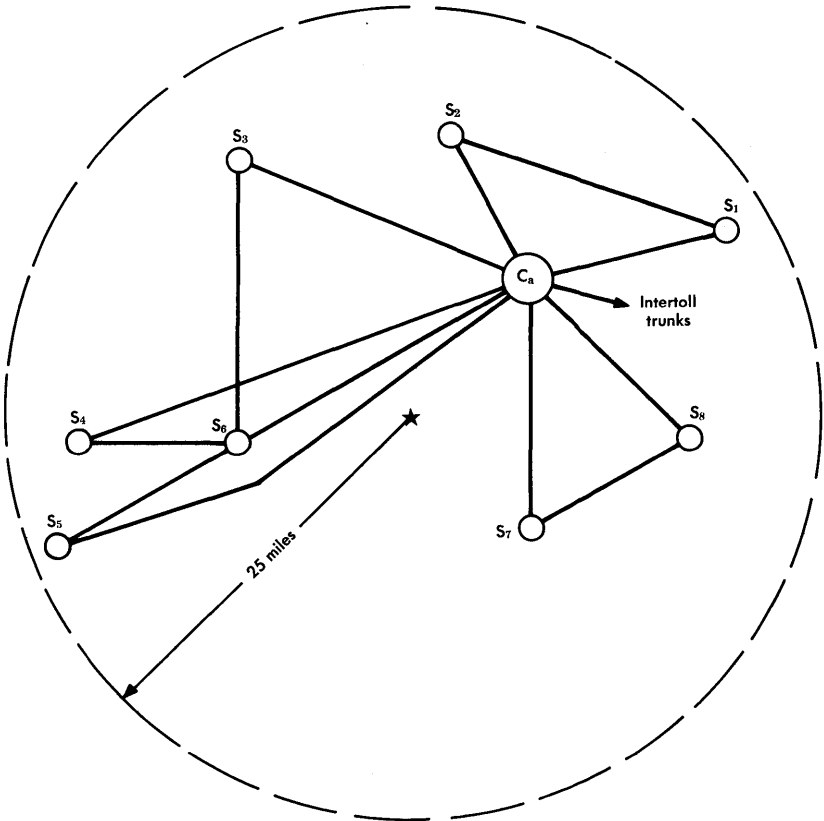


Figure 1-2. Illustrative city-suburban population distribution and telephone trunking.

In a highly developed area such as that depicted in Figure 1-2, distances are short. Most of the trunks shown would be between five and ten miles long with a few, like those between  $S_4$  and  $C_a$  and  $S_5$  and  $C_a$ , 25 to 30 miles long. It is possible that service in this area

is provided by voice-frequency trunks. As the area continues to grow, the problem might be that of deciding whether to install more cable facilities or to start using N- or T-type short-haul carrier systems. However, there may already be a substantial number of N-type carrier systems between  $S_5$  and  $C_a$ . If there appears to be a high probability that the anticipated growth of an industrial park area at  $S_5$  will create a demand for wideband data service, the question of converting one or more cables in the route from N-type to T-type carrier must be considered. Any such set of problems may be further complicated by the increasingly congested conditions in cable ducts, a major highway construction program, or public opinion pressure to convert pole-line cable to out-of-sight facilities.

The area depicted in Figure 1-3 and the problems encountered are quite different from those of Figure 1-2. In Figure 1-3,  $C_b$  is a small city in a predominantly rural area. It is easy to imagine the rural towns and villages,  $r_1$  through  $r_4$ , spread out over a considerable distance, perhaps along a navigable river. Between  $r_2$  and  $r_3$  there may be some natural barrier which prevents the development of a strong community of interest and which makes direct trunking between the two communities uneconomical. Thus, calls between  $r_2$  and  $r_3$  are routed through  $C_b$  in spite of the longer distance involved.

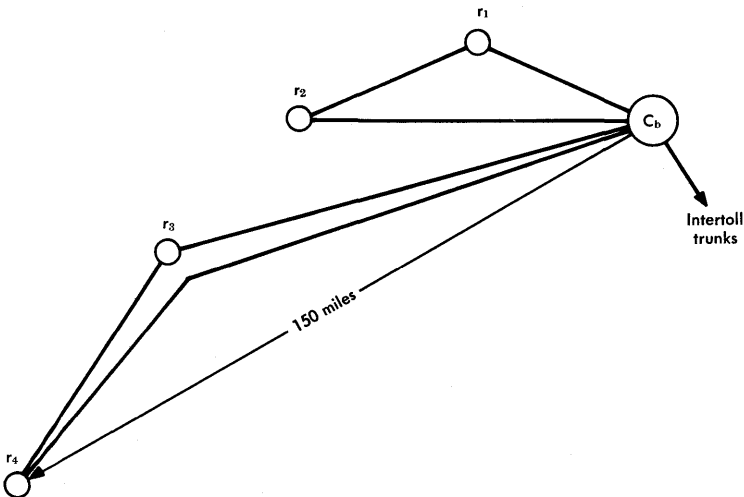


Figure 1-3. Illustrative population distribution and telephone trunking for small city and rural environs.



In the remote rural areas, service requirements might be met by open-wire installations. However, facilities used in areas typified by Figure 1-3 would most likely be loaded voice-frequency cables or N-type or T-type carrier systems. The trunks may be direct, tandem, toll connecting, or intertoll depending on the specific conditions in the area and their relation to the DDD network hierarchy.

The simple examples discussed are multiplied in many dimensions when facility planning is undertaken on a larger scale. The congested area of Figure 1-2 may be expanded, for example, to represent the crowded northeast corner of the country, the Boston-Washington-Chicago triangle and the geography of Figure 1-3 could be expanded to represent the sparsely-populated plains states and the mountainous areas of the west. Urban, suburban, and rural areas all present different problems in the planning and implementation of facility networks. Different compromises must be made in providing trunks between switching machines, the types of transmission facilities, and the plant and outside plant to be used. Equally affected are the facility choices that must be made for feeder and distribution cables in the loop plant. As new cables are installed, the cable size and design plan must be selected to provide the most economical solution. Where long loops are involved, consideration must also be given to the use of electronic devices and systems that may provide acceptable service.

**Service Effects.** In addition to creating demand for more service and more facilities, population growth brings other related effects. The nature of the growth may bring significant changes in community relationships that require different trunking patterns between central offices. For example, the trunking pattern must be changed when a new switching machine is added to the network.

Another effect related to facility growth is an increase in the amount and kind of services provided in an area. With an increase in overall standard of living, many people desire to upgrade their service from multiple party to two-party or individual line service. Such upgrades require additional loop facilities and the accompanying increase in calling rate makes trunk facilities necessary. Growth of *extended area service*, the area over which unlimited calls may be placed or within which local message units are counted, also stimulates calling rates and leads to the need for more facilities.

As areas grow and business becomes more diverse, the demand for a greater variety of services increases. Some of these services

have stringent transmission requirements particularly in the field of data communications. This diversity demands the provision of more sophisticated switching machines and improved transmission facilities that can meet modern requirements for both the message network and for a wide variety of special services.

### Facility Forecasts

The process of providing new and expanded transmission facilities is based on spare facilities in place, availability of new types of facilities, and forecasts of needs. While the plant is administratively divided into two parts, loop and trunk, there are many special services circuits that share both parts. Thus, forecasts must include special services needs in addition to loop and trunk needs.

The loop plant must be under constant scrutiny to determine when it is necessary and timely to install new facilities in response to growth or other changes. Regular forecasts are made of new demands for station sets and other customer premises equipment. These forecasts are based on information obtained from many sources such as building permits issued by local communities, plans announced by builders and developers, and the types of new building construction anticipated. In newly developed areas, the latter information affects the types of anticipated services such as residence, business, PBX, coin, etc. The forecasts and proposed facility construction must be related to the type of central office and related limitations on transmission and signalling ranges. The condition of existing facilities and related underground and overhead structures and the extent to which these facilities are in use must also be taken into account.

The statistics of trunk and trunk facility growth are under continuous study. As the switched network expands, traffic engineering studies are made to determine how and when new switching facilities are to be installed. Special services circuit forecasts, which take into consideration the possible effects of new service offerings and changes in applicable tariffs, must also be included in the facility studies. From combinations of such studies of traffic network and special services circuit growth, forecasts are made of trunk and trunk facility needs.

Newly installed trunk facilities must be compatible with existing central offices and with planned central office installations. The capacity of existing plant and the expected date of exhaustion of

spare capacity must be taken into account. Transmission and signaling objectives and the related performance of proposed facilities must also be considered.

## 1-6 ENGINEERING CONSIDERATIONS

The selection of facilities to replace or to augment existing facilities must be based on the results of thorough studies and on sound engineering judgment. The decisions are influenced by economic and technological factors.

### Economics

Before new facilities are provided, studies must be made to determine which of several alternatives is most economical. Economics must also be considered when new systems are to be developed. The question then is whether the development costs can be recovered within a reasonable time.

When new loop or trunk facilities are under consideration, the question of introducing carrier systems along a route previously served only by voice-frequency cable facilities must be examined. In general, the carrier systems make more efficient use of transmission media because a number of channels can be provided simultaneously by multiplexing techniques. The cost relationships involve the substitution of electronics for copper, i.e., line repeaters and terminal equipment for additional cable pairs. Efficiency in using the transmission media can only be achieved at the expense of the increased terminal costs incurred by the necessary use of multiplexing equipment. Improved maintenance techniques, increased craft training, and increased service protection and emergency restoration must also be introduced.

Cost relationships in such cases are sometimes quite complex but, in general, the results of cost analyses tend to favor carrier systems when distances are great and cross sections are large. Under these conditions, line costs are greater than terminal costs and emphasis is placed on maximizing the efficiency of utilization of the medium. When distances are short and cross sections are small, terminal costs are dominant and the economic balance often favors cable facilities. Each case is affected differently by local conditions and must be studied on its own merits.

The design, operation, application, and maintenance of all types of systems and their interactions with environmental conditions also carry economic implications. For example, there is growing pressure to change some of the basic criteria of telephone building construction in an effort to improve the efficiency of plant design. Most equipment designs in the past were based on a ceiling height of about 14 feet and the standard equipment bay height was 11 feet, 6 inches. Recent technological advances have resulted in increased density of components on these equipment bays. Growth of plant has, in addition, created difficult problems of congestion of cabling and wiring between equipment units. These factors combine to make a 7-foot bay height appear much more attractive. Floor loading, cable and wire distribution, and maintenance requirements (narrower aisles and lack of need for ladders) have all been made more manageable by the lower bay height.

In addition, efforts to improve the efficiency of plant design have led to new equipment arrangements that have provided for mounting functionally related equipment units on bays specifically designed for this purpose. The arrangements result in less office cabling and therefore less cable congestion, space savings, improved maintenance capabilities, and lower overall costs [20].

Although economic analyses play an important role in decision-making when new facilities are required, some decisions are made in response to other forces. Plant integrity and survivability may lead to the selection of multiple routes and facility types that provide diversity and increase overall reliability. Uniformity of plant might be sacrificed and a higher price might be paid in order to satisfy particular service reliability requirements. The pressure of public opinion might lead to the use of out-of-sight plant in preference to new or added pole-line construction. In this instance, economic advantages might be marginal at best; the use of out-of-sight plant is generally more costly than the use of more conventional installations.

The economic solutions to loop facility problems involve the selection of optimum wire gauges for both feeder and distribution cables. Depending on the nature of the geographical area, the design plan must be selected from among those available, i.e., resistance, uni-gauge, or long route design. Consideration must be given to the use of carrier systems, range extension equipment, repeaters, etc., to

offset the cost of additional cable, large wire gauge, or loading. The choice must be made in a manner consistent with long range planning studies.

For trunk facilities, many of the same factors must be considered. In addition, the reuse or rearrangement of facilities often offers an attractive solution.

### Technology

The continuing shift from analog to digital technology is an example of how new technology interacts with the facility provision process. Pressures for the development and application of new systems, new concepts of operation, and new services occur with evolving technology to create demands for new ways of organizing systems and facilities.

Much of the growth of communications technology in this century can be traced to research in physics and chemistry. From this research have come the new devices and new materials which have formed the basis for most of the dramatic advances in telecommunications. These advances have made possible much wider bandwidths for analog transmission and have enabled much higher rates of digital signal transmission.

Recent developments in digital transmission and time division switching have made possible the long-predicted combination of these two techniques. Research studies in this area culminated in the construction of a laboratory model of an experimental system described in the late 1950s [21]. While this experiment was deemed to be a successful demonstration of the feasibility of combining the time division switching and transmission functions, practical implementation in the field had to await the accumulation of additional experience in developing, designing, and applying the concepts to each of the two fields separately. Some of the techniques which have helped to achieve these goals have been incorporated into a digital toll switching system [22].

With these advances, new modes of operation of the network must be considered. Time division switching is four wire; thus, as integrated systems come into use, intertoll transmission circuits will become more and more heavily oriented toward four-wire transmission from end to end. Concepts of network operation will also have to change in order to adapt to these new systems. It is highly probable

that the via net loss design of the network will be changed with most trunks operating as fixed loss digital trunks in an integrated system.

Another interplay among technological and other forces may be called mutual stimulation. Significant improvement in performance stimulates more frequent use of a service which in turn stimulates the installation of new systems and facilities. The improved performance in transoceanic telephony with the installation of the first repeatered submarine cable system and the accompanying increase in traffic is a case in point. Additional systems of advanced design have now been installed in all oceans, new technology has permitted the initiation of transmission by satellite, costs per unit circuit have come down, and international traffic is still rapidly increasing. Similarly, the mutual stimulation of digital services and digital systems has fostered rapid growth which has been supported by advances in the technology.

The facilities used in the Bell System are in a constant state of flux. Old systems wear out or become obsolete and must be continually repaired and ultimately replaced. New technology brings into being new systems and techniques such as digital transmission systems and the use of waveguide as a transmission medium. The expanding demands for more facilities at lower cost and the introduction of new services insistently leads to a demand for new systems, new procedures, and new ways of organizing the network.

Certain services have been provided for many years but are continually expanding. Examples are the growth of extended area service in the local plant and the extension of customer dialing of long distance calls to international services. The demand for digital data services has led to the introduction of the Digital Data System, a network of data transmission facilities which is being integrated with existing facilities used for message network and special services.

All these forces of growth, change, and replacement require the application of a high level of expertise in building, operating, and managing the plant. A snapshot view of the systems and facilities available at any given time is certain to become out-dated within a relatively short time. The evolutionary nature of the plant requires much planning for the future since all new systems must be integrated into the existing plant and must be compatible with what is already in service [23]. Adequate responses to the pressures of change can only come about by careful planning.

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## Chapter 2

# Transmission Media

The transmission of communications signals between two points must involve the use of some interconnecting medium. This medium may constrain and guide the signals in some manner or may permit the signals to be transmitted in an unguided or semi-guided manner. Examples of guided wave media are shielded and nonshielded pairs of wires that may be installed individually or combined in cables with other pairs, coaxial conductors, and wave guides. The atmosphere and the void of space provide unguided media for the transmission of radio signals. These media may be used for the broadcast of signals in all directions or, with directional antennas, for the transmission of signals within a controlled narrow beam between the transmitting and receiving devices.

Individual pairs of conductors in the form of open-wire lines have been giving way to other forms of media for many years. Thus, the treatment here of open-wire lines is brief and superficial to allow more thorough discussion of shielded and nonshielded cable pairs and of coaxial conductors. The designs of cables in which such conductors are combined vary significantly according to the field of application. Requirements depend on whether these cables are to be used in local or toll portions of the network.

Radio communication may be implemented in any portion of a very wide spectrum of frequencies. Allocations of the spectrum to various uses are controlled in the United States by the Federal Communications Commission. Discussion here is confined to the characterization of the medium and its exploitation in those bands allocated to common carrier services. The discussion of waveguide transmission is confined to its applications in microwave radio systems.

## 2-1 OPEN WIRE

Open-wire lines have been largely supplanted as loop and trunk facilities in most locations by various forms of paired cable or multiple line wire which may be carried on poles or buried in the ground. For this reason, only a summary of open-wire characteristics is presented [1]. A typical open-wire line, usually consisting of bare copper wires 0.165, 0.128, 0.104, or 0.080 inch in diameter, is supported on utility poles spaced about 40 to the mile.

All open-wire pairs are transposed (frogged) in predetermined patterns to minimize their susceptibility to crosstalk from other pairs and to noise from nearby power lines. The transposition pattern provides, ideally, for each pair to have equal positive and negative exposures to power lines and to all other pairs. In practice, regularity in pole spacing, wire sag, and alignment of crossarms is important in achieving sufficiently close balance of the two polarities of exposure.

Variations from the standard open-wire line are numerous: (1) long-span construction (saves poles and pole placement but requires stronger wire or copper-clad steel in some situations), (2) use of galvanized steel wire, (3) closer spacing of the wires of a pair, (4) greater separation of pairs on crossarms, (5) greater spacing of crossarms, and (6) the use of more transpositions. All except (1) and (2) are used in order to control crosstalk, which became of increasing importance as carrier systems, such as types C, J, and O, were applied to open-wire lines.

Open-wire lines have always been vulnerable to the effects of water, sleet, frost, and ice on transmission as well as on the physical structure. A considerable amount of reserve amplification is required to compensate for the effects on transmission, especially where carrier systems are used. In certain localities, corrosive components in the atmosphere have reacted with the wire, particularly at splices, to reduce conductivity and strength and to increase attenuation.

The development of cables carrying many pairs of insulated wires resolved many of the problems encountered in the use of open-wire lines as trunk facilities. Most open-wire lines have been supplanted by paired cables, coaxial cables, and microwave radio systems.

## 2-2 LOOP AND LOCAL TRUNK CABLES

Cables used for the provision of loops from central offices to subscriber locations are called loop cables. Cables used for trunks between

local central offices or between local offices and toll offices are called trunk cables. The several types of trunks and their uses in the general switching plan are discussed in Chapter 6 of Volume 3. Some cables have been used for both loops and trunks, usually as temporary expedients. The present trend is to avoid the dual use of cables although trunk cables may contain carrier as well as voice-frequency trunks. In addition, some local cables are produced with mixtures of shielded pairs or coaxial units and local loop or trunk pairs.

### Physical Characteristics

Most cable pairs in the local telephone plant are made up of copper wires twisted together, each wire insulated with strip or pulp paper or some type of plastic. Groups of such pairs, twisted (stranded) into a rope-like form are called *units*. The degree of pair twist in a unit is varied or staggered. The variation in twist tends to reduce crosstalk coupling in much the same manner as do transpositions in open-wire circuits. Several units are twisted together (cabled) to form a *cable core*. Although aluminum has a lower electrical conductivity than copper, it is sometimes used when copper is too expensive or in short supply.

Figure 2-1 shows the gauges of copper wire generally used and the corresponding gauges of aluminum wire that have the same resistance per unit length as the copper. Since aluminum pairs are more bulky than corresponding copper pairs, aluminum cables make less efficient use of duct space.

APPLICATIONS	WIRE GAUGE	
	COPPER	ALUMINUM
Special services circuits and carrier systems	19	17
Special services circuits, trunks, long loops, and carrier systems	22	20

Figure 2-1. Comparison of copper and aluminum wire usage.

Loop and local trunk cables are made in a number of standard sizes, which are designated by the number of pairs they contain. Figure 2-2 shows the range and number of cable sizes of the several available gauges for polyethylene-insulated conductors (PIC) and pulp-insulated conductors.

NUMBER OF PAIRS	CABLE GAUGES													
	WATERPROOF PIC					PIC					PULP-INSULATED			
	17*	19	20*	22	24	26	19	22	24	25	26	22	24	26
6		✓					✓							
11		✓		✓			✓	✓	✓†		✓†			
16		✓		✓			✓	✓	✓†		✓†			
25	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓			
50	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓			
75	✓	✓	✓	✓			✓	✓†	✓†		✓†			
100	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓			
150	✓	✓	✓	✓			✓	✓†	✓†		✓			
200	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓			
300	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓			
400			✓	✓	✓	✓		✓	✓	✓	✓			
600			✓	✓	✓	✓		✓	✓	✓	✓	✓		
900					✓	✓			✓		✓	✓	✓	✓
1200										✓		✓	✓	✓
1400										✓				
1500													✓	✓
1800										✓			✓	✓
2100														✓
2400														✓
2700														✓
3000														✓
3600														✓

✓/Available in 1977

\*Aluminum conductors; all others, copper

†All sheath types not available

Figure 2-2. Standard local cable sizes.

Each standard cable is made up of an array of cable units formed into a cable core by being twisted together around a common axis prior to being sheathed. The number of pairs per unit varies from 12 to 100 depending upon wire gauge and cable size. Although unit construction is the common type now used, cables of layered construction may still be found. In the layer design, pairs are configured in concentric layers each of which is given a different direction or degree of twist from that of the preceding layer.

Figure 2-3 shows the relative positions of the several units of a 600-pair 22-gauge cable in the cable cross section. Wire-insulating material and the binding strings around individual units are used in different colors for identification purposes. In cables using polyethylene insulation, every pair is color coded and can be identified visually at any splice without recourse to electrical testing. Earlier forms of color coding, used in paper and pulp-insulated local cables, did not provide for visual identification of specific pairs.

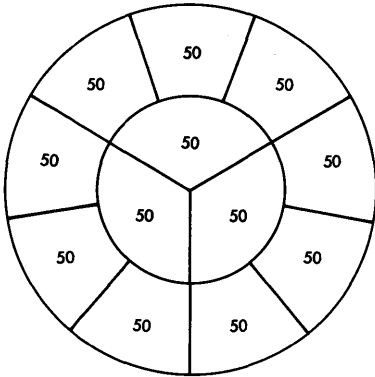


Figure 2-3. Location and form of 50-pair units in a 600-pair cable.

Insulation resistance between each conductor in a cable and all other conductors interconnected and grounded is required to be at least 500 megohm-miles (the product of the measured leakage resistance in megohms and the cable length in miles).

The basic requirements in dielectric strength of pulp- and polyethylene-insulated conductors are given in Figure 2-4. Insulation between cable core and sheath may be paper, polyethylene, rubbermylar, or combinations of these materials. Requirements for dielectric strength of core-to-sheath insulation range from 1.2 to 1.4

peak ac kV for paper core wrap to 20 kV dc for cables with an inner polyethylene jacket.

TYPE OF INSULATION	VOLTAGE, kV			
	19 GA	22 GA	24 GA	26 GA
Pulp (peak ac)	0.7	0.5	0.5	0.5
PIC (dc)	5	4	3	2.4

Figure 2-4. Conductor-to-conductor dielectric strength requirements.

Other materials are utilized for physical and electrical protection of cables. The lead sheaths of the older cables provide both waterproofing and electrical protection against noise induction. However, they are also subject to electrolytic corrosion at points of stray earth current leakage. Electrical drainage systems, installed to provide noncorrosive paths for such currents, have prevented damage at many points but it has seldom been economical to make such systems complex enough to be 100 percent effective. Many lead sheaths of underground cables, especially those in urban areas, ultimately admit moisture and the affected lengths of cable must be replaced.

Materials used outside the core insulation in newer cables include various combinations of (1) tacky waterproof coatings, (2) corrugated aluminum and steel shields, and (3) polyethylene jackets. The combination used depends on the cable application and on environmental conditions. The aluminum shields provide electrical protection against noise induction and the steel provides physical protection. Both shields are necessarily cut back at splice points but electrical continuity of the shields across splices is provided. Most loop and local trunk cables have outer jackets of polyethylene and are not subject to electrolytic corrosion.

### Transmission Characteristics

The properties of a cable pair that must be known in order to calculate circuit performance are *characteristic impedance* and *propagation constant*. These secondary constants are derived from the four primary constants, series resistance and inductance and shunt conductance and capacitance. The primary constants are expressed in values per unit length of the pair. To permit accurate transmission engineering on the basis of secondary constants, cable length, and

other derived parameters, the primary constants must be rigidly controlled during manufacture.

**Primary and Secondary Constants.** The relationships between the primary and secondary constants of a transmission line were developed in Chapter 5 of Volume 1. The constants are temperature and frequency dependent in some degree. It should be emphasized also that the primary and secondary constants at any frequency depend on the medium alone and are not affected by sending- or receiving-end impedance. On the other hand, the actual transmission from a source to a termination depends on the source and termination impedances as well as on the properties of the medium.

Figure 2-5 shows the relation between attenuation and frequency, Figure 2-6 shows the relation between delay and frequency, and Figure 2-7 shows the relation between characteristic impedance and frequency for 22-gauge cable pairs. The trends are similar for all gauges.

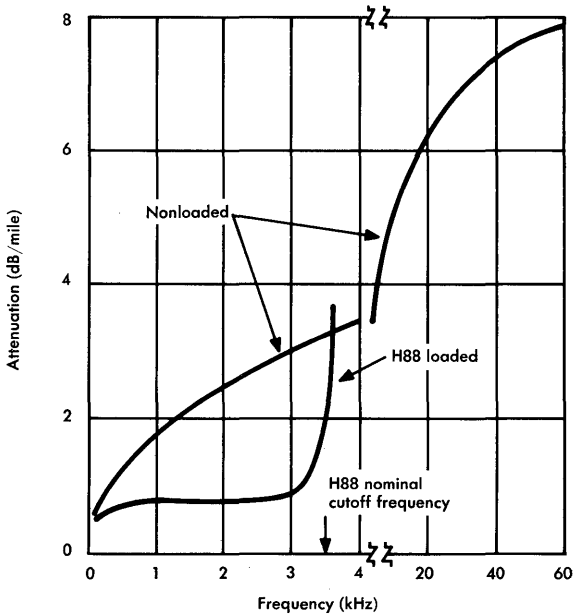


Figure 2-5. Attenuation/frequency characteristic of 22-gauge local cable pair.

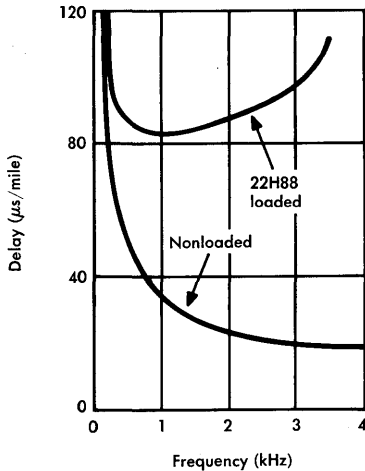


Figure 2-6. Delay/frequency characteristic of 22-gauge local cable pair.

area trunks (MAT). The MAT cable is designed for major metropolitan routes that may economically utilize 1400 or 1800 pair complements. Cable pairs are 25-gauge copper with expanded plastic insulation. Their transmission characteristics make them approximately equivalent to 22-gauge pulp-insulated cable pairs for T1 systems. When loaded, the 25-gauge pairs are equivalent to 24H88 loaded pairs for voice-frequency circuits. The lighter gauge conductors result in a slight penalty in respect to dc signalling performance on some circuits. The 25-gauge wire size was selected as a compromise for maximum compatibility with existing equipment that would, at the same time, yield a significant cost saving in respect to the use of copper. The new design produces characteristic impedances different from those of earlier designs; as a result, somewhat different terminating impedances must be used in the affected equipment. These impedances may be obtained by different adjustments in some existing equipment and design modifications in other equipment types.

**Crosstalk.** Coupling between pairs in the same cable is unavoidable and results in the transfer of a small amount of signal power from each energized pair to other pairs [2]. Although design and manufacture are effective in limiting the coupling to acceptable values,

A special low-capacitance (LOCAP) cable has been made available to provide reduced attenuation in cable pairs used for the T2 Digital System. These pairs have a nominal capacitance of 39 nF per mile (46 nF in waterproof cable) instead of the 83 nF per mile found in earlier designs. The LOCAP cables are made up of 22-gauge copper conductors insulated with dual expanded plastic. They are available with 26, 52, or 104 pairs.

Another low capacitance cable, introduced for use in metropolitan areas, is designed to optimize transmission performance for T1 carrier system applications and overall costs for all types of metropolitan



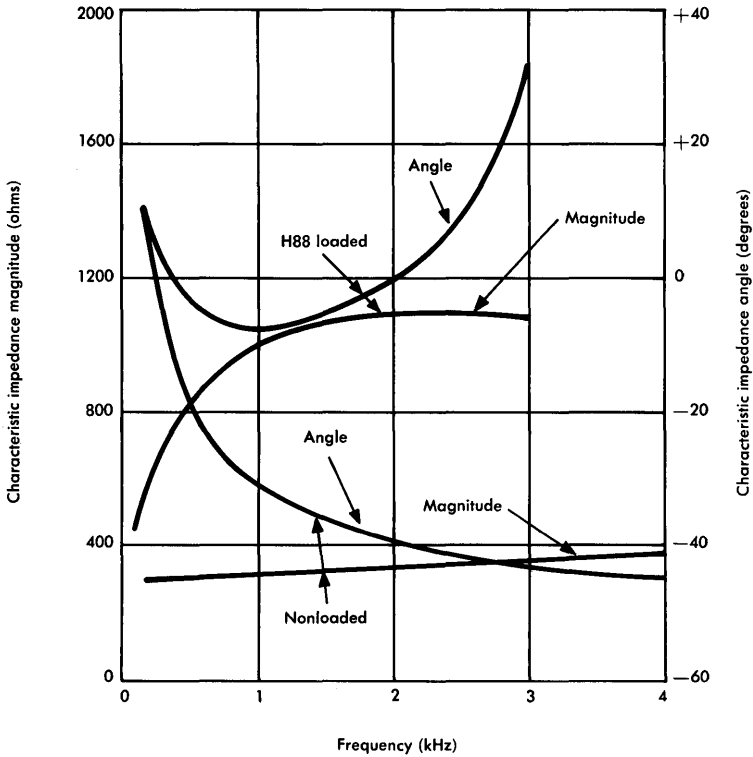


Figure 2-7. Characteristic impedances for 22-gauge cable pair.

crosstalk influences circuit design and system layout. For example, differences between signal amplitudes transmitted into a cable at a repeater point and the amplitudes received from the same cable at that point must be limited in order to control near-end crosstalk. This, in turn, limits the difference in amplitudes from a repeater output to the next repeater input and thereby establishes a repeater section loss limit. In some systems, such as the T-type, crosstalk limits performance.

Pulp-insulated loop and local trunk cables are designed with nine different lengths of pair-twist, or pitch, in order to guard against adjacent pairs having the same twist lengths. Each unit in a cable may be thought of as made up of several layers of pairs twisted

around a common axis with a common length of layer twist. A different twist length is used for every pair, up to 25 pairs, in a PIC-insulated cable.

If approved circuit designs are followed, annoying crosstalk usually occurs only when cables are damaged or when significant unbalance exists between pair conductors or between the conductors and ground. Crosstalk also occurs when two adjacent pairs are inadvertently split during splicing operations along the cable route, as shown at point A in Figure 2-8. If the error is detected and corrected at a subsequent splice, point B, in an attempt to compensate for the split at A, high coupling remains in the length A-B. Moreover, the usual dc tests made between the ends of the cable after splicing has been completed do not reveal the split. It is important, therefore, to avoid splitting pairs and, whenever split pairs are detected, to take immediate steps to correct the error at the splice where the error was made.

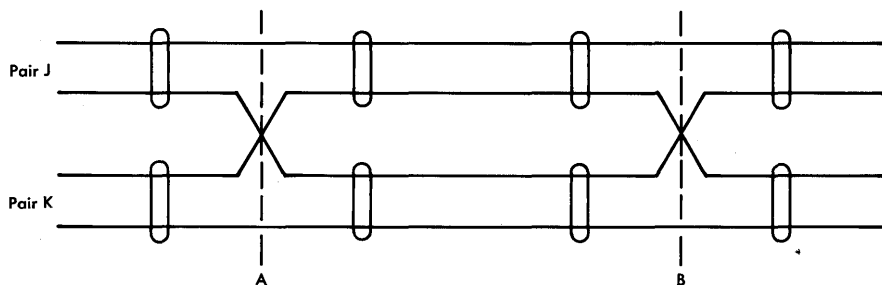


Figure 2-8. Split pairs.

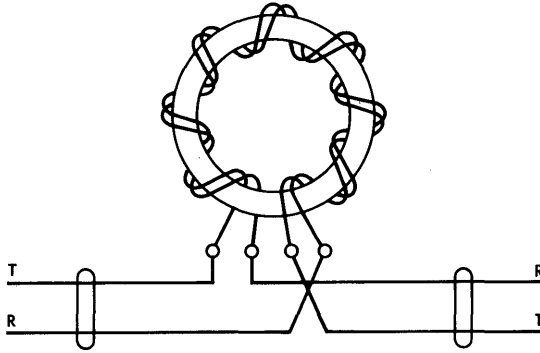
Crosstalk couplings at voice frequencies in local cables are generally controlled by design and manufacture to the extent that no special splicing procedures are required. For T-type carrier systems, however, it is sometimes necessary to use different cables for the two directions of transmission; with same-cable operation, it is necessary to select pairs for opposite directions of transmission according to carefully specified rules unless screened cable is used. Such cables have a shield between equal sets of binder groups which provides isolation between the two sets of binder groups.

**Inductive Loading.** Inductive loading of cable pairs is effective not only in reducing attenuation but also in making attenuation, impedance, and delay more uniform throughout the passband of the loading system [3]. These transmission improvements are obtained at the sacrifice of all frequencies outside the passband. Figures 2-5, 2-6, and 2-7 show the attenuation, delay, and characteristic impedance of 22-gauge H88-loaded pairs in comparison with the same characteristics of 22-gauge nonloaded pairs.

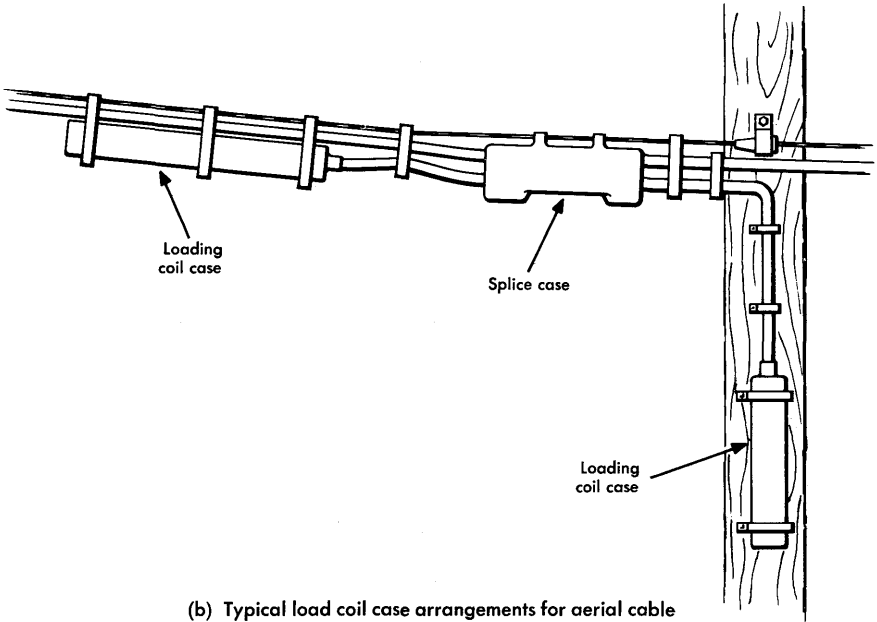
Load coils are made by winding two coils simultaneously on a core of high-permeability metal, one coil for each conductor of a pair. This bifilar method of winding ensures equal effects of the load coil inductances in the two wires of a pair and minimizes the likelihood of longitudinal unbalance. It also, by cancellation effects, reduces the danger of damage to the coils that might result from unwanted surge currents due to lightning or power system faults. The inductance of each winding alone is about one-fourth of the required total; the two windings are connected "series-aiding" in the circuit so that the total inductance is the sum of that of the two windings alone plus twice the mutual inductance. Since the total inductance is not independent of direct current flowing in the windings, allowance is made in design for the resulting decrease in inductance.

The bifilar method of winding load coils is illustrated in Figure 2-9(a). The complete coil with terminals has a volume of one to two cubic inches. Various quantities of coils, from 6 to 900, are housed in watertight cases to serve different needs. Coil connections are provided to a stub cable which can be spliced into the cable to be loaded. The cases may be mounted aerially or underground. A typical aerial installation is shown in Figure 2-9(b).

Structural regularity of a loaded cable pair is essential; irregularities such as misplaced or omitted load coils can make the pair useless for a repeatered two-wire trunk by seriously reducing echo return loss. Regularity of a loaded pair, however, can be no better than the uniformity of the capacitance,  $C$ , along the pair or the variations in load-coil values. For that reason, the cost of attaining more accurate load-coil spacing than afforded by following specified rules would not be justified [3]. Good factory control of capacitance and of load-coil inductance and good field control of load-coil



(a) Bifilar wound loading coil



(b) Typical load coil case arrangements for aerial cable

Figure 2-9. Typical loading coil and application.

spacing should provide adequate structural regularity for local area transmission.

When it is necessary to locate a load point out of limits, the affected load section is made shorter than normal and then built out to the

required length with a build-out capacitor (BOC) or a build-out lattice (BOL). The BOC is simply a capacitor shunted across the pair. Although it lacks series resistance, it is adequate for a short build-out and the resultant return loss is generally adequate for loop applications. For a trunk, a BOC may not provide adequate return loss and a BOL may be needed. The BOL is a network of two balanced resistors and two balanced capacitors configured as in Figure 2-10. Close matching of the two resistors and the two capacitors in the lattice is essential for maintaining longitudinal balance. The characteristic impedance is exactly the same as if the total capacitance of the crisscrossed branches were evenly distributed along the resistors. It is therefore an excellent approximation to real cable throughout the passband and may be used for simulating any length of cable up to

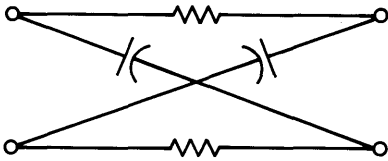


Figure 2-10. Build-out lattice.

the resemblance of the real pair to the ideal model in which load spacing, pair capacitance, and load-coil inductance all match the objectives perfectly in all load sections. Structural return loss is the ratio of the power of a signal sent into one end of a pair to the composite power reflected back to that end by all the small structural irregularities in the pair. The receiving end of the pair must be properly terminated in order to avoid mixing a reflection from that end with the structural reflections from within the pair. Since each reflection traverses a different distance, the components from the several reflections do not arrive in phase. Moreover, the relative phases and the relative magnitudes change continuously with frequency. Thus, a measurement at a single frequency is not a reliable indication of structural regularity. To overcome this difficulty, a mixture of many frequencies in the voiceband is used as a source and the structural return loss is measured directly with a return-loss measuring set.

a full load section with little or no degradation in return loss. The lattice is not used on loops since the resistors are subject to burn-out during loop breakdown tests.

**Return Loss.** Structural return loss is a convenient and sensitive measure of the structural quality of a loaded cable pair, that is, of

Results of such measurements on all newly loaded cable pairs are essential in judging the suitability of the pairs for service. If there

are no irregularities, the return losses for a complement should cluster around a figure not more than 2 dB under the expected median value and none should fall more than 3 dB below the actual median. Return losses below the general distribution usually should be located and corrected. Return losses higher than the general distribution do not signify irregularities.

The effect of load-spacing deviations on the structural return loss of normal 22-gauge H88-loaded pairs is illustrated in Figure 2-11. The return losses of polyethylene-insulated pairs are higher than those of paper-insulated pairs because it is practicable to control the capacitance constant of the former more closely as insulation is applied to the wires. The structural return losses expected for various loading systems, wire gauges, load-spacing deviations, average splicing lengths, and pair insulations are tabulated for engineering use.

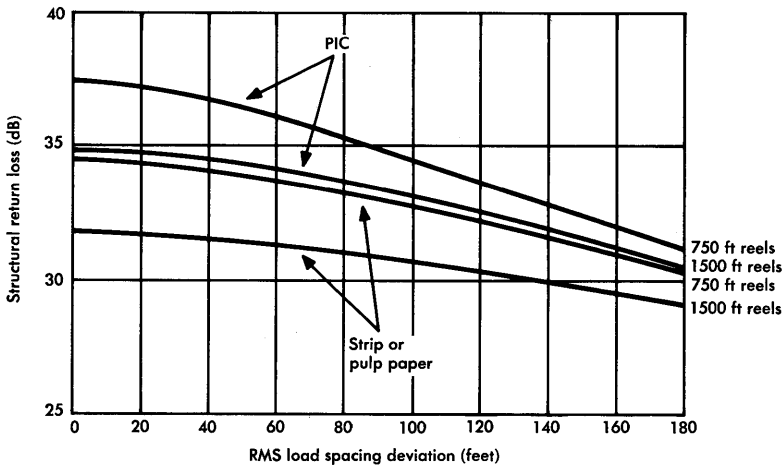


Figure 2-11. Expected median structural return losses in complements of 22-gauge H88 loaded pairs.

The cable between a central office and the first load coil is called an end section. In order to provide flexibility for connecting one loaded cable to another by way of cross-connection in a central office, end sections are usually made slightly less than half a load section in length so that the section including the path through the central office is a full load section.

**Velocity of Propagation.** The velocity of propagation over wire facilities is  $\omega/\beta$ , where  $\omega$  is the radian frequency and  $\beta$  is the phase con-

stant [3]. This velocity increases monotonically with frequency in nonloaded pairs. In loaded pairs, it reaches a maximum within the passband and then decreases as shown in Figure 2-12. Since echo tolerance decreases as echo delay increases, velocity of propagation is an important factor in long-haul transmission system design. Lengths for which loaded facilities can be used for such transmission without echo-suppressors are sharply limited.

### 2-3 TOLL TRUNK CABLES

Intertoll trunks carry traffic between class 4 or higher toll offices. Among other media, these trunks may use cable pairs equipped with T- or N-type carrier systems or coaxial cable units equipped with T- or L-type carrier systems. The trunks may also use cable pairs equipped as voice-frequency circuits.

#### Cable Pairs

Cable pairs formerly shared toll telephone traffic with open-wire lines. However, open-wire lines are now largely obsolete and cable pairs are used for trunks no longer than about 200 miles. Toll cable is still manufactured, mainly for replacing damaged sections of existing cables or for rerouting.

**Physical Characteristics.** Toll cable pairs are insulated with paper tape helically applied. Most of the pairs are twisted together, two pairs at a time, to form quads from which a phantom circuit (now rarely used) could be derived. In general, there are ten different quad types, as defined by the lengths, or pitches, of the pair twists and quad twists. Each type is keyed to a different combination of pair insulation colors.

A toll cable is formed of cylindrical layers of quads and pairs twisted helically around the cable axis. In order to keep the layers intact and the quads and pairs in order around the layers, adjacent layers are given opposite directions of rotation around the axis. This also prevents long adjacencies of pairs in different layers. All these design features are essential for control of crosstalk within and between quads and reduce coupling to noise sources both within and outside the cable.

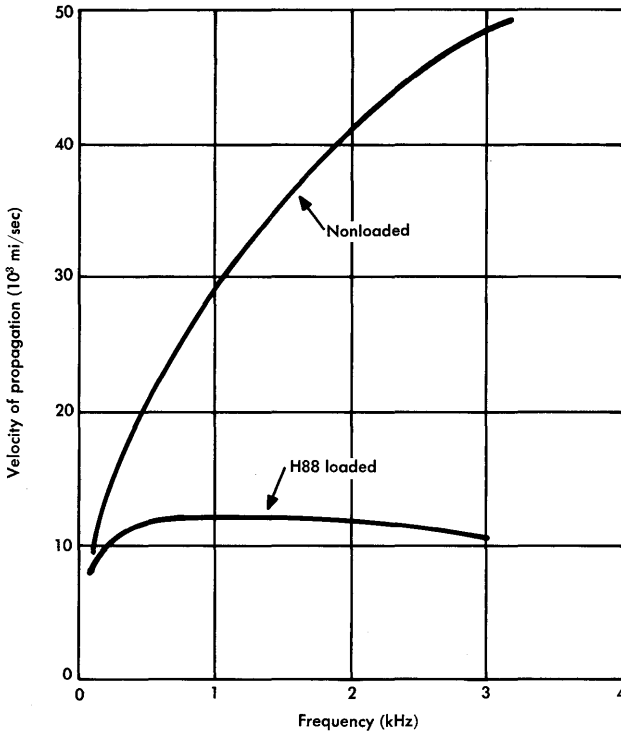


Figure 2-12. Velocity of propagation, 22-gauge cable pairs.

Copper wire gauges now being used in the manufacture of toll cables include 16 and 19 gauges for voice-frequency trunks and carrier systems. Nonquadded 16-gauge cable pairs are also provided for voice-frequency trunks and special services circuits. Cables with selected complements of numbers and gauges of pairs are available. Some of these have been retained in the wire-armored type so that replacements of existing sections do not require two cables in a submarine section.

A number of standard sheaths, provided to protect the cores, are specified according to the physical and electrical environments in which the cables are to be placed and the hazards to which they may be subjected. Electrical insulation may be provided by paper wrap or an inner polyethylene jacket on the core. Polyethylene is also used as an outer jacket for insulation and for physical protection. Physical



protection is also provided by corrugated steel sheaths or lead sheaths and by steel armor wires for submarine cables. Lead or one or two sheaths of aluminum are used to provide shielding against electrical induction. Thermoplastic compounds are used to prevent the penetration of moisture. Problems of electrolytic corrosion of lead sheaths are similar to those encountered in local cables.

Insulation between conductors of various designs of quadded toll cable pairs must withstand for two seconds a 60-Hz test voltage having approximately a sine-wave form and a peak value of 700 to 1100 volts. For cables that contain pairs for local applications, lower values apply; however, for wire armored cables, the requirements are somewhat higher especially where double strip-paper insulation is used.

Paper insulation is wrapped around the cores of quadded cables so that at least two thicknesses of paper lie between the core and the sheath. Cables with additional core insulation are available for use where extreme lightning conditions and high earth resistivity are prevalent. The required dielectric strength between core and sheath ranges from 1000 volts rms for normal dielectric strength lead-sheathed cable to 20,000 volts dc for lepeth or tolpeth-K sheathed cable. The lepeth sheath consists of several protective layers over the core, the most important of which is a polyethylene jacket, and an outside layer of extruded lead. The tolpeth-K sheath includes an inner polyethylene jacket, corrugated aluminum and steel shields, and an outer polyethylene jacket.

The minimum requirement for insulation resistance between each conductor and all other conductors plus sheath is 1000 megohm miles for a 60-second test. The average actually attained is about 20,000 megohm miles.

**Transmission Characteristics.** The principal difference between the electrical characteristics of toll and local cable pairs is the lower capacitance of toll cable pairs. As a result of the lower capacitance, toll pairs have a higher cutoff frequency when both are identically loaded. For example, 22-gauge local cable with 83 nF per mile cuts off at about 3500 Hz when H88-loaded; 19-gauge toll cable with 62 nF per mile cuts off at about 4000 Hz. Present production of standard toll cables is limited to 16 and 19 gauges.

The use of ten quad types with different pair-twists and quad-twists serves to control interquad crosstalk couplings in the same way that different pair twists control couplings in local cable. Continuous quad-adjacencies are limited to one splicing length by means of random and test splices in the field. Since quads must stay intact for entire repeater sections, test splices are made to reduce couplings within quads. This is done by measuring capacitance imbalances of all the quads in the lengths to be spliced and then by selecting and splicing the quads in such a way that the imbalances in one length tend to neutralize those in the other.

The loading of nonquadded toll pairs is quite similar to that of pairs in local cables. No allowance is made in manufacture for the effect of direct current on the load-coil inductance since such currents are not generally present on toll pairs. Load coils for toll cables have lower resistance than those used on local cables and generally have greater insulation resistance.

Structural uniformity is especially important in toll cables since toll trunks are longer than local trunks and require more amplification. The capacitance constant is well controlled in the factory and when load-coil spacing in the field is as well controlled, structural return losses are a few dB higher than those in local cables. Build-out of quadded cables is accomplished by using finer gauge quads in a calculated length of the main cable in order to increase the resistance and then adding the required capacitance by connecting a calculated length of stub cable in parallel with the main cable. The capacitance imbalance in the stub cable must be taken into account.

The relationship between velocity of propagation and frequency for toll pairs is the same as that shown for local cable pairs. Because of the lower capacitance, the velocity at 1 kHz is somewhat greater for 19-gauge toll cable pairs than that for local cable pairs (46,900 versus 29,300 miles per second for nonloaded pairs and 14,300 versus 12,000 miles per second for H88-loaded pairs).

**Shielded Conductors.** Some signals and systems are so sensitive to noise and crosstalk that the facilities used must be individually shielded. Video pairs, used for transmission of television signals in local areas, are a prime example.

The standard 16-gauge video pair consists of two copper conductors insulated with expanded polyethylene and twisted together with two expanded plastic fillers. The pair and fillers are helically wrapped with polyethylene tape followed by a longitudinal copper shield and a helically wrapped copper shield. An outer longitudinal crepe-paper wrapping is bound with continuous strings of rayon or cotton, colored for identification purposes. As with nonshielded conductors and to minimize crosstalk, pair twists ranging from 5.3 to 7.5 inches are used so that adjacent pairs in the same or adjacent layers can always be given different twists.

These video pairs have a dc resistance of 42 ohms per loop mile at 68 degrees Fahrenheit and an attenuation of 17 dB per mile at 4.0 MHz. The characteristic impedance is  $125.5 \pm 3.5$  ohms at 1.0 MHz. Manufacturing and splicing techniques are designed to produce reflections of 38 dB or more below the amplitude of pulses used in measurement. Insulation resistance exceeds 1000 megohm-miles and the dielectric strength of the insulation between pair conductors and between the conductors and the copper shields must be in excess of 3000 volts dc.

## Coaxial Cables

Coaxial cables are now used to carry a substantial portion of long-haul special services circuits and switched network trunks in the Bell System. In addition, this medium is finding increasing use for digital and analog trunks in metropolitan networks. Although the cost of coaxial cable is high relative to paired cable, the adaptability of coaxial cable to very broadband systems makes it a contender for providing service where heavy cross sections of traffic flow exist. The per-channel-mile cost of these systems is relatively low.

**Physical Characteristics.** A coaxial cable is made up of 4 to 22 coaxial units with interstitial wire pairs and single wires all wound helically around the cable axis. Various sheath components perform the same functions as similar layers used in quadded toll cables. Because of the helical winding, or stranding, the coaxial units and some of the wire conductors are appreciably longer than the cable. This extra length ranges from about 0.5 percent in 4-unit cables to about 2.4 percent in one of the larger sizes.

The interstitial pairs and wires are used for maintenance support and operational functions such as order wires and alarms. The characteristics of the pairs are similar to those in toll cables. The single wires are used only for dc alarm and control circuits. Pairs assigned to order-wire circuits in the L5 system are loaded at coaxial repeater points which are spaced about a mile apart but not nearly as uniformly as loading points usually are. This loading system, Q44, is satisfactory for these four-wire circuits because reflections from structural irregularities are prevented from becoming echoes by one-way amplifiers; the slight unevenness in transmission caused by the reflections is acceptable in an order-wire circuit.

The serrated-seam coaxial unit, the present standard, consists of a 0.1003-inch axial copper conductor centered within a 0.369-inch (inside diameter) copper tube by polyethylene insulating disks spaced about 1 inch apart. The tube is a strip of copper 0.012 inch thick formed into a cylinder around the disks. It is held closed by the interlocking of its serrated edges in a longitudinal seam and by two strips of steel tape wound helically around the copper tube with the outer tape overlapping the gap between turns of the inner one.

**Transmission Characteristics.** For coaxial cable units, primary and secondary constants are expressed in the same manner as for local or toll cable pairs. The derived transmission characteristics are shown in Figure 2-13. Note that  $\alpha$  is approximately proportional to the square root of frequency. This is primarily because of skin effect in the inner and outer conductors; as frequency increases, current flow is progressively restricted to the portions of the conductors near the surface. The constant  $\beta$  is nearly proportional to frequency, while delay and  $Z_0$  are comparatively insensitive to frequency.

FREQUENCY, MHz	$\alpha$ , dB/mi	$\beta$ , rad/mi	DELAY, $\mu$ s/mi	$Z_0$ , ohms
0.1	1.217	3.66	5.83	77.5
1.0	3.845	35.7	5.69	75.5
10.0	12.15	354	5.64	74.9
100.0	38.68	3533	5.62	74.7

Figure 2-13. Transmission characteristics of serrated seam coaxials per mile of coaxial unit.

Because of the shielding effect of the outer coaxial conductors, the equal-level coupling loss between coaxial units increases with frequency, despite the lack of insulation between the outer conductors of the coaxial units.

As in loaded cable pairs, it is important to minimize reflections in coaxial conductors. Although transmission on each coaxial unit is in only one direction, reflections can cause interference among signal components traveling in that direction. Reflections result from internal impedance variations caused by splices, sharp bends, dents, gas plugs, and terminations at equipment units. Factory measurements are made on each coaxial unit by means of a pulse technique to verify that internal reflections are sufficiently small. Random splicing lengths are used in the field to avoid in-phase buildup of reflections from regularly-spaced splices; the latest coaxial splicing techniques are designed to minimize the reflections at splices.

## 2-4 MICROWAVE RADIO TRANSMISSION

Microwave radio transmission media include propagation paths, antennas, and the waveguides used to couple the transmitters and receivers to the antennas [4]. Comprehension of radio propagation and the path losses encountered, antenna patterns and efficiencies, and waveguide transmission characteristics are essential to an understanding of these media. For microwave transmission, portions of the 2 to 40 GHz spectrum are made available by the Federal Communications Commission for fixed, common-carrier service. This range corresponds to wavelengths of 150 to 7.5 mm respectively where it is practicable to direct the radiated energy in a narrow beam.

### Propagation Paths

The principal propagation paths in the microwave range are the direct (free-space) wave and the ground reflected wave as illustrated in Figure 2-14. If the antennas are located to provide a line-of-sight path with adequate clearance, the path loss for a large percentage of the time approximates the free-space loss. This loss obeys the inverse square law.

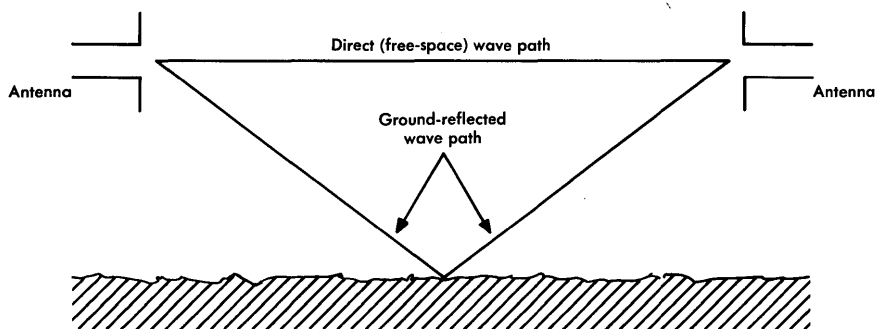


Figure 2-14. Microwave propagation paths between antennas.

**Line-of-Sight Transmission.** Imagine a radiated wave expanding as a spherical surface from a point source. The power density, in terms of power per square unit of that surface at distance  $d$  from the source radiating power  $p_T$  watts, is the radiated power divided by the spherical surface at that distance, or  $\frac{p_T}{4\pi d^2}$ . If that radiated power is now concentrated in a narrow beam by means of a suitable antenna and accurately aimed at a receiving antenna, the latter receives many times the energy it received before the beam was concentrated. The actual power it receives before concentration is

$$p_R = \frac{p_T A_R}{4\pi d^2} \quad , \quad (2-1)$$

where  $A_R$  is the effective area of the receiving antenna and  $p_T$  is the power transmitted at the transmitting antenna. It can be shown that the on-axis power gain of the transmitting antenna having its radiation concentrated in a narrow beam is  $\frac{4\pi A_T}{\lambda^2}$ , where  $\lambda$  is the wavelength and  $A_T$  is the effective area of the transmitting antenna.\* When Equation (2-1) is modified to account for the transmitting antenna gain, the received power is

\*Antenna gain is defined as the ratio, in dB, of the signal amplitude received or transmitted by an antenna to the amplitude that would be received or transmitted by an isotropic antenna at the same location and fed with the same power.

$$p_R = p_T \left( \frac{4\pi A_T}{\lambda^2} \right) \left( \frac{A_R}{4\pi d^2} \right). \quad (2-2)$$

These factors may be regrouped so that the transmitting and receiving antenna gains are in the same form; thus,

$$p_R = p_T \left( \frac{4\pi A_T}{\lambda^2} \right) \left( \frac{4\pi A_R}{\lambda^2} \right) \left( \frac{\lambda}{4\pi d} \right)^2. \quad (2-3)$$

Trmtg	Rcvg	Free-space
ant.	ant.	path loss
gain	gain	

Note that the antenna gains are frequency-dependent and that the free-space path loss is both distance and frequency dependent as shown in Figure 2-15. In dB, the loss from the transmitter to the receiver is:

$$10 \log \frac{p_T}{p_R} = 10 \log \frac{4\pi A_T}{\lambda^2} - 10 \log \frac{4\pi A_R}{\lambda^2} + 20 \log \frac{4\pi d}{\lambda} \quad (2-4)$$

where the units of length in  $A_T$ ,  $A_R$ ,  $\lambda$ , and  $d$  are all the same. The effective areas,  $A_T$  and  $A_R$ , are smaller than the physical areas because of power dissipation and reflections in the antennas.

**Reflections.** It is not enough that the line-of-sight path be unobstructed. It is also necessary to have adequate clearance all around that path in order to reduce the likelihood of reflections that may set up secondary paths longer than the direct path. Waves taking a longer path can arrive at the receiving antenna in any phase relationship with the direct wave. The phase relationship depends upon the wavelength, the difference in length between the two paths, and whether or not the grazing angle at the projection is small enough to cause a phase reversal at the reflection. The strength of the reflected wave determines the limits of reduction or reinforcement of the direct wave and the phase relative to the direct wave determines where, within those limits, the effect will lie.

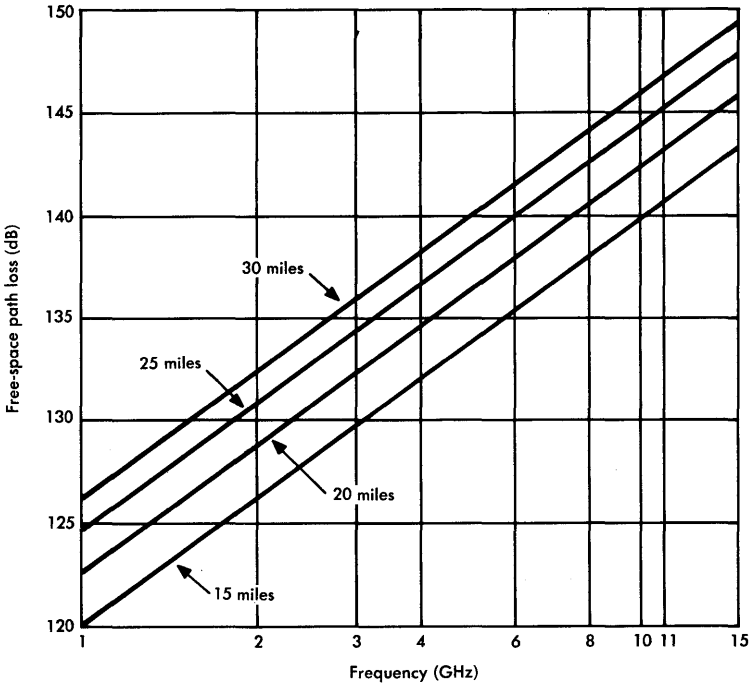


Figure 2-15. Free-space path loss versus frequency and path length.

Figure 2-16 illustrates a direct path,  $d$ , from A to B and an indirect path,  $d_1$ , from A to C to B. Clearance above intervening terrain is usually described in terms of Fresnel zones which are ellipses of revolution around the line-of-sight path, as shown in vertical cross section in Figure 2-16. The first Fresnel zone is the surface from which a reflection reaching the receiving antenna will have traveled one-half wavelength farther than the direct wave. The  $n$ th Fresnel zone defines paths  $n/2$  wavelengths longer than that of the direct wave. The locations of the zones depend on the wavelength and the length of the direct path. Experience indicates that clearance should be at least 0.6 times the distance to the first Fresnel zone all along the direct path in order to achieve transmission loss that approximates the free-space loss. Somewhat greater clearance than that is usually provided, however, in order to reduce deep fading under adverse atmospheric conditions. Effective path clearance is not constant



but varies with atmospheric conditions which can bend the direct wave away from a straight line as a result of variations in dielectric permittivity.

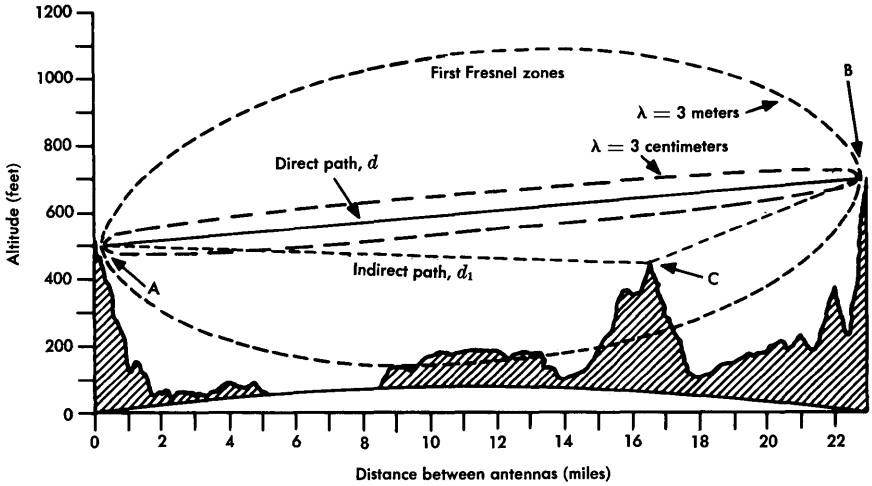


Figure 2-16. Typical profile plot showing first Fresnel zones for 100 MHz (3 meters) and 10 GHz (3 centimeters).

For determining suitable antenna heights, the obstacle having the least Fresnel clearance for prevalent atmospheric conditions is located and then used as a fulcrum to allocate height to the antennas to provide suitable clearance. Path tests with portable antennas are often made to verify the height of the principle obstructions, path reflectivity conditions, and optimum antenna heights.

**Fading.** Heavy ground fog or very cold air over warm earth can cause enough atmospheric refraction to obstruct the line-of-sight path and increase its loss substantially throughout a wide frequency band. This type of fading takes place slowly and clears up slowly; its only remedy is the use of higher antennas.

Another, faster type of fading is caused by interference between two or more rays in the atmosphere. These separate rays between transmitter and receiver are the result of irregularities in the way dielectric permittivity varies with height. Fading of both types influences the margins that must be built into the transmission system.

Figure 2-17 shows the median duration of fast fading on a 4-GHz system. It indicates an inverse relationship, that is, the deeper the fade, the less its duration. For example, a 16-dB fade has a median duration of 50 seconds; a 43-dB fade, only 2 seconds. About 1 percent of the fades may last ten times or more as long as the median and about 1 percent may last only one-tenth as long or less. On line-of-sight paths, much of the multipath fading occurs at night when there is little or no wind or convection to break up atmospheric layers that cause irregularities in refraction and result in multipath transmission.

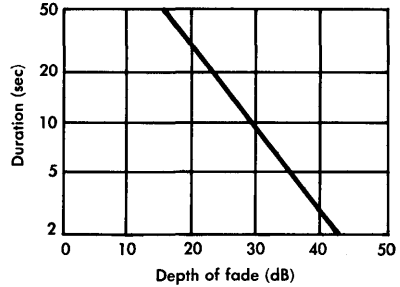


Figure 2-17. Median duration of fast fading at 4 GHz.

Both the number and severity of fades increase with repeater spacing and with frequency. Although multiple paths are usually overhead, ground reflections are sometimes involved. Effects of multipath fading can be reduced by the use of alternate frequencies, alternate routes, or alternate antennas at different heights.

**Absorption.** Rain and water vapor increase path losses markedly at the higher microwave frequencies. Figure 2-18 shows the estimated atmospheric absorption versus frequency for several concentrations of rain in the atmosphere. The increase of loss with frequency is caused by the greater absorption and scattering of energy as the wavelength approaches the size of the rain drops. Systems operating in the upper part of the superhigh-frequency ranges (3 to 30 GHz) are vulnerable to rain attenuation and cannot rely on inband frequency diversity for protection of service.

## Antennas

A number of different types of antennas have been used for Bell System microwave radio systems. Today, most long-haul and many short-haul systems utilize a horn-reflector design that has proved to be economical, versatile in its broadband capability, and rugged in the face of exposure to the elements. Other short-haul systems are equipped with parabolic antennas.

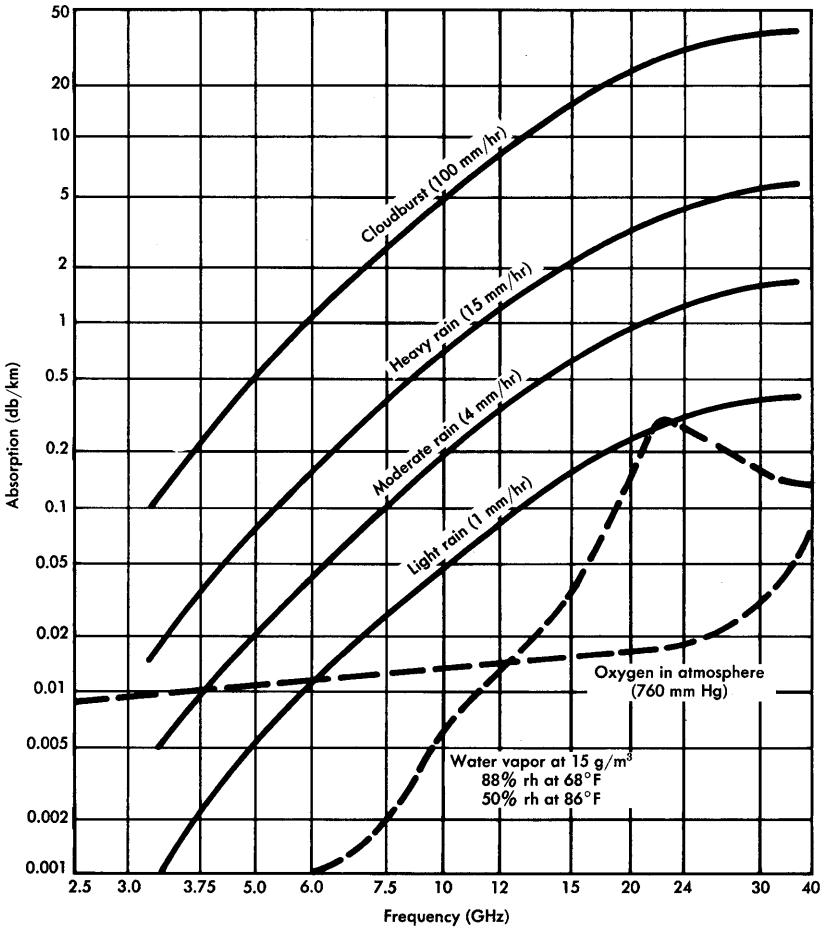


Figure 2-18. Estimated atmospheric absorption.

**Characteristics.** The gain of an antenna is closely associated with the width of the beam it radiates; the narrower the beam, the greater the gain. Although a narrow beam minimizes interference from outside sources and adjacent antennas, too narrow a beam may be deflected from its target by unusual stresses on the antenna tower. Therefore, there must be a balance between antenna gain and resistance of the tower to such stresses. Most of the antennas in modern microwave systems have half-power beam widths of about one to two

degrees. Figure 2-19 shows relationships among antenna area, gain, and beam width.

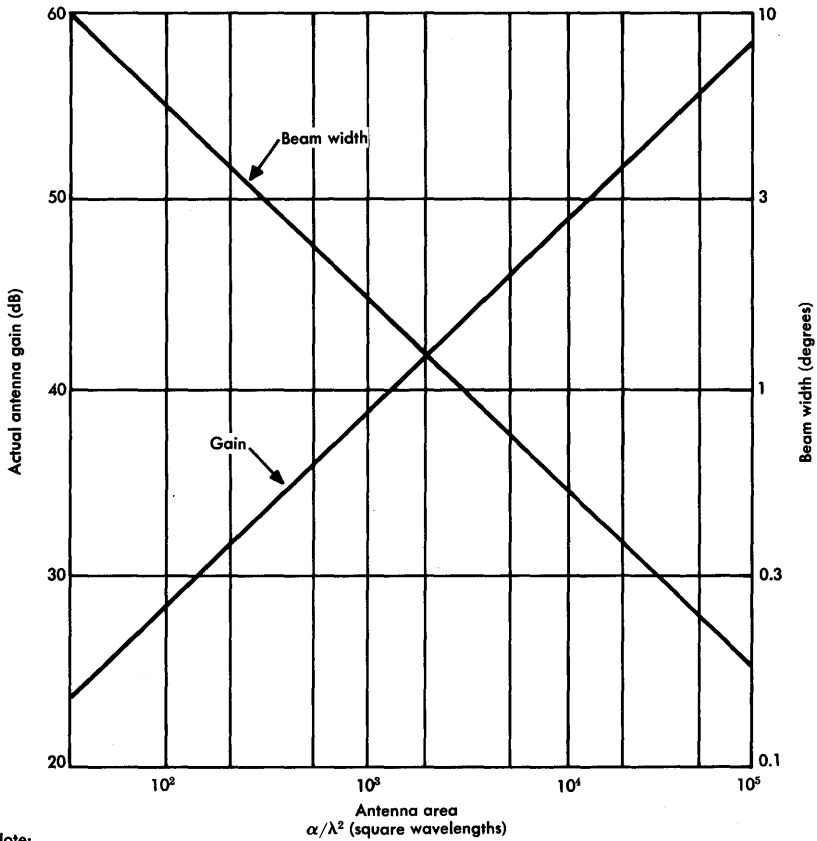
Not all the energy from an antenna is radiated in the main beam. Some is radiated in minor beams, called sidelobes, which are potential sources of interference. The energy radiated in the backward direction must be well controlled in repeater systems that transmit the same frequency in both directions. (In most systems, the frequencies are different in the two directions.) Side-to-side and back-to-back coupling losses between various combinations of transmitting and receiving antennas, all at the same station, must be high to avoid interference especially when fading is being experienced. Transmitter outputs are some 60 dB higher than receiver inputs.

**Polarization.** Adjacent channels in the frequency spectrum have opposite polarizations of the transmitted signals. This improves discrimination between adjacent channels and facilitates the design of networks for combining and dropping channels. Cross-polarization discrimination, the ratio of the power received in the desired polarization to that in the undesired, is usually in the range of 25 to 30 dB for an entire repeater section.

**Typical Designs.** Beaming microwave energy is quite similar to beaming light energy with reflectors and lenses. In both cases, the function of the equipment is to transform a spreading spherical wavefront into a plane wavefront that travels toward its objective in a narrow beam. Antenna gains of 30 to 50 dB are usual in microwave transmission.

The parabolic (or dish) antenna is fed from waveguides having outlets at the paraboloid focus. As many as four waveguides may be used to feed the antenna at the same time. Such antennas of 5- to 10-foot diameter are used mostly on short-haul systems but sometimes on lightly loaded long-haul routes.

The horn-reflector antenna, shown in Figure 2-20, combines a vertical horn and a small section of a large paraboloid surface. The energy is fed from a waveguide orifice placed at the focus of the paraboloid and flows upward, spreading out in the horn. The paraboloidal surface changes the direction of the energy to horizontal and also changes the wave front from spherical to plane, thus confining



Note:  
 Abscissa is actual antenna area; "actual antenna gain" is taken to be 3 dB below theoretical

Figure 2-19. Approximate antenna area, gain, and beam width.

the energy to a beam spread of about 2 degrees. This type of antenna is capable of about 40-dB gain at 4 GHz and of successively higher gains in the 6- and 11-GHz regions. Good impedance match of the waveguide feed to the antenna results in high return loss. The horn-reflector is a broadband antenna that can be used with both vertical and horizontal polarization in the 4-, 6-, and 11-GHz bands. It has only small sidelobes and a front-to-back ratio (the ratio of the power measured at the front of a directional antenna to the power measured at the back of the antenna) of about 70 dB.

Another type, the delay-lens antenna is somewhat less versatile than the horn-reflector and is seldom used. Within its limitations, it provides gains up to 45 dB. The limitations are imposed by the lens structure which embodies a large number of parallel aluminum strips shaped in plano-convex form and set in slabs of foamed polystyrene.

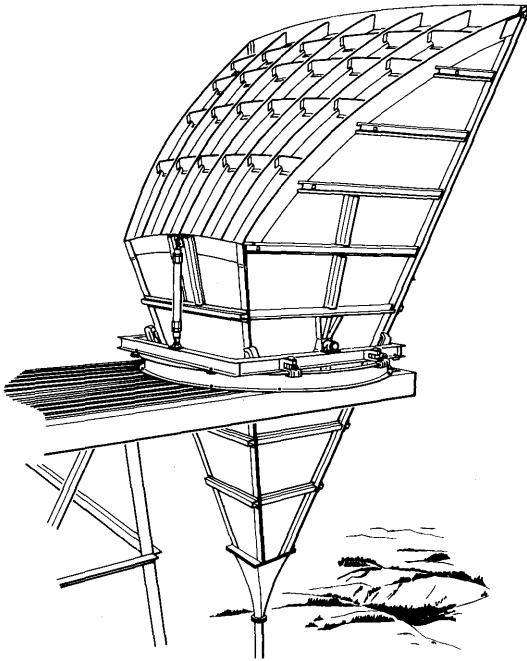


Figure 2-20. Horn-reflector antenna.

This structure is effective over only a limited frequency range determined by the separation of the aluminum strips and can transmit only waves that are polarized in the direction in which the strips are aligned.

Since path losses between two microwave antennas are the same no matter which transmits and which receives, separate consideration of receiving antennas is unnecessary except when considering space diversity arrangements. The reversibility of the two roles, however,

makes it clear that each antenna must be precisely aimed at the other in order to achieve maximum gain.

## Waveguides

Waveguides prevent radio waves from spreading as they emanate from a source, usually a precisely placed loop or coaxial probe, and force them to propagate within a restricted path. At present, the major use of waveguides is to conduct energy in microwave radio systems between receiver and transmitter components, from transmitters to transmitting antennas, and from receiving antennas to receivers. New systems utilizing waveguide as the transmission medium are under development.

In order effectively to propagate radio energy, a rectangular waveguide must have a cross-sectional dimension of about one-half wavelength. This restriction limits the practical use of waveguides to high frequencies at which wavelengths are at most a few inches. Within this limit, there are a number of possible configurations of the electromagnetic field within the guide. These configurations are known as *modes of propagation*. The major modes are the transverse electric (TE) modes and the transverse magnetic (TM) modes. In the TE mode, the electric field is transverse to the axis of the guides and the magnetic field is parallel to the axis. In the TM modes, the reverse is true.

Propagation of a specific mode is possible only when the wavelength of the applied energy is less than the "cutoff wavelength" of the waveguide. Longer wavelengths, or lower frequencies, are not transmitted. The same guide, however, may transmit longer wavelengths in some other mode. The mode that has the longest cutoff wavelength is called the dominant mode. It is the preferred mode because, for a given frequency, the waveguide can be smaller than it could be for any other mode.

Many waveguides in current use are rectangular in cross section with a two-to-one ratio of the two dimensions. The cutoff wavelength of the dominant mode of such a design is twice the dimension of the longer side of the cross section. The other modes have cutoff wavelengths no more than half that of the dominant one. Therefore, the band of frequencies propagated in the dominant mode alone ranges from the frequency corresponding to the cutoff wavelength of that

mode to twice that frequency; all other modes are suppressed within that range. Circular waveguide is also used, particularly from tower base to antenna; 4-, 6-, and 11-GHz may be transmitted in this waveguide in two polarizations.

Losses in waveguides are minimized by using the dominant mode but attenuation is still considerable because of power losses in the walls of the guide where the traveling waves induce currents. At 4 GHz, the loss in a 1.25 x 2.50-inch bronze guide is about 1.5 dB per 100 feet. This is high in comparison with losses in wire lines at much lower carrier frequencies but substantially lower than the losses that would be experienced in wire lines or coaxial cable at microwave frequencies. The velocity of propagation in a waveguide is close to, but always less than, that of light.

Uniformity of structure is just as important in waveguides as in other linear transmission media. Changes in size or shape of cross section, holes or projections in the walls, and lack of homogeneity in the metal distort the electromagnetic field and generate unwanted modes that result in transmission losses. Reflection losses can be caused by bends or twists that are not gradual enough or by improper terminations at the sending or receiving end. Where irregularities are unavoidable, they are minimized by means of impedance matching techniques.

Waveguides can be made effectively to limit transmission to only one direction by means of accurately placed magnetic ferrites and magnets. The magnets are placed outside the waveguides to produce magnetic fields in the ferrites which are placed inside. These devices, called isolators, prevent energy reflected from transmitting antennas or discontinuities in the waveguides from interfering with the operation of components such as klystron oscillators or traveling-wave tube amplifiers.

## 2-5 MOBILE RADIO TRANSMISSION

Since mobile radio transmission requirements are different from those of microwave transmission, the medium is used in a different way and lower frequencies are better suited to the service. First, transmission between the base and mobile antenna is in the nature of a broadcast. Second, since unobstructed paths are the exception, the frequencies employed must be capable of delivering a useful



amount of energy to and from areas that are not in line-of-sight paths from fixed transmitters. Fortunately, the frequencies available for mobile service are able to accomplish that result. They lie mainly in the VHF (30 to 300 MHz) and UHF (300 to 3000 MHz) ranges [5, 6, 7].

In mobile services, where transmitting and receiving antennas are comparatively close to reflecting surfaces of the earth, path losses in the VHF and UHF ranges increase at about 12 dB per octave (doubling) of distance rather than 6 dB per octave as in free-space transmission. A simplified explanation of this rate of increase is that the total field strength at any point in the covered area is the sum of the direct wave and the ground-reflected wave. The latter undergoes a 180-degree phase change in being reflected and only because of its slightly longer path length arrives a little out of phase opposition to the former. The net field, therefore, is the relatively small vector sum of the two nearly opposing main components. As the receiver recedes from the transmitter, the strength of each main component decreases by 6 dB per octave of distance, the departure from phase opposition decreases, and the degree of cancellation increases. The net result is a loss change of approximately 12 dB per octave of distance.

The influence of antenna heights is also closely related to path loss. Within practical ranges of transmitting and receiving antenna heights, there is a gain of 6 dB when the height of either antenna is doubled. The variation of path loss with frequency is very slight because of two opposing effects. Power received at a half-wave dipole decreases with increasing frequency if field intensity is kept constant but the lower wavelength reduces the degree of cancellation of the direct wave by the ground-reflected wave. The result of these two opposing effects is to keep the loss substantially constant.

For the conditions commonly encountered in land mobile service, the following idealized relationships provide a good starting point from which the effects of earth curvature, topography, and obstructions can be added to give a realistic picture in specific situations. Path loss is substantially independent of frequency, increases at about 12 dB per octave of distance, and decreases at about 6 dB for doubled antenna height at either terminal.

Earth curvature does not cut transmission off sharply; atmospheric refraction tends to bend waves so that they follow the curvature to

some extent and diffraction tends to dilute the radio shadows cast by hills, buildings, and other obstructions. As an example, transmission losses between a base-station antenna at an elevation of 200 feet and a car 35 miles away (several miles beyond the geometrical horizon) might typically be increased over flat-earth-path losses by about 5 dB at 40 MHz, 8 or 9 dB at 160 MHz, and 12 dB at 460 MHz.

Since both fixed and mobile antennas in mobile services must generally radiate in all compass directions, the half-wave dipole antenna and variations of that design are natural choices. When mounted vertically, a dipole radiates mainly near the horizontal plane where the associated receiving antennas are located; there is very little vertical radiation. For the lower frequency ranges, for which half-wave dipoles are impracticable in size for vehicles, simple vertical antennas are suitable. Such a radiator is tuned to resonance at the carrier frequency by making its length a convenient fraction of the carrier wavelength and by adding lumped reactance at the top or bottom. In any case, the effect of tuning to resonance is to produce a standing wave of current along the antenna.

The considerations that apply to the choice of transmitting antennas at fixed stations also apply to mobile antennas, which serve for both transmitting and receiving. It is often sufficient to consider transmission only from fixed to mobile stations because path loss is usually the same in both directions of transmission at the same frequency. However, shadow losses may be significant and transmission from the vehicle to the base location may be controlling. Furthermore, the base location often uses higher power in transmission; even though path loss is reciprocal, satellite fixed receivers are often necessary.

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**Telecommunications  
Transmission  
Engineering**

*Section 2*

*Local Plant Facilities*

The quality of transmission is influenced in many ways by local plant facilities among which are loop or access line facilities and station sets. These are significant in determining transmission quality because two of each are used on every connection. Many trunks are also included in local plant facilities and they too have an effect on transmission quality.

The variety of transmission equipment located in central office buildings and the switching equipment itself, which provides a multitude of transmission paths, must all be carefully controlled to assure satisfactory service. In addition, there are a number of switching facilities located on customer premises that provide transmission paths that must be equally well controlled.

Chapter 3 is devoted to discussions of loop facilities and station equipment. The loop facility portion briefly discusses the resistance, unigauge, and long route design plans and describes a number of supplementary electronic equipment types that are used to improve transmission and to extend loop ranges. Analog and digital loop carrier facilities are also described. Finally, the 500-type telephone station set is discussed with special attention given to ringing considerations.

In Chapter 4, voice-frequency trunk transmission facilities are discussed. After a brief review of the via net loss trunk design plan, consideration is given to the use of negative impedance and gain-type voice-frequency repeating equipment. The performance and applicability of various types of equipment are compared. The application of echo suppressors to network trunks is discussed.

Chapter 5 discusses voice-frequency data transmission in the loop plant and the adaptation of loop facilities to the needs of data trans-

mission. The types of equipment found at typical data stations are described and the features of the 208-type DATA-PHONE® data set are discussed as representative of a large class of data sets.

Chapter 6 covers wideband facilities found in the local plant. Included are descriptions of wideband data access facilities and station equipment with discussions of the relationship of these facilities to wideband carrier terminals. The access facilities and customer premises equipment used in the digital data system and the local plant facilities used for television signal transmission are described.

The switching machines are unquestionably the largest items of central office equipment but there are also many items of transmission equipment mounted in central offices. Chapter 7 describes the transmission paths through the switching machines together with transmission circuit terminating and auxiliary equipment and some switching system functions that affect transmission performance. The sources and control of central office transmission impairments are also discussed. With the introduction of digital switching in the toll plant (No. 4 ESS), new transmission-switching interface equipment is found in central offices and the principal equipment items are described. Central offices contain equipment relating to the transmission of television signals. This equipment is also described.

Chapter 8, the final chapter in this section, is a parallel to the previous chapter but covers switching equipment used at customer premises. Included are private branch exchanges and key telephone equipment. Emphasis is placed on transmission characteristics of this equipment that differ significantly from those of central office equipment.

## Chapter 3

# Loops and Station Sets

A loop and the associated station set are uniquely related to the communication service received by an individual customer. Since the same loop and station set are common to every connection to that station set, their performance has a direct effect on service to that customer and the cost of these items has a direct effect on the cost of furnishing service. Thus, the problem of providing satisfactory service at a reasonable cost is brought into focus in the design, installation, and operation of loops and station sets.

Several plans, called resistance, unigauge, and long route designs, are used in the loop plant. Application of these plans leads to the specification of cable pair wire gauges and to the economic application of electronic equipment to extend the length and/or improve the performance of loops. In general, loops are designed in bulk rather than on an individual basis. When design rules are followed, overall performance in the loop plant is satisfactory on a statistical basis. Occasionally, individual loops must be treated to improve performance because they represent extremes in the statistical distributions.

Carrier system techniques are being increasingly applied to loops to improve performance, to extend ranges, and to make more efficient use of cable facilities. Single-channel and multichannel analog systems and multichannel digital systems all have been found to be economical in various situations.

Telephone station set designs, which have been substantially improved over the years, have focused recently on the 500-type station set. Although there are now many types of station sets available, the 500-type design is sufficiently representative that it may be used to illustrate the transmission performance of telephone station equipment generally.

### 3-1 LOOP BASEBAND FACILITIES

A loop is defined as the connection between a station set and the switching machine in the serving central office. It includes a cable pair connection from the termination at the switching machine line circuit to the main distributing frame (MDF), a cross connection at the MDF, the loop facilities, a "drop wire" pair to extend the connection into the customer premises, a protector unit, and inside wiring or cabling at the customer premises to complete the connection from the protector unit to the station set. The loop facilities that comprise the connection from the MDF to the drop wire are the only parts of these connections that materially affect transmission.

Loop conductors are usually contained in a multipair cable which may be located overhead (aerial cable), below ground by direct burial (buried cable), or in conduit (underground cable). They may consist in part of one of several designs of paired multiple line wire or of paired open wire. In some cases, the loop facility may include an analog or digital carrier system.

Loops play a large role in transmission because two are used in every network connection. Loop facilities often share supporting structures with power lines and are thus highly susceptible to power line influence. They may be exposed to the weather and various construction activities and are thus subject to damage and abrasive effects that can result in loss of service or deterioration of performance from excessive noise, crosstalk, or other interference. Switched and nonswitched special services circuits also use these facilities and may be subject to the same impairments.

Transmission performance in the loop plant is controlled by loop cable layouts that are designed and engineered to take advantage of the statistical distribution of resistance and loss values. If the design rules are not applied, the number of limiting (high loss) loops may be significantly increased and grade of service for built-up connections may deteriorate substantially because the number of connections between high-loss loops would increase.

Where loop lengths are limited by signalling considerations, it may be possible to extend the ranges by application of signalling range extenders. However, if this is done without regard to transmission considerations, performance may suffer noticeably unless voice compensation (gain and/or equalization) is applied. The more modern

electronic equipment which provides for improvements in both signalling range and in transmission performance should be used.

### Loop Design Plans

The design procedures used to control the installation and use of these media are previewed here to the extent necessary to relate loop losses to the electronic equipment that can be provided to increase loop ranges and to improve performance under normal conditions [1]. Loop design plans determine the gauge of cable conductors and where and how supplementary electronic equipment may be used to increase signalling ranges or to improve transmission performance. These plans are called *resistance design*, *unigauge design*, and *long route design*.

The design plans have evolved as a result of efforts to satisfy economically the needs of ordinary telephone service to residential and business main station loops. The resulting network of facilities is also used to satisfy many special services circuit needs. In some cases, these needs are fulfilled without special treatment of the facilities; in other cases, treatment is required and in many of these situations, must be tailored to the specific service.

**Resistance Design.** When new distribution and feeder cables are to be installed, the choices of cable gauges and sizes are based on an economic analysis of the existing distribution of customer locations and the anticipated growth of the area. The design and layout of such new routes are based on a loop resistance which is known to satisfy transmission requirements. If loops in the area under study can be served by no more than two wire gauge sizes in such a way that the loop resistance design limit (1300 ohms in most cases) is not exceeded, the entire area can be served under the resistance design plan.

With resistance design, cable pairs serving the more distant customers are often loaded inductively. Design rules call for H88 loading for loops longer than 18 kilofeet; i.e., 88 mH coils are located along the line every 6000 feet. The rules specify within close tolerances the lengths of all loading sections including the end sections. In addition, the maximum allowable lengths and characteristics of bridged taps are also specified.



When loop facilities provide service to areas that have few special services needs, ancillary equipment for gain, equalization, or signaling is seldom required when resistance design rules are otherwise satisfied. However, where there is substantial demand for special services, additional loading is often installed and a variety of electronic equipment may be used to reduce loss or otherwise to improve transmission performance.

**Unigauge Design.** It can be shown that, in certain situations, it is more economical to provide loop plant of the same fine-gauge cable pairs (26-gauge) and to compensate for transmission and signalling limitations by the use of electronic equipment at the central office. In this unigauge design plan, the greatest economies are realized where the electronic equipment is switched into a connection as needed rather than being permanently connected in each loop requiring compensation [2].

At present, the unigauge plan can be applied only in areas served by No. 2 ESS or No. 5 crossbar switching machines. In No. 2 ESS, unigauge capability has been provided as a part of the basic design with generic programs available to cause the appropriate gain to be switched into a connection as required [3]. To achieve similar operation in No. 5 crossbar, logic wiring changes must be made, test arrangements must be modified, and additional equipment must be installed. Thus, the theoretical economic advantage of unigauge design may be negated by the additional equipment and switching system modification costs.

The unigauge plan is primarily applicable as permanently connected plant for new growth areas since interconnection points permit economical flexibility in loop extension using coarse gauge cable pairs. Additionally, the number of line and station transfers that would require central office rearrangements are limited. There are four ranges associated with the unigauge plan as shown in Figure 3-1. The shortest range, which includes loops less than 15 kilofeet long, consists entirely of 26-gauge nonloaded cable pairs. The longer ranges are shown in the figure as utilizing a combination of electronic equipment such as range extenders, inductive loading of the cable pairs, and larger gauge cable pairs (a departure from the theoretical unigauge concept). Loops from 30 to approximately 52 kilofeet long may be equipped as extended unigauge loops by using heavier (22 gauge) wire and H88 loading with the first load coil at the 15-kilofeet point rather than at 3.0 kilofeet as in resistance design.

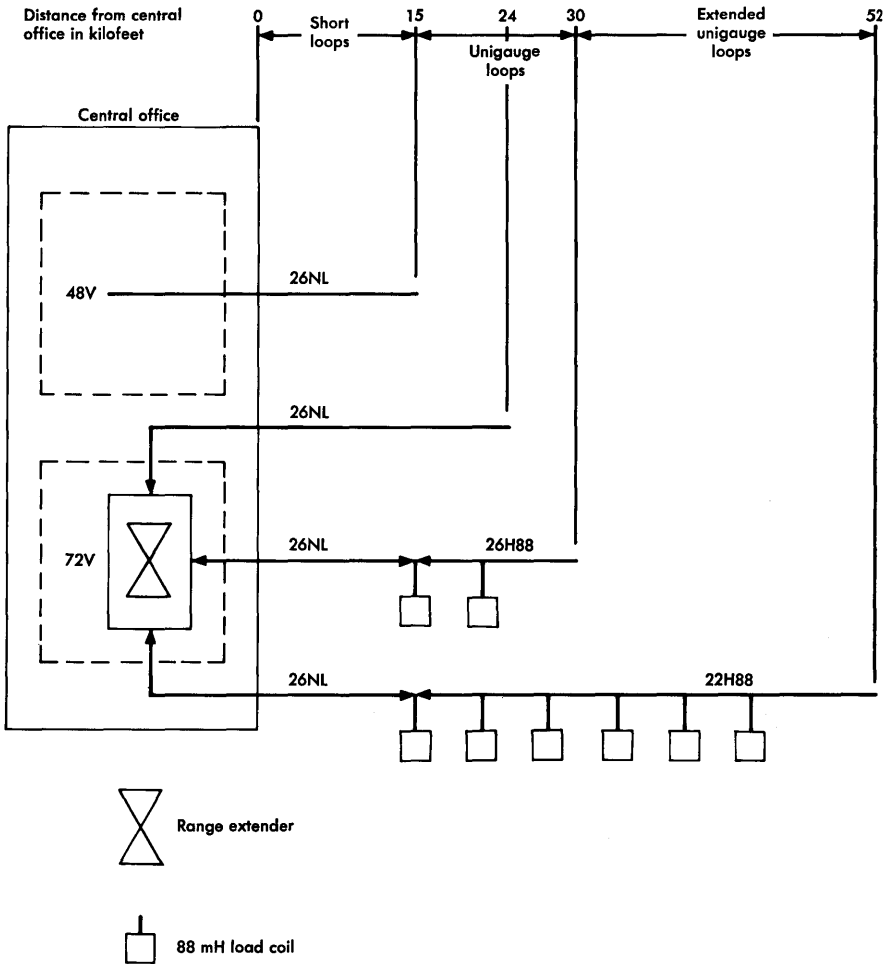


Figure 3-1. Unigauged loop plant layout.

Plant installed according to the unigauged design plan is often troublesome in respect to special services circuit design. Beyond 15 kilofeet, the unigauged loops have higher losses than loops provided under resistance design rules. These losses must often be compensated for by electronic equipment.

**Long Route Design.** Most rural routes are served by voice-frequency (baseband) loop arrangements. The design procedure for such long routes involves the establishment of several resistance range zones in excess of the normal 1300-ohm resistance design limit. The procedure provides for a specific combination of electronic range extension and/or fixed gain devices to be applied to all loops falling within each of the several ranges. The devices and resistance ranges are selected so that the maximum insertion loss of each loop is limited to 8 dB. The distribution of the resulting losses provides a grade of service not significantly poorer than normal [4]. The long route design plan provides for loop lengths up to about 210 kilofeet.

The general features of long route design are illustrated in Figure 3-2. The design of No. 2 ESS permits operation through zone 16 without the use of auxiliary equipment. However, in some offices (step-by-step, for example), a 2A range extender must be used to extend dial pulsing, ring tripping, and call origination ranges. For zone 18 (the upper boundary of which has been moved to 2000 ohms), the use of a range extender with gain (REG) is recommended. However, many installations are still operating with the older dial long line (DLL) unit and a central office-located E6 repeater. Operation in zone 28 is similar to that in zone 18 but 6-dB gain is required.

Operation in zone 36 formerly required the use of a DLL in the central office; an E6 repeater with 9-dB gain was remotely located along the route as indicated in the figure. A recently designed version of the REG is now used to extend signalling and supervision to loops up to 3600 ohms with no remote repeater. However, the REG is constrained to a maximum gain of 6 dB which is insufficient to compensate for the added loop loss; a new design of handset (type G-36) must be used. This handset provides 3 dB of transmitting and 3 dB of receiving gain relative to a 500-type station set.

### Voice-Frequency Electronic Equipment

A wide variety of electronic equipment is used in the loop plant to provide message signal gain, equalization, direct current resupply, address signal repeating and/or regeneration, ringing range extension, and bridge lifting. Since these functions are combined in various ways in different equipment items, logical categorizing of the equipment is

rather difficult. For present purposes, two some what arbitrarily chosen major categories are discussed. The first category includes items whose primary function is to supply message signal gain. The second category includes items whose primary function is to provide address signal repeating or regeneration.

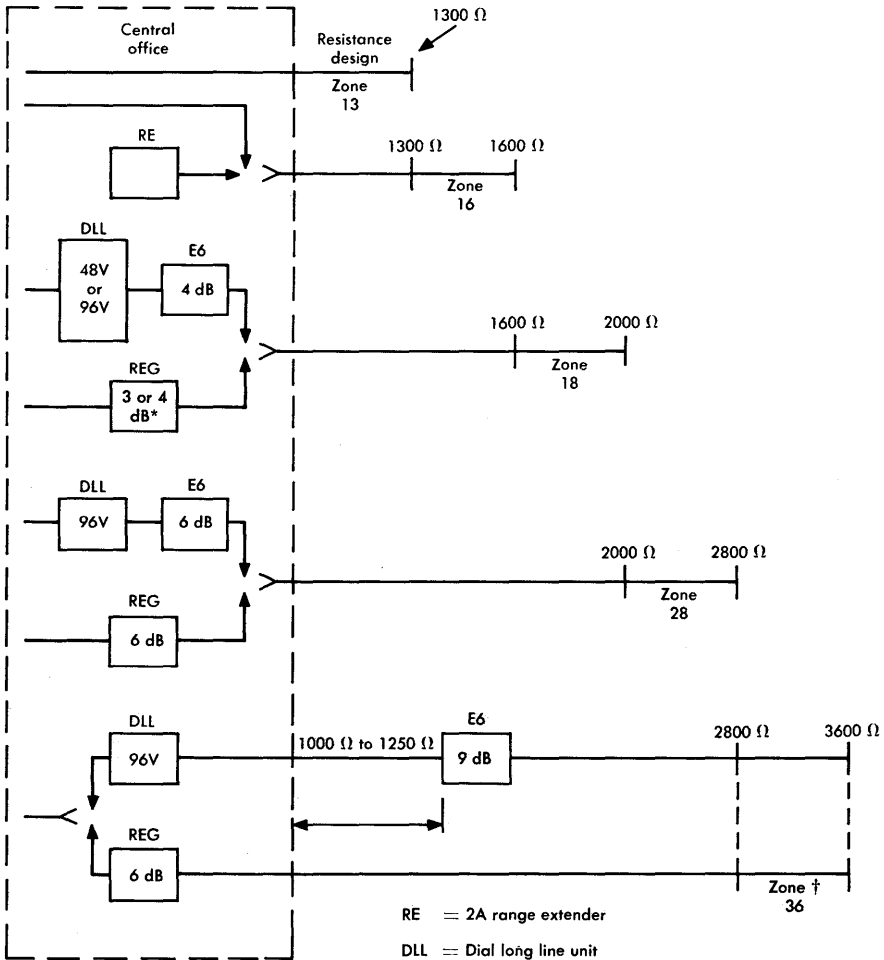


Figure 3-2. Long route design.

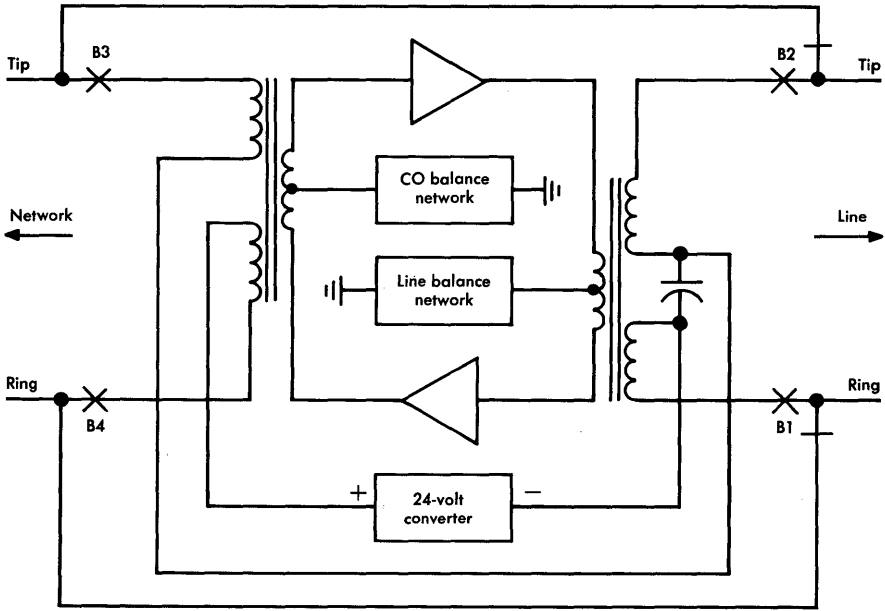
**Message Signal Gain.** The application of dedicated voice-frequency gain equipment to individual loops tends to be uneconomical. However, where service must be furnished over routes longer than about 45 kilofeet, long route design with E-type repeaters, V-type repeaters, or metallic facility terminal arrangements is sometimes economical. In most cases, the equipment for these applications is mounted at the central office end of a loop. However, customer premises mounting of facility terminal equipment is used, especially to improve the performance of PBX-related circuits such as PBX-CO, foreign exchange, and wide area telecommunications service trunks, long distance and off-premises station lines, and similar connections in the loop plant. In addition to voice-frequency gain, this type equipment can provide impedance compensation, equalization, and signalling range extension. Since E- and V-type repeaters and facility terminals have their greatest field of application in the interoffice trunk plant, they are discussed in Chapter 4 as trunk facilities rather than as loop facilities.

The application of message signal gain is much more economical where a fixed value of gain can be provided and switched into a connection only when needed. As previously mentioned, this is the basis of operation in the unigauge design concept applied in areas served by No. 2 ESS or No. 5 crossbar switching machines.

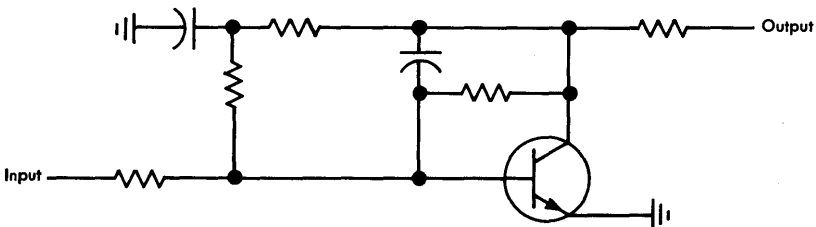
In No. 2 ESS, range extension capability is provided as a basic design feature of the system. Repeaters are installed in sufficient quantities to meet service requirements with an approximate ratio of one repeater for each three range extended lines to be served. They are placed (electrically) within the switching network at a location such that they may be switched into a connection when required; when not used, they present no obstacle to ordinary switching operations. In addition to voice-frequency gain, they provide a 72-volt battery supply circuit (instead of the normal 48-volt battery supply) in order to deliver adequate current to the station set and supervisory circuits on loops of up to 2500 ohms.

The repeater, shown schematically in Figure 3-3(a), is designed to serve all unigauge loops for which gain is required. The gain characteristic is determined primarily by the unbalanced amplifiers, one of which is shown in Figure 3-3(b); the gain increases with frequency to compensate for nominal loop loss. The gain at 1000 Hz is 5.1 dB and at 3000 Hz, 8.5 dB. The 24-volt converter supplements the normal

48-volt battery. Thus, the dc path is carried through the repeater for signalling and supervision. The circuits are designed to be stable under all conditions including an open circuit on the central office side of the repeater and to operate satisfactorily in the presence of a wide range of foreign potentials on the loop. Since the 26-gauge loops present a reasonably constant impedance, a fixed balancing network design is used. The tip and ring conductors can be bypassed around the repeater so that connections not requiring gain can be made; the



(a) Block diagram



(b) Unbalanced amplifier circuit

Figure 3-3. No. 2 ESS unigauge repeater.

bypass is accomplished by the contacts of relay B controlled by the ESS call processor.

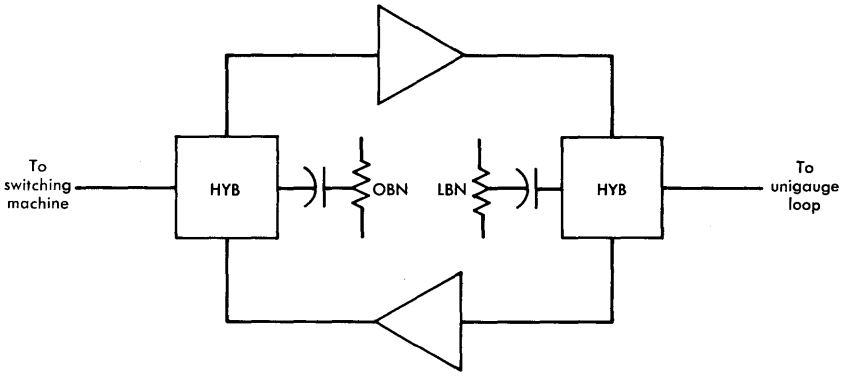
In No. 5 crossbar systems, the range extender units are added and the required voice-frequency gain is furnished by a plug-in 306A repeater. The repeater, as illustrated in Figure 3-4, is a balanced, hybrid type that provides 4.6 dB gain at 1000 Hz and 8.8 dB gain at 3000 Hz when measured between 900 ohms and a unigauge loop. The office balancing network (OBN) and the line balancing network (LBN) must provide a good match to the office and line transmission circuits respectively for satisfactory operation. The unigauge plan generally provides the match required, especially on the line side.

The unigauge design plan applies primarily to main station loops. The plan may be applied in some cases to PBX-CO trunks and other special services circuits. However, the additional treatment that is often necessary with special services circuits must be applied to a larger number of such circuits under unigauge than under resistance design principles.

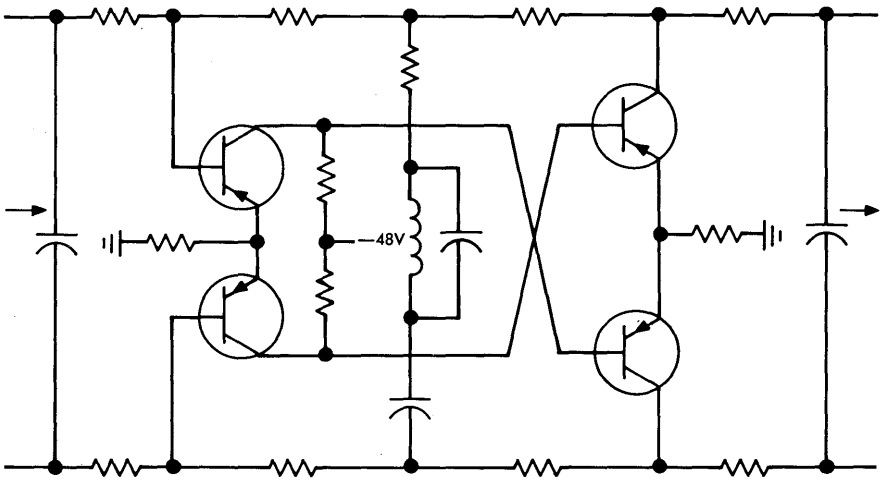
For residence and business main stations, the REG is a useful device that operates on H88 loaded loops having a resistance range of 1300 to 3600 ohms [5]. This need had been previously met by various combinations of 96-volt dial long line units and E6-type repeaters. In addition to voice-frequency gain, the REG unit, illustrated in Figure 3-5, provides range extension of supervision, dial pulsing, and ringing trip and increases the voltage applied to the loop to bring loop current into the station set operating range. It also provides a through path for testing and ringing and, when a talking path is established by the operation of a transfer relay (HRO), it connects a negative impedance repeater as shown in Figure 3-5(a) to provide up to 6 dB of gain. In addition, the dc path in the REG unit permits automatic number identification for 2-party lines.

The operating sequences required for the REG are implemented by the dual-mode current detector shown in Figure 3-5(b). A threshold sensor is connected to the loop pair by a linear resistance bridge with negligible insertion effects. The output at nodes A and B is proportional to loop current and is independent of longitudinal current and voltage to ground.

**Signal Repeating Equipment.** A wide variety of loop facilities without voice-frequency gain features are available. These are known as range extenders, dial long line units, or dial long trunk circuits. The func-



(a) Block diagram, 306A repeater

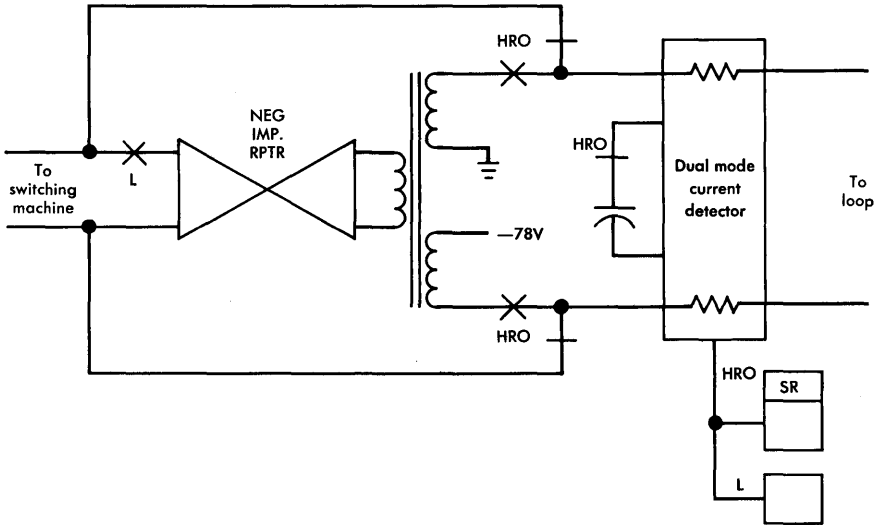


(b) Amplifier schematic

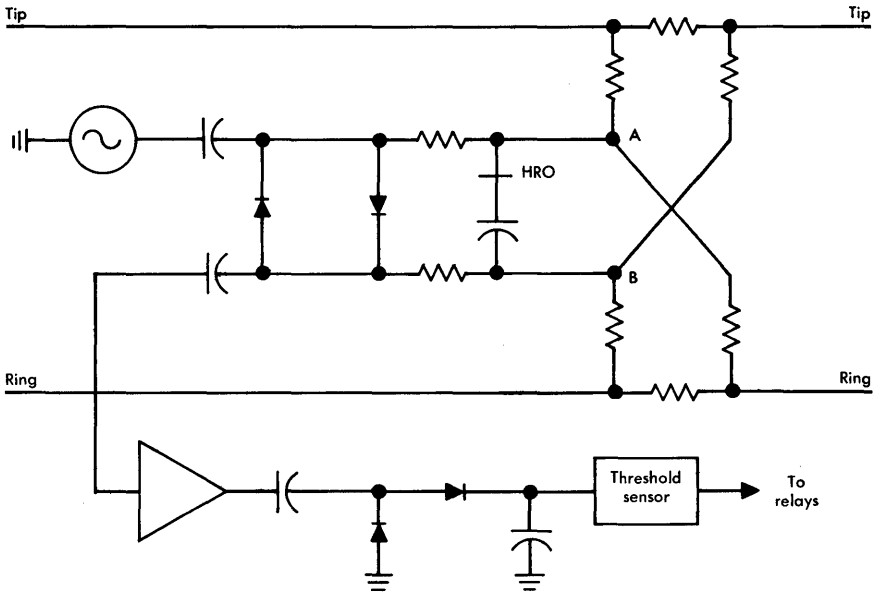
Figure 3-4. Unigauge repeater for No. 5 crossbar.

tions fulfilled by these units include the repeating of ringing signals, the repeating and/or regenerating of dial pulses, and the boosting of dc line current for improved performance of supervisory circuits, station set microphones, and TOUCH-TONE® oscillators. Some designs provide for the disabling of E-type repeaters and, in some cases, can apply idle circuit terminations. Designs are made more complex





(a) Block diagram



(b) Dual-mode current detector

Figure 3-5. Range extender with gain.

when party line or coin line service is involved and when automatic number identification is needed in connection with automatic message accounting procedures.

*Miniature Dial Long Line Units.* A number of designs of dial long line and dial long trunk facilities are used on long central office loops, PBX station lines, and various special services circuits. Since the REG has become available, many of these units are no longer recommended but there are still a large number in operation. Among these units is a design known as the miniature dial long line circuit. Eleven plug-in units, each a complete circuit except for ballast lamps, may be mounted in a single tray. Two tray designs are used to accommodate the various design options that are available. These units incorporate terminating impedances that provide high return losses in the circuit applications where they are used. They also offer such features as idle circuit terminations and E6 repeater disabling. Extended transmission and supervisory ranges are achieved by the use of 72-volt battery.

Three different designs are provided to operate with all types of local switching systems. Individual lines, some PBX lines, 2-party full-selective loops (without party identification), 4-party full- or semi-selective loops, 10-party coded ringing loops, and 8-party semiselective loops can be extended. These units are not generally applicable to special services circuits. These circuits operate with either TOUCH-TONE or rotary dial stations. Pulsing, supervisory and ring-trip ranges depend on the battery supply. The maximum external resistance is 2500 ohms with 48-volt operation. With 72-volt operation, the individual and party-line units provide extended ranges which are limited by restrictions imposed by requirements to trip during either the ringing or silent interval.

*Signalling Range Extender.* Central office coin line loop resistance limits may be extended to a maximum of 2400 ohms by using a signalling range extender (SRE). The SRE equipment provides range extension on up to ten coin lines in a single shop-wired shelf assembly. In addition to the range extender plug-in units, the shelf accommodates an inverter unit which converts 48 volts dc to a 10-kHz square-wave output voltage. An alarm and transfer unit distributes the inverter output to the range extenders, provides alarm indications in the event of failure, and optionally provides transfer to an alternate inverter.

Each range extender rectifies the squarewave signal received from the inverter. The 24-volt rectified signal is filtered and applied to the line as illustrated in Figure 3-6. When the station set is on hook, no current flows and the range extender is idle. When the station is off hook, current flow is sensed and 24-volt battery of appropriate polarity is connected in series with the line. This battery augments the current flow, assists in the operation of the ring tripping circuits in the central office, and improves supervision, dialing, and transmission performance. The SRE provides no gain; however, it may be used with an E6 repeater when gain is required.

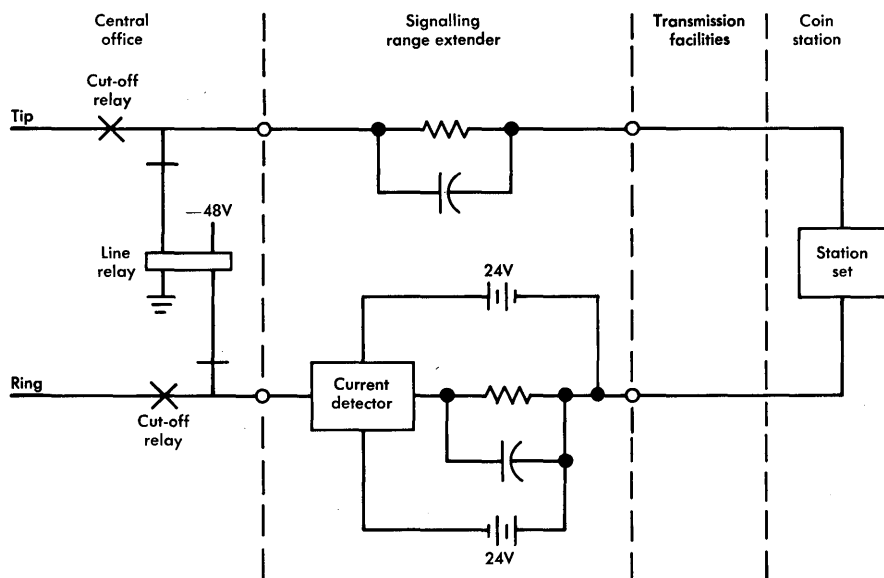


Figure 3-6. Application of signalling range extender to coin station line.

*Type 2A Range Extender.* This unit is used in step-by-step and No. 5 crossbar offices to extend loop ranges from 1300 ohms to about 1600 ohms. It cannot generally be used with special services circuits. The circuit assemblies are of miniature size so that they may be mounted in groups of 10 or 20 units on the horizontal side of the main distributing frame. Jumpers are then used to interconnect the range extender with the switching equipment and the loop pair.

The range extender circuit, shown in Figure 3-7, consists of two identical but oppositely poled transistor circuits connected in and across the tip and ring conductors. The oppositely poled circuits are required because battery and ground may be reversed in a number of frequently-used call sequences.

The principal function of the extender circuits is to increase line current flow to assist the operation of supervisory, dial pulse, and

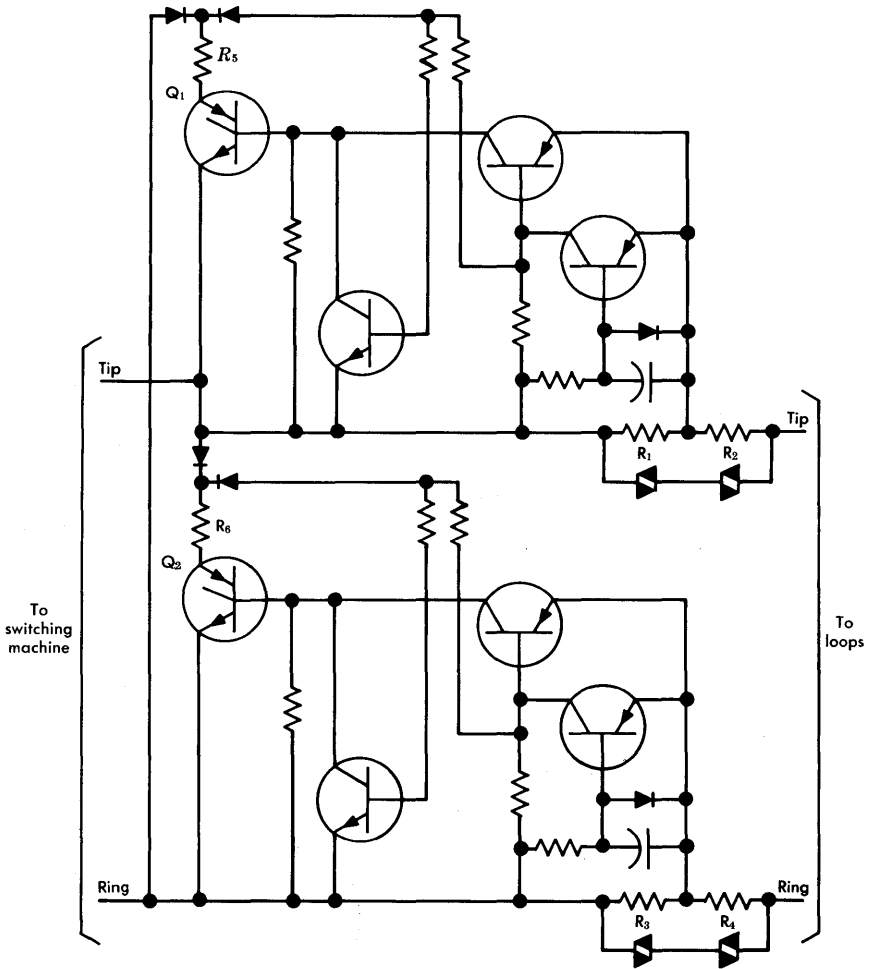


Figure 3-7. Type 2A range extender.

ring-tripping relays. The circuit responds to a flow of line current in excess of 6 mA in resistors  $R_1$  and  $R_2$  or  $R_3$  and  $R_4$ . Such a current flow causes transistor  $Q_1$  or  $Q_2$  to change to the operate condition and thus to increase the line current. (Line current is not increased in the talking condition.) Other components in the circuit provide surge current protection and a low impedance signal path for voice signals.

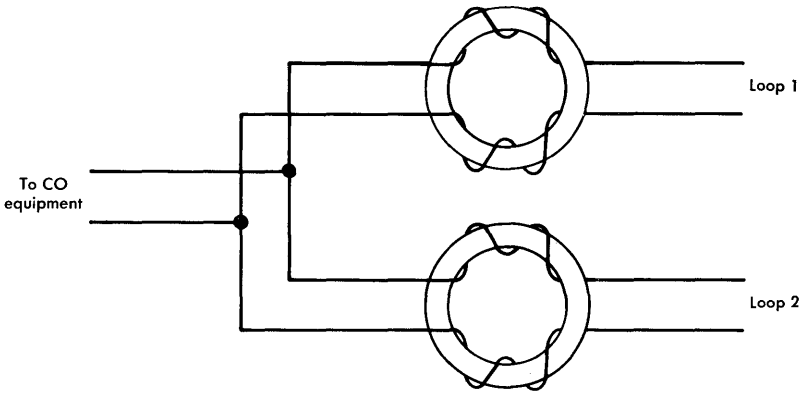
### Bridge Lifters

The transmission degradations caused by a parallel or bridged connection (bridged tap) may be substantially eliminated by the use of a bridge lifter. This device produces low-series impedance in the current-carrying pair and produces simultaneously high impedance in the unused shunting or bridged pair(s); thus, the impedances of the unused pairs are isolated from the through connection.

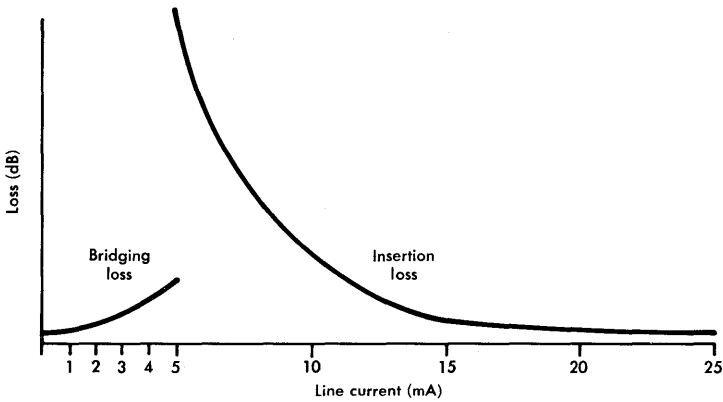
Relays and semiconductors may be used but saturable inductors are more commonly used as bridge lifters because they are relatively inexpensive and require little maintenance. A typical application is shown in Figure 3-8(a). When no current flows in loop 1 or loop 2, the inductance of the toroidal core coils is high and the bridging loss of either loop is low. When current flows, as in the off-hook condition, the toroid is magnetically saturated so that the insertion loss of the affected windings is low. Thus, transmission in the circuit that carries current is not materially affected by the coil insertion loss nor by the bridging loss of the parallel connection. The losses are shown qualitatively in Figure 3-8(b). Actual losses are functions of frequency and of the impedances of the connected circuits.

The most commonly used inductor is the type 1574. Early designs (1574A and 1574B) have been replaced by the 1574C and 1574D which utilize bifilar-wound coils. This method of winding results in less circuit noise than that observed with conventional windings where each coil was wound independently. Each of the two windings of a 1574-type bridge lifter has 12 ohms resistance so that each bridge lifter adds 24 ohms to the loop resistance. In the 1574B and 1574D types, a 5600-ohm resistor is connected in parallel with each winding to make the device less susceptible to low-frequency noise components.

Although bridge lifters may be installed at remote locations, they are usually used in the central office to improve transmission perfor-



(a) Typical bridge lifter application



(b) Typical loss characteristics

Figure 3-8. Saturable inductors used as bridge lifters.

mance on party lines. Under the permanently connected plant design concept, each party line is provided a separate cable pair from the central office and the pairs are bridged at the main distributing frame by an arrangement that incorporates the bridge lifters. Bridge lifters are similarly used on secretarial service lines and off-premises extensions.

## Concentrators

The cost of providing service to remote stations on long routes can theoretically be materially reduced by using line concentrators. Located remotely from the central office, these are switching arrangements that permit a number of loops to be served by a smaller number of trunks. Loops terminate at the concentrator and the trunks connect the concentrator to the central office.

A number of concentrators are in use, some of Bell System design and some of outside design. A ratio of loops to trunks as high as 50 to 10 has been used but, with the traffic generated in many areas, blocking has been found to be excessive and concentrator costs have been higher than desirable where service and reliability needs have been met. These problems are under active study.

Most designs cause little transmission impairment. A full-access switching matrix and relatively simple line and trunk terminating circuits make the concentrator essentially transparent to transmission. Loss through a concentrator is typically held to 0.5 dB or less and other transmission impairments tend to be negligible.

## Program Facilities

A number of wideband services furnished by the Bell System require loop facilities that can provide gain and/or equalization. The facilities discussed here are those provided for special program services such as "wired music," local and network radio, and the audio portion of television. Excepting the cable pairs, essentially all the facilities used for these purposes are manufactured to Bell System specifications by outside suppliers.

For "wired music" service, a cable pair is used to connect the program source to the local central office. Here, distribution amplifiers are used to connect the serving loop to many receivers and/or trunk facilities which may be used with distribution amplifiers to serve receivers through other offices. Many hundreds of receiving stations may be served simultaneously by this type of arrangement. Equalizers are built into the distribution amplifiers to satisfy transmission requirements on various types and gauges of nonloaded cable. Repeating coils are usually located at the customer premises to isolate customer-provided equipment from Bell System facilities and to provide a

150-ohm termination. The bandwidth provided for this type of service may be either 5 or 8 kHz.

High-quality service may be provided for radio or television program signals transmitted over circuits such as studio-to-transmitter links. Rugged amplifiers may be mounted in central offices, at customer premises, or remotely in manholes or on telephone poles. When mounted remotely, these amplifiers are powered over a separate wire pair. Bandwidths of 5, 8, or 15 kHz may be provided and built-in equalizers are used to adapt the amplifiers to these bandwidths and to a variety of nonloaded cable types and gauges. In some cases, program circuits may be furnished on specially loaded cable pairs. The loading may include arrangements such as B22 or B11, i.e., 22 mH or 11 mH coils at 3000-foot spacing.

### 3-2 LOOP CARRIER FACILITIES

Continued growth of demand for telecommunication services has led to use in the loop plant of electronic techniques and, in many cases, to the application of carrier systems. Both analog and digital carrier systems are used to achieve acceptable transmission performance and to increase the efficiency of use of cable conductors where long route designs are necessary. However, carrier systems are not yet generally used for special services circuits.

#### Analog Systems

Both single channel and multichannel analog carrier systems are available for loop applications. Single channel systems utilize carrier techniques to place a voice signal in a frequency spectrum above the voice-frequency band. When added to an existing VF loop, this technique provides an additional channel, called an add-on channel. The arrangement may be used to defer the installation of additional cables or, in congested areas, to increase the utilization of cable pairs. Multichannel systems, which may provide up to eight voice channels on a single wire pair, are used primarily on long low-growth routes to provide increased cable utilization and to defer new cable installations. Equivalent four-wire transmission is used in both single channel and multichannel systems.

Technical requirements for these systems are specified by the Rural Electrification Administration (REA) of the United States Department of Agriculture [6]. These specifications are applicable to station carrier equipment purchased by telephone companies that borrow from the REA and cover equipment intended for use on cables meet-



ing REA specifications. Thus, systems of outside manufacture are generally designed to meet these specifications and many are used by the Bell System. However, the REA specifications are not applied to Bell System designs.

**Single Channel Systems.** A number of single channel carrier systems are currently used. The SLC\*-1 system, recently introduced in the Bell System, is generally represented by Figure 3-9 [7]. It may be used to provide service over a carrier-frequency channel on a nonloaded cable pair in which the loss does not exceed 53 dB at 76 kHz. This loss corresponds to the maximum value for a resistance designed loop less than 18 kilofeet long. Allowance must be made for bridged taps.

A single channel system consists of two terminals, a central office terminal unit and a subscriber terminal unit. As shown on Figure 3-9, the voice-frequency channel and the carrier channel are combined at the line side of each unit. The two paths are isolated electrically by low-pass filters (LPF) for the voice-frequency channel and bandpass filters (BPF) for the carrier channel. The operation of the carrier channel may be explained by first considering an incoming call to station set 2 and then an outgoing call from station set 2.

*Incoming Call.* When a ringing signal is applied at the central office to the carrier channel, the ringing detector activates and modulates the 76-kHz oscillator by way of the transmit switch. The 76-kHz oscillator provides a modulated carrier signal via the modulator to transmit the ringing indication to the distant end. After detection at the subscriber terminal unit, the modulated 76-kHz carrier activates the ringing generator which then applies the ringing signal to the station set. When this signal is answered (station set off-hook), the loop detector turns off the ringing generator and turns on the 28-kHz oscillator. The oscillator output is transmitted to the central office to signal the off-hook condition through the loop relay. With both oscillators energized and with the ringing signal turned off, the circuit is set up for voice communication. Transmission away from the central office is by double sideband amplitude modulation of the 76-kHz carrier and toward the central office by double sideband amplitude modulation of the 28-kHz carrier.

*Outgoing Call.* The initiation of a service request from the station set follows a sequence somewhat similar to the incoming call sequence. When an off-hook condition is recognized by the loop detector

\*Trademark of the Western Electric Company

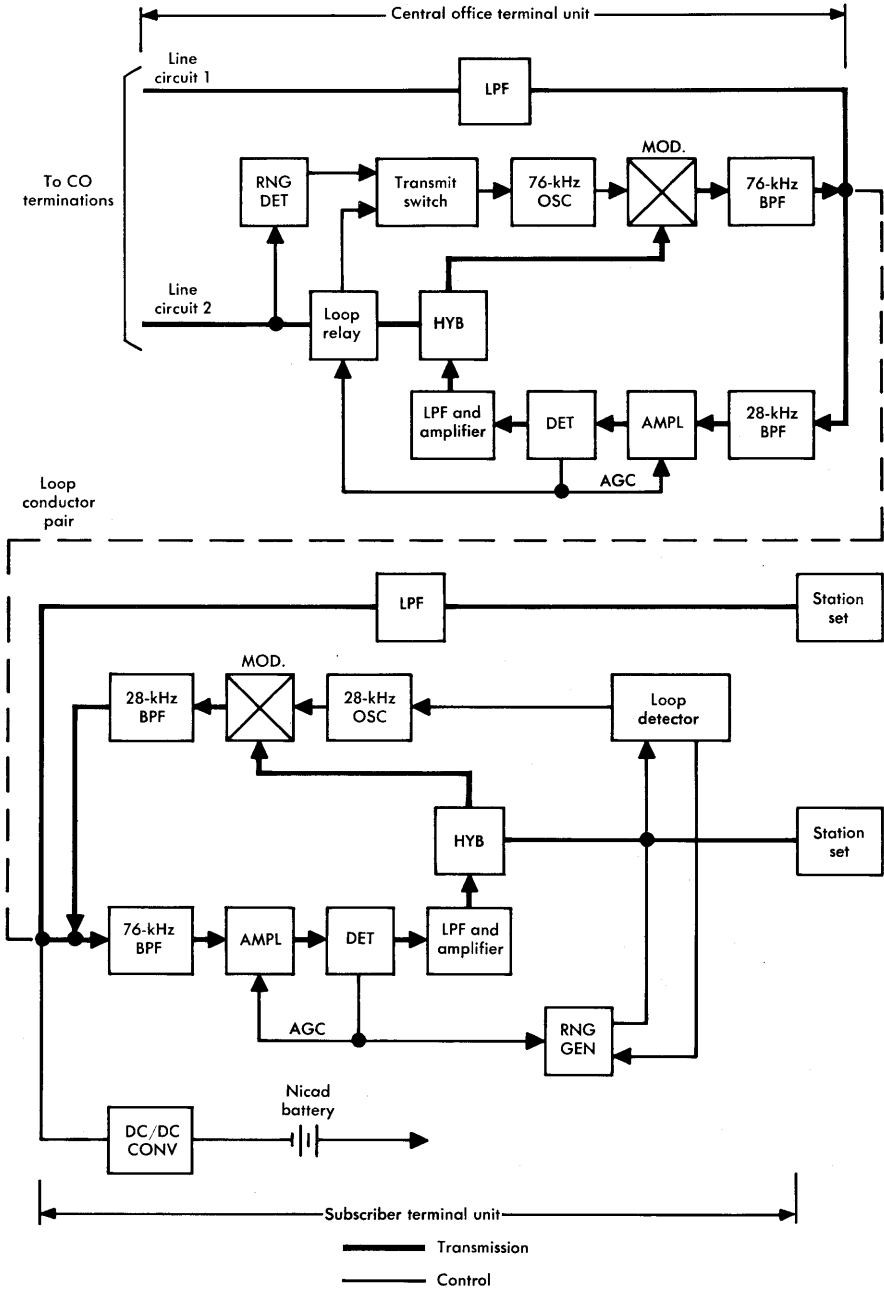


Figure 3-9. Typical layout of a single channel loop carrier system.

at the subscriber terminal, the 28-kHz signal is transmitted to the central office to indicate the service request. It operates the loop relay which turns on the 76-kHz oscillator and extends the off-hook signal indication to the central office line equipment. Normal loop signalling can now take place by interruption of the 28-kHz oscillator in response to dial pulses or by the transmission of TOUCH-TONE signals from the station set.

*The SLC-1 System.* The operating sequences described apply generally to single channel systems of outside suppliers or of Bell System design. One significant difference between the SLC-1 System and others is that the SLC-1 uses a compandor (not shown in Figure 3-9) on the carrier channel for transmission from the central office to the station set. This transmission path, at 76 kHz, has relatively high loss and is therefore susceptible to noise impairments which are reduced by the compandor.

**Multichannel Systems.** In applying carrier techniques to multichannel loop transmission systems, double sideband amplitude modulation is generally used to supply four to eight channels on a single cable pair by the equivalent four-wire transmission mode. In these systems, no voice-frequency channel is provided. Systems generally are designed to meet REA Specification PE-62 [6]. These systems may have lumped customer terminal arrangements, in which there is only one remote terminal with all customer connections made from that terminal, or they can accommodate distributed remote terminals which provide one or more customer connections at each of several locations.

In systems that meet the REA specifications, the design must permit the use of up to three remote repeaters powered from the central office. Longer systems may be accommodated by providing remote power feed arrangements and additional repeaters. Each repeater must provide gain to compensate for 35 dB of cable loss at 112 kHz. The system objective for total line loss is thus to accommodate up to 140 dB at 112 kHz using central office powered repeaters.

Transmission level points are specified so that crosstalk is tolerable in the presence of T- and N-type carrier systems or wideband data or video channels in the same cable. Transmission toward the central office is usually in the band from 8 to 56 kHz. Transmission toward the station sets is at higher frequencies, usually in the band from 64 to 112 kHz. Higher frequencies, up to 136 kHz, may also be used.

## Digital Systems

Two digital transmission systems, a Subscriber Loop Carrier 40 (SLC-40) System and the Subscriber Loop Multiplexer (SLM\*) System, have been designed to serve long route needs. Of the two, the SLC-40 System has proven to serve telephone company needs more economically and is more commonly found in service. However, a number of SLM Systems are also in use. Both utilize T1-Carrier System line equipment, discussed in Chapter 22, but the terminal arrangements and system configurations are quite different.

**The SLC-40 System.** When fully equipped, the SLC-40 System can provide up to 40 speech channels between a central office and a remote terminal as much as 50 miles away [8]. Channel units provide service to individual (single party) lines, two-party lines with automatic number identification, and a variety of multiparty lines (up to eight party) with combinations of semi-selective, fully-selective, or coded ringing and automatic or operator number identification. Other applications are being developed to expand further the field of use of this system.

*System Layout.* Figure 3-10 shows a typical layout of an SLC-40 system. The system is composed of a central office terminal and a single remote terminal interconnected by a T1-type repeatered line. The system provides 40 full-time voice-grade channels as loops between the central office and the remote terminal. Standard voice-frequency distribution facilities are used to extend the loops from the remote terminal to customer premises.

The length of the repeatered line depends on the type and gauge of cable. For 22-gauge cable, the maximum length is 10 miles for systems powered only from the central office. The length may be increased to 20 miles for systems powered from both the central office and the remote terminal and to 50 miles for systems powered from both ends and from an intermediate power feed point.

Two remote terminal arrangements are available. In one, a weather-proof cabinet that may be pole- or pedestal-mounted is used to house channel units, common circuit units, batteries, battery charger, and a ringing generator. In the other arrangement, the equipment for two SLC-40 systems may be mounted on a seven-foot frame in an equip-

\*Trademark of the Western Electric Company.

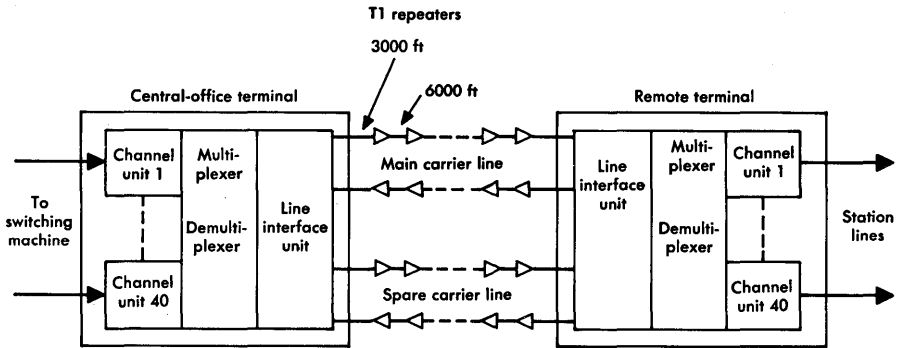


Figure 3-10. SLC-40 system layout.

ment hut, in a community dial office building, or at a customer premises.

Central office and remote terminal equipment must be synchronized. A 41st channel is assigned to carry timing and maintenance information between terminals. The system can detect loss of synchronization within one millisecond and can correct such a condition within three milliseconds.

As shown in Figure 3-10, the first repeater is placed about 3000 feet from the central office. Other repeaters are spaced about 6000 feet apart, the exact spacing depending on type of cable, gauge, number of systems on the route, and practical problems of land and right of way acquisition. The short spacing at the central office is provided to minimize impulse noise impairments that might result from switching transients.

The SLC-40 system is provided with a protection line and automatic protection switching. One protection line may serve to protect two working lines where the remote terminal equipment is rack mounted. An alternative arrangement is available for rack mounting in which one protection line may protect 5 or 11 lines. In some cases, patching is provided and a single protection line may serve more than two regular lines.

*Terminal Equipment.* The 40 voice-frequency circuits of an SLC-40 system are each connected at central office and remote terminals

through a channel unit. The channel signals are sampled, coded, and multiplexed by the multiplexer-demultiplexer common circuits to form a single 1.544 Mb/s pulse stream. The coding process is adaptive delta modulation, a differential pulse code modulation (DPCM) process which is a modified form of the PCM process used in the T-type carrier systems. The 1.544 Mb/s signal is processed in the line interface unit to form a bipolar 50-percent duty cycle signal suitable for transmission over a T1-type transmission line.

**The SLM System.** This system combines carrier and switching techniques to serve up to 80 station lines by the use of 24 multiplexed digital channels (the T1 line capability) on two nonloaded cable pairs [9]. The configuration and typical layout of an SLM system is shown in Figure 3-11. A control terminal, located in the central office, contains most of the logic circuits that control switching and multiplexing functions. At the control terminal, up to 80 switching machine line appearances may be connected to the SLM through a concentrator made up of 8 miniature crossbar switches. Each of the 24 channel connections is then applied to a channel modem which processes the signals for transmission. A channel signal is sampled at a rate of 57.2 kb/s by a process called delta modulation; each signal is time division multiplexed with various control and framing bits and with the signals from 23 other channels to form the 1.544 Mb/s line signal.

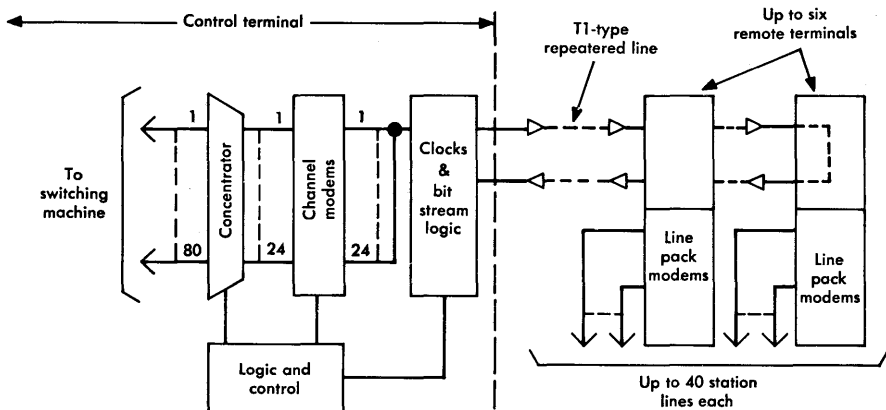


Figure 3-11. SLM system layout.

A maximum of 6 remote terminals may be placed as required along the cable up to 50 miles from the central office to interconnect with

individual station lines. Each remote terminal may serve up to a maximum of 40 lines. The total served at all remote terminals may not exceed the system capacity of 80 station lines. Switching at remote terminals is accomplished in channel pack modems by time division techniques. At any remote terminal, a given channel may be connected to any station line in accordance with control information carried by specified bits transmitted from the control terminal at the central office. When a connection is to be established, the next successive free channel is assigned to that connection. The assignment, as in any time division multiplex system, is accomplished by inserting the coded signal in preassigned time slots in the line bit stream.

Service for one SLM system is provided over a single digital carrier line equipped in a manner similar to that of a T1 carrier line. However, the format of the transmitted signal differs from that used in the T1 Carrier System. The line is looped at the remote terminal farthest from the central office so that both ends of the line are terminated at the control terminal in the central office. Thus, two cable pairs are used for one complete working SLM system. In addition, it is common practice to equip another complete line (two additional pairs) to be used with an automatic switching arrangement as protection against equipment failure.

Normally, pulse code modulation is used with time division multiplexing of signals for transmission on T1 carrier lines. However, this mode of operation requires a substantial amount of common equipment which cannot be conveniently dispersed among the remote terminals of an SLM system. The delta modulation technique is used in SLM because it requires much less common equipment.

Alerting, addressing, and supervisory signals of the SLM are coded into the line bit stream and are translated at the terminals to satisfy station set and switching machine signalling needs. Ringing signals from the central office are coded and transmitted to the remote terminals, each of which is equipped with a 20-Hz ringing signal generator. On-hook, off-hook, and dial pulse signals are recognized at the remote terminals and transmitted to the control terminal in the form of coded signalling bits. The system is capable of serving individual or 2-party lines with operator or automatic number identification. It can also serve 4-party selective or semiselective lines and prepay coin lines.

### 3-3 TELEPHONE STATION EQUIPMENT

The telephone station set accepts an acoustical signal from a talker and converts it to an electrical form suitable for transmission to a receiver which reverses the process at a distant point. The set is composed of a transmitter, a receiver, electrical networks to provide equalization and to control sidetone, a ringer, a rotary dial or TOUCH-TONE pad, and switch contacts having several functions.

There are a large number of different designs of station sets in use. However, the majority are either 500-type sets or have equivalent circuits and transmission performance [10]. Although the discussion here concerns principally the characteristics and performance of the 500-type station set, some special purpose sets are discussed briefly. In addition, some design details relating to party line operation are also considered.

#### The 500-Type Telephone Station Set

In a modern telephone transmitter, such as the 500-type, granules of carbon are held between two electrodes; one is a cup which holds the granules and the other, a diaphragm. Varying sound pressure on the diaphragm changes the contact resistance between granules to modulate the direct current flowing between the electrodes, thereby translating the acoustic message into an electrical signal. Thus, the electrical signal magnitude is a function of acoustic pressure and the direct current flowing through the transmitter. In the telephone receiver, the varying component of this current passes through a winding positioned in the field of a permanent magnet. The resulting variations of the magnetic field cause the diaphragm to vibrate and generate sound waves corresponding to those delivered to the transmitter by the talker.

The transmission circuit of the telephone set must separate the transmitter and receiver circuits so that the direct current in the transmitter is blocked from the receiver and the amount of speech signal in the receiver (sidetone) is controlled. Subjective tests have shown that some sidetone coupling between the transmitter and receiver must be allowed. Too much sidetone causes the talker to lower his or her voice, thereby reducing the received volume at the distant end; too little sidetone makes telephone conversation seem unnatural



and tends to cause people to talk too loudly. The circuit used in the 500D-type station set is shown in Figure 3-12. The three-winding transformer and the sidetone balancing network form an improved hybrid circuit which interconnects the transmitter and the receiver so that the interaction between them is controlled. Capacitors in the balancing network prevent the direct current flowing in the transmitter from appearing in the receiver. Improvements in sidetone control were made necessary by increases in the efficiencies of the transmitter and receiver relative to sets of earlier design [11].

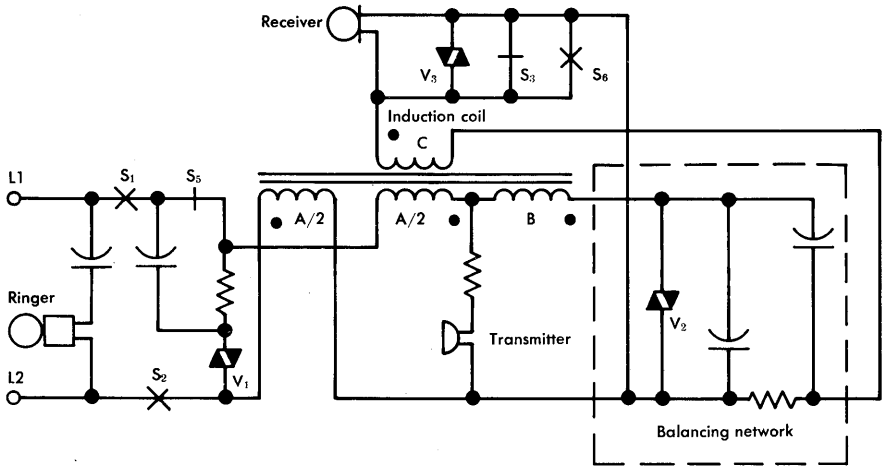


Figure 3-12. Schematic of 500D station set.

When the handset is removed from its mounting, switchhook contacts S1 and S2 are closed to connect the transmission elements of the set to the loop. Contact S3 closes when the station set is in the on-hook condition; it short circuits the receiver to protect the listener from sharp transients that would be heard when contacts S1 and S2 are operated. Removal of the handset allows direct current from the central office to pass through the transmitter and removes the short circuit from across the receiver. On the answering of an incoming call, the direct current actuates a circuit that disconnects the ringing signal at the central office (ring tripping). Dial contact S5 interrupts the battery current to form the dial pulses required to control the central office equipment. Contact S6 short circuits the receiver during dialing to prevent dial pulses from being heard by the user. Other features of the circuit are a filter to suppress high-frequency inter-

ference into radio sets caused by dial pulsing and a varistor,  $V_3$ , to suppress clicks in the telephone receiver.

To prevent excessive volumes on very short loops that would result from the improved overall performance of the 500-type station set, an equalizer that employs two varistors, shown in Figure 3-12 as  $V_1$  and  $V_2$ , has been provided. This equalizer helps to solve the transmission problem resulting from the interdependence of the transmitting and receiving efficiencies and the wide range of operating current caused by the large variation in loop resistances. On long loops, the direct current from the central office battery supply is low and the resulting varistor impedances are high; on short loops, the direct current is high and the varistor impedances are low. The resulting changes in efficiency with loop current are conveniently expressed in terms of the change in conversion loss, i.e., the change in loss of converting acoustic to electric and electric to acoustic energy. Without an equalizer, the change in transmitting conversion loss is an inverse function of the loop current. Typically, the increase in loss is about 6 dB for a decrease in line current from 80 to 20 milliamperes. This variation is reduced by the equalizer to about 4 dB. For the range of currents considered, the receiving loss is nearly constant when no equalizer is used. With the equalizer, the conversion loss increases with loop current. These conversion loss variations are illustrated in Figure 3-13. As the loop current increases, more current is shunted

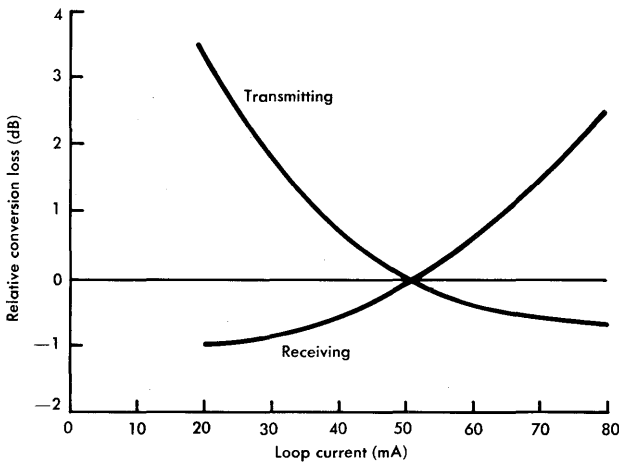


Figure 3-13. Relative conversion losses of a 500-type station set with equalizer.

through varistors  $V_1$  and  $V_2$  and a lower speech amplitude is delivered to the receiver. Thus, variations of transmitted and received speech volumes due to variations in loop loss are reduced. These volumes are highly variable in any case because of differences in customer talking habits and the manner in which the transmitter is held to the mouth.

Varistors  $V_1$  and  $V_2$  serve an additional purpose. By a mechanism similar to the one described for the equalizing function, they compensate for differences in customer loop impedances which would otherwise tend to produce imbalance in the sidetone circuit. Imbalance can produce sidetone that is objectionably high or low.

The asymmetry of transmitting and receiving efficiencies is cause for concern when large concentrations of customers are located near the resistance design limit. Although proliferation of such clusters throughout the DDD network and the attendant higher loop losses can cause substantially lower transmission quality, a small percentage of customers can be served satisfactorily under these conditions due to the equalizing nature of the receiver characteristic shown in Figure 3-13. However, low transmitted volume resulting from a long loop (high loss and low current) could result in poor received transmission quality. Thus, the probability of occurrence of this condition must be kept small. This probability has been controlled by the nature of the distribution of loop lengths and the conventional resistance, unigauge, and long route design plans. The impact of station set efficiency asymmetry on network transmission performance must be considered as the use of concentrators is expanded, central offices are consolidated, and the use of finer gauge cable pairs is increased.

If the telephone station set is equipped for TOUCH-TONE signaling, additional circuits, not shown in Figure 3-12, are provided in the form of voice-frequency oscillators and pushbutton switches which connect the oscillators to the loop. By switch selection, two single-frequency signals are simultaneously transmitted for each digit. The oscillators generate the appropriate signals in accordance with resistance-capacitance or inductance-capacitance combinations connected by the switches. The oscillators are powered from a common battery supply in the central office; thus, they too are sensitive to variations in loop current. These switches and oscillators replace that part of the circuitry of Figure 3-12 associated with the conventional rotary dial.

### Other Station Set Types

Many other telephone station sets and associated circuits are available with transmission performance corresponding closely to that of the 500-type set [12]. These include the PRINCESS® and TRIMLINE® telephones, many coin station sets, and the telephone circuits of key sets and DATA-PHONE data sets. In addition, a number of decorative models called DESIGN LINE® telephones are also available and have similar transmission performance characteristics.

Some types of telephones are designed to meet special needs, such as operation in a potentially explosive atmosphere or in an area of high ambient noise. Wherever possible, these are also designed to have transmission characteristics similar to those of the 500-type station sets. Several sets, designed to aid the handicapped, depart from the 500-type characteristics significantly. Such sets may have amplifiers in the receiver circuits for the hard of hearing or amplifiers in the transmitter circuits for users with weak speech.

Modern operator headsets and a new handset, primarily for use in zone 36 of the long route design plan, depart in a number of ways from the 500-type [13, 14]. They employ microphones based on electromagnetic principles rather than the carbon granule resistance modulation principle. In fact, the design principles of the microphone and receiver are similar and differ only in detail. Amplifiers are used in both transmitting and receiving circuits to provide approximately 3-dB gain in each direction relative to 500-type set performance.

In many cases, operator headset circuits must be designed to suit the characteristics of the trunks with which they are associated. These circuits must take into account the transmitting and receiving gains in each particular application so that grade-of-service objectives are met. Special consideration must also be given to the sidetone performance of the circuit and headset [15].

### Ringling Considerations

An incoming call is usually indicated by an alerting signal in the form of a ringing bell. The ringing is accomplished by transmitting an ac signal at a nominal frequency of 20-Hz over the loop from the central office to the telephone station. The ringing cycle of two seconds

on and four seconds off is initiated by switching machine circuits which connect a source of ringing signals to the called loop.\* When the called station is answered, the signal source is disconnected. This action, called *ring tripping*, is performed in modern systems whether a call is answered during a ringing or silent interval. This is accomplished by superimposing the ac ringing current on a dc current component used for ring tripping.

The ringing function is made complex by the many variations in loop lengths and electrical characteristics and by the need to satisfy a wide range of service requirements, such as multiple ringers and party lines. The imbalance of loop impedances to ground that may be caused by party line ringer connections can produce excessive noise due to induced longitudinal currents. In addition, coupling of ringers to the loop can have adverse effects on dial pulse signals. These effects must both be controlled.

Party line ringing may be full selective, coded semiselective, or coded. Two-party lines are always full selective in that the bell is rung only at the intended station set. Four-party service may also be full selective but is often semiselective; where semiselective, two station sets are rung with the distinction between the two indicated by some form of ringing code. Eight-party service is usually semiselective and 10-party to 20-party services are always furnished by coded ringing only.

The design of station set ringing circuits must avoid such ringing impairments as *bell tap*, an intermittent ringing of the bell that can occur during dialing, and *cross ring*, a brief ringing of the bell on an uncalled party line that can occur when a called party on the same line answers an incoming call. Some circuits designed to avoid these impairments can introduce another problem called *pretripping*, the unwanted tripping of the ringing signal before the call is actually answered. This can be avoided by providing adequate design margin.

**Circuit Design Features.** Each ringer is connected in series with a coupling device either between the loop conductors or between one conductor and ground as shown in Figure 3-14. The coupling device may be a capacitor, a relay, or an electronic circuit utilizing electron tubes, diodes, or transistors. The coupling device provides a trans-

\*Other ringing cycles, such as one second on, three seconds off, are also used.

mission path to the ringer for the 20-Hz ringing current and, simultaneously, prevents dc from passing through the ringer coils which would interfere with the supervisory signalling function.

Capacitors are most commonly used to couple ringers to the loops. Capacitors in the range of 0.4 to 0.52  $\mu\text{F}$  are used with ringers that have a total coil resistance of 2500 ohms or more. For ringers of lower resistance, no longer manufactured though many are still in service, capacitors of 0.1 or 0.2  $\mu\text{F}$  are used. The series circuit made up of the coupling capacitance and the ringer coil inductance forms a 20-Hz series resonant circuit that allows the ringer to operate efficiently at 20 Hz but to present a high impedance at 60 Hz.

As previously mentioned, the 20-Hz ac ringing signal is superimposed on a dc voltage which may be of either polarity. The composite ac-dc signal may be applied between the two loop conductors

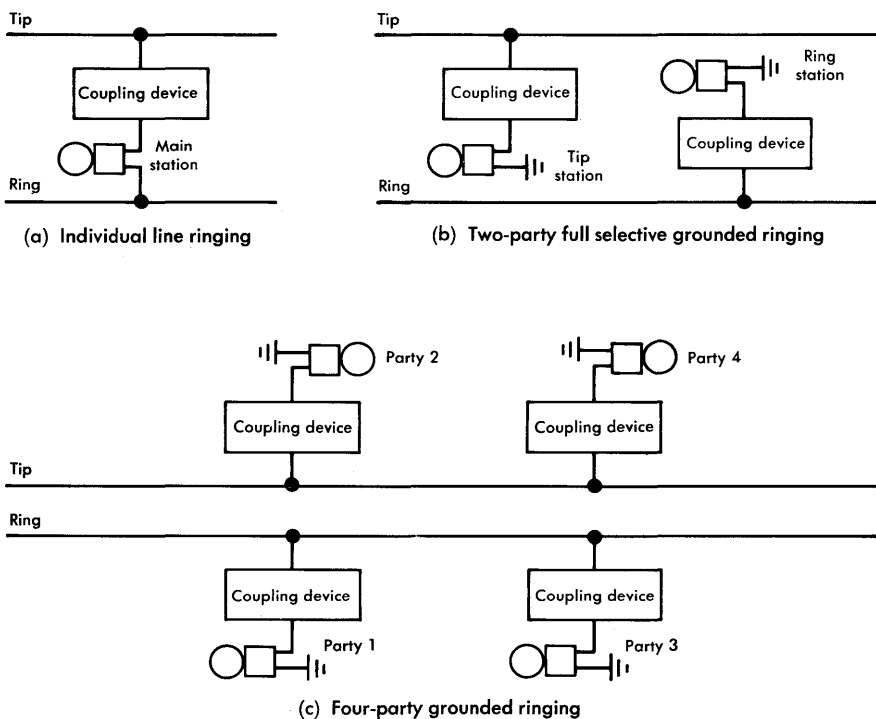


Figure 3-14. Typical station ringer connections.

or between one loop conductor and ground. The four combinations of dc polarity and conductor selection provide the flexibility required for 4-party full selective ringing and for 8-party semiselective ringing. The dc component of the ringing signal is also used to operate central office relays required for ring tripping.

In the 500-type station set, the usual ringer consists of two bells with a striker between them. The striker is attached to a nonmagnetized steel armature which is pivoted at one end. The other end is free to oscillate between the two poles of an electromagnet that is energized when ac is passed through the coil. The oscillation of the armature causes the striker to hit the bells. The armature is normally held against one pole of the electromagnet by a permanent biasing magnet. This arrangement provides for ringer operation on the positive half-cycles of the 20-Hz ringing signals and prevents bell tap due to line transients. An adjustable spring provides for further biasing of the armature. Weak or stiff spring tension, provided by inserting the spring in appropriate notches, may be used to control the sensitivity of the ringer. For 2-party service, the spring is placed in the stiff tension position to prevent cross ring. The ringer circuits are designed to permit up to five ringers to be bridged across a loop or to be connected between each side of the loop and ground.

The ringer coil may consist of two windings or a tapped single winding. These arrangements are combined with switch-hook contacts so that in the off-hook condition the ac connection to the ringer is broken and a connection is established from ground through a part of the ringer winding (which has a high impedance at speech signal frequencies) to the loop conductors. This arrangement is used to provide the central office with a means for automatic identification of the station connected to the tip side of a 2-party loop.

In special cases, the alerting signal is other than a ringing bell. For these cases, *ring-up circuits* are available to respond to the ac signal and to produce the necessary alerting signal.

**Coupling Devices.** A ringer is normally connected in series with a coupling device across the loop conductors as shown in the left-hand sketch of Figure 3-14(a). Occasionally, the connection is made from one loop conductor to ground as in the right-hand sketch of Figure 3-14(a). This arrangement can be used to extend the ringing range since the resistance of only one loop conductor is in the circuit;

it also allows the bell to be rung when the station set is inadvertently left in the off-hook condition. Figures 3-14(b) and 3-14(c) are illustrative of 2- and 4-party line connections. The 4-party configuration of Figure 3-14(c) may be semiselective or, where the dc component of the ringing current is reversible, it may be full selective. Many other arrangements are used, e.g., for 8-party semiselective ringing and for 10- or 20-party coded ringing.

Two-party line coupling devices commonly use capacitors as for individual line ringing. The ringing circuit for one station, called the ring station or ring party, is connected between the ring side of the line and ground. The tip party ringing circuit is connected between the tip side of the line and ground. Since neither station responds to ringing signals intended for the other, the arrangement is full selective.

**Ring Range Extension.** There are many factors that affect the distance over which telephone ringers can be successfully operated. These include the ringing voltage, the sensitivity, number, and locations of ringers connected on a loop, the impedances and other design characteristics of ringers and coupling circuits, and the electrical characteristics of the loop.

One method of extending the ringing range is to use a coupling circuit which avoids unbalanced impedances from loop conductors to ground. This imbalance results in induced noise on party-line arrangements. This type of limit, not truly a ringing range limit, is closely related to ringer coupling circuit design; it may be overcome by the use of a coupling circuit that effectively isolates the ringer(s) from the line except when ringing current is applied. This is accomplished by using electron tubes or solid-state devices. Figure 3-15 illustrates the application of an isolator circuit that contains silicon controlled rectifiers (SCR 1 and 2) which break down upon application of ringing current (to the ring side conductor in this illustration). The ringing current is thus passed to the ringer circuit.

Another form of coupling device is the range extender shown in Figure 3-16 which illustrates 4-party full selective or 8-party semiselective operation. This circuit, which performs functions similar to those of Figure 3-15, acts as a voltage controlled switch that connects a ringer to the loop when the proper amplitude and polarity of a composite ac-dc ringing signal is applied. The circuit utilizes a silicon controlled rectifier and two solid-state diodes. The field of application



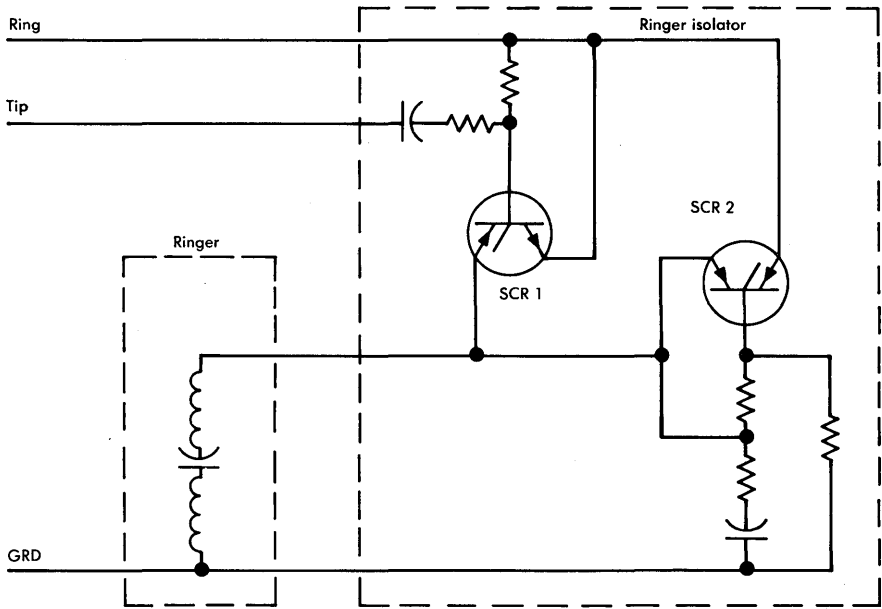


Figure 3-15. Typical connection of ringer isolator (ring party).

is somewhat more restricted than that for the circuit of Figure 3-15 since the dc current component can cause pretripping. One range extender must be used at each station set involved.

Figure 3-17 shows a third circuit that uses diodes, silicon controlled rectifiers, and a transistor to provide range extension and ringer isolation. The circuit is connected to respond to a negative dc voltage on the ring conductor. Other connections can be made for positive voltage on the ring side and negative or positive voltage on the tip side of the line. This circuit is somewhat more complex than the previous two but is designed so that only one extender is required for each party instead of one for each station. It is the most flexible of the three circuits since it may be used on long or short loops for ringer isolation and on long loops for range extension. It can provide 4-party full selective ringing and it can be used with ringers adjusted for weak spring tension. There is no pretripping because no direct current is transmitted.

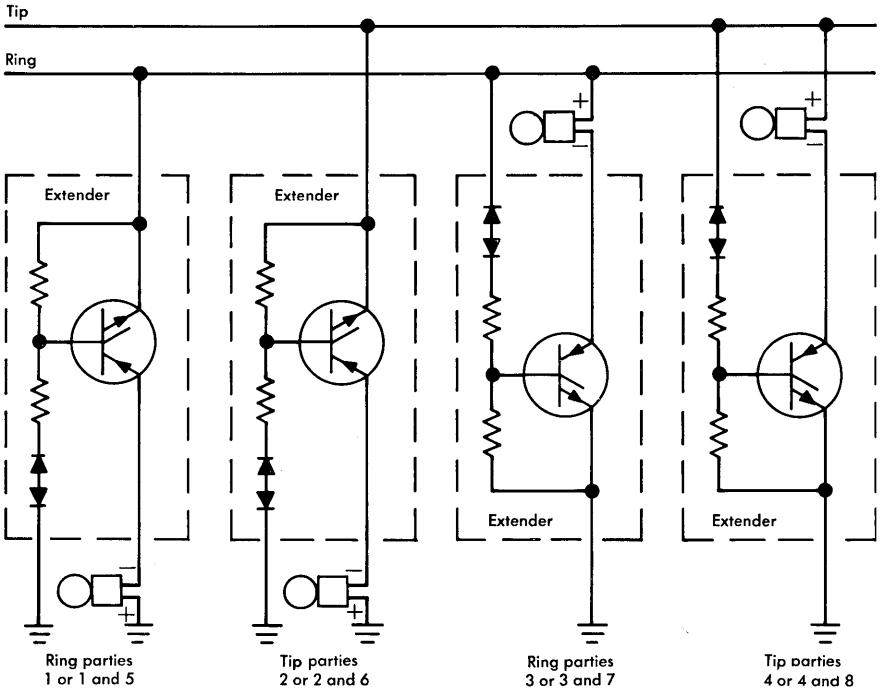


Figure 3-16. Solid-state range extender applied to 4-party full selective or 8-party semiselective stations.

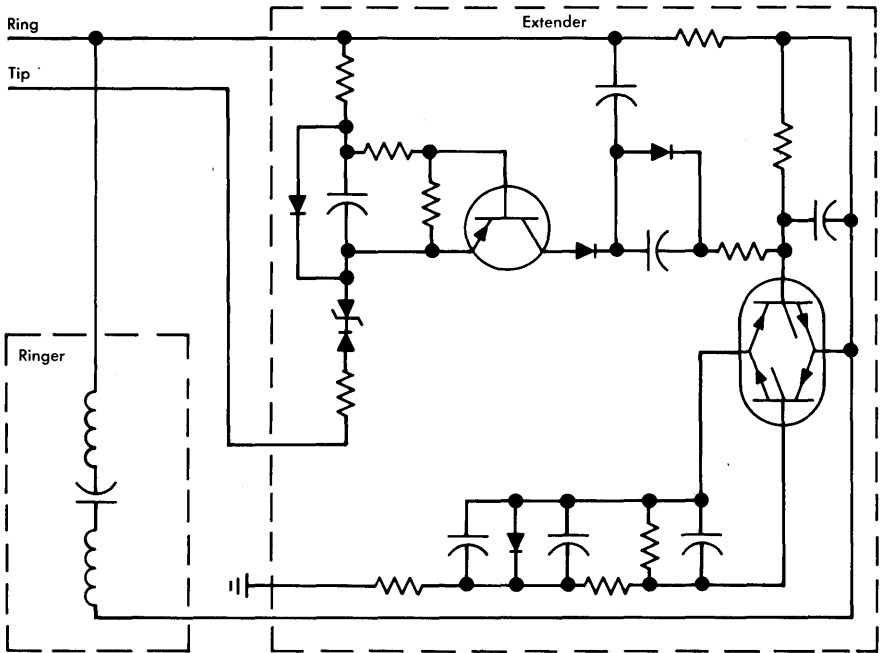


Figure 3-17. Solid-state range extender and isolator.

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## Chapter 4

# Voice-Frequency Trunk Facilities

Network trunks, the uses they fulfill, and the transmission requirements they must meet in order to operate properly in telecommunications networks may be considered separately from the physical facilities that must be provided [1]. These facilities include transmission media (open-wire lines, cable pairs, or carrier system channels) and central office or remotely mounted transmission equipment. Voice-frequency trunks use various types of loaded and nonloaded cable pairs almost exclusively.

Voice-frequency trunk transmission equipment provides amplification, impedance matching, equalization, suppression of echoes, and interface circuitry between voice-frequency and carrier-frequency channels. A number of types of hybrid metallic facility terminal (MFT) or negative impedance (E-type) repeaters are used for gain, impedance matching, and equalization of two-wire trunks. The most common of these is the solid-state E6 repeater which has found many applications throughout the voice-frequency plant.

For four-wire circuits and for interface applications between two-wire and four-wire circuits, V-type or MFT repeaters are most commonly used. These repeaters can provide amplification, impedance matching, and equalization in voice-frequency circuits including trunks and many special services circuits.

The MFTs are the latest equipment designs available for these applications. A wide variety of circuit needs can be fulfilled by this type of equipment in a very efficient manner. They are used for all-voice-frequency applications to provide two- and four-wire repeater and interface capabilities.

Analog facility terminals and digital facility terminals are used to provide interfaces between voice-frequency and carrier-frequency channels. Facility terminal equipment is available for two-wire or four-wire circuits and for interfaces between two- and four-wire circuits.

Trunks are designed to perform satisfactorily in many different switched network positions some of which require the use of echo suppressors. Several types of echo suppressors, equipped with enabling and disabling features that must be used to permit the transmission of certain types of data signals, are available.

#### 4-1 TRANSMISSION CONSIDERATIONS

A switched network must satisfy simultaneously a number of transmission objectives in order to assure generally satisfactory communication. The objectives include those relating to impairments such as noise and crosstalk and those relating to loss and echo. Keeping noise at acceptable values requires longitudinal balance of inside and outside plant, good cable shielding, and signal amplitudes that ensure adequate signal-to-noise ratios. Controlling crosstalk requires strict control of level point differences that occur in groups of cable pairs. Meeting the echo objectives requires a good impedance match between lines and repeaters and low enough loss for good received volume but not so low that echo or near-singing becomes annoying.

Although nearly all connections that involve voice-frequency transmission exclusively are short enough so that echo is no problem, most long connections include voice-frequency end links. Since echoes produced in these end links cannot be eliminated, they must be controlled by maximizing the structural return loss in cable pairs. It is also important that all other voice-frequency facilities and equipment be kept as free as possible of echo-producing reflections. It is clear that an echo from a distant terminal may be attenuated by an increase in net loss. However, this is not practicable in individual connections since net loss cannot be adjusted for each built-up connection as a function of echo; each link must have an assigned loss, dependent upon delay, that limits echoes in that link to allocated values. Loss and echo are controlled by the via net loss (VNL) design of the network [2].

Initially, loading was the only economical means for reducing attenuation in cable pairs and, by modern standards, load-coil spacing

was kept reasonably long and inductance quite high. A number of loading systems evolved but the H88 system ultimately became the most commonly used. It combines a reasonably long spacing with acceptably low attenuation and its passband in local cable (where capacitance is  $0.083 \mu\text{F}/\text{mile}$ ) is only slightly narrower than that achieved in channels of widely used carrier systems.

Loading makes attenuation of a cable pair more uniform throughout the passband but still introduces attenuation/frequency distortion sufficient to require equalization in trunks or lines long enough to need gain. The equalization serves two purposes: (1) it provides naturalness in the transmitted speech and (2) it prevents instability of the facility at frequencies where echoes would otherwise cause singing or near-singing. The apparatus needed for equalization is incorporated in modern voice-frequency repeaters. A repeater is commonly understood to mean a two-way amplifier and the ancillary equipment needed to support its operation.

Modern repeaters are the result of continued efforts to reduce cost, size, and power requirements and to group in one assembly as much as possible of the equipment needed at any given location. Early designs of repeaters depended on electron tube amplifiers requiring two sources of power, one for the filament or heater (usually 24 or 48 volts) and the other for the plate (usually 130 volts). The invention and development of the transistor reduced the power requirements to the type of supply common in most local central offices for switching and signalling. The use of transistors and advances in the designs of capacitors, inductors, and transformers have contributed materially to the reduction of repeater size and cost.

The development of economical repeaters has resulted in significant improvement in transmission on local trunks and special services circuits and has saved materially on cable costs by permitting the use of finer-gauge wires. These efforts led to the design of the negative impedance E6 repeater for two-wire circuits, the V4 repeater for four-wire circuits, and the subsequent integrated circuit designs in the various types of MFT equipment.

## 4-2 NEGATIVE IMPEDANCE REPEATERS

The provision of gain for both directions of transmission in a two-wire transmission circuit is a complex problem accentuated in typical telephone circuits by variabilities in circuit losses and im-

pedances and the necessity for providing margin against singing and near-singing. A common solution is the 2-way repeater that operates on the basis of introducing negative impedance in the two-wire line [3, 4]. These repeaters are generically designated as exchange or E-type repeaters. Some older versions which utilize electron tube circuits are still in use but the most common type is the solid-state E6 repeater [5]. Negative impedance repeaters are currently being superseded by the more flexible MFTs.

### Repeater Design

The gain unit of the E6 repeater uses two solid-state active elements (series and shunt) that work in combination as negative impedances to provide gain in both directions of transmission. They are oriented somewhat like the elements of an attenuation pad with respect to the transmission path to facilitate the image impedance design of the repeater. To promote stability of the circuit under the widely varying impedance conditions encountered in normal service, the series element is designed to be open-circuit-stable and the shunt element is designed to be short-circuit-stable. In order to achieve longitudinal balance and to provide a low-resistance dc path for signalling and supervisory currents (not provided in early repeater types), the two elements are transformer-coupled to the cable pair and the shunt path contains a blocking capacitor, as shown in Figure 4-1.

The line build-out (LBO) networks shown in the figure serve to match the line impedance to the image impedance of the repeater. When the E6 is used as an intermediate repeater, two LBO networks are needed; when it is used as a terminal repeater, the LBO position on the terminal side is equipped with a small dummy network which is electrically transparent and serves only to make metallic connection between the gain unit and other equipment in the central office. In some special services applications, the dummy network may be replaced by a range extension unit.

A completely assembled E6 repeater is approximately 3-1/2 inches wide, 3-1/2 inches high, and 10 inches deep. Shelf mountings are arranged to accommodate six repeaters. The gain unit and networks are assembled in the repeater by sliding them from the front and back ends of the extruded aluminum case along internal rails that guide the units to appropriate connector points; screw-down connectors are used to complete the interunit electrical connections. The overall as-



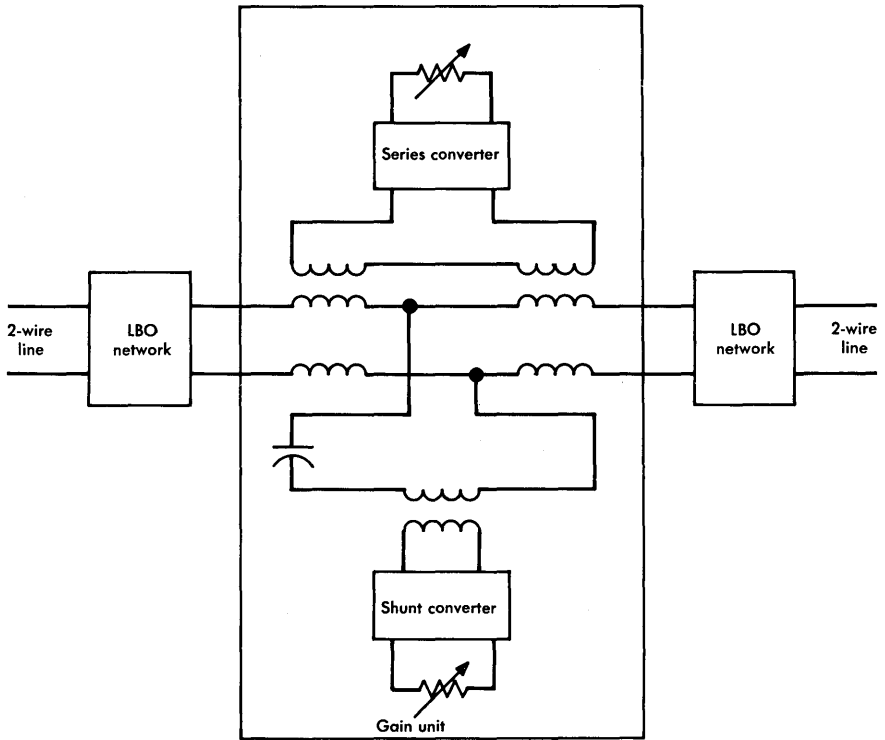


Figure 4-1. Block diagram of an E6 repeater.

sembly makes electrical connections to the mounting shelf wiring by plug-in connector arrangements. Each repeater dissipates about 1.5 watts supplied by the standard 48-volt office battery.

### Gain

The circuit of the E6 gain unit is shown in Figure 4-2. The gain-control networks,  $N$ , shown at the right-hand side of the circuit are adjustable in a series of binary-scaled steps by means of screw-type switches that are accessible only when the repeater is not plugged into the shelf. The adjustments for the series and shunt units are coordinated according to tables designed to keep the image impedance constant as the gain is changed. Steps of 0.1 dB are specified and the maximum possible gain is 13.3 dB. The gain must compensate for

equalizing and impedance matching network (LBO) losses as well as for cable pair loss. Since E6 repeaters are used on short-haul circuits, the changes in that loss with temperature are normally small and no gain regulation is provided. The loss changes that may occur must be considered in the overall design of circuits that utilize the E6 repeater.

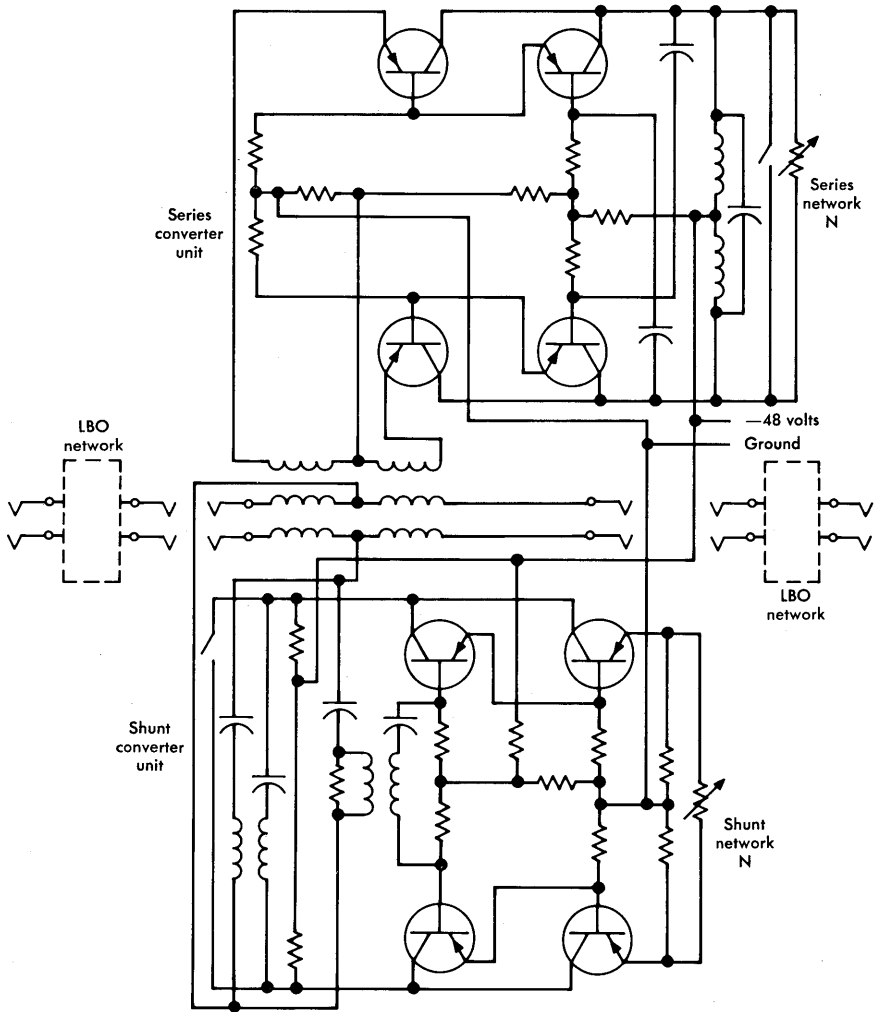


Figure 4-2. Schematic of an E6 repeater.

### Impedance Relationships

Satisfactory echo and stability performance of negative impedance repeaters is largely dependent on meeting stringent requirements on impedance relationships. The required impedance match is achieved by the use of LBO networks and impedance compensators.

A family of networks, coded as the 830-type, has been designed to match the impedance of loaded and nonloaded cable pairs to the gain unit of the E6 repeater, nominally 900 ohms resistive. It was not practicable to incorporate in a single LBO network enough components and switches to permit adjusting it to match a variety of loading systems with different cutoff frequencies and impedances. It was also not practicable to manufacture a different network for each of three gauges of loaded cable pairs. A compromise was reached by designing a network for each loading system and to provide adjustments for cable gauge in each one. A similar plan was followed for the nonloaded-cable LBO networks. In addition to impedance matching, all the networks provide some attenuation/frequency equalization generally required for nonloaded cable.

Most of these networks have conventionally adjusted elements, such as potentiometers and screw-type switches which are used to connect and disconnect resistors, capacitors, inductors, or lattice networks. The element interconnections, which determine the impedance characteristics of the network, are selected according to printed instructions to meet the requirements of cable pair gauge and location and the location of the repeater at an intermediate or terminal point in the trunk. The 830D network, used for high-impedance (6800 ohms) bridging on TSPS trunks, has no adjustments. The 830F network, also nonadjustable, is used on the terminal side of a terminal repeater for delay equalization where required. The 830C network, used for matching an E6 repeater impedance to that of a 22-, 24-, or 26-gauge nonloaded cable pair, supplies partial equalization but requires the use of an impedance compensator (837D-type network) at the non-repeated end of the pair for complementary equalization. The 830E network performs an equalization function similar to that of the 830C and the 837D networks combined; it is used only when terminal balance requirements do not apply at the distant end. Other 837-type impedance compensators are available to match cable pair to office impedances where good terminal balance is required at the non-repeated end.

The previously mentioned networks for loaded cable include series build-out resistance (BOR) and shunt build-out capacitance (BOC) adjustments for building out adjacent sections to the optimum equivalent length for impedance matching. They also contain high-frequency correction (HFC) and low-frequency correction (LFC) networks. Figure 4-3 shows the LBO circuit for H88 loaded cable facilities.

### Disablers

Repeater gains must be limited to provide margin against singing at all times whether facilities are in use or idle. In some cases, a repeater disabler may be used to remove the power supply ground of an E6 repeater when a repeated trunk is idle and to reconnect it whenever the trunk is seized. While disablers are usually not required on switched network trunks that are designed to 3-dB loss or more, they may be required for E6 repeaters on special services lines or trunks that include intermediate dial long line equipment since such equipment reduces return loss during dialing and can cause singing during dial pulse break intervals. Disablers can be adjusted to operate and release in response to various values of direct current. Where required, an older relay-type disabler is plugged into a separate shelf immediately below the E6 it serves. Built-in electronic disablers are also in common use.

### Applications

In most applications, E6 repeaters are mounted in the central office where standard 48-volt dc power supplies may be used. The design has also been adapted for mounting in the outside plant where power must be supplied from a central office over separate pairs dedicated to that purpose.

Repeater gain must be carefully limited so that overload, crosstalk, and stability requirements are not exceeded. Generally, the gain of repeaters located at the terminal end of a trunk is limited to about 6.5 dB gain while at intermediate points, the gain is limited to about 12 dB. In all cases, computations should be made of the achievable return loss at the terminals of the gain unit to be sure that stability margins are adequate.

## 4-3 FOUR-WIRE V-TYPE REPEATERS

Where voice-frequency trunks or special services circuits have too much loss for two-wire repeaters or where structural return

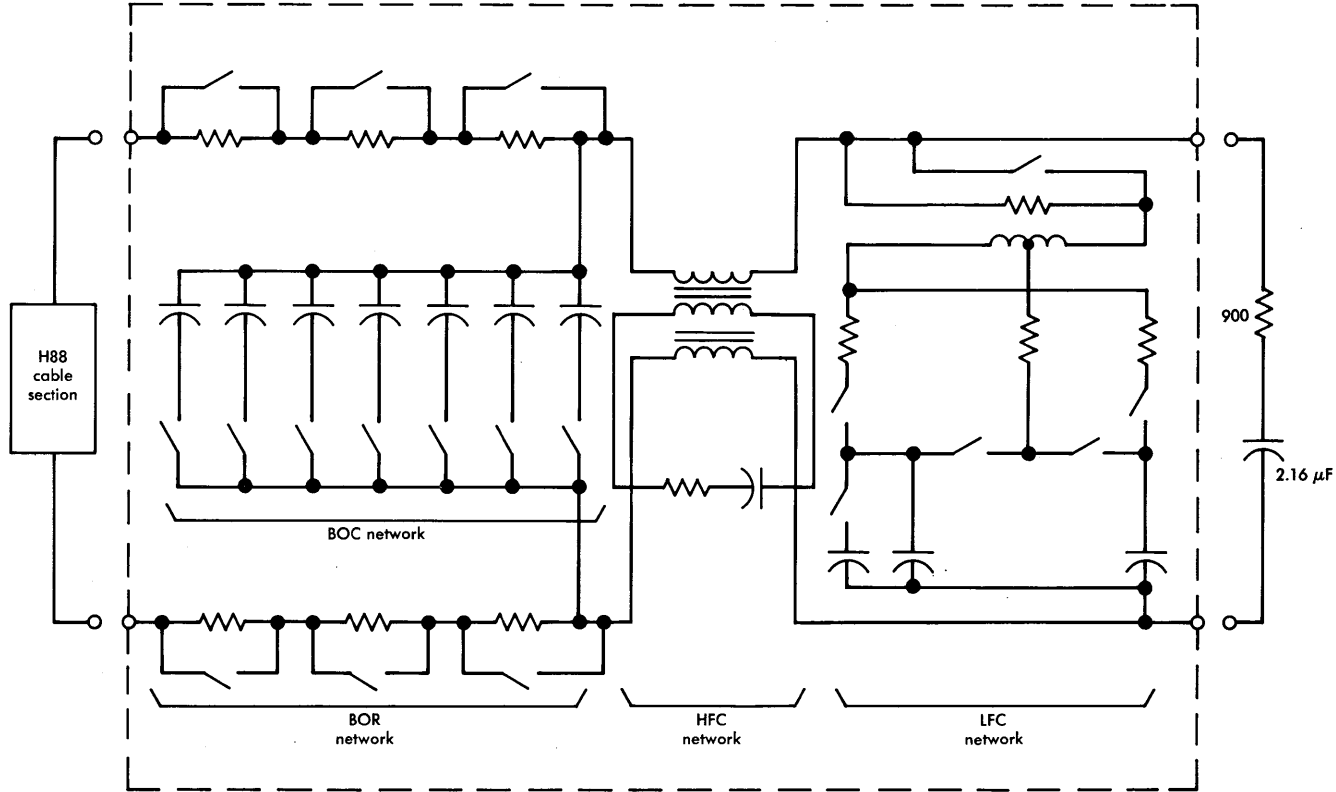


Figure 4-3. Line build-out network for H88 loaded cable pairs.

losses of cable pairs are too low to support two-wire circuits, four-wire operation may be employed. In addition, all trunks designed to meet via net loss requirements must also be four-wire. In a four-wire section, amplifier-type repeaters pass signals in the desired direction but prevent echoes that arise between amplifiers from reaching the talker or listener and from creating circuit instability. Amplification for four-wire circuits is provided by units of the V4 repeater family and of the MFT repeaters of similar design.

### Equipment Arrangements

A V4 repeater consists of a mounting shelf and a number of plug-in units designed to provide most of the transmission equipment needed for one circuit at a given office. The repeater may be mounted in a central office or at customer premises. Cross-connections, needed between units of older equipment grouped according to function in different parts of a central office, are not needed for the V4 repeaters. All connections are made permanently at the factory between sockets on the mounting shelf and the required units are plugged into the sockets.

There are two major types of V4 repeater shelves. The 24V4 repeater provides gain for each direction of transmission in the four-wire branches at a four-wire to two-wire interface. It is typically used at a trunk terminal or customer premises where two-wire switching is used but four-wire cable facilities are required. The amplifiers are always in the four-wire part of the repeater. The 44V4 repeater is a four-wire repeater that provides gain separately in each direction of a four-wire circuit. Block diagrams of these two repeaters are shown in Figures 4-4 and 4-5. Shelf configurations for various repeater types are given in Figure 4-6. This type of equipment may also be used for mounting a number of miscellaneous items such as four-wire terminating sets, 227-type amplifiers, pads, and various networks. A test jack field is usually included in each shelf.

There are many possible combinations of equipment units that may be plugged into V4 shelves. The proper combinations are usually determined by the type of service required and the type of cable facilities used. Since it is not practicable to provide schematics showing all workable combinations, special drawings are provided which consist of a large schematic for each V4 shelf and a smaller one for each plug-in unit. Several areas on the shelf schematics are left blank for

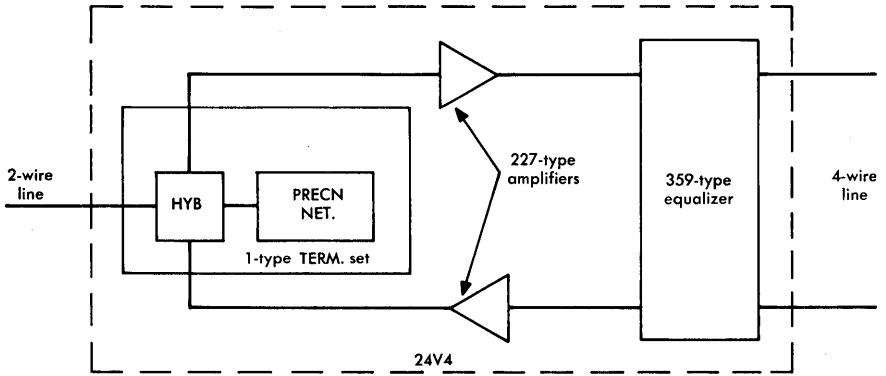


Figure 4-4. Block diagram of 24V4 repeater.

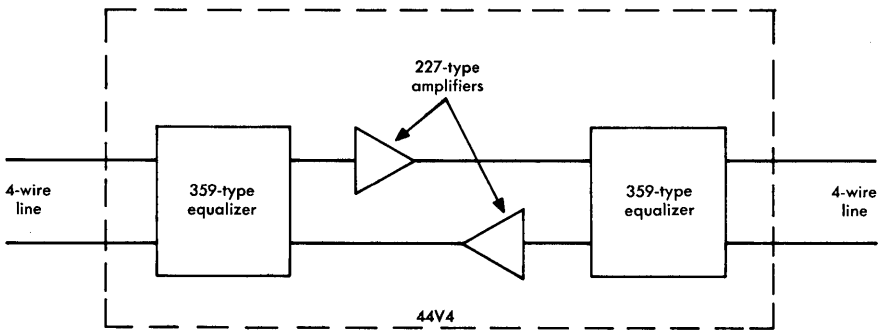


Figure 4-5. Block diagram of 44V4 repeater.

the appropriate plug-in unit schematics. Shelf wiring to the plug-in sockets is shown terminating at the edges of the blank areas. When the proper plug-in unit schematics are placed in those areas, the unit wiring meets that of the shelves to complete the desired transmission path.

Another variety of repeater, called the 424V4, is available for use on four-wire operator trunks associated with the Traffic Service Position System (TSPS) No. 1. This repeater utilizes the same design principle as do the 24V4 and 44V4 in that a single shelf design is coordinated with a combination of plug-in units required with the

CONFIGURATION	TYPE OF REPEATER SHELF			
	24V4A, B	24V4C	24V4D	44V4A, B
Repeaters per shelf	1	1	1	2
UNITS PER REPEATER 1-type terminating set or 4182-type network	1	1	1	—
227-type amplifier or 849-type network	2	2	2	2
359-type equalizer	1	1	1	2
434A plug	—	0 or 1	0 or 1	—
4066-type network	—	0, 1, or 2	0, 1, or 2	—
648A filter	—	0 or 1	0 or 1	—
Relay for bypassing repeater lacking emergency power	—	—	1	—

Figure 4-6. Shelf configurations for V4 repeaters.

TSPS. Most frequently used are four-wire terminating sets, amplifiers (or connect-through dummy networks or pads where amplification is not required), and relay units which provide suitable interconnection with signalling equipment. This repeater is being replaced by a newly designed bridging arrangement; there are significant numbers of 424V4 repeaters now operating in TSPS systems.

### Amplifiers

The 227-type amplifiers used in V4 repeaters are solid-state, two-stage circuits with negative feedback. The maximum gain of these amplifiers is about 36 dB. Selection of one of three slightly overlapping gain ranges is made as a coarse adjustment by means of screwtype switches; a fine adjustment within each range is made by means of a potentiometer with calibration marks of about 1 dB. Precise gains can be achieved with the aid of measuring sets. Each amplifier requires approximately 1/2 watt from a noise filtered, regulated, 24-volt



power supply. A regulated 48-volt supply may be used with the current fed through a 1400-ohm resistor to reduce the supply to 24 volts.

Automatic gain regulation to compensate for temperature-induced variations in cable loss is not provided. Since V4 repeaters can be equipped with adjustable equalizers, they can be used on longer trunks than can E6 repeaters; however, some repeatered facilities may have enough loss and annual temperature range to require seasonal adjustment of gains in order to avoid instability at low temperatures. The alternative to making such adjustments would be to operate the repeatered facilities at higher average losses than permitted by the objectives.

The input and output circuits of 227-type amplifiers contain coupling transformers that have multiple windings with several connection options. Center taps provide simplex leads for dc signalling over the cable conductors. Other optional connections may be made so that the impedance presented at the input or output is nominally 600 or 1200 ohms to match central office or H88 loaded line impedances respectively. For special applications, input and output impedances of 150 or 300 ohms can also be obtained.

Figure 4-7 provides a summary of 227-type amplifier characteristics and features. The 227A and 227B amplifiers are identical except that the 227B design was provided with diodes for protection from damage by voltages induced by lightning or power-line faults. For data services, it is desirable to provide amplifiers with less low-frequency delay distortion than that of the 227A and the 227B. The 227C and 227D amplifiers provide less delay distortion and have been recommended for use on data circuits. As a side effect of the improved delay characteristic, the flat-gain range is extended from 0.3 kHz to about 0.1 kHz. Many types of data signals are subject to errors produced by impulse noise and the susceptibility to this impairment has been reduced in the 227D, E, and F amplifiers. The 227A, B, and C amplifiers are no longer manufactured but many are still in use where their characteristics are adequate.

The jacks and plugs of the V4 shelves and plug-in units are wired in such a way that a four-wire terminating set is always connected to the 600-ohm ports of the amplifiers. An equalizer for nonloaded facilities is also connected to the 600-ohm amplifier ports. An equalizer for loaded facilities is always connected to the 1200-ohm input of the

AMPLIFIER	HIGH-VOLTAGE PROTECTION	REDUCED DELAY DISTORTION AT LOW FREQUENCY	LOW SUSCEPTIBILITY TO IMPULSE NOISE	RANGE OF FLAT GAIN, kHz
227A	No	No	No	0.3-10
227B	Yes	No	No	0.3-10
227C	Yes	Yes	No	0.1-10
227D	Yes	Yes	Yes	0.1-10
227E	No	No	Yes	0.3-10
227F	Yes	No	Yes	0.3-10

Figure 4-7. Characteristics and features of 227-type amplifiers.

amplifier on the receiving side of the line and to the 1200-ohm output of the amplifier transmitting in the opposite direction. The 1200-ohm impedances are a compromise between the minimum impedance of H88-loaded facilities in midband and the impedance at the lower and upper edges of the transmitted band.

Where no gain is needed, an 849-type network may be used economically in place of an amplifier to provide continuity for the voice-frequency and signalling circuits. Each network is provided with a socket for an 89-type resistor (plug-in pad modifier) which is required for control of loss through the amplifier position.

### Equalizers

Equalizers promote stability and compensate for attenuation/frequency distortion in transmission circuits. A wide variety of equalizers is used with V4 repeaters to equalize loaded and nonloaded cable pairs. These equalizers, the 359 type, include several codes which are dummy units provided for strap-through connections where equalization is not required. The 359A, the most commonly used unit, equalizes H88 loaded cable. Its features illustrate overall design principles of the 359-type equalizers.

The frequency-sensitive part of the 359A equalizer for loaded cable is applied at the input to the 227-type amplifier to compensate for attenuation/frequency distortion in the preceding line section. The equalizer has low-frequency and high-frequency sections, as shown in Figure 4-8. The low-frequency section, in series with the line, has

a loss characteristic that increases inversely with frequency to compensate for the opposite trend in the line. It consists of a variable capacitor ( $C_{LF}$ ) and a variable resistor ( $R_{LF}$ ) connected in parallel; both are adjustable in steps for length and gauge of cable pairs. The high-frequency section is an antiresonant circuit precisely tuned slightly above 3000 Hz and connected in shunt with the line. The bridging loss is minimal at the tuned frequency and increases above and below that frequency. Adjustment for length and gauge of facility is accomplished by means of a step-adjustable resistor ( $R_{HF}$ ) in series with the antiresonant circuit. Figure 4-9 shows loss/frequency characteristics for several adjustments of the equalizer elements. The use of this equalizer is recommended to increase circuit stability as well as to provide equalization.

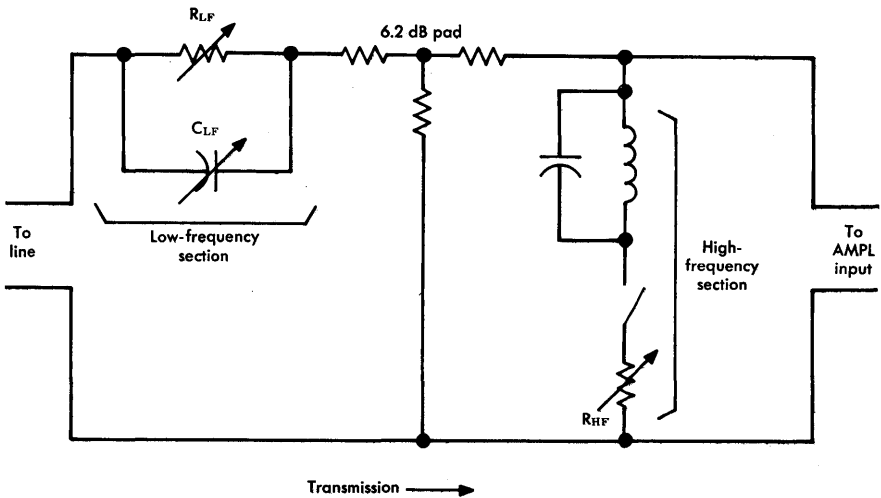


Figure 4-8. Schematic of 359A equalizer.

The 359-type equalizers for nonloaded cable applications are made up primarily of repeating coils. For short repeater sections, 600:600-ohm coils are placed at both ends; for intermediate length, 600:600-ohm coils are placed at one end and 600:150-ohm coils at the other; and for longer lengths, 600:150-ohm coils are placed at both ends. The equalizing action results from a combination of the natural low-frequency roll-off of repeating coils and the impedance mismatch between the line and coil. Both effects become more pronounced as frequency decreases and thus they tend to compensate for decreasing

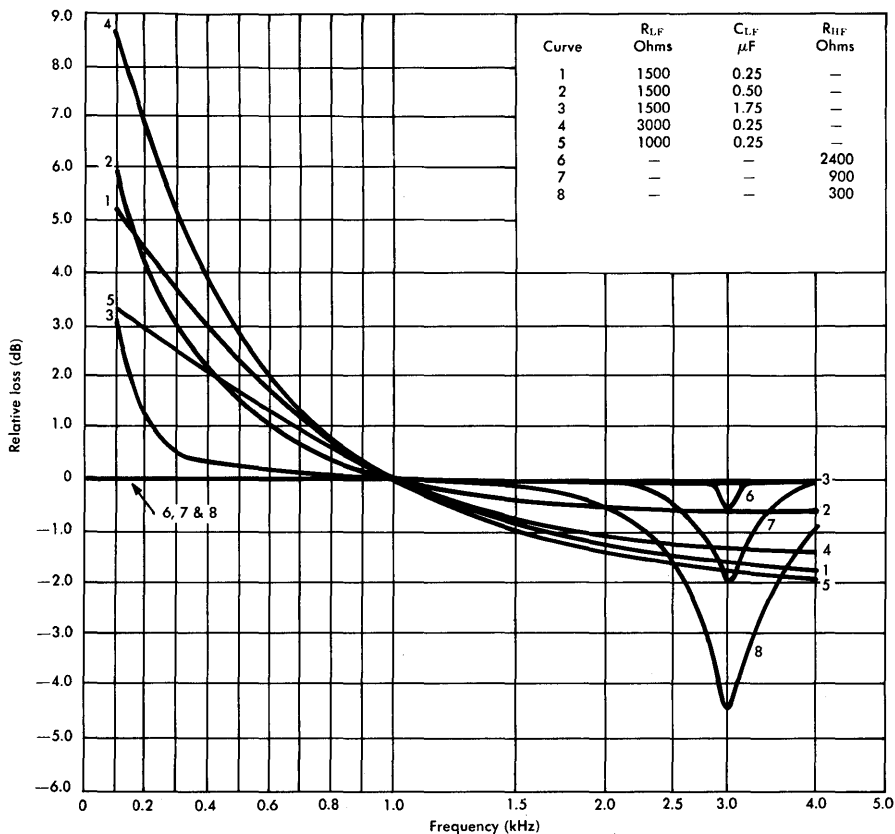


Figure 4-9. Typical loss curves of 359A equalizer.

attenuation in the cable pairs. The effects are greater in the 600:150-ohm coils. It has not been practicable to design equalizers for loaded and nonloaded facilities in the same repeater section. Where both types of facility must be used, a repeater should be placed between the two.

Dummy units are used when the amplifiers are connected to 600-ohm equipment in the same central office and also for short repeater sections. They provide electrical continuity and have no other function.

### Four-Wire Terminating Sets

Several designs of terminating sets have evolved to satisfy various 24V4-type repeater requirements. Each terminating set includes the hybrid transformers necessary for achieving the transition from two-wire to four-wire operation, a compromise network for balancing the impedance facing the two-wire port, a network building-out capacitor (NBOC) adjustable in fine steps, impedance-correcting networks for the four-wire ports, and reversing switches for aligning the polarities of simplex leads. Some sets have inductors in the dc signalling leads to prevent the circuit from noticeably affecting the impedance at the two-wire port, to block noise picked up in the simplex path formed by the two pairs in the four-wire section from reaching the two-wire ports, and to prevent voice transmission via the simplex path. Such undesired transmission could combine, in various phase relations, with the desired transmission via the voice-signal path to result in undesirably irregular attenuation/frequency characteristics. The signalling path inductors must not have enough inductance to impair signalling appreciably but must have enough to block voice transmission. Figure 4-10 illustrates some of the features of 1-type terminating sets.

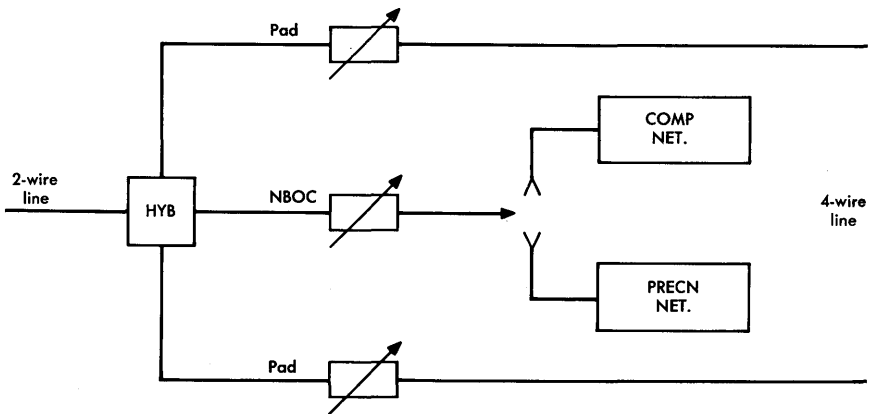


Figure 4-10. Schematic of 1-type terminating set.

**Balancing Networks.** Precision balancing networks (4066-type) are available for loaded and nonloaded cable pairs. The networks for loaded and one for nonloaded pairs simulate an infinite length of line and have only one port. Two of the networks for nonloaded pairs are adjustable for simulating different line lengths and have two ports.

The two-port networks are generally used for balancing subscriber loops. A build-out capacitor for a 4066-type network is available in each 1-type terminating set and is automatically connected to the network when both are plugged into a 24V4C shelf.

**Resistance Pads.** Transmission level points may be adjusted at each of the four-wire ports of many terminating sets. The adjustment is made by inserting appropriate values of 89-type resistors in 1C pad sockets provided in the four-wire legs. The resistors are assembled as plug-in devices each containing three resistors and six prongs for connections in the socket. In combination with resistors that are factory-wired to the 1C sockets, the plug-in resistors form 600-ohm H-pads. Loss values are provided in steps of 0.25 dB from zero loss upward over a wide range.

#### Four-Wire Extension Networks

A 4182-type network may be used instead of a 1-type terminating set and mounted in the same position in a V4 shelf. The main function of the network is to permit extending a line or trunk from a carrier terminal or four-wire facility to customer premises or a central-office switching machine on four-wire rather than two-wire cable facilities. All 4182-type networks provide transmission level point control through suitable choice of 89-type plug-in resistors. Other provisions, found in specific designs, include the derivation of simplex leads for signalling purposes, transformers with adjustable impedance ratio for matching purposes or for equalization of nonloaded cable pairs, and adjustable H88 loaded cable pair equalizers.

When a 4182-type network is used in place of a 1-type terminating set in a 24V4A repeater shelf, the repeater becomes the equivalent of a 44V4A repeater if the leads that normally connect a precision balancing network to the 24V4A repeater have been provided. These leads are used to provide a second path to the four-wire extension. Where these leads are not available, the 4182-type network cannot be used. Although the 4182-type networks permit use of a 24V4 repeater as a 44V4 repeater, it should be recognized that such use is wasteful of shelf space, since one shelf accommodates two 44V4 repeaters but only one 24V4.

Where no level point control, equalization, or signalling provisions are required, a dummy unit, the 437A, can be plugged into the terminating set socket of a 24V4-type repeater shelf to establish simple

four-wire electrical continuity through the terminating set position. The plug contains no equipment; it is used to connect the amplifiers to two four-wire pairs on what is normally the two-wire side of the repeater.

### Low-Pass Filter

In order to prevent singing and near-singing, a low-pass filter may be necessary in a four-wire section operated at a net gain between two two-wire circuits and extended in a two-wire section on at least one end. The 648A is a low-pass filter with 600-ohms nominal impedance and a 3-dB cutoff frequency of 3150 Hz. It is placed electrically at the input of the amplifier transmitting into the four-wire section; singing is prevented by the loss inserted in the circulating path around the four-wire section through the terminating sets for frequencies at which a balancing network cannot provide adequate balance for two-wire lines.

A 434A plug is provided solely for electrical continuity through the 24V4C shelf when the 648A filter is not used and when certain plug-in unit combinations are used. When the 434A plug is not used, external equipment (such as SF signalling units) may be connected into the circuit configuration.

## 4-4 METALLIC FACILITY TERMINALS

All transmission and signalling functions required at the terminals of message network trunks and many types of special services circuits can now be provided in one standard equipment assembly called a metallic facility terminal (MFT). The required functions are provided by selected plug-in units which are appropriately and automatically interconnected when inserted into the equipment shelf of a facility terminal. The connectors on the shelf are permanently wired in a manner to produce the desired interconnections. By this design approach, facility terminals eliminate many of the wiring congestion problems associated with earlier designs. This concept was used in the design of V4-type repeaters but it has been extended considerably and made more flexible in the facility terminal designs [6].

There are several other facility terminal arrangements used in the trunk plant: analog facility terminals (AFT), digital facility terminals (DFT), and customer premises facility terminals (CPFT).

Voice-frequency terminations are provided at analog and digital carrier system terminals for message network trunks and special services circuits and at customer premises for special services circuits such as PBX-central office trunks and PBX tie trunks. The types and capabilities of AFT, DFT, and CPFT equipment are generally similar to those provided in MFTs.

Metallic facility terminal equipment is compatible with existing E-type and V-type repeater equipment which may be in use in other parts of a trunk or circuit. The terminals provide interface circuits for most central office switching machines and a number of PBXs. The MFTs may be used on circuits employing loaded or nonloaded 19-, 22-, 24-, or 26-gauge cable pairs and for many special cases involving bridged taps, mixed gauges, and a variety of end-section lengths.

### Equipment Features

Metallic facility terminal configurations may be selected to provide a repeater for any one of three transmission modes. The first, called the 22-type, utilizes hybrid transformers and two amplifiers in two-wire circuits rather than the negative impedance principles of the E6 repeaters. It is functionally similar to an E6 repeater. A second type, the 44-type repeater, is used when four-wire circuits are connected at both terminals; it is arranged to function like a 44V4 repeater. Two versions of this repeater are available, one for use at an intermediate point and one for use at a terminal of a four-wire circuit. The third type provides an interface between a two-wire circuit and a four-wire circuit. It is similar to the 24V4 repeater in its functions and is also available in two versions, the 24-type and the 42-type. The two versions provide the necessary flexibility for circuit interfaces of two-wire to four-wire or four-wire to two-wire in progressing from the designated repeater input port to the designated output port. The three basic configurations are illustrated in Figure 4-11.

Two facility terminal shelf arrangements are provided, each with spaces for twelve plug-in units. Where treatment is required only for transmission, plug-in equipment for twelve circuits may be used. If both signalling and transmission treatment is needed, adjoining pairs of plug-in transmission and signalling units are used. Each shelf is arranged to provide treatment for six circuits. The interface



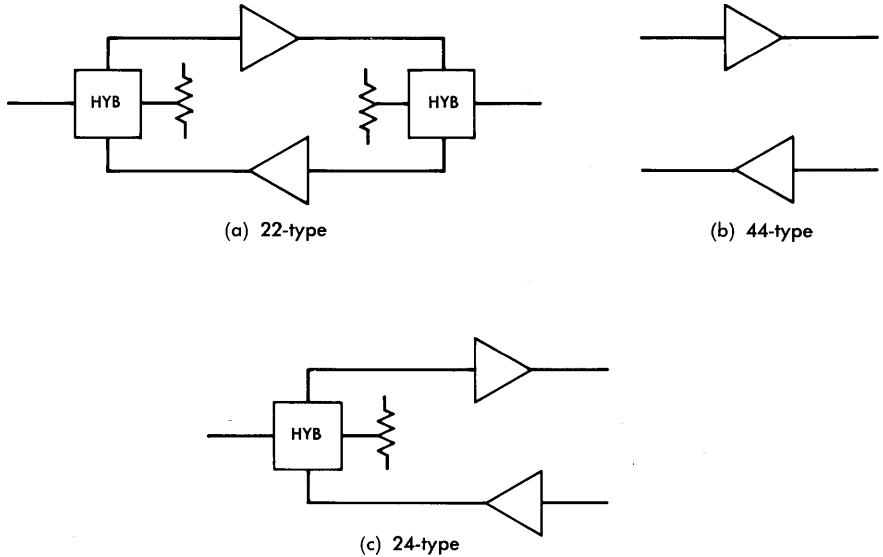


Figure 4-11. Metallic facility terminal transmission configurations.

is provided by standard signalling leads normally designated as the A and B, E and M, and SX and SX1. Test access for modern maintenance systems, such as the Switched Maintenance Access System (SMAS), may be provided.

### Transmission Features

A number of different transmission features are available and may be selected for appropriate use in various applications of facility terminal equipment. For example, terminating impedances of 600, 900, or 1200 ohms may be provided to satisfy specific circuit needs. Gain adjustment of the amplifiers is continuous over the range from  $-20$  to  $+24$  dB. Transmission plug-in units containing various types of impedance compensators, balancing networks, and equalizers are available to satisfy network trunk or special services circuit needs.

Equalizers compatible with the 359-type are used in the receiving portions of the repeaters. These equalizers are active circuits. In many cases, equalizer and amplifier gain settings are made in accordance

with tabulated data that pertain to the various applications in which these repeaters can be used. Adjustment and alignment is also possible on the basis of measurements made after installation.

There are several coded equalized gain units to satisfy various MFT transmission needs. The 309A unit provides flat gain in the transmitting path only of the four-wire portion of 24-, 42-, and 44-type repeaters. The 309B unit provides flat gain and equalization in the receiving path of the four-wire portion of 24-, 42-, and 44-type terminal repeaters and in both directions in 44-type intermediate repeaters. Designs are available for loaded and nonloaded cable pairs. In the four-wire portion of one 24-type repeater application, equalization is also provided in the transmitting path.

The 309C unit provides flat gain for loaded cable applications of 22-type repeaters. The 309D unit provides gain and equalization in 22-type repeaters used with nonloaded cable pairs and in repeaters used with mixed loaded and nonloaded cable pairs.

#### 4-5 VOICE-FREQUENCY EQUIPMENT COMPARISONS

Each of the three types of voice-frequency equipment has had advantages in its application and has fulfilled major needs at the time it was made available. Facility terminal equipment is now used in preference to E-type or V-type repeaters though there are still some of the older types of equipment in operation throughout the network.

##### Bandwidth and Stability

The attenuation/frequency characteristic of the E6 repeater is not adjustable. It provides the required amplification in midrange and rolls off in the high and low ranges in order to promote stability. This characteristic counteracts the low-frequency decrease in cable attenuation and, in the high-frequency range, counteracts decreased return loss near the cutoff frequency of loaded cable pairs. Since these characteristics are fixed and cannot be adjusted to match specific cable layouts, the use of more than two E6 repeaters in a specific trunk or special services facility generally precludes meeting bandwidth requirements.

In the two-wire facility terminal design shown in Figure 4-11(a), the impedance matching and equalization functions are separate and independent. Impedance match to the transmission lines is provided

by the balancing networks of the two hybrid transformers while equalization is provided by a portion of the amplifier circuitry. Therefore, both functions can be fulfilled with greater accuracy and flexibility than in E6 repeaters.

Circuits consisting of several four-wire sections equipped with V4 and/or MFT repeaters and associated adjustable equalizers can meet bandwidth and stability requirements. Where return losses of cable pairs are inherently too low for two-wire operation with negative impedance repeaters, four-wire operation with V4 or MFT repeaters is usually practicable. As previously mentioned, reflections in the four-wire section are confined to the repeater sections in which they originate by the blocking effect of the one-way amplifiers. The length limits of four-wire voice-frequency trunks in specific situations are imposed by lack of temperature regulation or by costs exceeding those for providing carrier facilities.

### Return Loss and Echo

The substantial blocking of reflections that originate within the transmission medium and at medium and repeater junctions makes the echo performance of four-wire facilities practically independent of such reflections. In V4 and four-wire MFT repeated facilities, the reflections are attenuated by approximately 70 dB of loss at each amplifier. In contrast, an E6 or a 22-type MFT repeater amplifies reflections as well as the speech signal. As a consequence, it is usually difficult, if not impossible, to attain and sustain acceptable return loss performance and control of echoes on a switched facility employing more than two of these repeaters.

### Losses and Transmission Level Points

The E6, V4, and MFT repeaters can transmit into loaded or non-loaded cables at a maximum transmission level point (TLP) of +6 dB with only a small chance of creating crosstalk problems or of being overloaded by the loudest talkers. Crosstalk-coupling magnitudes between loaded cable pairs in the same cable dictate that level point differences between repeater outputs and inputs be limited to 15 dB. That figure, therefore, is the limiting repeater section length for repeated loaded trunks and -9 dB TLP is the lower limit for inputs

from cable pairs to repeaters. Because crosstalk coupling between nonloaded pairs is less than that between loaded pairs, transmission level point differences for nonloaded cable pairs could be allowed to reach 21 dB but equalization capabilities are not generally sufficient for repeater sections with that much loss.

Loss objectives for direct and toll-connecting trunks can usually be met by two- or four-wire voice-frequency facilities. Where the loss and annual temperature range of the metallic facilities are very large, it may be impractical to avoid instability at the lowest temperatures or an unacceptable loss at the highest temperatures. Experience has shown that seasonal manual adjustment of the repeater gains is not practical. However, carrier facilities are usually more economical than metallic facilities where temperature-induced loss variations are excessive.

### Signalling

Voice-frequency repeaters must be capable of passing address and supervisory signals. In some cases, it is necessary that these signals also be amplified. The various types of repeaters that have been discussed differ in the manner in which such signals are processed.

All types of ac signals in the voiceband, such as 2600-Hz single-frequency, multifrequency, TOUCH-TONE, and inband coin-control signals, are amplified and transmitted by E6 and MFT repeaters. Expensive arrangements for bypassing low-frequency and dc signals around the amplifying elements of the E-type repeaters were eliminated by the method of coupling those elements to the transmission path. The transmission takes a split path through the repeater and supervisory and signalling components below the voice range are not amplified but are somewhat attenuated by the resistances of LBO networks and transformer line windings. These become part of the total loop resistance and thus reduce the maximum permissible facility length for a specified minimum supervisory current. In addition, the capacitor in the shunt element of the gain unit causes delay distortion of dial pulses, thus adversely affecting the operation of certain types of switching systems. Although these effects of E-type repeaters on supervision and signalling must be taken into account, they have not been limiting in enough cases to prevent the wide application of the repeaters.

All ac signals in the voiceband are also amplified and transmitted satisfactorily by V4 and MFT repeaters. Supervisory dc, dial pulse, and 20-Hz ringing signals are bypassed around amplifiers and other units on separate paths included in the shelf wiring and the plug-in units. Penalties must be accounted for in computing signalling ranges.

#### 4-6 ECHO SUPPRESSORS

Under the VNL network plan, every connection with an echo-path delay of more than 45 milliseconds should contain an echo suppressor. The echo suppressor is located in a four-wire intertoll trunk that is part of the built-up connection. It inserts a loss of 35 dB or more in the echo return path when speech energy is present in the direct path. Echo suppressors are always applied at points where speech or other signals are transmitted at voice frequencies.

##### Operation

Two configurations of echo suppressors are currently in use. In one configuration, called split, suppression is applied at both ends of a trunk and in the other, called full, suppression occurs at only one end of the trunk for both directions of transmission. A block diagram of the split echo suppressor is shown in Figure 4-12. It consists of two parts, one at each end of the four-wire portion of a trunk. When speech energy is transmitted from A, the part at the B end is operated by the speech signal and inserts a loss,  $L_B$ , in the B-to-A path. When speech is transmitted from B, the part at the A end similarly inserts loss,  $L_A$ , in the A-to-B path. Threshold circuits determine the sensitivity of the suppressor detection circuitry. The sensitivity is adjusted so that the suppressor does not operate in response to normal circuit noise but does operate on speech or other signal energy. The nominal operate sensitivity for all echo suppressors is  $-31$  dBm<sub>0</sub>; that is, a 1-kHz tone of  $-31$  dBm<sub>0</sub> just operates the suppressor. Thus, the *zero-level sensitivity* of the suppressor is said to be 31 dBm. The actual sensitivity, called *local sensitivity*, is the sum of the zero-level sensitivity and the loss between 0 TLP and the level point at which the suppressor is applied. At the  $-16$  dB TLP, local sensitivity must be  $31 + 16$ , or 47 dBm; at the  $+7$  dB TLP, it must be  $31 - 7$ , or 24 dBm.

The time interval between the passage of voice energy past the point  $q$  and the arrival of the echo at point  $r$  in Figure 4-12 depends

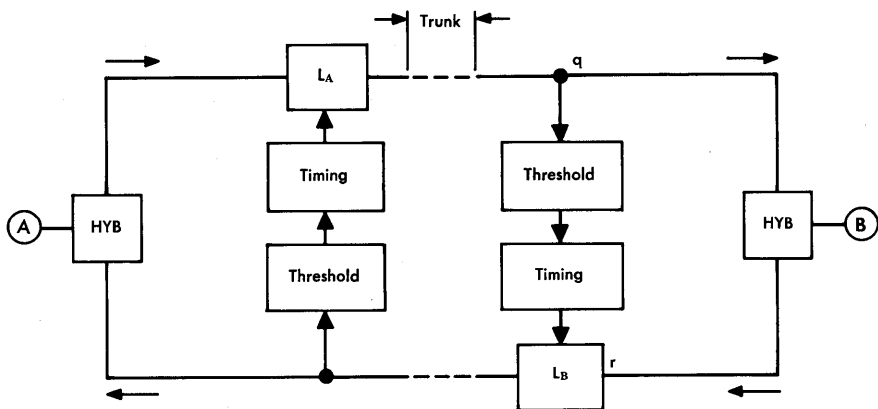


Figure 4-12. Split echo suppressor.

on the length and makeup of the circuit between the suppressor and the B station set and may be quite short. Thus, the suppressor must operate quickly to switch in the loss,  $L_B$ , so that the beginning of the echo signal does not return to the A end unsuppressed. On the other hand, the  $q$ -to- $r$  delay interval may be as long as about 20 ms and the suppressor must not release as quickly as it operates but must keep  $L_B$  in the path long enough to suppress all of a delayed echo signal. The time it takes to switch in  $L_B$  is called *suppression pickup* or *suppression operate* time. The time the loss  $L_B$  stays in the path after the speech signal has passed  $q$  is called *suppression hangover* time.

As in face-to-face conversations, there are times when the speaker at B may try to interrupt the speaker at A. If the suppressor had only the features previously described, the speaker at B could not interrupt the speaker at A because the loss  $L_B$  would be kept in the B-to-A path until the speaker at A paused. Since experience has shown that such situations lead to confusion, hence to inefficiency of circuit use, another feature is included to permit interruptions. A differential circuit, illustrated in Figure 4-13, compares the signal powers at points  $q$  and  $r$ . Whenever the power at  $r$  is high enough to indicate that it is probably speech from B and not an echo of the signal from A, the suppressor removes  $L_B$  from the B-to-A path and holds it out for a short time after B has finished speaking. The time between detection of double talking and removal of suppression is

called *break-in pickup* or *break-in operate* time. The time that suppression stays removed after double talking ceases is called *break-in hangover* time; it avoids, as much as practicable, the continued mutilation of speech from B as heard at the A end. Without break-in hangover, not only the first break-in syllable from B but also subsequent syllables would be clipped by suppression restored to the B-to-A path between syllables. Of course, the echoes of speech from A return to A during break-in but they are overridden by speech from B which must be the stronger in order to achieve break-in.

Where the intertoll circuit is provided via a synchronous satellite and the speaker at B breaks in with a single word, the echo of a signal from A can be delayed long enough (about one-half second) to ride through the break-in hangover "window" after the word from B passes through; it is, therefore, entirely exposed as it returns to A. The disturbing effects of such echoes are mitigated in practice by an additional feature that permits the differential circuit to add attenuation in each direct speech path during break-in, shown as  $R_A$  and  $R_B$  in Figure 4-13. The additional loss in the speech path is generally preferable to unattenuated exposed echoes.

The full echo suppressor, shown in Figure 4-14, provides suppression for both directions of transmission by means of equipment located at one terminal. The part at the left for suppressing echoes from B is the same as in Figure 4-13 but the part at the right for suppressing echoes from A is now closer to A than in Figure 4-13. The suppression hangover and differential circuitry, therefore, must be adjusted to take into account the echo delay in the intertoll trunk as well as that in the toll-connecting trunk and the loop. The break-in characteristics of this type of suppressor are inferior to those of the split type and its use is limited to certain types of terrestrial intertoll trunks.

## Types

The echo suppressors in current use in the Bell System are known as the 1A, 2A, 3A, 3B, and 4A. Their characteristics and other pertinent data are shown in Figure 4-15.

The amplifiers of the 1A echo suppressor employ electron tubes and require both 130- and 24-Vdc power supplies. The 1A can be used either as a full or as a split suppressor but full suppressor use is limited. Since the 1A does not have a differential circuit, suppression

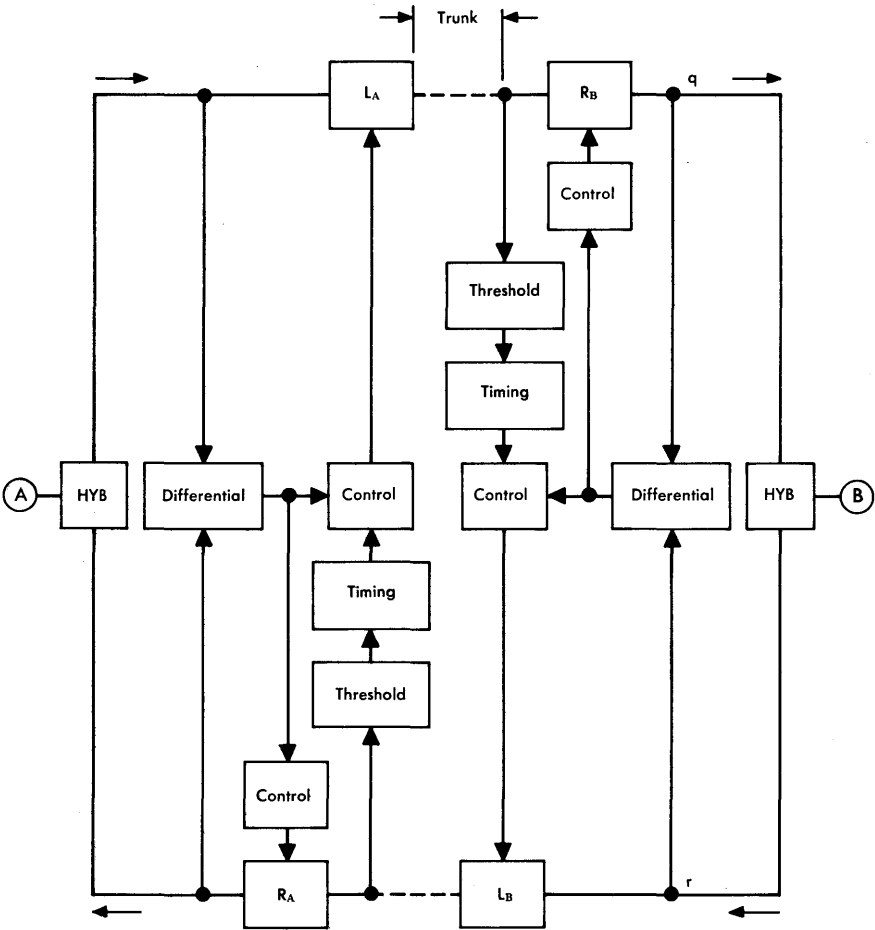


Figure 4-13. Split echo suppressor with differential circuits.

hangover must expire before break-in can occur; break-in cannot be forced. It can take place only when some pause in the opposing speech train is longer than the hangover time. Even then, the break-in speech train may be clipped until the hangover interval expires. For this reason, the 1A cannot be used as a full echo suppressor on terrestrial circuits more than 2500 miles long; since it has no receiving loss, it cannot be used as a split echo suppressor on satellite circuits.



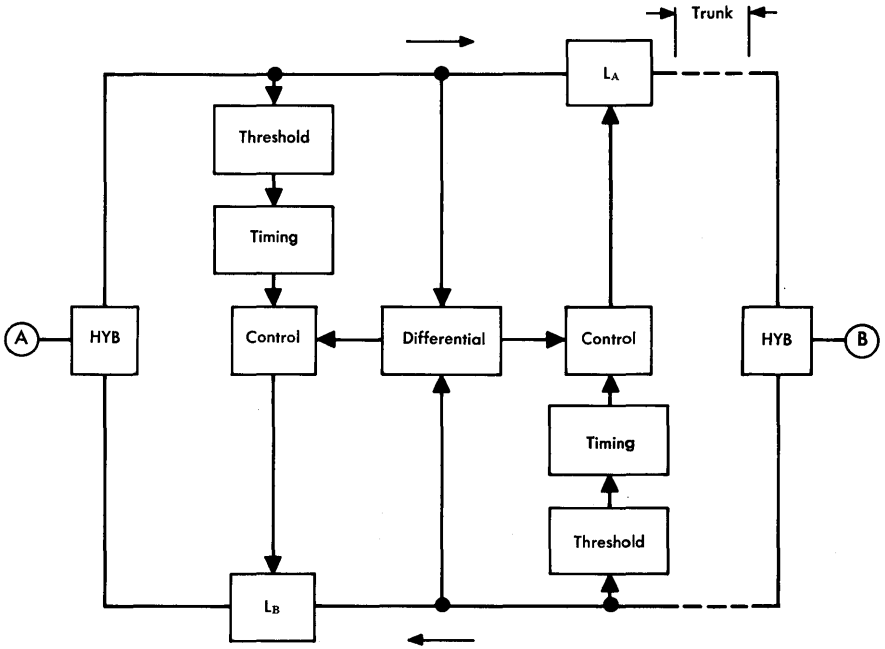


Figure 4-14. Full echo suppressor.

	TYPE OF ECHO SUPPRESSOR				
	1A	2A	3A	3B	4A
Full	Yes	No	No	No	Yes
Split	Yes	Yes	Yes	Yes	Yes
Break-in capability	No	Yes	Yes	Yes	Yes
Receiving loss during break-in	No	Yes	Yes	Yes	Yes
Compressor	No	Yes	Yes	No	No
For trunks	Yes	Yes	Yes	No	Yes
For access lines	No	No	No	Yes	Yes
Superseded by	4A	3A	—	—	—

Figure 4-15. Echo suppressor types and features.

The 3A echo suppressor is solid-state, operates from the 24-Vdc battery supply, and is designed for split use only. It has a modular shelf design with plug-in units. Break-in is facilitated by the operation of a differential circuit; an optional plug-in unit provides for insertion of receiving loss during double talking. The receiving loss consists of a speech compressor in early models and a 6-dB pad in later models. The 3A echo suppressor is suitable for all split applications. The receiving-loss unit is generally not needed for terrestrial circuits.

The 3B echo suppressor is the same as the 3A except for sensitivity, which is adjustable to compensate for various transmission level points and for the omission of the speech compressor option. The 3B suppressor is used in private switched network access lines rather than trunks.

The 2A echo suppressor was produced in limited quantities and is functionally and physically similar to the 3A. The 2A is used only on about 200 overseas circuits. In addition to the bridging amplifier, logic unit, and tone-operated disabler, similar to comparable circuits in the 3A echo suppressor, the 2A includes a speech compressor. Whenever the transmitting power exceeds the receiving power, the compression mode is initiated and loss is inserted in the receiving path. The inserted loss varies from 0 dB at a receiving power of  $-40$  dBm to about 16 dB at 0 dBm.

The 4A echo suppressor may be used for either full or split operation as selected by means of a switch. When used as a split suppressor, it is functionally the same as the 3B echo suppressor with a 6-dB receiving-loss pad. Since break-in occurs through operation of a differential circuit, the 4A echo suppressor can be used in the full mode on longer circuits than the 1A in the full mode. When the 4A is used in the full mode, a switch option permits a choice of zero or a 6-dB receiving loss.

### Enablers and Disablers

In some applications to private switched networks, it is necessary that echo suppressors normally be nonoperative and function only as required. In these applications, the suppressors are enabled by a control lead of a switching machine. Disabling is needed for echo suppressors on network trunks since such trunks at times carry data

signals. In these applications, suppressors are normally operative but are deactivated by a single-frequency signal which operates a tone-activated disabler.

When data signals are to be transmitted in both directions simultaneously, the echo suppressor must be disabled. The break-in feature cannot be relied on to remove suppression because of the wide range of amplitudes of the two oppositely-directed data signals at the suppressor on various built-up connections. The tone-operated disabler is bridged across the transmission path in the echo suppressor. When the called data set goes off-hook, a 2000- to 2200-Hz disabling signal is transmitted for at least 400 ms. The disabler recognizes such a signal and actuates a relay that disables all echo-suppressor operation. The suppressor then remains disabled until the data signal stops for at least 0.1 second, at which time it returns to normal operation.

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## Chapter 5

# Voice-Frequency Data Facilities

The transmission of various types of analog and digital data signals is an increasingly important part of providing telecommunications services. Many signal formats are used and the required bandwidths vary from the extremely narrow bands used for telegraph signals, which are multiplexed in the voiceband, to the full voice-bandwidth transmission of one data signal.

Voiceband data service may be provided by point-to-point or switched private line operation or over the switched public network. Although the facilities used for these modes of service provision may be similar or identical, the nature of the service is such that the manner of treating the facilities may be quite different. In private or public switched network operation, the variety of transmission paths and the variable number of trunks that may be encountered in successive connections make precise equalization difficult. For point-to-point line operation, the transmission facilities are usually dedicated to a particular service and may be engineered to optimize performance. As a result, satisfactory service can often be provided at a higher transmission rate than is possible over switched facilities.

Performance parameters that affect the quality of data signal transmission include random and impulse noise amplitudes, channel bandwidth and distortion, and such digital signal impairments as phase jitter, frequency shift, and gain and phase hits. These impairments must be related to appropriate transmission objectives and must be evaluated in respect to the available types of facilities.

The large range of facilities used for data signal transmission includes various transmission media and related equipment as well as

station interface equipment and data sets. While some of these facilities can be described in general terms, specific examples are used for illustrative purposes.

## 5-1 TRANSMISSION CHANNELS

Data signals are usually transmitted between two customer-owned business machines. Data station equipment provides the interfaces between the business machines and the transmission channel or channels. These channels have a number of components that can be classified according to the facilities that provide them and the way in which those facilities are related to the message network.

Each data station is connected to a central office by a facility that may be compared functionally to a customer loop. For data service, these connections are more commonly called access facilities because connections must often be made to a distant central office. The normal serving office may not be equipped to satisfy certain data operating needs or may have transmission characteristics that cannot satisfy data transmission objectives. Where access facilities connect data stations to distant central offices, problems due to added length and added exposure to certain types of impairment are introduced.

Access facilities are usually dedicated to or at least known to be needed for data signal transmission. For switched services, the interoffice facilities are shared with message telephone services and special treatment or engineering cannot be justified economically as is possible with access facilities. However, for point-to-point private line services, interoffice channels are usually dedicated to data signal transmission and special engineering can often be justified.

### Access Facilities

In addition to loops, access facilities include remote exchange (RX), foreign exchange (FX), and wide area telecommunications service (WATS) lines and trunks. Most voice-frequency circuits utilize loaded or nonloaded cable pairs but RX, FX, and WATS circuits may be routed over a dedicated channel of a carrier system. For data transmission, access facilities are often provided with gain or equalization equipment beyond that normally provided for telephone service.

Access facilities are usually provided on local plant cable pairs that have been installed according to resistance design, unigauge design, or long route design rules. Where data transmission requirements for

loss, attenuation distortion (slope), or envelope delay distortion cannot be met, alternative engineering design must be used. For example, bridged taps might be removed to improve transmission characteristics or, where economically justified, the available facilities might be improved by the application of loading or the use of electronic equipment such as repeaters or dial long line units. Dial long line units, used to increase signalling range, and repeaters sometimes increase delay distortion and delay equalizers may be needed. In other cases, circuits might be routed over facilities with coarser gauge cable pairs and thus less loss and slope or loading might be applied to improve loss and slope characteristics.

Figures 5-1 and 5-2 illustrate improvements in transmission characteristics that may be realized by the use of E6 repeaters and the line build-out networks that are available for use with the repeaters. In Figure 5-1, the indicated cable loss is the insertion loss between

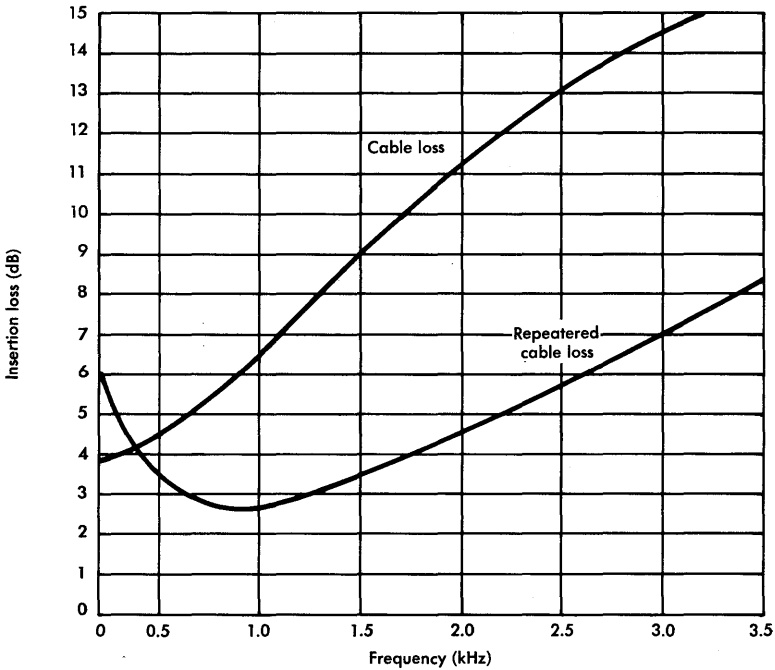


Figure 5-1. E6 repeater effects on loss.

900-ohm terminations of 12 kilofeet of a nonloaded 26-gauge cable pair having a 6-kilofeet bridged tap near the station end. The repeated cable loss characteristic represents the same circuit equipped with an E6 repeater at the central office. The maximum gain is 12.5 dB but since the repeater is equipped with an 830E build-out network which has substantial loss, the overall repeater gain is about 4 dB at 1000 Hz. Figure 5-2 shows the delay distortion of the same circuit. The characteristic shown without delay equalization includes the effect of the 830E network; the equalized characteristic shows the effect of adding an 830F delay equalizer to the repeater.

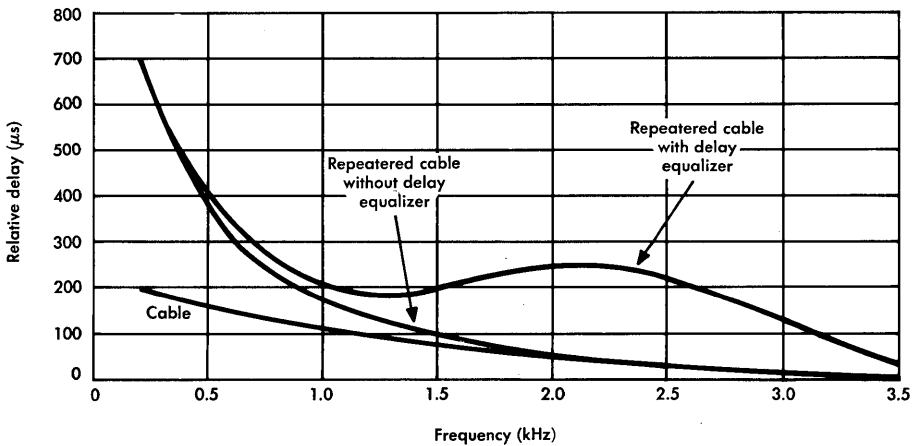


Figure 5-2. E6 repeater effects on delay distortion.

Another E-type repeater, the E7, is available to improve transmission on nonloaded access facilities devoted to the transmission of data signals. These facilities should be no more than 18 kilofeet long and must not exceed 1200 ohms resistance. There are also restrictions on gauges (22-, 24-, or 26-gauge cable pairs may be utilized singly or in combination) and on the length and makeup of bridged taps (maximum of 6 kft). The repeater is installed at the central office end of the facility. The E7, which consists of a negative impedance converter transformer-coupled to the line, acts as a series repeater at low frequencies and as a shunt repeater at high frequencies. The principal functions are to improve amplitude equalization and return loss at the central office end. It also provides a small amount of gain (less than 1 dB) above 1 kHz.

Plug-in equalizers, available for V4 and E6 repeaters, improve the transmission characteristics of specific gauges of loaded and non-loaded cable pairs. In some V4 applications, repeating coils (assembled as equalizer networks) having impedance ratios greater than 2 to 1 may be used to improve the slope characteristics of cable pairs. The insertion loss between lower impedance terminations thus provided increases more at 1000 Hz than at 2800 Hz. As a result, circuit loss is increased at all frequencies but the slope is reduced. This method is particularly effective for nonloaded cable pairs 9 to 12 kilofeet long. Improved equalization can be achieved with metallic facility repeaters which are superseding E6, E7, and V4 types for data service.

Although most electronic PBXs provide performance equal to that of direct access facilities, data transmission performance on connections through an electromechanical PBX is sometimes poorer than on direct facilities largely due to impulse noise. Therefore, it is often desirable to use the direct facility, especially for signal transmission at rates above 300 bits per second (bps). If a separate facility is not provided, any treatment necessary to meet data transmission requirements must be applied to all PBX-CO trunks over which service may be routed and the signal amplitude at the station must be adjusted accordingly. Where data signals must be transmitted through an electromechanical PBX, performance can not be assured.

### Interoffice Facilities

Between end offices, there is a wide variety of transmission facilities that may provide channels for data signal transmission. These include analog cable carrier systems, analog microwave radio systems, digital carrier systems, and voice-frequency cable facilities. Where service is provided over the switched message network, the trunks used are designed for speech signal transmission; for data signal transmission, echo suppressors are disabled. Message network trunk designs are adequate on most connections provided the number of toll trunks in tandem is not excessive. The number of trunks is a function of network routing under a given traffic load; speech and data transmission quality are both affected.

Where data signal transmission is provided as a point-to-point private line service, the channels used for interoffice connections are furnished over the same types of facilities as those used for message network trunks. However, the channels are dedicated to data trans-



mission and can be economically treated for optimum signal transmission. Gain units, equalizers, and impedance compensators may be installed as required to obtain the desired performance. Furthermore, facilities may be selected for optimum transmission; for example, if the normal routing takes a circuit through a central office with excessive impulse noise, consideration can be given to bypassing that office by using other facilities. If the signals to be transmitted are particularly susceptible to delay distortion and the normal routing includes an analog carrier system with excessive delay distortion in the multiplex equipment, special equalization may be provided or the circuit may be rerouted over facilities with less delay distortion.

## 5-2 TRANSMISSION PERFORMANCE

As in any type of signal transmission, satisfactory performance in providing data service involves the generation of a suitable signal format, the control of channel transmission characteristics, and the control of impairments. The relationships among these important parameters differ somewhat in switched network and point-to-point services [1, 2].

The differences are due mainly (1) to the variable length and makeup of connections in switched services versus the fixed channel composition in point-to-point services and (2) to the fact that a wider range of facilities is available for optimizing performance in point-to-point services. Many impairments are uniquely identifiable with specific types of facilities.

### Objectives

Transmission objectives for digital signals are specified to satisfy the transmission of signals defined for three ranges of transmission rates [3]. Type I signals are low-speed signals transmitted at rates less than 300 bps. Type II are medium-type signals transmitted at rates of 300 to 2400 bps. Type III are high-speed signals transmitted at rates in excess of 2400 bps. Objectives for type I signals are less stringent than for type II or type III signals. The objectives and the design rules for type II and type III signals and circuits are generally the same but additional transmission tests are specified if carrier channels are used in circuits provided for type III signals. For low-speed, type I, asynchronous service, transmission quality is measured as *telegraph distortion* for start-stop operation. Error rate is not used.

The basic criterion for judging the quality of synchronous data signal transmission is error rate. In many cases, the objectives and performance values are expressed in terms of bit error rate, i.e., the number of errors in a given number of transmitted bits. However, methods of administering business machine operations that involve type II and type III signals result in the transmission of bulk data in large blocks. Where errors are detected, the entire block is retransmitted. Thus, for these services, error performance is more appropriately expressed as a *block error rate*. The error performance objective is stated in terms of blocks containing 1000 data bits, a representative number for business machine operation. Typical block error objectives for Bell System services state that an average of no more than 1 block out of 100 should contain errors (expressed as a block error rate of  $10^{-2}$ ). One advantage of this error performance criterion is that it better reflects data transmission throughput (a term used to express data transmission efficiency) with data sets that use data scrambler and descrambler circuits. These circuits, used in type III data sets, tend to deliver several bit errors for each isolated bit error in the received signal; as a result, the bit error rate may be significantly increased but the block error rate is affected only slightly since the added errors tend to follow the initial error closely in time and thus fall within the same data block.

Most data channel transmission impairments can be expressed in terms of an equivalent *noise impairment*. An impairment, such as envelope delay distortion, can be rated by determining the improvement in signal-to-noise ratio needed to maintain the error rate obtained in the channel when impaired only by Gaussian noise. This method of rating quantifies the extent to which transmission is degraded by the added impairment and can be used to estimate the error rate due to other interferences. The equivalent noise impairment also provides a method of evaluating the accumulation of impairments from several tandem links of a connection.

To avoid excessive crosstalk or intermodulation and to prevent overloading of transmission amplifiers and carrier systems, the amplitudes of voiceband data signals are limited to a maximum power at the main distributing frame of  $-12$  dBm ( $-13$  dBm<sub>0</sub>) averaged over a 3-second interval [4]. Private line circuits are designed to have a nominal 1-kHz loss of 16 dB from transmitter to receiver. The tolerance on this value is  $+4$  dB to provide margin for loss variations. Switched network losses are controlled by the via net loss design.

## Impairments

Many of the impairments to which data signals are particularly sensitive are more commonly encountered in certain types of facilities. One notable exception is random noise. Since this impairment appears in all circuits, it can be controlled only by proper transmission facility and equipment design.

Impulse noise is commonly related to particular systems or environments and is often the dominant cause of data transmission impairment. A common source of impulse noise is the pulse transients associated with switching machine operations. Some types of switching machines, notably panel and step-by-step, produce excessive impulse noise and it is often necessary to route data circuits around offices that use such switching machines.

Delay distortion is another type of impairment that can be related to certain facilities. A common source of delay distortion is that due to the sharp cutoff characteristics of analog multiplex equipment, especially the characteristics associated with channel banks. For private line service over dedicated facilities, these characteristics can be equalized; in switched network applications, the number of multiplex terminals encountered varies from connection to connection and only an estimated average amount of distortion can be equalized. Departures from the average values must be tolerated (by providing adequate margin in data set design and operation) or must be equalized by adaptive equalizers which are included in some types of data sets.

Similarly, frequency shift, nonlinear distortion, and phase or gain jitter and hits may be identified with particular facility assignments or specific systems. When these impairments are excessive in point-to-point data circuits, the selection of alternate facilities is often the most economical solution to the problem. When troubles of certain types occur persistently in switched message network service, the trouble is likely to be in the data station or access facilities (which are not switched). The trouble then must be cleared or alternative facilities can be used if available.

The evaluation of data transmission performance and the identification and correction of specific trouble conditions are often of such a nature that data technical (DATEC) support effort must be given to assist craft personnel in installation and maintenance procedures.

The DATEC program provides for assistance where normal methods do not suffice. The assistance may be in the form of consultative or on-site participation by technical, engineering, or design personnel as required. The program is applied to intercompany as well as intra-company problems. Test procedures to determine the most likely source of impairment have been devised; they are used to identify a trouble, to help in isolating the trouble to a specific part of a circuit, and to provide insight as to how adjustments can be made to favor one solution or another as seems appropriate.

For switched network services, tests are made and results compared with objectives to determine the *minimum acceptable performance* (MAP). In these procedures, tests and measurements are made of attenuation/frequency distortion (slope between 1000 and 2800 Hz), envelope delay distortion, C-notched noise (C-message noise measured while a holding tone is transmitted), phase jitter, second- and third-order nonlinear distortion, frequency shift, and impulse noise. The procedures involve taking a statistical sample of data from several independently established connections.

### 5-3 VOICEBAND DATA STATIONS

Standard voiceband data service is supplied by a variety of DATA-PHONE data sets which may be connected to transmission facilities directly or through appropriate data auxiliary sets to provide the necessary interface (called the analog interface) between the data set and the line. A data set or customer-provided equipment designed for private line use is connected to the line through a data auxiliary set (DAS) such as the 828A and 829 type. A data set designed to transmit over and receive from the switched message network is connected directly to the access line. Where customer-provided equipment is operated on the switched message network, the analog interface is provided by a data coupler, referred to as a data access arrangement (DAA). The DAAs provide the following features: (1) protection of the network from hazardous ac and dc voltages, (2) protection against the transmission of signals of excessive amplitude or bandwidth, (3) call charge protection to allow automatic message accounting (AMA) of toll calls, (4) dial pulse signal control, and (5) longitudinal balance control to protect the network from excessive noise.

In some older equipment, the DATA-PHONE data set and the telephone instrument used for network signalling and speech transmission were designed as separate units. In these cases, the telephone instru-

ment was coded as an 804-type data auxiliary set. In newer data sets for the switched network, a standard 6-button key telephone set is used but is not called a data auxiliary set as in the earlier designs.

A second interface (called the digital interface) is provided by data station equipment between the DATA-PHONE data set and the customer operated terminal equipment, such as a computer, that provides the data message signal. This interface must satisfy a standard interface specification, either one issued by the Electronic Industries Association [5] or one covered by a series of Technical References issued by the American Telephone and Telegraph Company [6].

### Data Sets

Each type of DATA-PHONE data set uses the voiceband spectrum to transmit a signal format appropriate to a given application. The wide variety of signal spectra and formats and the transmission characteristics of the switched message network lead to variations in transmission performance from data set to data set and from connection to connection. Standard service offerings for private line and switched network use are provided by four series of data equipment identified as the 100, 200, 400, and 600 series data sets.

The 100 series equipment provides low-speed (up to 300 bps) transmission of data signals in a serial format to provide type I services. Signals are typically asynchronous and operate in a start-stop manner to transmit each character of a teletypewriter signal. Each transmitted character is represented by a 5- to 8-bit code.\* The initiation of each character is recognized by a start bit; the receiver recognizes the end of the character by counting the information bits, a parity bit, and a stop bit. Intercharacter timing is not controlled, thus making the overall bit stream asynchronous.

Some 200 series data sets operate at medium and high speeds (300 to 2400 bps) to provide type II synchronous or asynchronous serial data transmission over private line or network facilities. Others of the 200 series sets provide type III data transmission at rates up to 4800 bps over switched network facilities and up to 9600 bps over dedicated private line facilities.

\*The American Standard Code for Information Interchange (ASCII) 7-bit code is most commonly used in the Bell System.

The 400 series data sets operate asynchronously at low speeds to transmit data characters in a parallel mode. Multifrequency signals are used to represent data characters in 2-out-of-8 or 3-out-of-14 codes. These multifrequency signals are transmitted at rates of 10 to 75 characters per second.

The 600 series data sets provide primarily for the analog transmission of facsimile, analog telemetry, or medical electrocardiographic signals.

### Analog Interface

The tip and ring appearance of a cable pair at the customer premises is the interface point for voice-frequency data stations with the facilities network. Certain electrical and transmission characteristics may be described at this analog interface.

Since the impedances of access facilities vary widely, the input impedance of data stations must be a compromise value. A resistive value of 600 ohms has been selected for compatibility with the impedances of V4 and carrier system equipment. This standard data station termination is now being used in preference to the former value of 900 ohms for all applications since recent studies show that return loss performance is not very sensitive to the station set impedance.

In Bell System equipment, surge and hazardous voltage protection is provided at the analog interface by a line coupling transformer in most data sets, data auxiliary sets, and/or data access arrangements. These transformers are designed for at least 1500 volts rms isolation between primary and secondary windings to protect data set circuitry against any large longitudinal voltage that might result from contact of the cable pair with power lines or from lightning surges. They are also designed to provide good longitudinal balance in order to minimize induced power line interference and crosstalk between the cable pair used for data signal transmission and other pairs in the same cable. The station equipment is protected from high transient voltage by carbon protector blocks or gas discharge devices which automatically ground the line conductors when voltages exceed 250 to 600 volts, depending on the type of protector.

When a data circuit is installed, the data set or DAA equipment is adjusted to meet the previously mentioned signal power limit of  $-12$  dBm at the main distributing frame. This adjustment must

simultaneously meet a limit of 0 dBm at the data station. Thus, the station equipment compensates for up to 12 dB of loop loss. Where these limits cannot be met, supplementary amplification must be used. The DAA coupler is designed to limit the transmitted signal amplitude to the appropriate value; it automatically introduces attenuation to maintain a satisfactory signal amplitude and eliminates extraneous out-of-band signal components.

Other features may be furnished at the analog interface. These include automatic calling and answering, access and other arrangements for maintenance and testing, and loop-back facilities to permit testing from the central office.

#### 5-4 THE 208-TYPE DATA-PHONE DATA SET

Among the data sets most commonly used are the 200-series which provide type II and type III data transmission. The 201-type data sets provide for the transmission of serial binary data at rates of 2000 bps and 2400 bps over the switched message network and on conditioned and unconditioned private line channels [7]. The modulation method used is phase shift keying. There are large numbers of these sets in use.

Another, more recently designed data set has also been introduced for service over private lines designed to meet D1 conditioning requirements for message circuit noise and nonlinear distortion. This set, the 209-type, operates at 9600 bps [8]. It offers options of accepting and delivering several signals at lower bit rates (by time division multiplexing) with the sum not exceeding 9600 bps. It has a number of other unique operating features.

A new service offering which utilizes the 208-type has been introduced. This set operates at 4800 bps and is expected to replace the 201-type set in many applications. The 208-type data set, shown in block diagram form in Figure 5-3, is discussed as representative of DATA-PHONE facilities used for voiceband data services [9].

#### Description

The 208A data set transmits and receives 4800 bps synchronous serial binary data on unconditioned 3002-type four-wire private line channels [10]. These private lines provide a transmission band from 300 to 3000 Hz. The 208A is capable of duplex, half-duplex, or simplex

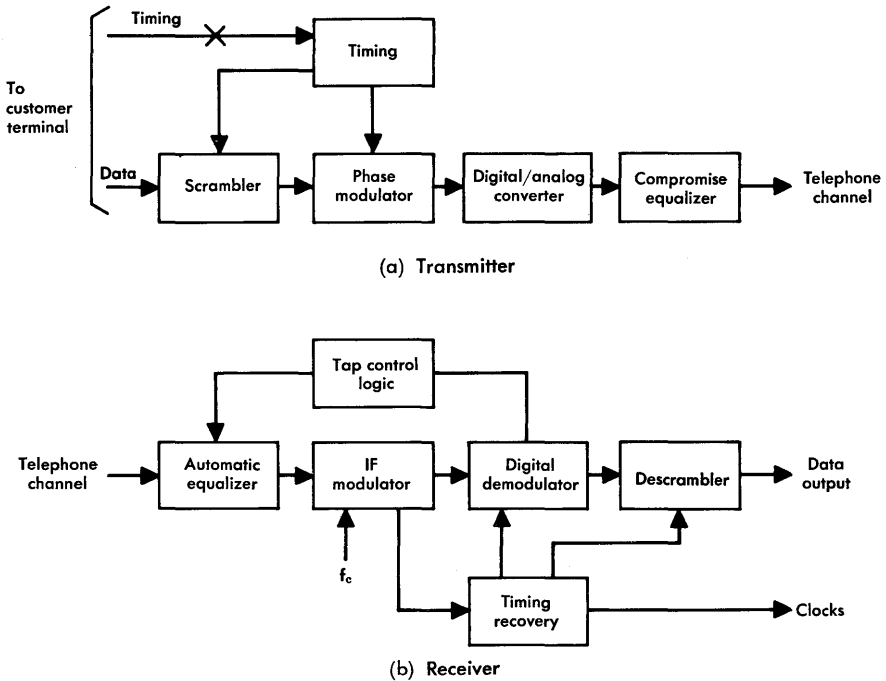


Figure 5-3. Block diagram, 208-type data set.

operation on four-wire facilities in point-to-point or multipoint private line applications. Another 208-type set, coded 208B, is capable of simplex or half-duplex operation over the two-wire facilities of the switched message network [11].

**Physical Characteristics.** Both data sets use solid-state integrated circuit technology. The circuit boards are mounted in a housing 16 inches wide, 4-1/4 inches high, and 11-1/2 inches deep. The sets may be placed on a convenient table, desk, or stand or they may be equipped with brackets for rack mounting in standard 19- or 23-inch wide equipment racks.

On the front of both data sets are a number of switches and indicator lamps used to control data set operations and to indicate the operating mode. At the rear there are receptacles for plug-in connections to commercial power, to the customer terminal equipment (digital interface), and to the transmission facility (analog inter-



face). Connections to the transmission facility are made directly from a 208B data set to a connecting block with a transfer control to a standard 6-button key telephone station set. For the 208A data set, connection is made through an 828A or an 829-type data auxiliary set. The choice is dependent on the application and the required features.

**Operating Features and Procedures.** A 208A data set may be operated in a number of optional modes which depend on the particular application. Among these options are internal and external timing, continuous or switched carrier, a one-second holdover, and new sync operation. The 208A may also operate on the switched message network for dial backup of the private line but only by using an 828C or 48B1 data unit; two two-wire loops must also be provided. The use of alternate voice operation depends on the need for coordination between attendants. Where a 208B data set is used for switched network applications, automatic calling and answering may be provided for network signalling; speech transmission is provided by a standard 6-button key telephone set.

The 208-type data set receiver incorporates an adaptive equalizer that self-adjusts according to certain signal characteristics and permits operation in the presence of a wide variety of channel characteristics. At the start of transmission, the 208-type data set requires a 50-ms training interval. During this interval, the transmitter generates a special signal sequence, called the training sequence, that permits the self-adapting equalizer at the distant receiver to be properly adjusted. While data is being transmitted, the equalizer is automatically readjusted according to the incoming signal characteristics whenever the error rate approaches 1 error in 100 bits. In nonswitched private line applications, an option is provided to permit the transmission of a continuous carrier signal when data is not being transmitted. This signal, received continuously at receiving data stations, obviates the need for transmitting a training sequence.

On connections exceeding 2000 miles in length, echoes may have more than 50 ms round-trip delay and, as a result, they may interfere with proper data set operation. In the 208B data set, an option switch is provided to allow the training interval, sometimes called the request-to-send-clear-to-send (RS-CS) interval, to be increased to 150 ms. Round-trip echo delays on channels provided over satellites exceed 150 ms; thus, the 150 ms interval may be insufficient on such channels.

The one second holdover option is applied to the timing recovery portion of the data set receiver. It permits the receiver to maintain synchronization with the transmitter to which it is connected for up to one second in the absence of a received signal. This option also provides for a quicker receiver recovery time in the event of a short-interval line interruption or dropout.

The new sync option is most advantageously applied to the receiver of the master station in a multipoint private line arrangement. In this arrangement, the master station receives messages in rapid sequence from a number of remote transmitters whose clock signals are not mutually synchronized. Upon receipt of an end-of-message code, the receiver timing circuit at the master station may take a longer time to decay than the interval between messages. The new sync option permits the customer data terminal to squelch the timing circuit rapidly upon receipt of the end-of-message signal. The timing circuit is thus readied for the next message and the synchronizing or timing signal associated with it.

In nonswitched private line applications, the 208A data sets are capable of operating in direct point-to-point applications and in a number of multipoint applications. The initiation of a message signal from the transmitter of one set triggers a fast start-up (50 ms training interval) of the timing circuits in the receiver of the addressed set. The use of the continuous carrier guarantees that the receiver timing circuits are already operating at the correct rate when a message is initiated. The adaptive equalizer in the receiver is also arranged for fast start-up adjustment or continuous carrier operation.

With alternate voice operation, the telephone key set controls must be used to switch between voice and data modes of operation. With the 208B data set, the voice mode may be used to establish a connection. Both ends of the connection are then switched to the data mode. However, an 801-type automatic calling unit (ACU) can also be used to set up dial connections; optionally, the receiving data set answers such calls automatically.

Operating procedures for the 208B data set are implemented by a built-in line control circuit. This circuit provides the analog interface between the data set and the access line. Circuit functions include the detection of ringing signals, line impedance matching, and lightning protection. When the automatic answering option is used, the control circuit responds to an incoming call by an answering sequence that

starts with a 2-second quiet interval during which no signal is transmitted from the data set. This interval is followed by a 2-second period during which a 2021-Hz signal is transmitted for the purpose of disabling any echo suppressors on the connection. The echo suppressors are kept disabled by either a 600-Hz signal from the data set or the normal data signal. The 600-Hz signal is transmitted when a data signal is not being sent or received. The circuit also contains data-voice transfer and call termination capabilities. The 801-type ACU responds to the 2021-Hz answer signal from the called data set. The ACU generates a 32-ms interrupt interval and then puts the data set directly into the data mode. It bypasses the 2-second quiet and answer-signal intervals of the answer sequence.

### Electrical Characteristics

The 208-type data set, as previously mentioned, is designed to provide the highest practical transmission rate commensurate with the transmission performance capabilities of unconditioned, 3002-type, four-wire channels. It uses phase shift keyed (PSK) modulation and compensates for amplitude and envelope delay distortions with an automatic adaptive equalizer. Each set incorporates a scrambler to randomize the data signal. By this technique, long strings of 0s or 1s in the transmitted signal are avoided thus precluding the necessity for placing restrictions on input data sequences.

**Signal Format.** Serial binary data signals are accepted by the data set at a synchronous rate of 4800 bps. The input bits are encoded as discrete phase shifts of an 1800-Hz reference carrier signal. The signalling rate is limited to 1600 bauds in order to minimize the effects of channel impairments. To transmit 4800 bps, three bits of input information (called tribits) form a symbol that is encoded in each baud. Thus, eight ( $2^3=8$ ) possible phase shifts of the reference carrier must be recognized and decoded at the receiver.

The phase shifts differ by 45 degrees and correspond to odd multiples of 22.5 degrees. The encoding of tribit input data to carrier phase shifts is illustrated in Figure 5-4 where it can be seen, for example, that the tribit 010 causes a carrier shift or symbol of 112.5 degrees and the tribit 000 causes a carrier shift or symbol of 67.5 degrees from reference. During data transmission, these phase shifts occur as multiples of  $\pm 45$  degrees from the previous state of the

carrier. The receiver circuits detect the differential phase shifts in the received carrier signal by measuring the time interval between zero crossings.

The PSK signal format was selected because of its ruggedness in the face of impairments normally encountered. In addition, the signal is transmitted at essentially constant power which can be controlled at the transmitter to conform to channel requirements in the switched message network.

**Timing.** The transmitter portion of each 208-type data set contains circuits that generate clock signals required to control the rate at which output signals are transmitted (1600 bauds) to within very close tolerance. However, a timing signal may be furnished optionally from the customer terminal equipment. In this case, the clock in the data set transmitter is phase locked to the customer-provided clock signal.

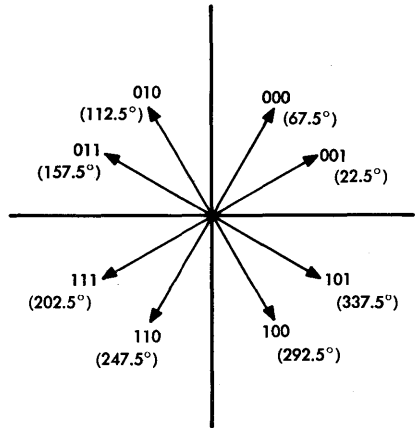


Figure 5-4. Signal coding in 208-type data set.

At the distant receiver, the line signal is modulated to an intermediate frequency (IF) as shown in Figure 5-3. The IF signal is then filtered, full-wave rectified, and applied to a narrow bandpass filter with a center frequency at the symbol rate of the data set. The output signal from this filter is amplified and sliced to produce a square-wave signal at the received symbol rate which is used as the reference frequency input to a digital phase locked loop in order to provide additional phase stability for the receiver timing. The output of the phase locked loop is thus an extremely stable signal locked to the line signal in phase and frequency. The final processes in the receiver, carried out in the digital demodulator and descrambler circuits, involve the decoding of the tribit symbols to binary signals and operations that are the inverse of the scrambler unit of the transmitter.

**Equalization.** A compromise equalizer is located with the transmitter circuits in the data set. This equalizer is adjusted at the time of installation to one of four possible settings to provide nominal equalization of the transmission facilities.

In the receiving portion of the data set, a tapped delay line equalizer is used to compensate adaptively for amplitude and delay distortion introduced by the channel. Six delay sections, as shown in Figure 5-5, are used; each has a delay of one symbol interval. At each of six tap points on the delay line, two attenuators are connected, one to minimize the in-phase component and the other to minimize the quadrature component of intersymbol interference. Such interference results from the distortion of pulses causing the pulse intended for transmission in one time interval to spread into time intervals assigned to other information pulses. Each set of delay line outputs is summed, the output of the quadrature summing amplifier is shifted 90 degrees relative to the output of the in-phase summing amplifier, and the two outputs are again summed to form the equalized output signal. The attenuators are adjusted automatically by an algorithm that minimizes the error rate in the output signal.

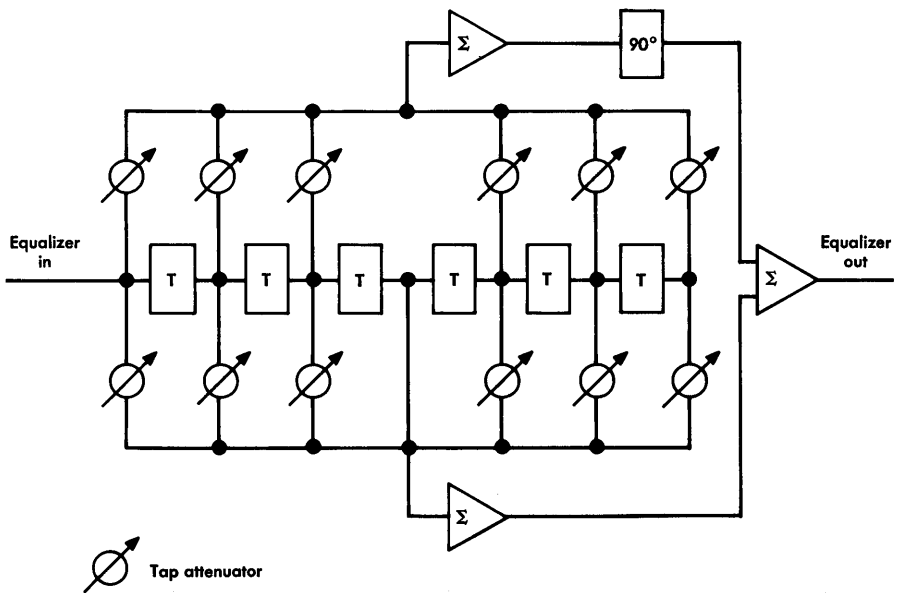


Figure 5-5. Block schematic of adaptive equalizer.

**Signal Scrambling.** To prevent the transmission of a long series of identical phase shifts and to preclude the necessity for placing restrictions on input data sequences from customer terminal equipment,

the data is scrambled at the input to the data set transmitter. The scrambler circuit, especially effective in avoiding the transmission of long sequences of 0s or 1s, maintains a random-appearing sequence of phase shifts in the line signal. This feature is required to prevent the adaptive equalizer from diverging and to allow the receiver to be properly synchronized to the incoming signal. It also results in a signal power spectrum that meets requirements specified in the applicable tariff.

As shown in Figure 5-3, a descrambling circuit, complementary to the scrambler in the transmitter, restores the signal to its original form before delivering it to the customer terminal equipment. The use of scrambling and descrambling involves a penalty in that the descrambler produces an increase in bit errors; however, the block error rate is not materially affected.

**Ancillary Features.** Primary power for the 208-type data set is furnished from a commercial 60-Hz power source. Provision is made within the data set for primary power shut-down in the event of an excessive rise of temperature. If internal voltages increase excessively, a circuit is brought into action automatically to reduce voltages to safe values. The thermal protection feature automatically resets when the internal temperature drops to a safe value. The overvoltage circuit must be reset by removing and then reapplying the ac voltage to the data set.

A number of test modes and maintenance features have been provided in these data sets. Test conditions are established by the operation of test option switches located on the front panel of the data set. An analog loop-back test can be performed at the data set without involving customer terminal equipment or telephone line facilities. A simple test signal is generated in the transmitter and looped back through the receiver. Errors in the received signal are indicated by a flashing front-panel lamp.

Similarly, a digital loop-back test can be performed. With this arrangement, the remote data set is looped at the digital interface and acts as a regenerator. Test data is transmitted from and returned to the local data set and checked for errors. This type of test can be carried out only on four-wire private lines utilizing a 208A data set.

Type-208 data sets can be placed in a test mode so that tests can also be performed by telephone company personnel operating from a data set center. Circuits are arranged for one-man testing throughout.

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## Chapter 6

# Wideband Facilities

Signals that occupy a bandwidth wider than voiceband often require specially treated transmission facilities. Among these signals are wideband data signals, some Digital Data System (DDS) signals, and baseband television signals. The types of facilities involved are the transmission media, the terminal equipment used at the customer premises, and central-office-mounted equipment. Both customer-premises and central-office equipment may provide gain, equalization, impedance matching, and a number of operating and maintenance features necessary to integrate wideband services with the telephone plant.

In some cases, local plant facilities furnished for wideband services are similar in design and operation to equipment required for inter-exchange and long distance transmission. These equipment items are discussed in later, more appropriate chapters but they are mentioned here in order to show more clearly the nature of the design relationships.

A number of wideband facilities are also provided for visual telephone service, program services, and high-speed local baseband data service furnished primarily by using customer-provided equipment. A method of diplexing television video and audio signals by frequency modulation of a carrier at about 6 MHz by the audio signal is under consideration but design details are not now firm.

### 6-1 WIDEBAND DATA FACILITIES

A substantial number of equipment types have been designed and produced for the transmission of specialized data signals required



for business and government purposes. Attention is confined here to a family of wideband data facilities originally designed for compatibility with half-group, group, and supergroup bandwidths available in the L-multiplex equipment. Included are several arrangements for high-speed data transmission on T-carrier systems [1]. The short-haul N-carrier system has also been adapted to the transmission of these signals where bandwidth is suitable. In some cases, provision has been made for the alternate use of these bandwidths for data or voice channels. Wideband data applications are confined to switched and nonswitched private line services.

### Wideband Data Station

Excluding the DDS, the 303-type data station is the principal equipment design used for coupling customer-owned data terminal equipment to Bell System transmission facilities [2, 3]. Serial signals synchronized to clock rates of 19.2, 40.8, 50.0, 230.4, or 460.8 kilobits per second (kb/s) may be transmitted. Asynchronous signals may also be transmitted with minimum permissible signal element (pulse) widths of 52.0, 24.5, 20.0, 4.3, or 2.2 microseconds respectively for the available options. These options are provided by the appropriate selection of coded data set within the 303-type family.

**Optional Features.** In most installations, the 303-type data station equipment can be housed in a single cabinet 24 inches high, 24 inches wide, and 12 inches deep. A somewhat smaller cabinet is also available for use where equipment requirements are minimal; in a central office environment, the equipment can be rack mounted without a cabinet. Optional units that may be used to provide selected available features include the 404-type voiceband data set and the 809-, the 804-, and the 806-type data auxiliary sets.

The 303-type data set processes the signal from the customer terminal for transmission over various types of local and toll transmission facilities. A selection of data auxiliary sets must be made in order to satisfy requirements, such as operating speed and synchronous or asynchronous operation, of the specific service to be furnished. If synchronous operation is required, internal or external timing must be selected and a signal scrambler and descrambler must be provided. The options selected determine the code designation of the required 303-type data station equipment.

The 404-type voiceband data set may be used to transmit parallel data at low speed over the voiceband coordination channel associated with each high-speed data channel. It is used primarily to control and coordinate operations at the two ends of a circuit over which asynchronous signals (such as 2-level black and white facsimile) are to be transmitted.

The 809-type data auxiliary set is used when the 303 data station is equipped to transmit 19.2 kb/s synchronous data or the equivalent asynchronous data (52  $\mu$ s minimum permissible signal element duration). It translates the baseband signal from the data set to a vestigial sideband signal in the band between 28 and 44 kHz for transmission and then translates it back to baseband at the receiver. With the carrier at 29.6 kHz, the signal spectrum is made up of a 1.6 kHz vestigial lower sideband and a 14.4 kHz principal upper sideband.

The 804-type data auxiliary set provides a telephone instrument and the circuitry needed for operational control of the voiceband coordination channel and the wideband facilities. Voice communication may be carried on while the wideband channel is in use; if the 404-type data auxiliary set is used to provide low-speed data communication, voice communication and low-speed control signal communication cannot be carried on simultaneously.

The 806-type data auxiliary set provides line termination and test capabilities. It contains test access jacks and circuits that may be used for loop-around connections which can be established by signals transmitted over the voiceband coordination channel from the central office. This feature is useful in isolating trouble conditions without visiting the station.

**Electrical Characteristics.** Although data signals can be transmitted by a 303 data station at a number of different rates, the most common is 50 kb/s. In all applications, the wideband data channel is provided as a four-wire channel and full duplex operation is possible. The voiceband coordination channel may be either two- or four-wire.

*Signal Format.* Signals are transmitted between 303-type data stations in a modified polar two-level form. A polar signal has low-frequency and dc components which are blocked when the signal is transmitted through circuits that contain transformers and/or series capacitors. In addition, these signal components are difficult to cope with in the vestigial sideband mode of transmission which is desirable for band conservation. Therefore, the polar signal is modified by re-

removal of the low-frequency and dc components. In the receiving data set, these signal components are reinserted. A simplified schematic showing how low-frequency and dc components are removed at the transmitter and restored at the receiver is shown in Figure 6-1 (a). The resulting waveforms are shown in Figure 6-1 (b). Note that the variations of the feedback signal at C are opposite in phase to the variations of the signal at B. At the output, the sum of the two is a restored form of the polar signal at A. These processes have led to the designation of the transmitted signal as a *restored polar signal* [4].

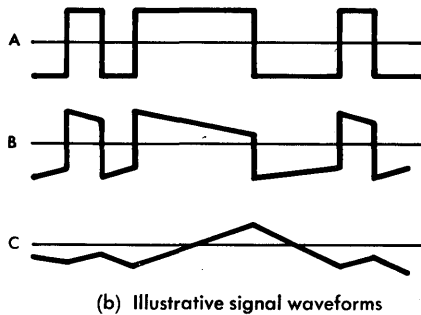
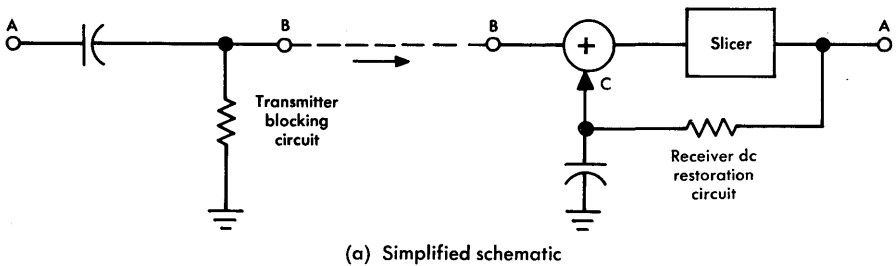


Figure 6-1. Restored polar signal processing.

The receiving portion of the 303-type data set contains a low-pass filter which shapes the signal spectrum to provide the required 100 percent roll-off characteristic [5]. The filter must be selected according to the data rate.

**Data Signal Scrambler.** Multichannel analog transmission systems are susceptible to intelligible crosstalk impairment due to intermodulation between speech signals and high-amplitude single-frequency

data signal components. The strong single-frequency signal components are produced when synchronous data signals contain a repeated bit pattern. For example, alternate 1s and 0s would concentrate the data signal power at one frequency. To prevent these objectionable bit patterns, a scrambler is used in the transmitting portion of the data set to spread the energy in the data signal more uniformly over the wideband data channel. This technique reduces the probability of crosstalk and permits operation of the data channel at higher signal amplitudes resulting in an improved signal-to-noise ratio. At the receiving data set, the signal is restored to its original form by a descrambler before transmission to the business machine. Scramblers and descramblers are not used for asynchronous data signals. Such signals are expected to be sufficiently random so that single-frequency components of troublesome amplitudes are not generated.

### Access Facilities

Wideband data signals share the Bell System facility network with many other types of signals. In most cases, access to the facility network is provided over the same wire pair cables that are used for telephone loops; the wire pairs that connect a wideband data station to the serving central office are called a wideband data loop. In some cases, an N- or T-carrier system may be used but baseband transmission over the wire pairs usually provides good performance economically; where necessary, wideband loop repeaters are also used.

**Transmission Media.** Certain engineering rules must be applied in the design of wideband data loops because of the required bandwidth and the susceptibility of data signals to random and impulse noise. These loops may be provided over any of the types of 19-, 22-, 24-, or 26-gauge nonloaded cable pairs ordinarily used for telephone service. However, all bridged taps must be removed and mixed gauges should not be used in nonrepeated loops nor in a repeater span. Where it is possible to use a repeater at a junction point between gauges, satisfactory performance can usually be achieved.

To minimize noise susceptibility, office and customer premises wiring is double-shielded with special attention paid to the grounding of the shields. Battery and ground leads are also shielded and central office repeaters are mounted in an electrically quiet location, usually in or adjacent to the wideband service bay.

**Loop Repeaters.** A number of wideband loop repeaters are available to provide the gain, gain regulation, and equalization needed for wideband data transmission. These repeaters are designed for bidirectional four-wire transmission. They are used at customer locations, in central offices, or at intermediate locations and are designated respectively as customer repeaters, terminal repeaters, or intermediate repeaters. There are two general categories to be considered, wideband loop repeaters (WLR) and wideband regenerative repeaters (WRR).

*Repeater Types.* The WLR-1 repeater was designed to extend wideband loops for 40.8 kb/s data signals transmitted for the type 301B data set [6]. This data set is used only in private line applications and generates the transmitted signal by a four-phase phase-shift-keying (PSK) method. This signal is of constant amplitude and is used to regulate the gain of the WLR-1. The WLR-2 is similar to the WLR-1 except that it is remotely mounted and usually receives power over the loop from a WLR-1.

The WLR-3 repeater provides amplification and equalization over the band from 1 to 50 kHz. It may be used for half-group and group-band data circuits but it is used infrequently because there is no provision for automatic gain regulation.

The WLR-4 repeater provides amplification, equalization, and gain regulation over the band from 1 to 250 kHz. It is used with data loops engineered for the transmission of data at a rate of 230.4 kb/s; such signals occupy the supergroup band of the L-multiplex. The regulation of this repeater is controlled by a pilot signal transmitted above the data signal at 280 kHz.

The WLR-5 was designed primarily to provide gain, gain regulation, and equalization for the transmission of 50 kb/s restored polar signals. It can also be used with loops on which 19.2 kb/s or synchronous 40.8 kb/s four-phase PSK signals are transmitted.

The WRR-1 is a regenerative repeater designed to expand the flexibility and scope of wideband data networks. It is capable of regenerating half-group, group, and supergroup synchronous and asynchronous signals. The mode of operation is changed to accommodate signals of either type. Asynchronous signals are reshaped before being retransmitted so that any previously accumulated pulse distortion or noise remains only as jitter in the data transitions; synchronous signals are retimed before being retransmitted.

*Transmission Plan.* The application of WLR-type repeaters is best illustrated by the WLR-5, the most commonly used of these repeaters. Figure 6-2 shows how terminal, intermediate, and customer WLR-5 repeaters might be used on a 50 kb/s loop. Only one direction of transmission is shown. The typical system level points given show that the gain is 0 dB between the wideband service bay in the central office and the 806B data auxiliary set in the 303-type data station. The maximum gain of a repeater at 25 kHz is 30 dB. This gain must compensate for the loss of a cable section and any cabling in the central office or at the customer premises. As shown in the figure, regulators and adjustable amplifiers are used at intermediate and customer repeaters. For the opposite direction of transmission, regulators and adjustable amplifiers are used at intermediate and terminal repeaters. Where there is a very short loop, one having 6-dB loss or less at 25 kHz, only a nonregulating terminal repeater is necessary.

The WLR-5 repeaters maintain the proper system level points at the wideband service bay and at the data station in order to facilitate loop-back testing. The repeater output is at a system level point of +6 dB which limits the maximum total signal power on the loop to +6 dBm.

The 50 kb/s loop is limited to a length which produces 90 dB of cable loss at 25 kHz under nominal conditions. This maximum loop contains three sections and requires the use of one terminal repeater, one customer repeater, and two intermediate repeaters. Depending on the type of cable used, the maximum loss criterion is equivalent to approximately 22.5 miles for 19-gauge cable, 14 miles for 22-gauge cable, 10 miles for 24-gauge cable, and 7.5 miles for 26-gauge cable.

While the frequency band of WLR-5 repeaters is usually referred to as 1 to 50 kHz, flat gain and linear phase characteristics are provided to much lower frequencies than 1 kHz because performance at higher frequencies is affected by the low-frequency cutoff characteristics. The principal element that controls this characteristic is the transformer that couples the repeater to the cable pair. Each transformer has a natural cutoff with 3 dB of discrimination at about 15 Hz. A connection may include a number of these transformers in tandem and discrimination must be limited to no more than 3 dB at 100 Hz in overall channel response. A critical factor is the envelope delay distortion that arises at moderately low frequencies from sharp low-frequency discrimination.

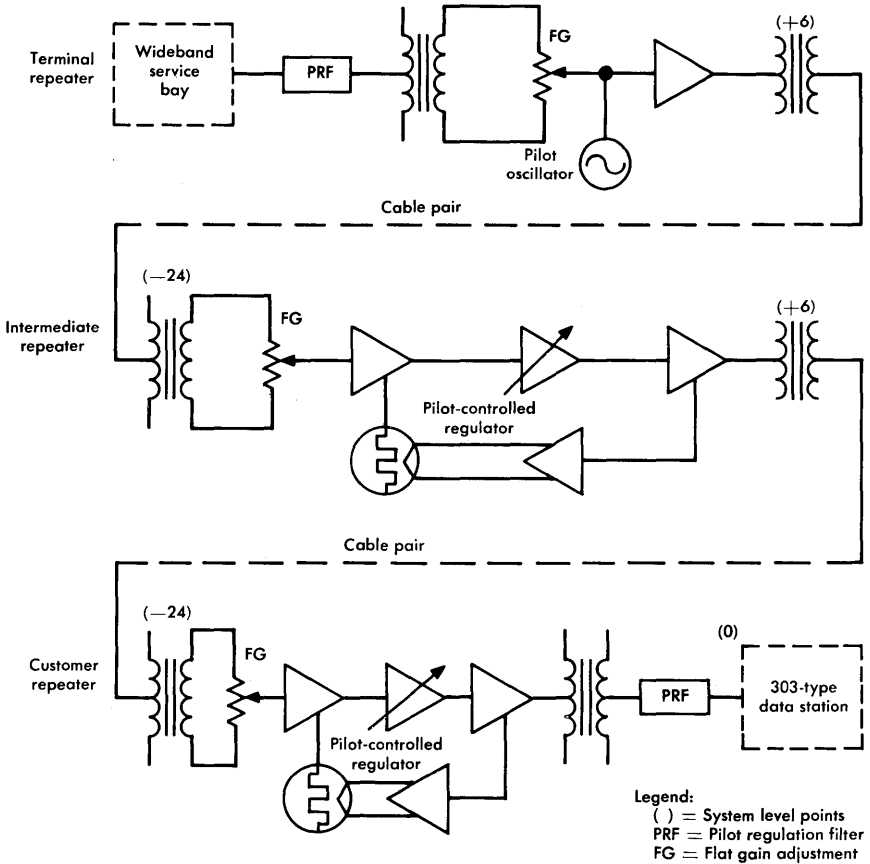


Figure 6-2. Transmission plan for WLR-5 application to 50 kb/s loop.

**Equalization.** In Figure 6-2, an adjustable preamplifier is shown in the intermediate and customer repeaters. A similar preamplifier (not shown) is used in the terminal repeater for the opposite direction of transmission. These preamplifiers are designed to compensate for the loss/frequency characteristics of the preceding section of cable pair. Adjustments are made at the time of installation. A 1-kHz signal is first transmitted over the pair and the flat-gain adjustment of the repeater is made to provide the required output signal amplitude.

The preamplifier contains six equalizer networks, each of which may be adjusted to provide the required gain at a specified frequency and to control the gain over a limited band near that frequency. Each gain-adjusting potentiometer is labeled with the frequency at which a measurement should be made for the adjustment of that network. A signal is transmitted over the line at each adjustment frequency, starting with the lowest. The gain of the preamplifier is thus set to match the loss of the preceding section of cable to within  $\pm 0.5$  dB at all frequencies. The best results are obtained with 22- and 24-gauge cable where the loss can be matched to within about  $\pm 0.12$  dB.

Adequate delay equalization of the line is also accomplished as a result of the loss equalization. A low-frequency-compensated regulator is available for use in special situations to correct excessive phase distortion at low frequencies. It replaces the flat-gain adjusting circuit and, in some cases, permits a loop to be extended to four repeatered sections.

*Regulation.* Pilot regulation of WLR-5 repeater gain is provided where required. A 60-kHz pilot signal is transmitted from the customer or terminal repeater to control the gain of the regulating repeater at the receiving end of each repeater section. The loss of a regulating network is controlled to compensate for cable pair loss characteristic changes that result from temperature variations. A switch may be operated to alter the network characteristic at the time of installation where the repeater is used with 19-gauge cable pairs in which the dynamic loss characteristic differs significantly from those associated with 22-, 24-, and 26-gauge pairs.

### Central Office and Carrier System Equipment

For each of the carrier systems commonly used, terminal equipment is available to permit the transmission of wideband data signals. These terminal arrangements are described here briefly in order to show how the local plant facilities are related to the carrier plant. As previously mentioned, carrier systems equipped with data terminals are also used in the loop plant.

All central office equipment associated with wideband data transmission is coordinated at wideband service bays. These bays are available in small and large capacity arrangements. They provide distributing frame capability, miscellaneous jack fields for cross-connections and for test and maintenance access to voiceband coordination and wide-



band circuits, and mounting space for terminal and intermediate loop repeaters. Provision is also made for mounting a variety of test and data station equipment useful in central-office controlled maintenance activities. Bay arrangements permit orderly growth by the installation of different combinations of service and test bays.

**L-Multiplex Equipment.** A number of modulator-demodulator units, called modems, are available to permit wideband data signals to be combined by frequency division multiplexing with many other signals. Each of the wideband channels has been designed to occupy the basic group and supergroup frequency spectra of the multiplex facilities, 60 to 108 kHz and 312 to 552 kHz, respectively. A dedicated voiceband channel in each spectrum is normally used to coordinate the operation of the wideband channel. The wideband equipment units are designated as LWM-type modems [7].

The LWM-1 modem, now obsolete and rarely used, provides for the transmission of 40.8 kb/s signals in the group band. These four-phase PSK signals, generated in the 301B data set, occupy the spectrum from 10.2 to 51 kHz. The LWM-1 shifts that spectrum to the band from 60 to 104 kHz and provides a voiceband coordination channel between 104 and 108 kHz. The modem replaces a channel bank which ordinarily accommodates twelve voice channels.

The LWM-2 modem provides a bandwidth such that any baseband signal that occupies the band from 1 to as high as 190 kHz is modulated in a vestigial sideband format that occupies most of the L-multiplex basic supergroup band, 312 to 552 kHz. The LWM-2 is used for 230.4 kb/s wideband signals generated by one version of the 303-type data sets and provides a voiceband coordination channel between 312 and 316 kHz. The LWM-2 replaces, electrically but not physically, the L-multiplex group bank. The equipment must be mounted in a miscellaneous bay and wired into the L-multiplex equipment.

The LWM-3 and LWM-4 are companion units; each is designed to place a 19.2 kb/s data signal (28 to 44 kHz) and a related voiceband channel from a 303-type data station into a portion of the basic groupband spectrum. Each modem requires the same bay space as an A5 channel bank and is mounted in a miscellaneous bay. The LWM-3 places the data signal in the band from 86 to 102 kHz and the associated voiceband signal between 104 and 108 kHz. The LWM-4 places

the data signal in the band from 66 to 82 kHz and the voiceband signal between 60 and 64 kHz. Two data signals may thus be transmitted simultaneously in the group band.

The LWM-6 modem has replaced the LWM-5 modem which is no longer manufactured. The LWM-6 provides a 63- to 104-kHz channel in the L-multiplex group band for the transmission of 50 kb/s data signals generated in type 303 data stations. A voiceband coordination channel is also provided between 104 and 108 kHz. These modems are mounted in miscellaneous bays. Electrically, the high-frequency LWM-6 signal replaces that of an A-type channel bank.

In each of the group and half-group applications, signals may be applied to the L-multiplex system through an LWA-1 alternate use panel. This panel allows the group band to be used, under customer control, alternatively for the transmission of twelve voice signals. In the case of half-group transmission, the LWA-1 is used to combine signals from an LWM-3 and an LWM-4 modem and, under customer control, permits the alternate use of either half-group band for the transmission of six voice signals or both bands for twelve voice signals. Alternate use is not furnished with the LWM-2 supergroup data service.

**N-Carrier Equipment.** The bandwidth of the N-carrier system is sufficient to permit transmission of group band or lower speed data signals. The system can be used to transmit 19.2 kb/s and 50 kb/s signals from 303-type data stations and 40.8 kb/s data from the 301B data set. Three equipment units are involved, the N2WM-1 modem, the N2WM-2 modem, and the N2WT-1 terminal.

The N2WM-1 modem consists of plug-in units that can provide a 40.8 kHz band for transmission of a 301B data set signal or a 19.2 kb/s vestigial sideband signal from a 303-type data station. The plug-in units may be used to replace six of the twelve channel units in an N2 terminal. In this arrangement, the composite signal consists of six voice signals and the wideband data signal.

The N2WM-1 modem units may also be plugged into an N2WT-1 terminal. In this arrangement, the transmitted signal consists of the wideband data signal and four single-frequency signals used for regulation of N-carrier line repeaters. Two voice channels are also available, one for voice coordination and one for telephone company administrative use. A customer-controlled alternate use feature pro-

vided in the N2WT-1 permits the substitution of standard N2 voice channels for the composite wideband signal. The administrative channel is retained so the system is used for a total of thirteen voice channels in this arrangement.

The N2WM-2 modem provides for the transmission of a 50 kb/s signal or 19.2 kb/s baseband signal from a 303 data station. The equipment is mounted in the N2WT-1 terminal which contains circuits so that the N-carrier spectrum may carry a wideband signal and two dedicated voice channels or may alternatively carry the two dedicated voice channels and eleven standard voice channels. Only one single-frequency signal is required for line regulation.

**T-Carrier Equipment.** Terminal units, called T1WB-type wideband data banks and T1WM-type modems, are available to process wideband data signals for transmission over the T1 Carrier System. Some of these units require that the entire T1 system be dedicated to data signal transmission; others are designed to transmit time division multiplexed combinations of data signals and pulse code modulated speech signals. This terminal equipment can transmit either synchronous or asynchronous signals from 303-type data stations.

The organization of the 1544 kb/s T1 line bit stream is intended primarily for transmission of 24 speech signals that are pulse code modulated and time division multiplexed. In this organization of the line signal, 64 kb/s are used for each coded speech signal. Thus,  $64 \times 24 = 1536$  kb/s of the 1544 kb/s line signal rate carry voice signal information. The remaining 8 kb/s are used as framing pulses to provide synchronization for the demultiplexing processes at the receiving terminal.

The need to accommodate asynchronous signals led to the assignment of 3 line signal bits to carry the information regarding each input data signal transition thus eliminating the possibility of transmitting a 50 kb/s data signal in a voice channel of 64 kb/s. The first of these three line bits identifies the time slot in which the transition occurs, the second bit indicates whether the transition occurs in the first or second half of the time slot, and the third bit indicates the direction of the transition, i.e., positive-to-negative or negative-to-positive [8]. This format, sometimes called sliding index or transition coding, results in the design of a flexible and inexpensive terminal with an output signal which displaces three pulse code modulated speech signals. Since wideband data channels are relatively few in

number and are provided on T1 carrier for only short distances, the economic advantage of an inexpensive terminal generally outweighs the inefficient use of the line facility.

With transition coding, the T1 line bit stream can theoretically provide up to 8 channels to carry asynchronous signals at 64 kb/s, 4 channels for 128 kb/s signals, 2 channels for 256 kb/s signals, or 1 channel for a 512 kb/s signal. The maximum rate of each wideband channel is ample for the signalling rates delivered by 303-type data sets. Several terminal arrangements have been designed to accommodate such signals and are arranged to provide flexible combinations of wideband data and pulse code modulated speech signals. The available combinations, which require T1WB-1, T1WB-2, T1WM-1, or T1WM-4 wideband terminal units, are shown in Figure 6-3. The T1WM-4 is similar to the T1WM-1 except that it is designed for customer premises mounting and the digital interface is somewhat different. These modems may be used to provide one 19.2, one 50, or one 230.4 kb/s channel but, under these conditions, the T1 line is used very inefficiently.

WIDEBAND TERMINALS	NO. CHANS.	MAX. BIT RATE, kb/s	
		SYNCHRONOUS	NONSYNCHRONOUS
T1WB-1	8	50	50
	4	50	50
	1	230.4	250
	2	230.4	250
T1WB-2	2	230.4	250
T1WM-1	1	460.8	500
T1WM-4	1	460.8	500

Figure 6-3. Combinations of wideband data signals on T1-carrier.

The T1WB-3 bank permits the time division multiplexing of speech and wideband data signals in various combinations. Figure 6-4 shows the achievable combinations expressed in terms of supergroup, group, or half-group signals.

The voiceband coordination channel normally furnished with the wideband data channel in analog systems is administered separately from the wideband channel in the T1 system. It is usually treated as an ordinary voice-frequency channel in the same or in a paralleling T1 Carrier System.

NUMBER OF CHANNELS		
WIDEBAND DATA		VOICEBAND
HALF-GROUP OR GROUP	SUPERGROUP	
1	—	21
2	—	18
3	—	12
4	—	12
—	1	12

Figure 6-4. Multiplexing combinations with one T1WB-3 and one D1 channel bank.

A number of other data terminals (T1DM, T1WB-4, and T1WB-5) are available for use with the T1 Carrier System. These are used primarily for interoffice connections in the Digital Data System (DDS) [9].

## 6-2 LOCAL PLANT FACILITIES FOR DDS

DATA-PHONE digital service is provided over the Digital Data System. Switched message network service and DATA-PHONE digital service are independently provided but the systems that provide these services share the facility network. Synchronous digital data transmission is provided at a number of signalling rates called *service speeds*. Duplex service is presently provided on point-to-point and multipoint private lines. The signals are routed exclusively over digital transmission facilities. No provision is made in the DDS for alternate speech signal transmission or for voice coordination; however, DDS signals may be combined with other signals for transmission over shared facilities [10].

The four service speeds provided in the DDS are 56, 9.6, 4.8, and 2.4 kb/s. Synchronous signals are accepted at any one of these signalling rates from customer terminal equipment. They are transmitted over loop facilities to the central office and combined with other DDS signals by time division multiplex techniques. Note that the available service speeds include several voiceband applications and one wideband application.

The DDS facilities are also used to provide private line wideband data service. Two service rates are possible. By adapting a 306-type data set to this type of service, synchronous data may be transmitted at 1.344 Mb/s. The facilities may also be used to transmit non-synchronous data at the DS-1 rate, 1.544 Mb/s.

### Customer Premises Equipment

Two types of equipment are used at customer premises to link the transmission facility with the data source (computer or business machine). The first, called a channel service unit (CSU), terminates the transmission facility and connects with customer-provided terminal equipment. The second, called a data service unit (DSU), is functionally equivalent to a data set in that it provides total data service from one customer business machine to another.

**Channel Service Unit.** Where customer-provided terminal equipment is used to transmit and receive signals that meet the DDS specifications, a CSU is used to terminate the four-wire loop at the customer premises. The CSU provides equalization of the receiving loop cable pair, loop-around testing capability, and network protection. A specific CSU design must be selected to accommodate the service speed required for each installation [11, 12]. Signals furnished from the customer terminal to the CSU must be synchronized at the specified service speed and must conform to the interface requirement for a bipolar, return-to-zero, 50-percent duty cycle format. In the transmitting direction (toward the central office) the CSU amplifies, filters, and couples the signals to the loop. In the receiving direction, the CSU amplifies, equalizes, and slices the incoming signals before transmitting them to the customer terminal equipment.

**Data Service Unit.** Where the customer chooses complete data service, a DSU of the appropriate service speed is provided at the customer premises. The DSU performs all of the functions previously described for the CSU. In addition, the DSU provides signal coding and decoding, timing recovery, synchronous sampling, and the generation of and response to control signals. All timing is derived from the bipolar bit stream received from the loop. The DSU accepts synchronous binary data signals from the customer terminal and converts them to a properly shaped, bipolar, return-to-zero format for transmission on the loop. In the opposite direction, this process is reversed.

The interface with the customer terminal must meet the standard RS-232-C specifications for a Type D or Type E interface at the 2.4, 4.8, and 9.6 kb/s service speeds [13]. The interface for 56 kb/s is based on CCITT standard V.35.

**Signal Formats.** The bipolar signal used for data transmission between the customer premises and the central office is illustrated in Figure 6-5. The signal is transmitted at the rate corresponding to the

service speed selected by the customer. The 2.4, 4.8, and 9.6 kb/s rates are called subrate speeds.

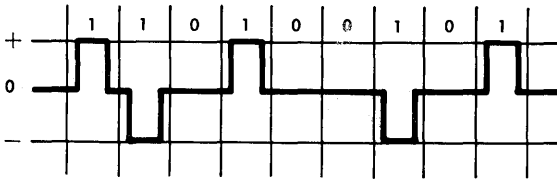


Figure 6-5. Bipolar, return-to-zero, 50% duty cycle data signal.

While data is normally transmitted in the bipolar form, which requires that successive 1s in the signal be transmitted with alternate plus and minus polarities, bipolar violations are used in the signal to convey special information. Specially coded sequences are used when: (1) the distant DSU is transmitting an idle code to indicate that there is no data message being transmitted; (2) a trouble condition exists in the receiving path; (3) the DSU is being tested from the serving test center; (4) a series of 6 or more 0s (7 for 56 kb/s) appears in the customer data signal. Such a series of 0s, not allowed in the transmitted signal, is replaced by coded bipolar violations which are detected at the receiving DSU. The bipolar violations are then removed and the proper number of 0s replaced in the signal before it is passed on to the customer receiving terminal equipment. Thus, there is no restriction on customer data sequences.

### Access Facilities

The CSU or DSU at the customer premises is connected to a DDS office by a four-wire nonloaded loop. Where the local serving office is not equipped for DDS service, the loop must be extended through that office over interoffice cable facilities to a DDS office. The local serving office is then called a baseband office and the interoffice connection is regarded as a part of the loop. For 56 kb/s service, a repeater may be used in the loop.

**Loop Facility Selection.** The maximum allowable insertion loss for a DDS loop is 31 dB at a frequency numerically equal to one-half the bit rate. Thus, the selection of loop facilities is dependent on the gauges of cable pairs available and on the specified service speed. The relationships among service speeds, wire gauges, maximum loop

lengths, and insertion losses are given in Figure 6-6. For mixed gauge applications, the maximum loop length is specified approximately by the 31-dB overall loss limitation and the insertion losses given in the figure.

WIRE GAUGE	BIT RATE, kb/s							
	2.4		4.8		9.6		56	
	LENGTH,* kft	LOSS,† dB/kft	LENGTH,* kft	LOSS,† dB/kft	LENGTH,* kft	LOSS,† dB/kft	LENGTH,* kft	LOSS,† dB/kft
19	114.8	0.27	86.1	0.36	67.4	0.46	40.8	0.76
22	73.8	0.42	56.4	0.55	43.1	0.72	24.2	1.28
24	56.4	0.55	42.5	0.73	32.3	0.96	17.2	1.80
26	41.9	0.74	32.3	0.96	24.8	1.25	12.9	2.40

\*Lengths are maximum acceptable.

†Losses are insertion losses between 135-ohm terminations at the frequency corresponding numerically to one-half the bit rate.

Figure 6-6. Loop lengths and losses for DDS.

In addition to these limits, the use of cable pairs in separate cable units is recommended to minimize the risk of interference with other services and transmission systems. Load coils are not permitted and the length of allowable bridged taps is limited. Mixed cable pair gauges are permissible; insertion loss for each gauge can be determined for any length by linear interpolation of the length and loss values given in Figure 6-6.

Where customer locations are outside the established serving area for the DDS, service may be provided by analog extensions based on engineering criteria similar to those applied to conventional analog private line data services. Data sets have been adapted to terminate these links at both ends.

**Central Office Terminations.** All DDS access facilities are terminated in the DDS central office by an office channel unit (OCU). This unit must be selected to match the customer service speed. On the loop side, the OCU functions in a manner similar to that described for the CSU and DSU in respect to gain and equalization. In addition, a low value of dc, called sealing current, is transmitted from the OCU to



the loop and customer premises equipment. This current maintains a low resistance at splices and other connection points by breaking down small accumulations of dirt and oxides. A reversal of the sealing current polarity, initiated in the OCU, is used at the CSU or DSU to establish a loop-back condition. The dc current reversal is made in response to a control signal from the serving test center or OCU location.

On the central office side of the OCU, other functions are performed to satisfy system operations requirements for the DDS. These include flexible cross-connection, submultiplexing, and digital hierarchy multiplexing [9].

### 6-3 BASEBAND TELEVISION FACILITIES

The intercity network of television transmission facilities in the United States is provided almost exclusively by microwave radio transmission systems. However, intracity facilities must be provided to interconnect broadcast studios, control sites, and broadcast transmitters and to connect these points through a telephone company television operating center (TOC) to the intercity facility network. The intracity facilities may also be used to provide closed-circuit service for drama or sports presentations. Most of the needs for intracity transmission are met by A2-type video transmission systems. The A4 system is used for very short (0.5 mile or less) applications.

#### The A2-Type Video Transmission Systems

Baseband A2 video transmission systems, first developed to meet intracity transmission needs, were based on electron tube technology. Improvements in design were introduced in the A2A system which had greater flexibility and broader application than the A2 [14]. This system was subsequently replaced by the solid-state A2AT system.

**Media.** Most baseband video signals are transmitted on 16-gauge shielded cable pairs which are often assembled in cables with ordinary trunk pairs used for telephone service. The 124-ohm characteristic impedance of the pairs is carefully controlled in design and manufacture so that, when properly terminated at a repeater or terminal, reflections are held to a minimum. The attenuation characteristic of these cable pairs is illustrated in Figure 6-7. The low-frequency at-

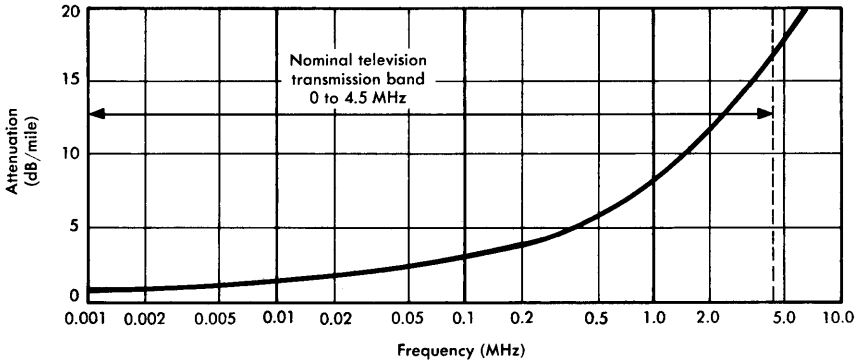


Figure 6-7. Typical attenuation/frequency characteristics for 16-gauge video pairs.

attenuation is very low and amplifier gains and equalizer designs are determined primarily by the high-frequency loss of the cable pair.

Television signals are highly susceptible to interference from crosstalk of other signals into the television channel. In addition, the concentration of energy at discrete frequencies in television signals causes problems of crosstalk interference from the television channel into other channels. These problems are minimized by the use of shielded cable pairs. For intraoffice wiring, 75-ohm coaxial cable may be used.

**Equipment Arrangements.** Although the A2A and A2AT systems are compatible and there is some A2A equipment still in service, the discussion here is confined to the A2AT system. Each system can be regarded as a one-direction transmission facility. Even where two directions of transmission are provided, the system for each direction can be considered as independent of the other.

A basic system consists of a transmitting terminal, a receiving terminal, and the interconnecting shielded cable pair. Such a minimal system can be used to compensate for 82.5 dB of video cable pair loss at 4.5 MHz, the loss of about 4.5 miles of cable. Repeaters may be used to extend the length of the system. Each added repeater increases the permissible cable loss by 82.5 dB. Thus, one repeater added at the midpoint of the cable span extends the length of a system to about 9 miles. Individual multirepeater systems up to 30 miles long are currently in operation.

Each terminal and repeater is arranged to permit flexible combinations of the pads, equalizers, and amplifiers required for different circuit lengths. With the exception of the 331A variable equalizer, used at a receiving terminal, these are all plug-in units. The 331A is too large to be packaged conveniently as a plug-in unit. The terminals and repeaters mount in standard 19-inch equipment bays. A transmitting terminal requires 5-1/4 inches of vertical bay space, a repeater 10-1/2 inches, and a receiving terminal, (including the 331A equalizer) 15-3/4 inches. Power units are not included and must be provided separately.

In addition to these standard equipment arrangements, portable terminal and repeater units are available to permit temporary installations. These are often required in order to broadcast sports events or unusual news stories.

**Electrical Characteristics.** The A2AT system provides a well-equalized, 4.5-MHz video channel on shielded cable pairs. The equalization corrects both attenuation/frequency and delay distortion.

Tandem operation of 12 systems is permitted; a total of three repeater sections in the 12 systems may be of the maximum 4.5-mile length. Where the number of maximum-length sections exceeds three, intermediate repeaters must be used in order to meet signal-to-noise objectives.

Signal voltage levels are expressed in dBV (dB relative to 1 volt peak-to-peak) and are sometimes written in a fractional form, e.g., 0/0 dBV. The numerator of the fraction represents the level for low video frequencies (near dc) and the denominator represents the level for 4.5 MHz. The A2AT input signal is usually received from an unbalanced source at a 0/0 dBV level. The output level delivered to a balanced or unbalanced termination is also 0/0 dBV; thus, the A2AT introduces zero insertion loss.

*Transmission Layout.* Figure 6-8 shows a typical two-section layout of an A2AT system. All amplifiers used in the receiving and transmitting terminals are designed with negative feedback and have a flat gain/frequency characteristic. The compensation for the loss/frequency characteristic of the cable is provided entirely in the A2AT equalizers. Therefore, the amplifier gains must compensate for the losses of these equalizers as well as for cable loss. The system is

lined up in accordance with the voltage levels shown in Figure 6-8. These levels have been established at values designed to prevent excessive noise penalty and to minimize the likelihood of amplifier overload.

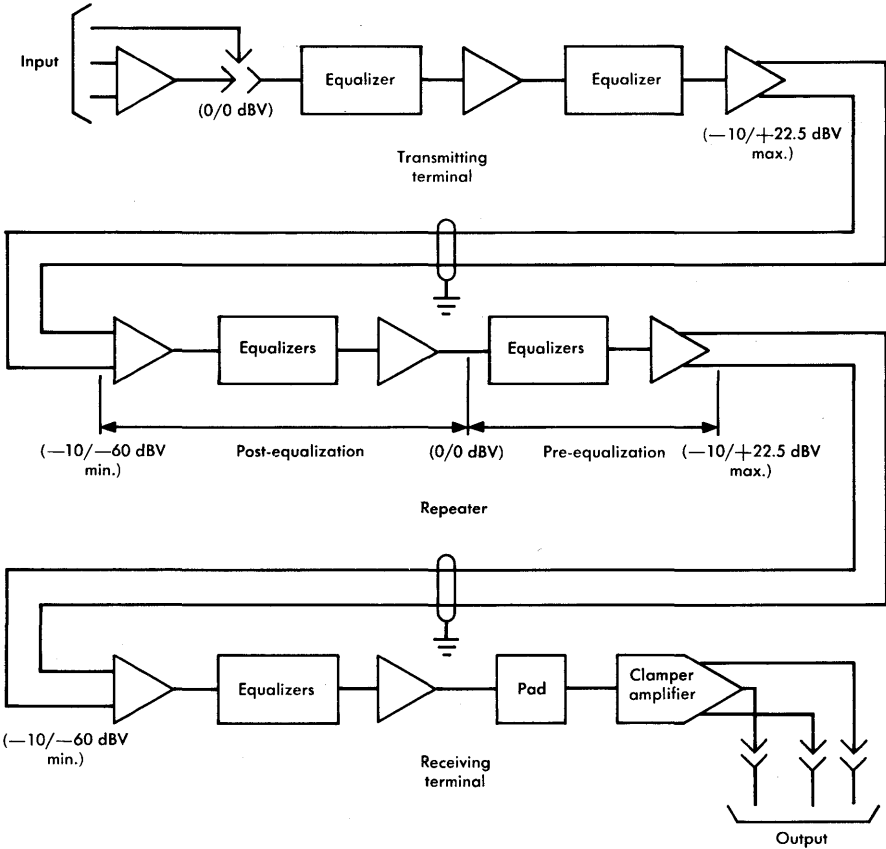


Figure 6-8. Typical A2AT system transmission layout.

The system is arranged for either 124-ohm balanced (two-wire) or 75-ohm unbalanced (coaxial) input and output. At the input to the transmitter, connections may be established through a jack to balanced or unbalanced circuits. The required connection is made by internal jack and plug arrangements not shown in the figure. For an unbalanced input, the connection is made directly to the equalizer when

the incoming circuit shield is grounded. For a balanced input or for an unbalanced input with ungrounded shield, the connection is made through an amplifier with 0-dB gain. At the output, the selection is made by inserting the clamper amplifier into the appropriate jack receptacle. No wiring changes or other adjustments are required.

**Equalization.** Fixed 330-type plug-in equalizers are used in terminals and repeaters to provide most of the equalization of the cable characteristic. With these equalizers, the square-root-of-frequency component of line loss can be equalized to within a residual deviation of  $\pm 1.25$  dB at 4.5 MHz. For short repeater sections, a flat-loss pad must be used so that the loss of pad plus equalizer is properly compensated by the following flat-gain amplifier. Equalization of the residual deviation is provided by adjustable equalizers located in the receiving terminal. With the combinations of equalizers and amplifiers that can be used in the A2AT system, the video channel can be equalized to be flat to within  $\pm 0.1$  dB over the band from 30 Hz to 4.5 MHz, a span of over 17 octaves in frequency. This wide band contributes significantly to the complexity of equalizers and makes highly accurate impedance matching between the cables and the electronic equipment mandatory. Pre- and post-equalization is used in order to limit the required range of adjustable equalizers, to maximize the signal-to-noise ratio, and to minimize overload penalties that may be incurred when all equalization is placed at one end of a link [15]. Delay distortion at the high-frequency end of the band is corrected by delay equalizers installed in the receiving terminal according to prescription that depends on the overall length of the circuit.

The A2AT system is equalized from the transmitting end to the receiving end on a section-by-section basis. This procedure provides the most accurate achievable gain equalization.

### The A4 Video Transmission System

This system provides a video channel 10 MHz wide over shielded cable pairs up to 0.5 mile long. In addition, a span of about 0.3 mile is achievable with unshielded balanced cable pairs; with unbalanced coaxial cable, a span of about 500 feet is the recommended maximum. The system can be used economically as a temporary or permanent intracity video link and is especially appropriate for portable use to connect a mobile pickup unit to telephone company facilities.

The A4 system consists of a very small and simple transmitter, a cable pair transmission medium, and a receiver that provides all of the amplification, equalization, clamping, and power supply functions in the system. No repeater is required because the system is designed only for very short single-link circuits.

The only function of the transmitter is to convert an unbalanced 75-ohm input to a balanced 124-ohm output with 0-dB gain. If the medium is 124-ohm balanced at the input, a transmitter is not used. When used, it receives power over the medium from the receiver.

Equalization is provided in the receiver over the video band up to 10 MHz. Receiver gain can compensate for a loss of up to 9 dB at 4.5 MHz. Since there are differences in low-frequency characteristics among the various transmission media that may be used, a variable low-frequency equalizer is also provided. Amplification is provided by several fixed-gain amplifiers and a clamper amplifier which maintains the signal at a fixed 0-dBV reference value. Levels are adjusted by means of adjustable attenuators to give a 0-dB insertion loss for the system.

The transmitter and receiver are available as small, neatly-packaged portable units to make them convenient for temporary installations. The transmitter is 1-3/4 inches high, 3 inches wide, and 5 inches deep. The receiver is 1-3/4 inches high, 17-1/2 inches wide, and 14 inches deep. This equipment can also be mounted permanently on central office equipment racks.

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## Chapter 7

# Central Office Equipment

The transmission characteristics of central office equipment result from a wide variety of circuits, transmission paths, and interrelated switching and transmission functions. The transmission paths through the central office include all of the wiring and cabling between cable vaults where central office cable is connected to outside plant cabling, terminating trunk circuits, and (where switching is involved) transmission paths through the switching machine. In addition to being parts of the office transmission paths, trunk circuits provide many auxiliary functions, such as a signalling interface and impedance matching, that are indirectly or directly related to transmission. These functions as well as switching system features and functions are discussed in terms of transmission effects. For example, the sequencing of calls involves many processes such as battery feed transfer, battery feed reversal, the switching of idle circuit terminations, and repeater or echo suppressor enabling and disabling. These processes can deteriorate transmission and must be adequately controlled.

Transmission through a central office is further complicated by two- and four-wire operation used for both switching and transmission. In addition, the several types of switching and signalling systems in use require a variety of transmission circuits and terminations. Line and trunk impedance values vary widely and strongly influence the design of the central office auxiliary and interface circuitry.

Many central offices provide interface functions for the transmission of digital signals. Some of the interfaces are points of transition between analog and digital signal formats such as those required to switch voice signals in a digital toll switching system.



The video network for broadcast television service also requires considerable equipment for signal administration. This equipment is often located on telephone company premises in central office buildings.

All of these circuits, features, and functions must be designed and maintained in such a manner as to limit and control transmission impairments. All of the impairments that normally affect transmission (noise, echo, loss, crosstalk, and harmonic distortion) may be caused by central office equipment.

## 7-1 CENTRAL OFFICE TRANSMISSION PATHS

Multipair outside plant cables usually terminate in a vault in the basement of or immediately outside a central office building. These cables are spliced to other cables that are routed through the building to main distributing frames (MDF). Jumpers are used at the MDFs to connect switching machines with other central office equipment and with loops and trunks. The MDF also provides protection from unwanted voltages such as those due to lightning and crosses with power lines. The interconnections involve interfaces among signalling, switching, power, and transmission equipment. While the cables between the distributing frames and the vaults are within the central office buildings, they are usually considered as part of the outside plant. Central office transmission performance is typically evaluated between main distributing frame appearances.

In addition, there are many other distributing frames used throughout a central office. These cross-connection facilities are subject to continuing change accomplished by the movement of jumpers in the frames so that cable pairs may be connected to different equipment items or to other cable pairs as required. The frequency of change is very low but, in principle, the interconnection functions are similar to those of a switching machine. Important differences are that a switching machine operates on a per-call basis and is engineered to concentrate traffic as it is routed through the machine.

### Intraoffice Wiring

Direct and multiple wiring is used to provide transmission paths within a central office. In addition, there is a large amount of wiring that is not directly related to transmission such as the wiring that carries the control signals to operate the switching machine.

The direct wiring interconnects various items of transmission, signalling, and switching equipment in the office. These wiring paths must meet stringent requirements for transmission loss, return loss, and interference. Path lengths may be quite varied and in order to maintain control of cross-office losses and loss variations, the maximum lengths of these paths are often specified as design requirements. Similarly, wire gauge, pair twisting, separation between wires that carry different amplitudes or types of signals, and, in most cases, the relative locations of various equipment items are also specified so that transmission objectives can be met.

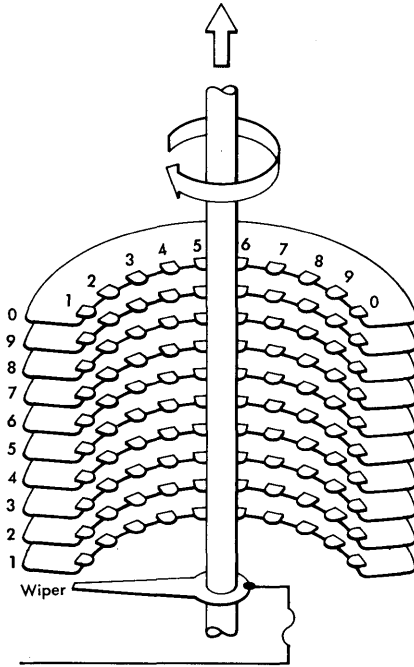
Multiple wiring is the term applied to the many interconnections within a switching matrix or a manual switchboard. The varying lengths of the multiple wiring paths can cause different degrees of exposure to certain types of induced interferences. These multiples also act as bridged taps which often result in transmission impairment. The design of these multiple paths must be carefully specified if transmission performance is to be controlled.

### Switching Networks

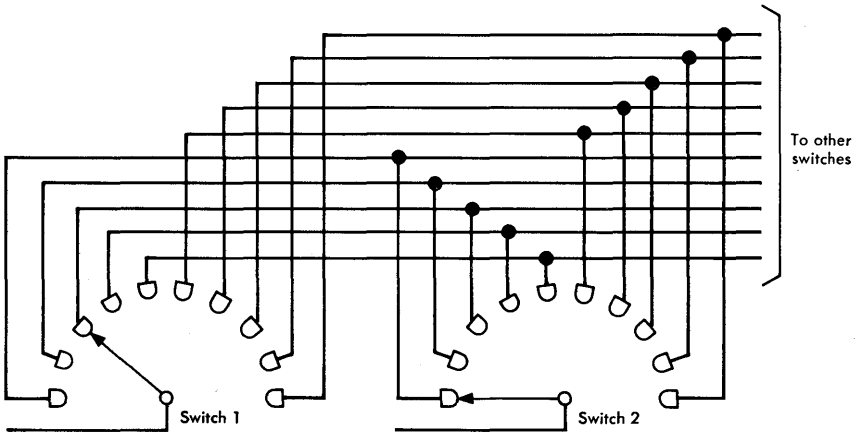
The matrix of interconnected switching devices through which connections are established is called a switching network. The switching devices and the manner in which they are arranged in a network in different types of switching machines vary widely. The variations may result in a different set of transmission problems in each type. The machines most commonly used are step-by-step, crossbar, and electronic switching systems (ESS).

**Step-by-Step Systems.** For each digit dialed in these systems, a switch like that shown in Figure 7-1 (a) is used to advance a call step-by-step through the switching network. This mode of operation is called *progressive control* or *dial control* because switch operation is controlled directly by the station set dial. Different types of switches, called line finders, selectors, and connectors are used in the switching network.

Each switch contains a shaft which steps vertically and then rotates. Attached to the moving shaft are a number of contactors (wipers) which wipe across a series of fixed contacts to establish a connection at the final or rest position. The fixed contacts are usually arranged in a  $10 \times 10$  matrix as illustrated in Figure 7-1(a). The matrix shown, called a switch bank, provides contacts for the tip or ring conductor or a supervisory (sleeve) lead.



(a) Wiper and fixed contact matrix for one set of conductors (tip, ring, or sleeve)



(b) Multiple wiring between fixed contacts for one set of conductors

Figure 7-1. Step-by-step switch bank and wiring.

In order to reduce blocking and provide adequate service, switch banks are multiplied together in complex wiring patterns. One layer of contacts is shown for two switches in Figure 7-1 (b). These multiple wiring paths may extend to many switches. Because of the lengths of the paths involved, the wiring must be very carefully controlled to prevent excessive loss or exposure to noise and interference.

**Crossbar Systems.** While there are a number of types of switching machines that utilize *common control* of crossbar switches to establish connections (No. 1, No. 5, crossbar tandem, and No. 4A), the methods of interconnecting the switches to form a network are sufficiently similar in respect to transmission that a single description should suffice.

Two switch sizes are available to provide the switching crosspoints required in various types of switching systems. A 100-point switch has 10 horizontal paths and 10 vertical paths; a 200-point switch has 10 horizontal paths and 20 vertical paths. At each crosspoint, the contacts may be arranged in groups of three to six depending on the type of transmission paths (two-wire or four-wire) and the number of supervisory and control leads to be switched. In order to achieve high reliability and low probability of noise, each precious metal contact is arranged as a parallel pair on a bifurcated contact spring.

Five selecting bars are associated with the horizontal paths, two paths to each of the bars. Under control of the switching machine logic circuits, each bar may be rotated slightly in either direction to operate selecting fingers which enable a connection to be made from the selected horizontal row to any vertical path through the switch. The vertical paths are equipped with a configuration of coil-controlled magnets. The ability of these magnets to operate the crosspoint contacts and to hold them operated depends on the position of the horizontal selecting fingers. Thus, when a crosspoint is to be operated, the appropriate horizontal bar rotates in a direction to move the upper or lower selecting fingers. When the appropriate vertical magnet operates, only the selecting finger at the desired crosspoint can operate the contacts. When the contacts are closed, the operate magnet is released leaving the crosspoint contacts latched in the operated position by a hold magnet which is released upon call completion. To avoid double connections, the switch and its control circuits are arranged so that only one crosspoint can be closed at one time in any horizontal or vertical path. However, each switch can establish up to 10 simultaneous connections.

Arrays of crossbar switches are assembled and interconnected in various ways to provide switching networks for use in local, tandem, or toll offices. The common control logic circuits for these networks are called markers.

As with the step-by-step system, the interconnections among switches are complex and may result in different path lengths and a large amount of multiple wiring. The transmission path lengths, multiple wiring, and control wiring must all be carefully designed to prevent excessive transmission impairment.

**Electronic Switching Systems.** Electronic switching systems operate in a mode called *stored program control*. Some ESS networks are electromechanical; others utilize electronically controlled time division switching of digital signals. In the electromechanical networks, the basic element commonly used to switch a transmission path is called a miniature sealed reed contact. This contact assembly is used in pairs or quads to switch a two-wire or four-wire transmission path. Switching is accomplished by changing the polarity of magnetic forces inherent in square-loop magnetic material. The desired polarity to operate or release the reed contacts is induced by the application of high-current, short-duration control pulses to coils surrounding the contact assembly. A pulse applied only to a horizontal row or vertical column of switches places all the contacts in the row or column in the open condition. When a pulse is applied simultaneously to a row and column, the crosspoint at the intersection of the row and column is closed. The square-loop magnetic material commonly used is called remendur; the reeds are ferrous material and the switch assemblies are called ferreeds [1, 2]. In later designs, the square-loop material is used for the reed contacts; external magnetic materials is not required. These switch assemblies are called remreeds.

Most ferreed and remreed switches are combined in matrices of 64 crosspoints arranged in a square array of 8 horizontal rows and 8 vertical columns. Within these  $8 \times 8$  arrays, switching controls and transmission paths may be organized in a number of combinations to provide optimum network configurations as required. Control circuits are arranged so that only one crosspoint can be operated at a time in any row or column.

As in all switching networks that utilize electromechanical crosspoints, satisfactory transmission performance is related to the lengths of paths through the switches and the lengths of multiple wiring. The exposure of the transmission paths to the wiring that carries

the high-current pulses to operate crosspoints must be controlled to avoid excessive impulse noise.

In some electronic switching systems (e.g., No. 4 ESS), the message signal is coded and used in digital form and transmission and switching are integrated functions; logic circuits, time division multiplexing, and gate circuits are used in combination to achieve the desired interconnections electronically. Transmission problems of the type found in electromechanical networks, such as those due to multiple wiring, are essentially nonexistent. However, there are other problems. For example, different delays due to different path lengths can produce pulse transpositions.

## 7-2 TERMINATING AND ANCILLARY CIRCUITS

Many individual circuits in a central office have a direct bearing on transmission performance. For example, trunk and switchboard cord circuits provide battery feed and are directly in the transmission path of message network connections. These battery feed circuits often perform multiple functions and, in many systems, their design is quite complex. Circuits indirectly related to transmission provide interfaces with other circuits such as those required for control of charging information, number identification, and signalling interfaces. There are also circuits directly in the transmission path to perform special functions. Among these are conference circuits, switchable pads and amplifiers, and idle circuit terminations. Additionally, a large number of connections made to call services and number services operators involve transmission problems that have a direct impact on DDD network performance [3].

The manner in which the signalling/transmission interface is provided involves a compromise between signalling range and transmission performance for each type of switching machine. Resolution of the compromise often has a direct effect on the selection of facilities (wire-gauge, voice-frequency, carrier, etc.) in a particular wire-center environment. Trunk and switchboard cord circuits also provide impedance matching; this function and the use of drop build-out capacitors are closely related to the necessity for meeting through and terminal balance requirements for the control of echo [4].

A comprehensive discussion of individual line and trunk circuits is impractical because of the large number involved. For each of the categories to be discussed, circuit functions are first described and then some specific circuit arrangements are presented in order to illustrate the functions.

## Line Circuits

A line circuit is used at a switching machine to terminate a loop, PBX station line, or any of the access lines to the switched services network or the switched public network that are functionally equivalent to loops. The function of a line circuit is primarily the signalling of a request for service to the central office switching machine or to an operator.

A typical line circuit, as shown in Figure 7-2, consists simply of a sensing element (a relay or, in ESS, a ferrod) through which battery and ground are fed to the line [5]. When there is a request for service (station set off hook), current flows through the sensing element. This produces a change in signalling state. For example, if the sensing element is a relay in an electromechanical office, contact A closes to place a ground on the start lead, S. The switching machine recognizes the request for service and connects the calling line to a source of dial tone and a different source of battery and ground. Simultaneously, the B contacts in the line circuit are opened to disconnect the original source of battery and ground from the line. When the switching machine has operated in response to a request for service, the line circuit is disconnected from the transmission path. Only the transfer of battery and ground, to be discussed subsequently, has an indirect effect on transmission.

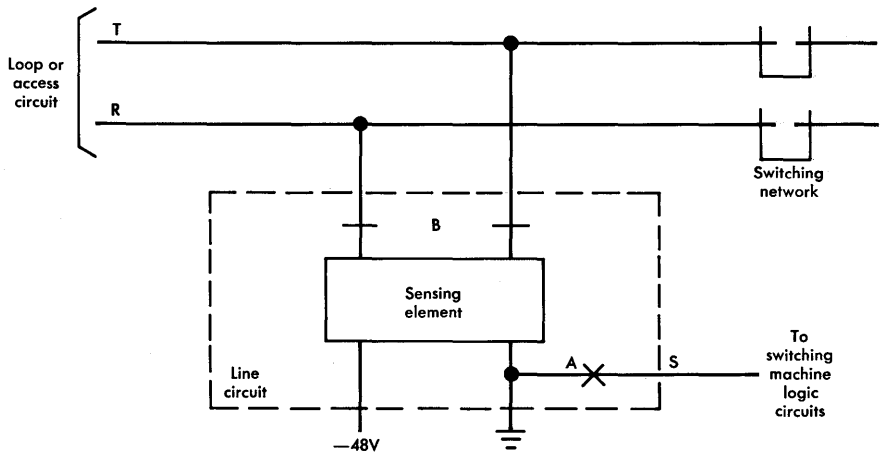


Figure 7-2. Typical line circuit.

## Trunk Circuits

Trunks are the transmission paths that interconnect switching machines, portions of switching machines, and/or switchboards. Most trunks terminate in a trunk circuit at each end. Each trunk circuit connects the transmission medium to a specific terminal on the switching network at which the trunk terminates. Many trunk circuit types are found in the telephone plant because of the variety of functions performed, the variety of trunks used in the network, and the requirements of the different types of switching machines and switchboards.

**Functions.** Trunk circuits must perform many functions because they provide switching, signalling, and transmission interfaces. In many cases, battery and ground are furnished from a trunk circuit at one end of a connection. Such a circuit typically contains a transformer or blocking capacitors (or both) which provide coupling for speech signals between the two parts of the circuit and prevent the dc from that circuit from interfering with dc supplied at the distant end.

Trunk circuits must be designed to provide a high degree of balance so that longitudinally induced noise and interference is not transformed into more interfering metallic disturbances. In trunk circuit design, circuit arrangements determine to a large degree the extent to which interface impedances are matched so that terminal and through balance requirements may be met. Many trunk circuits must also provide additional protection against unwanted high voltage that may appear on the trunk conductors due to lightning or power line faults.

Most trunk circuits provide the interfaces that permit signalling over the trunk. Included are supervisory components which recognize the on-hook, off-hook, or reverse battery state of the connection. These differences in state may provide both supervisory and address signalling information on the tip and ring (T and R) leads or on standard signalling leads for use locally and at a distant office. In addition, signalling information may be extended from the trunk circuit to automatic message accounting equipment.

**Effect of Trunk Type.** Trunks are classified in a number of ways to satisfy the needs of transmission engineering and traffic organizations [6]. However, none of these classifications can be used adequately to discuss the effect of trunk type on required trunk circuit transmission and operating characteristics.



One method of classifying trunks is by the number of directions of call origination. A two-way trunk provides for call origination in either direction; a one-way trunk permits origination in one direction only. The various trunk circuits for one-way and two-way trunks have different signalling system interface requirements which are further complicated by the signalling requirements of the switching machine or switchboard at each end of the trunk.

Both trunks and switching machines can be either two-wire or four-wire. Any combination of these may be found and provision must be made accordingly in the transmission design of the trunk circuit which provides the interface at the point of interconnection.

As previously mentioned, trunks are used to interconnect switching machines, portions of switching machines, and/or switchboards. Each different application requires the use of a different design of trunk circuit. Many intramachine trunks are required to provide connections to signal sources such as dial, busy, audible ringing, and reorder tones and to announcement machines associated with certain number services (reached unassigned number, disconnected service, etc.).

Intermachine trunks include all of the various trunks required in the message network hierarchy. Each of these may be one-way or two-way, two-wire or four-wire, direct, tandem, toll connecting or intertoll, high-usage or final route. Operation of any one of these trunks may involve echo suppressors and their enabling and disabling, switched gain, switchable pads, or the use of idle circuit terminations. Most of these options require the use of a different type of trunk circuit.

Some trunks that interconnect switching machines and switchboards provide operator services only and others remain in a network connection after the operator has disconnected (e.g., secondary intertoll trunks). Each of these applications requires a different type of trunk circuit to accomplish the desired functions. Where the connection from the operator to the network trunk is made by bridging, the trunk circuit must have low loss in the through-trunk connection and high-impedance bridging of the operator trunk. The bridged operator trunk is connected to the through trunk by a path through a switching machine network. After the operator has completed the necessary action, the bridged connection is released.

Some trunks provide connections from a network trunk to local or centralized automatic message accounting (LAMA or CAMA) equipment. The requirements on these trunks depend on whether the message trunk is in a flat rate, message rate, or toll rate portion of the network and the nature of the trunk circuit is affected accordingly.

**Typical Trunk Circuits.** Detailed illustration of trunk circuits is impractical because of the large number of circuit types that are in use. However, the more significant features and functions of these circuits can be demonstrated by a few schematic drawings chosen to illustrate specific points.

The principal connections to trunk circuits are those dedicated to transmission and signalling. In order to effect a reasonable amount of standardization, certain designations are consistently used for trunk circuit leads having specific functions. In many cases, these designations are applied to leads other than those used in trunk circuits (e.g., many signalling unit and voice-frequency repeater leads).

*Lead Designations.* Standard designations for the tip and ring transmission leads are T,R,T1, and R1. The T and R designations are used generally to designate the tip and ring leads of two-wire circuits where no distinction between the two circuit ports is needed. Where a distinction must be made, T and R are usually used for the leads at the port facing the switching equipment and T1 and R1 for the leads at the port facing the transmission facility. At two- to four-wire conversion points, the two-wire port leads are designated T and R. The four-wire port leads that transmit away from the conversion point are also designated T and R; the leads that transmit toward the conversion point are designated T1 and R1.

Where an equipment item interconnects two four-wire circuits, the T, R, T1, and R1 leads are assigned in various ways depending on the application and functional designation of the interconnecting circuit. Signalling leads are also given standard designations. These include E, M, SX, SX1, A, B, SG, and SB. Illustrations of some applications are given in Figure 7-3.

The designations, E and M, identify leads that interconnect trunk circuits and signalling circuits. These leads are always functionally related in such a way that the E lead is used to signal from the trunk circuit toward the local switching system through signalling circuits

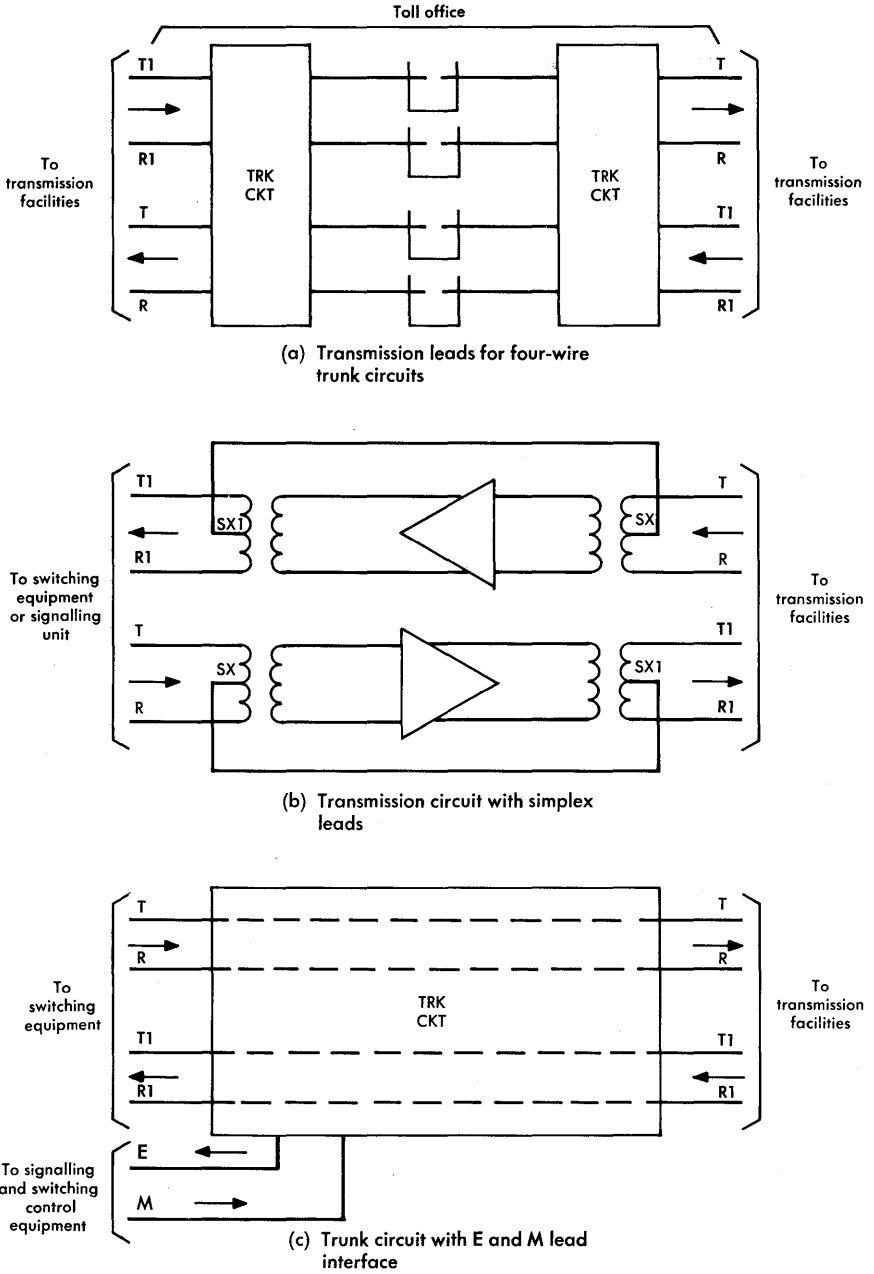


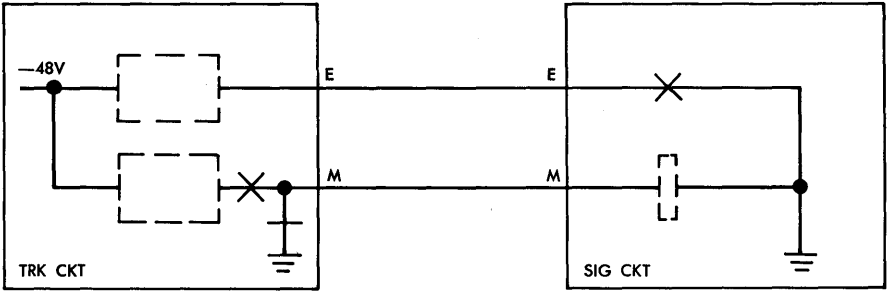
Figure 7-3. Transmission and signalling lead designations.

and the M lead is used to signal from the local switching system through signalling circuits toward the distant end of the trunk. The relationship of E and M signalling leads to transmission circuits and the directions of signalling are illustrated in Figure 7-3(c). An open-circuited E lead represents an on-hook condition at the distant end of the trunk; a ground on the E lead represents an off-hook condition at the distant end. Similarly, the M lead is used to signal toward the distant end of a trunk; an on-hook condition at the near end is represented by a ground on the M lead and an off-hook condition by  $-48$  volts.

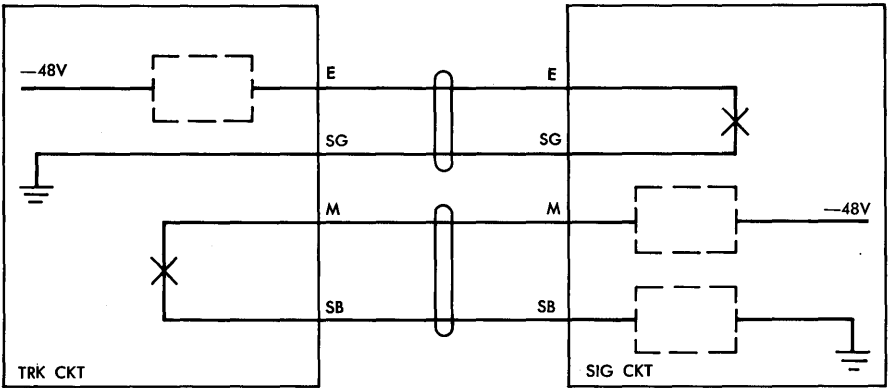
The E and M lead method of signalling is in common use but, as shown in Figure 7-4(a), the signals are changed by opening and closing single-wire circuits. With each change of state, this arrangement produces high-amplitude transients which may be induced into other circuits to cause errors in control or impulse noise in transmission. The circuit arrangement of Figure 7-4(b) is used to overcome these impairments by providing paired-wire signalling. The SG (signalling ground) and SB (signalling battery) leads are doubled back between trunk and signalling circuits so that transients are suppressed by cancellation. In this arrangement, the local on-hook condition is represented by an open rather than a grounded M lead and the off-hook condition by the application of  $-48$  volts to the M lead.

Where dc signals are transmitted over cable pairs, dc continuity can be provided around a transmission circuit by use of simplex leads (SX and SX1) as illustrated in Figure 7-3(b). Such signals may also be applied across the tip and ring conductors of a pair. In this case, access to the pair may be over A and B leads connected directly to the tip and ring leads or by way of the terminals of the midpoint series capacitors in line transformers. Lead associations are maintained in order to provide logical interfaces between transmission and signalling circuits. The A lead is associated with the T-lead side of a transmission circuit and the B lead with the R-lead side. Where A and B leads of DX signalling circuits connect to SX and SX1 leads, an association is maintained between A, SX1, T1, and R1 leads and between B, SX, T, and R leads.

*Battery Feed Circuits.* When a connection is established, current is generally supplied to a loop and/or a trunk from a trunk circuit or a junctor circuit. (Junctors are used to interconnect certain portions



(a) Single-wire signalling

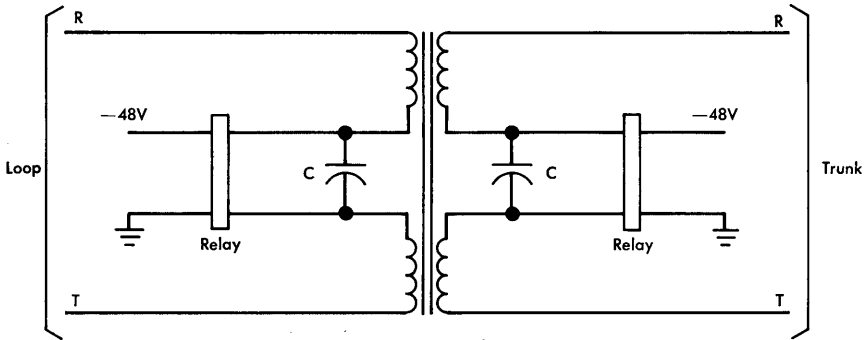


(b) Paired-wire signalling

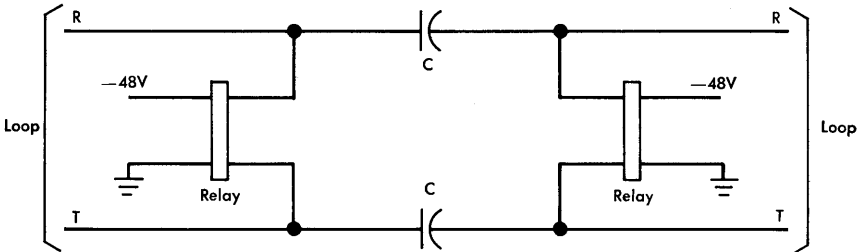
Figure 7-4. Simplified schematic of E and M lead signalling.

of the switching networks of ESS and crossbar systems.) There are many forms of battery supply (or battery feed) circuits most of which can be classified in one of two general categories, repeating coil circuits and bridged impedance circuits.

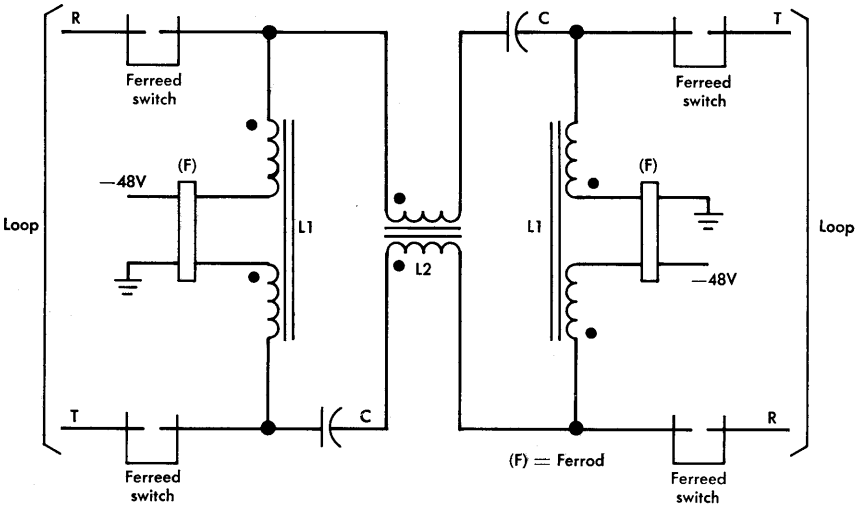
Figure 7-5(a) illustrates a repeating coil battery feed circuit for an interoffice connection at a step-by-step switching machine and is typical of a number of other applications. Battery and ground are fed independently to the loop and trunk. The capacitors, designated C, furnish voice signal current coupling through the repeating coil windings. The capacitance values are chosen to be as small as practicable without inserting excessive transmission loss or distortion.



(a) Repeating coil circuit



(b) Bridged impedance circuit



(c) No. 1 ESS junctor circuit

Figure 7-5. Typical battery feed circuits.

The relays are used for supervisory signal information. The relay and repeating coil windings have sufficient resistance to limit the battery feed current on extremely short loops to acceptable values; at the same time, these windings are capable of carrying the maximum values of dc that may arise from trouble ground or short-circuit conditions on a loop.\* Shunt losses to speech currents are limited by the relatively high inductance of these coils. The windings are well balanced to prevent the conversion of induced longitudinal interference to the more interfering metallic form of interference.

Figure 7-5(b) illustrates a bridged impedance battery feed circuit. It is used for intraoffice connections in step-by-step and crossbar systems and is typical of a number of such applications. Although it does not provide longitudinal isolation, it is much simpler and less expensive than the circuit of Figure 7-5(a) and performs satisfactorily in many applications.

Intraoffice (loop-to-loop) connections in No. 1 ESS receive battery current from a junctor circuit located at the midpoint of the switching network connection. The circuit, shown in Figure 7-5(c), is an example of a bridged impedance battery feed arrangement with some unique features. The windings of the inductors designated L1 act as a filter to suppress noise originating in the battery supply. The two-winding inductor designated L2 limits surge currents that might be caused by power crosses or lightning in order to prevent damage to fragile circuit elements, especially the sealed reed switch contacts used in No. 1 ESS networks. The polarities of the windings of L2 are such that the inductance is minimized for voice signals that circulate through the circuit but has a relatively high value for unwanted longitudinal currents. This battery feed circuit has an insertion loss of about 0.25 dB over the voiceband.

Figure 7-6 shows the originating and terminating trunk circuits of a typical direct trunk interconnecting two local central offices. In both trunk circuits, battery current is supplied through the windings of an S relay which also provides certain signalling and supervisory functions. The A relay windings in the terminating trunk circuit furnish battery and ground to the trunk for supervisory and signalling purposes. These three battery feed circuits are prevented from interfering with one another by the blocking capacitors, designated C.

\* A design criterion used for these circuits is that a trouble ground condition may destroy the component but may not create a fire hazard.

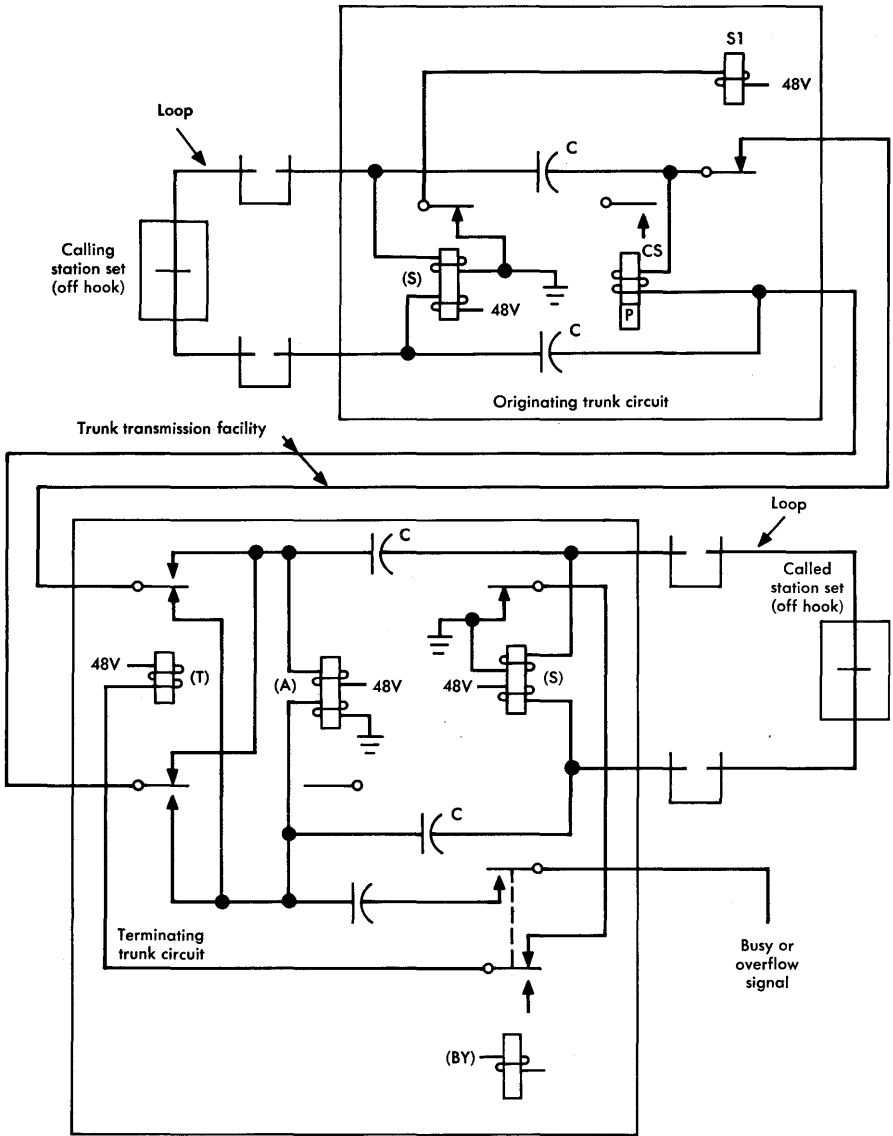


Figure 7-6. Bridged impedance battery feed circuits and dc signalling.

*Signalling.* Figure 7-6 may also be used to illustrate a number of signalling features commonly provided in trunk circuits. The connection shown is one in which dc signals from the calling station set



are extended by relay operations in the trunk circuits at the two ends of the trunk. On-hook and off-hook conditions at the calling station set (supervisory and dial pulse signals) are detected by the S relay in the originating trunk circuit. This relay operates (off-hook) and releases (on-hook) in response to calling station set conditions. The S1 relay operates and releases under control of the S relay. The S1 relay contacts open and close the trunk loop to extend signalling to the terminating trunk circuit.

The A relay in the terminating trunk circuit operates through the normally closed contacts of the T relay when the trunk loop is closed by the S1 relay in the originating trunk circuit; it releases when the S1 relay releases. Thus, the A relay repeats dial pulses and supervisory conditions received from the originating end of the trunk to operate the switching machine at the terminating end of the trunk. When the called station set is answered, the S relay in the terminating trunk circuit operates to actuate a ring tripping circuit (not shown) and also to operate the T relay which reverses the direction of current flow from the A relay through the trunk. This polarity reversal causes the polarized CS relay in the originating trunk circuit to operate, thus providing an indication of the called station off-hook condition to the originating switching machine. This sequence is called reverse battery supervision. If the called station is busy, the BY relay operates and connects a busy signal to the trunk to notify the caller of the busy condition.

**Two-Wire Switching of Four-Wire Trunks.** In No. 1 ESS, provision is made for the two-wire switching of four-wire toll trunks by a technique called HILO. Trunk circuits are used to convert the two balanced (two-wire) paths of a four-wire trunk to two unbalanced (one-wire, ground return) paths for transmission through the switching network. As a part of the conversion process, the impedances of the two paths are transformed from nominal 600-ohm values in such a manner that an impedance in excess of 100,000 ohms faces the switching network at the transmitting end of each path and an impedance of 5 ohms or less faces the receiving end; hence, the designation HILO. A block diagram of the resulting transmission layout is given in Figure 7-7.

The HILO technique is applicable only to No. 1 ESS machines equipped with remreed-type networks. The high transmitting-end impedance makes the currents transmitted through the switching

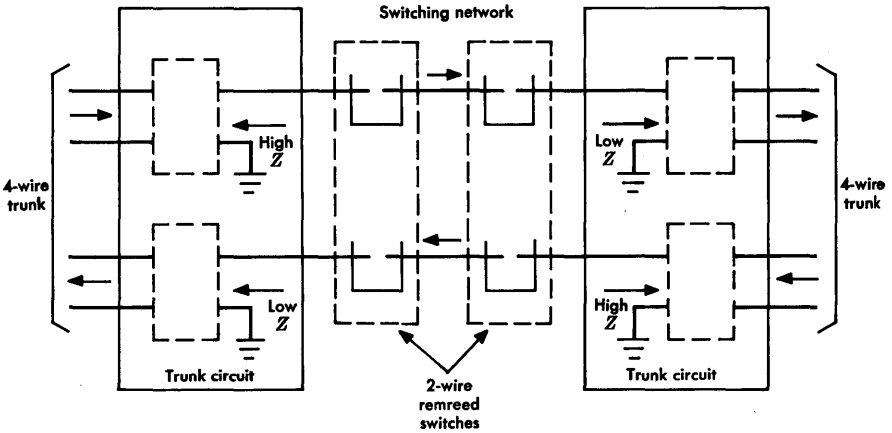


Figure 7-7. Two-wire switching of four-wire trunks.

network relatively insensitive to inductive crosstalk coupling between transmission paths. The remreed-equipped networks are more compact than ferreed-equipped networks. As a result, the transmission loops through the network are shorter and inductive crosstalk coupling, normally limiting in single-wire switching networks, is controlled. Capacitive crosstalk coupling is also controlled by virtue of the low-impedance used at the receiving end of each path.

This method of converting four-wire circuits to two-wire circuits significantly increases the No. 1 ESS capability for switching toll trunks. It thus provides for the application of No. 1 ESS to the switching of limited numbers of toll trunks in situations where a machine wholly dedicated to toll switching could not be economically justified. The HILO technique was originally proposed for use in switching networks employing solid-state crosspoint devices [7].

### 7-3 TRANSMISSION-RELATED SWITCHING OPERATIONS

The operation of every switching system involves sequences and call manipulations that have a direct impact on transmission. Some of these involve the transfer or reversal of battery and ground connections in the transmission path. Other sequences are performed by the switching machine to satisfy certain transmission requirements. Still others are signalling circuit manipulations that affect trans-

mission at the points of interface between switching, signalling, and transmission circuits. In addition, there are a number of service features that involve transmission in direct or indirect ways.

Each of these general classes of transmission-related switching operations has involved problems that had to be solved to assure satisfactory transmission performance. Some of the solutions have affected station set designs; others have affected transmission circuits and some have had their primary impact on switching system designs.

### Call Sequencing

In the course of establishing connections, the sequence of operations in a switching machine often involves the transfer of battery and ground connections from one circuit to another. Each time such a transfer is effected, electrical transients may be transmitted to the station set at one or both ends of a connection. These transients are sometimes minimized in respect to the frequency of occurrence by the sequence of operations designed into the switching machine but they cannot be eliminated completely. Station set circuits have been provided with diodes bridged across the receivers to suppress such transients and to make them less annoying to a listener. These diodes break down to absorb the sharp instantaneous voltage peaks of the transient.

A similar phenomenon results when the battery and ground connections to a loop or trunk are reversed. This reversal is used as a signalling mechanism for a number of sequenced functions within a switching machine. When reversal occurs, it is equivalent to opening and closing the battery and ground connections just as in battery transfer. The transient suppression feature in station sets is also effective in limiting the annoyance due to these transients.

### Switched Transmission Operations

There are a number of transmission features and functions that are provided by switching system operations. For example, the stability of transmission equipment frequently depends on the existence of a suitable termination at the input and/or output terminals. A circuit condition that can often produce instability is the open-circuit termination that may exist when a line is idle. To prevent instability under these circumstances, the switching system is arranged in many cases to apply an idle circuit termination.

The enabling and disabling of E6 repeaters and echo suppressors are also often controlled by switching machines. The disabling of E6 repeaters accomplishes the same purpose as the application of idle circuit terminations; i.e., by removing the power ground, it prevents repeater instability when the line is in the idle condition. The disabling of echo suppressors is sometimes necessary to prevent having more than one echo suppressor in tandem in a long built-up connection in private switched networks. In many cases, they are also disabled in the public as well as private switched networks to allow duplex data signal transmission.

Loss pads are sometimes switched in or out of an intertoll trunk. If the intertoll trunk is switched to a high-loss toll connecting trunk, the pad is switched out of the intertoll trunk circuit. If the connection is to a low-loss toll connecting trunk, the pad is switched into the circuit [6].

#### 7-4 DIGITAL SWITCHING INTERFACES

In addition to the facilities and equipment required for voice-frequency telephone communications, central office buildings house a great variety of other types of transmission equipment. Among these are equipment units that provide interfaces between digital and analog portions of the facility network. Some of the interface equipment units are more conveniently described as parts of major systems; among these are the D-type channel banks used with various T-type carrier systems.

Telephone switching has evolved as a means of interconnecting transmission circuits (loops and trunks) by providing complex switching networks primarily utilizing the previously mentioned electromechanical step-by-step, crossbar, or sealed reed switches. These are sometimes referred to as space division switching networks. Now, switching may also be accomplished by electronically directing the pulses of digitally encoded signals according to the desired interconnection pattern, a method known as time division switching.

The first major central office system to utilize time division switching is the No. 4 ESS toll switching system [8]. Signals to be switched by this machine must be coded in accordance with a specific format based, in part, on the DS-1 signal format employed in the T1 Carrier System. The coding may be accomplished by *voiceband interface units* (VIU), which accept up to 120 voice-frequency signals at the input,

or by *digroup terminals* (DT) which accept DS-1 signals at the input; in both cases, the signals are processed into the appropriate format for digital switching of voiceband signals. Switching is implemented by making appropriate changes in time slot assignments of the pulses that represent specific signals. These changes are accomplished in the switching machine by circuits that are collectively called the *time slot interchange* (TSI).

### Digroup Terminal

The most efficient method of processing large numbers of DS-1 (bipolar, 50-percent duty cycle) signals terminated at a No. 4 ESS is by the use of digroup terminals. Each DT has the capability of terminating 40 DS-1 digroups, a total of 960 voiceband circuits. A digroup terminal consists of eight digroup terminal units (DTU) each of which can process five digroups (120 circuits). In addition, a switchable spare DTU is incorporated for protection and maintenance purposes.

On the switching side of the digroup terminal, the five DS-1 signals of each DTU are multiplexed by time division techniques into a single serial bit stream of 16.384 Mb/s for transmission to the time slot interchange of the ESS switch. This signal is in a two-level (unipolar) format and has 128 channel time slots. Of these, 120 provide for the multiplexed circuits of the five DS-1 signals; the remaining eight are used for maintenance.

Circuits are provided in each digroup terminal for timing and buffering so that incoming DS-1 signals can be synchronized to the operations of the time slot interchange. In addition, signalling information and digroup terminal maintenance information is transmitted between a digroup terminal and the No. 4 ESS common control over a 2.048 Mb/s link.

### Voiceband Interface Units

Although the processing of signals in No. 4 ESS is most efficient when the input signals are in the DS-1 format, many voice-frequency signals must be accepted and processed at the interface into a suitable digital format. The equipment units used for this processing, called *voiceband interface units* (VIU), are mounted in a three-bay *voiceband interface frame* (VIF). Seven working VIUs, each arranged to terminate 120 trunks, are mounted in one VIF together with a switchable VIU for maintenance and protection.

On the voice-frequency side of a VIF, connections are made to any of a large number of alternative equipment types. These include voice-frequency trunk terminal equipment, short-haul analog (N-type) or digital (D-type) carrier terminals, or long-haul (A-type channel bank) terminal equipment. Some of these equipment types are standard items associated with particular transmission systems; others are unitized equipment bays developed specifically for this application.

Signals between either the VIU or the digroup terminals and the time slot interchange are of the same format. Signals from the VIU are processed and multiplexed into a 16.384 Mb/s unipolar signal. Signalling, timing, and maintenance signals are treated separately as with the digroup terminal.

## 7-5 TELEVISION EQUIPMENT

The nationwide network of television channels is provided primarily over microwave radio transmission systems. The administration of the major broadcasting networks is coordinated largely by telephone company personnel located at the television operating centers (TOC). The TOC equipment is usually located in telephone central office buildings. The TOCs, the equipment required, and the operating staff are variable in respect to size and assigned manpower. In some cases, equipment locations called television facility test positions are provided with minimum facilities.

The TOC is provided with switching, patching, and a wide variety of transmission and maintenance items needed for network operations. Switching equipment is provided for both video and audio circuits. The switching is coordinated and controlled so that local circuits between studios, pick-up points, broadcast transmitter locations, or the long distance network can be switched in a variety of combinations with minimum delay or interruption. The control circuits for these switches are located in the TOC and the control elements (pushbuttons) may be located at the TOC or at a remote location or both. Switching matrices of various sizes are available up to a maximum of  $30 \times 36$  inputs and outputs. The TOCs, studios, transmitters, and receivers are interconnected by video trunks. Amplifiers, clammers, equalizers, etc., are provided so that trunks can be adjusted to meet transmission requirements.

A patch bay is provided so that video circuits can be patched through the switching matrix as desired. This bay is also used as a

common transmission level point where levels are not only equal but are adjusted to be flat across the video band.

The TOC is the control point for television video and audio circuit maintenance activities. A wide variety of test equipment, most of it permanently mounted, is used with switching or patch cord access to the video trunks for test and maintenance work.

Signal generators, level meters, transmission measuring sets, and other test equipment items are used for troubleshooting and for the adjustment and evaluation of video and audio circuits. Order wires are provided so that maintenance personnel can communicate easily and directly with personnel at other locations. Two types of monitors are normally used. One type displays the picture being transmitted to give assurance that correct connections have been made through the patch bay and the switching matrix and to judge the quality of the picture. The second type is an oscilloscope that is used to display and evaluate the waveforms of signals transmitted on circuits under investigation.

## 7-6 SOURCES AND CONTROL OF IMPAIRMENTS

In many cases, the unique environment and specific design problems involved in central offices make the control of transmission impairments essential if high quality performance is to be maintained. Central office circuits and equipment arrangements may be the source of transmission deterioration, partly because of the high concentration of equipment and wiring and partly because of the many interfaces between different kinds of circuits.

### Noise

A predominant transmission impairment generated in many central offices is impulse noise. Switching functions, such as the operation and release of relays and switches, produce high transient voltages. Care must be taken in design and layout so that excessive transients are not induced into circuits that carry data or other signals susceptible to such noise.

Of particular interest in respect to impulse noise generation are alarm, bay power distribution, and control leads. Wherever possible, these leads and the circuits they interconnect should be operated as balanced circuits and the leads installed as twisted pairs. The cost

savings resulting from single-wire ground-return operation is often tempting but where circuits are so operated, induced transients are difficult to control.

Another source of impulse noise is the switching system operations that require the transfer or reversal of battery feed connections to transmission circuits. In general, these take place during the connect and disconnect processes of call sequencing. Thus, the effect is minimal on data signal transmission and, as previously mentioned, the effect on voice circuits is minimized by the design of the receiver circuits in telephone station sets.

Other central office noise sources produce interferences, such as contact noise and battery noise, that are more nearly like random circuit noise. Contact noise is due primarily to the build-up of dirt and other high-resistance materials on the surfaces of electrical contacts. Switchbank contacts and wipers on step-by-step switches are of base metal (copper), and are thus subject to wear. They must be cleaned regularly to prevent deterioration of performance. Contacts on relays and other switching elements are made of precious metals and the contacts are designed to have a wiping action as they make and break to help prevent the accumulation of unwanted dirt and other pollutants. Most relay contacts now are of the bifurcated design which, in effect, puts two contacts in parallel to minimize the deleterious effects of high resistance that may build up in one contact.

Common battery supply circuits are also a source of interference similar to random noise. All of the transmission and switching circuits in an office that operate from the common battery share the battery feed circuits as a common impedance which is kept as low as possible (a small fraction of an ohm). Even though the coupling impedance is extremely low, the total power of the many coupled-in signals can be significant and usually has the quality of random noise [9]. The coupling of this impairment into transmission circuits must be controlled in design so that it is not a significant source of message circuit noise. In some situations, special filters must be installed in battery supply leads on each equipment frame to prevent excessive noise accumulation.

### Crosstalk

In central office equipment, there are many exposures to crosstalk between transmission circuits and from announcement and tone sources into transmission circuits. These sources of impairment are



controlled in design and by careful and continuing maintenance effort. Signal amplitudes and transmission level points must be maintained at design values.

In some cases, where wide discrepancies exist between signal amplitudes in adjoining circuits, crosstalk is minimized by routing the circuits through cable or wiring paths that are separated physically. The separation is specified by installation instructions and must be maintained if performance is to be satisfactory.

### **Coupling Circuits**

The combined need for isolating battery feed circuits from one another while providing signal coupling between circuits is generally solved by the use of capacitors and/or transformers. These circuits can degrade performance by introducing transmission deviations or by restricting bandwidth. However, their characteristics are determined primarily by design and unsatisfactory performance is usually due to a trouble condition or to errors in wiring.

### **Loss and Return Loss**

Impairments can result from excessive transmission loss or insufficient return loss in central office circuits and equipment. Transmission losses are controlled primarily by design and, where excessive, are usually caused by a trouble condition. Return losses must be controlled by the application of through and terminal balance procedures [4].

### **Battery Voltage**

The common battery supply used in central offices consists of large batteries in which voltage is maintained at nominal values with permissible fluctuations of several volts. The charge is maintained by applying a primary power source of commercial 60-Hz ac through appropriate power rectification and control equipment.

In the event of failure of the primary commercial supply, the load is taken up by emergency ac generating equipment driven by a diesel or turbine engine. In the event of multiple failure, the battery carries the operating load without primary supply but only for a limited time. Most batteries are selected to provide a minimum of 4 hours reserve capacity at peak traffic load. Under such conditions of power failure, battery voltage may gradually decrease. As the voltage drops, indi-

vidual circuits deteriorate in ways that depend on circuit functions and the applied voltage. Switching and transmission performance gradually deteriorates until total failure occurs.

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## Chapter 8

# Business Communications Systems

Business customers have many communications needs that are not satisfied by the ordinary telecommunications services provided by the message network. One of these needs is rapid, convenient, and economical intercommunications among their employees. In some cases, these needs must be fulfilled at a single location and, in other cases, between two or more locations that are distant from one another. This type of service is furnished by a class of equipment called business communications systems (BCS). In some instances, these systems are also used for residence services.

The strategy of furnishing business communications service depends on the size of the customer organization, the manner in which it is dispersed over different locations, and the number of people at each location. In addition, the manner in which the needs are fulfilled depends on the service features to be provided in addition to the basic feature of intercommunication.

Typically, where customer needs are concentrated at one location, service is provided by a key telephone system (KTS) or a private branch exchange (PBX) system. These provide local intercommunication services and can also be furnished with a number of other desirable features. The equipment is usually located at the customer premises.

Where corporate activities are dispersed, business communications systems may be expanded to include a network of interconnected PBXs and/or key telephone systems. The scattered locations may each be served locally by a PBX and the PBXs may be interconnected by

tie trunks; the overall network in this case is called a tandem tie trunk network (TTTN). For very large service needs, a network of switching systems usually located in central office buildings may be interconnected by network trunks. A PBX at each customer location is connected by access lines to the network, called a switched services network (SSN). On intranetwork connections, these private switched networks perform functions similar to the local, toll connecting, and intertoll switching functions of the switched message network. Many aspects of transmission are now recognized as unique to this type of equipment.

Other types of business communications services include those provided by commercial automatic call distributors (ACD) and telephone answering systems (TAS). The ACDs are arranged to distribute a large number of incoming trunks or lines to a smaller number of positions at which incoming calls are usually served directly by attendants. The service at a TAS is one in which incoming calls are answered for the customers of the answering service. Messages are recorded and forwarded at a later time.

In some respects, KTS and PBX equipment have significant common operating features; ACD and TAS equipment features are also somewhat similar. The main points of similarity between KTSs and PBXs are that both provide multiple access to a switched network (public or private) and both provide intrasystem communications without requiring access to the network. Thus, there are circuits in these layouts that are similar in function to customer loops, i.e., circuits that connect station sets to the switching equipment. Circuits, similar to PBX-central office (PBX-CO) trunks, connect the ACD or TAS equipment to a switched public or private network. Incoming calls terminate at attendant positions. The service is predominantly incoming and there is very little provision for initiating outgoing calls. In TAS equipment, there is usually no way of extending a connection to another switchboard or station; however, provision is made to transfer connections from an ACD to an associated PBX switchboard or station.

The majority of PBXs, ACDs, and TASs are administered by attendants at key-type consoles or, in older installations, at cord-type switchboards. In some cases, KTS arrangements also have a central station which may be regarded as an attendant position. Thus, all four equipment categories use some form of attendant administration.

The market for business communications systems comprises a wide variety of customer preferences, environments, and communicating styles. As a result, there is available a very wide variety of products and services that add to the complexity of this field of application. While most of the variations primarily affect the switching and signalling designs, transmission designs are also somewhat affected.

## 8-1 KEY TELEPHONE SYSTEMS

A key telephone system allows a station set to be used to pick up and/or hold one of several lines or trunks. Customer requirements for key telephone service may be satisfied by a wide variety of available systems. Some have only one station or line and others have up to 40 stations or lines. Most key station sets are provided with pushbutton access to 6, 10, or 20 lines; also, the CALL DIRECTOR® telephone set can be used to provide access to as many as 30 lines.

These systems also provide for intercommunication (intercom) between stations of the system. The circuits that terminate at a key telephone set may be PBX station lines or any of a number of central office connections including loops, private lines, foreign exchange (FX) lines, wide area telecommunications service (WATS) lines, or long distance (LD) lines. Transmission on connections to each of these lines must be nearly equivalent to satisfy customer needs and the necessity for providing high quality transmission over the various types of connections to KTSs offers many design challenges. In addition to the primary requirements of pickup, hold, and intercommunication, KTSs also may provide a number of other features, some of which may affect transmission. Some features are:

- Controlled privacy or exclusion
- Interstation signalling
- Battery supply for intercom
- Use of CO or PBX talking battery
- Incoming call transfer
- Conference and drop-off transfer
- Multistation intercom and outside conferencing
- Tie line connections to other KTSs.

Key telephone systems may be used in a number of different ways to achieve conference or add-on service. In some key station sets, non-locking pushbuttons are used. Thus, more than one button may be depressed simultaneously giving a station access to more than one connected line at a time and/or to the intercom circuit. Transmission quality is not guaranteed because, with each line added to the connection, transmission loss increases and the return loss deteriorates due to changes in the terminating impedance. In other systems, an add-on key and circuit are provided so that a second line can be bridged to an existing connection. Similar loss impairments are incurred.

Remotely located, independently operated key telephone systems may be interconnected by tie lines similar to intercom lines. These tie lines cannot ordinarily be interconnected with other circuits to establish connections beyond the KTSs.

Key telephone systems are designed so that features can be provided as selected by the customer. One commonly used feature is a lamp display that indicates the state of each station set line. Figure 8-1 shows the indications normally provided. In addition to the line state indicators, a separate lamp may be provided to indicate that the attendant has a message waiting for the user and another lamp may indicate that the add-on feature (for conferencing) is in use. In addition to these commonly used features, others may be optionally provided. These include voice signalling over the intercom to a loudspeaker, privacy and exclusion arrangements, and manual or dial intercom signalling. In some systems, provision is also made for music to be transmitted to calling parties when their connections are placed on hold and tones to be transmitted to calling parties placed in a camp-on condition (waiting for a busy called party to become free). The music source is a customer responsibility; access for the connection is provided in the key telephone system. This feature involves the application of stringent design requirements so that two callers whose connections are in the hold condition cannot communicate. The loss between two such connections, called talk-through loss, must be in excess of 60 dB.

Key telephone service was initially provided by custom-engineered assemblies of lamps and keys which were subsequently standardized and called *wiring plans*. The service has expanded and evolved to include a number of systems which provide the range of features previously discussed by packaged units called key telephone units

LINE STATE	LAMP INDICATION
Idle	Not illuminated
Busy	Steady illumination
Ringling signal	Flashing (60 per minute)
On hold	Winking (120 flashes per minute)

Figure 8-1. Key telephone lamp signals.

(KTU) which may be mounted and interconnected in apparatus cabinets and key service units (KSU). By proper selection and interunit wiring of KTUs, a wide range of custom-engineered options can be provided by use of standard equipment and apparatus. Cross-talk must be carefully considered in design because of constant exposure between the same potentially disturbing and disturbed circuits. Most of the telephone station transmission circuitry in KTSs is provided in the form of 500-type station set circuits. Thus, the basic performance of these stations is equivalent to that of the 500-type station set.

The equipment and components used in KTUs have undergone many changes in technology and service applications. The circuits that provide the numerous options are assigned code numbers and are designed for use in apparatus cabinets and KSUs. The latest versions of these circuits use solid-state components, printed wiring boards, and miniature relays mounted on plug-in circuit cards to make most efficient use of available space and power. The most recent version of this type equipment assembly is the 1A2 KTS.

Another trend in customer premises switching is the integration of PBX and KTS functions. Four systems, shown in Figure 8-2, are available to provide features that are a mix of those usually found in PBXs or KTSs. A station on any of these systems may be connected to any line terminating at the system. Most of the newer features such as tone signalling, loudspeaker intercom, music on hold, tone on add-on, and multiline conferencing are provided.

TYPE	CO OR PBX LINES	STATIONS
4A	4	16
7A	7	18
14A	14	34
21A	21	52

Figure 8-2. Key telephone communication systems.

## 8-2 EQUIPMENT FOR PBX AND CENTREX SERVICES

Where a customer has a large number of employees that have need for telephone communication among themselves as well as with others outside the organization, the required services are often provided most economically by the use of one or more PBXs. In this type of business communication system, connections may be established between stations served by a PBX, between these stations and trunks terminating at the PBX, and between various types of trunks.

Services are provided by PBXs covering a wide range of sizes, features, uses, and applied technology. Sizes range from small, manual systems that can accommodate up to 40 station lines to machine switching systems of various types that can serve up to 10,000 station lines. Features, some optional, include intraPBX dialing by any station, attendant services, direct inward dialing, direct or attendant-assisted dialing to remote locations over PBX-CO or PBX tie trunks, toll diversion, and direct outward dialing with automatic identification of outward dialing. Multiport conference circuits are available for use with PBXs. These circuits can simultaneously bridge up to six PBX-CO trunks or PBX station lines in various combinations. Key telephone station lines can be among those connected together through such a conference bridge. Simple, single-station, add-on capability is also provided in some PBXs by the dialing of an appropriate code.

A PBX may serve just one group of users at a single location or at a number of locations and it may be used as a switching center in a large and complex private telecommunications network [1]. There are many thousands of PBXs in service utilizing a range of technology that includes manual switchboards and step-by-step, crossbar, and electronic switching systems. Both space division (ferreed and solid state) and solid-state time division ESS machines are used.

### Station Lines and Tie Trunks

Station sets are connected to an associated manual or dial, attended or unattended PBX by means of PBX station lines. These are analogous to loops that connect station sets to the serving central office in the switched message network. The station sets may be collocated with the PBX or remotely located (off-premises). In either case, they may be individual or multiplied station sets or they may comprise a key telephone system operating from the PBX. The loss and resistance limits for on- and off-premises station lines are estab-



lished by complex relationships with the loss and resistance limits for PBX-CO trunks so that objectives can be met for a wide variety of connections [2]. Among other complications, these limits must satisfy transmission contrast and signalling requirements with battery feed circuits located at the central office on some connections and at the PBX on others.

The interconnection of PBXs is accomplished by circuits called tie trunks. There are numerous types of tie trunks and many interconnection patterns may be established to form parts of extensive tandem tie trunk networks. These are sometimes considered as a class of networks within a larger class called switched services networks in which separate locations are interconnected by network trunks and access lines. However, the latter networks provide services covered by specific tariffs; furthermore, they are well-organized networks controlled by common control switching arrangements. Therefore, for present purposes, the two types of networks are to be considered as separate classes [1].

### **PBX Types and Services**

While there are many manual PBX systems still in operation, especially in small installations, the trend is toward machine switching; most PBXs are now machine switching types with some form of attendant switchboard or console. Another type of dial PBX service, called centrex, includes certain specific features. This service may be provided by all or a portion of the serving central office switching machine.

**Manual PBXs.** In small business installations, most service requirements are satisfied by key telephone systems. However, one modern manual PBX, the 558A, operates with a 29-type console to serve up to 40 lines.

There are still manually-operated key-type switchboards of the 506 and 507 types in service. These switchboards, no longer manufactured, provide service to a maximum of seven and twelve PBX station lines, respectively. Other outmoded cord- and jack-operated manual switchboards are still found in service. These include the 552-type, which can serve up to 420 lines, the 555-type, which can serve up to 120 lines, and the 606 and 607 types, which can serve up to 5000 and 3500 lines respectively.

The 608-type cord switchboard can serve up to 1600 lines. This switchboard, together with the 552, 606, and 607 types, can function as an attendant switchboard for dial PBX operation in addition to being used as a manual switchboard.

**Dial PBXs.** As previously mentioned, most PBX service is now provided by switching machines, supplemented by attendant consoles, rather than by manual key-type or cord-type switchboards. Switching and attendant equipment is located on customer premises in most installations. In some cases, PBX or centrex services are provided by central office switching equipment. Like central office switching machines, dial PBXs are of two general categories, electromechanical coded with 700-series numbers and electronic with a variety of code number series.

Figure 8-3 lists the principal types and general characteristics of the systems now in use. While they are of early design, the 701-type and 711-type PBXs still provide a large proportion of these services. These systems are progressive, direct-control, step-by-step switching systems. In application, they are very flexible, can economically serve relatively small business needs, and can also be used to serve very large installations (up to 10,000 lines). They are the only PBXs available to serve more than 4000 lines. The 702-type PBX, capable of serving a market similar to that served by the 701- and 711-types, is no longer manufactured. Only a few systems remain in service. Similarly, the 740-type systems, designed to serve smaller installations, are no longer manufactured nor commonly used.

PBX TYPE	CATEGORY	MAX. SIZE, LINES
701	S × S	10000
702	S × S	9600
711	S × S	10000
740	S × S	300
755	X bar	20
756	X bar	60
757	X bar	200
770	X bar	400
800	ESS	80
801	ESS	270
805	ESS/X bar	57
812	ESS/X bar	2000
101	ESS	4000
CSS 201	ESS	2000

Figure 8-3. Dial PBX types and line capacities.

The 755-, 756-, and 757-type PBXs are relatively small relay-controlled crossbar systems. Though a number of these systems are in operation, they are no longer manufactured. The 770-type system is a common-control crossbar system capable of serving up to 400 station lines. Its features make it attractive for use in hotel and motel applications as well as in general business applications.

Recent designs of PBXs utilize electronic technology; some are all-electronic and others utilize electronic control of electromechanical networks. The 800- and 801-type PBXs listed in Figure 8-3 have ferreed networks combined with an electronic common control mode of operation. The designs are generally similar with the 801 an expanded version of the 800-type. The 805-type PBX is a compact machine designed to provide basic services in small installations.

The 812-type PBX utilizes a large crossbar switching network with electronic common control. It can serve medium to large service needs and, in many cases, offers an attractive alternative to the bulky step-by-step systems previously used for this market.

The 101-type PBX, properly referred to as the No. 101 ESS, utilizes time division switching units located at customer premises. The system is unique in that the switching units are controlled by a stored program unit located at the serving central office. The control unit is capable of operating several independent switching units for different PBX customers at different locations. Service requirements of the various customers may differ considerably in terms of the size of the installations and of the specialized features that can be provided. The control and switching units are interconnected by a data link. Switch unit sizes range from one serving a maximum of 340 station lines to one serving as many as 4000 station lines. System application is limited to one large or several smaller customer locations that require service in an area served by the same central office.

The CSS201 is designed to provide economically a wide range of features that have evolved in business communications systems. It is a versatile all-electronic customer switching system called the Dimension\* PBX. It is capable of serving up to 2000 station lines depending on the traffic load. It uses stored program control executed by a special-purpose minicomputer and time division switching [3, 4]. Development of systems of larger capacity is continuing.

\*Trademark of AT&T Co.

A family of systems, coded in the SS300 series (SS300, SS301, . . .), is used to provide a wide range of private switching and transmission services for the specialized needs of a number of U.S. government departments and agencies. A few general features are of interest. The SS300 system, for example, is a switching arrangement that uses crossbar switches in a nonblocking network array. It provides flexible and switchable circuit arrangements between Federal Aviation Administration (FAA) air traffic control positions and remote locations that permit direct communication by radio with aircraft in flight. The system accommodates several hundred control positions. The SS301 system is more nearly like a key telephone system that provides the same type of service for up to 40 control positions.

Other systems in the SS300 family provide switched access arrangements that can be used for conferencing among several hundred stations that may be widely scattered. Special distribution amplifiers are used in a conference bus-bar circuit to assure satisfactory transmission performance. Several other smaller conference arrangements are also provided by these system types. The SS310 system provides two- or four-wire switching of private line circuits. It is used for crew dispatching by maintenance organizations of power companies and for truck dispatching by large trucking organizations.

**Direct Dialing Services.** The introduction of direct distance dialing in the switched message network led to the provision of new features in PBX services. Two significant features that have resulted are the capability of direct inward dialing (DID) to a PBX station without attendant assistance and direct outward dialing (DOD) over the switched message network with automatic identification of outward dialing (AIOD) by PBX stations for billing of long distance calls.

These features and many more are provided by some PBXs and by central office switching machines that provide a service called centrex. For centrex service, the operator console or switchboard is usually located at the customer premises. The switching equipment may be dedicated to centrex service or it may be a portion of the serving central office switching machine. Central office switching equipment that can provide centrex services includes the No. 5 Crossbar System, and No. 1 and No. 2 ESS. The DID and AIOD service features can be provided by the 701, 770A, 812A, and CSS201 PBXs and by No. 101 ESS where these systems are served by central offices that provide outpulsing and automatic number identification (ANI). The stored

program mode of operation of No. 1 ESS permits a wide range of service features to be provided within complex arrangements of main and satellite central office switching machines and PBXs. Several forms of automatic (dial-controlled) call transfer services can be furnished.

In centrex service arrangements, each station line terminates directly at the central office switching machine. These arrangements involve a cost penalty that is dependent on the distances of the centrex stations from the central office as compared to the PBX-CO trunking used in ordinary PBX service. However, this penalty is offset by the fact that with centrex arrangements, there is no switching equipment at the customer premises; thus, maintenance is more convenient and less costly and much less customer premises floor space is required. In general, the centrex arrangements appear more attractive where a customer is located close to the central office.

**Attendant Facilities.** With most PBXs, there are attendant consoles or cord switchboards operated by a customer employee or employees. These attendant facilities are usually located at the customer premises, even when the switching equipment is located at the central office. The attendant answers and completes incoming calls routed to the customer directory number and provides operator assistance to the PBX station users as required. In a network that contains main and satellite PBXs, the main PBX attendants serve the satellites by way of tie trunks. There are no attendant facilities at satellite PBXs.

There are many types of operator consoles used for these attendant services. The selection must be based on the number of lines and trunks involved and on the desired operating features. In console operation, as contrasted with cord switchboard operation, the attendant connection can be held, if necessary, for monitoring but is broken in most cases after the attendant has established the desired through connection.

### **Transmission Considerations**

Many aspects of transmission in PBX installations are similar or identical to those found in central offices. The same care in design, manufacture, installation, and operation must be exercised in respect to direct and multiple wiring layouts, trunk and line circuits, switching network organization, and office cabling as in similar central office

situations. However, there are a number of ways in which PBX transmission problems differ significantly from those found in central offices.

Central office and PBX transmission problems differ primarily because, as previously mentioned, PBXs can often be regarded as comprising additional (sixth and seventh) levels in the switched message network hierarchy and because of PBX service features that are not normally associated with message network services. Included are problems such as those relating to the design and layout of private switched networks and the circuits that are used in these networks. These circuits, which have counterparts in the message network, provide communication channels for the added network levels; examples are PBX-CO and PBX tie trunks, on- and off-premises station lines, and trunk and operator circuits for attendant facilities. Most PBX transmission problems are discussed in Volume 3 [1].

In some installations, PBXs provide service to a specific group of stations that are essentially collocated while in others, the PBXs are interconnected as parts of tandem tie trunk networks or switched services networks. These may be very large and the trunks between PBXs must be designed to meet transmission requirements according to the same general criteria, such as the via net loss design, as those applied to the message network. The establishment of suitable objectives is further complicated by *universal service connections* which permit the interconnection of the private switched network and the message network but with certain restrictions designed to facilitate the maintenance of an acceptable grade of service. Another somewhat similar complication is introduced in providing centrex and PBX-CO services. Connections that are routed through the PBX attendant facilities may involve up to three intermediate tandem loop facility links, instead of one, before a connection is finally established between a message network trunk and a PBX station line. Design objectives must include the losses of the extra links. In order to meet loss and return loss objectives in private switched networks, it may be necessary to provide four-wire trunks, terminal and through balance in the switching machines, and switchable pads on many trunks and access lines. Transmission circuits for PBXs are now designed to have a nominal impedance of 600 ohms. This provides a closer match to PBX station set impedances than the previous value of 900 ohms and thus improves transmission performance on network connections by reducing talker echo.

The design of transmission circuits associated with attendant facilities presents additional challenges. These circuits must not introduce excessive loss or degrade echo performance by reducing return losses. In addition, they must not introduce excessive transmission contrast for attendants or other network users and they must provide satisfactory sidetone performance for the attendant console or switchboard. Sidetone objectives are similar to those established for auxiliary services in the switched message network [5].

In addition to the network and trunk aspects of PBX services discussed above, transmission performance is significantly affected by station lines and the interactions between station lines and network connections such as private network access lines, PBX-CO trunks, FX trunks, and WATS trunks.

The transfer of battery and ground connections encountered in switching system sequences has an added impact in PBX operation. Signalling and transmitter current may be fed from one of several points in the central office, from some part of the PBX switching machine, or from the attendant console or switchboard. These changes of battery connections can result in transmission degradation if they are not well controlled in design. Impedances may vary widely causing changes in echo performance; transmission contrast may be excessive; transmission quality may be affected by changes in battery supply voltage, the resistance of the battery feed circuits, and the resulting changes in transmitter current supply.

Typically, battery feed circuits are based on 48 volts and 800 ohms or 24 volts and 400 ohms. These supply circuits are based on maintaining a transmitter current of  $50 \pm 15$  milliamperes. Departures from the nominal value are caused by variations in loop length and tolerances on supply voltage and circuit constants. In worst cases, the current should be held to a minimum of about 23 milliamperes and a maximum of about 90 milliamperes.

### 8-3 CALL DISTRIBUTORS AND TELEPHONE ANSWERING SYSTEMS

Incoming calls from the switched message network constitute most of the traffic for these systems. These calls terminate at an attendant console or switchboard and only a small percentage are extended beyond the attendant position. Transmission problems at the terminating positions for these systems are similar to those involved in

incoming service to a PBX operator position. Central office connections are by way of trunks similar to PBX-CO, foreign exchange, and incoming WATS trunks. Attendant circuits are like those used at PBX switchboard or console positions.

The switching functions performed by an automatic call distributor (ACD) provide service approximately according to the sequence of arrival of calls and distribute the calls among available attendants equitably so that the efficiency of the group of attendants is maximized.

Automatic call distributors are widely used by telephone companies to provide auxiliary operator services such as directory assistance and call intercept services [5]. Similar services are also supplied commercially for such business customer applications as airline or railroad reservation bureaus and department store catalog departments. The types of equipment used for commercial applications are different from those used for telephone company services. Installations range in size from about 10 operator positions to 500 or more. Most are in the 10- to 100-position range.

While incoming calls are seldom extended beyond the attendant position, provision is usually made for attendant origination of outgoing calls and reception of other than ACD calls. These features, usually needed so that an attendant can obtain information necessary for the proper servicing of the incoming calls, are provided through an associated PBX. Provision is also made to extend calls under overflow or night transfer conditions and for call transfer.

Commercial ACD service is provided by a number of systems. The 2A ACD uses standard crossbar switches and provides for up to 56 incoming trunks and 60 attendant positions; the 2B ACD, using a small crossbar switch, provides for up to 68 incoming trunks and 70 attendant positions. Up to three 2B ACDs can be combined and operated to expand the size of the attendant group; the expanded 2B can serve up to 180 attendant positions depending on the traffic pattern. It can also be arranged to forward overflow traffic to another ACD when the offered load cannot be adequately handled. Both the 2A and 2B can provide announcements on queued incoming calls to assure waiting callers that they will be answered if they continue to wait.



The 3A ACD is a step-by-step switching arrangement that can provide for up to 198 incoming trunks and 200 positions. Several 3A systems can be combined and load balanced to provide up to 600 positions. The 3A can provide for the diversion of overflow traffic to a distant ACD, can be arranged to allow for several independent groups of attendant positions, and (like the 2-type ACD) can provide announcements on queued incoming calls.

The 4A call distributor is designed for smaller applications than the 2- and 3-types. It provides for up to 20 incoming trunks and 15 attendant positions. It does not automatically distribute incoming calls to attendant positions. The calls are received at console positions at which the flashing rates of the call indicators are varied to indicate the queue priority to the attendants.

Automatic call distributor facilities are sometimes used to provide centralized attendant service for several PBXs. Calls that require attendant service at any of these PBXs are routed over release link trunks to the ACD. When the attendant determines the required disposition of the call, this information is feed into the machine; after the proper connection is established, the link to the attendant is released.

Automatic call distributor services can now also be furnished to relatively simple attendant positions by appropriate programming of No. 1 and No. 2 ESS central office switching machines. This is a specialized version of centrex service applied primarily to incoming call distribution to the attendant positions.

Telephone answering service is provided by organizations whose principal functions are to receive incoming calls for telephone customers, record messages, and relay the messages to the customers at a later time. There is little or no provision for switching or interconnection among the circuits that terminate at a telephone answering system position. The telephone connection for each client usually has just one appearance at the attendant switchboard or console.

There are several methods of making connections to the attendant switchboard or console position, as shown in Figure 8-4. The most common is a simple bridging arrangement as shown at A in the figure. In this arrangement, the connection to the attendant position is a bridged tap on the normal loop analogous to an off-premises extension line. A bridge lifter is used to isolate the leg not in use thus minimizing transmission impairment. In some cases, the incoming

line (B) appears only at the attendant position; in this arrangement, the connection is analogous to a PBX-CO trunk that is not extended to a PBX station line. The third arrangement, shown at C, is used when the system is served by a central office that is remote from the serving office of the attendant position. In this arrangement, the connections between the two offices may involve concentration at the distant office and expansion and identification at the serving office. The connections in this case are analogous to foreign exchange trunks.

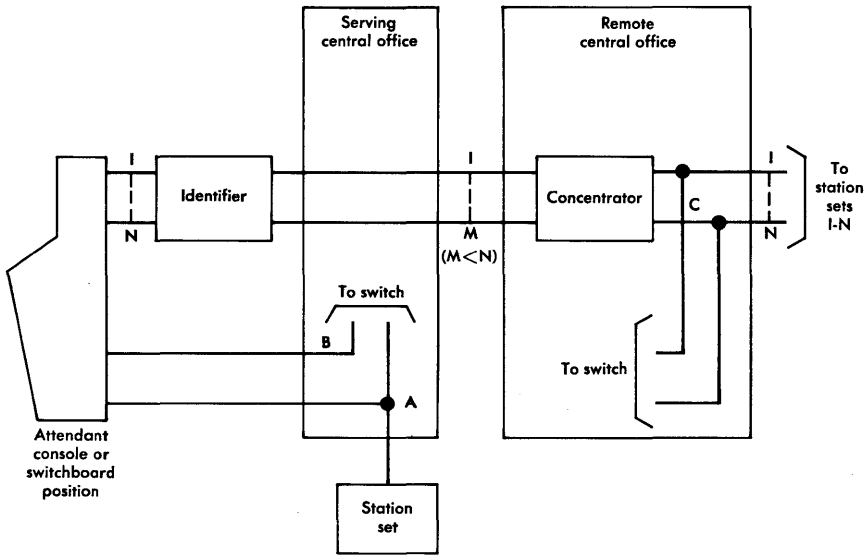


Figure 8-4. Typical telephone answering system serving arrangement.

Several types of switchboard and console arrangements are available for telephone answering services. The 557A is a double-ended cord switchboard that is not much used. It combines regular PBX service and answering service. The 557B, a single-ended cord switchboard, is more commonly used. The 1A TAS console features push-button answering of incoming calls. Though no longer manufactured, a number of 1A consoles are still found in service. In some cases, key telephone equipment is used, especially for small installations.

In all cases, the telephone answering service equipment can be furnished in flexible arrangements that may involve a single attendant position or may involve as many as 20 or more positions. Typically, a three-position installation can serve most answering service needs.

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**Telecommunications  
Transmission  
Engineering**

*Section 3*

*Analog Carrier Systems on Metallic Media*

The technology that has evolved from the invention and development of electron tube and solid-state devices has made possible increasingly wider bandwidths for wire-pair and coaxial cable transmission. The resulting broadband analog transmission systems have required the development of modulation and multiplex equipment capable of combining large numbers of voice-frequency channels into a single broadband channel by frequency division multiplex techniques; i.e., each channel is assigned a separate portion of the broadband channel. Increased demands for service have brought about a significant increase in the total cost of transmission facilities; however, with the increased efficiency of utilization of transmission media that has been achieved by the application of electronic techniques, the cost per channel-mile has steadily decreased. These analog systems have been used primarily to satisfy trunk requirements. Subscriber loop applications are covered in Chapter 3.

The long-haul, high-capacity wire pair and coaxial transmission systems created the initial pressure for the development of suitable multiplex equipment. The organization of this equipment has evolved into a hierarchy of multiplex capability ranging from a 12-channel group to a spectrum of 13,200 channels for a fully equipped L5E Coaxial Transmission System. Many of the multiplex arrangements are also used with microwave radio systems. The various types of multiplex equipment and their channel capacities are described in Chapter 9.

Broadband analog transmission systems are designed to satisfy certain signal-to-noise requirements over specified bandwidths. The spacing between repeaters is an important parameter that depends on bandwidth and signal-to-noise objectives as well as on achievable circuit designs. The relationships among these parameters are dis-

cussed in Chapter 10 in general terms that may be applied to any broadband analog cable transmission system.

The general principles of analog cable transmission system design are covered in Chapter 10. In Chapter 11, the design of analog systems for use on open-wire lines and wire cable pairs is described. The principal systems involved are the O-type systems for use on open-wire lines and the N-type systems for use on cable pairs. Each type of system utilizes multiplex equipment designed especially for system compatibility. As the use of open-wire lines declined, it became desirable to adapt terminals designed for O-type systems to cable pair systems. Equipment designed for this purpose, called ON type, is also described in Chapter 11. Chapter 12 discusses the design of coaxial cable transmission systems. General characteristics of each are described and a detailed description of the latest designs, L5 and L5E, are presented.

## Chapter 9

# Frequency Division Multiplex

The development of broadband analog cable and microwave radio transmission systems has been, of necessity, accompanied by the development of multiplex equipment capable of providing efficient bandwidth utilization of the medium. In some cases, the multiplex equipment bears a unique relationship to and is really a part of the transmission system with which it is associated; these multiplex terminals are discussed with the systems of which they are parts. In other cases involving coaxial cable and microwave radio systems, the multiplex arrangements have evolved in a hierarchical manner and can be regarded as a terminal multiplex system.

Frequency division multiplex (FDM) equipment is composed of a complex assortment of oscillators, modulators, demodulators, amplifiers, pads, hybrid coil circuits for combining and splitting transmission paths, and filters. The circuits and equipment that are used have evolved with new technology and with new transmission systems. The basic group of twelve 4-kHz channels in a frequency band of 60 to 108 kHz was established for J- and K-type carrier systems in the 1930s. The multiplex hierarchy has since expanded to include equipment for the 13,200 channel spectrum that forms the line signal for the expanded L5 Coaxial System, L5E.

A number of different combinations of multiplex units have been used to provide signal spectra for coaxial cable and microwave radio systems. In addition, a 600-channel, FDM signal has been used to drive a coder/decoder which converts the composite analog signal to a pulse code modulated signal for transmission over a high-speed digital transmission system. This equipment provides a useful inter-

face between frequency division and time division multiplex hierarchies and offers a means of interconnecting broadband analog and high-speed digital transmission systems.

The modulating and multiplexing processes that are used to assemble a broadband, multichannel signal are reversed at receiving terminal points where individual signals must be recovered so that each may be routed to its destination. In many cases, modulating and demodulating circuits are combined in one unit designated as a *modem*.

## 9-1 THE FDM HIERARCHY

Many variations of the FDM hierarchy have evolved to serve the changing needs of coaxial and microwave radio systems as they have been developed to provide ever wider bandwidths. Economic and operational pressures have also been imposed to make more efficient use of available bandwidths in existing systems. Each step in the process of FDM evolution was built upon and utilized existing equipment designs in order to achieve timely and economical terminal arrangements for new transmission systems.

Figure 9-1 shows schematically how one form of the FDM hierarchy is derived by means of five separate frequency translations each of which places signals at higher frequencies and in larger groupings. In this arrangement (for purposes of discussion called the basic plan), the input and output frequency bands of each block of equipment is designated (except the initial input and final output) as a *basic* grouping of channels. For example, the outputs of channel banks and the inputs to group banks are known as *basic groups*. Each is a block of 12 channels occupying the band from 60 to 108 kHz. Similarly, groupings at other points in the hierarchy are the *basic supergroup* (60 channels placed between 312 and 552 kHz), the *basic mastergroup* (600 channels in the band from 564 to 3084 kHz), and the *basic jumbogroup* (3600 channels in the band from 564 to 17,548 kHz). The outputs at any level in the hierarchy may be used totally or partially as a line signal or as a portion of a line signal feeding a broadband analog transmission system.

Four-wire transmission is used throughout the FDM equipment. The four-wire paths are provided over balanced shielded pairs or coaxial cable depending on requirements imposed by the frequency band at each point in the hierarchy. However, in many cases 4-kHz

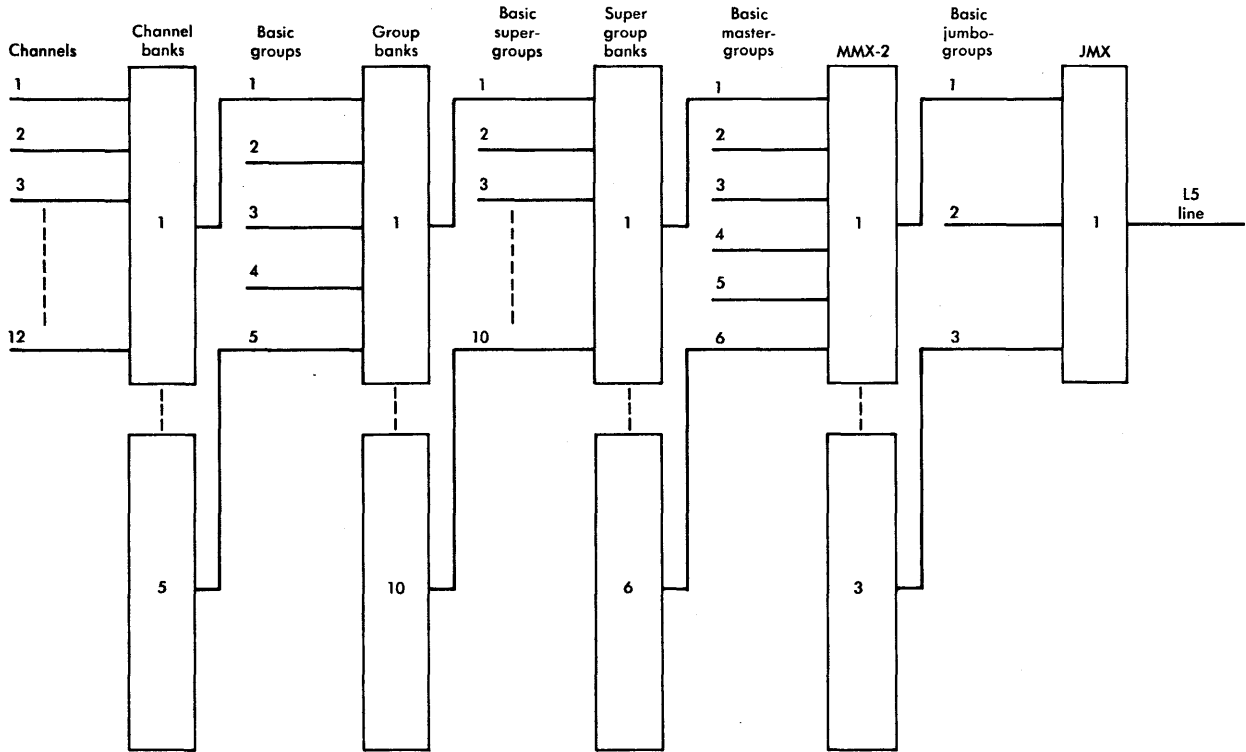


Figure 9-1. Basic FDM hierarchical plan.



channels connected to the multiplex are two-wire. The necessary interface equipment, in the form of four-wire terminating sets, E- or F-type signalling units, etc., is provided as individual units or as facility terminal units which integrate all needed functions in a single assembly with plug-in units.

### Channel Banks

Two designs of channel bank are now in general use in the Bell System. Although the A5 is found in large quantities throughout the plant, the A6 is the newest design available and has superseded the A5 in new installations. The two designs are completely compatible; i.e., circuits operate satisfactorily with an A5 bank at one end and an A6 bank at the other.

A third design, not called a channel bank although it performs similar functions, is the direct formed supergroup bay. It combines 60 voice-frequency signals into a supergroup spectrum without intermediate group level modulating and multiplexing stages.

**The A5 Channel Bank.** Early channel bank designs utilized electron tubes for amplification, a copper oxide shunt varistor bridge as a modulator, and filter elements that limited performance. The A5 channel bank was a redesign that represented a significant advance [1]. It was the first large-scale equipment item in the long-haul plant of the Bell System to use transistors. The modulating elements followed earlier designs in using copper oxide but these elements were subsequently replaced by solid-state diodes. Filters represented design advances in the use of ferrites for magnetic devices, mylar capacitors, and synthetically grown quartz crystals.

A block diagram of the transmitting portion of the A5 channel bank is given in Figure 9-2. The speech signal modulates a carrier for translation to the assigned frequency band in the group spectrum. At the output of the modulator, the resulting double sideband signal is passed through a highpass filter to suppress any voice-frequency energy that may have passed through the modulator and a bandpass filter to suppress upper sideband signal components and any carrier signal that may have leaked through the balanced modulator. Thus, only lower sideband components are retained to be combined with eleven other such signals, each in a different portion of the group spectrum. The figure also shows the carrier frequency for each channel, the lower sideband signal allocation for each channel, and the channel numbering sequence that is used.

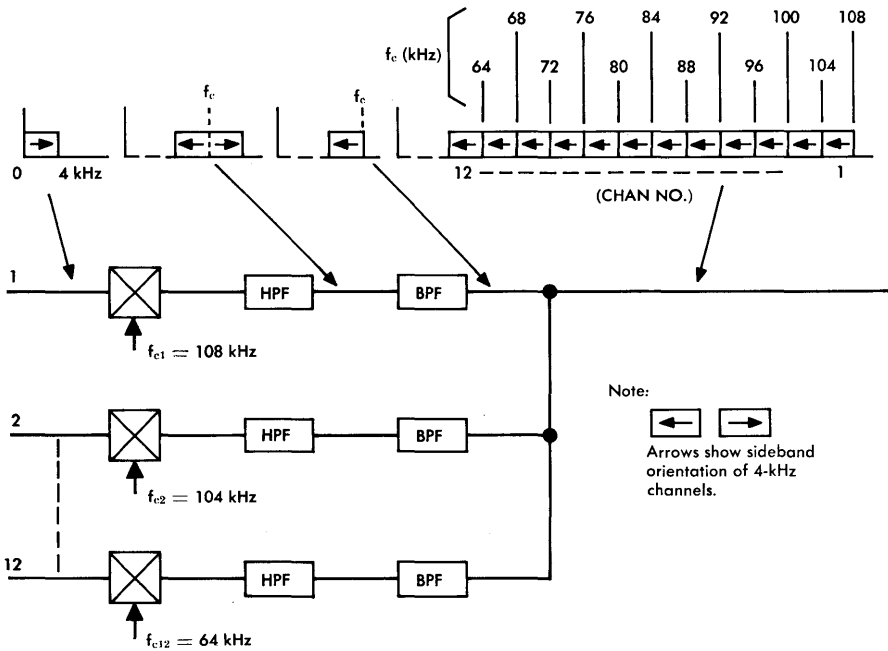


Figure 9-2. Transmitting A5 channel bank block diagram and channel number assignments.

The A5 channel bank represents improvements over previous designs in respect to its smaller size, superior gain stability with time, improved attenuation/frequency response and nonlinear distortion performance, better maintenance accessibility, lower power consumption, and longer life. It has been the standard analog channel bank in the Bell System until the introduction of the A6 channel bank.

**The A6 Channel Bank.** The addition of the A6 to the family of A-type channel banks represents another step in miniaturization, cost reduction, and adaptation of new technology. Input and output signal spectra are identical to those associated with the A5 channel bank to provide end-to-end compatibility of the two designs.

A block diagram of the A6 bank is shown in Figure 9-3. Note that the group band is formed by two steps of modulation. The first step places each channel in a preassigned frequency position near 8 MHz.

The channels are combined and then, in the second step of modulation, the entire group is translated down to the basic group frequency band. This two-step process was adopted in order to permit the application of a new design of channel filters using monolithic quartz crystals. These filters are more readily optimized at frequencies close to 8 MHz than at the basic group band frequencies as would be necessary if the A5 plan had been followed [2]. Other new technology used in the A6 includes a number of hybrid integrated circuits for amplifiers, pads, and other circuit elements [3].

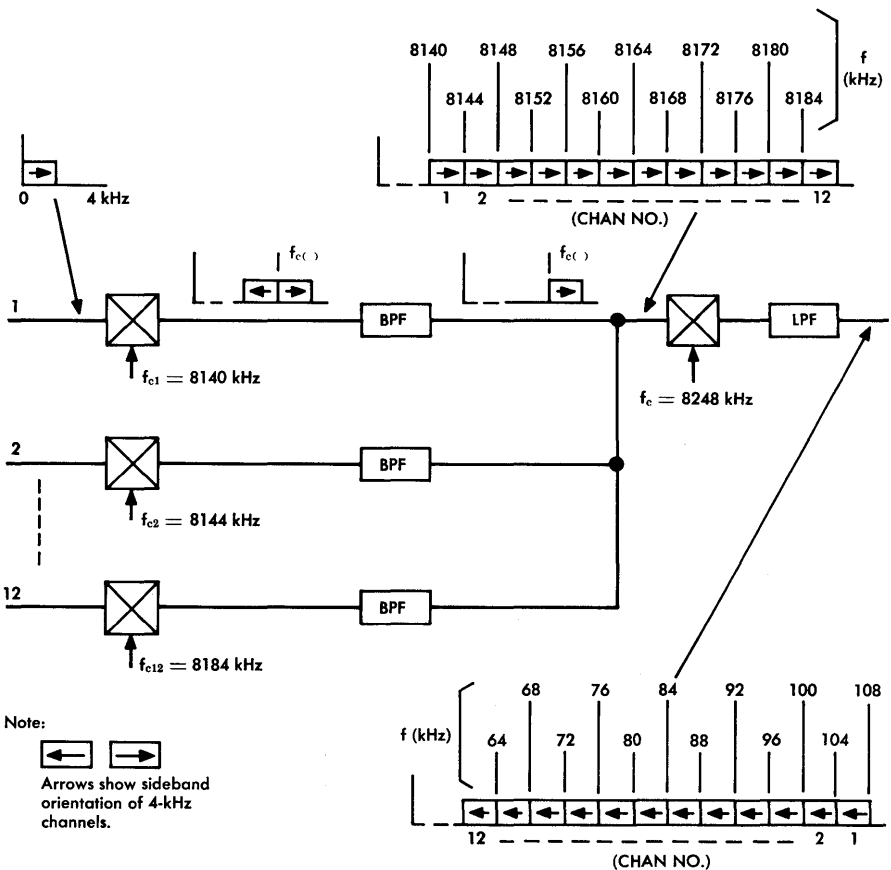


Figure 9-3. Transmitting A6 channel bank block diagram and channel number assignments.

Each of the twelve A6 input circuits is coupled to a modulator which is provided with a carrier in the range of 8140 to 8184 kHz. The double sideband output of each modulator is passed through a bandpass filter which selects the upper sideband. The twelve signals are combined to form a band from 8140 to 8188 kHz. This signal band is next passed through a second modulator driven by a carrier at 8248 kHz. The double-sideband modulator output signal is then filtered to select its lower sideband which is a signal spectrum between 60 and 108 kHz, identical to that at the output at an A5 channel bank.

**Direct Formed Supergroup.** Sixty voice-frequency signals may be combined directly to form a supergroup signal in the frequency band between 312 and 552 kHz. This direct formed supergroup (DFSG) may be used economically where the number of circuits originating in an office for transmission along the route approaches 60. In this application, group banks are not required. The signal spectrum and individual channel sideband orientation is identical to that of the basic supergroup. Thus, it is not necessary to have a DFSG at both ends of a channel. One end may use a DFSG and the other may utilize conventional group bank terminal equipment.

The modulation and multiplexing plan for the DFSG is similar to that used in the A6 channel bank. Twelve channels are modulated to the 8 MHz region and combined into a group band spectrum. The five group bands are then modulated into appropriate portions of the supergroup band. Thus, the DFSG combines the functions of the A6 channel bank and the group banks.

### Group and Supergroup Banks

Blocks of channels are combined in the next steps of the multiplex hierarchy to form 60-channel supergroups in a group bank and 600-channel mastergroups in a supergroup bank. The equipment now most commonly used for these functions is called the LMX-2 [4, 5]. A new version, the LMX-3, has been introduced and will supersede the LMX-2 [6].

One of the features of the LMX-2 and LMX-3 equipment that represents a departure from earlier designs is that of automatic gain regulation. Pilots are inserted in the transmitting equipment and picked off to control regulation loops in the receiving equipment after demodulation to basic supergroup and basic group frequencies.

**The LMX-2 Equipment.** Figure 9-4 shows how the group banks in the LMX-2 equipment are arranged to produce the 60-channel basic supergroup in the band between 312 and 552 kHz. The channel orientation is inverted in the process so that voice-frequency channels appearing as lower sidebands in the basic group appear as upper sidebands in the basic supergroup. Note that there is no space allowed in the spectrum between 4-kHz channels or between group bands. Filters designed to separate the 4-kHz channels must have very sharp cutoff characteristics in order to provide the necessary discrimination between adjacent VF channels and adjacent group frequency bands. The

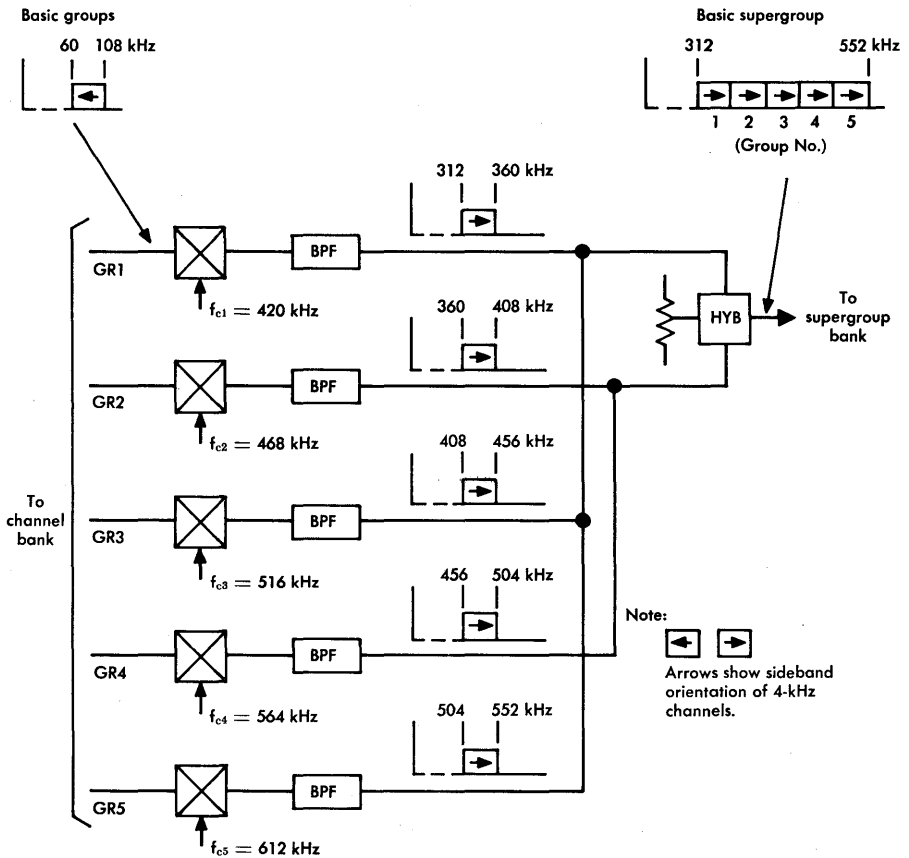


Figure 9-4. Transmitting group bank in LMX-2.

cutoff characteristics of these filters are responsible for the reduction of effective bandwidth from 0 to 4 kHz to about 0.2 to 3.4 kHz.

In order to facilitate the process of combining, the even-numbered groups are bridged together and the odd-numbered groups are bridged together. The even and odd groups are combined in a hybrid transformer, as shown in Figure 9-4. This arrangement minimizes impedance interactions where filter cutoff characteristics overlap.

The transmitting supergroup bank is shown in Figure 9-5. One notable feature of the arrangement is the supergroup numbering which covers the ranges 13 to 18 and 25 to 28. This unusual numbering scheme is a result of the way in which the multiplex evolved. In each of the numbered sequences, the second digit corresponds to a supergroup number taken from the original L600 multiplex hierarchy. The first digit in each of the sequences refers to the *submastergroup* designations. There are frequency spaces (often called guard bands) of 8 kHz between most pairs of supergroups. The guard band between supergroups 18 and 25 (submastergroups 1 and 2) is 56-kHz wide. The band was initially provided to facilitate separating the two submastergroups and to provide for the transmission of a line pilot for carrier system regulation.

The supergroups are combined at the outputs of the bandpass filters in a manner similar to that used for combining groups. The even-numbered supergroups and the odd-numbered supergroups are each bridged together and then the two circuits are combined in a hybrid transformer. The composite signal forms the basic mastergroup designated U600 (U for universal). The U600 is the standard format used on most microwave radio and coaxial cable carrier systems.

**The LMX-3 Equipment.** This new design of multiplex equipment is fully compatible with existing designs that utilize the U600 frequency allocations; i.e., systems may be operated with LMX-2 equipment at one end and LMX-3 equipment at the other end. The new equipment features significant reductions in space, power consumption, and cost. In addition, it provides better access arrangements for test and maintenance, is organized for logical and economical service growth through more extensive use of plug-in units and minimally equipped shop-wired bays, and includes several new distributing frame designs.

The LMX-3 equipment may be combined in various ways to provide the most economical arrangement required for each installation. This flexibility is achieved by making several optional preassembled and

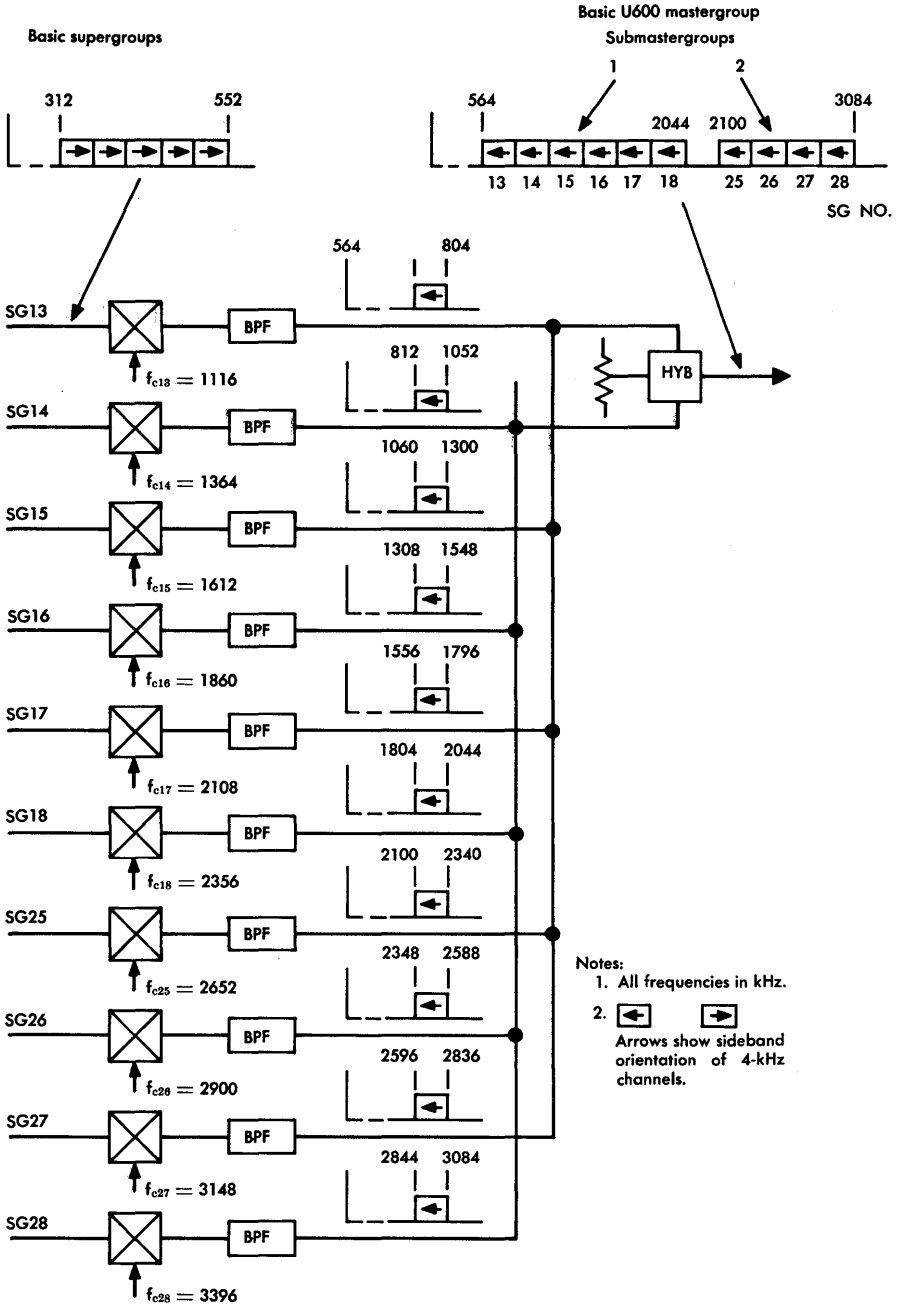


Figure 9-5. Transmitting supergroup bank in LMX-2.

prewired bays available. One bay design is made up entirely of group assemblies (group bank bay) with basic group inputs and basic supergroup outputs; another is made up entirely of supergroup assemblies (supergroup bank bay) with basic supergroup inputs and basic master group (U600) outputs. A combined bay, composed of group and supergroup assemblies to form one mastergroup, is also available. Most of the equipment for both group and supergroup assemblies is contained in plug-in modems that provide modulators and demodulators, common carrier supply drive amplifiers, bandpass filters, and pilot regulating amplifiers. Each bay thus provides for both directions of transmission.

One of the guiding factors in the development of the LMX-3 was the recognition of the large amount of work carried out in the field in respect to circuit installations and rearrangements. It has been estimated that the assignments of 50 percent or more of the groups are changed each year. Large numbers of supergroups and mastergroups assignments are also changed each year. Thus, the multiplex hierarchy, as illustrated in Figure 9-6, can be regarded as an extremely slow-speed switching system. The switching function requires considerable time and effort when carried out by wiring and cabling changes.

This point of view has led to the provision in LMX-3 of improved group and supergroup distributing frames and a new mastergroup distributing frame as shown in Figure 9-6. These frames are each designed with access points having equal transmission level points to permit simple, in-service rearrangements without readjustments. Changes can be made much more quickly than in any previous design.

The mastergroup distributing frame is arranged for direct application of the Carrier Transmission Maintenance System (CTMS). Access points are also provided to make mastergroups available for emergency broadband restoration purposes.

The performance of the LMX-3 equipment equals or surpasses that of predecessor systems in all respects. The most significant improvement is the reduction of spurious single-frequency interferences. There are also other improvements that affect maintenance activities and costs. For example, a large improvement in overall reliability has been achieved and the ranges of group and supergroup regulators have been increased.



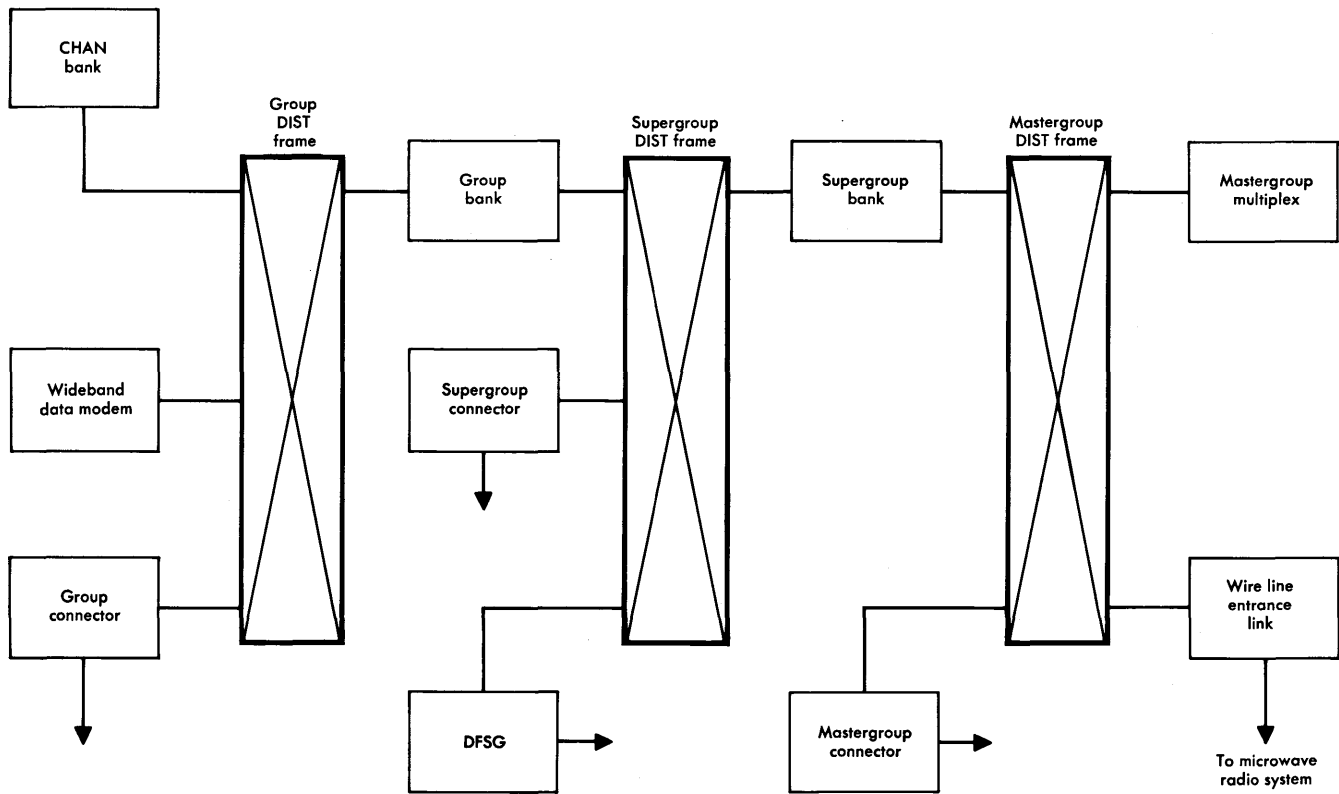


Figure 9-6. The FDM as a switching hierarchy.

The equipment designs are compatible with new building design requirements. All LMX-3 bays are designed to 7-foot bay heights; provision is made for bay extenders so that, where used in buildings with high ceilings, the extended bay space may be used for miscellaneous equipment mounting. Heat dissipation is controlled so that no forced cooling is required. The successive designs of multiplex equipment have all had floor space savings as a primary objective and LMX-3 units are from three to six times smaller than LMX-2 counterparts.

**The L600 Mastergroup.** This multiplex arrangement, shown in Figure 9-7, utilizes standard groups to form 60-channel supergroups. The L600 mastergroup evolved from the early needs of the L1 Coaxial Carrier System which was designed for 480 channels. When the performance of L1 was shown to be adequate, two additional supergroups were added above the original eight. It was this arrangement that led to the numbering of supergroups from 1 to 10.

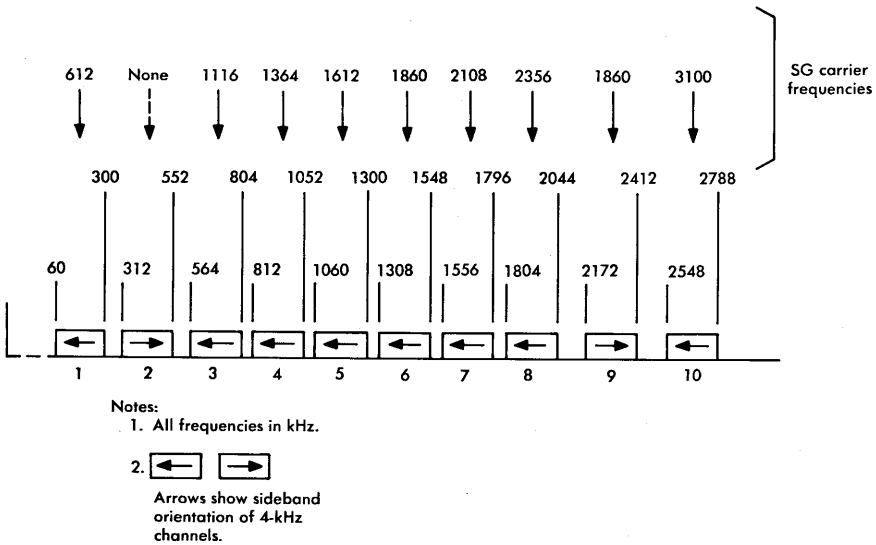


Figure 9-7. Frequency allocations for L600 mastergroup.

Output signals of the type developed by the L600 multiplex are sometimes used to feed TD-2, TJ, and TM/TL microwave radio systems. The U600 multiplex arrangement is now used with transmission systems capable of carrying 600 channels or more. This mastergroup is considered standard; however, much L600 equipment

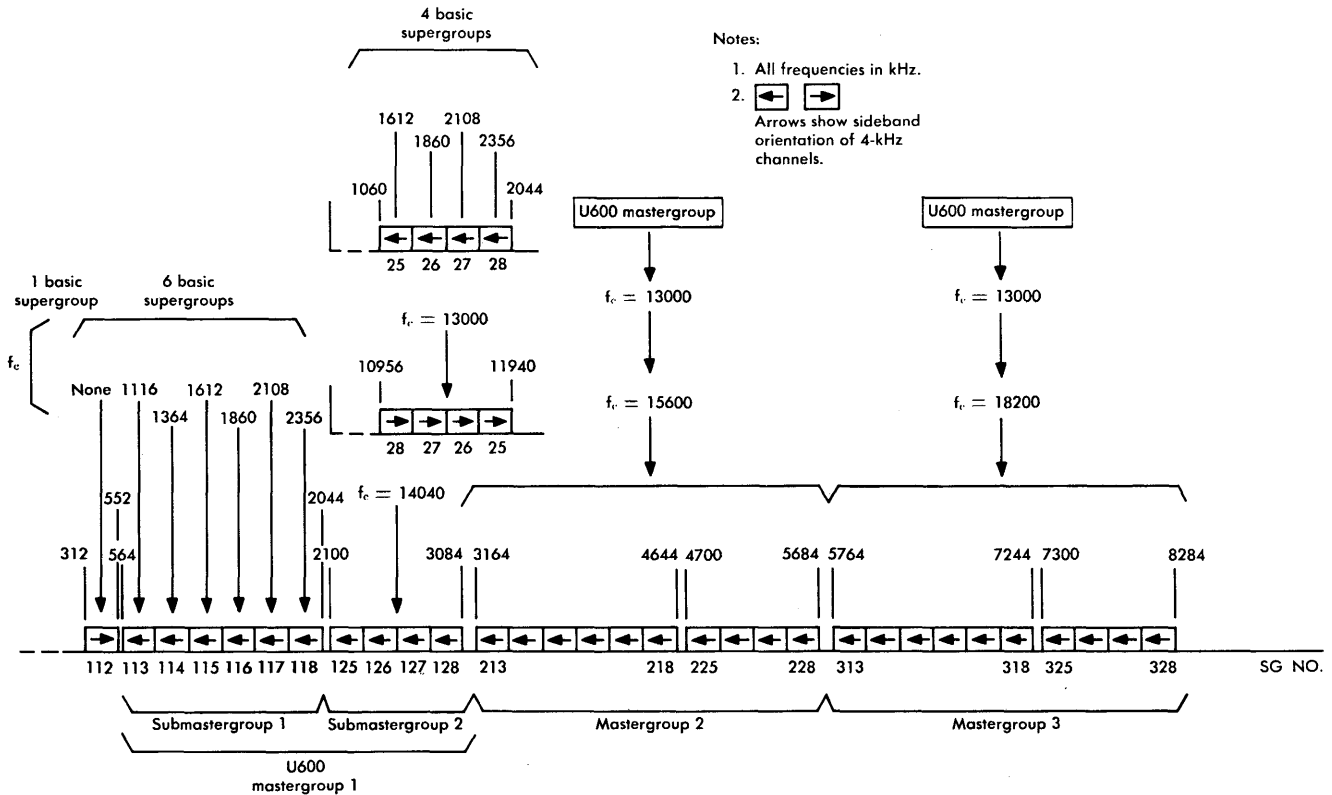
remains in service. Where "data-under-voice" arrangements are used on microwave radio systems, the L600 multiplex spectrum cannot be used and the U600 spectrum is usually provided.

An increasing number of 2-GHz common carrier radio channels are being made available to the Bell System. Supergroups 1, 2, 3, and 4 of the L600 arrangement can be used economically to serve systems that utilize these radio channels. To provide this capability, LMX-3 equipment is being made available to supply the L600 or portions of the L600 frequency spectrum. This equipment is compatible with the earlier L600 design.

### The Mastergroup Multiplex

A number of multiplex arrangements are available to translate and combine U600 mastergroup signal spectra for transmission over broadband coaxial and microwave radio systems. While there is still a significant amount of MMX-1C (cable) and MMX-1R (radio) in the plant, the equipment now most commonly used is the MMX-2C and MMX-2R. The latest designs, called mastergroup translators (MGT-A, MGT-B, and MGT-AT), are available or in development to satisfy a number of coaxial cable and microwave radio system needs.

**Mastergroup Multiplex, MMX-1.** The MMX-1 was developed initially to serve the needs of the L3 Carrier System; in addition, it is widely used to furnish baseband signals for multimastergroup microwave radio systems. As shown in Figure 9-8, six basic supergroups are modulated individually and combined to form submastergroup 1, a spectrum of signals from 564 to 2044 kHz. Four other basic supergroups are similarly modulated and combined to form submastergroup 2 in the spectrum from 1060 to 2044 kHz. Submastergroup 2 is further translated in two steps of modulation and placed in the spectrum between 2100 and 3084 kHz; it is then combined with submastergroup 1 to form the complete U600 mastergroup. Three such mastergroups are formed at basic mastergroup frequencies. One remains as a basic mastergroup, the second is translated in two steps of modulation to fall in the spectrum between 3164 and 5684 kHz, and the third is similarly translated in two steps of modulation to the spectrum between 5764 and 8284 kHz. These three mastergroups and an additional basic supergroup are then combined to form the L1860 spectrum. There are no mastergroup pilots in this spectrum since neither gain regulation nor protection switching is used in MMX-1.





- Notes:
1. All frequencies in kHz.
  2.    
Arrows show sideband orientation of 4-kHz channels.

Figure 9-8. Derivation of L1860 spectrum.

The 3-digit numbering system shown in Figure 9-8 was adopted to identify each supergroup. The first digit represents the mastergroup number and the second digit the submastergroup number. The third digit represents the supergroup number in the L600 spectrum. Elements of this numbering system have been retained in later designs but the frequency translations of submastergroup 2 as an entity is used only in MMX-1.

**Mastergroup Multiplex, MMX-2.** This equipment provides a step in the FDM hierarchy but it is not a part of the L-type multiplex. The MMX-2 was designed initially to provide the line frequency signal for the 3600-channel L4 carrier system [7]. It was later adapted to provide a baseband line signal spectrum for microwave radio systems.

Figure 9-9 is a block diagram of the transmitting MMX-2. In this arrangement, the usual combination of signal input, modulator, and bandpass filter is supplemented by a protection switching arrangement, not shown in the figure, which requires the insertion at the input of a 2840-kHz mastergroup pilot. The pilot is picked off at the output and detected. Loss of pilot produces a dc voltage on the control lead to the switch which operates to transfer service to the spare equipment. One spare and associated switching is arranged to protect three working circuits. Provision has been made to operate the transmitting equipment without the switching feature and to modify existing equipment to eliminate the switching feature where unprotected operation is desired.

The MMX-2 terminal is provided with many test access points and patch jacks that permit very flexible use of the circuits for maintenance and for emergency broadband restoration. The receiving circuits perform the demodulation function in a conventional manner. Three-for-one protection switching of the receiving circuits is accomplished in a manner similar to that used in the transmitter. The 2840-kHz pilot is used at the receiver for controlling the switching circuits and the mastergroup regulator circuitry. Switching arrangements may be disconnected or omitted.

**Mastergroup Translators.** Several designs of multiplex equipment have now been introduced to supersede the MMX-2 equipment. These designs incorporate individual self-contained mastergroup shelf mountings which permit more flexible and economical applications to transmission systems that require more than one mastergroup. These system applications include the provision of two mastergroups for

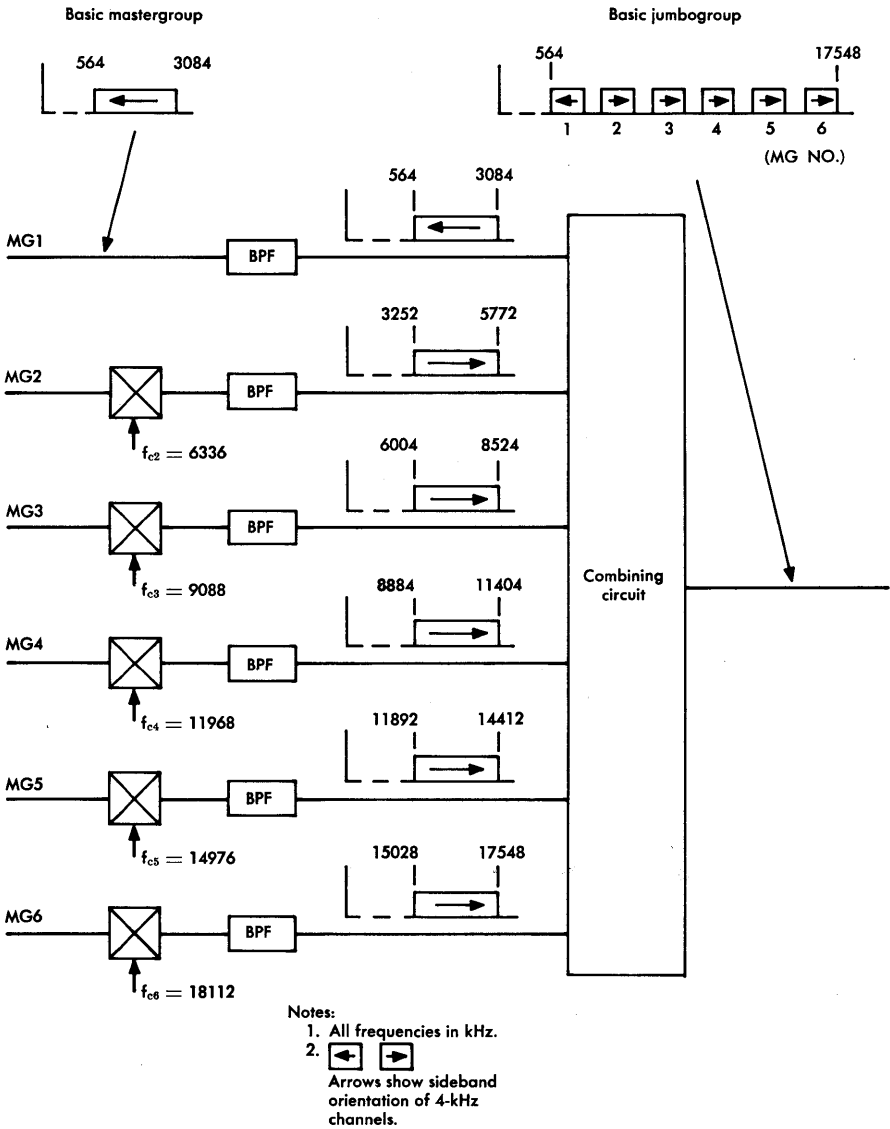


Figure 9-9. Transmitting MMX-2 terminal.

TM-, three for TD-, and four for TH-type radio systems. In addition, five mastergroups are combined for the AR 6A radio system, six mastergroups for the L4 Carrier System and the jumbogroup multi-

plex, and seven and eight mastergroups for the 22-mastergroup L5E Carrier System. Reliability of this type equipment has been such that costly protection switching arrangements are not required. Standby equipment, maintained in operating condition, may be patched into service if required for maintenance or for restoration of failed service.

Several designs of the new equipment are available. The first, called mastergroup translator, series A (MGT-A), provides a spectrum identical to that of the MMX-2. The inputs to the MGT-A are normally U600 mastergroups. However, it is possible to transmit an L600 spectrum in the first (lowest frequency) mastergroup position since it is not modulated to another frequency band. This feature permits the reuse of existing L600 equipment where frequency allocations are compatible with the transmission system bandwidth.

A second design, called MGT-B, translates the mastergroups to frequency spectrum positions such that the guard bands between mastergroups are a constant 168 kHz. This spacing, shown in Figure 9-10,

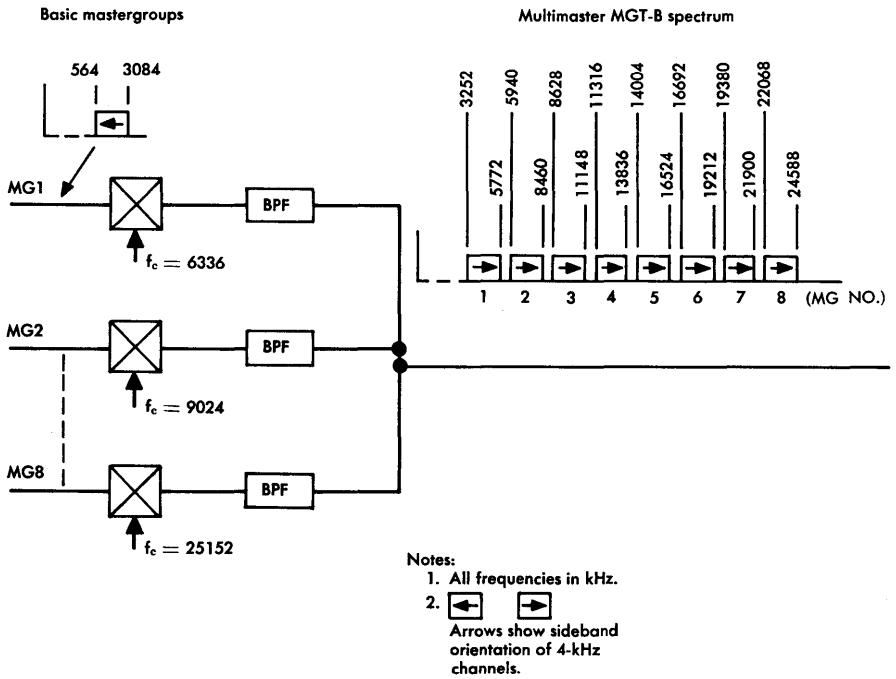


Figure 9-10. Formation of MGT-B spectrum.

makes more efficient use of the overall spectrum and makes feasible the transmission of a larger number of 4-kHz channel signals over the L5E Carrier System and over certain microwave radio systems. The MGT-B is somewhat less flexible than the MGT-A and precludes mastergroup branching except by demodulation to basic mastergroup frequencies.

A third design, for light-route terminating applications, utilizes the same frequency allocations as the A-series and is designated MGT-AT. It does not provide several of the features, such as squelch and regulation, found in other designs. As an option, redundant path transmission is provided to increase reliability. It is expected to be used often to terminate mastergroups at unmanned locations.

The mastergroup translator equipment differs in many respects from the MMX-2. Each MGT unit has built-in carrier and pilot generation, alarm, and dc power supply circuits. Frequency translation is performed by plug-in modulators and demodulators. These plug-in units also provide regulation and squelch functions. Mastergroup signal combining and separating are accomplished in a separate panel. The segregation of modulation and demodulation functions from signal combining and separating functions and the use of plug-in circuits results in an equipment arrangement that is much more flexible than that of the MMX-2 arrangements.

### Multimastergroup Multiplex Equipment

In the basic plan of Figure 9-1, multimastergroup translation is effected in equipment called the jumbogroup multiplex (JMX) [8]. This equipment, developed specifically for the L5 Carrier System, was used only in early installations. The channel capacity of the L5 system has been increased from 10,800 to 13,200 channels (L5E). This expansion required the development of new equipment called the multimastergroup translator (MMGT-C). Another multimastergroup translator, the MMGT-R has been developed for use with the AR 6A microwave radio system. The output signals of these translators have different spectra and the equipment provides a number of different features due to differences in the systems they serve.

**The Jumbogroup Multiplex.** While the general layout of circuits in the JMX follows a conventional pattern, there are a number of significant departures.



Three basic jumbogroups (18 mastergroups) are used as the input signals to the JMX as shown in Figure 9-11. Jumbogroups 1 and 2 are translated to their positions in the L5 spectrum by two steps of modulation. Jumbogroup 3 is translated to its position in the spectrum by three steps of modulation, the first two of which are identical to those used for jumbogroup 1.

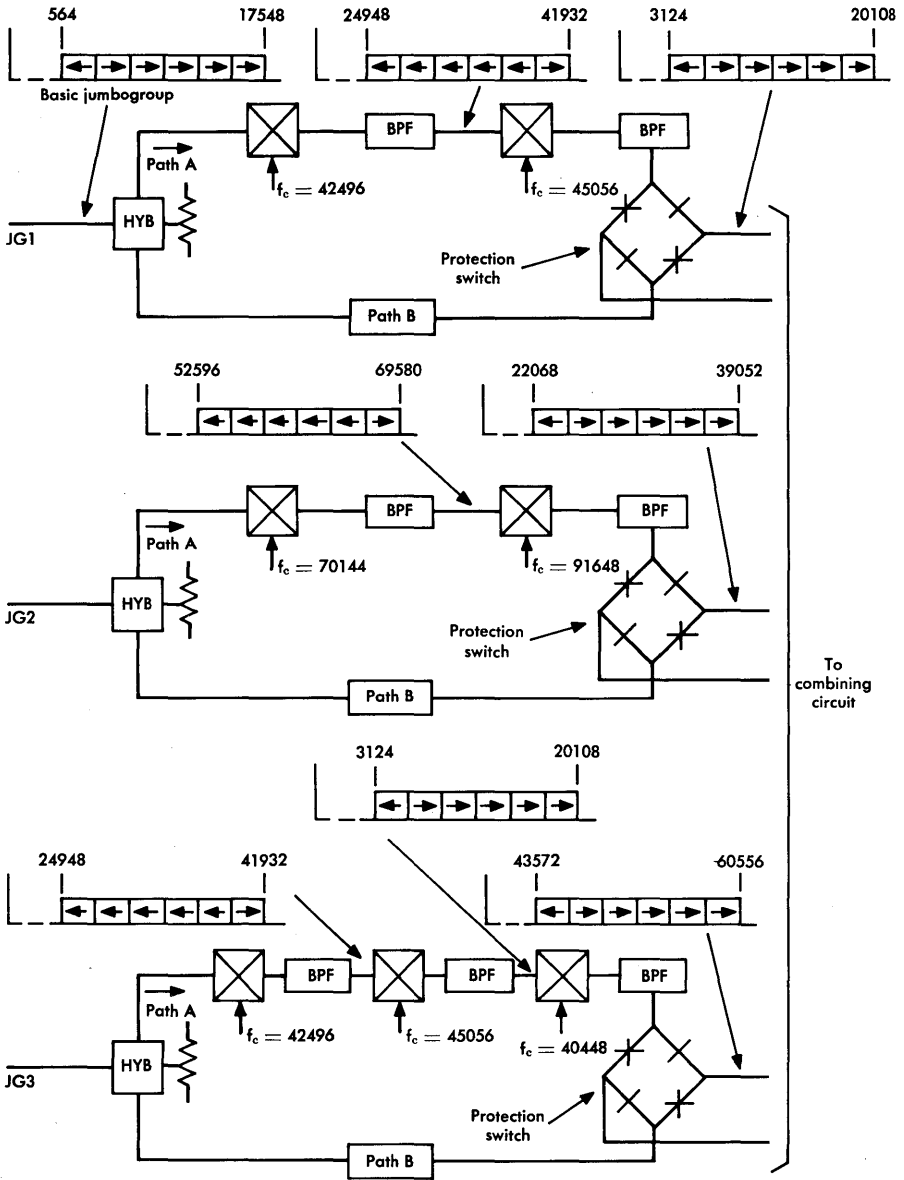
Protection switching is provided in the JMX by a spare path (B) for each working path. This mode of operation is used in order to simplify the switching circuits and logic. Each path is split by a hybrid transformer. A relatively simple transfer switch is used at the output of the two redundant paths, either of which may be selected. The two paths are made available, by circuits not shown in the figure, for emergency broadband restoration use.

The complete L5 line spectrum is not formed in the JMX. The three jumbogroups are carried in assigned frequency locations to line connecting equipment where they are combined for transmission over the L5 line. This arrangement is used in order to provide maximum flexibility in assembling the line signal.

Portions of the receiving JMX are illustrated in Figure 9-12. The complete paths of jumbogroups 1 and 2 are not shown since they are demodulated by circuits which follow the conventional pattern of performing the inverse of the transmitting circuit functions. Jumbogroup 3 which is formed by three steps of modulation in the transmitting circuits, is returned to the basic jumbogroup spectrum in one step of modulation in the receiver. Patterns of unwanted (interference) signals found in the transmitter do not appear in the receiver thus permitting the simpler mode of operation.

The L5 line signal is split into six independent paths in line connecting equipment. These signals are transmitted to the JMX equipment where bandpass filters select the appropriate jumbogroup. Switching arrangements in the receiver are similar to those used in the transmitter.

The gain of each basic jumbogroup is accurately regulated at the output of the receiving JMX. This is accomplished by the use of a 5888-kHz pilot which is added to the basic jumbogroup signal before it is applied to the JMX transmitting circuits. The pilot is removed by a band elimination filter at the JMX output.



Notes:

1. All frequencies in kHz.

2.  

Arrows show sideband orientation of 4-kHz channels.

Figure 9-11. Simplified schematic of the transmitting JMX.

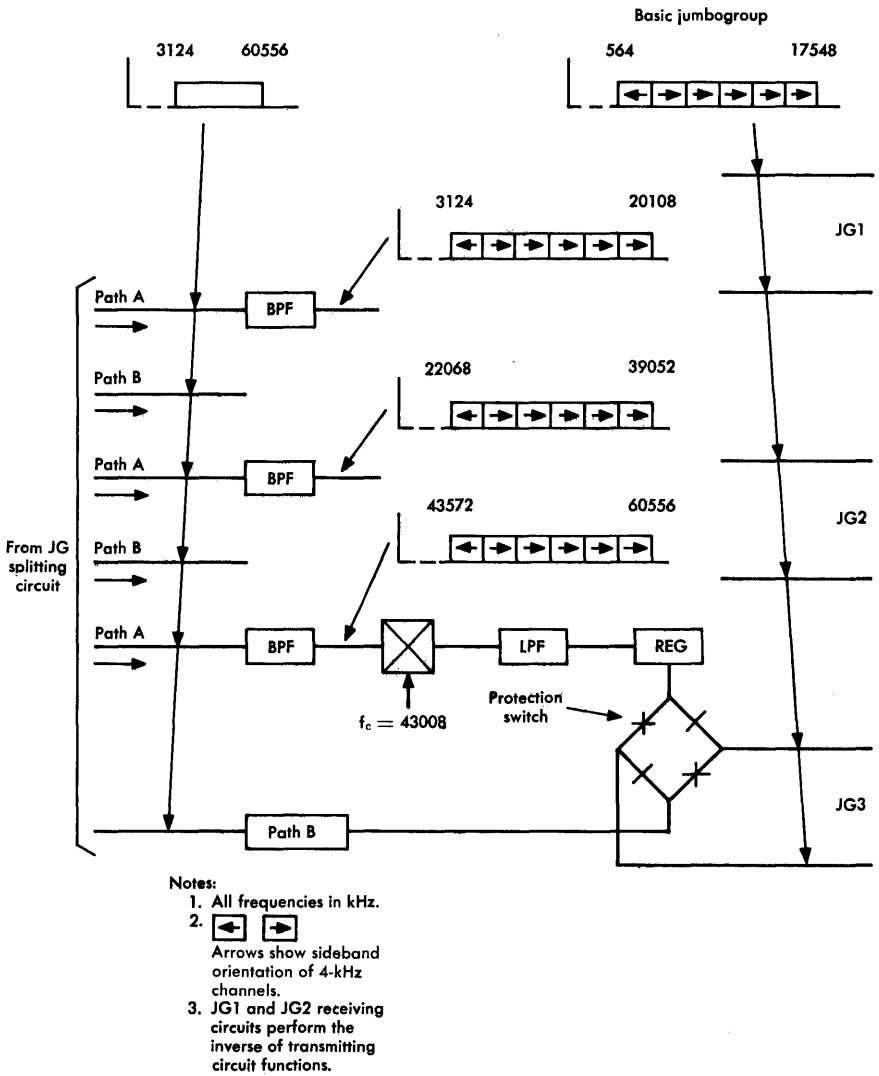


Figure 9-12. Simplified schematic of the receiving JMX.

**Multimastergroup Translators.** The multimastergroup spectrum shown in Figure 9-10 may be used in various combinations to provide signals required for transmission over specific systems. Figure 9-13 shows how the spectrum is formed for the 22 mastergroup L5E Carrier System. A single step of modulation is used to place each mastergroup

in its assigned place in the spectrum. Note the relatively close spacings between multimastergroup spectra. This close spacing and the close spacing between mastergroups in the MGT-B arrangement permit the fitting of 22 mastergroups into the L5 system passband. Figure 9-14 shows the formation of a ten-mastergroup array for transmission over the AR 6A single-sideband microwave radio system.

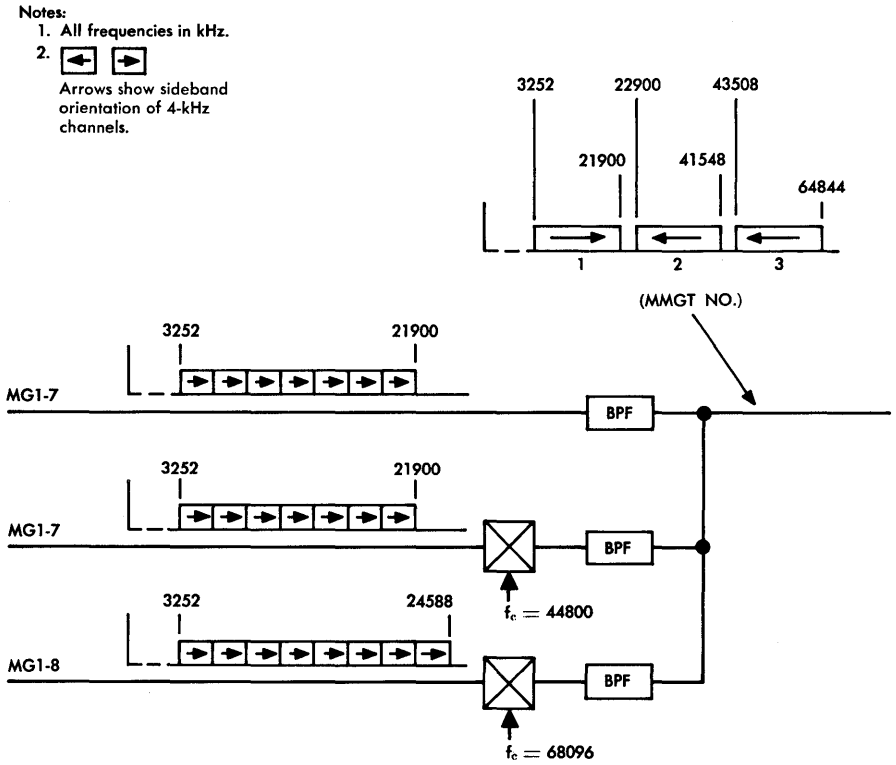




Figure 9-13. Formation of L5E line signal using three MGT-B spectra.

The multimastergroup transmitting and receiving equipment is furnished with automatic protection switching systems arranged so that one working spare multimastergroup modulator or demodulator can protect up to 20 working circuits in the MMGT-C and up to 15 in the MMGT-R. Transmitting and receiving circuits are protected independently. A 13,920-kHz pilot signal is used to actuate the switching circuits. These switching arrangements are controlled by modern electronic logic and control circuitry.

Notes:

1. All frequencies in kHz.
2.    
Arrows show sideband orientation of 4-kHz channels.
3. LIF = lower intermediate frequency; UIF = upper intermediate frequency.

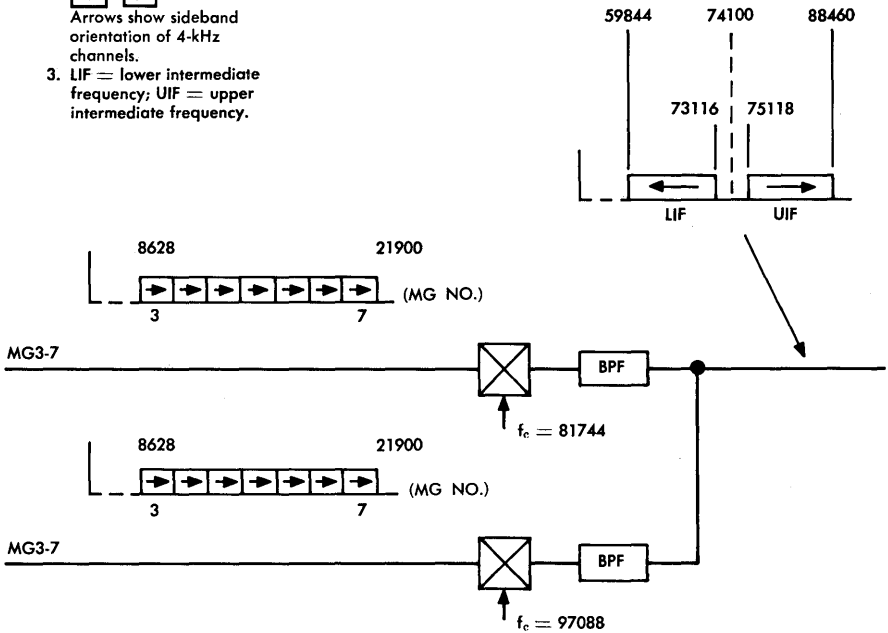


Figure 9-14. Formation of the 10-mastergroup spectrum for AR 6A microwave radio system.

## 9-2 DESIGN CONSIDERATIONS

The designs of the various portions of the analog multiplex hierarchy have evolved from a number of specific transmission system needs. Each step has been featured by the application of new technology, the consideration of many interrelated and interacting objectives, and a recognition that compatibility with existing arrangements was essential. Also, the overall process had to allow for flexible expansion and the possible application of future innovations. Features that have been given particular attention in this on-going design process include the overall efficiency of the multiplexing arrangements, the transmission requirements that have had to be satisfied at each step, and the reliability of the services carried by the multiplex equipment.

### Efficiency Factors

In addition to supporting the increased efficiency of bandwidth utilization in transmission media, other advantages have been found as the analog multiplex hierarchy has evolved. These advantages include the use of common equipment, the cost of which is shared by many transmission circuits. Such common equipment includes pilot and carrier supplies, maintenance equipment, and, in many cases, identical circuits in both the transmitting and receiving portions of the multiplex. Advantages have also been gained from the multiplex arrangements that permit different levels of the hierarchy to be used as terminal equipment for systems of different bandwidths and transmission modes, e.g., microwave radio, coaxial cable, and high-speed digital systems.

**Bandwidth Utilization.** As each step is taken in the evolution of a given type of transmission system, the use of the medium is extended in bandwidth by system design techniques such as using shorter repeater spacing in cable systems or increasing the transmitted power in a microwave radio system. These bandwidth increases must be supported by commensurate increases in terminal equipment bandwidth and channel capacity but complexities appear in multiplex design that are different from those that influence transmission system design.

In order to make most efficient use of assigned bandwidth, there is always pressure to place channels in the spectrum as close together as possible. However, close channel spacing imposes stringent requirements on the bandwidth allowed for filter discrimination, i.e., for the filter attenuation to increase from its minimum (inband) value to its maximum (out-of-band) value. This problem is accentuated as the top transmitted frequency is increased because the bandwidth required for the transition region is a percentage of the frequency at which the transition must be achieved. Thus, a more complex design is required for the higher frequency filters than for lower frequency filters if the same guard bandwidth is provided.

The sharp cutoff and high out-of-band attenuation requirements produce inband amplitude/frequency and phase/frequency distortions that are hard to control and that tend to accumulate systematically when terminals are connected in tandem. The attempts to control these distortions or to correct them by the use of equalizers cause undesirable increases in terminal equipment costs. Ultimately, designs

must be a compromise between performance and costs when technical feasibility has been established.

One example of how a design compromise was effected in the design of multiplex equipment is illustrated by the shift in frequency allocations of the mastergroup multiplex, MMX-2, shown in Figure 9-9, as compared to the mastergroup multiplex, MMX-1, shown in Figure 9-8. In the MMX-1 design, the frequency allocation provided a constant guard bandwidth of 80 kHz between mastergroups. In the design of the MMX-2 equipment, the guard bands are approximately 4 percent of the center frequency of each band. This approach made possible improved transmission/frequency performance in the multiplex filters and related equipment used to provide flexibility in system layouts. Without the proportional bandwidth, the functions of dropping, blocking, reinserting, and through connecting cannot be accomplished except by demodulation to basic mastergroup frequencies.

In the design of the B-series of the mastergroup translator and the multimastergroup translators, the approach of minimizing the guard bandwidths at the expense of reduced flexibility was again taken. Thus, increased numbers of channels were made available. The approach was deemed appropriate because the growth of service has made it desirable to administer channels in larger blocks.

Another feature of the multiplex hierarchy that was introduced to increase the efficiency of bandwidth utilization is the location of group and supergroup pilots. Originally, these pilots were assigned frequencies near the middle of their respective bands. However, they later were reassigned to frequencies near the band edges to make possible the more complete utilization of these bands for wideband data signals. In anticipation of later needs for wideband signals in the mastergroup and jumbogroup, pilots for those bands are provided at frequencies fairly near the respective band edges. The multimastergroup pilot is placed near the center of the multimastergroup translator spectra at a frequency selected to more nearly optimize analog transmission. These pilot frequencies are shown in Figure 9-15.

**Common Equipment.** The details of how common equipment advantages are realized are numerous. A limited discussion of the application of common circuits and equipment is appropriate. Four categories of equipment are of interest: carrier supplies, pilot supplies, modulators and demodulators (modems), and maintenance equipment.

SPECTRUM	FREQUENCY (kHz)
Basic group	104.08
	100.08*
Basic supergroup	315.92
Basic mastergroup	2840
Basic jumbogroup	5888
Multimastergroup	13,920†

\* Used only for carrier failure alarm.

† Used for alarms and switch control.

Figure 9-15. Pilot frequencies in FDM equipment.

Carrier and multiplex pilot supplies are sufficiently alike that they may be discussed as a single item. Carrier frequencies must be provided at every stage of the multiplex; pilots are used for regulation, alarms, and/or protection switching control in all steps in the multiplex above the channel bank level. All carrier frequencies are multiples of 4 kHz; these signals and pilots must be precise, accurate, stable, and reliable. Amplitude and phase jitter must be held to extremely small values even in the presence of noise or variations in supply voltages. Such factors have all contributed to the use of common equipment because the cost of supplying large numbers of individual signal generators meeting such stringent requirements would be excessive. However, in the more recent designs, such as the mastergroup and multimastergroup translators, emphasis has shifted from common equipment to flexibility of application.

Typically, an office that uses FDM equipment contains one or more reliable primary frequency supplies (PFS) and/or a jumbogroup frequency supply (JFS) the circuits of which are redundant and switched automatically from working to spare in the event of failure. The operating frequencies of these units are controlled by synchronization with reference signals transmitted from the Bell System Reference Frequency Standard [9]. These signals are transmitted nationwide through regional frequency supplies. In the event of failure of the Reference Frequency Standard, synchronization is maintained by the regional frequency supplies.

The output signals of the primary frequency supplies are at 4, 64, 128, and 512 kHz [10]. These signals are fed to multiport distribution networks and a number of bays of L-multiplex equipment may be supplied from each. Signals at 1.024, 2.56, and 20.48 MHz are



generated in jumbogroup frequency supplies to synchronize JMX and multimastergroup equipment [11]. Within the multiplex bays, pilots and carrier frequencies are generated and distributed as required to serve their assigned functions [12].

Many modulators and demodulators use identical circuit and equipment arrangements to fulfill their functions and are combined in single-unit modems. Maintenance features that have been incorporated in the multiplex equipment are also furnished on a common basis so that external and built-in maintenance test sets and circuits can serve one or more bays of transmission equipment.

### Transmission

A transmission system must simultaneously meet service and transmission objectives such as bandwidth, reliability, signal-to-noise performance, and specified input/output linearity relationships. For economic reasons, allowable transmission impairments are allocated primarily to the transmission line with only small amounts allocated to terminal equipment. It is also important to recognize that overall transmission performance of systems is dependent on certain operating features that must be provided. Included are the provision of flexibility in respect to the interconnections between systems and circuits, adequate transmission stability, and the provision of specified transmission level points (TLP) for compatibility with other parts of the transmission plant.

In some transmission systems, TLPs must vary with frequency. Where these specifications are expressed as stepped functions of frequency (for example, each mastergroup may be applied to a transmission system at a different TLP), appropriate gain (or loss) adjustments may be applied in the FDM equipment. Where the TLPs are specified as continuous functions of frequency, the appropriate characteristic is provided by a network placed between the multiplex and the line equipment.

The input to FDM terminals consists primarily of four-wire voice-frequency circuits. Where the incoming circuit is two-wire, it must be converted to four-wire by a four-wire terminating set. The TLP at the four-wire voice-frequency FDM input on the transmitting side is  $-16$  dB and at voice-frequency output on the receiving side of the circuit, the TLP is  $+7$  dB. These standard TLPs are used in all carrier systems including the N- and T-types. Thus, it can generally

be stated that a carrier system channel has 23 dB of gain from the input to the output. These standard TLPs and system gains facilitate the interconnection of systems and orderly administration throughout the plant. Even though transmission system designs require a wide range of TLPs internally, the input and output TLPs are always  $-16$  dB and  $+7$  dB. These standards may well be subject to change with the introduction of No. 4 ESS and the fixed loss transmission plan [13].

**Stability.** Broadband amplifiers used in FDM equipment are designed to maintain high gain stability in spite of component characteristic changes, temperature changes, or battery supply voltage changes. This stability is achieved by the use of negative feedback and by the use of pilot-controlled regulators in the receiving circuits of the multiplex. Group, supergroup, and mastergroup transmission is usually regulated. Generally, regulators maintain transmission at the pilot frequency to within  $\pm 0.1$  dB of the required value. The frequencies of pilots used in the multiplex equipment are shown in Figure 9-15.

**Transmission Response.** At each level in the multiplex above channel bank, the attenuation/frequency characteristic is designed to be flat within approximately  $\pm 0.05$  dB over any 4-kHz portion of the transmission band. This accuracy in transmission is easily met over the center frequencies but band edges tend to roll off in spite of the use of crystals in filter designs. The cumulative departure from flat transmission through ten pairs (transmitting and receiving terminals) is typically 0.25 dB or less.

Delay distortion is not normally corrected in the multiplex equipment since FDM design is based primarily on the transmission of speech signals. When voiceband or wideband private line data channels are provided by FDM equipment, any required delay distortion correction is accomplished in circuits external to the multiplex.

**Combining and Separating Circuits.** Many combining and separating points must be provided to combine signals of different frequencies into a composite spectrum and to separate them at receiving terminals so they may be directed as separate signals to the appropriate destinations. Hybrid coil and resistance pad circuits are commonly used in conjunction with filters for these purposes.

The choice between hybrid coil and resistance pad circuits depends on allowable loss at the point of application, impedance relationships at the interfaces, circuit-to-circuit interaction sensitivity, and costs. Hybrid coil circuits tend to have somewhat less through circuit loss and higher coupling loss (transhybrid loss) but are more costly than resistance pad circuits. The control of impedances involves the designs of the required filters and combining and separating circuits. The relationships among echo, attenuation/frequency distortion, power transfer, and cost must all be considered.

**Signal-to-Noise Considerations.** In a newly designed long-haul, broadband transmission system, the terminals are usually allocated only a small portion (31.2 dBrc0) of the overall 4000-mile noise objective (40 dBrc0) [14]. This low value of noise must be allocated to the individual terminals (the number of tandem terminals in a long system must be estimated), to various levels of the FDM hierarchy within each terminal, and to other kinds of terminal equipment such as group, supergroup, and mastergroup connectors. The noise allocation must be further broken down to various types and sources of noise. The large number of variables involved and the flexibility in system application that must be provided make it difficult to describe specific processes of allocating objectives and design approaches.

As previously noted, the TLPs at the voice-frequency input and output of all channel banks have been standardized to  $-16$  dB and  $+7$  dB respectively. At other points within the multiplex equipment, gains and losses (and therefore TLPs) are selected to optimize signal-to-noise performance and to meet objectives. The basic requirements are generally satisfied by optimizing performance in respect to the combined effects of thermal and intermodulation noise; however, compromises must sometimes be made in order to solve other problems such as those associated with unwanted single-frequency interference or crosstalk.

Due to the large number of modulation steps and the various carrier signals that must be used, the generation of unwanted single-frequency signals is a common phenomenon in FDM equipment. Carrier leakage through a modulator, ground circuit paths, intermodulation among pilots and carriers in amplifiers, and inadequate suppression by filters are all sources of both single-frequency interferences and crosstalk. All circuit elements in FDM equipment must

be carefully designed to minimize these problems and must be carefully laid out relative to one another if signal-to-noise performance is to be satisfactory.

### Reliability

The design of all levels of the FDM hierarchy has been influenced in many ways by reliability considerations. This has become increasingly true as bandwidths and the number of channels in the multiplex equipment have increased. The goals of minimizing the likelihood of complete failure or significant deterioration of performance are achieved by the use of fundamentally reliable components, the selective application of redundancy, the use of well defined maintenance equipment and procedures, and the provision of alarms to indicate failure or (in some cases) incipient failure. Pilot signals are used to control automatic gain regulators and are monitored continuously to determine whether circuits are drifting from established gain settings. The loss of a pilot signal triggers an alarm and, where protection switching is available, causes maintenance facilities to be switched into use.

Alternate transmission paths are provided in some multiplex equipment for use in case of failure of the working path. Input and output ports to these standby paths are provided so that they can be used for restoring service in the event of high-frequency line failure. In such circumstances, emergency broadband restoration plans are often implemented by using the standby equipment to bypass a failed section of line. In some cases, this equipment is switched into service and in others it must be patched into service.

Redundancy is also used in many of the ancillary circuits associated with the multiplex equipment. Carrier, pilot, and synchronizing signal supplies are all supplemented by redundant circuits which can be called into service as required.

A maintenance feature, called carrier group alarm (CGA), minimizes the effect of a carrier system failure on calls that are involved directly or indirectly in the failure. Blocking and delay in completing calls not involved directly in the failure are minimized by making failed trunks appear busy, thus reducing the unproductive use of switching machine common equipment. Connections involved in the

failure are immediately released and false charges are thereby eliminated. Alarm indications and the trunks-made-busy feature reduce the effect of failure on central office maintenance.

A single-frequency alarm pilot is transmitted in the basic group band for carrier frequency alarm (CFA) control at 100.08 kHz. The pilot transmission and detection and the alarm functions are associated with the channel bank output, the basic group frequency of the FDM. Trunk processing is applied to the supervision leads of individual trunks at the input (and output) of the channel banks. The CGA feature is provided optionally for A5 or A6 channel banks and for the direct formed supergroup.

Maintenance arrangements include the provision of test points, to permit manual measurements of voltages or pilot amplitudes, and automatic measuring systems of different degrees of sophistication. In the LMX-2 equipment, for example, a scanner sequentially checks all group and supergroup pilot amplitudes and amplifier gains. When a parameter exceeds limits, office alarms are initiated and an alarm lamp indicates the type and location of trouble.

### 9-3 SPECIAL MULTIPLEX EQUIPMENT DESIGNS

Each level of the multiplex hierarchy has been redesigned several times in order to exploit new technology, to save space, power, and costs, and to increase flexibility of application. In addition to these redesigns, special modulators and demodulators have been provided for signals having certain unique characteristics. Among these are program and wideband data signals.

#### Program Terminals

Program signals are transmitted, according to tariff specifications, in 5-, 8-, and 15-kHz bands. Separate terminal equipment is used to translate such signals into a preassigned portion of the 60- to 108-kHz basic group frequency band. Where toll facilities are required for 15-kHz service, special arrangements must be made. The 5-kHz program channel displaces voice-frequency channels 6 and 7 (80 to 88 kHz) and the 8-kHz program channel displaces voice-frequency channels 6, 7, and 8 (76 to 88 kHz). The channel bank equipment for the displaced voice-frequency channels must be disabled. The program signal is combined with the remaining A-type channel bank signals between the channel bank output and the group bank input. The two

sets of signals are separated at the receiving terminal by separating circuits located between the output of the group bank and the input of the channel bank.

### Wideband Data Terminals

Standard terminal equipment is available for transmission of 50 kb/s data signals in the group band and up to 250 kb/s signals in the supergroup band [15]. This terminal equipment, like the program terminals, is not actually a part of the LMX-2 equipment. The data terminals are separately mounted and combining and separating circuits are provided as required.

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## Chapter 10

# System Design Features

Electron tubes followed by the transistor have made it possible to overcome the losses of transmission media over increasingly wide bandwidths and to modulate and combine a multiplicity of signals. These factors increase the efficiency of use of open-wire and cable conductors. Both single sideband and double sideband modulation modes have been used but, as the design of electric wave filters improved, signals have been transmitted increasingly by single sideband methods. Other advances have permitted improvements in transmission response characteristics, transmission stability, signal-to-noise performance, and reliability.

The optimization of system design requires that a number of inter-related system parameters all meet established transmission objectives. This is accomplished by the solution of a number of simultaneous equations that relate these objectives to signal-to-noise performance, repeater spacing, bandwidth, load capacity, transmission losses in the medium, and achievable repeater gain. The process is highly iterative in practice. Results must be reevaluated continually as performance, objectives, and the computation process are refined and improved in technique and accuracy.

Initial computations, intended only to demonstrate technical feasibility and economic practicality, are usually simple and straightforward. However, the processes become complex as refinements are introduced. System equalization and regulation, intermodulation phenomena, overload performance, and the provision of margins in the design for inherent variabilities all make system calculations



more complex and more difficult to evaluate. Other complications may be introduced by frequency allocations, the mode of transmission (e.g., equivalent four-wire), repeater spacing or placement constraints, and the need for providing additional margin for the use of specialized terminal equipment.

All modern analog cable carrier systems employ either a four-wire mode of transmission, in which the two directions of transmission are carried over separate, unidirectional facilities, or an equivalent four-wire mode of transmission, in which the two directions of transmission are carried in separate frequency spectra over a single pair of conductors. The four-wire design is used in the L-type coaxial carrier systems. The N-type systems were originally designed for four-wire transmission but have now been adapted for the optional use of equivalent four-wire transmission. Equivalent four-wire transmission is also used in most submarine cable systems and in analog loop carrier systems.

The system design discussion is presented for the purpose of clarifying terminology and to demonstrate the importance of specific parametric relationships. However, these relationships are not given in sufficient detail to permit a complete system design [1].

## 10-1 THE DESIGN PROCESS

The transmission plan and design of an analog cable system are determined analytically by adjusting bandwidth, repeater spacing, and signal amplitudes so that prescribed signal-to-noise objectives may be met over the life of the system. Many parameters enter into the determination of the optimum achievable performance. The process involves the determination of the minimum allowable signal amplitude consistent with signal-to-thermal noise objectives and the maximum allowable signal amplitude that satisfies intermodulation or overload objectives. If there is no spread between these two values, a design cannot be achieved. If there is a spread, the design may then be optimized at values of signal amplitude that provide the largest total signal-to-noise ratio without exceeding overload objectives and the greatest margins for departures from this ideal. Finally, if these margins are too small or too large, a matter of engineering skill and judgment, design adjustments may be made in bandwidth, repeater spacing, or cost.

In this process, the limits of permissible signal amplitudes are often discussed in relation to the "noise floor" and the "intermodulation or overload ceiling." These are convenient references to design limits that may not be exceeded by signal amplitudes if objectives are to be met.

### Design Relationships

The design parameters for an analog transmission system may be expressed in mathematical terms and related to one another by the concept that system performance must equal system objectives. Most of the parameters are time-variable and/or functions of frequency. For refined design computations, they must be expressed as functions of frequency and in statistical terms. For initial calculations and for present purposes, fixed average values are generally assumed and the highest transmitted frequency is used to determine feasibility. Where margins are appropriate, they may be included as mathematical terms in the performance expressions.

In considering the relationships among various parameters, a common reference point for analysis must be chosen. The 0 transmission level point (TLP) is commonly used. Another reference point conveniently used in many intermediate computations is the output of a repeater. The TLP at this point is related to 0 TLP by a factor defined as  $C$  dB, the nominal gain from the output of a repeater to 0 TLP. This factor may be a function of frequency or it may be constant with frequency depending on specific design criteria. For initial calculations, the value of  $C$  is usually assumed constant with frequency and equal to the top-frequency value.

**Repeater Gain.** A basic design requirement is that the transmission loss of the medium must be compensated by the gains of repeaters distributed along the line. This design requirement may be expressed by

$$L_X = nG_R \quad \text{dB}$$

and

$$G_R = L_X/n \quad \text{dB} \quad (10-1)$$

where  $L_X$  is the loss of the medium for the distance  $X$  over which the design is to apply,  $G_R$  is the gain of each repeater, and  $n$  is the number of repeaters. Thus, the nominal repeater spacing for the system is  $X/n$ . Equation (10-1) assumes that the losses of a series of identical lengths of cable are exactly compensated by the gains of an equal

number of repeaters. The equation must apply at all frequencies in the transmitted band even though it is used in initial design studies as if it applied only at the top transmitted frequency.

**Thermal Noise and Load Capacity.** These two parameters sometimes combine to limit the design of a system; thermal noise may provide the "noise floor" and load capacity the "overload ceiling." Thus, it is necessary to determine how the performance may be computed for each of these parameters and how the two may be related.

In a system of  $n$  repeaters, it can be shown that the total thermal noise accumulated in a 3-kHz band, expressed as an annoyance factor, is

$$W_{n0} = N_R + G_R + 10 \log n + C + 88 \text{ dBm}0. \quad (10-2)$$

The term  $N_R$  defines the noise in dBm at the input to a repeater (where the signal amplitude is lowest) in a 3-kHz band [1]. The terms  $N_R$ ,  $G_R$ ,  $C$ , and  $W_{n0}$  in Equation (10-2), may all be functions of frequency. If the accumulated noise is to be equal to or less than the system objective for this impairment,  $W_{NS}$ , and if margin,  $A_N$ , is to be allowed for system misalignment, then

$$W_{n0} + A_N \leq W_{NS}$$

Thus,

$$N_R + G_R + 10 \log n + C + 88 + A_N \leq W_{NS} \quad (10-3)$$

The load capacity of a system is conveniently expressed in terms of a single-frequency signal, the power of which is equal to that of the total multichannel load. The repeaters must be capable of carrying this amount of power, usually expressed in dBm0, and margin must be allowed so that departures from normal system performance or from the predicted load do not cause impairment due to system overload. The single-frequency power values for repeater capacity and system requirement are designated  $P_R$  and  $P_S$ , respectively. These power values are related by

$$P_R + C - A_P \geq P_S \quad \text{dBm}0 \quad (10-4)$$

where  $A_P$  is the overload margin that must be provided in the design.

Equation (10-4) is deceptively simple in appearance. The factors that make up the load requirement are highly variable and must be treated by statistical analyses for the derivation of  $P_S$ . These factors

include the variation of talker volume, the number of signals simultaneously transmitted, the applicable activity factors, and the loading effect of combined signal power and its variation [2]. In addition, the load capacity of a repeater may be a function of frequency. For present purposes, it may be assumed that the value of  $P_R$  in dBm applies at the output of the repeater and at the top transmitted frequency.

**Intermodulation.** System design may be limited by an "intermodulation ceiling." Equations may be written for noise due to intermodulation among the multiplexed speech signals transmitted through the line repeaters. In these equations,  $W_2$  and  $W_3$  represent the annoyance factor of the noise due to second- and third-order nonlinearities, respectively, in the line repeaters. In broadband systems that provide at least several hundred speech channels, the interfering effects of these impairments are subjectively very similar to the interfering effect of thermal noise. The power of intermodulation noise is thus added to the power of thermal noise to evaluate the total impairment. However, the mechanisms by which  $W_2$  and  $W_3$  are generated and the manner in which they are related to signal amplitudes and system transmission response are quite different. Thus, the impairments must be computed separately and combined only in the final evaluation. The two equations are

$$W_2 = M_2 - C + 10 \log n + K_2 \quad \text{dBmnc0} \quad (10-5)$$

and

$$W_3 = M_3 - 2C + 20 \log n + K_3 \quad \text{dBmnc0} \quad (10-6)$$

In these equations,  $M_2$  and  $M_3$  represent the second- and third-order modulation coefficients for line repeaters in terms of the ratio of single-frequency 0 dBm signals to the second- and third-order harmonics at the repeater output. The factors  $K_2$  and  $K_3$  relate single-frequency impairments to the statistical properties of impairments due to intermodulation among speech signals. These properties include the number of channels in the system, the activity factors associated with a message load, the variation of signal energy in each channel with time and frequency, the number of intermodulation products generated, etc. [1].

Two essential differences between Equations (10-5) and (10-6) should be noted. First, the term  $C$ , which appears unmodified in Equation (10-5), is multiplied by 2 in Equation (10-6). This difference

results from the mathematical signal-to-interference ratio relationships of second- and third-order intermodulation phenomena. Second, the terms  $10 \log n$  in Equation (10-5) and  $20 \log n$  in Equation (10-6) represent the difference in the laws of addition of intermodulation products generated in successive repeaters. The difference results from the fact that cable and repeater phase/frequency characteristics are essentially linear.

The computed intermodulation noise must be equal to or less than the established objectives. Thus, Equations (10-5) and (10-6) may be used to write system design equations :

$$W_2 + A_2 \leq W_{2S}$$

or

$$M_2 - C + 10 \log n + K_2 + A_2 \leq W_{2S} \quad (10-7)$$

and

$$W_3 + A_3 \leq W_{3S}$$

or

$$M_3 - 2C + 20 \log n + K_3 + A_3 \leq W_{3S} \quad (10-8)$$

The factors  $A_2$  and  $A_3$  are margins that provide for uncertainties and variations.

**The Use of Design Equations.** Five of the previously derived equations may be used to establish system designs. Equation (10-1) specifies the cable loss-repeater gain relationship. Equation (10-3) specifies the relationships among parameters that, in effect, establish the "noise floor," the value below which signal amplitudes may not drop without exceeding signal-to-thermal noise objectives. Equation (10-4) establishes the "overload ceiling," (10-7) the "intermodulation ceiling" where second-order products predominate, and (10-8) the "intermodulation ceiling" where third-order products predominate.

Equations (10-1) and (10-3) may be combined with each of the other three equations to eliminate  $C$  and  $G_R$ . When this is done, three system equations may be written. The first is the equation for a system limited by thermal noise and overload:

$$\frac{L_X}{n} + 10 \log n \leq (W_{NS} - N_R) - (A_N + A_P) - (P_S - P_R) - 88. \quad (10-9)$$

The second is the equation for a system limited by thermal noise and second-order intermodulation:

$$\frac{L_X}{n} + 20 \log n \leq (W_{NS} + W_{2S}) - (N_R + M_2) - (A_N + A_2) - (88 + K_2). \quad (10-10)$$

The third equation represents a system limited by thermal noise and third-order intermodulation:

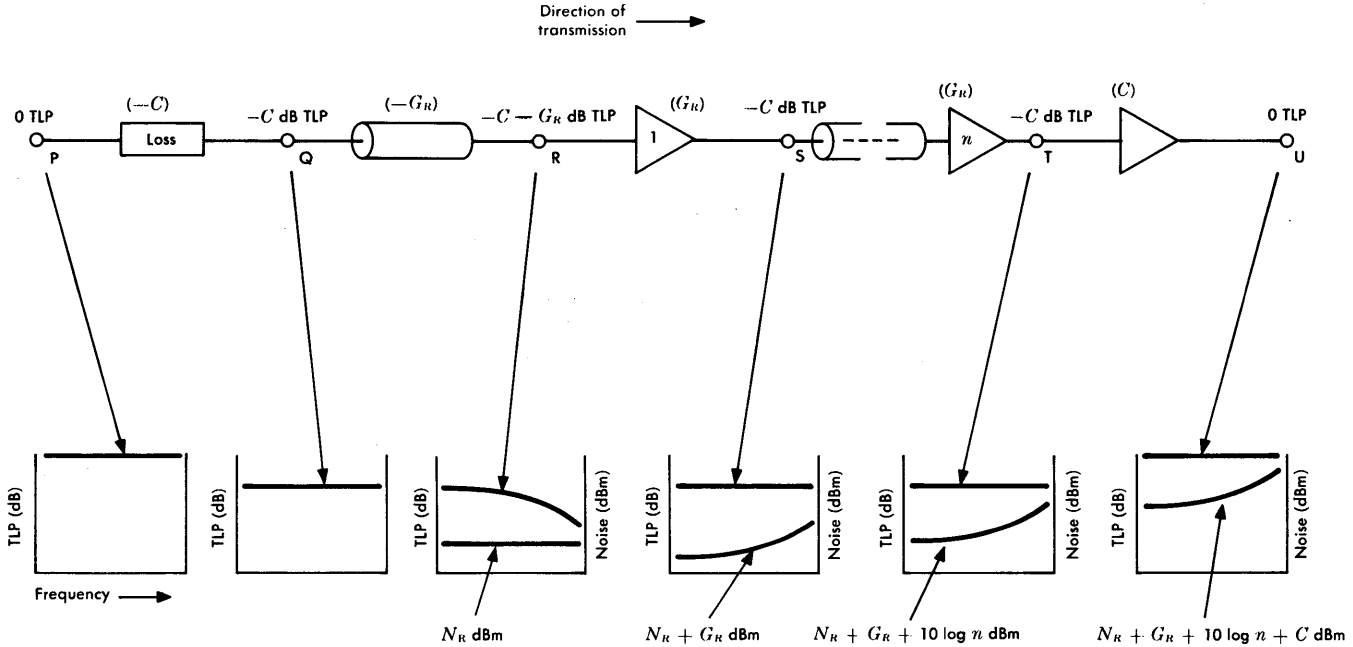
$$\frac{L_X}{n} + 20 \log n \leq \left( W_{NS} + \frac{W_{3S}}{2} \right) - \left( N_R + \frac{M_3}{2} \right) - \left( A_N + \frac{A_3}{2} \right) - \left( 88 + \frac{K_3}{2} \right). \quad (10-11)$$

When the development of a new system is initiated, the loss characteristic of the medium and the objectives ( $P_s$ ,  $W_{NS}$ ,  $W_{2S}$ , and  $W_{3S}$ ) are usually known. Estimates of many other parameters must be made on the basis of previous designs, desired goals in respect to bandwidth or channel capacity, state of the art, and engineering judgment. The estimates and the known values of objectives and media characteristics may then be used in these operations to assist in judging feasibility. The results determine approximate repeater spacing and provide information as to whether the proposed system is likely to be limited by overload or intermodulation. As development proceeds, the computations are continually refined and adjusted so that the final design represents an economical set of compromises. These compromises involve margins, repeater spacing, and bandwidth as well as manufacturing, installation, maintenance, and operating costs.

### Design Implementation

Some of the design relationships discussed above may be dealt with rather simply. However, most of the parameters are complex and their interrelationships are far more complex than may be evident. These complexities must be resolved in the design process.

**Transmission Level Points.** As previously mentioned, transmission level points at the outputs of line repeaters are specified by the term  $C$  used in developing the system equations. Figure 10-1 illustrates a simplified system layout in which the factor  $C$  is assumed to be a constant over the transmitted band. The layout assumes an ideal case in which there are  $n$  identical repeater sections in each of which the repeater gain,  $G_R$  dB, exactly compensates the cable loss,  $-G_R$  dB.



Note: ( ) gain in dB

Figure 10-1. Simplified system layout with level and thermal noise diagrams.

Only one direction of transmission is illustrated. Note that even though  $C$  is assumed constant over the band, the TLP is generally a function of frequency at points within the system other than the repeater output as shown at point  $R$ . In practice,  $C$  is also a function of frequency in most systems.

**Thermal Noise.** It can be shown that thermal noise can be computed by

$$p_a = kTB \quad \text{watts}$$

where  $k$  is Boltzmann's constant ( $1.3805 \times 10^{-23}$  joule per degree Kelvin),  $T$  is the absolute temperature in degrees Kelvin, and  $B$  is the bandwidth in hertz. The available noise power at 290 degrees Kelvin (near room temperature), may also be expressed as

$$P_a = -174 + 10 \log B \quad \text{dBm.}$$

These expressions apply at any point in a circuit but the effect of noise tends to be greatest at points where signal amplitudes are lowest. In general, these points are at the inputs to line repeaters. Where other thermal noise sources are found to be significant, the noise amplitudes are usually measured or computed, translated to equivalent values at the repeater input, and added to the input noise. Such sources are sometimes found internally within the repeaters. In addition, amplifiers that are used at equalization points or at terminals also contribute thermal noise that must be added, in computing total system noise, to that originating in line repeaters.

As illustrated at point  $R$  of Figure 10-1, thermal noise is constant over the frequency spectra at which wire pair or coaxial cable transmission is practical. However, the noise originating at point  $R$  is amplified in the repeater and appears at the repeater output (point  $S$ ) with an amplitude/frequency characteristic similar to the gain curve of the repeater. This characteristic is maintained as additional noise is accumulated and translated to 0 TLP as shown at points  $T$  and  $U$ . These factors must be carefully manipulated in the design process to achieve the desired objectives.

**Intermodulation Noise.** The analysis of impairment caused by intermodulation among multiple speech signals, very similar to that caused by thermal noise, is an extremely complex problem because of the nature and multiplicity of parameters involved. These include the



characteristics and amplitudes of the fundamental signals, the non-linearity of the repeater input/output characteristics, the system attenuation/frequency characteristic, the number of fundamental signals (which influences the number of intermodulation products), the order of the products, and the laws of addition from repeater to repeater. Most of these parameters are functions of frequency, time, system length, etc., and as a result, statistical methods of analysis must be used.

The variation with frequency of intermodulation noise as measured at 0 TLP can be made less pronounced by appropriate shaping of the TLPs across the band of the system. The shaping is accomplished by the use of electrical networks at the input and output of the system. These, in effect, result in a frequency-dependent characteristic of the term  $C$ . While this design technique is often used to advantage, variations with time of the attenuation/frequency characteristic have similar effects on intermodulation noise. These effects must be taken into account in system analysis and their control is one of the primary objectives of a system equalization plan. The departure of the system characteristic from ideal is called misalignment.

As a result of the highly linear phase/frequency characteristics of the transmission medium and repeaters, the dominant third-order modulation products tend to add in phase (often called voltage addition) from repeater to repeater. This effect can be reduced by the use of nonlinear phase networks at appropriate points in the transmission path. By this means, the law of addition may be reduced from  $20 \log n$  (where  $n$  is the number of repeaters) to more nearly  $10 \log n$ . This technique must be used carefully so that costs are not excessive and consideration must be given to possible impairment of signals, such as wideband data, sensitive to channel phase characteristics.

**Overload Effects.** The effects of overload, the criteria for defining overload, and many of the statistical properties of signals that may cause overload are discussed in Volume 1. Two types of system impairments are of concern. The first, associated with what is sometimes called "hard overload," results in a complete breakdown of transmission. This type of failure is relatively rare; even so, some systems have specific design features which minimize such occurrences.

More commonly, signal amplitudes exceed design values by amounts small enough so that the primary manifestation of an overload condition is an increase in intermodulation noise. It is for such signal

amplitude excursions that the margin,  $A_P$  of Equation (10-4), is provided. The amount of margin must be determined as a part of the design process. The statistical properties of the complex multi-channel signal to be transmitted must be carefully analyzed to determine its mean value and standard deviation. This analysis is influenced by the amplitude/frequency characteristic of the complex signal at the output of the line repeater. In addition to the nominal TLP characteristic, account must be taken of the effect of all sources of misalignment in the system.

Intermodulation noise is directly affected by the amplitudes of transmitted signals. The term  $C$  controls these amplitudes and thus, indirectly, the intermodulation noise. Below the repeater overload point, the change in noise is predictable from the power series representation of the system input-output characteristic. When measured at 0 TLP, modulation noise varies inversely with the change in the value of  $C$ . Second-order noise varies dB-per-dB and third-order noise varies 2-dB-per-dB change in  $C$ . When  $C$  is reduced to the overload point, the noise increases faster than predicted. Furthermore, just one overloaded repeater can cause a marked deterioration in system intermodulation noise performance. In operation, the most serious sources of overload are (1) the application and transmission of signals of excessively high amplitude and (2) the failure to maintain system equalization which causes signals of otherwise satisfactory amplitudes to reach overload values within the system.

Certain system design features must be used with care because of overload relationships that are involved. One is the use of companders which tend to increase the mean values and to reduce the standard deviations of the signals transmitted. Thus, it may be necessary to reduce signal amplitudes (by increasing the value of  $C$ ) depending on the overload margin in the system. The net result may be a significant reduction of the signal-to-noise advantage expected from the use of the companders. A second feature that affects overload performance is the use of a Time Assignment Speech Interpolation (TASI) System. This type of system, applied at the terminals of some transmission systems, increases the capacity of the system by assigning channels to speakers only when speech energy is present at the input. High-speed channel switching is initiated by speech detectors on each input channel and by high-speed logic circuits that connect appropriate incoming and outgoing lines through an idle channel. This arrangement effectively increases the talker activity on the system and can

increase the power load by a factor of 2 or 3; it must be taken into account in the provision of overload and intermodulation margin in system design.

**Optimization.** It can be shown mathematically that, for a given set of design parameters, transmitted signal amplitudes can be chosen to optimize the system signal-to-noise performance. While the mathematical treatment is a valuable part of the design process, noise loading tests of analog cable systems are often made during the development process to verify the design value of  $C$  and during field trials to evaluate system performance [3]. When systems are operational, such tests are not often conducted because the systems must be taken out of service during the tests. However, they are sometimes useful in identifying and isolating certain types of trouble conditions.

## 10-2 EQUALIZATION

The term equalization is used to cover a number of different techniques and methods for correcting the transmission characteristic of a system, a circuit, or a channel.

The difficulty of equalizing analog cable carrier systems is illustrated by the following. The loss of 4000 miles of coaxial cable at 60 MHz, a high transmitted frequency in the L5 system, is approximately 120,000 dB. In terms of the allowable variation of net loss of a network trunk (approximately  $\pm 1$  dB of the design value), the tolerance on the transmission variation after equalization is  $100 \times 1/120,000 = 0.0008$  percent.

Fixed and variable equalizers are used to correct attenuation/frequency characteristics or delay/frequency characteristics or both. Variable equalizers may be adjusted automatically or manually, locally or remotely, continuously or in discrete steps. In this treatment, the emphasis is placed on attenuation/frequency equalization of transmission systems.

### Functions and Objectives

The need to correct the attenuation/frequency characteristic of a transmission system derives from a number of different but inter-related transmission objectives. For each objective, margin must be provided for system misalignment. The design of system equalization is based in part on the need to maintain signal-to-noise and overload performance within the margins provided.

In the idealized system of Figure 10-1, it is assumed that repeater gain exactly compensates for the loss in the preceding section of cable. In a system designed for the maximum signal-to-noise ratio, any misalignment results in a penalty to signal-to-noise performance. Thus, one design objective is to provide equalizers of sufficient accuracy, adjustability, and bandwidth located at positions in the system such that the signal-to-noise margin is not exceeded when the system is properly operated.

A second equalization design objective is to control misalignment of a positive nature, that which results in increasing signal amplitudes, so that overload margin is not exceeded. Misalignment, even over a relatively narrow band, can cause overload that adversely affects performance over the whole bandwidth of the system due to the nature of feedback amplifier response to an overload signal.

A third objective concerns the relationship between 4-kHz channel loss objectives and system equalization. In the types of system under consideration, designed primarily to provide 4-kHz channels, misalignment typically covers a band much wider than the channel bandwidth. Thus, system misalignment has a minimal effect on the transmission characteristic within an individual voice channel; the principal effect is on the net loss of the channel. Pilot-controlled regulators are used in the multiplex equipment to maintain the net loss within rather close limits. The range over which these regulators operate is limited and most of that range has been allocated to the control of variations within the multiplex equipment. Thus, only a small proportion of the net loss objective can be allocated to the equalization system.

Another equalization objective, applicable to coaxial transmission systems, is to make a spare line as nearly as possible like the working lines it protects. Where the attenuation/frequency characteristics of such lines differ appreciably, a transmission gain hit is experienced each time lines are switched.

The final objective for the design of equalizers is the flat attenuation/frequency characteristic required for the transmission of wideband signals. This objective is most difficult to meet for television, PICTUREPHONE, or wideband data signal transmission. Television signals are rarely transmitted over analog cable systems and there are only limited applications of PICTUREPHONE and wideband data

signals to this type of system. Thus, while the possibility of such applications must be recognized in system design, they are not now dominant.

### Design Types

Equalizer designs may be categorized in a number of ways. For present purposes, consider fixed and variable equalizers as the two most important categories; within each of these, several subcategories may be discussed.

**Fixed Equalizers.** The most common fixed equalizer found in an analog cable system is the fixed-gain line repeater, often not even thought of as an equalizer. The principal function of a line repeater is to provide gain in compensation for cable loss. Since cable loss is essentially proportional to the square root of frequency, the repeater gain must match this characteristic as nearly as possible. Since this match is difficult to obtain economically, two additional types of fixed equalizer are usually required. Both are closely related to line repeater design.

In laying out a system geographically, line repeaters can seldom be located to match precisely the nominal specified spacing. In order to realize the manufacturing advantages of duplicative processes, it is common practice to provide a single design of line repeater. Tolerances in repeater spacing are then provided by a set of spacing rules that are often quite complex but which basically have two features: (1) spacings that are longer than nominal must be offset immediately by spacings that are shorter than nominal; (2) a series of long spacings is not permissible. Short spacings are generally not offset by compensating long sections. Instead they are built out to the loss of the nominal spacing by networks with loss characteristics that simulate closely the loss characteristics of short sections of line. These line build-out networks are, in effect, a series of fixed equalizers.

The loss characteristic of cable conductors tends to be a smooth function of frequency. The compensating gain of line repeaters can match this loss characteristic very closely but the match can never be perfect. Furthermore, the closer the match, the higher the cost of the repeater. An economic balance is commonly achieved by allowing deviations from ideal design to accumulate over a specified number of repeater sections and then to compensate with a fixed equalizer called

a deviation equalizer. The amount of accumulation allowed is a compromise between the performance penalties of misalignment (margins must be provided for these effects) and the cost of feasible equalizers. A degree of perspective may be gained by considering the L5 coaxial system which uses line repeaters at a nominal spacing of one mile. Suppose each repeater had an excess gain at some frequency of just 0.01 dB. If uncorrected, this deviation, small as it is, would accumulate through the 4000 repeaters of a maximum length system to  $0.01 \times 4000 = 40$  dB. Such small gain deviations (0.01 dB) are, in practice, difficult to measure and are essentially impossible to control in design, manufacture, and operation. The deviations are allowed to accumulate to some reasonable magnitude dictated by the margins provided and the feasibility of equalizer design. They are then corrected by deviation equalizers distributed strategically along the route.

**Variable Equalizers.** Many different types of variable equalizers are used. The attenuation/frequency characteristics provided and the range and manner of adjustment depend on the system characteristics that are to be compensated. A brief discussion of these characteristics can be used to relate system operating characteristics to adjustable equalizer designs.

The cause of the largest changes in system attenuation/frequency characteristics is the variation of temperature. In most modern systems, there are two major effects. The first, and usually by far the larger, is the change in the loss characteristic of the cable. This change occurs smoothly with temperature variations and is almost completely defined as a square-root-of-frequency effect, i.e., the dB change of loss at any frequency relative to the change of loss at another frequency is proportional to the square root of the ratio of the two frequencies. The second major effect is the change of the gain characteristics of the line repeaters with temperature.

For specific temperature ranges, the changes in gain and attenuation/frequency characteristics are predictable, of known magnitudes, and tend to be relatively smooth functions which can be accurately reproduced in discrete component networks. Loss changes due to temperature variations are usually corrected continuously since they are large effects and occur over periods of several days or weeks. The equalizers are adjusted automatically in response to changes in single-frequency pilot signals that are transmitted at carefully controlled

amplitudes. These signals are picked off the line, rectified, and compared with a dc reference voltage. The voltage difference, or error signal, is then used to adjust the equalizer in such a direction as to return the pilot signal to its proper value. This process is usually called *regulation* and the repeaters that incorporate this feature are called regulators or regulating repeaters.

Another cause of attenuation/frequency changes in a system is active component aging. These changes were important and large enough to warrant correction by regulation when electron tubes were the principal active components. However, circuits that utilize solid-state devices are extremely stable and aging can usually be ignored.

There are many causes of misalignment within a system. In addition to the fixed and variable systematic deviations previously discussed, many others occur randomly. These are usually small in each repeater or equalizer but may accumulate to excessive values. The usual method of correction is to distribute adjustable equalizers along the route so that misalignment can be limited to design values, i.e., within the established margins.

The equalizers used to compensate for accumulated random deviations are usually designed as a group of adjustable equalizers whose characteristics are interrelated in such a way that almost any transmission deviation in the band can be corrected. These equalizers may be adjustable in small discrete steps or they may be continuously adjustable by varying some element such as a capacitor or potentiometer. The adjustments are usually accomplished manually but may be remotely controlled from a central location by logic circuits.

Another type of equalizer, the adaptive equalizer, is designed as a tapped delay line. It is used to reduce attenuation/frequency distortion and/or delay distortion in digital circuits automatically in response to an algorithm based on the characteristics of the transmitted signal. The adjustment minimizes the error rate over the channel being equalized. It is used on some digital transmission channels derived from analog facilities. However, it is not used to equalize the analog facility itself as a part of the analog system design.

### Equalization Strategy

The provision of equalization for an analog cable transmission system usually requires that a number of different criteria be satisfied simultaneously. The design of equalization networks must be feasible

and must provide specified characteristics and range of adjustment. Adjustment procedures must be practical in the operating environment. The equalizers and application strategy must satisfy system objectives in respect to both equalization and signal-to-noise performance within the margins allocated.

Theoretically, equalizers may be placed anywhere in the transmission line of a system and may equalize any characteristic of any magnitude. However, the location of equalizers and the magnitude of the distortion to be corrected have profound effects on system overload and/or signal-to-noise performance penalties that may be incurred. Figure 10-2 shows the signal-to-thermal noise penalties for several equalization strategies and for a range of positive and negative values of channel misalignment. The penalties shown by curves 1 and 3 are mirror images in respect to nominal signal amplitude for a range of amplitudes and for positive and negative accumulated misalignments. If the equalizers are divided so that one-half the misalignment is corrected at each end of the line, the penalties are significantly reduced for the range of misalignments shown in Figure 10-2. For misalignments of about  $\pm 5$  dB, penalties are insignificant. With this method of equalization, it can be shown that signal-to-noise penalties in respect to intermodulation noise are also small for such misalignments.

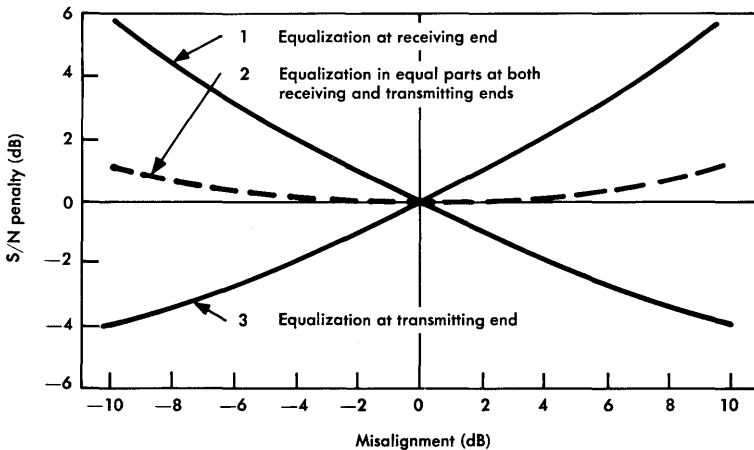


Figure 10-2. Signal-to-thermal noise penalties due to misalignment.



In system design, it is common practice to divide equalization between the transmitting and receiving ends of a line section for many types of misalignment. However, this strategy, called pre- and post-equalization, increases somewhat the complexity of equalizer adjustment. Thus, where misalignments are small, it is more common to place equalizers at the receiving end of a line section.

### 10-3 ANCILLARY DESIGNS

The transmission medium and the electronic equipment required to overcome line loss are of primary importance in system design. However, there are other essential facets of system design that have a direct or indirect influence on transmission performance.

#### Power

Primary power for essentially all communications equipment is obtained from commercial, 60-Hz, ac sources. The primary supply is rectified and used to provide a wide variety of dc voltages and currents required by transmission system equipment. The rectifier output is used to maintain a constant charge on 48-volt batteries. Individual system needs are met by a variety of electronic circuits which derive other voltages from the 48-volt supply. The batteries and the conversion circuits are located with the transmission equipment in central office buildings and in main station buildings located along the route of a transmission system.

The dc supply arrangements are provided with many backup features to assure high reliability for the communications equipment. The batteries are designed to carry the full load for short periods of time in the event of primary power system failure. Backup power generating equipment is usually made available to pick up the load if the primary power failure persists.

The remote repeaters of an analog cable system are usually powered by direct current transmitted over the conductors of the transmission medium. The direct current is furnished from the central office or main station and combined with the signal currents in appropriate filters at the connection to the line. At each remote repeater, similar filters are used to separate and recombine power and signal currents.

### Maintenance and Reliability

Many features are designed into analog cable systems to provide adequate reliability and to provide access and facilities for maintenance activities. In addition, building design, cable route selection, and cable placement (aerial, buried, use of ducts, etc.) all affect the reliability and maintainability of systems.

Transmission system equipment is distributed over long distances and, of necessity, is often located in out-of-the-way places which are difficult to reach. For these reasons, it is necessary to provide each system with specialized equipment designed to facilitate the recognition of trouble conditions, to isolate the trouble to a particular section of line, and then to identify the location of the fault so that repair personnel may be efficiently dispatched to the correct location. In addition, separate communications facilities for voice and/or data transmission (order wires) are also provided to assist maintenance personnel in their work.

Some transmission systems are provided with equipment for carrier group alarm and conditioning. With this equipment, system failure initiates an alarm and conditions affected trunks in various ways. Any connection established over these trunks is disconnected in such a manner that time charges are immediately terminated. The trunks are made busy until the system is repaired. They are then automatically tested and restored to service.

Most transmission systems are operated so that on each route there is at least one fully equipped and fully powered line that does not carry service. Service can be transferred to this spare line to facilitate maintenance work or to restore service in the event of failure of a working line. The transfer of service from the working line to the spare line may be accomplished manually or automatically by line protection switching equipment. As previously mentioned, the working and spare lines must be equalized to very nearly the same attenuation/frequency characteristics in order to minimize the transmission performance penalty that might accompany the transfer of service from one line to another.

### Terminal Arrangements

The main station and terminal buildings used with analog cable transmission systems contain many types of equipment in addition to those described in relation to power, maintenance, and reliability.

Most important of these equipment types are those associated with the multiplexing of signals in preparation for transmission over the line. Related equipment types include those that are required to drop, block, and add circuits; these facilities provide the flexibility needed for efficient system operations which include the interconnection of various types of systems. Carrier and pilot signal generators and highly precise frequency control equipment are also located at transmission system terminals.

#### REFERENCES

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2. American Telephone and Telegraph Company. *Telecommunications Transmission Engineering*, Volume 1, Second Edition (Winston-Salem, N.C.: Western Electric Company, Inc., 1977), Chapter 16.
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## Chapter 11

# Wire Pair Carrier Systems

A number of analog carrier systems have been designed to operate on open-wire lines and/or on wire cable pairs. The older of these system designs, based on electron tube technology, are no longer being manufactured but many are still in operation. Later designs are all based on solid-state circuit technology. In many applications, Hybrid Integrated Network (HIN) devices are being used to convert the older electron tube circuits to solid state.

These systems generally meet allocated transmission requirements for circuits up to about 200 miles in length. They are often referred to as short-haul analog carrier systems. Initial designs of line repeaters and multiplex terminals for open-wire and cable-pair applications were carried out concurrently. Later, as cable gradually replaced open wire, the terminal designs originally used on open-wire were adapted for use on cable-pair systems. The designations of systems that evolved in this manner were: (1) O-type line and terminal equipment for open wire; (2) N-type line and terminal equipment for cable pairs; (3) ON-type equipment to adapt O-type terminals for use on N-type transmission lines.

The use of syllabic companders in the design of these systems enabled signal-to-noise objectives to be met economically [1]. In the older designs, signalling was accomplished by arrangements that utilized a 3700-Hz tone, just outside the passband for voice signals.

The O- and N-type terminals and line equipment are more nearly integrated than in most other types of systems. Proper line repeater operation requires the application of well-controlled carrier signal power from the terminal equipment. Similarly, many aspects of terminal equipment design have been influenced in significant ways by repeated line considerations.

## 11-1 O-TYPE SYSTEMS

When the O-type analog carrier systems were developed, they economically fulfilled a need for circuits in the range of about 15 to 150 miles in length. Systems can be combined in various ways to provide up to 16 single-sideband, two-way, voice-grade channels on a single open-wire pair. Equivalent four-wire transmission is used [2, 3]. Crosstalk control sometimes requires special engineering of open-wire transpositions along the line.

Three of the four O-type systems use frogging repeaters which provide attenuation/frequency equalization by inverting and interchanging the frequency bands for the two directions of transmission. In the fourth, cable slope is small enough to be ignored in respect to overall equalization. As a result, only flat-gain regulation is required.

Achievable repeater spacings and the distances at which O-type systems are economical depend on local conditions. These parameters are significantly affected by terrain, population density, pole-line congestion, and environmental conditions such as rain, ice, sleet, and frost.

### O-Type Terminals

The O-type systems are designated OA, OB, OC, and OD. The signal spectrum for each of the four systems covers a different frequency band so that the four signals may be transmitted simultaneously over a single open-wire pair. Each system provides four single-sideband, two-way, voice-grade channels in a twin-channel arrangement illustrated in Figure 11-1. Two channels each modulate a single carrier at 184 kHz or 192 kHz. The upper sideband of one modulator output and the lower sideband of the other modulator output are selected and combined to form the twin-channel spectrum. The carrier signal is suppressed in the two modulators; where the two independent sidebands are combined, a carrier signal is added to provide power for regulation at the intermediate repeaters and for regulation and demodulation at the distant receiver.

Equivalent four-wire transmission is used on the open-wire pair. The four single sideband channels, numbered from 1 through 4, that make up each O-type system must be transmitted in one direction in one frequency band and in the other direction in a different frequency

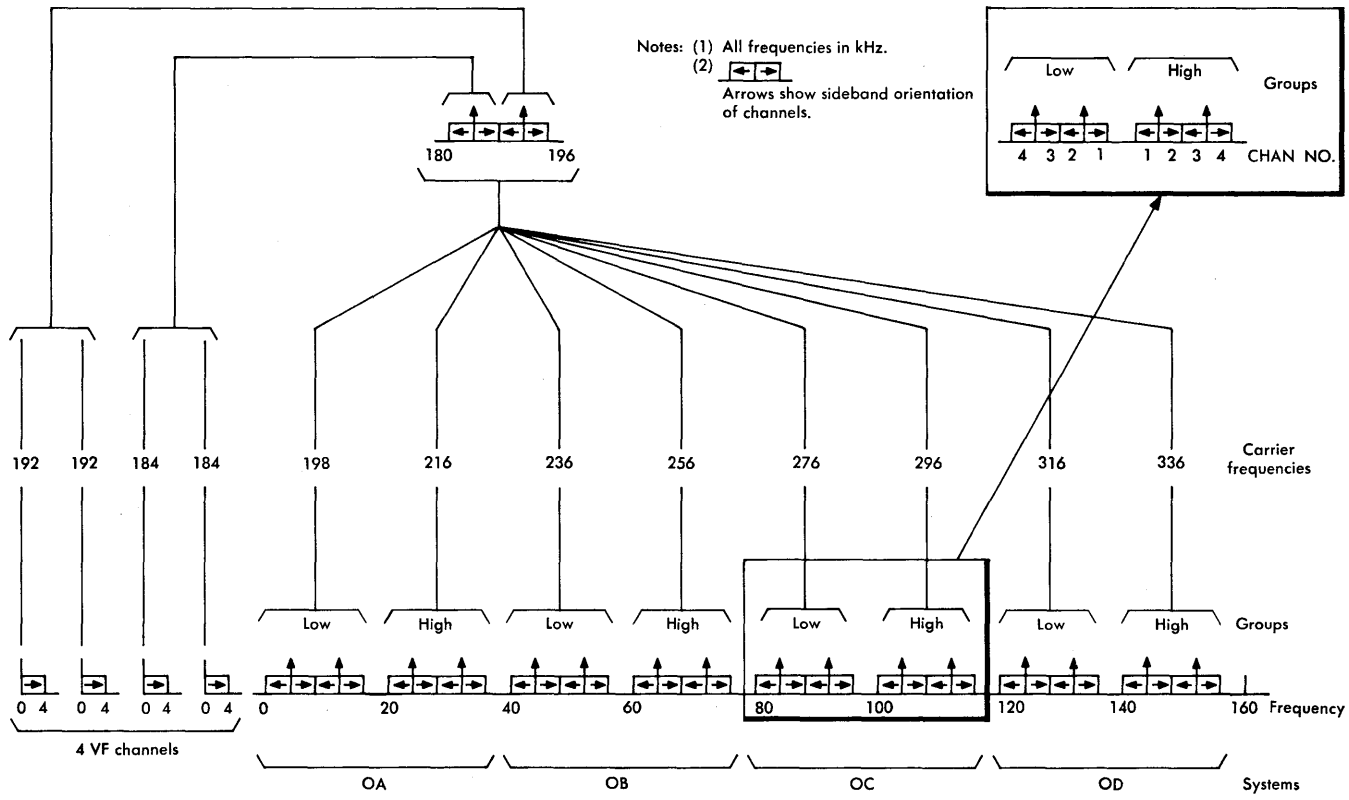


Figure 11-1. O-type carrier modulation plan and frequency allocations.

band. These bands, as illustrated in Figure 11-1, are called the *low group* and the *high group* for each system. At any terminal, either the high group or the low group may be used in the transmitting direction; the alternate group must then be used in the receiving direction. Thus, the modulation plan must provide for these alternatives.

The principal terminal functions of modulation, demodulation, multiplexing and demultiplexing are performed in the channel, twin-channel, and group units shown in Figure 11-2. Similarity among units required for the various O-type systems provide economic advantages in manufacture and maintenance. Only four types of channel units and two types of twin-channel units are needed. All of the channel units are identical except for the plug-in bandpass filters used in the carrier-frequency subassembly; thus, only two filter codes are required. The twin-channel units are also very similar and require only a selection of the oscillator crystal units and the pick-off filter used to select the incoming carrier signal. Group units are similar for OB, OC, and OD systems; they are different for OA systems because of the low frequencies of operation. Differences in the frequency ranges over which the OB, OC, and OD systems operate are accommodated by the selection of plug-in filters which determine the frequency spectrum and whether the operation is in the high or low group. Connections to the appropriate oscillator must also be selected for proper operation of modulators and demodulators.

**Channel Units.** Figure 11-3 shows how the signalling paths interconnect with the transmission paths in an O-type channel unit. The channel unit is made up of three subassemblies. In the compressor subassembly, provision is made for direct connection to a four-wire circuit or, optionally, through a resistance hybrid and network to a two-wire circuit. Each compressor and expander subassembly contains a low-pass filter to limit the VF band to about 3100 Hz. The carrier-frequency subassembly contains a modulator and a demodulator and a plug-in bandpass filter assembly to select the desired sidebands. The frequency and sidebands shown in the figure illustrate one set of options, (1) to transmit the lower sideband of a modulated 184 kHz carrier (channel 1) and receive the upper sideband of a modulated 192 kHz carrier (channel 4) or (2) to transmit the upper sideband of the 192 kHz carrier and receive the lower sideband of the 184 kHz carrier. A similar set of options must be chosen in respect to the opposite sidebands of the two carriers from those illustrated (channels 2 and 3).

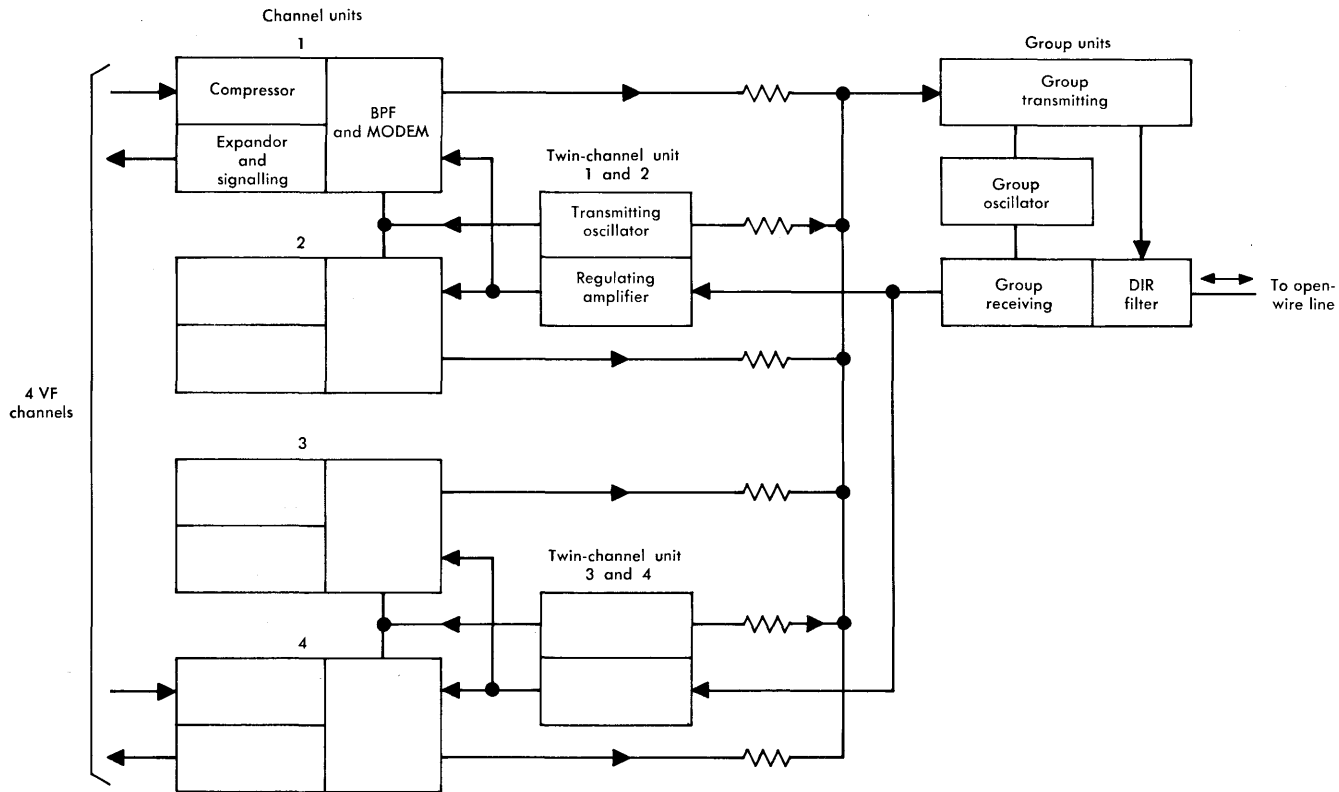


Figure 11-2. Block diagram of typical O-type system terminal.



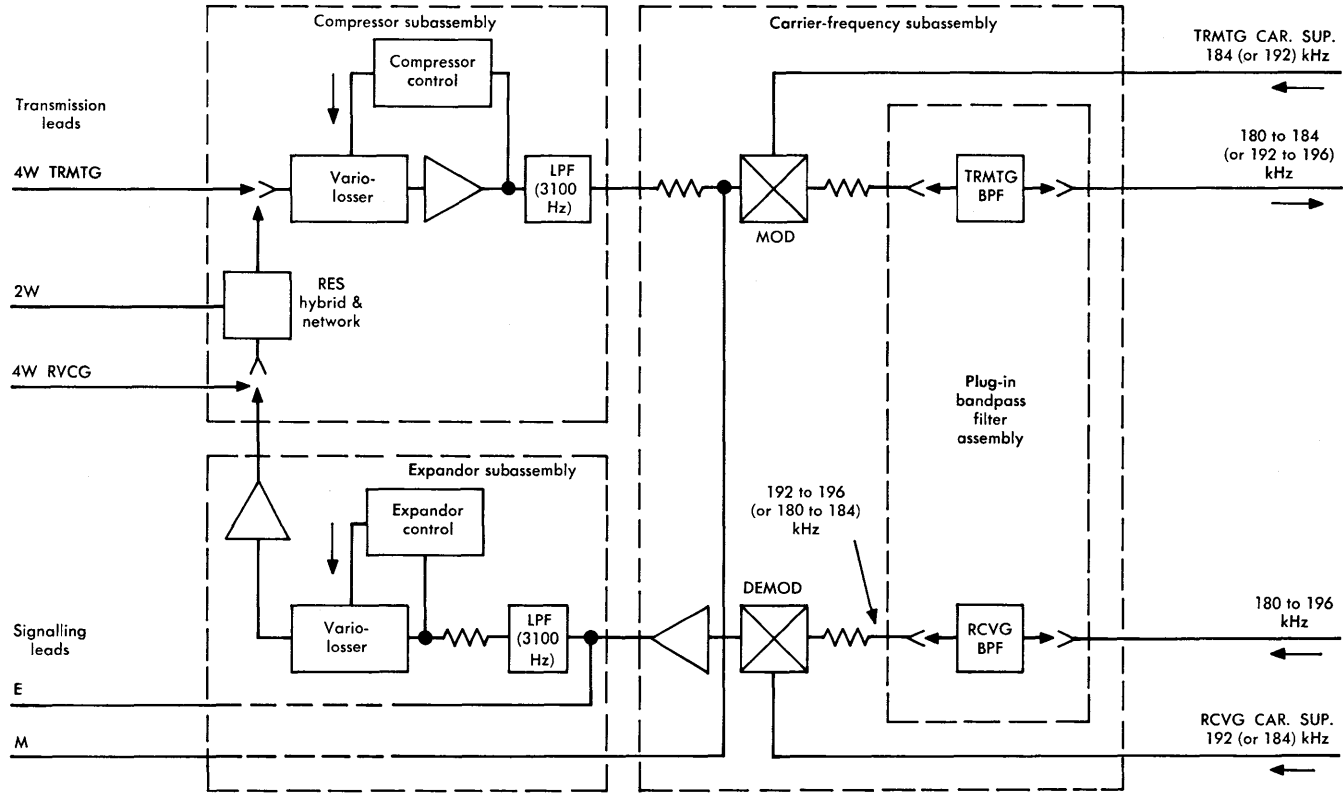


Figure 11-3. Block diagram of O-type channel unit.

**Twin-Channel Units.** As shown in Figure 11-2, the signal transmitted from the channel unit does not pass through the twin-channel unit. Figure 11-4 shows that for the transmitting direction, the twin-channel unit provides a carrier signal of 184 or 192 kHz to the channel unit modulator and demodulator. It also supplies a carrier signal to be added to the group signal for transmission over the open-wire line. In the receiving direction, the full twin-channel spectrum is transmitted through the twin-channel unit. The received carrier is picked off and used to regulate the incoming signal. It is also transmitted to the appropriate channel unit for demodulation of the signal.

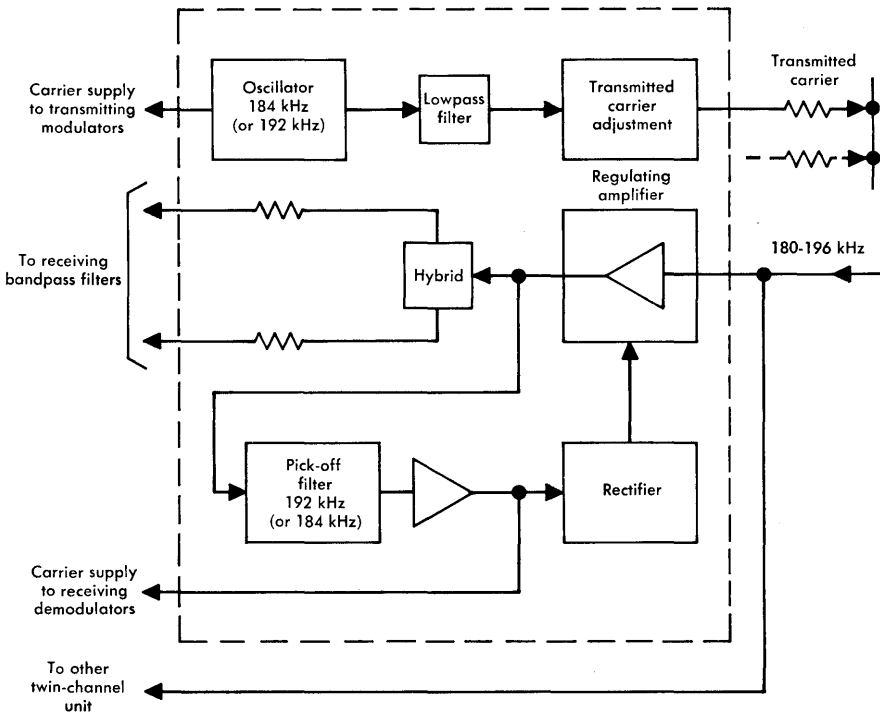


Figure 11-4. Block diagram of twin-channel unit.

**Group Units.** The block diagram of Figure 11-5 shows the manner in which group-band signals are treated. The figure shows frequency bands and carrier frequencies for the OB system. Similar circuits are used for OA, OC, and OD; the OA arrangements differ in some details

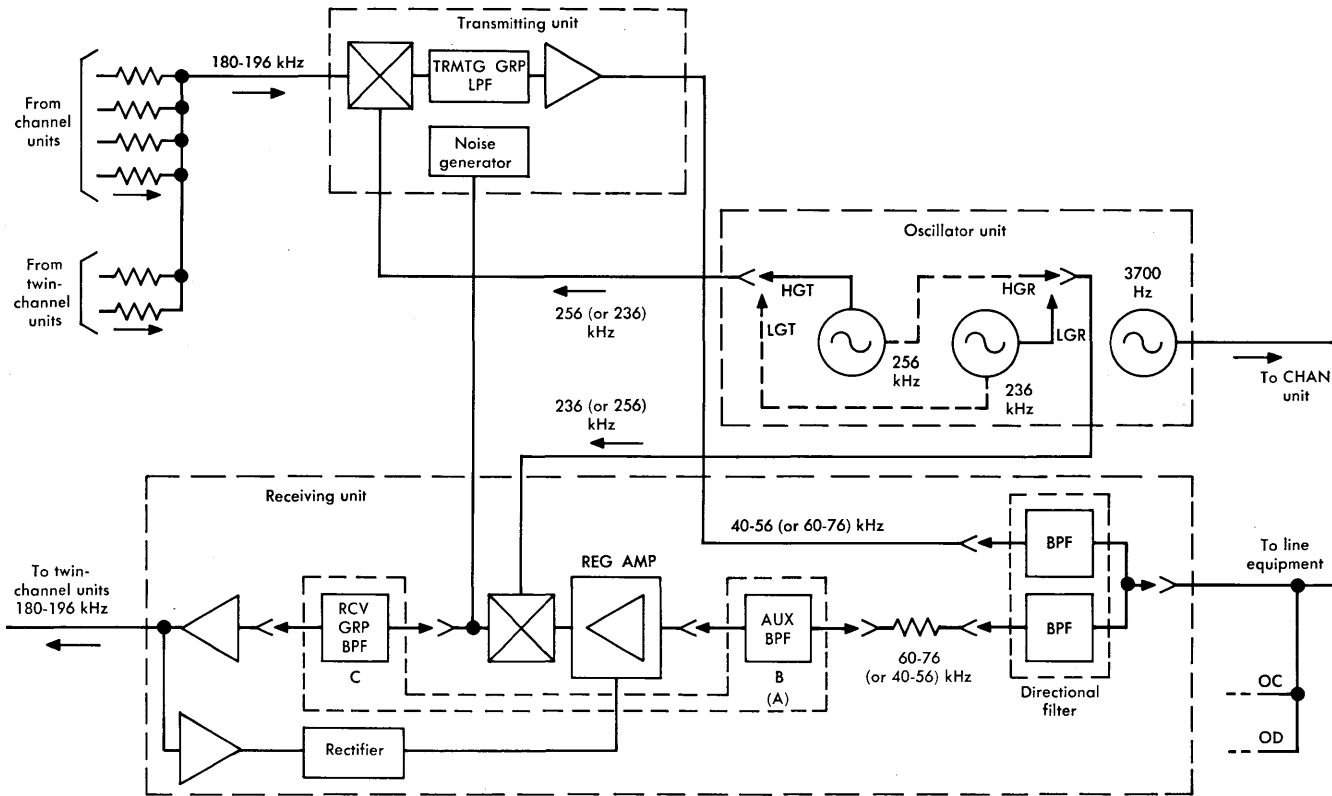


Figure 11-5. Block diagram of OB group transmitting, oscillator, and receiving units.

because of the low-frequency operation of this system. Three separate units are used for group-band signals. A transmitting unit accepts and combines at the input the four single sideband channels comprising the group and the two carrier signals associated with them. A receiving unit selects the desired four-channel group, regulates the signal amplitude, and modulates the signal to the common 180 to 196 kHz frequency band for transmission to the two channel units. An oscillator unit provides a 3700-Hz tone for out-of-band signalling over each of the channels of the group and the required carrier signals for use in the transmitting and receiving group modulators.

The optional connections shown in the oscillator unit of Figure 11-5 are used to select the required mode of operation of the terminal. The frequencies of the oscillators determine the operating frequencies of the system (OA, OB, OC, or OD) and the connections determine whether the terminal is to operate high-group-transmit-low-group-receive or low-group-transmit-high-group-receive. The frequencies shown are those required for OB system use.

After channel unit and twin-channel carrier signals are combined at the input to the transmitting unit, the composite group signal is modulated to the assigned position in the line signal spectrum. The signal is passed through a low-pass filter to remove the unwanted upper sideband, amplified, and combined in the directional filter in the receiving unit with the signal for the opposite direction of transmission. At the line side of the receiving group unit, the OB, OC, and OD system signals are combined for line transmission. Combining these signals with OA system signals is accomplished in an office- or pole-mounted line filter. This arrangement was provided so that OB, OC, and/or OD systems could alternatively be combined with C-type carrier system signals. A noise generator is also included in the group transmitting unit. Its output is added to received group signals to mask crosstalk from the line.

At the line-side input to the group receiving unit, the received line signal is applied to a directional filter as shown in Figure 11-5. This filter has the function of combining and separating (depending on the direction) the high- and low-group signals of the O-type system. It must be selected for the appropriate system frequency bands. In the receiving direction, the group-band signal is additionally filtered by the AUX BPF, B (or A), to eliminate residual unwanted signal components. The signal then passes through a regulating amplifier and is

modulated to the common group-band of 180 to 196 kHz. At the output of the modulator, the signal passes through the RCV GRP BPF, C, to select the wanted sideband. Plug-in filters C and B (or A) must be selected for the low or high group and appropriately applied for the particular O-type system. They are assembled in one subunit.

### Line Repeaters

The transmission plan for O-type systems involves a number of options that are determined by the distance between terminals, the number of systems to be combined on one open-wire line, and environmental weather conditions which exert a strong influence on transmission line losses. Repeaters are spaced at distances determined by the operating frequency band, the transmission line loss, and the regulation range required to compensate for line loss variations. The repeater spacing may be different for some systems than for others even though they are combined for use on a single open-wire pair. Where OA systems only are used, repeaters may be spaced at distances as great as 50 miles.

Line repeaters perform four functions: (1) they separate the frequency bands of the respective systems and separate the two bands used for equivalent four-wire transmission in each system; (2) by a modulation process, they transpose each incoming group for transmission over the next line section; (3) they provide amplification to compensate for line loss; and (4) they regulate repeater gain to compensate for line loss changes. Repeaters for OB, OC, and OD systems perform all four of these functions. Repeaters for OA systems do not modulate the signals into opposite transmission bands but otherwise perform the same functions as the others.

The transmission plan is illustrated in Figure 11-6. The figure shows the difference between an OA repeater and an OB repeater. The layout of OC and OD repeaters is similar to that of an OB repeater. To illustrate the effect of repeater modulation on the frequency plan, consider the translations that occur in an OB system under several conditions. Assume first that signals are transmitted from the west terminal in the high OB band, 60 to 76 kHz. These signals are translated at the repeater and are thus received at the east terminal in the low band, 40 to 56 kHz. The east terminal must be arranged to receive such signals and to transmit in the high band toward the west terminal. In this case, both terminals are arranged for high-

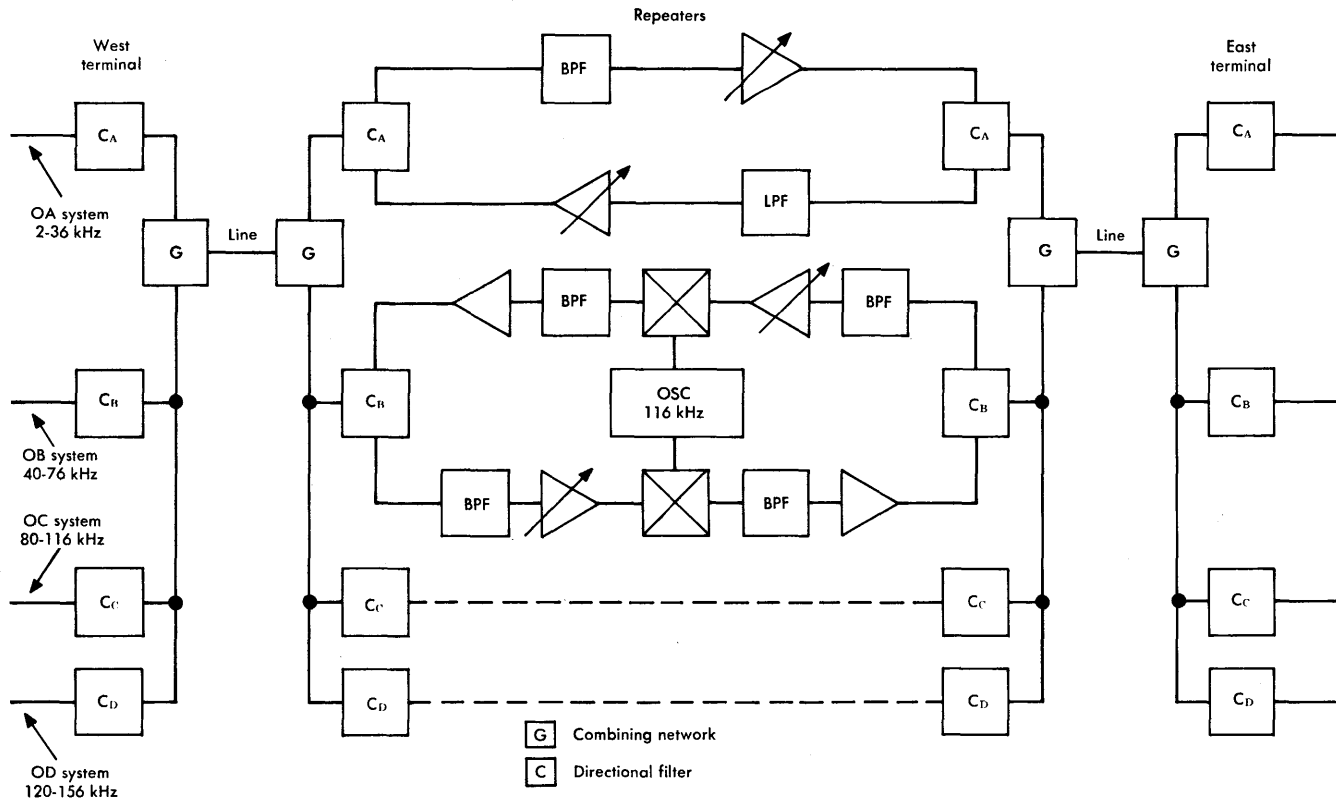


Figure 11-6. Transmission plan for O-type systems.

band transmitting and low-band receiving. However, if line cable losses require a second repeater, a second frequency translation occurs and the east terminal must be arranged to receive high-band signals and to transmit low-band signals. These translations occur in OB, OC, and OD repeaters but not in OA repeaters.

In order to distinguish between the two directions of transmission, O-system repeaters are arbitrarily designated in terms of east-to-west (EW) transmission or west-to-east (WE) transmission. Thus, an OB, OC, or OD repeater connection may be designated east-to-west high/low, east-to-west low/high, west-to-east high/low, or west-to-east low/high. In OA, the designations are east-to-west high/high, east-to-west low/low, west-to-east high/high, or west-to-east low/low.

In an OB system repeater, the equipment units used for the two directions of transmission are identical except for the bandpass filter units which must be selected for high/low or low/high operation. Amplifiers are all designed to cover sufficient bandwidths so that they may be used in OB, OC, or OD repeaters. In the OA system, the amplifiers are of the same design as those used in the terminal group receiving units. Nominal gain, which is flat with frequency, may be adjusted to accommodate the average line section loss and to center approximately the regulation range of the regulating circuits. These circuits operate so that an input signal amplitude variation of about 40 dB is reduced to about 1.5 dB at the output.

As previously mentioned, equalization of O-type systems is accomplished as a direct result of the frequency frogging scheme used at each repeater. The slope of the line loss is effectively inverted in succeeding repeater sections and cancels so that, over a channel bandwidth, the attenuation/frequency characteristic is within tolerable limits. Short nonrepeated systems do not normally require equalization. Frequency frogging is not employed in OA system repeaters because the line loss characteristic over the OA frequency band is essentially flat and does not require equalization.

## 11-2 N-TYPE REPEATERED LINES

The N-type carrier systems are designed to provide analog transmission over cable pairs. In most applications, two pairs are used, one for each direction of transmission. The two pairs may be in the same cable. Frequency frogging is used at each repeater in order to minimize crosstalk and to provide equalization.

Several versions of N-carrier repeaters have been designed. The earliest, called N1 repeaters, were based on electron tube technology. Many of these repeaters are still in service and many have been converted to solid-state operation by the use of Hybrid Integrated Network devices designed to replace the electron tubes. The N1A, a solid-state version of N1, is also in service; the N2, a completely new design, is now the only version in manufacture. All solid-state N-carrier repeaters can now be adapted for equivalent four-wire transmission to permit N-carrier operation over a single cable pair.

### Transmission Plan

All types of N-carrier line equipment use essentially the same transmission plan. The signals are transmitted in a high-frequency group (172 to 268 kHz) or in a low-frequency group (36 to 132 kHz)\*. The terminals are arranged to receive the group opposite to that transmitted. At each repeater, the two groups are interchanged by a modulation process in which a 304-kHz carrier is used. Thus, a repeater may receive signals in the low group from both directions and transmit in the high group in both directions (a low-high repeater) or vice versa (a high-low repeater). The high-low version is illustrated in Figure 11-7. Multiple frequency translations are illustrated in Figure 11-8. The modulation process at each repeater results in frequency frogging and serves three important purposes: circulating crosstalk paths around the repeater are blocked, the system is self-equalizing for as many as ten repeater sections, and average repeater spacing is equal for the two directions of transmission.

The design of N-type systems is based on the double-sideband transmission of 12 two-way voice-frequency signals with transmitted carriers. The total power of the carriers is used to activate the N-carrier regulation system. A later design of multiplex terminal equipment, the N3, provides for the transmission of 24 two-way voice-frequency single-sideband signals with suppressed carriers. Carrier signals, spaced at 8-kHz frequency intervals, are added to the multiplexed channel signals to provide signal power for regulation, frequency correction, and demodulation.

\* An additional 8-kHz band (132 to 140 kHz in the low band and 164 to 172 kHz in the high band) is available for use if interference precludes the use of any other channel.



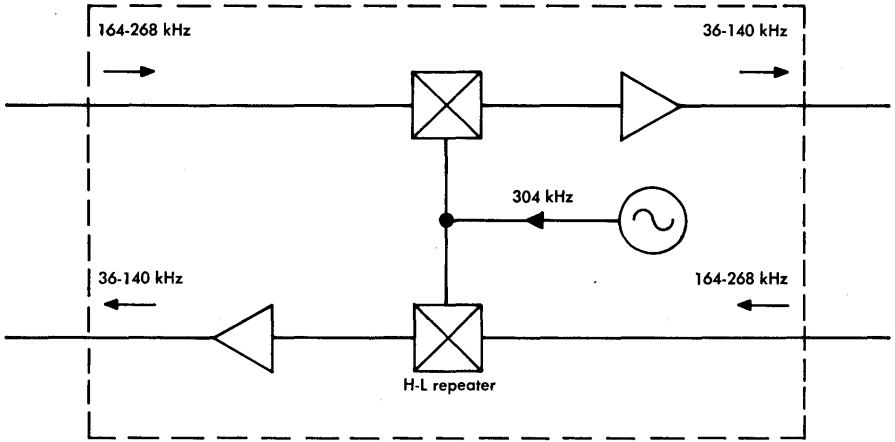


Figure 11-7. Frequency frogging at an N1 high-low repeater.

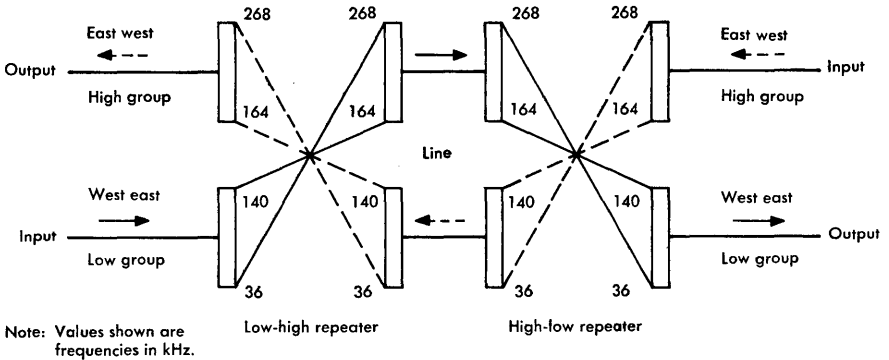


Figure 11-8. Frequency translations along an N-carrier repeatered line.

Paired or quadded cable conductors of 16-, 19-, 22-, or 24-gauge can be used with appropriate repeater spacing. The nominal spacing is 5 miles for 19-gauge and 3.5 miles for 22-gauge conductors. There is no specified limit on the percentage of pairs that may be assigned to N-carrier use in a cable.

Line repeater spacing in N-carrier systems is based on satisfactory noise performance rather than achievable repeater gain. In some

cases, noise (especially impulse noise in cable sections near a central office) is excessive and can be overcome by the installation in the offending section of a fixed 20-dB flat-gain amplifier to increase signal amplitudes. Pads must be installed at the central office or at the next repeater point to reestablish the proper transmission level points.

The N-carrier systems are designed to provide service over distances up to 200 miles. The line layout, repeater spacings, and repeater circuit designs are based on the general principles described in Chapter 10. However, the line noise requirements are approximately 25 dB less stringent than would be permitted on the basis of a proportional distance allocation of long-haul objectives. This less stringent requirement results from the use of compandors in the multiplex terminals and the hierarchical organization of the DDD network which limits the number of N-type systems that might be in tandem on long connections [4].

Performance of early N-carrier systems was degraded by a pulsating variation in overall system gain (carrier beat) caused by the lack of synchronization between the 304-kHz oscillators and by insufficient out-of-band discrimination in the repeater filters. Later repeater designs have incorporated sufficient loss in these filters and improved filter designs have been provided for installation in affected systems of early designs.

## N1 Repeaters

A block diagram of an N1 repeater is shown in Figure 11-9. Two versions of this repeater are used, the high-low and the low-high. The block diagram applies to both versions and the only circuit differences are in the frequency bands over which the high- and low-pass filters operate. Repeaters may be placed in pole- or pedestal-mounted cabinets, on equipment racks in central office buildings, or in repeater huts on routes with large numbers of systems.

The line repeaters of an N1 system can be discussed conveniently in terms of (1) amplification, modulation, and filtering, (2) equalization and regulation, and (3) remote powering arrangements. Much of the discussion applies equally to N1A and N2 repeaters.

**Amplification, Modulation, and Filtering.** The amplifiers shown in Figure 11-9 are of two-stage, electron tube, negative feedback design. The gain is nominally flat and is factory-adjusted to 48 dB. Automatic

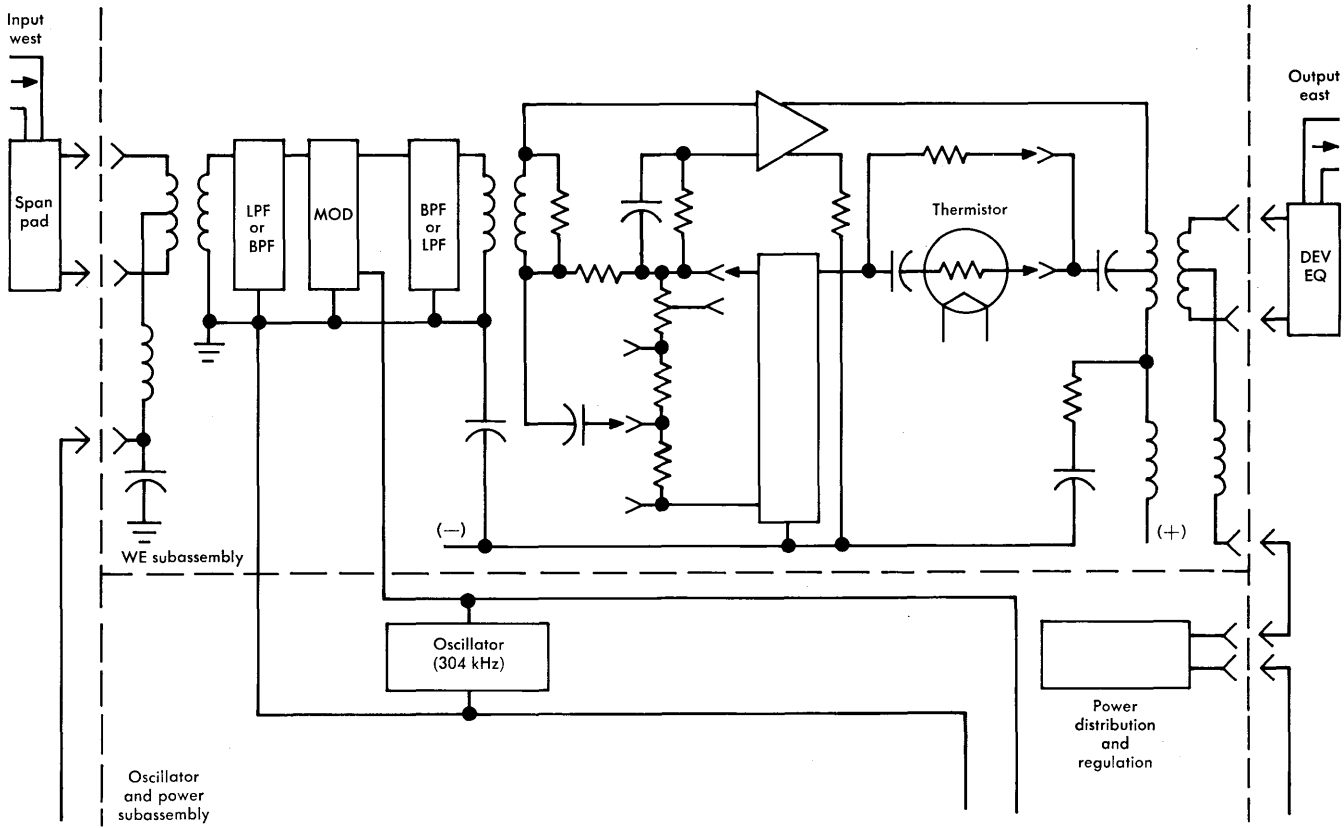


Figure 11-9. Block diagram of N1 repeater (continued).

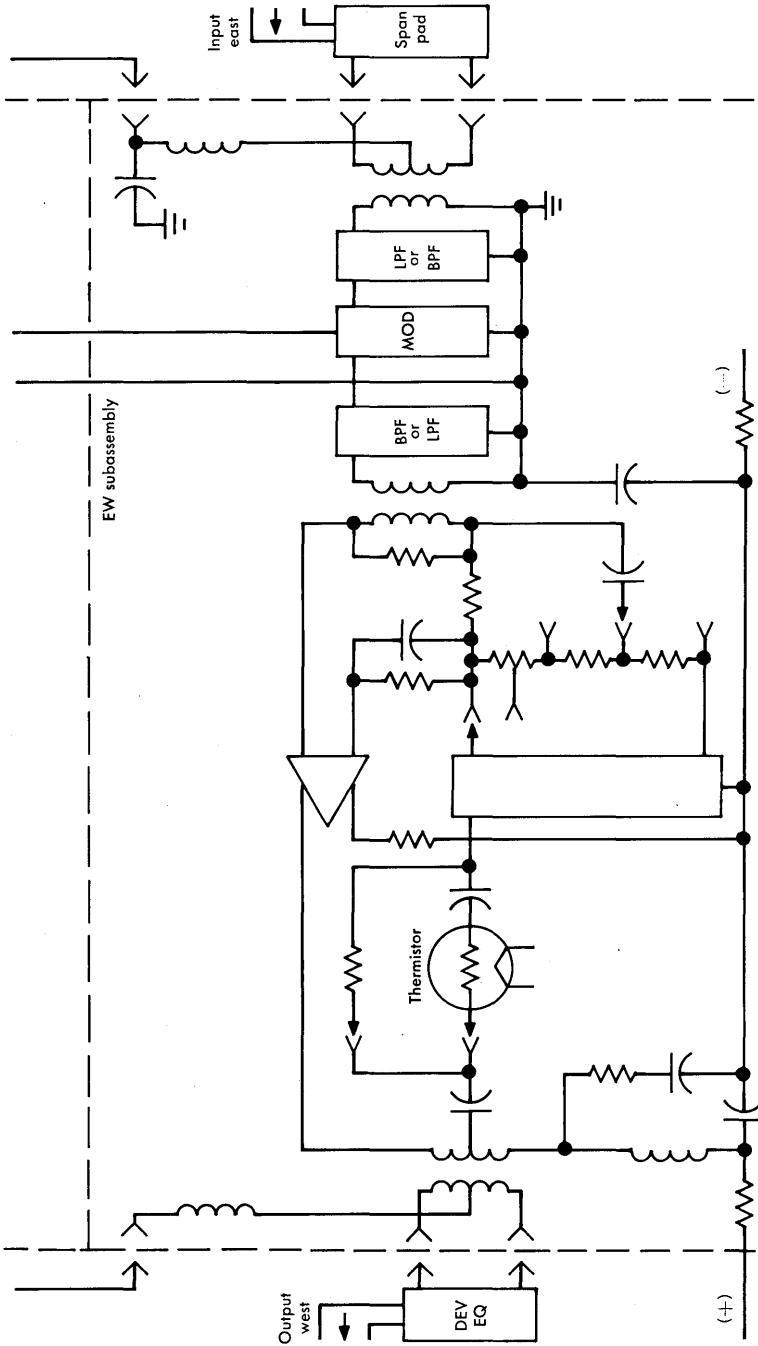


Figure 11-9. Block diagram of N1 repeater.

flat-gain regulation is provided by a thermistor in the feedback circuit. Slope can be introduced in the gain-frequency characteristic to supplement other forms of equalization of the system attenuation/frequency characteristic.

The filters shown at the input and output of the double-balanced, ring-type modulators in Figure 11-9 determine the mode of repeater operation, high-low or low-high. At the inputs to the modulators, filters accept the high or low group and suppress any noise or other unwanted signal outside the group band. The filters at the outputs of the modulators suppress the unwanted components of the modulated signal and any 304-kHz carrier signal that may leak through the modulator.

**Equalization and Regulation.** The several types of equalization and regulation used in an N1 repeatered line include the previously mentioned frequency frogging and amplifier feedback adjustments. In addition, span pads, artificial cable sections, and deviation equalizers are used. A dynamic deviation regulator may also be used where required.

The first step in equalizing N1 lines is the frequency frogging process in which the frequency bands are inverted at each repeater so that, for each group, the highest-frequency channel in one line section becomes the lowest-frequency channel in the succeeding section. Thus, the slope of the line loss characteristic is effectively inverted and for many systems, no further slope correction is needed.

The slope correction found in the feedback circuit of the repeater amplifier can be used to supplement the equalization resulting from frogging. Such supplemental adjustments may be required where repeater sections are not quite equal in length and do not balance out adequately or where there are an odd number of cable sections.

Resistive span pads are used as illustrated in Figure 11-9 to build out short repeater sections to have 47 dB loss at 136 kHz in the low group or 168 kHz in the high group. These pads are available in steps of 2-dB loss from 2 to 36 dB. The slope adjustment in the repeater amplifier is then used to adjust the repeater slope to match the cable loss slope. For line sections less than four miles long, networks that simulate line losses of one-, two-, or four-mile sections are also used where appropriate.

The flat gain of the repeater is adjusted at the time of manufacture to give a repeater gain of 48 dB with a regulator thermistor resistance of 9000 ohms. Line signal power is dominated by power in the carriers. A portion of the transmitted signal is picked off at the repeater output, as shown in Figure 11-9, flows through the thermistor, and provides the necessary regulator control. The thermistor resistance can vary between 1000 ohms and 20,000 ohms and varies inversely with total carrier power.

Originally, the final correction of N1 line deviations was to have been accomplished in the adjustable deviation equalizer designed for use in systems ten or more repeaters long. The equalizer characteristic was based on the use of 19-gauge cable pairs and on repeaters of early production. The equalizer is installed at the input or output of a repeater as appropriate.

Subsequent to the design of the adjustable deviation equalizer, it was shown that more sophisticated regulation would be needed for lines using cable conductors of other than 19-gauge and for variations with time of all long systems. Residual loss/frequency deviation characteristics of working systems were analyzed and it was determined that a combination of four equalizer network characteristics could adequately compensate for these deviations. These network characteristics, designated *slope*, *bulge*, *cubic*, and *quartic*, are illustrated in Figure 11-10.

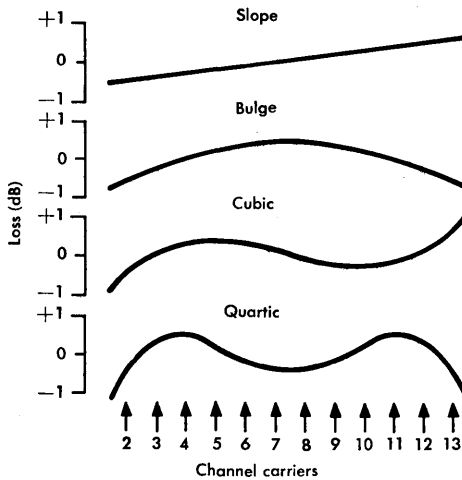


Figure 11-10. Loss/frequency characteristics of N-carrier deviation regulator networks.

The deviation regulator operates on departures from ideal amplitudes of the channel carriers in the N-carrier high group [5]. A separate regulator is used for each direction of transmission at the outputs of a low-high repeater. The power consumption is such that it must be used at a point where primary power is available (usually at a central office building). Figure 11-11 is a block diagram of the regulator.

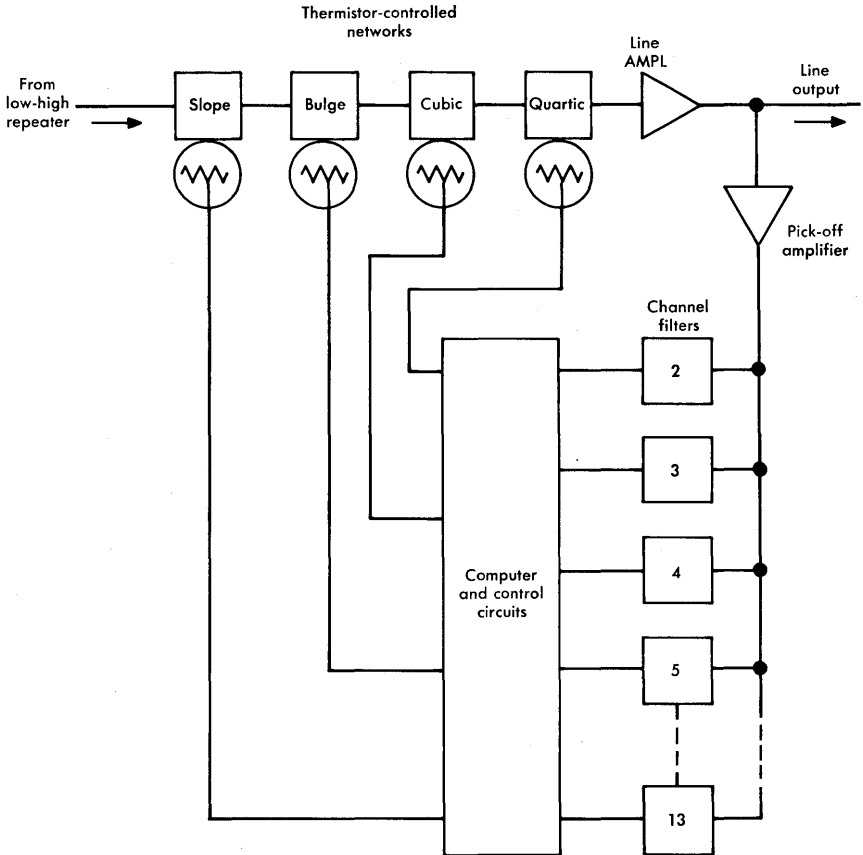


Figure 11-11. Block diagram of deviation regulator.

Various combinations of the four regulator network characteristics very closely correct deviations and, as a result, temperature changes are not now a controlling factor in limiting system length. The re-

quired amount of each characteristic is determined by a small, resistance-network computer that weights the deviation from ideal at each channel carrier frequency. The computer then applies a suitable value of direct current to each network thermistor to adjust the network and to correct the transmission deviation.

**Repeater Powering.** Where N1 repeaters are mounted in a central office, they are powered directly by central office batteries of  $-48$  and  $+130$  volts. Remote repeaters are powered by simplex circuit arrangements over the conductor pairs used for transmission. In this case, the battery supplies are of  $+130$  and  $-130$  volts. In all remotely powered repeaters, a series-parallel arrangement of electron tube and thermistor heaters is fed from a closely regulated voltage supply derived from a gas tube control circuit in the repeater. The electron tube heater voltage and current are held closely to lower nominal values than are used in central office equipment and, as a result, tube life is appreciably increased.

In most cases, only one remote repeater can be powered in each direction from a central office, especially where repeater sections are of maximum length. Thus, N1 systems are limited to a maximum of 3 cable sections between power feed points. Where central office buildings are not suitably located, special engineering is required to provide the necessary power feed.

### N1A Repeaters

The design of N1A repeaters was based on the need for improved repeatered line reliability and increased efficiency of remote repeater powering. Reliability was increased by the use of solid-state circuitry. In addition, the reduced power requirements of these circuits made it possible to serve three remote repeaters in each direction from a power feed point. Conversion from N1 to N1A operation requires only that the remote powering circuit arrangements be changed and new repeater mountings be provided.

The N1A may be considered as an interim solid-state repeater design intended to fulfill an urgent need for modern circuitry and more economical operation. As in all N-type repeaters, line equalization is primarily a result of the frequency-frogging technique used at each repeater. In addition, the N1A provides automatic flat-gain regulation on the basis of average transmitted signal power. Each N1A repeater also has manual adjustments of flat gain, slope, and bulge to correct deviations in the line characteristics.



## N2 Repeatered Line

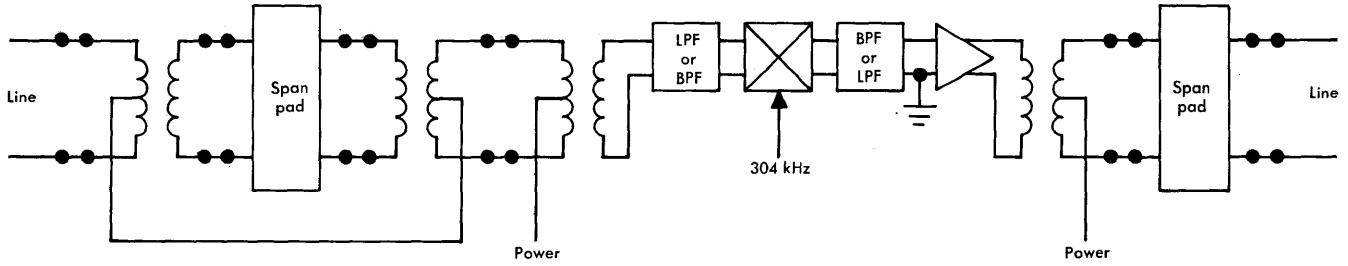
With the development of the N2 repeaters, all associated line equipment was redesigned for improved performance and the application of more modern technology. The transmission plan for N2 lines follows the traditional pattern of N-type systems. Two cable pairs are used, one for each direction of transmission, and frequency frogging is applied at each repeater point. Thus, high-low and low-high repeaters are used alternately along the line. However, there are many differences in detail between the N2 line equipment and that of earlier designs [6].

**Design Requirements.** A high degree of physical and electrical compatibility with the earlier N1 and N1A designs was a primary requirement in the design of N2 line equipment. Thus, the N2 line has the same repeater spacing, transmission level point, crosstalk, and gain control requirements as the earlier systems. In addition, dc power provision and system assignments are compatible with the earlier systems but somewhat more flexible due to the provision of new cross-connect facilities.

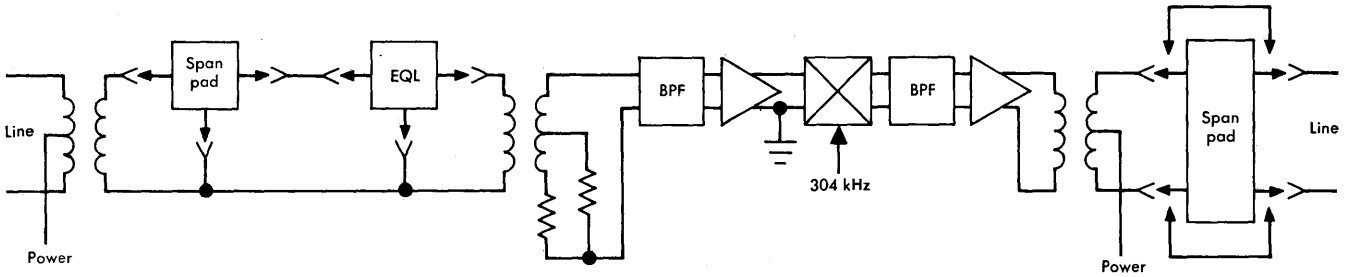
A number of transmission requirements were imposed on N2 that were more stringent than those of the earlier systems. These include a reduction from about 2.5 dB to 0.5 dB in the departure from flat over any 3-kHz band of the attenuation/frequency characteristic in a 40-repeater line, an improvement of initial oscillator stability in the line repeaters from  $\pm 20$  Hz to  $\pm 2$  Hz along with a substantial reduction in variations due to aging and temperature changes, and a 3-dB increase to 71 dB in the equal level crosstalk coupling loss between the two halves of a repeater.

**Repeater Design.** The N2 repeater, like the N1 and N1A, is a plug-in unit; it is made up of an assembly of five plug-in subunits. These subunits are composed of two identical modulator units, two identical amplifier units, and an oscillator unit. These plug-in arrangements make maintenance and operations significantly simpler than for the N1 and N1A.

Figure 11-12 shows block diagrams of N1, N1A, and N2 repeater equipment. Included in the figure are plug-in repeater and ancillary equipment mounted in the repeater frame. The many black dots in Figure 11-12(a) show how the ancillary equipment must be soldered into the circuit at an N1 or N1A repeater. Figure 11-12(b) shows that this is plug-in equipment in N2.



(a) N1 or N1A repeater equipment



(b) N2 repeater equipment

Figure 11-12. Repeater block diagrams (one direction of transmission).

The N2 repeater modulator differs from the earlier designs in that signals are amplified at the input by a preamplifier to provide improved noise performance. A three-stage amplifier provides additional gain after modulation. The bandpass filters are also of an advanced design so that crosstalk and transmission deviations are less than in the N1 and N1A repeaters.

The N2 repeaters use 3-stage transistor feedback amplifiers which provide proper terminations for the modulators and transmission lines. The linearity of these amplifiers is superior to the older designs; as a result, the intermodulation noise is lower than in the earlier designs. The gain of the repeater can be determined by an in-service ohmmeter measurement of the resistance of the regulating thermistor used in the feedback network of the repeater amplifier. The input span-pad value can be determined from this measurement and selected so that the regulator operates in the desired midrange. Improved maintenance features are also provided for the N2 repeater and the use of maintenance equipment is facilitated by the repeater design.

**Equalization and Regulation.** As in the earlier N-type repeaters, the primary equalization of cable slope is accomplished by means of frequency frogging. In addition, the N2 repeater can accommodate fixed plug-in equalizers which have characteristics inverse to those found in the line. These fixed equalizers are available in several values as shown in Figure 11-13. Methods are specified for determining which of the available fixed equalizers is optimum for the partial correction of the transmission characteristic at selected repeaters. Deviation equalizers are used in longer systems where the fixed networks used at repeaters cannot perform adequately. These equalizers are continuously adjustable over a range of  $\pm 10$  dB of slope correction and  $\pm 5$  dB each of bulge, cubic, and quartic corrections.

TYPE	VALUE, dB
Slope	$\pm 3, \pm 6, \pm 9$
Bulge	+2, +4
Cubic	$\pm 1$
Quartic	$\pm 1$

Figure 11-13. Fixed equalizers available for N2 repeaters.

Flat-gain adjustments are made by the selection of plug-in span pads used at the input and output of a repeater as shown in Figure 11-12(b). The span pads have flat losses in increments of 2 dB from 0 to 44 dB. Thus, by proper span-pad selection, the flat gain of a repeater may be adjusted to within  $\pm 1$  dB of the desired nominal value. More precise adjustment and automatic gain regulation to compensate for loss changes due to temperature variations are accomplished by the flat-gain regulator at each repeater. As in earlier systems, the N2 regulator operates on the basis of transmitted signal power which is concentrated primarily in the channel carriers.

**Repeater Powering.** In N1 and N1A repeatered lines, the power arrangements are based on constant-voltage circuit designs. In the N2 repeatered line, the power supplies are based on a constant-current regulator at the power source to hold the line current stable under all the variable conditions encountered. This design can also be used with N1, N1A and combinations of N1A and N2 repeaters on one line.

Other improvements in the power circuitry have made installation and maintenance activities much more efficient. For example, power pick-off points in N2 repeaters, shown in Figure 11-12(b), are located in repeater mounting shelves rather than in the plug-in repeater units. Thus, the repeater circuits are completely isolated from the line voltages and currents.

**Cross-Connect Facilities.** For each of the N-carrier line equipment arrangements, cross-connect facilities provide flexible means for interconnecting cable pairs and multiplex terminals. In the N1 equipment, the line equalizers are applied by means of soldered connections which make changes and rearrangements difficult and time-consuming. In addition, dc power for remote repeaters appears on the cross-connection wires. Thus, changes in cross connections involve service and possible personnel hazards which can be avoided only by removing the power feed fuses.

For the N2 repeatered line, the power feed connections are made in a separate equipment bay called a line build-out (LBO) bay. Line build-out networks and equalizers are also mounted in this bay by plug-in arrangements. The N2 cross-connect bay is separate from the LBO bay and thus all cross connections are free of power feed voltages. In addition, transmission level points are controlled to facilitate interconnection between incoming cable pairs, outgoing cable pairs, office-mounted repeaters, and/or multiplex terminals. The N2 LBO

and cross-connect bays may be used with any N-type line and/or terminal equipment.

**Equivalent Four-Wire Lines.** Any N-carrier line that employs solid-state repeaters may now be operated on a single cable pair as an equivalent four-wire transmission system. Directional filters that meet very stringent requirements have been developed to permit this mode of operation while still meeting crosstalk requirements and the overall transmission needs of frequency frogging. Phase equalizers are also available to correct the phase distortion introduced by these filters and thus prevent "washout" when double sideband signals are transmitted [7]. The block diagram of circuit arrangements at a repeater point is given in Figure 11-14. This mode of operation may be used with N1A or N2 repeaters or with N1 repeaters that have been converted to solid-state by the use of Hybrid Integrated Networks. The advantage of this arrangement is the 50 percent saving of cable pairs which is usually greater than the cost of adding directional filters.

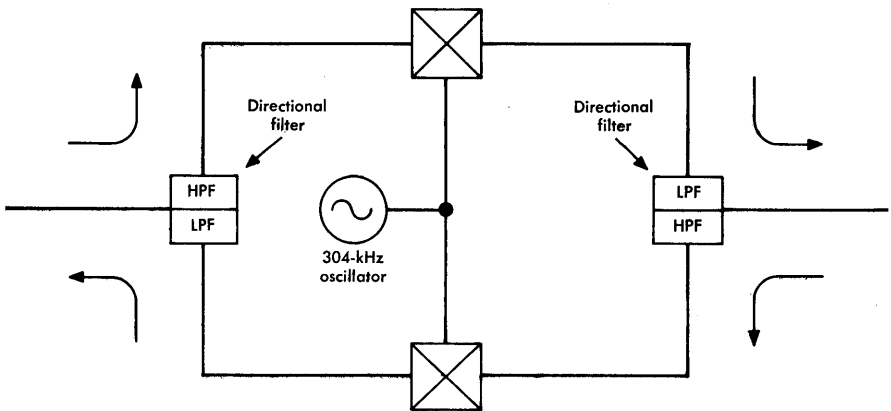


Figure 11-14. Equivalent four-wire N-carrier repeater arrangement.

### 11-3 N-TYPE TERMINALS

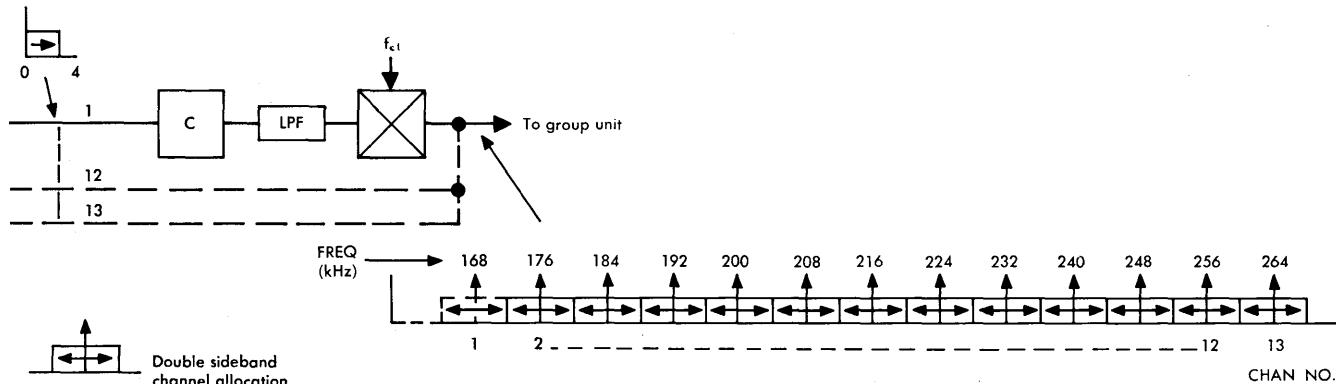
The development and design of new multiplex terminal equipment for N-carrier systems has kept pace with the evolution of N-carrier line repeater equipment. The N1 terminals were initially based on electron tube technology. As the use of open-wire line facilities was reduced, the O-type terminal equipment was gradually adapted for use on N-carrier lines. From this program evolved the ON1 and ON2

terminal arrangements both of which are also based on electron tube technology. These early designs may all be converted to solid-state operation by the use of Hybrid Integrated Network devices. Later terminals, designed specifically for use with N-carrier lines, include the N2 solid-state terminals which provide 12 double sideband channels in the same general format as that used in N1 terminals and the N3 terminals which provide 24 single sideband channels.

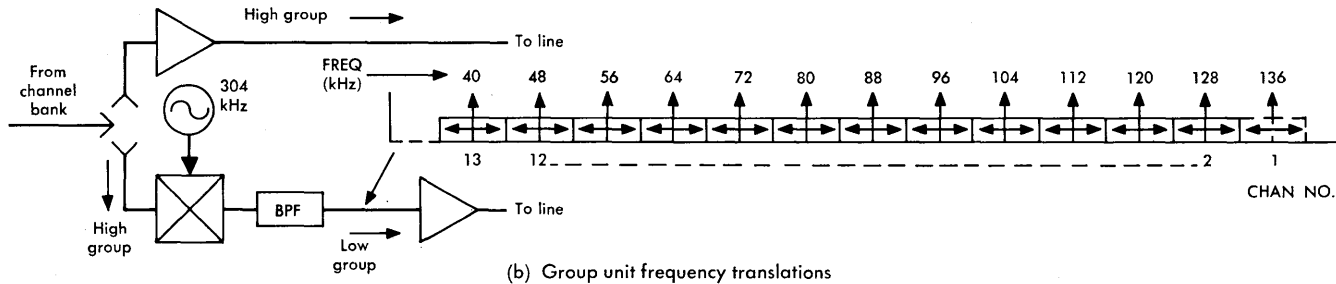
### The N1 Terminal

The transmission plan and frequency frogging technique used in N-carrier repeaters require that terminal equipment be arranged for high- or low-group transmitting and receiving. The N1 terminals provide 12 VF signals in a double-sideband transmitted-carrier format in the high-group band as illustrated in Figure 11-15(a). This group signal spectrum is applied directly to an N-carrier line where high-group transmission is required or, as shown in Figure 11-15(b), is modulated into the low-group frequency band where low-group transmission is required.

The N-carrier systems depend on the use of a syllabic compandor applied to each VF channel for achieving satisfactory signal-to-noise performance [4, 8]. As shown in Figure 11-15(a), the compressor portion (c) of the compandor is followed in the transmitting terminal by a low-pass filter. The high-frequency cutoff of this filter is between 3000 and 3200 Hz (depending on the equipment vintage). Where required, the 3700-Hz out-of-band signalling circuit is connected at the output of this filter. The VF signal (voice or signalling) is then modulated to the high-group N-carrier band where it is combined with 11 other signals that have been similarly processed to fall at different frequency positions in the group band. At the input to the channel unit modulator, there is a connection to a +130-volt dc bias supply. This voltage, controlled to within  $\pm 1$  percent of its nominal value, produces the necessary modulator unbalance to provide a well-controlled carrier signal component in the double-sideband modulator output. The power in these carrier signals is used at repeaters and receiving terminals to control the flat-gain regulators of the system. Although systems may be partially equipped, at least four channels must transmit the carrier signal to satisfy regulator operating requirements. The first four to be equipped are specified in the operating instructions.



(a) Voice-frequency to high-group modulation (channel bank)



(b) Group unit frequency translations

Figure 11-15. Frequency translations in N1 and N2 transmitting terminals.

Provision is made in the group units for a number of other features that are related to overall system performance. Random noise may be added to the channels to mask intelligible crosstalk on short trunks where noise may be of low amplitude. Cable slope pre- and post-equalization may also be introduced in transmitting and receiving terminals.

At receiving terminals arranged for high-group input from the line, the group signal is flat-gain regulated and then connected to filters where individual channel signals are selected and then demodulated. Additional regulation of each channel is provided at that point. Where the receiving terminal is arranged for low-group input from the line, the signal is first modulated into the high group and the above processes are followed.

### ON Junctions and Terminals

Two versions of ON-type equipment are available. The ON1 provides 20 channels and the ON2 provides 24 channels, each in the twin-channel O-carrier format, for transmission over an N-carrier repeatered line [9]. Wherever possible, existing O-carrier terminal equipment is used in the ON-type equipment. Additional modulators, filters, and other electronic equipment are used only where necessary to achieve the desired occupancy of the N-carrier frequency spectrum. Frequency allocations for ON1 and ON2, shown in Figures 11-16 and 11-17 respectively, are derived in the ON equipment from standard four-channel O-carrier groups.

The ON1 provides a signal primarily for transmission over a combination of wire-pair cable conductors with N-carrier repeaters and open-wire pairs with O-carrier repeaters. The ON2 signal is primarily transmitted over N-carrier lines only. Both signals may also be transmitted over microwave radio facilities.

An ON1 *junction* is used as an economical means of interconnecting O- and N-type lines without having to provide complete terminal equipment for both systems with voice-frequency interconnections. An ON1 *terminal* is used at the cable end of an ON1 system if it is not interconnected at that end with an O-type system. The ON2 terminals are used at both ends of an ON2 system.

An ON repeater is always required between an ON terminal or junction and the N-type high-frequency line in both directions of transmission. The primary function of this repeater is to convert the



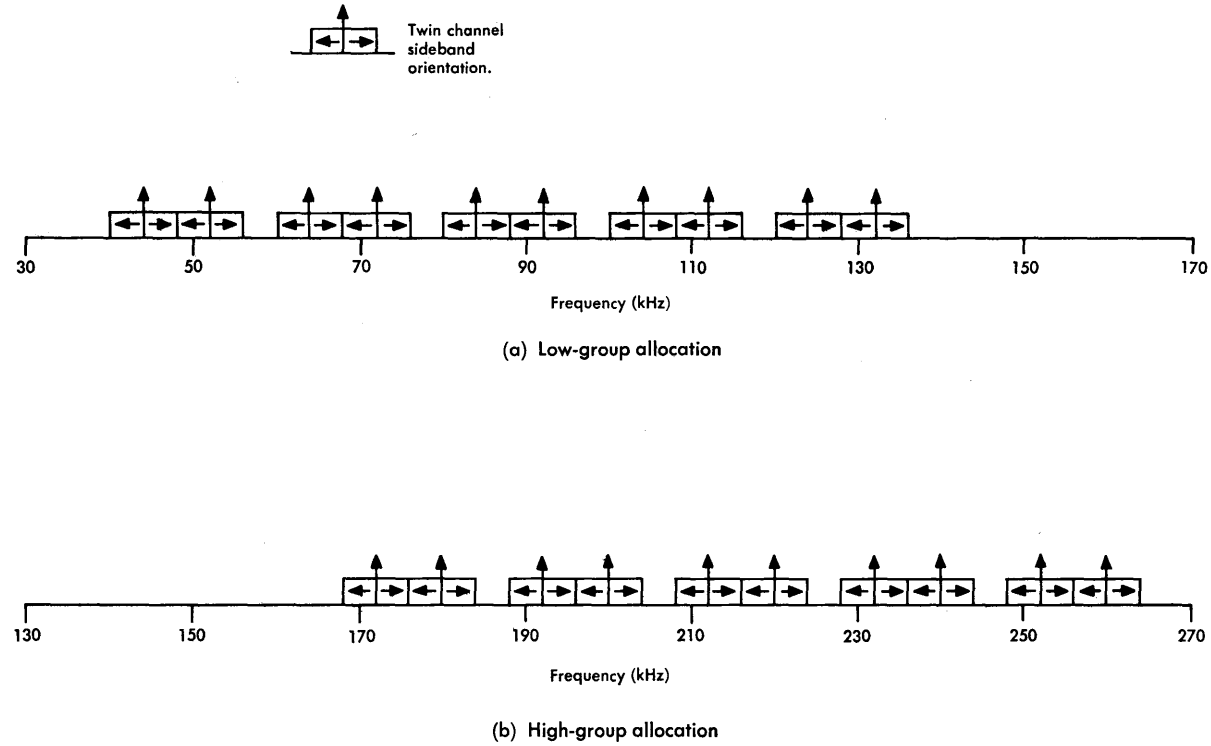


Figure 11-16. Frequency allocations for ON1 systems.

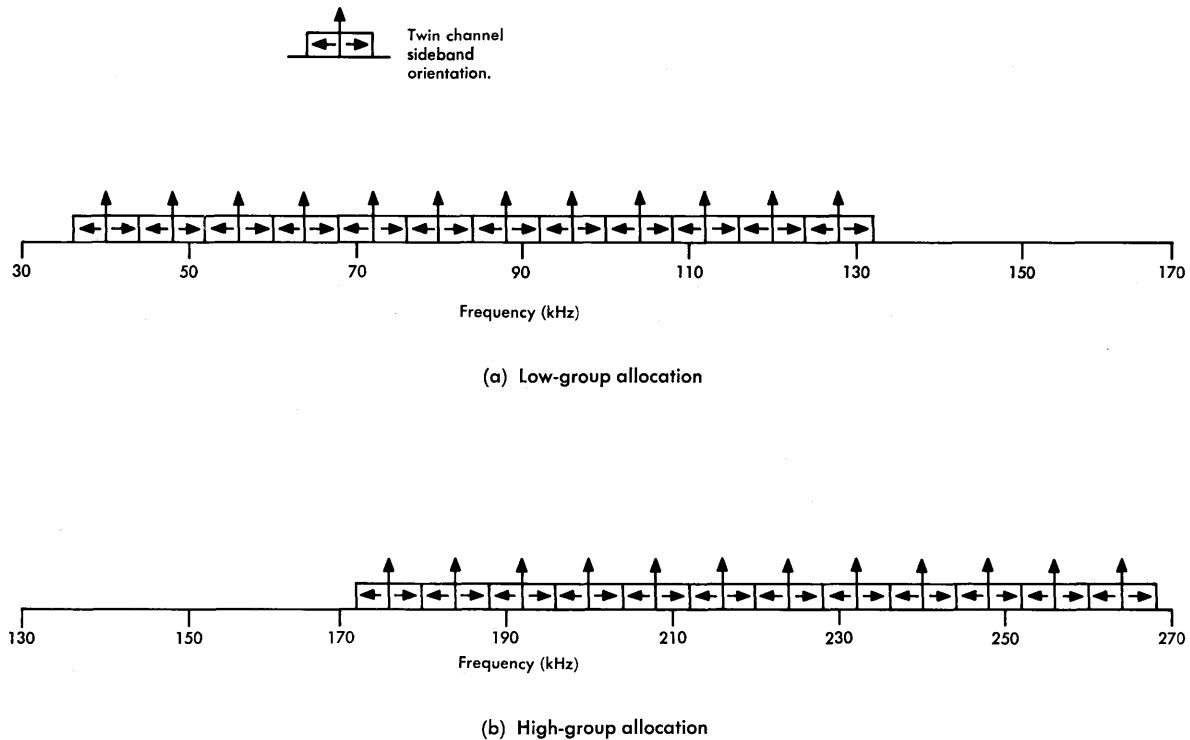


Figure 11-17. Frequency allocations for ON2 systems.

frequency spectrum of the low groups transmitted and received by junctions and terminals to the high- or low-group frequency band of the N-carrier line. The repeater consists of three subassemblies. One is a standard N-carrier low-high or high-low unit; one is a low-low unit; one is a 304-kHz oscillator unit.

## N2 Terminal

Although the previously described N1 terminal equipment is still in use in many locations, it is no longer manufactured. Where 12-channel systems are needed, N1 has been replaced by N2 terminal equipment which is based on solid-state technology [10]. The N2 also offers improved transmission performance, requires less space, uses less power, and provides better maintenance features.

**Objectives.** With the expansion of the switched message network and the rapid increase in demand for network trunks and special services circuits came a concomitant increase in demand for more stringent transmission and operating requirements on equipment such as N-carrier terminals. The more stringent objectives derive, at least in part, from the growing complexity of the facility network and the increasing probability of tandem operation of short-haul links. Thus, the transmission performance of each link had to be improved if overall connections were to continue to provide satisfactory service. Net loss variations with time, attenuation/frequency characteristics, channel bandwidth, random noise, impulse noise, and crosstalk all had to be improved in the N2 terminals.

In addition to these improvements, N2 terminals had to operate compatibly with existing line equipment. This meant that transmission level points, carrier frequencies, and transmitted carrier power had to match those of the earlier systems. However, no provision has been made for the operation of N1 terminals at one end of a line and N2 terminals at the other end because performance improvements in the N2 would be nullified by the N1 terminals with which they would be operating.

In the time interval between the development of N1 and N2 terminals, the inband E-type signalling system was developed. The performance of this system had proven to be superior to the 3700-Hz out-of-band signalling used with N1 and ON terminals. The inband signalling arrangement was used with N2 and permitted the design of channel bandpass characteristics that are significantly wider than

for N1. In N2, the high-frequency cutoff (3-dB point) is approximately 3400 Hz and for N1, 3000 to 3200 Hz. In both terminals, the low-frequency channel cutoff is about 200 Hz.

Other important objectives for N2 terminals were those involving system maintenance and operation. The equipment was designed to operate satisfactorily with a minimum number of transmission adjustments to be made during service life. In addition, an alarm and trunk processing arrangement was provided with N2 to recognize system failure and to remove failed trunks from service.

All of these improvements had to be realized without producing a significant increase in the per-channel cost of N2 terminals relative to N1. This cost objective was achieved primarily because of solid-state circuit advantages such as lower power dissipation, smaller space required, and less maintenance. Some of the improvements were applicable to the older equipment and, as a result, the performance of N-type systems generally has been improved.

**Frequency Allocations.** Operation of N1 systems showed that delay distortion in channel 1 tends to be excessive because of filter cutoff characteristics at frequency frogging points. However, it was found that N-carrier repeaters could pass the equivalent of a channel 13 without equipment modification and with less distortion than that incurred by channel 1. Thus, channel 13 was added to the spectrum but the number of transmitted channels was held to 12. Most N1 and N2 terminals are now equipped to transmit channels 2 through 13 although channel units are available for channel 1 where it is needed. Frequency allocations of the N1 and N2 terminals are shown in Figure 11-15.

The channel units in N2 terminals are identical except for channel bandpass filters and oscillator frequencies. The carrier frequencies place the channel signals in the high-group N-carrier band. They are shown in Figure 11-15 (a).

**Terminal and Line Design Interactions.** In a design program as extensive as that involving the N2 terminals, certain interactions with repeated line performance must occur. For example, the total power of the carriers transmitted at high- or low-group frequencies was set by the need for lines operating with N2 terminals to perform satisfactorily in the same cable with lines operating with N1 or ON ter-

minals. With N2 terminals, the slope of the channel carrier amplitudes is used as a parameter in engineering N-carrier lines. A much wider range of slope equalization is provided in N2 terminals than in N1. In N2, slope may be provided by plug-in networks available in 3-dB steps from +9 to -9 dB. With positive slope, the power of the channel 13 carrier is greater than the power of the channel 2 carrier and with negative slope, the channel 2 carrier power is greater than that of channel 13.

With this added flexibility in line engineering provided by N2 terminals, significant performance improvement can be realized, particularly in respect to induced impulse noise performance. The method of engineering lines associated with these terminals is called "natural-slope" engineering. It takes full advantage of the natural line-loss slope and facilitates the equalizing of carrier signal amplitudes where required at locations of severe noise induction.

**Maintenance Features.** Some N2 terminals are referred to as "packaged terminals" because all the equipment required for transmission, signalling, circuit conditioning, patching, and monitoring is assembled in one equipment bay. The equipment is shop-wired with operating requirements met by the choice of appropriate plug-in units and strapping at the bay according to standard templates. The equipment for several systems can be mounted in a single bay. Most troubles in the terminal equipment can be cleared by simple substitution of plug-in units. Other designs of both early and late vintage are called "terminal-only" bays; signalling equipment is mounted in separate bays.

During complete N-carrier system failures, alarms are sounded at both terminals to alert maintenance personnel; trunk conditioning processes that minimize the effect of the failure on users or prospective users of the affected channels are automatically initiated. The trunk conditioning circuits are designated carrier group alarm (CGA) circuits because the alarms originate from loss of group carrier energy. Upon recognition of system failure at one terminal, a transmission failure is induced in the opposite direction of transmission to start the alarm and processing sequence at the distant terminal. All trunks involved in the failure are disconnected in order to terminate charges on any calls that were in progress at the time of failure. The trunks are made to appear busy so that no new connections can be attempted over the affected trunks. A *restoral tone* is transmitted at

2600 Hz over one channel of the failed system in each direction and the received amplitude and tone-to-noise ratio is observed at the distant end. When repairs are completed and the restoral tone and tone-to-noise ratio is satisfactory in both directions for a specified time period, the trunks are returned to service simultaneously at both terminals. The return to service is initiated by the transmission of a signal in both directions on a different channel.

A portable test stand is used with N2 terminals to facilitate routine tests on plug-in units. The test stand serves as an extender to provide convenient access to each contact of the connector of the plug-in unit under test. A special arrangement is also used to permit in-service switching of a working group unit so that a new unit can be substituted with only a minor (about 1-dB) transmission hit on the circuits involved. Other maintenance facilities are provided to permit the patching of service around a defective unit and the in-service monitoring of circuits for lineup and maintenance purposes.

### N3 Terminal

The application of solid-state technology to N-carrier line and terminal equipment was completed with the development of N3 terminals. These terminals, which effectively replace the ON2 terminals in respect to field of application, provide 24 single-sideband voice-grade channels by frequency division multiplex [11]. The N3 supplements the N2 by providing economic short-haul carrier channels over distances from 10 or 15 miles up to somewhat more than 200 miles. Typically, N2 is more economical at distances below 35 miles and N3 above 35 miles.

The transmission objectives for N3 terminals are basically the same as those applied to N2. Signal-to-noise objectives are met by the use of syllabic compandors. In addition, improved performance is achieved in respect to net loss, net loss stability, and channel bandwidth by the use of modern circuit components and design technology.

The N3 terminals operate compatibly with all existing N-carrier lines and signals from old and new systems are transmitted over pairs in the same cable. These constraints dictated the design of circuits to provide the usual high- or low-band transmission capability and frequency allocations consistent with the frequency frogging feature used in N-type line repeaters. Transmission level points had to be consistent with crosstalk objectives in new and old systems.

In addition to meeting transmission and compatibility requirements, the N3 terminals had to be economical, reliable, and easily maintained. Among the features that make N3 attractive economically are a common carrier supply, shared by as many as 26 N3 terminals, and an integrated bay design that combines all the equipment necessary for meeting transmission, inband signalling, VF patching, and system alarming with trunk processing for use in the event of system failure. As in N2 terminals, separate bays are now provided to accommodate new signalling system needs.

**Modulation Plan.** The 24-channel high- or low-group line signal in N3 is composed of two identical channel groups. For each channel group, 12 VF signals are used to modulate twelve carriers spaced at 4-kHz intervals from 148 through 192 kHz as shown in Figure 11-18. For each channel, the upper sideband is selected and the lower sideband and carrier are suppressed. Six of the twelve carriers are reinserted at controlled amplitudes to provide the line signal power required for repeater regulation. These carriers are also used at the receiving terminals for regulation, frequency correction, and demodulation.

Each channel-group signal modulates a different carrier frequency (280 kHz for channel group 1 and 232 kHz for channel group 2). At the output of the channel-group modulators, the two channel groups are combined to form the line signal in the low-group N-carrier frequency band. If high-group transmission is required, the line signal modulates a 304-kHz carrier in the usual manner. Channel carriers are numbered consecutively in the line-frequency signal for administrative convenience.

The N3 uses a single-sideband signal format but, unlike the twin-channel format of the O and ON systems, all sideband signals are similarly oriented. This plan was chosen for N3 to ease an intelligible crosstalk problem and to simplify the design of the channel filters. It should be noted that the frequencies of the transmitted carrier correspond to those used for channels 2 through 13 in N2. No provision is made in N3 to use the frequencies assigned to channel 1 of the N2 spectrum.

**Circuit Features.** The N3 has a number of circuit features that are different from those of other N-type systems. The transmitting terminal operates with conventional application of amplifiers and pads

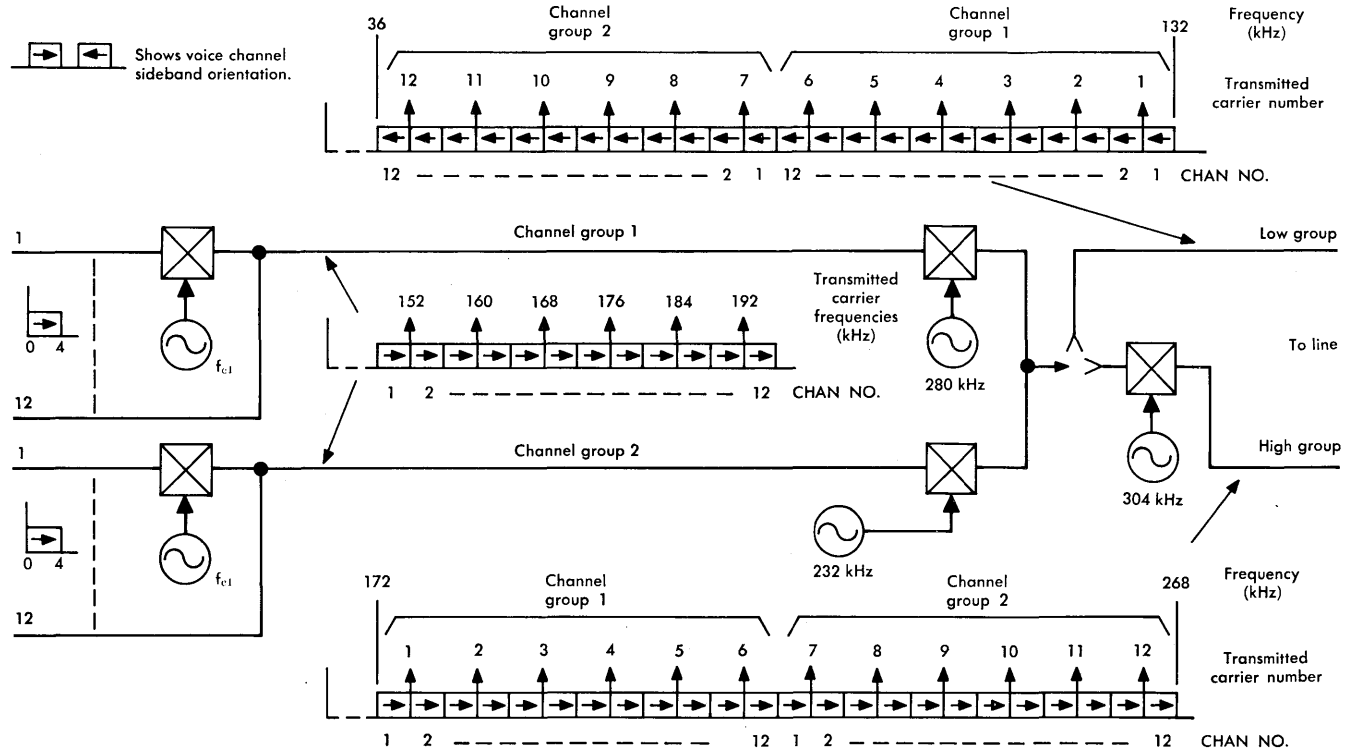


Figure 11-18. N3 transmitting terminal frequency translations.



(to control signal amplitudes and transmission level points) and filters (to limit frequency bands). Most of the features unique to N3 are in the receiving portion of the terminal where the frequency translations are inverse to those described for the transmitter.

*Group Receive Unit.* A span pad is used at the input to the receiving terminal to adjust the channels to their approximate transmission level points. The signal is then applied to a group receive unit for equalization, amplification, and regulation. If the received signal is in the high group of the N-line, it is modulated to the low-group spectrum. Thus, in all cases, the output of the group receive unit is a multiplexed signal in the 36- to 132-kHz band.

*Channel-Group Modem.* Two frequency-selective channel-group modems are used in each N3 terminal. The desired channel group is selected, demodulated to the 148- to 196-kHz channel-group frequency band, and amplified for application to double-channel regulator units.

The oscillators in the demodulators must operate at nominal frequencies of 232 and 280 kHz, the same frequencies as those used in the far-end channel-group modulators. However, the received signal has undergone a frequency shift, due to the drift of line repeater oscillators, that can exceed the maximum allowable deviation of about 20 Hz by a factor of five to one or more. Thus, corrective action must be taken.

The necessary correction is made by a frequency correction unit separate from the channel-group modem but associated with it electrically and operationally. In the correction unit, the 168-kHz channel group 1 carrier or the 152-kHz channel group 2 carrier received from the line is picked off after demodulation, amplified, and filtered. This carrier signal has accumulated the full frequency shift from the line. It is compared in a phase detector with a stable reference frequency. The output of the phase detector is a dc voltage proportional to the frequency error in the received signal. The error voltage is then used to shift the nominal 280-kHz or 232-kHz channel group demodulator carrier to a frequency that is offset by the frequency error of the line signal. Thus, the correct carrier frequency is derived for use in demodulation.

*Double-Channel Regulator.* The purpose of the double-channel regulator circuit is to regulate each pair of channels by using the carrier

signal located between them as a regulating pilot. This is made possible by the fact that the amplitude of the carrier and the carrier-to-sideband power ratios are carefully controlled at the transmitting terminal.

There are six regulators, with different filters but otherwise identical, one associated with each channel group. Each regulator unit consists of a flat-gain amplifier the gain of which is automatically adjusted inversely with the magnitude of the carrier received signal between the channels of interest. This carrier is selected from the output signal of the amplifier by a highly selective filter. It is amplified, rectified, filtered, and compared to a reference dc voltage. The difference voltage (error signal) is used to control the resistance of a thermistor or to change the drain-to-source resistance of a field effect transistor in the input circuit of the transmission amplifier.

*Common Carrier Supply.* Many individual oscillators were used in earlier N-carrier systems. In N3, one carrier supply is used to provide all the carrier signals for up to 26 terminals. Signals are generated at 16 different frequencies for use as carriers in the 12 channel modulators, the 2 channel-group modulators, and the 304-kHz group modulator. The sixteenth frequency, 256 kHz, may be used to translate the N-carrier channel-group band from the 148- to 196-kHz band to the 60- to 108-kHz band for compatibility with L-type multiplex transmission.

The common carrier supply may use a highly accurate 4-kHz crystal controlled oscillator; however, where a suitable 4-kHz signal is available from an L-multiplex primary frequency supply, it may be used directly. All required carrier frequencies are derived as harmonics of this primary source. Frequencies and amplitudes are held to close limits. Duplicate circuits and automatic protection switching in the event of failure are features of the common carrier supply. Alarms are initiated in the event of failure.

*Maintenance and Reliability.* Provision for maintenance and trunk processing in N3 is similar to the features provided in N2. The trunk processing in N3 is usually carried out independently on the two channel groups. In an optional arrangement, a single alarm and restoral circuit may be used to control both channel groups but, in this case, all circuit responses depend on transmission in only one of the channel groups.

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## Chapter 12

# Coaxial Carrier Systems

Coaxial conductor cables are more expensive than paired wire cables but the transmission characteristics of the coaxial medium permit the accommodation of many thousands of voice-frequency channels. As a result, the cost per channel mile of coaxial carrier systems is relatively low and use of these systems is economical where a large cross-section of message channels is needed and where the demand growth rate is high. A number of systems have evolved and have been assigned the designations L1, L3, L4, and L5. The L5E, an expanded version of the L5 system, has also been developed.

Coaxial carrier systems are used primarily in the long-haul plant to provide telecommunications services over distances of a few hundred up to about 4000 miles. There have also been several installations of these systems, notably L3 and L4, in metropolitan areas where high channel capacity is needed. Current manufacture is essentially of the L5E system for new long-haul routes and for conversions of older systems.

While there are many aspects of undersea cable system design and operation that are similar to the L-type systems, the submarine environment leads to significant differences. These differences affect the design of multiplex and other types of terminal equipment as well as the design of the transmission line. Many repeatered undersea cable systems have been installed throughout the world. Those of Bell System design are designated SA, SB, SD, SF, and SG.

## 12-1 COAXIAL SYSTEMS ENGINEERING

The engineering of coaxial systems requires detailed knowledge of the transmission medium, interactions between the medium and system components, the environment, and operational procedures. Careful consideration must be given to the elements of cable route selection such as right-of-way complexities, the necessity of crossing or circumventing natural and man-made obstacles, and reliability requirements on "hardening" [1]. The relationship between route selection and flexibility in repeater spacing rules is also an important consideration in engineering a route.

Other aspects of route engineering include route maintenance needs, accessibility, and the relation to power transmission lines along the route. All of these considerations have affected the L-type systems in various ways and to different degrees.

### Transmission Media

The current standard coaxial cable unit consists of a copper-wire conductor 0.1003-inch in diameter centered in a copper tube having a nominal inside diameter of 0.375 inch. The center conductor is held in place by thin polyethylene insulating disks spaced about 1 inch apart. The copper tube is formed of a flat strip of copper 0.012 inch thick. The strip has serrated edges which interlock when it is formed into a tube. The secondary transmission constants of the medium and the manner in which the cable units are combined with single paired interstitial wires to form a cable are covered in Chapter 2.

**Design Evolution.** The first cables were made up of 0.27-inch inside diameter (nominal) coaxial units with hard rubber disk insulators. Most of these cables, some of which are still in service, contain only four coaxial units.

It was found that polyethylene disks produced substantially less loss than hard rubber disks and the first significant design change involved the substitution of polyethylene for rubber. Meanwhile, studies showed that a coaxial unit of 0.375-inch diameter would result in more economical systems and this unit was adopted as standard in 1946 in anticipation of the availability of the L3 system. The early cable designs had been used for L1 systems many of which have since been converted to L3 or L4.

In addition to improvements in the loss characteristics of coaxials, a higher channel capacity was first realized by increasing the number of coaxial units assembled into a cable to eight. Later designs consisted of 12 and 20 coaxials for use with L3 and L4 systems. A 22-unit cable designed for use with L5 systems and an 18-unit cable to accommodate duct size limitations in metropolitan areas have been introduced. Cable designs involving increases in the number of coaxial units had little effect on coaxial unit transmission characteristics. The principal effect was to change the stranding factor, a factor that defines the ratio of the length of coaxial unit to the length of cable. This factor differs for each cable design because of changes in cable lay or twist.

**Design Interactions.** A number of electrical parameters related to cable design have significant, if not first order, effects on transmission system design. These parameters include the power factor, the high voltage breakdown characteristics, and the characteristic impedance of the coaxial unit.

The power factor of a coaxial is a minute variation of the phase relationship between signal currents and voltages. The variation, which tends to be a linear function of frequency, is caused by changes in the parallel leakage (conductance) between conductors. Although the factor is small enough to be ignored at low frequencies, it causes a departure of a few tenths of dB per mile from the expected square-root-of-frequency loss characteristic at high L5 frequencies, which approach 70 MHz, and must be corrected. A nominal correction is made in each repeater and variations are corrected by equalizers placed strategically along the line. The effect is relatively time invariant but can vary significantly from one vintage of coaxial to another.

Repeaters located along a coaxial cable route are powered from centralized main station locations over the center conductors of the coaxial units. In some cases, the voltages required are high enough to approach the voltage breakdown point of the polyethylene disk dielectric or of gaseous elements in the hollow tube. As a result, corona (incipient voltage breakdown between conductors due to ionization) may be formed especially where there are burrs or other sharp edges of the inner or outer coaxial conductor protruding into the dielectric region between the conductors. System voltages must be held to values below which corona may be formed to prevent the generation of unwanted circuit noise. Where burrs or sharp edges exist, they may

sometimes be burned out by the application of suitably high voltage at the factory or after the cable has been installed. Such action might be taken as a result of factory or preservice corona tests. Where high ac voltages are required for long power feed sections in the L3 system, corona is controlled by filling the coaxials with sulphur hexa-fluoride, a heavy gas with high-dielectric strength.

As discussed in Chapter 2, the characteristic impedance of 0.375-inch diameter coaxial units is 75 ohms. While the impedance normally varies only slightly, physical discontinuities in the coaxial structure can cause significant departures from the nominal value. For example, lightning, back-filling operations, or subsequent shifts in terrain may produce dents in the cable. If a dent is deep enough to short circuit the coaxial conductors, the unit becomes unusable and must be repaired. In other cases, the dent may cause an echo impairment due to the resulting impedance discontinuity. Splices may also cause such discontinuities and splice distances must be randomized to avoid systematic build-up of echoes. As a result of the stranding operation, minute systematic deformities in the outer conductor may be produced and cause departures from the expected transmission characteristic over a narrow range of frequencies determined by the stranding factor.

### Survey of Systems

The principal features of existing coaxial cable systems are shown in Figure 12-1. All of the systems were designed according to the general principles set forth in Chapter 10. These principles have evolved as successive systems were developed.

Several interesting trends may be identified by examining the data in Figure 12-1. For example, the pressure to provide increasingly larger channel cross sections can be seen by the growth in size of cables shown in Figure 12-1(a) and by the increase in channel capacity shown in Figure 12-1(b). Improvements in performance are also apparent from the more stringent noise objective applied to L4 and L5 systems relative to L1 and L3 systems. In addition, the transition from huts to manholes for repeater station housings resulted in improvements in repeater reliability and transmission stability with temperature changes.

SYSTEM	PREDOMINANT CABLE SIZES, UNITS	REPEATER STATIONS		PROTECTION SWITCHING
		TYPE	SPACING, MILE*	
L1	4-8	Huts	8	1:1
L3	8-12	Huts†	4	Multiline
L4	12-20	Manholes	2	Expanded
L5	12-22	Manholes	1	Digital control
L5E	12-22	Manholes	1	Digital control

\*These nominal spacings apply to the use of 0.375-inch diameter coaxials.

†Underground structures are used on one hardened route.

(a) System features

SYSTEM	NOMINAL BANDWIDTH, MHz	CHANNELS PER COAXIAL PAIR	4000-MILE NOISE OBJECTIVE, dBmCO
L1	2.8	600	44
L3	8	1860	44
L4	17	3600	40
L5	57.5	10800	40
L5E	61.5	13200	40

(b) Service features

SYSTEM	REPEATER TECHNOLOGY	REPEATER CONFIGURATION	EQUALIZATION AND CONTROL	POWER
L1	Electron tube	Parallel tubes, soldered in	Bumps & dynamic — local, out-of-service	60 Hz
L3	Electron tube	Single path, plug-in	Cosine & dynamic — local, out-of-service	60 Hz
L4	Solid-state	Single path, printed wiring	Bumps & dynamic — remote, in-service*	dc
L5, L5E	Solid-state	Parallel transistors, hybrid IC, thin film	Bumps & dynamic — local, out-of-service	dc

(c) Design features

\*In L4 systems of late vintage, bump equalizers may be manually adjusted out-of-service.

Figure 12-1. Coaxial system features.



As indicated by the principles discussed in Chapter 10, a significant increase in the bandwidth of an analog cable carrier system must be accompanied by a decrease in repeater spacing if comparable signal-to-noise performance is to be achieved. Figure 12-1(a) shows that the nominal repeater spacing is halved for each successive system; thus, conversion of one system to another is relatively simple and straightforward.

To minimize the effects of system failure and to facilitate maintenance, coaxial carrier systems are operated with one pair of coaxial units reserved in each cable for maintenance of service. Service may be transferred to this standby or spare line facility manually or automatically upon recognition of a failure. The earliest designs of L1 systems were protected on the basis of one spare for each working facility. The two facilities were fed in parallel and the receiving end only switched manually or automatically from working to spare upon demand.

With the design of the L3 system and cables having 8 or 12 coaxial units, the 1-for-1 protection switching arrangement was deemed uneconomical and unnecessary because of the proven reliability of electronic components. With the introduction of the 8-unit cable, a 1-for-3 protection switching system was designed and when 12-unit cables became available, the system was expanded to accommodate a 1-for-5 arrangement. This system was modified and further expanded for L4 systems so that 9 working systems could be protected by automatic switching of just 1 spare line.

The analog control signals for L3 and L4 switching are carried in the band between 280 and 300 kHz. While this frequency band is marginally acceptable in L4, it is unusable in L5 and a complete redesign was necessary. As a result, digital techniques are used for logic circuits and control signal transmission in L5. The system is designed to permit 1 standby line to protect up to 10 working lines. If it is installed initially for fewer than 10 working lines, expansion to 10 is a simple and straightforward process.

Analog system design advances have been accompanied by changes in applied technology, some of the more important of which are shown in Figure 12-1(c). In L1, electron tubes were used in a soldered-in parallel configuration to improve system reliability. In L3 and L4, improved device reliability and the success of the multiline

protection switching systems permitted the use of single series arrangements of active devices. In L5, the circuit configuration again uses parallel devices to achieve the required linearity and signal power handling capability in the repeaters rather than for reliability.

Methods of design and implementation of equalizers have also changed with the evolving technology as has the method of supplying power to remote repeaters. The requirement for relatively frequent adjustment of L3 equalizers led to the desire for remote adjustment of L4 equalizers on an in-service basis. In the L4 system, however, the innate stability of solid-state circuits was demonstrated and the remote control feature was not considered necessary for L5. The transition from ac to dc powering of remote repeaters was made feasible by the lower operating voltages and lower power consumption of solid-state devices relative to electron tubes.

The network of coaxial cable systems and the multiplex equipment associated with them have become important parts of a system of broadband circuit restoration. The effect of a failure of a coaxial cable, microwave radio, or satellite system anywhere may be minimized by the planned rerouting of service over other facilities normally used only as maintenance and protection standby equipment.

The engineering of a new coaxial system is not complete without consideration of maintenance and reliability. For each of the systems from L1 to L5, the equipment and methods specified for system maintenance have become more sophisticated. Surveillance, alarm, and control functions can be arranged for remote operation. In some cases, centralized facilities control all systems within a radius of several hundred miles. In addition, the protection switching systems have become more reliable and more versatile so that system reliability has been increased without significant increase in cost.

Many modern systems are "hardened." Cables are buried about four feet underground, repeaters are housed in underground manholes designed to withstand earthquakes or atomic blasts (short of a direct hit), and main station buildings are erected well below grade. These buildings are shielded and, in the most hardened locations, the equipment is shock mounted. Life support systems are provided to permit maintenance forces to continue their jobs in the building for a month or more in the event that enemy attack makes it necessary to seal the building.

## Route Engineering

The problems of engineering a route for a new coaxial system are mixtures of technical, economic, and socio-political considerations. A satisfactory route must be selected; the right-of-way must be procured through legal means occasionally involving the exercise of the right of eminent domain; environmental and ecological effects must be taken into consideration; the possibility of conversion of an existing system to one of higher channel capacity must also be examined.

**Route Selection.** An important criterion that is commonly applied in selecting a route for a new coaxial carrier system is that it should not pass through highly developed centers of population or business activity. Service into these areas is provided over side legs from the main route. This practice is followed because overall construction and operating costs tend to be lower, the cable and equipment are less subject to damage, and the likelihood of damage to the main route in case of enemy attack on the city is reduced.

There are many other factors to consider in selecting a route most of which can be evaluated in terms of cost, reliability, or service quality. For example, it may be more economical to add several miles to a route in order to avoid some natural or man-made obstacle such as a swamp, lake, river, rocky terrain, or major highway. The effect on performance of the added mileage would be trivial.

Where it is necessary to cross a large river, such as the Mississippi or the Hudson, much study must be given to optimizing the crossing site. The width and depth of water, the strength of current flow, protection against anchor and ice damage, and concurrence of responsible governmental agencies must all be taken into consideration. In some cases, special engineering is applied in order to permit a longer repeater section than normally permitted by the spacing rules or to provide special cable made up of nonstandard coaxial units of large diameter and low loss.

Another important factor in route selection is that of accessibility to the cable and to repeater sites for economical maintenance and repair operations. There may be a choice between selecting a route to the north or to the south of a range of hills or mountains. Prevailing winds and weather patterns might strongly favor one of these choices because, for the other, there are long periods of time when

the route would be covered by deep snow. Another example might involve a route through a swamp that might be quite feasible insofar as construction is concerned; however, access to repeater points located in the swamp might be quite difficult. Generally, an attempt is made to select a route that parallels a highway so that relatively inexpensive access roads can be provided from the highway to repeater sites.

**Right-of-Way.** Acquiring the legal right to place cable and repeater equipment is a significant part of the cost of a new system, especially in highly developed areas. Costs are also materially affected by considerations involving the environment. The clearing of timber to allow access by construction and maintenance crews is often subject to review by environmentalists and it is often necessary to plant grass or other ground cover after a route has been installed.

Every coaxial carrier system is designed to operate with line repeaters spaced along the route at nominal distances determined by the system signal-to-noise objectives. Spacing rules are written to provide as much flexibility as possible in locating repeater sites without incurring excessive performance penalties. Practical considerations regarding the application of these rules are also important factors in determining the right of way.

**Environment.** The problems of route selection and right-of-way determination can be complicated by environmental factors in addition to those already mentioned. Temperature, terrain, building design and construction, and equipment designs all interact in ways that can affect costs and/or performance.

Where coaxial systems cross deserts or other areas where temperatures are high, the control of hut temperature has been a difficult problem. In another situation, the cable might be laid in the median strip of a divided highway in a southern region. If the median is devoid of trees, ground temperature around the buried cable may be higher than estimated in system design and regulation range might prove to be insufficient. These hazards can be overcome when recognized but might be overlooked when a route is being selected and engineered.

**Conversions.** As previously mentioned, the repeater spacings for coaxial carrier systems have been selected so that the nominal spacing for each system is one-half that of the preceding system. This practice

has been followed so that when a route is converted from one system to another of later design most existing repeater sites can be reused. This possibility must be always be examined from the point-of-view of economical desirability and technical feasibility.

The number of coaxials in a cable is one factor that may limit the economic desirability of conversion. If the cable is too small, the increase in channels may not satisfy the need. Furthermore, conversion is more difficult because the percentage of working circuits that must be taken out of service while conversion work takes place may be too high. There may also be incompatibilities in the application of repeater spacing rules between the old and new systems that make conversion difficult and/or expensive.

Cable design must also be evaluated if conversion is being considered. For example, rubber disk-insulated 0.27-inch cable cannot support L5 transmission. In addition, power factor losses are excessive in some older designs of polyethylene disk-insulated cable and, at the very least, new designs of deviation equalizers are required to compensate for these losses in L5 applications.

## 12-2 THE L5 COAXIAL CARRIER SYSTEM

While there is a substantial amount of L1, L3, and L4 coaxial carrier equipment in service, their similarity is such that a detailed description of each is unnecessary [2, 3, 4]. The latest systems, L5 and L5E, utilize essentially the same repeatered line equipment. Thus, the L5 system is described with an occasional reference to one of the older systems. The relatively minor changes required in the L5 line equipment for L5E operation are discussed.

The large channel capacities, 10,800 channels per coaxial pair for L5 and 13,200 channels for L5E systems, are provided by previously described multiplex arrangements. The increased capacity of L5E is possible because the original design of L5 line equipment provided slightly more bandwidth than needed for 10,800 channels. A more closely packed arrangement of mastergroups and multimastergroups in the new multiplex equipment and a slight increase in top frequency provide for the additional channels.

To achieve a satisfactorily engineered line for an L5 system, the transmission design and layout, maintenance features and arrangements, protection switching system features, and constraints of power

distribution to remote repeaters must all be thoroughly understood and carefully evaluated. Each of these aspects of line engineering imposes certain limitations on the achievable system performance [5].

### Transmission Design and Layout

The transmission design of the L5 and L5E systems provides wide frequency bands for signal transmission over coaxial cable. The system layout specifies the placement of repeaters and the provision of regulators and equalizers at strategic locations. As previously discussed, these design features and parameters are all interrelated and dependent on the established signal-to-noise objectives. For both systems, the objective is 40 dBrnC0 for voice-grade channels 4000-miles long. Of this objective, 39.4 dBrnC0 is allocated to the high-frequency transmission line.

**Frequency Allocations.** The frequency division multiplex equipment described in Chapter 9 provides the message signal spectra for L5 and L5E systems. In L5, the spectrum from 3.124 to 60.556 MHz is that provided by the jumbogroup multiplex equipment as illustrated in Figure 9-11. The L5E spectrum from 3.252 to 64.844 MHz is provided by mastergroup and multimastergroup translators as shown in Figure 9-13. The frequency allocations of line pilots used for dynamic equalization (regulation) and of control signals for protection switching system signals, fault location, and reference frequencies used at terminal points to synchronize the multiplex equipment are shown in Figure 12-2.

The shift in message signal frequency allocations in L5E relative to L5 systems resulted in two other significant frequency allocation changes both of which are shown in Figure 12-2. The equalizing pilot transmitted at 20.992 MHz in L5 was shifted to 21.956 MHz in L5E; this shift caused some change in line equipment design. The reference frequency signal, transmitted at 20.480 MHz in L5, was shifted to 2.048 MHz in L5E. This shift had no effect on line design or layout but required changes in the synchronizing circuits used in conjunction with the multiplex equipment at terminal points. The new frequency made L5E consistent with other long-haul transmission systems that use 2.048 MHz.

**Repeater Designs and Spacing Rules.** The L5 repeaters are designed and installed along the cable route according to the hierarchical pattern illustrated in Figure 12-3. The simplest repeater, called a basic

SIGNAL FUNCTION	FREQUENCY, MHz	
	L5	L5E
Switching control	68.78	68.78
Switching control	68.76	68.76
Fault location	68.65	68.65
Fault location	68.60	68.60
Equalization	66.048	66.048
Equalization	42.88	42.88
Equalization		21.956
Equalization	20.992	
Synchronization	20.480	
Equalization	2.976	2.976
Synchronization		2.048
Fault location	1.60	1.60
Fault location	1.59	1.59

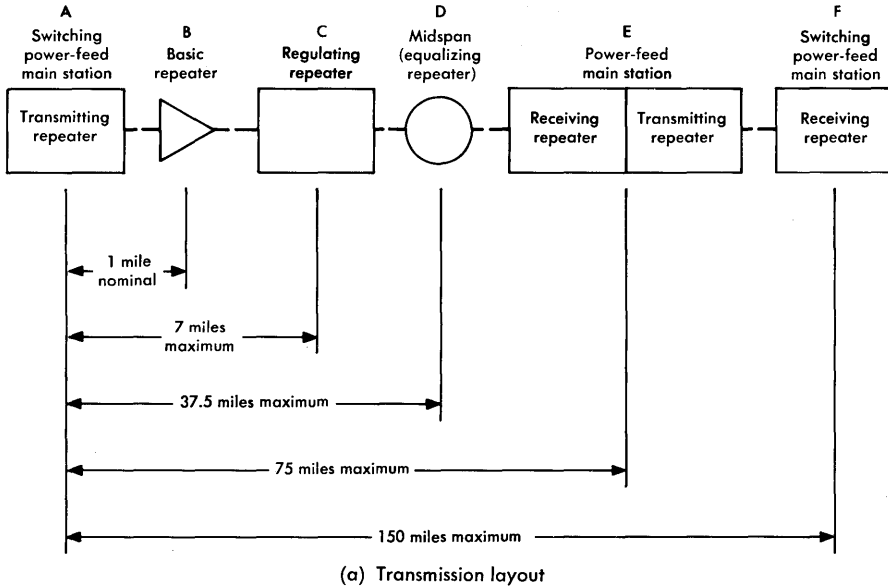
Figure 12-2. Control signal frequency allocations in L5 and L5E systems.

repeater, is installed at nominal 1-mile intervals to compensate for line loss. At a maximum of every 7 miles, a regulating repeater is installed to correct line-loss variations caused primarily by cable temperature changes. At the midpoint of a 75-mile power feed span, a maximum distance of 37.5 miles, an equalizing repeater is used to correct fixed and variable deviations that occur along the line in addition to the temperature-caused line-loss change.\* These three types of repeaters are housed in pressurized water-tight apparatus cases and mounted in manholes along the cable route.

Power for manhole-mounted repeaters is supplied to the line over the center conductors of the coaxial units from power feed stations (usually underground) spaced at maximum intervals of 75 miles. A transmitting repeater or receiving repeater, depending on the direction of transmission, terminates each coaxial line at the power feed stations.

In L5 and L5E systems, one pair of coaxial units is always equipped as a fully-powered protection line to be switched automatically into service in place of a failed coaxial line or to be switched in manually

\*As a result of a modification of the transmission layout, an equalizing repeater need not now be used in most power spans less than 75 miles long.



FUNCTION	A	B	C	D	E	F
Fixed Equalizer	X	X	X	X	X	X
Adjustable Equalizer	X		X	X	X	X
Manual	X			X	X	X
Power Feed	X				X	X
Protection Switching	X					X

(b) Station and repeater features

Figure 12-3. L5 system switching span.

to permit maintenance on one of the working lines. The switching equipment and control circuits are located at distances not exceeding 150 miles. Thus, a switching span may encompass two power feed sections. Main stations that supply power but no protection switching are called power-feed main stations. Where power feed and pro-



tection switching are found, the station is called a switching power-feed main station. The most complex stations provide power feed, protection switching, and various combinations of complex operating features such as signal and pilot administration, transmission surveillance, and multiplexing and related signal-processing functions. This type of station is called a terminal station when it terminates a side leg or a terminal main station when it is a junction station along a backbone route.

*Basic Repeater.* Transmission performance of the L5 system is dominated by basic repeaters not only because they are used at one mile intervals but also because basic repeater circuits constitute a portion of all the regulating, equalizing, and main station repeaters. Thus, about 4000 basic repeaters are used in a system of maximum length and extremely stringent repeater performance requirements must be met in respect to noise figure, power-handling capacity, linearity, return loss, gain characteristics, and temperature coefficient.

The basic repeater is designed to provide a fixed gain to compensate (within  $\pm 0.15$  dB) for the attenuation of 1 mile of a coaxial cable unit, shown in Figure 12-4.\* This requirement applies at a temperature of 55 degrees Fahrenheit over the frequency band of 3.1 to 65 MHz. The gain is thus approximately 6.9 dB at 3.1 MHz and 31.5 dB at 65 MHz and varies in dB essentially as the square root of frequency. A wider band, from 1.6 to nearly 70 MHz, is also controlled but less precisely outside the 3.1 and 65 MHz limits. A block diagram of the repeater is shown in Figure 12-5.

The repeaters must be designed to withstand the high voltages to ground that result from the method of remote powering used. They include circuits for separating and combining the operating and signal powers at the input and output respectively. They are protected against damage due to lightning and other high-voltage surges by the low-frequency networks shown in Figure 12-5. The earth-ground filters shown in the figure isolate the earth ground, required in the outer wall of the repeater housing for personnel safety, from the circuit ground within the repeater. A line build-out (LBO) network, provided in each basic repeater, has a loss characteristic equivalent to

\*The repeater gain is actually designed to compensate for the attenuation of 1.006 miles of coaxial unit; the added gain provides margin for variations in cable length due to "snaking" in the trench, etc.

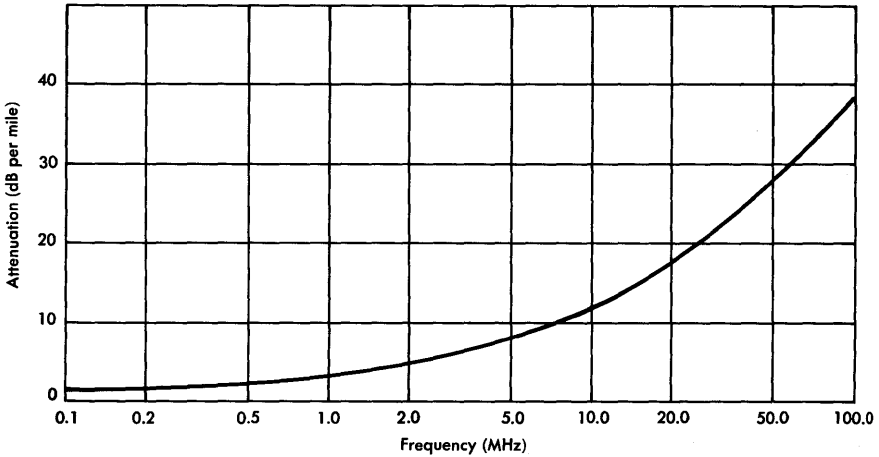


Figure 12-4. Attenuation/frequency characteristic of 0.375-inch diameter coaxial cable unit.

a given length of coaxial unit. It is used to reduce the gain of the repeater in increments of 0.1 mile from zero change to the equivalent of 1/2 mile of cable unit loss. Thus, there are six repeater codes corresponding to the equivalent overall gains provided. This feature accommodates the necessary flexibility in repeater spacing. The LBO network is placed electrically in the repeater between the output of the low-noise input amplifier and the input of the high-power output amplifier.

*Regulating Repeater.* As shown in Figure 12-6, the regulating repeater contains all of the circuits of the basic repeater, a second LBO network, and circuits that perform pre- and post-regulating functions. These additional circuits have an insertion loss of zero dB at nominal temperature and repeater spacing.

As discussed in Chapter 10, there is a significant signal-to-noise advantage in dividing the regulation about equally between the transmitting and receiving ends of a line section. This is accomplished for the transmission deviations caused by cable temperature changes by the use of two independent regulating networks. The pre-regulator, located in the transmitting portion of the repeater, responds directly

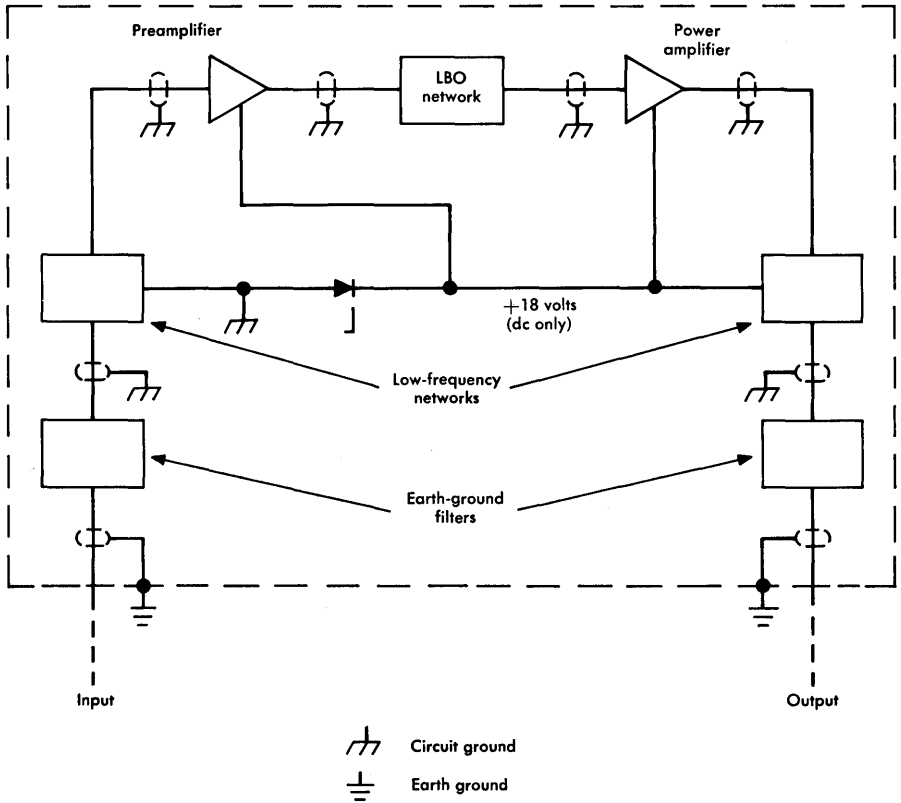


Figure 12-5. Basic repeater block schematic.

to changes in ground temperature near the repeater. The temperature-sensing element is a thermistor that must be buried at the same depth and in an earth environment similar to that in which the cable is buried. The mapping circuits convert the nonlinear temperature/resistance function of the buried thermistor into a linear function of temperature-versus-regulating network loss which is controlled by the indirectly heated thermistor in the regulator network.

Post-regulation is performed by the pilot-controlled regulating network in the receiving portion of the regulator. The signal received at the pick-off hybrid is amplified and the narrowband crystal filter selects the 42.88 MHz pilot. This pilot is again amplified, detected, and compared with a carefully controlled reference dc voltage. The

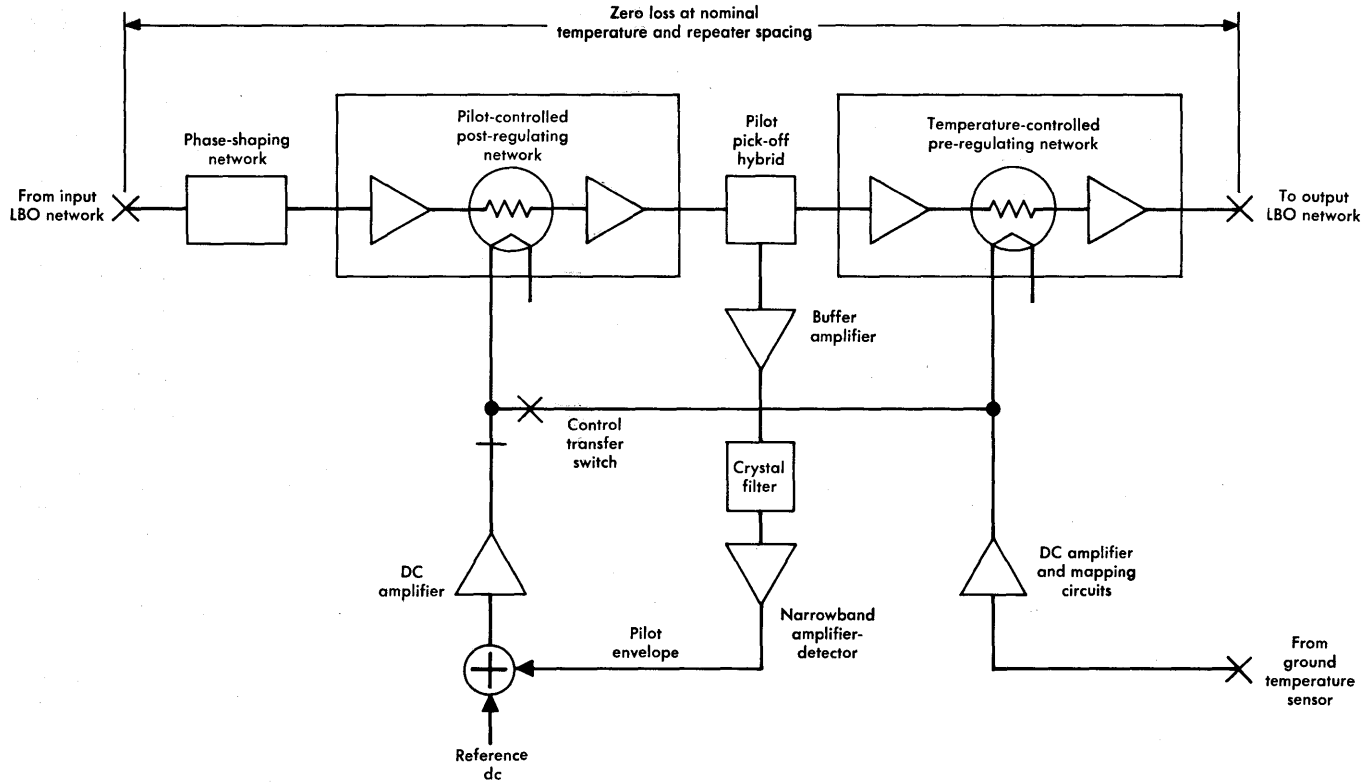


Figure 12-6. Regulator circuitry of regulating repeater.

difference between the two, called the error signal, is amplified and applied to the indirectly heated thermistor of the post-regulator to provide accurate control of the overall repeater gain.

In a line on which the 42.88 MHz pilot is lost, the regulating repeaters could all be driven to their maximum gain condition causing large unequalized misalignment. This action would introduce high gain to signals and/or noise in the affected line and could cause overload of circuits well beyond the directly affected section. To prevent this potentially catastrophic overload phenomenon, the regulators contain a transfer circuit. Upon loss of pilot, the control of the post-regulator is transferred to the ground-temperature sensing thermistor; an imperfect adjustment results but it is far less deleterious to performance than complete loss of control.

The phase shaping network in the receiving portion of the regulating repeater is used to introduce a nonlinear phase/frequency characteristic in the transmission band. Due to the linear phase/frequency characteristic of a repeatered coaxial transmission line, certain types of third-order intermodulation products add in phase from repeater to repeater. Thus, the accumulated amplitudes of these products tend to be proportional to  $20 \log n$ , where  $n$  is the number of tandem repeaters. With the phase shaping networks, the intermodulation product accumulation is reduced to being proportional to about  $15 \log n$ , a little less in some cases.

*Equalizing Repeater.* In addition to the circuits and features of a basic and a regulating repeater, an equalizing repeater contains several networks designed to equalize an L5 line approximately so as to limit signal-to-noise penalties due to misalignment. System studies relating to the L5E development program have shown that equalizing repeaters need not be installed in many power feed sections for L5 or L5E. The need depends on the length of the section and on the cable vintage.

One of the networks used in the regulator portion of an equalizing repeater is a fixed equalizer, called a deviation equalizer, designed to compensate for the difference between the average gain of 22 repeaters and the nominal loss of 22 miles of a coaxial cable unit. The number of repeater sections was selected as an estimate of the average length of an equalizing repeater section. This type of equalizer is applied to L5 and L5E lines at equalizing and main station repeaters

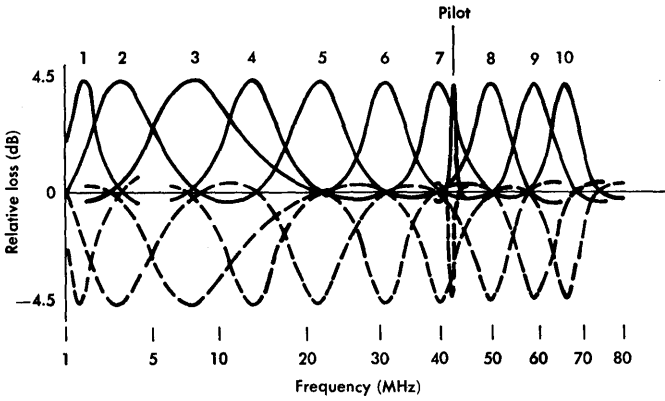
according to well-defined rules.\* The residual deviations are partially corrected by manually adjustable E1 equalizers.

These adjustable networks of the E1 equalizer are continuously adjustable over a limited loss range and the effect of the adjustment is to introduce a "bump" of loss over a limited frequency range. Ten such bumps, numbered in ascending order with frequency, are used at an equalizing repeater. A very narrow unnumbered bump is centered at the 42.88 MHz regulating pilot frequency. The network loss characteristics are illustrated in Figure 12-7(a). As shown in Figure 12-7(b), a number of the bump networks are connected in series with the amplifiers; four of the bumps are in the feedback circuits of these amplifiers. Test access is provided at the input and output to facilitate measurement and evaluation of the system attenuation/frequency characteristic.

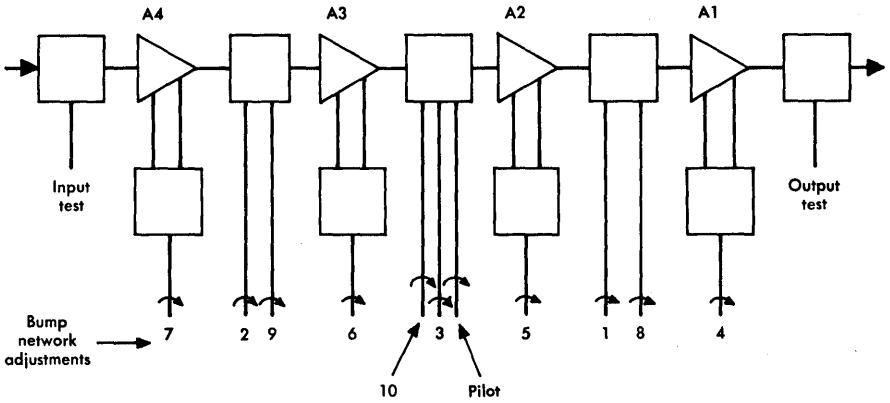
*Main Station Repeater.* Each L5 main station contains the transmitting and receiving components of basic and regulating repeaters and, in addition, E1 and E2 equalizers. The E1 equalizer is functionally the same as that used at an equalizing repeater but it is packaged for central office rack mounting instead of manhole apparatus case mounting. The E2 equalizer resembles the E1 in a number of ways. It has bumps of loss over 18 narrow frequency bands to supplement the E1 equalizer bumps and provides fine-grained equalization of the L5 frequency band. Each loss bump is continuously adjustable over a range of  $\pm 3.5$  dB. In a 150-mile switching span, the E1 and E2 equalizers together can equalize the band from 1.6 to 66 MHz to within  $\pm 0.4$  dB.

The E2 equalizer contains 7 amplifiers and 6 intermediate 2-bump equalizer networks. Six of the amplifiers also contain bump networks in the feedback circuits. Access is provided at the input and output for test and system evaluation. For the L5E system, E2 equalizers are not used at power-feed stations. They are omitted at intermediate power-feed main stations. A dynamic (pilot-controlled) equalizer, the E3, is used in the receiving main station repeaters. It is controlled by line pilots transmitted at 2.976, 20.992, 42.88, and 66.048 MHz in L5 and at 2.976, 21.956, 42.88, and 66.048 MHz in L5E. In adapting the L5 system to L5E operation, the change in frequency of the pilot near 21 MHz required the design of a new pilot-frequency generator and pick-off and control circuits in the equalizer.

\*Where an equalizing repeater is not used, a deviation equalizer is incorporated in the regulating repeater.



(a) Network loss characteristics



(b) Block schematic

Figure 12-7. E1 equalizer.

The transmission variations that are corrected by the E3 equalizer are primarily those due to temperature changes that affect repeater gain. The temperature within a manhole changes seasonally and also as the number of equipped systems increases. In addition, the regulator networks designed to compensate for cable loss changes match the desired loss characteristic imperfectly; the discrepancy increases with the amount of compensation.

Corrections are made in the E3 by four networks, the characteristics of which are illustrated in Figure 12-8. Three of these are bump shapes and one (No. 2) is a flat-gain correction for the entire band. A pilot pick-off circuit at the output of the equalizer selects the four pilots, rectifies them and compares the resulting dc voltages to appropriate reference voltages. The error signals are then used in a computer-like circuit to provide appropriate measures of each of the network characteristics to be introduced for correction of the line characteristic. The corrections are determined by digital circuits which maintain the last-established setting of the equalizer in the event of the loss of pilots.

The adaptation of L5 line equipment for L5E has involved a redesign of E3 equalizers. The new designs utilize only equalizer network shapes similar to No. 1 and No. 4 of Figure 12-8. At power feed stations, only the high-frequency (No. 4) equalizer is used. At all other types of main stations, both are used.

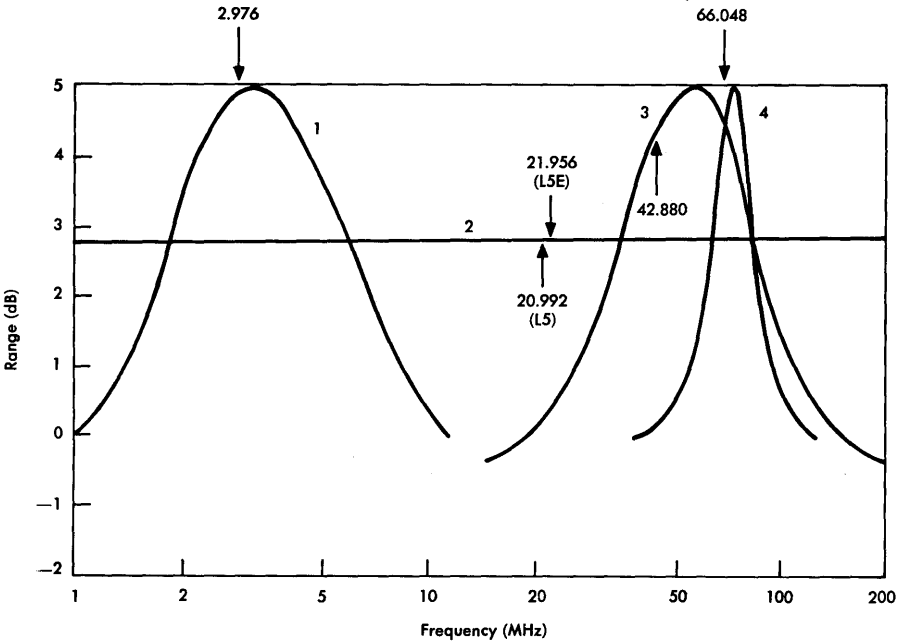


Figure 12-8. Line pilots and related E3 equalizer characteristics.



*Spacing Rule Flexibility.* All of the spacings previously discussed are established with permissible variations that allow for geographic anomalies, population distribution, and right-of-way complications. With basic repeaters, some spacings in excess of 1 mile are acceptable. Such excess spacings must be compensated by short spacings on both sides of the long section. Short sections that are not being provided as compensation for long sections are built out to match the nominal 1-mile spacing by the use of repeaters with LBO networks of appropriate values.

**Main Station Administration Equipment.** At every main station, equipment must be provided to interconnect line and terminal equipment. Among the items of terminal equipment are the multiplex terminals, branching filters, line pilot and synchronizing signal administration circuits, protection switching equipment, transmission surveillance and fault location equipment, restoration access arrangements, jumbo-group trunk circuits, and line connecting equipment. The line connecting equipment is mounted in a transmit-receive bay with transmitting and receiving repeaters. These bays are standard in three arrangements, one for power-feed main stations, one for switching power-feed main stations, and one for terminal stations and terminal main stations. Arrangements for other types of terminal equipment are unique to the needs of each main station.

Significant differences in detail exist in the main station arrangements for L5 and L5E systems. These differences are due to changes in the pilot frequencies (near 21 MHz) and the reference frequencies used for synchronization, and the difference in the multiplex equipment used for the two systems.

### **Maintenance and Reliability**

The L5 system design has many maintenance and reliability features; some are improved versions of similar features previously used and some are newly developed. Since L5 and L5E have such large circuit capacities, probability of failure must be minimized and outage time must be kept as short as possible.

As in other broadband systems, many circuits are duplicated and provided with automatic switching features. Also, access points are provided for test and emergency broadband restoration purposes. However, features unique to L5 include aspects of line maintenance

and administration, a newly designed protection switching system, a transmission surveillance system with new fault location features, and a new design of four-wire order wires.

**Line Maintenance and Administration.** Many features of L5 line operation are important for efficient maintenance and administration. Among the most significant are the equalization system and the procedures for repeater replacement.

*Equalization System.* The individual components of the equalization system, previously described, are the fixed, manually adjustable, and automatically controlled equalizer networks. The principal fixed equalizers are the fixed-gain basic repeaters, the line build-out networks, and the deviation equalizers. All of these fixed equalizers are installed in new L5 systems according to carefully defined application rules. The designs are such that residual deviations from an ideal (flat) attenuation/frequency characteristic can be corrected by the manually adjustable bump equalizers.

The bump equalizers are distributed along the line for pre- and post-equalization at equalizing and main station repeaters. The characteristics and the method of adjustment are designed to minimize the mean-squared error in the resulting characteristic after adjustment. The equalizers are adjusted at the time of installation and occasionally thereafter. When later adjustments are required, service must be removed from the line under adjustment by operation of the line protection switching system.

Automatic adjustment of the transmission characteristic is provided by regulating repeaters and by E3 dynamic equalizers. These adjustments compensate primarily for system loss/frequency changes due to temperature variations.

*Repeater Replacement Procedures.* Operating dc power is supplied to manhole-mounted repeaters over the center conductors of the coaxial units. Removal of a repeater, for test or replacement, opens the dc circuit and special means must be provided to maintain power continuity. The means are illustrated in Figure 12-9. At the input and output of each manhole-mounted repeater, twin jacks are provided. When a repeater is to be removed from its apparatus case, the bridging pads are removed from the twin jack assemblies and a coaxial patch cord is plugged into the vacant jacks. By this action, the repeater is short-circuited and direct current continuity is pro-

vided through the patch cord. The repeater can then be removed without causing dc power shutdown. In addition, the twin jacks provide a bridging connection for fault location oscillator signals which can be applied through the bridging pads to the repeater at input and output. The pads are of relatively high impedance to minimize the bridging loss.

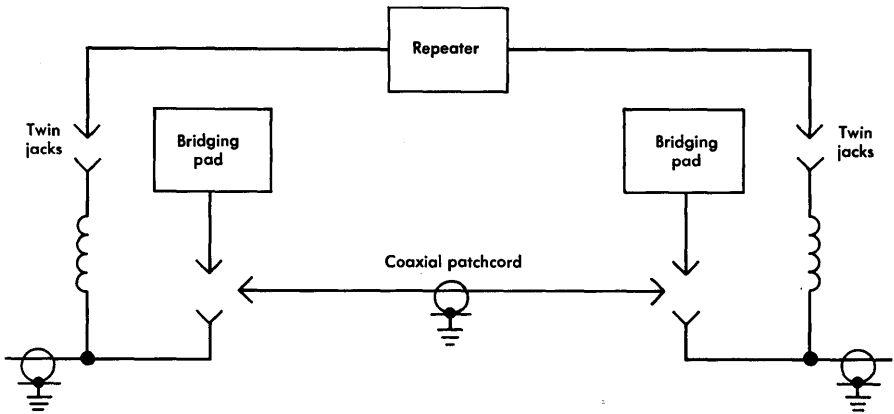


Figure 12-9. Manhole repeater patching.

The inductors in the twin jack assemblies are provided to maintain a good impedance match at the repeater/cable interfaces. The inductance of these coils and the parasitic capacitance of the jack assemblies provide a good simulation of a 75-ohm cable section.

**Protection Switching System.** The development of the L5 system required the design of a new line protection switching system. As previously mentioned, the frequencies used in earlier systems for the transmission of control information between switching points are completely unsuited for use in the L5 system. In addition, the development of L5 and a 22-unit coaxial cable coincided and no existing switching system was capable of providing the 1-for-10 protection switching arrangements required for this large cable.

The new system, designated the Line Protection Switching System No. 3 (LPSS-3), was designed to be relatively immune to line noise and line hits (short-duration service outages) because a signalling error can cause a service failure due to improper switch activation.

The system was also designed to permit gradual growth with minimum effort and initial expense because, in a high-capacity system like L5, it is seldom that all coaxial units are simultaneously equipped for service at the time of cable installation.

Two criteria are used to initiate an automatic transfer of service from a working line to the standby protection line. If the amplitude of the 42.88-MHz pilot departs by 5 dB or more from its nominal value at the receiving end of a switching span, a switch is called for by a detector circuit. The received signal power is used as another criterion for switching. If the power exceeds a preestablished threshold, a switch is also initiated. In both cases, the completion of the switch is dependent on many conditions.

After the need for a switch has been indicated, the operation of circuits at both ends of the switching span must be properly sequenced and coordinated. These functions are accomplished by a signalling system that utilizes frequency shift keying of line signals at 68.76 and 68.78 MHz to communicate between the two ends of the span. The signalling rate is 2 kilobits per second. The necessary circuit functions are coded into a total of 39 digital code words, each seven bits in length. The first of the seven bits is a parity bit. In the idle condition, the signalling system transmits an idle code of alternate 1s and 0s. The beginning of a seven-bit code word is preceded by the transmission of two successive 1s. A 1 bit corresponds to signal energy transmitted by the 68.76 MHz signal and a 0 bit by energy in the 68.78 MHz signal. At the receiving end, the two signals are independently detected. With no errors, the two signals are complementary on the high-frequency line and identical at the detector output in the receiver.

The coded signals are normally transmitted over all equipped coaxial units in the switching span although, in some cases, the signals are transmitted over only one working line or over the standby line. The signalling receiver is normally connected to the lowest numbered working line on which signals are transmitted. Controls are provided so that service may be switched manually to the standby line when required. In general, the manual controls can be used to override any automatic switch.

**Transmission Surveillance.** The complexities of L5 system operation require a sophisticated arrangement of equipment designed to accomplish a number of transmission measurements and to identify the

location of faulty remote repeaters and main station equipment. These functions are carried out by a transmission surveillance system (TSS). Units of this major support system for L5 include a transmission surveillance center (TSC), transmission surveillance auxiliary (TSA) units, an E2 Status Reporting and Control System, switched access networks, precise and programmable transmission measuring equipment, and a small but versatile miniature computer. Some of the principal features and functions of this surveillance system have a direct influence on the quality of transmission and on the efficiency of operation and maintenance of L5.

Many of the surveillance functions of the TSS are carried out automatically under the control of the miniature computer. In addition, manual override of the automatic features is possible to enable specific measurements or procedures to be carried out as required.

The TSC is located strategically at an L5 main station from which remote control of TSA units may be exercised efficiently and economically. All automatic operations of the TSS originate at the TSC. Remote TSA units located at other main stations, are controlled by the TSC. At the TSC and at each TSA unit, a switched access network is arranged to provide switched connections to selected measuring points and to a fault location system from which troubles at remote repeaters can be identified and isolated. Transmission of data and control signals between the TSC and TSA units is by means of the E2 Status Reporting and Control System; the latter system is time shared to provide TSC-TSA communications as well as other services such as alarm surveillance at locations remote from the TSC or the E2 central location.

*Transmission Measurements.* The test equipment located at L5 main stations is capable of measuring pilot amplitudes in all L5 systems operating through the main station and in all multiplex equipment located at the main station. Furthermore, the test equipment can be programmed to make such measurements automatically and to report the results back to the TSC upon command. Analysis of the measurements is made at the TSC by computer manipulation.

In addition to pilot amplitude measurements, the test equipment can also be programmed to measure attenuation/frequency characteristics between distant locations and to transmit the results over the E2 system to the TSC for analysis. Measurements of this type must be made on an out-of-service basis; thus, the E2 system must

be capable of switching service from normally operating equipment to standby facilities while the tests are being performed.

*Remote Status and Control.* Alarm polling is the principal function of the E2 system as applied to L5 operations. Typically, all remote stations under alarm surveillance by an E2 central station are polled during a 2- to 4-second interval. This polling function continues automatically until interrupted by a request for operations such as status reporting, remote switching, data collection and transfer, etc. When the alarm polling function is so interrupted, it automatically takes precedence and performs a polling cycle at least once every 30 seconds in order to update the alarm status throughout the system.

*Fault Location.* As shown in Figure 12-2, there are two low-frequency and two high-frequency fault location signal frequencies in the L5 spectrum. Oscillators, normally inoperative, are located in each manhole apparatus case. The fault location oscillator signals may be activated and connected (by remote control from the TSC or the nearest main station) to the input and output of the repeater under test; one low-frequency and one high-frequency signal is connected to the input and one of each is connected to the output. The amplitudes of the signals are adjusted to be equal at the output when the gain of the repeater is normal. Thus, measurement of these signal amplitudes provides a sensitive indication of the operation of the repeater. The process is complicated at regulating and equalizing repeaters, especially in evaluating high-frequency gains, because repeater gain varies with cable temperature changes. However, tables are provided so that the variations in gain can be taken into account.

The processes of operating the fault location oscillators are all accomplished on an in-service basis by the TSS. Control signals and power for the oscillators are transmitted over interstitial wires in the coaxial cable.

*Order Wires.* Coordination of maintenance and repair activities in L5 is supported by an order-wire system that provides for voice communications between all manhole and main station locations. The interstitial pairs in the cable are used for this purpose. Four-wire transmission is used and, to reduce transmission losses, the pairs are sometimes inductively loaded at L5 repeater points (Q-loading) as described in Chapter 2. Electronic circuits are used to provide gain and interlocation signalling.

### Power System

A simplified block diagram of the L5 power feed system is shown in Figure 12-10. Two designs of power converter are available. One converts 140 volts and the other converts 24 volts dc to the required line feed voltage. The power converters are located at main stations along an L5 route at distances not exceeding 75 miles.

At the main stations, the dc is fed to the center conductors of the coaxial units through power separation filters which combine (or separate) the dc power and signal power. The dc is supplied by constant-current feed circuits that maintain a well-regulated 910 milliampere current. In standard installations, the voltage to ground at each end of a power feed section may be as high as 1150 volts; end-to-end, the maximum voltage differential is thus as high as 2300 volts. In some sections, subject to special engineering, these voltages may be increased to 1250 and 2500 volts, respectively.

Power feed to the coaxial units that are associated for the two directions of transmission are basically independent. A failure of power feed for one direction of transmission causes operation of the protective grounding circuit shown in Figure 12-10, thus permitting the unaffected direction of transmission to continue in operation. The protective grounding circuit also operates under a number of other trouble conditions such as abnormal dc earth potentials, a nearby lightning strike, or abnormal 60-Hz induction.

Where a coaxial route is less than 37.5 miles long, the converters normally used at one end of the section are omitted and power is fed from one end only. Another feature of the power feed system is that converters can be turned on by remote control from the central location of an E2 Status Reporting and Control System.

### 12-3 UNDERSEA CABLE SYSTEMS

The transmission design principles of undersea coaxial carrier systems are very similar to those applied to land systems. The greatest differences between the two types of systems derive from differences in the environment. These differences are manifested in installation and repair methods, system equalization, efficiency of utilization of the medium, and reliability considerations. Since the first repeatered undersea system was installed in 1950, a new design has emerged approximately every six or seven years. Each new design has represented a significant forward step in providing more channels at a lower per-mile channel cost.

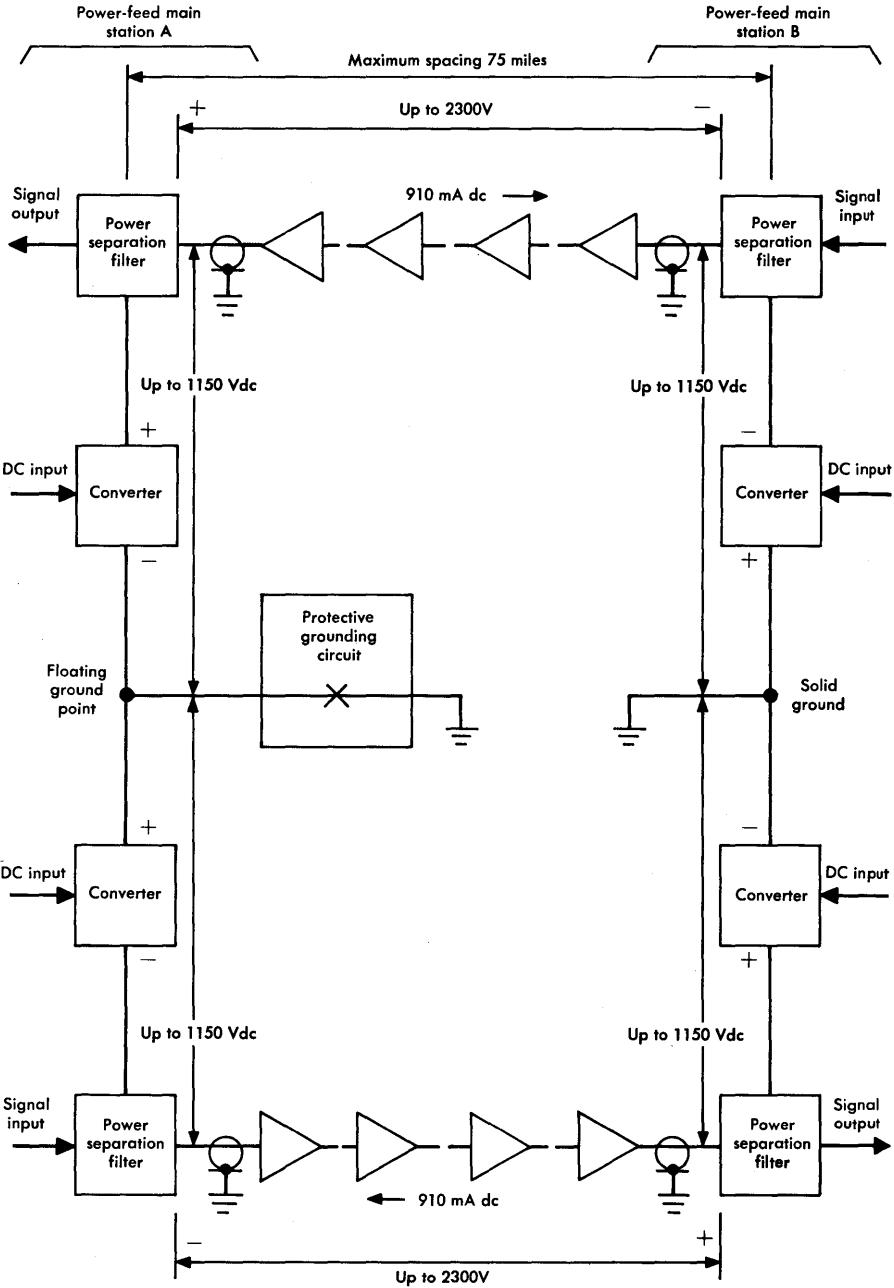


Figure 12-10. Power feed system.



### System Comparisons

Among the technological advances that have permitted the increase in channel capacities of later undersea cable systems has been the increase in the diameters of the coaxial cables. The effect of the larger diameters is analogous to the effective increase in channel capacities of land-based systems achieved by increasing the number of coaxial units in a cable. Figure 12-11 shows some of the pertinent data that apply directly or indirectly to the cables used for systems designated SA, SB, SD, SF, and SG [6, 7, 8, 9].

CHARACTERISTICS	SYSTEM DESIGNATION				
	SA	SB	SD	SF	SG
Coaxial diameter (inches)	0.460	0.625	1.0	1.5	1.7
Type of cable (deep sea)	Armored	Armored	Armorless	Armorless	Armorless
Maximum dc voltage	500	2600	6000	4200	7000
Number of cables/system	2	2	1	1	1
Transmission mode	4W	4W	Equiv 4W	Equiv 4W	Equiv 4W
Spacing (nautical miles)	36	38	20	10	5
Equalizer spacing (nautical miles)	None	200	192	192	150
Maximum gain (dB)	65	62	50	40	41
Active device	Tube	Tube	Tube	Transistor	Transistor
Repeater housing	Flexible	Flexible	Rigid	Rigid	Rigid
Maximum length (nautical miles)	125	2000	3500	4000	4000
Number of channels	24	36	138	845	4000
Channel spacing (kHz)	4	4	3	3	3
Top frequency (MHz)	0.12	0.17	1.1	6.0	30.0

Figure 12-11. Comparison of undersea systems.

All the cables used for repeatered undersea systems have been solid dielectric coaxials with one coaxial unit per cable. The outer diameter of the coaxial structure has been increased with each successive system design. In the early designs, the strength of the cable (important during laying and especially during repair operations) was incorporated in the outer sheathing. In the cable used for SD and later sys-

tems, the strength is in the center conductor. This design makes more efficient electrical and structural use of the available cross-section; for a given tensile strength, the armorless cable provides a larger coaxial diameter. Other significant cable-related changes include the increased voltages that have been applied to power undersea repeaters and the transition from four-wire to equivalent four-wire transmission.

Other comparisons of various design parameters of the systems now in service are given in Figure 12-11. Repeater and equalizer spacings are shortened as the bandwidth of the system increases. In spite of the increasing bandwidth in the later systems, maximum repeater gain has tended to decrease, a reflection of the shorter spacings and larger cable diameters. The required gains have been obtained by the application of electron tube technology for SA, SB, and SD systems. Solid-state technology has been used in SF and SG systems.

A significant advance in design was accomplished when the flexible (or articulated) repeater housing of the SA and SB systems was replaced by the rigid housing made possible by improved shipboard cable and repeater handling techniques. Better control of feedback loops became possible and overall system performance was accordingly improved. The improved feedback control, the larger cables, and the shorter repeater spacings have permitted the design of longer systems with greater bandwidth and channel capacity.

The cable and repeater housing design changes required the development of entirely new cable handling machinery for use on cable ships. This requirement, together with the more stringent transmission requirements resulting from wider bands and equivalent four-wire transmission, led to the design and construction of the modern cable laying vessel, the C. S. Long Lines. The SD system was the first to be installed by this vessel.

Of the undersea systems listed in Figure 12-11 approximately 250 nautical miles of SA system, 20,000 nautical miles of SB system, 20,000 nautical miles of SD system, 12,000 nautical miles of SF system, and 3,500 nautical miles of SG system have been installed.

### Design Features

While the transmission design principles are the same in undersea cable systems as in land coaxial systems, a number of details differ significantly. As previously mentioned, most of the differences derive from the difference in the environment.

One environmental effect that favors undersea system design is the stability of deep-water temperature which makes dynamic regulation to correct for cable loss changes unnecessary. What little change does occur can be corrected in most systems by the adjustment of shore-end equalizers which are used to give about equal amounts of pre- and post-equalization. In the SG system, shore-controlled adjustable undersea equalizers are installed about every 700 nautical miles to provide compensation for possible cable aging effects. The stability of the medium also permits the allocation of smaller signal-to-noise margins in undersea systems than in land systems for such misalignments.

The economic advantages of equivalent four-wire transmission have led to a repeater configuration in which a single amplifier is used for both directions of transmission. The frequency bands for the two directions are separated and combined by complex networks, called directional filters, that must be used in every repeater. The configuration used, shown in Figure 12-12, results in a very large number of electrical networks of identical designs being connected in tandem. To achieve satisfactory transmission, particularly in respect to the attenuation/frequency characteristics of the system, the design and

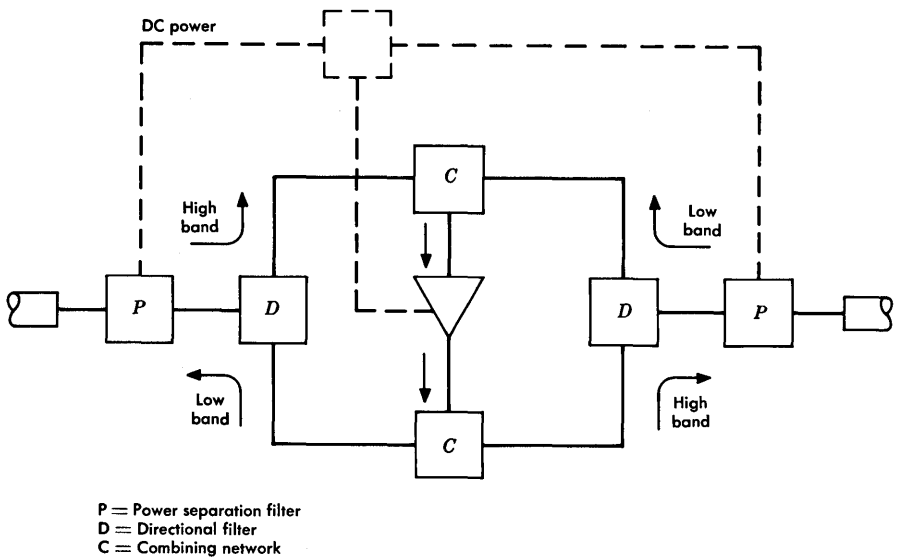


Figure 12-12. Equivalent four-wire repeater.

manufacturing requirements imposed on these networks are extremely stringent.

The entire process of cable laying, repeater connections to the cable, and system equalization is most efficient when the process is made as continuous as possible. Cable, repeaters, and equalizers are stored on shipboard according to carefully prepared plans; the repeaters and equalizers are spliced in advance at proper places along the cable so that the process of laying is not interrupted. Initially, the land-end cable sections are installed and shallow water cable (with added sheath protection) is buried in trenches to protect it from ship, anchor, and sea damage [10]. Connections to the cable are immediately established on shipboard and at the shore end to power sources and transmission test equipment. Measurements of the system transmission characteristics are then made continuously as the cable and repeaters are laid on the sea bottom. Required equalizer characteristics are determined on the basis of these measurements and appropriate equalizer networks are switched in or out of the transmission path before the equalizer is sealed. The process requires highly sophisticated test and computer equipment which is used intensively during the laying process. The equalizers, installed at intervals shown in Figure 12-11, are called ocean block equalizers.

Cable repair operations lead to unique transmission problems. Aside from the problems of locating damaged or severed cable or defective repeaters, repair operations usually result in the addition of cable equal in length to about twice the depth of the water at the repair location, depending on the available slack in the cable. In some cases, where the water is shallow, the loss of this added cable can be absorbed; otherwise, a repeater must be added to the system.

Since the cost of undersea cable systems is dominated by repeated line costs, every effort is made to use the medium as efficiently as possible. Thus, the voice-channel spacing in these systems is 3 kHz rather than the standard 4 kHz used for land system operations. The 3-kHz spacing is made possible by the use of channel bank filters with sharper cutoff characteristics and by a reduction of approximately 200 Hz in the voice band. In addition, the capacity of certain undersea systems can be increased substantially by the use of time assignment speech interpolation (TASI) equipment at the terminals.

The unique characteristics of undersea systems leads to the evaluation of signal-to-noise design parameters not usually important in

land systems. The use of equivalent four-wire transmission, the stability of the environment, the effects of repair operations, the loading effects of 3-kHz channel assignments and TASI, and the differences in speech habits of overseas service users all add to the complexity of design analyses. These factors are further complicated by the division of responsibility among many private and governmental agencies in respect to design, manufacture, operation, and ownership since they exist in an international environment.

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# Telecommunications Transmission Engineering

## *Section 4*

### *Analog Radio Systems*

A high percentage of trunks and special services circuits in the toll portion of the network and most network television circuits are now carried by analog microwave radio systems. The designs of many of these systems are based on solid-state technology. Most of these systems operate by frequency modulation of a carrier signal. However, they are capable of transmitting a variety of signals in a digital format. The AR6A system, currently in development, operates as a single sideband amplitude modulation system. In analog microwave system design, the AR6A represents the first significant departure from FM techniques.

A number of FM systems currently in operation are being adapted for digital transmission by multiplex techniques, by digital signal deviation of the RF carrier, or by the application of phase shift keying digital technology (including regenerative repeaters) throughout. These applications of digital transmission techniques are covered in Section 5 since a discussion of digital technology is prerequisite to descriptions of these modes of transmission on microwave radio systems.

In Chapter 13, there is a general discussion of the design features of microwave radio systems. A description of the entrance links that interconnect the radio equipment and signal sources is followed by a characterization of the transmission medium, its impairments, and methods of overcoming these impairments. The transmission layout of radio terminal and repeater equipment is then discussed. The chapter concludes with a consideration of system signal-to-noise relationships.

The engineering of microwave systems and the routes they traverse are the subjects of Chapter 14. Common carrier radio-frequency bandwidth allocations and the manner in which these bands are utilized

are discussed in considerable detail. The criteria for choosing a specific type of system are described as are the relations of those choices to the type of application. The methods of selecting a route and determining the repeater sites are discussed in relation to terrain characteristics, atmospheric and path transmission aberrations, and intersystem and intrasystem interference control.

The provision of protection channels and the use of automatic protection switching equipment are features of microwave radio systems that are necessary for maintenance and the achievement of adequate service reliability. In Chapter 15, these subjects are discussed and descriptions are given of frequency and space diversity switching of repeated sections as well as hot standby switching to protect against equipment failures at repeaters and main stations.

Chapter 16 covers descriptions of short-haul microwave systems such as the TJ, TL, TM, and TN types. Chapter 17 covers descriptions of the TD- and TH-type systems designed for long-haul applications.

Chapter 18 discusses transmission over satellite facilities and the types of equipment now in use. The AT&T Comstar domestic satellite system is described as an example of this type of facility.

Chapter 19 covers a number of customer loop services that are provided by a variety of miscellaneous radio equipment. Included are mobile radio and personal paging services. There are also brief descriptions of overseas and tropospheric transmission facilities.

## Chapter 13

# Microwave Radio System Design Features

A wide variety of multiplexed signals is transmitted over microwave radio transmission systems in the telecommunication network. These are versatile systems that provide a majority of the long-haul trunks and network television circuits. Other special services circuits and a large proportion of short-haul and metropolitan area trunks are also provided by these systems.

The microwave radio frequencies allocated for common carrier use by the Federal Communications Commission (FCC) include bands near 2, 4, 6, 11, 18, 22, 28, 31, and 39 GHz.\* These frequency allocations strongly influence many aspects of microwave radio system engineering, design, transmission layout, field of application, and operation.

Frequency modulation (FM) is commonly used as the transmission mode in these systems. Signals are transmitted in *radio channels* within the common carrier bands allocated by the FCC. The channel spectrum of one or more of the available bands is often used to full capacity by multiplexed voice-frequency signals. To eliminate the need for guard bands between the radio channels and thereby maximize usage of the spectrum, the signals in adjacent channels are usually transmitted with orthogonal polarizations.

Circuit and system techniques are being developed to permit the transmission of frequency division multiplexed signals by single-sideband amplitude-modulation (SSB-AM) of the radio-frequency carrier. Previously, microwave system repeaters were not sufficiently linear to permit this mode of transmission.

\*The 22, 28, and 39 GHz bands have not yet been exploited for use in the Bell System.



Digital transmission techniques are also being introduced in microwave radio systems. However, the design features of digital systems are different from those of FM and SSB-AM systems. Where similarities exist, they are described in this chapter but greater detail is given in Chapter 23.

The principal components of a microwave radio system are the transmission medium, protection switching equipment, repeaters, terminal equipment and entrance facilities. Terminal equipment includes frequency-modulation transmitters and receivers (FMT and FMR) where FM is used, transmitter and receiver modulators for SSB-AM systems, and digital processors for digital systems. The entrance facilities are used to interconnect the radio terminal equipment and other parts of the facility network.

Two methods are used to generate the transmitted FM signal. One, used primarily for short-haul systems, involves the direct application of the input signal (usually regarded as the *baseband signal*) to an FM deviator. Thus, the microwave carrier is frequency modulated by the baseband signal. However, the recovery of the baseband signal is greatly facilitated by using an intermediate step of modulation. The received RF signal is applied to a down converter which translates the signal to an intermediate frequency (IF) near 70 MHz. In long-haul systems, the demodulation to baseband and remodulation to RF at each repeater would be costly in terms of economics and performance. In these systems, the connection from the receiving to the transmitting portion of a repeater is made at IF and the IF signal is applied to an up converter for transmission at RF. The intermediate step of modulation at transmitting terminals is also used in long-haul systems in the transmitting portion of a terminal. The baseband signal frequency modulates a carrier near 70 MHz and the IF signal is applied to an up converter to translate it to the proper RF band in the same manner as that used at repeaters.

### 13-1 THE TRANSMISSION MEDIUM

In microwave radio systems, the transmission medium may be regarded as including the atmosphere, the transmitting and receiving antennas at repeater points and/or terminals, and the waveguide components that connect the antennas to the repeater or terminal equipment. The general characteristics of these components of the medium are discussed in Chapter 2. The effects of these characteristics

on system design features depend somewhat on the frequency bands transmitted, the nature of the radio repeaters, and the reliability requirements appropriate to the field of application.

### Transmission Medium Impairments

The control of impairments is quite different depending on the origin, whether in the atmosphere, antennas, or waveguides. In every case, the methods used to control and minimize the effects of impairments have evolved over a period of years and often have resulted from studies that were initiated for the development of new systems and then applied to existing systems [1, 2, 3, 4].

Microwave radio transmission normally requires a line-of-sight path between transmitting and receiving antennas. When the atmosphere is well-mixed and adequate clearance is provided between the line-of-sight path and potential obstacles, the transmission loss is highly predictable and stable. However, when different strata of atmospheric temperatures and/or humidities exist, components of the direct signal and reflections can interact to reduce or increase the net received signal amplitude, a phenomenon called *multipath fading*. A fade may cover the entire frequency spectrum of a route but it is usually frequency selective, affecting only one or two radio channels in a switching section at any one time. The depth of fade can vary widely and, in some instances, may cause a complete failure of transmission in one or more channels for short periods of time. Protection switching usually prevents loss of service during fades.

Systems that operate at frequencies higher than 10 GHz, where raindrop size is an appreciable fraction of a wavelength, are subject to variations in attenuation due to absorption and scattering. Service may be seriously impaired by heavy rainfall. The repeater spacings for such systems tend to be shorter than in lower frequency systems and are thus less susceptible to multipath fading. At 18 GHz, rain attenuation and scattering are the dominant media impairments.

Impairments produced by antennas result from the use of an unsuitable type, departures from design specifications, damage, or improper orientation. The antenna most commonly used for Bell System long-haul microwave radio transmission is the horn reflector [5]. This antenna provides high gain, a narrow transmitted beam, the ability to transmit both horizontal and vertical signal polarizations, and a wide bandwidth that permits the simultaneous transmission of

signals in the 4-, 6-, and 11-GHz bands. Short-haul systems, most of which operate at 6 or 11 GHz, are usually equipped with parabolic "dish" antennas. By proper selection of the feed method, this type antenna can also be used for simultaneous transmission of the two polarizations and one or two frequency bands.

The wide bandpass characteristic of the horn reflector results in little delay distortion across the allocated frequency bands. At the frequencies for which it is designed, the horn reflector confines the bulk of the radiated energy to a beam two degrees wide or less. The transmitting and receiving antennas must be precisely aligned as departures from proper alignment cause excessive path loss, increase the delay distortion significantly, and reduce the cross-polarization discrimination.

Microwave antennas are usually mounted at or near the tops of high buildings or towers or, often, at the tops of hills or mountains in order to provide adequate clearance in the line-of-sight path. They are connected to the radio repeater or terminal equipment by sections of waveguide. The wideband horn-reflector antenna is fed by a circular waveguide of such a diameter (2.81 inches) that it can transmit 4-, 6-, and/or 11-GHz signals of both horizontal and vertical polarizations. Parabolic antennas are fed by rectangular waveguide to a point near the antenna where there is a transition to circular or square waveguide.

The major sources of impairment in the waveguide portion of the transmission medium are the points between waveguide sections, connections to the antenna feedhorn, waveguide bends or flexible waveguide sections, and system networks. The latter are used to combine and separate the 4-, 6-, and 11-GHz bands and the two polarizations that might be used in each band. The impedance discontinuities that may occur at these points result in intermodulation noise. Thus, stringent return loss requirements are imposed on all individual waveguide sections and components. For this reason, the mechanical alignment of all the pieces that comprise a waveguide system must be precise. Irregularities due to foreign matter inside the waveguide or to dents or other imperfections on the inside surface must also be avoided.

### Continuity of Service

Several protection switching arrangements are used to provide the necessary continuity of service. They operate automatically to pro-

tect against equipment failure and fading. They may also be controlled manually to facilitate maintenance of working radio channels, to provide for part-time or incidental television transmission of special events, or to effect emergency broadband restoration. In some arrangements, automatic switching is initiated by automatic gain control (AGC) circuits; in others, the switching is initiated by an increase of noise beyond an established threshold value or by the loss of RF carrier power. The protection channel may be at a different position in the RF spectrum than the channel in trouble (frequency diversity switching) or it may be at the same frequency as that of the channel in trouble but received from a separate antenna system (space diversity switching).

**Frequency Diversity Switching.** Since fading phenomena usually affect only certain portions of the microwave radio spectrum (one or two radio channels) at a time, automatic switching arrangements are often used to transfer service during deep fades from the assigned RF channel to a protection channel. This mode of operation requires the assignment of a portion of the available microwave band to protection use; stringent rules established by the FCC govern the use of the spectrum for these purposes [6].

Arrangements are available to provide protection switching for various combinations of portions of microwave radio transmission systems. Those most commonly used to protect against atmospheric fading operate over several repeater sections. They switch at intermediate frequencies and thus entrance links or radio terminal equipment are not protected. Some of these switching arrangements are designed to provide intrasystem protection switching (where the protection and working channels are all at the nominal 4-, 6-, or 11-GHz frequencies) and some provide intersystem switching called crossband diversity switching.

Protection circuits are sometimes arranged to protect an entire radio channel from baseband input to baseband output including entrance links and radio terminal equipment. Systems are also available in which a protection channel may protect just one working channel and others are available in which one protection channel may protect several working channels. These baseband-to-baseband arrangements are used primarily on short-haul systems.

**Space Diversity Switching.** The FCC rules which reduced the permissible number of frequency diversity protection channels make relia-

bility criteria on routes subject to severe fading difficult to meet without adding space diversity switching to some repeater sections. With this technique, the signals are normally received by a "regular" antenna usually mounted at or near the top of a high tower. To provide space diversity, a "diversity" antenna is usually mounted lower on the tower than the regular antenna [7, 8].

The regular and diversity antennas are independently connected by waveguide to the radio equipment. Space diversity switch control circuits are arranged so that when any channel signal received from the primary antenna fades below an established threshold, the receiving circuits are immediately switched to the secondary antenna. The process is called blind switching because the switch is made without knowledge of the quality of the signal being received by the diversity antenna. Service for the affected channel is carried by the diversity antenna for a predetermined time interval (typically thirty minutes) and is then switched back to the regular antenna. If a fade is experienced on the diversity antenna during this interval, service is immediately switched back to the regular antenna. If reception is satisfactory, the service is carried by the regular antenna until the next fade. If not, the receiver is again switched to the diversity antenna. On routes equipped with space diversity switching, each repeater section for which such a need has been established is equipped with the necessary diversity antenna and switching equipment.

## 13-2 REPEATERS AND TERMINALS

As previously mentioned, either baseband or IF repeaters are used in FM microwave radio systems. Baseband repeatered systems are most commonly used in short-haul service to permit ready access to the baseband signal thus facilitating the adding and dropping of voice-frequency channels at intermediate stations. Systems that utilize IF repeaters are usually used in long-haul service.

### Baseband System Repeaters

Figure 13-1 shows one direction of transmission through a microwave radio baseband repeater. Signals are received by an antenna and transmitted through waveguide to the channel separating network shown at the left of the block diagram. The desired signal is selected by a bandpass filter and connected to a down converter which trans-

lates the FM signal to an IF band centered at 70 MHz. This signal is amplified and limited in amplitude before being applied to a discriminator which demodulates it to baseband frequencies where it is again amplified. This portion of a baseband repeater might serve as the receiver at a terminal point in the system. In this case, the signal would be connected through a wire-line entrance link to multiplex or other suitable terminating equipment.

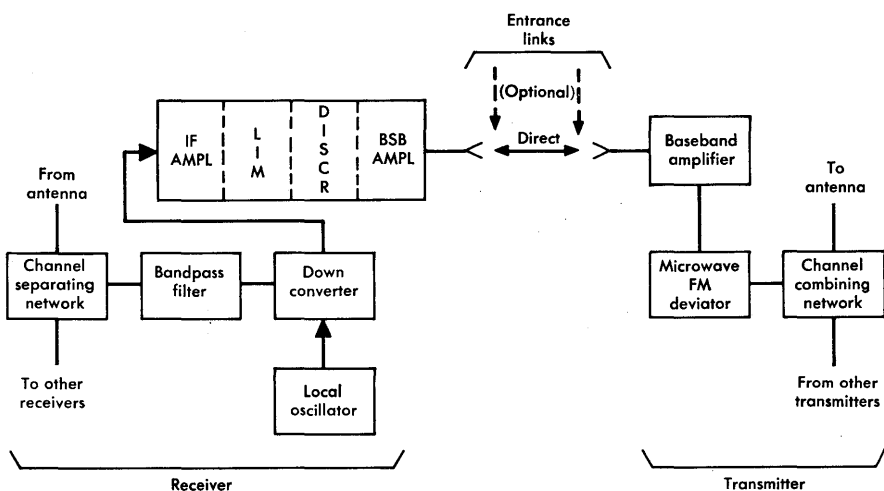


Figure 13-1. Microwave radio baseband repeater.

In repeater applications, the baseband signal would be connected directly to the transmitter portion of the repeater. After additional amplification, the baseband signal is applied directly to a microwave FM deviator, usually to the repeller of a klystron tube in equipment of early design. In more recent designs, a solid-state deviator is used to translate the baseband signal to an FM signal. At the output of the deviator, the signal is amplified and combined with other channel signals for transmission by waveguide to the antenna. The frequency of the carrier in this transmitter is usually different from that of the carrier received from the previous repeater section in order to minimize crosstalk and interference impairments. Occasionally, where interferences are well controlled, transmitters and receivers may be operated at the same frequency.

### Intermediate-Frequency Repeaters

Figure 13-2 shows one direction of transmission through an IF repeater typical of those used in long-haul microwave radio systems.

After the received channel signal has been modulated to the IF band by the down converter, it is amplified and connected directly to the limiter and/or up converter of the transmitting portion of the repeater. Thus, at repeater points the signal is not demodulated to baseband. A microwave carrier supply furnishes carriers at different frequencies,  $f_{c1}$  and  $f_{c2}$ , to the up and down converters. Transmitter output power for IF repeated systems is in the range of 1.0 to 12 watts, depending in part on equipment vintage.

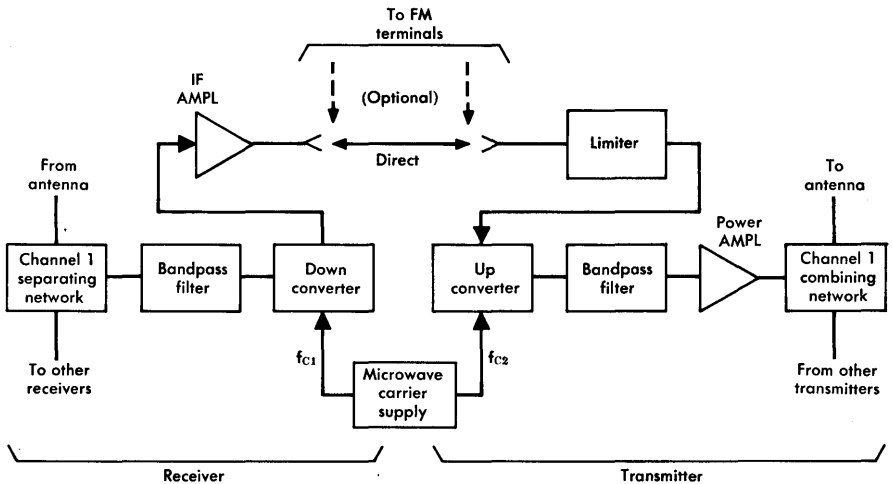


Figure 13-2. Microwave radio IF repeater.

The IF connection between the receiving and transmitting portions of the repeater may be opened and connections made instead to FM terminal equipment. This arrangement would be used where voice channels must be added or dropped and where the two portions of the repeater are to be used at a terminal station.

### FM Terminals

The initial and final steps of modulation in microwave systems that utilize IF-type repeaters are performed respectively by FM

terminal transmitters and FM receivers. These units are often referred to simply as terminals. A modern version of this equipment, the 4A FM, was designed for use with TH-3 and TD-type microwave radio systems [9].

Figure 13-3 is a block diagram of a 4A FM transmitter. The balanced input signal is amplified and converted to an unbalanced signal in the baseband amplifier. This signal is applied to the deviator in which the signal voltage modulates a 70-MHz oscillator. The oscillator, varactor diode biasing circuits, and buffer amplifier elements of the deviator, are assembled in a controlled temperature oven to provide the prescribed IF stability of  $\pm 25$  kHz. The output of the deviator is filtered to eliminate unwanted signal components and amplified to the required amplitude.

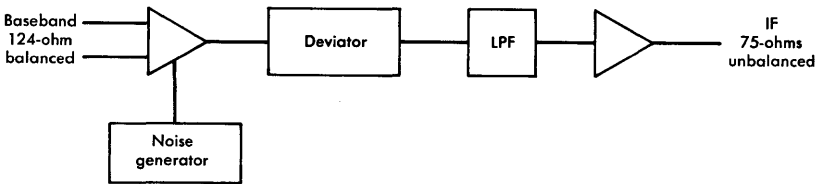


Figure 13-3. Block diagram of 4A FM terminal transmitter.

The noise generator may be used when multiplexed message signals are transmitted. It must be disabled when a television signal or a digital signal with very low frequency components is transmitted. The noise, confined to the band from 0 to 1 kHz, provides a random variation of the carrier frequency, called spreading. This causes certain tone interferences that may appear in the radio channel to be spread over several voice channels, thus making the interference more like random noise and thereby substantially reducing the subjective effect of the tones.

In an earlier design of transmitter, as shown in Figure 13-4, two oscillators, 70 MHz apart in frequency, are frequency modulated by a baseband signal. The oscillator frequencies are typically about 186 and 256 MHz. The circuits are arranged so that an applied input voltage that causes one oscillator to increase in frequency causes the other to decrease in frequency. The output of the mixer is the frequency difference between the two oscillators, a frequency deviation



twice that of either oscillator. Thus, each oscillator is required to provide only one-half the total deviation and at the same time, even-order intermodulation products cancel. The complexities of this dual oscillator arrangement (many of which are in service) have been overcome by recent technology advances.

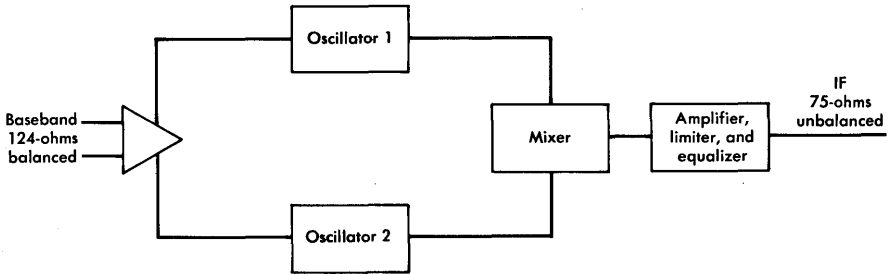


Figure 13-4. Early designs of FM terminal transmitter.

Figure 13-5 shows a circuit arrangement typically used in an FM receiver. The limiter is used to remove amplitude variations in the signal before demodulation in the discriminator.

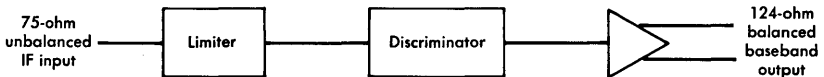


Figure 13-5. FM terminal receiver.

### 13-3 ENTRANCE FACILITIES

Radio-frequency circuits and equipment are usually located in close proximity to the associated antennas but are often physically removed from signal sources for the radio system. In metropolitan areas, the antennas are usually mounted atop tall buildings while the associated transmitting and receiving equipment is located nearby on one of the highest floors of the building. Other equipment, such as the multiplex, is likely to be located on one of the lower floors of the building or even in a nearby building; the radio equipment and signal sources may thus be several hundred feet apart. In suburban and rural areas, the antennas are normally mounted on high towers with the RF equipment at the base of the tower. The distance to the signal source is

typically several hundred feet and may be up to eight miles in extreme cases. The facilities that interconnect signal sources and RF equipment, called *entrance facilities*, must be designed to meet stringent transmission, reliability, and operating requirements. They are allocated only a small portion of the overall allowable impairment.

### Signal Sources

The signals transmitted over microwave radio systems originate in various types of equipment. The design of entrance facilities depends on the characteristics of the source equipment as well as on the characteristics of the signals. Sources include multiplex and connector equipment, television video and audio circuits, digital multiplex cross-connect frames, and direct connections from other systems.

The signals most commonly transmitted on microwave radio systems are those generated in the frequency division multiplex equipment described in Chapter 9. Similar signals are also used as radio system inputs by connection from an adjacent or intersecting radio system or route. In this case, the signal may be a composite signal made up of a portion of a signal from another route and of signals generated in local multiplex equipment. Filters, combining networks, and separating networks must be arranged to form a signal spectrum compatible with the radio system involved.

Where a microwave radio channel is to be used for television signal transmission, the signal source is most likely to be a television operating center or a television facility test position, especially if signal administration (switching, equalization, etc.) is required. Where there is no signal administration, the signal source may be an A2A-type or an A4 baseband transmission system or an intersecting radio system by direct interconnection at intermediate or baseband frequencies. The audio portion of television service can be carried either on a separate facility or on the same radio channel as the video signal. Where both are carried on the same channel, the audio signal modulates a subcarrier in the baseband spectrum above the video signal.

A digital signal at the DS-1 rate (1.544 Mb/s) may be transmitted over a microwave radio system in the band below the lowest frequency normally allocated to the L-multiplex channels, 0.564 MHz. Where this

signal is to be added to multiplexed voice-frequency signals, the two spectra are carried over separate facilities from the sources and combined at the input to the radio system terminal. This transmission arrangement is sometimes referred to as data under voice (DUV). The digital signal is received from a DSX-1 cross-connect frame, is processed by the 1A Radio Digital System (1A-RDS) into a seven-level format that occupies the frequency band from near 0 to 470 kHz, and then is transmitted to the radio terminal over a double-shielded balanced pair.

In other digital arrangements involving microwave radio transmission, one or more channels of the radio system may be dedicated to the transmission of high-speed digital signals. In the 3A-RDS, a 44.736 Mb/s, bipolar, return-to-zero, DS-3 signal is transmitted from the DSX-3 cross-connect frame over distances up to 450 feet on solid-dielectric coaxial cable to the radio terminal where it is processed for transmission over the microwave radio system.

The DR 18A microwave radio system transmits DS-4 level signals (274.166 Mb/s) on 18-GHz carriers. The signal is received from a DSX-4 cross-connect frame and transmitted to the radio terminal usually over solid-dielectric coaxial cable.

### Wire-Line Entrance Links

These entrance facilities are used between signal sources and microwave radio system terminals where compensation for loss and attenuation/frequency distortion is required. In most cases, these facilities are protected by some form of automatic switching arrangement. Additional features of wire-line entrance links (WLEL) include pre- and de-emphasis of the baseband signal spectrum and the combining of speech and data signals required when the 1A-RDS is used.

Most entrance links provide baseband transmission of the signals to the radio terminal as shown in Figure 13-6. However, it is desirable in some cases to transmit signals at the 70-MHz IF band used in radio repeaters. Such applications are somewhat rare but their usefulness will probably increase in the near future. For example, it is expected that entrance links for the SSB-AM AR 6A system will operate exclusively at IF.

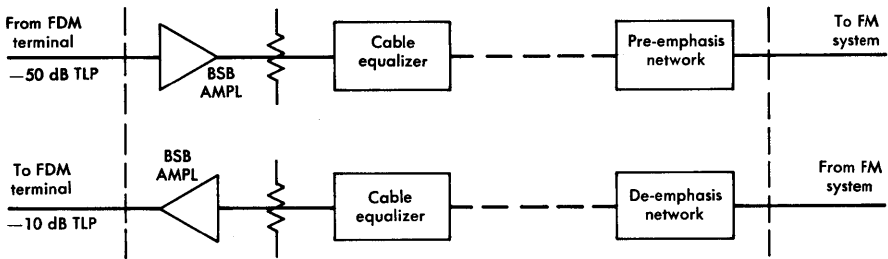


Figure 13-6. Simplified schematic of a baseband wire-line entrance link.

**Baseband Entrance Links.** A number of entrance link types have been developed to satisfy the needs of new microwave radio systems as they were introduced into service. Earlier design (designated A-, B-, and C-type) were used for single mastergroup transmission. While many of these are still in service, they are no longer manufactured. Now the most commonly used is the 3A WLEL which provides a wide range of options that make it applicable to most microwave radio systems under a variety of loading and operating conditions.

The amplifiers, equalizers, and other frequency-dependent components of the 3A WLEL have been designed to operate with a number of cable types having nominal insertion losses that increase in proportion to the square root of frequency. Components must be selected for compatibility with the type and length of cable to be used and with the channel capacity of the radio system being served. Entrance links may include intermediate repeaters as well as terminal equipment located at the multiplex and radio ends. Distance limits, as shown in Figure 13-7, depend on type of cable, channel capacity of the served radio system, use of repeaters, and standard or "dedicated" applications. The latter category refers to 3A WLELs dedicated to broadband restoration use. The distance limits are the same as those applied to standard WLELs for 1800 channels.

Satisfactory signal-to-noise performance of most FM microwave radio systems carrying frequency-multiplexed signals depends in part on the pre-emphasis of high baseband frequency signal components. The networks required to achieve this pre-emphasis are installed in the transmitting portions of 3A WLELs. The compensating de-emphasis networks are installed in the receiving portions of 3A WLELs. These networks, shown in Figure 13-6, must be selected to satisfy the requirements of the radio system being served and the

CABLE		NONREPEATERED WLEL, miles		REPEATERED WLEL, miles
TYPE	Z, ohms	UP TO 1200 CHANNELS	1800 CHANNELS	UP TO 1800 CHANNELS
724 unbalanced	75	0.5	0.5	NA
754 balanced	124	0.5	0.5	NA
16 PVL balanced	124	2.81	1.92	3.84
0.375-inch coaxial unbalanced	75	5.85	4.0	8.0

Figure 13-7. Length limits for the 3A WLEL.

bandwidth it covers. Figure 13-8 illustrates the loss/frequency characteristics of some typical networks. Curves 1a and 1b are complementary as are curves 2a and 2b.

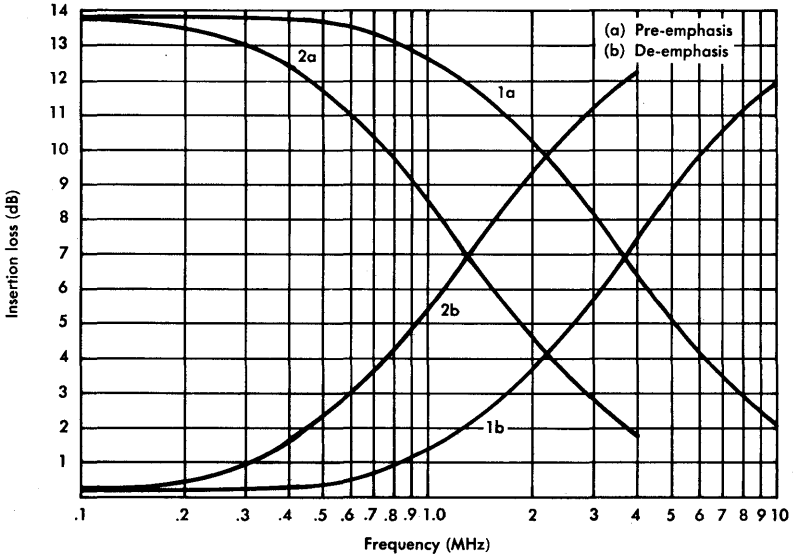


Figure 13-8. Insertion losses of typical pre- and de-emphasis networks.

Wire-line entrance link equipment contains amplifiers and carries large numbers of multiplexed signals. For these reasons, automatic protection switching systems are used to assure service reliability. In most cases, the protection switching operates between the baseband and intermediate frequencies thus protecting the wire-line entrance link as well as the associated FM terminal transmitter or receiver. In other cases, the protection switching is applied to the entrance link only. In yet other arrangements, the protection switching covers the entire radio system from the WLEL at one end through the WLEL at the other end.

Where required, the 3A WLEL may include equipment to combine message circuits from multiplex equipment with the digital signal from a 1A-RDS terminal. When so equipped, the WLEL is usually protected by a baseband-IF switching system which includes protection of the FM transmitting and receiving terminal equipment. However, other protection arrangements are also used, especially in TH-1 and in short-haul systems.

**Intermediate-Frequency Entrance Link.** In some microwave radio terminal locations, it is undesirable to use the normal transmission mode because of existing or potential interference problems. One such situation may occur where a radio route terminates at the earth station of a satellite communications system. The terrestrial system may induce excessive interference into the satellite system. Another situation may occur where a radio route traverses a congested urban area in which new building construction may obstruct the transmission path. Alternate routing of the radio path may be expensive or perhaps impossible.

In these cases, the radio system might be terminated at the last repeater before the terminal and the last section might consist of a baseband entrance link to the terminal location. However, it is often not economically or operationally desirable to use baseband facilities for this purpose and an IF entrance link is used. It is capable of transmitting up to 2400 multiplexed message signals over 0.375-inch coaxial cable units for distances up to about 8000 feet. Somewhat greater distances can be accommodated where fewer channels are involved, for example, up to 9000 feet for 1200 channels. Limits are established by cable loss and the resulting noise penalty in the top transmitted channel. The IF link has added advantages over a baseband link; it can be protected as if it were a part of the radio system and can be tested from the terminal station by the use of radio rather than baseband test equipment.

### 13-4 SIGNAL-TO-NOISE CONSIDERATIONS

Until recently, frequency modulation has been used in microwave radio systems because the technology has not permitted the design of intermediate and microwave frequency AM amplifiers with sufficient gain, power output, and linearity to permit signal-to-noise requirements to be met in the transmission of broadband signals.\* Although the amplitude linearity characteristics of available amplifiers have been unsatisfactory for AM use, FM signals are relatively insensitive to such impairment.

The determination of a satisfactory transmission layout of microwave radio systems involves many considerations. Among these are achievable transmitter performance in respect to power output, receiver performance in respect to noise figure, route layout to provide line-of-sight transmission with adequate clearance from obstacles, achievable modulation noise performance, system bandwidth and voice channel capacity, and RF channel allocations. In addition, transmission and reliability objectives consistent with system application must be well documented and properly applied.

The concept of establishing optimum signal amplitudes between an overload or intermodulation "ceiling" and a noise "floor," discussed in Chapter 10, is applied in the design of microwave radio systems as well as in the design of analog wire transmission systems. However, bandwidth, repeater spacing, and signal-to-noise are not nearly as closely related in radio systems as in wire systems.

The maximum signal amplitude may be considered in terms of the radiated power of the RF wave or in terms of the maximum frequency deviation of the FM carrier. Limits on transmitted power and frequency deviation are imposed by the Rules and Regulations of the FCC.

The minimum allowable RF signal amplitude, set by the noise floor, is found at the input to a radio repeater. The repeater noise figure is dependent on the noise at the input and on the random noise generated within the repeater. These additional noise components are translated to equivalent values at the input and added to the input circuit thermal noise to derive the repeater noise figure.

\*An SSB-AM microwave radio system, the AR6A, is currently in development. Improved active devices and advanced technology have permitted this system design.

If the signal-to-noise ratio in an FM system of the type under consideration deteriorates so badly that the noise power is only 10 to 15 dB below the carrier, a phenomenon called *breaking* may occur. In these circumstances, the signal-to-noise ratio at baseband decreases faster than it does at radio or intermediate frequencies. The resultant noise has a highly impulsive characteristic and is especially damaging to data transmission. The effect is more pronounced at low baseband frequencies (below 2 MHz) than at higher frequencies.

Modulation noise in FM systems is a function of frequency deviation, rather than of signal amplitudes and repeater amplitude linearity relationships, and of AM-to-PM conversion effects. Thus, the major sources of this type of noise are relatively small attenuation/frequency deviations, delay/frequency deviations, and echoes due to impedance mismatches. The analysis of intermodulation noise amplitudes is rather difficult and requires the application of sophisticated mathematical techniques. In operating systems, special test equipment is used to measure system performance parameters and to identify sources of excessive noise.

Radio repeater spacings are determined primarily by line-of-sight path clearance, the required signal strength at the receiver, and the geographical locations of points where access is needed for connection to multiplex equipment or with other systems. In relatively flat terrain, an increase in path length dictates an increase in antenna tower height and thus is an economic factor in repeater site selection. Transmitter power output and antenna gain similarly enter into the economics of selection but the performance of radio systems, unlike that of AM cable systems, is not a sensitive function of the repeater spacing. The primary reason for this divergence lies in the transmission medium. Cable loss is measured or expressed directly in dB per mile; doubling a length of cable multiplies its loss in dB by two. Radio path loss varies as 20 log of the path length; therefore, doubling a path length increases its loss only 6 dB. It follows that there is greater flexibility in the choice of repeater spacings in a radio system than in AM cable systems where a specific spacing is determined by repeater performance, medium transmission characteristics, and system noise requirements. In a radio system, the problem involves tower economics, geography, fading or rain attenuation, interferences, and system requirements. Consideration of these factors results in typical 4- and 6-GHz microwave repeater spacings of 20 to 30 miles and somewhat shorter spacings for short-haul systems that operate at higher frequencies.



The performance of microwave radio systems is often evaluated experimentally (during development) and in operating situations (out of service) by a technique called noise loading [10]. This technique may be used to establish or to verify signal amplitudes and transmission level points and to determine system performance.

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## Chapter 14

# Microwave System Engineering

Facility planning studies based on forecasts of network growth and restructuring and/or specific orders for television video services often indicate the need for new point-to-point microwave radio systems. Engineering studies are then used to determine the radio frequency (RF) band to be used, the type of system to be installed, and the specific locations of terminal and intermediate main stations. These determinations depend, at least in part, on the length of the system between terminals, required initial and ultimate circuit capacity, and costs.

In addition to these overall studies, much detailed work is required to establish the specific route and to determine the system layout along that route. In this aspect of the work, studies must be made of both real and potential interferences into the new system from outside sources and by the new system into existing systems. Specific repeater sites must be selected and the required heights of antenna towers determined. Consideration must also be given to accessibility of reliable sources of power and repeater station maintenance.

### 14-1 OPERATING FREQUENCIES AND SYSTEM CHARACTERISTICS

The Federal Communications Commission (FCC) has allocated frequency bands for common carrier transmission use at nominal frequencies of 2, 4, 6, 11, 18, 22, 28, 31, and 39 GHz. Systems are available for use in each of the allocated bands through 18 GHz; however, the higher frequencies are not yet being used in the Bell System. Metropolitan, short-haul, and long-haul services are provided; distances associated with these services are generally regarded as up to 50 miles, 250 miles, and 4000 miles respectively.

### The 2-GHz Band

Common carrier system signals are limited to 20-MHz wide bands between 2.110 and 2.130 GHz and between 2.160 and 2.180 GHz. The limited telephone channel capacity, the complications of sharing the frequency bands with other users,\* and FCC-imposed limitations on 2-GHz systems have made these allocations relatively unattractive in the Bell System. However, consideration is being given to the use of this band for digital signal transmission and some general trade systems have been installed to provide service to remote areas as well as order-wire and alarm facilities for other systems.

### The 4-GHz Band

The majority of Bell System long-haul microwave radio message channels are carried on the TD-2 and TD-3 systems. In these systems, baseband signals frequency modulate a 70-MHz intermediate frequency (IF) carrier. The resulting IF signal (carrier plus side bands) is used to modulate an RF carrier in the band between 3.7 and 4.2 GHz. This band accommodates twelve two-way radio channels each 20 MHz wide. Each radio channel in the TD-2 and TD-3 systems has a capacity of 1500 message channels although most systems are now equipped to carry only 1200. These high capacities have been achieved by a series of circuit and operating improvements which have permitted the increase from the 480 message channels for which the TD-2 was originally designed. Bell System network television service is also provided by these systems.

The two systems are functionally similar, differing mainly in circuit and equipment details. While the TD-2 was designed on the basis of electron tube technology, many of its circuits have been converted to solid-state designs. The TD-3 incorporates circuits that are essentially all of solid-state design. Both systems utilize an intermediate frequency band of 60 to 80 MHz within which a 70-MHz carrier is frequency modulated by the baseband signal. The repeaters in both systems are of the heterodyne (IF) type.

### The 6-GHz Band

The nominal 6-GHz band utilizes frequencies between 5.925 and 6.425 GHz. This 500-MHz band is divided into eight two-way, 30-MHz

\*The band from 2.160 to 2.162 is largely preempted by television distribution systems in large metropolitan areas.

channels and is used by several major Bell System designs and by others of outside supplier design. Those of Bell System design are the TH- and TM-type FM systems; the AR6A single-sideband AM system is now being developed. The TH-1, TH-3, and AR6A systems use heterodyne repeaters; the TM-type systems use heterodyne or baseband remodulating repeaters. The TH-1, TH-3, and AR6A systems are intended primarily for long-haul applications and the TM-type for short-haul applications.

In each 30-MHz radio channel, the TH-1 system can carry 1860 message channels (usually used for 1800 channels); the TH-3 and the TM-type systems can carry up to 1800 message channels.\* The TH- and TM-type systems can be also used for television transmission. The AR6A system is being designed for a capacity of 6000 message channels.

### The 11-GHz Band

Several systems are used to provide short-haul service in this band which extends from 10.7 to 11.7 GHz. The TJ system utilizes electron tube technology and baseband remodulating repeaters. It has a capacity of 600 telephone channels in each of six 20-MHz wide two-way radio channels formed from the allocated 1-GHz spectrum. The system does not conform with the more stringent FCC regulations on channel usage now in force and is no longer being manufactured.

Solid-state baseband repeatered systems of the TL-type are also in service. Each of the six radio channels, which require a 40-MHz band in each direction, may provide 1200 telephone channels or one television channel.

The solid-state TN-1 system is the most recent of Bell System designs for analog service in the 11-GHz band. This system can provide either 12 two-way radio channels with 1800 message channels in each or 23 two-way radio channels with 1200 message channels in each. It is an FM system that utilizes heterodyne repeaters and an IF band at 70 MHz. Where dropping and adding of message channels are required, FM terminal equipment is used. This system may also be used to transmit digital signals derived from the 3A Radio Digital System.

### The 18-GHz Band

The spectrum allocated to common carrier use at 18 GHz extends from 17.7 to 19.7 GHz. The DR 18A System is primarily used for

\*The feasibility of expanding the message channel capacity of the TH-3 system is under study.

transmission of digital signals at the DS-4 rate. Eight two-way RF channels are allocated by the FCC, one of which is used as a protection channel for the other seven. Each regular RF channel can transmit one DS-4 rate signal which can carry up to 4032 message signals or 168 DS-1 rate digital signals.

## 14-2 CHOICE OF SYSTEM

In engineering a new route, the selection of the type of system to be used requires engineering studies of route factors, type of application, signal-to-noise objectives and performance, and many cost factors that include the relative advantages of digital and analog modes of transmission. In addition, the selection of the RF band to be used interrelates with all other considerations and ultimately leads to establishing the most appropriate system type.

Some of the route factors that influence the system choice include length, initial and ultimate message channel capacity, interference or potential interference between intersecting routes, and the existence of other systems along the route. Geographical and environmental factors also influence the choice of system; for example, site-to-site antenna visibility or rain attenuation may be controlling factors. The system may have to meet long-haul or short-haul requirements and may require frequent or infrequent dropping and adding of message channels at intermediate points. Signal-to-noise performance of the various systems, particularly in respect to transmitter output power and the path losses that may be expected along the planned route, must be considered. The transmission band selected tends to determine the specific system choice but it must be chosen to satisfy all the other criteria. Costs are an overriding consideration and where engineering studies show that several system types may be satisfactory, the most economical system is the one selected.

The route length, required message channel cross-section and the existing or potential congestion of frequency bands all have an influence on system selection. In addition, the selection of a system may be influenced by corporate policy which might dictate route diversity, the provision of a separate route or different type of transmission facility between the route terminals in order to provide greater service reliability and network survivability.

As previously mentioned, microwave radio system applications are generally divided into overlapping categories, long-haul, short-haul,

and metropolitan; the design objectives and features provided by various systems are appropriate for specific applications but usually not for more than one. The long-haul TD-2, TD-3, TH-1, and TH-3 systems are designed to meet message network signal-to-noise objectives for distances up to 4000 miles. Initially, the long-haul objectives specified that, in the worst (noisiest) message channel, the noise should not exceed 44 dBrc0. These design objectives have been made more stringent and the worst channel noise for new systems must not exceed 41 dBrc0.\* The noise objective for short-haul systems is 32 dBrc0 in the worst message channel for systems up to the maximum length of about 250 miles. System costs are accordingly affected.

Additional capacity may possibly be provided on existing routes by under- or overbuilding. These terms are used to describe the addition of a second radio system sharing the land, buildings, towers, antennas, waveguides, and power supply of the existing system. The new system must operate in a different portion of the radio-frequency spectrum. The existing route must be equipped with broadband (dual-frequency) antennas and band combining and separating networks. For example, a 6-GHz TH-type system might be added to a route already equipped with a 4-GHz TD-type system and, in the short-haul field, an 11-GHz TN-type system might be used to overbuild an existing route equipped with a 6-GHz TM-type system.

The selection of the new system is influenced by the anticipated growth along the route as well as the immediate augmentation of service. Anticipated growth is especially pertinent since the FCC regulations now impose stringent requirements on the ratio of protection channels to regular channels. Thus, selection is influenced by the total message channel capacity required, its relation to the total system capacity, the ease with which the growth can be accommodated by equipping additional radio channels as required, and the costs associated with each of these factors.

In long-haul applications, system performance and costs tend to be dominated by repeater equipment rather than by terminal and multiplex equipment. For such systems, heterodyne type repeaters are preferable because they are usually less costly and prevent the accumulation of impairments that would result from the extra steps of modulation and amplification required in baseband repeaters.

\*These objectives do not apply during the brief intervals of atmospheric fading. Protection channels are usually switched into service when noise reaches 55 to 60 dBrc0.

In short-haul applications, repeater equipment has less influence on system performance and costs. The layout of the system is often dictated by the need for flexibility in dropping and adding circuits which requires the translation of the signal to baseband frequencies at all dropping and adding points. Thus, most short-haul systems utilize baseband repeaters. The impairments introduced by modern baseband systems are comparable to those of heterodyne systems.

The selection of the RF band is made for consistency with all of the other route factors previously discussed. The overriding considerations are likely to be the result of propagation and interference studies and the interaction between these factors and the selection of suitable repeater sites. When these technical requirements have been satisfied, the final system selection depends on cost.

### 14-3 ROUTE SELECTION AND LAYOUT

The establishment of a final route layout for a new system and the precise specifications for locating each required repeater constitute the most important and, in some ways, the most difficult aspect of microwave system engineering. Signal propagation must be studied carefully to give reasonable assurance that the appropriate objectives can be met. Interference studies must be made to give assurance that intra- and intersystem interferences are held to specific limits. Repeater sites must be selected to satisfy transmission and interference requirements. After sites have been selected, antenna towers must be designed and placed to satisfy many operating and environmental requirements. In addition, governmental agencies exert considerable influence on radio system design, layout, and operations and the requirements imposed by these agencies must be met.

All of these facets of route selection and layout are highly interactive and requirements must all be simultaneously satisfied. The process is iterative and successive compromises must be made in order to establish a satisfactory overall system [1].

#### Site Selection

Route layout work is based on a preliminary selection of several alternate radio repeater sites at each prospective location. The criteria for final selection involve site availability, zoning and land use restrictions, building and tower design and construction problems, maintenance and access, environmental considerations, power availability,

and the results of propagation and interference studies and measurements. Frequently, a site selection tour is made so that preferences for one of the several alternate sites at each location may be expressed.

The first step in the design of a new route is to find acceptable paths from all existing terminals and from junction points with other routes. Figure 14-1 illustrates a problem involving the introduction of a new TD-3 route from the south to terminate at station A. The permissible location of station C, the TD-3 station nearest A, is to be determined in terms of the angular sector relationships with the two TD-2 routes which already terminate at A. One route enters from station B and the other from station D. Involved in the problem of meeting transmission objectives are the polarizations of the channels in the new and existing routes, the angles of incidence for signals transmitted between stations A and D, A and B, and A and C, the transmitted power of the three systems, the number of message or video channels in each system, the discrimination between routes provided by the antennas, and the distances between stations on the proposed new route.

The layout of stations and routes illustrated in Figure 14-1 is commonly derived from a radio route map. Often called an overreach map, it is used to depict microwave station locations and common interference situations.

The polarization pattern found on the existing TD-2 paths is indicated by the abbreviated nomenclature associated with the directional transmission arrows.\* In TD-2 12-channel RF arrangements, the two-way channels designated 1 through 6 are usually called *regular* channels and those designated 7 through 12 are called *interstitial* channels. In the figure, the regular channels are designated 1 and the interstitial channels designated 7. Each two-way channel has a low-frequency allocation, designated A, for one direction of transmission, and a high-frequency allocation, designated B, for the opposite direction of transmission. The horizontal and vertical signal polarizations are designated H and V respectively. Thus, transmission from station B to station A, designated 1 BH 7 BV, is in the high-frequency allocations for all 12 channels. In this example, channels 1 through 6 are transmitted in horizontal polarization and 7 through 12 in vertical polarization.

\*Polarization refers to the alignment of the electric field in the radiated wave.



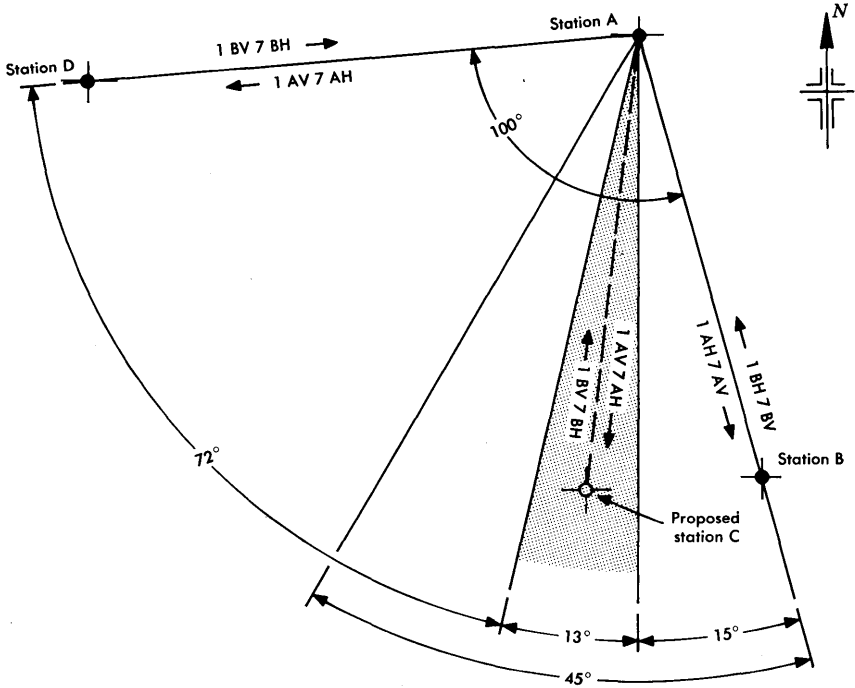


Figure 14-1. Discrimination study for a new TD-3 path to junction at station A.

Examination of the D-A and B-A paths shows that the two converging TD-2 systems are cross-polarized relative to one another. Thus, the new TD-3 path must be cross-polarized in respect to one TD-2 path and co-polarized in respect to the other.

A trial assumption may now be made that the new TD-3 path is to be cross-polarized with the B-A TD-2 path, as shown in Figure 14-1. With this assumption, the discrimination between the D-A and C-A paths must be achieved by the directivity of the antennas at station A. The achievable discrimination is determined from charts that show the transmission loss between same and opposite polarizations as a function of the angle between the incident wave and the orientation of the antennas. These charts are available for each of the common carrier RF band allocations. From such curves, it can be shown that the like-polarized D-A and C-A paths must have angular separation

of at least 70 degrees to achieve the same discrimination as that between the cross-polarized B-A and C-A paths at an angular separation of about 15 degrees.

Radio-frequency interference objectives involve complex relationships among many factors. Tabulations of these objectives are available for many combinations of signal loadings, radio frequency stability, channel frequency separation, type of signal (FDM, video, or digital), and applications of pre- and deemphasis or signal coding. By properly accounting for output powers, antenna gains, antenna discriminations, path losses, waveguide losses, and frequency separations, a new path that satisfies intersystem interference requirements may be established.

In the example of Figure 14-1, it is found that station C may be located anywhere in the sector defined by an angle of 15 degrees minimum from the A-B route up to a maximum of 45 degrees from the A-B route and at least 72 degrees from the A-D route. Thus, there is a sector about 13 degrees wide within which station C may be located.

After the sites for the repeater stations closest to the terminals and junction points along the route have been tentatively selected, the other intermediate sites are similarly selected. These selections are made so that the route zig-zags to minimize interferences from within the new system due to *overreach*, the transmission from one station to another far removed. Overreach may occur as a result of unusual atmospheric conditions or lack of terrain blockage. In the preliminary selection of these intermediate sites, RF interference between the new route and other nearby or crossing routes must also be considered.

The factors that determine the desirability of a repeater site are numerous and varied. Among the most important are drainage, soil characteristics, visibility and grade of access road, proximity to hazards or undesirable neighboring property, proximity to major highways that might be subject to construction or relocation work, possibility of flooding, area of land available, and relative location of power and telephone lines. In addition, consideration must be given to local zoning and land use laws and to legal requirements on building and tower construction and guy wire usage.

After an option to buy has been obtained, each site must be surveyed. Magnetic and true bearings must be shown and true north must be indicated to an accuracy of  $\pm 1$  degree. The spherical co-

ordinates of the proposed tower location must be determined and shown to an accuracy of 1 second of latitude and longitude. The survey results are used to check elevation of the tower location. Detailed information of this type and accuracy is required by the FCC for its records.

The size of the site depends on the type of station and the required height of the tower. Adequate consideration must be given to the type of construction to be used so that, to the extent possible, the buildings and tower blend into the surroundings. Adequate clearance must be provided between the buildings and abutting properties and highways or roads. Provision must be made for vehicle parking.

Where other criteria are satisfied equally, the final selection of a repeater site may well be related to accessibility for maintenance and availability of power for the repeater operation. Investigation and record should be made of unusual weather in the environs. The amount of snow and rain, wind characteristics, and range of temperatures may all have an impact on system operation and maintenance.

After the desired sites have been agreed upon from all points of view, site purchase activities are started. When title is obtained for all sites, construction work may be started provided approval has been obtained from the FCC for the construction of the route and, where necessary, from the Federal Aviation Administration (FAA) for tower construction.

### Path Transmission Characteristics

When engineering a new microwave radio route, it is necessary to determine propagation effects that might be encountered along the proposed route. After preliminary repeater sites have been chosen, a frequency and polarization plan must be selected, terrain profile studies and measurements must be made, path propagation tests may be made along the route, studies of environmental weather data must be undertaken, and fade margins must be determined.

**Terrain Profile Studies.** After preliminary selections of repeater sites have been made, it is necessary to determine the topographical characteristics of each path between proposed repeater sites. This type of information is needed in order to be certain that there are no obstacles in the path between stations and no points from which radio waves

might be reflected to cause transmission impairment. When obstacles or objectionable reflection points are discovered, it is necessary to change one or more of the proposed repeater sites.

*Beam Bending.* When the atmosphere is well mixed by convection or turbulence, *standard atmosphere* conditions are said to exist. Under these conditions, pressure, temperature, and water vapor content decrease with altitude. As a result, the dielectric constant of the atmosphere decreases monotonically with altitude and microwave beams are curved downward by refraction. If the beam curvature corresponds to the curvature of the earth, the beam path can be represented graphically as a straight line relative to a flat earth. This observation suggests that a radio beam path may be represented by a straight line relative to an earth contour having a suitably adjusted radius or the earth may be represented as a flat surface with the beam paths depicted as curves adjusted to display the proper relationship to the flat earth surface. In many radio engineering studies, it is convenient to adopt the former representation and to assume beam paths are straight. Earth contours may then be plotted relative to an earth radius that has been appropriately adjusted.

To accomplish this form of graphical representation, the earth curvature must be assigned a value that makes allowance geometrically for the actual bending of the beam. The factor that relates the actual and fictitious earth radii,  $k$ , is only approximately constant in that the bending of the beam varies with the change in the gradient of the dielectric constant that occurs with the change in altitude. However, for the conditions involved in microwave system engineering, departures from constant gradient are small and may usually be neglected [2].

The factor  $k$  is defined for engineering purposes by

$$k = \frac{C_E}{C_F} = \frac{1/r_E}{1/r_F} = r_F/r_E \quad (14-1)$$

where curvature,  $C$ , is the inverse of radius,  $r$ , and the subscripts  $E$  and  $F$  represent true earth and fictitious earth respectively. Thus,  $k$  is the ratio of the fictitious earth radius to the true earth radius; it is sometimes called the effective earth radius factor.

A range of values of  $k$ , commonly used in most of the country, is given in Figure 14-2. More extreme values are also used in some situations. The value of  $k$  is sometimes as low as 0.5 and, in certain coastal areas, it sometimes assumes a negative value. The curvature  $C_I = -0.5 C_E$  is normally used as the maximum engineering value for inverse curvature (upward bending) of a microwave beam. The corresponding value of  $k$  is 0.67. The curvature  $C_O = 0$  represents an unbent beam. The corresponding value of  $k$  is 1.0. The value of  $C_S = 0.25 C_E$  ( $k = 1.33$ ) is used for beam bending in a standard atmosphere. The curvature  $C_E$  ( $k = \infty$ ) represents the situation in which the beam is bent to follow exactly the earth curvature; this value is usually taken as the maximum engineering value for downward beam curvature.

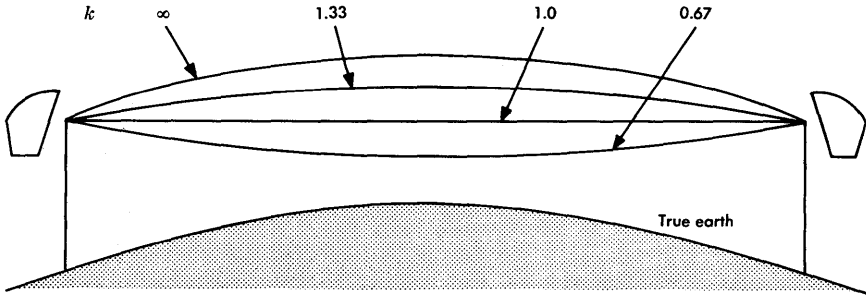
BEAM CURVATURE	RELATIVE FICTITIOUS EARTH CURVATURE, $C_F/C_E$	$k$
$C_I = -0.5 C_E$	$(C_E - C_I)/C_E = 1.5$	0.67
$C_O = 0$	$(C_E - C_O)/C_E = 1.0$	1.0
$C_S = 0.25 C_E$	$(C_E - C_S)/C_E = 0.75$	1.33
$C_E = C_E$	$(C_E - C_E)/C_E = 0$	$\infty$

Figure 14-2. Range of values for  $k$ .

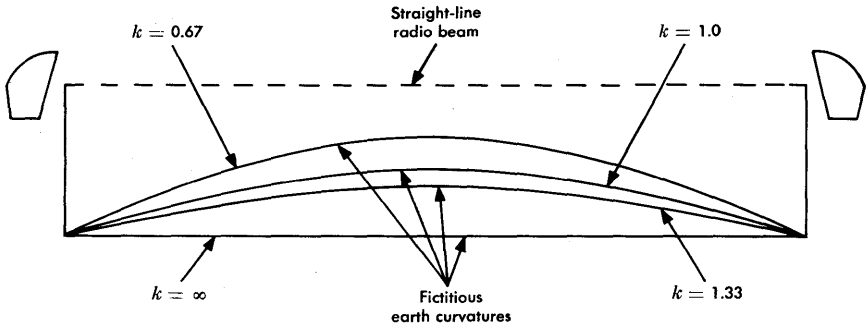
Figure 14-3, not drawn to scale, shows beam paths relative to real earth curvature and fictitious earth curvatures for a straight radio beam. The values of  $k$  are the same as those given in Figure 14-2.

*Atmospheric Variations.* When near-standard atmosphere conditions exist for microwave radio transmission,  $k = 1.33$ . However, temperature, pressure, and water vapor gradients may vary from those associated with the defined standard atmosphere. Other values of  $k$  then apply and the atmosphere is referred to as nonstandard.

Other anomalies may occur. Under certain types of weather conditions, the atmosphere may be stratified. In these cases, reflections or refractions may occur at the interface between layers and whole regions of the atmosphere may produce a focusing effect, sometimes called ducting. These are significant factors in producing selective fading of microwave signals.



(a) Atmospheric beam bending between antennas



(b) Relative earth curvatures for straight radio beams

Figure 14-3. Beam-bending relationships.

*Path Profile.* A profile plot of the earth surface must be prepared for each path between proposed repeater sites. Figure 14-4 illustrates a *path profile sketch* obtained from detailed topographic maps, aerial surveys, or field surveys. The profile is plotted on special graph paper the vertical coordinate of which represents height above sea level. The other coordinate represents horizontal distance along the surface of the earth. The earth curvature is modified by  $k$  to permit the representation of the radio beam as a straight line between transmitting and receiving antennas.

In addition to the profile of the earth surface, other obstructions and possible reflecting surfaces must be determined by field observation and plotted. For example, tree heights are designated by  $T$  in Figure 14-4. These heights are plotted with suitable allowance for

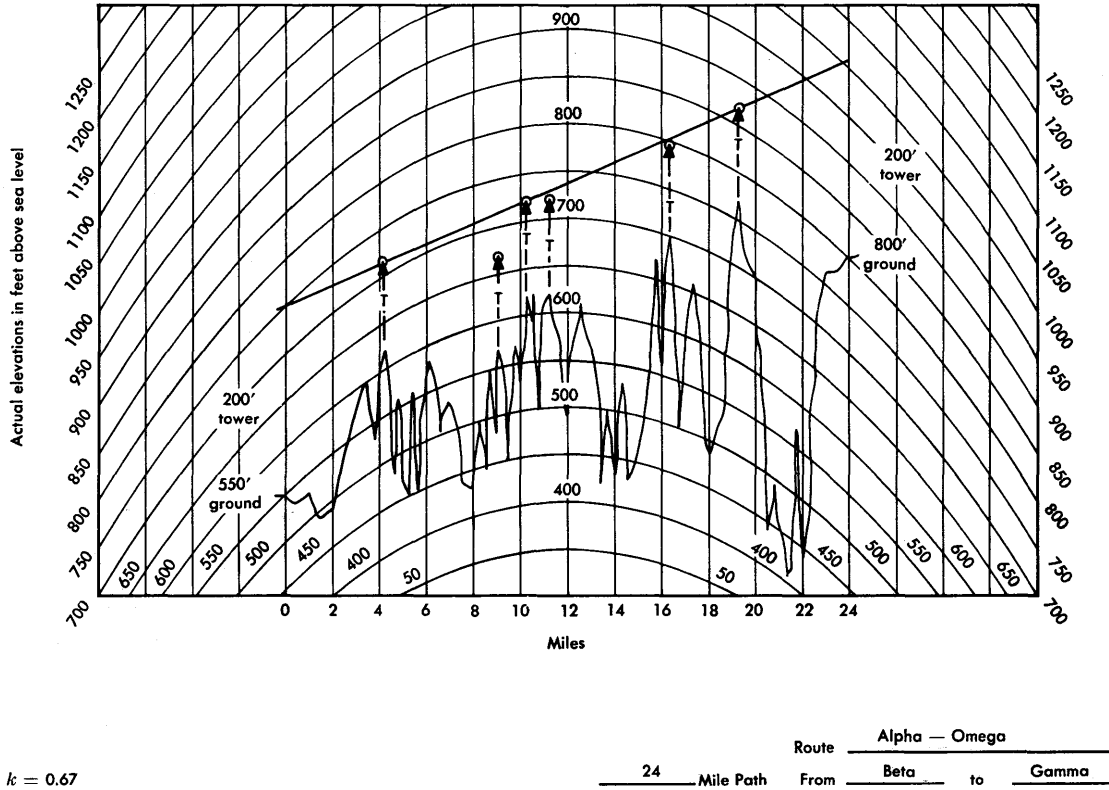


Figure 14-4. Typical path profile sketch.

growth. If a lake were located along the path, its presence would be appropriately noted as would an obstructing or reflecting building.

After allowance has been made for Fresnel zone clearance, as described in Chapter 2, the profile plot may be used for a tentative estimate of required tower heights at each of the repeater sites. Unless the path is very short, final determination is made after path testing or after expected reflection or obstruction fading has been calculated for the chosen antenna heights.

Occasionally, path profiles are drawn on rectangular graph paper. When this is done, a line representing the earth curvature must be drawn. This line must simulate the earth curvature for the appropriate value of  $k$ . Templates or calculated clearances are sometimes used, typically for  $k = 0.67$  or  $1.33$ . Clearances are measured relative to the earth surface. This method is particularly useful when the effects of different  $k$  values must be considered. It also eliminates the need for special graph paper.

**Path Testing.** The best combination of antenna heights at the two ends of a repeater hop is often determined by path testing. In spite of the fact that the process is costly, careful and efficient path testing is frequently undertaken on new routes and on routes subject to over- or underbuilding, especially when profile studies and subsequent field surveys are judged to yield inadequate or questionable data regarding the height of obstructions or the reflectivity of the path. However, these costs are justified by the fact that the correction of an error in antenna placement may be more costly. For example, if the antenna must be moved after the initial installation, antenna weight and wind loading factors may require changes in tower design and waveguide connections must be lengthened or shortened to accommodate the new antenna location. Furthermore, the antenna mounting platform is not readily movable.

Path tests usually involve the transmission of an RF carrier signal between antennas mounted on temporary test towers erected at the two proposed adjacent repeater sites. Since the transmitted power and antenna gains are known, measurement of the received power may be used to determine the transmission loss between the two points. Regulations regarding signal transmission and tower construction established by the FCC and the FAA respectively must be observed in conducting these tests. In addition, advance arrangements



must be made for access to and use of the sites and various work permits must be obtained. Provision must also be made for temporary power and for construction operations.

A temporary guyed tower, up to about 300 feet high, is erected at the location of each proposed permanent tower. Each temporary tower contains a vertical track on which is mounted a carriage that supports an antenna. The elevation and azimuth of the antenna can be adjusted by motors. The carriage also supports a transmitting or receiving unit and one end of the connecting power and control cable. The carriage may be raised or lowered by a winch the cable of which feeds through a counter calibrated to indicate the height of the antenna. Controls, power supplies, and communications equipment are located in a van at the tower base.

With these test arrangements, the two antennas (one at each end of the path) may be raised and lowered according to specified patterns. The transmission loss between the two sites is measured for each set of antenna positions. The resulting data, referred to as a height-loss run, may be used to determine antenna placement to minimize reflections and loss, to establish the location of reflection points, and to determine the value of the factor  $k$  at the time of measurement. The analysis of the data involves the application of the principles of optical geometry. Microwave signals are subject to many of the same fundamental laws as light waves.

*Free-Space Loss.* Under standard atmospheric conditions, the ratio of the power emitted by an isotropic transmitting antenna to the power captured by an isotropic receiving antenna closely approaches the *free-space loss* (FSL). By definition, the FSL is restricted to the propagation over the path of a direct wave remote from the earth and its effects. This loss may be calculated by

$$\text{FSL} = 36.6 + 20 \log d + 20 \log f \quad \text{dB} \quad (14-2)$$

where  $d$  is the distance in miles between transmitting and receiving antennas and  $f$  is the frequency in MHz.

*Reflection and Diffraction.* The measurement of path loss is seldom made under conditions so ideal that true free-space loss is observed. Losses may be affected by reflections from terrestrial objects or from atmospheric strata and by diffraction at an obstruction located in or

near the edge of the direct transmission path. However, with most microwave paths, earth effects can be minimized under normal conditions so that the path loss is essentially free-space loss.

When path-loss measurements are made, the results may be compared with the free-space loss computed by Equation (14-2). Analysis is then necessary to determine the source or cause of the difference and to determine the best course of action to improve the condition if the departure from expected loss is excessive. The analysis, greatly aided by the data obtained from the height-loss run, involves the determination of reflection point locations and the phase lag of the reflected signal relative to the direct signal.

Many terrain factors must be taken into account in this analysis. For example, in areas featured by extensive plains, a phenomenon called *convergence* may be observed. The terrain may be slightly concave and, as a result, energy arrives at the receiving antenna by a number of independent paths. One or more of the reflected waves in such a case may be of larger amplitude than the direct wave.

Path-loss measurements should be made as nearly as possible under standard atmospheric conditions. Strata of temperature, moisture content, and/or pressure can cause reflections that are difficult to account for in analyzing test results. Variations during the test period are also difficult to analyze. When atmospheric conditions are stable but not exactly standard (i.e.,  $k = 1.33$ ), measurements can be made successfully but test results must be used to determine the value of  $k$  at the time of test.

In certain cases, attenuated transmission in the presence of an obstacle in or at the edge of the direct path can be measured. Transmission takes place because of diffraction of the wave into the region beyond the obstacle. The phenomenon may be explained by Huygen's principle which states that "every point on a wavefront may be considered to be a new source from which new wavelets issue." Thus, some rays are bent around the obstacle and no reflection is involved. This form of interference, called knife-edge diffraction, can often be overcome by suitable adjustment of antenna heights; such a phenomenon is inconsequential where there is sufficient clearance. Clearance of at least 0.6 times the distance to the first Fresnel zone is usually provided along the direct path in order to achieve loss that approximates free-path loss. More clearance is provided where increased fading margin is needed.

## Interference Studies

Radio-frequency interference may originate in the impaired system (intrasystem) or in a system that parallels or crosses the impaired system (intersystem). Of concern here are those interference patterns that relate to the route layout of microwave systems and to the selection of repeater sites [3]. In addition, these studies involve the frequency allocations used in the systems of interest [4].

Presently, the FCC requires that all interference coupling problems be resolved before filing for a construction permit. Thus, layout studies must be carried out well in advance of any preparations for actual route construction. Studies must cover a swath 125 miles wide on each side of the desired path.

Where routes are lightly loaded and in areas that are uncongested in respect to radio system use, interference problems are often easily avoided by allocating frequency bands so that different radio channels are used in the potential interference situations. However, this solution often cannot be used, particularly if growth is considered.

There are a number of route layout relationships that involve the potential for causing intra- or intersystem interference. These include interferences between similar systems as well as interferences that may be induced by radar, satellite, or tropospheric transmission systems. These must all be related to the practice of transmitting and receiving at different frequencies in alternate sections. Some of the important sources of such interferences are illustrated in Figure 14-5 where the high and low bands are distinguished by the designations  $f_1$  and  $f_2$ .

**Frequency Plan.** The layout of a new route must include the selection of a frequency plan and the assignment of RF channels to specific frequency bands in a manner such that interferences within the route and between routes are minimized. The TD-type systems may be used to illustrate the nature of the selection process.

Figure 14-6 shows four frequency assignments found at junction stations and used at TD-type repeater points; plans (c) and (d) are irregular and not recommended. The terminology is consistent with that used in Figure 14-1; channels 1 through 6 are called regular channels and channels 7 through 12 are called interstitial channels. For simplicity, the two groups of channels are designated as 1 and 7

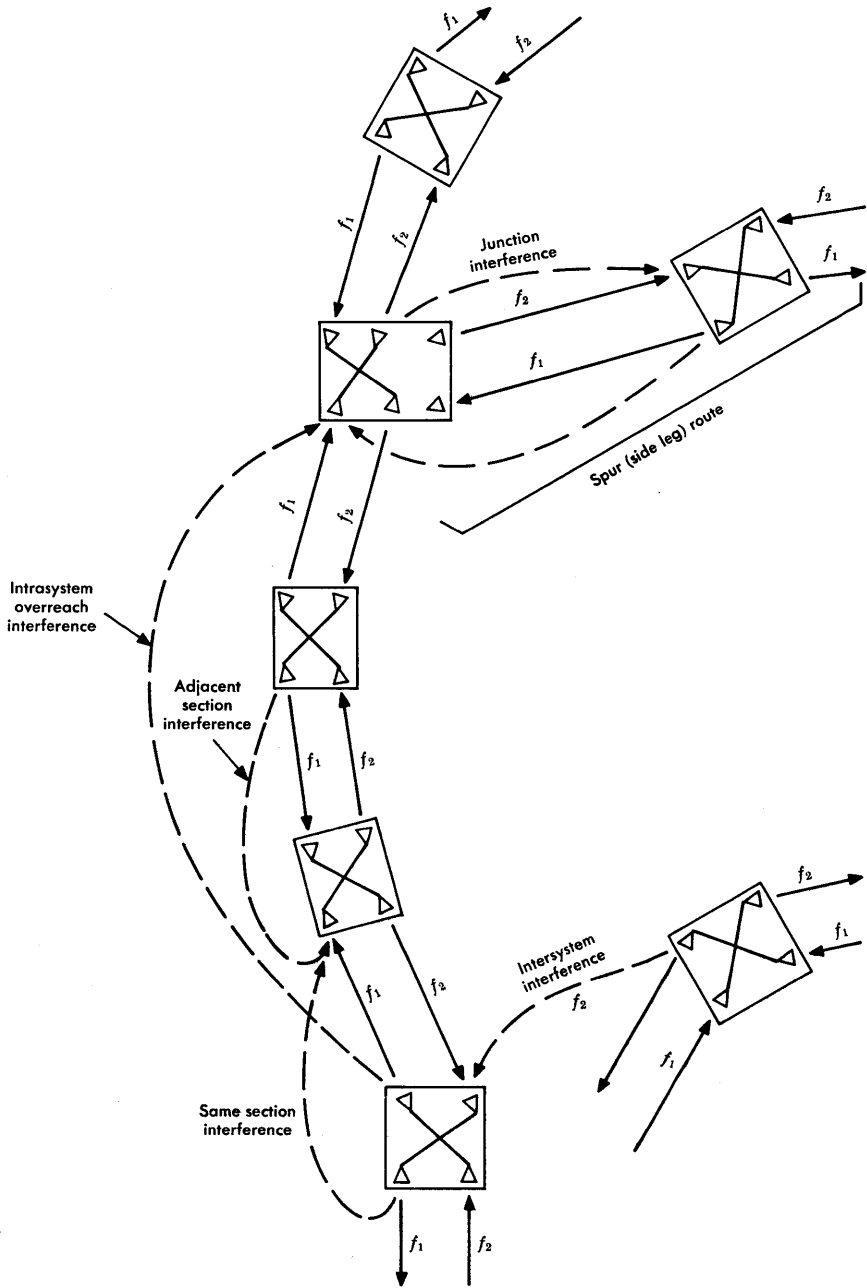


Figure 14-5. Intra- and intersystem interference paths.

respectively. For each channel, a low-frequency allocation is designated A and a high-frequency allocation is designated B. In addition to the selection of the frequency plan for each repeater, it is necessary that for any plan, the regular channels must be cross-polarized relative to all interstitial channels on a given path.

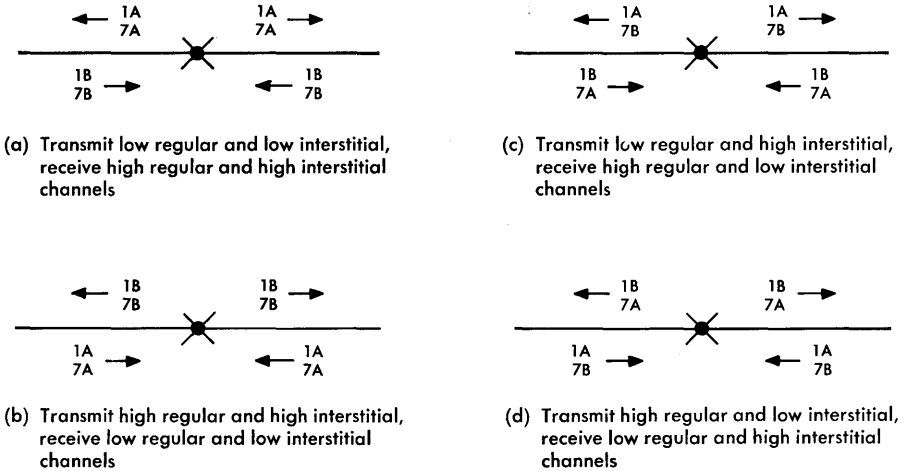


Figure 14-6. Alternative frequency plans for use at TD-type repeater stations.

If the frequency plans of two existing routes that establish the terminals of a new route are the same, an even number of repeater hops is required in the new route to match the patterns at the junction stations. If the frequency plan of the two existing routes differ in the high-low patterns used, an odd number of repeater hops is required to achieve the appropriate match.

As illustrated by plans (c) and (d) in Figure 14-6, an undesirable intermix of the regular and interstitial frequency patterns may exist at junction stations. Special engineering is then required at an intermediate repeater. This may involve the provision of a special repeater frequency plan, the addition of an extra repeater hop, or the use of the 6-GHz or 11-GHz frequency bands for one hop in order to satisfy RF interference requirements.

Certain specially engineered repeater stations are called full- or half-bucking stations. A full-bucking station transmits and receives all channels at the same frequencies. A half-bucking station transmits

and receives at the same frequencies for all regular or all interstitial channels but not both. Terminal stations cannot be bucking stations. Figure 14-7 illustrates a half-bucking station with the regular channel frequencies shifted at the repeater and interstitial channels transmitted and received at the same frequencies. Bucking stations should be avoided whenever possible.

**Intrasystem Interference.** Three examples of intrasystem interference are illustrated in Figure 14-5: same-section, adjacent-section, and overreach interferences. For adjacent- and same-section interferences, like frequencies but opposite directions of transmission are involved. In the illustration of overreach interference, like frequencies are involved but, in this case, the same directions of transmission are involved for the interference and the impaired channel. The impairment is an increase in channel noise; for data signals, an increase in error rate due to phase differences between the two signals may be observed, especially where the impairment appears as a distortion of the RF signal which is common with overreach interference.

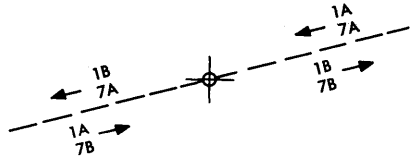


Figure 14-7. A frequency plan at a TD-type half-bucking repeater station.

For same-section interference, the path loss from transmitting to receiving antennas is very nearly the same for both impaired and interfering signals. The largest attenuation to the interfering signal results from the fact that the path involves transmission through one antenna from front to back. For adjacent section interference, the impaired and impairing path lengths may be significantly different. Adjacent-section interference from the shorter section into the longer may be greater due to the lower attenuation in the shorter path. The largest attenuation to the interfering signal is the back-to-front discrimination of the receiving antenna in the impaired path.

For intrasystem overreach interference, the two major sources of attenuation to the interfering signal are the overreach distance, which approaches three (or even five) times the normal repeater spacing, and the directional discrimination of the transmitting and receiving antennas. The location of the repeater site and the resulting antenna orientation are thus important considerations in route layout and the

control of overreach interference. In some cases, where the terrain is favorable, earth blocking may also be used to advantage; a repeater site may be chosen so that the overreach path is effectively blocked by some natural earth contour.

Much intrasystem interference is a result of microwave reflections, many from man-made objects. The reflecting surfaces are often created after radio routes have been in operation for some time.

**Intersystem Interference.** Figure 14-5 shows two examples of intersystem interference that must often be considered in route layout studies. A junction between the main route and a sideleg is depicted near the upper part of the figure. If the sideleg is regarded as a separate system, perhaps being added to the layout after the main route has been in operation, the potential interferences between systems must be taken into account in locating the first sideleg station. Where path lengths are about equal, the path losses for interfering and impaired signals are nearly the same and the principal attenuation factors are those relating to antenna discrimination. Thus, relative orientation of the main route and sideleg antennas must be adjusted by sideleg repeater location to maximize the discrimination and thus to minimize the interference. This problem is identical to that discussed in relation to Figure 14-1.

The second example of potential intersystem interference, shown in the lower portion of Figure 14-5, occurs when the route of one system approaches or crosses that of another. If the two routes cross, every effort must be made to have them cross at right angles so that both are benefited by maximum antenna discrimination or to locate the stations so that interference paths are blocked. Distances between repeater sites on the two routes are also of considerable importance as the longer path is generally more susceptible to interference due to higher path loss.

In some cases of intersystem interference, advantage can be taken of terrain characteristics. Where the terrain permits, earth blocking may be used to advantage by appropriately locating one repeater site and thus introducing high attenuation in the interference path.

Potential intersystem interferences must be considered in respect to other types of systems assigned to similar frequency bands such as other common carrier systems, satellite communications systems, tropospheric systems, and radar systems. In addition, where a system

is to operate in close proximity to a national border, the possibility of interference between systems on both sides of the border must also be considered. Nearby AM, FM, and television broadcast stations may also introduce interference into baseband or IF portions of microwave systems. These problems are sometimes solved by shielding or filtering but, in many cases, practical solutions have not been found.

Where a new installation takes the form of underbuilding or overbuilding, the same considerations of frequency coordination exist but there is less flexibility in finding solutions to problems than where a completely new route is being laid out. For example, all repeater sites and antenna orientations have been established and cannot economically be changed.

**Computer Aids.** A centralized time-shared computer system is used for the recording of all pertinent information regarding Bell System and other microwave radio routes, repeater locations, frequency assignments, antenna data, interference patterns, etc. [5]. Access to this information is provided by remote data terminals located at strategic points throughout the country for use in radio system engineering studies. A number of programs are used to perform computations and comparisons required in microwave route engineering and layout.

When information on a new route has been firmly established, it is added to the data stored in the computer. A vital step in the layout process involves a study of radio-frequency interference problems by means of programs designed to use these stored data.

### Governmental Jurisdictions

Many aspects of telephone company operations are subject to regulation by a variety of local, state, and federal agencies. By its nature, radio transmission is impossible to constrain to specific geographical boundaries. Thus, all radio transmission is regarded as an interstate form of communication and is regulated by the FCC. However, there are aspects of route engineering other than those involving propagation that are subject additionally to the regulations of other government agencies.

**Federal Communications Commission.** The FCC has been granted jurisdiction over all forms of nongovernment communications within the



United States. In exercising its role, the FCC in cooperation with the State Department coordinates specific radio matters with the corresponding organizations of neighboring countries and, where appropriate, with the International Telecommunication Union, a specialized agency of the United Nations [6, 7].

During the preliminary engineering of a new route, when path testing is undertaken, a temporary license must be obtained from the FCC and the Commission must be kept informed of test activities and completion. Construction may not be undertaken without approval from the FCC in the form of either a construction permit or a waiver of section 319(d) of the Communications Act of 1934. The project must be approved from a technical standpoint, judged to be in the public interest, and justified economically. With each application for a construction permit, an environmental impact statement must also be submitted.

After construction is completed and before operation may be started, an operating license for each repeater station must be obtained from the FCC. To be issued a license, Commission requirements must be met in respect to hop spacing, transmitted power, frequency and frequency stability, bandwidth restrictions, circuit loading, and interference between systems. Public notice of the license application is published by the FCC for 30 days before approval.

**Federal Aviation Administration.** This agency, commonly known as the FAA, is concerned directly with the design and maintenance of towers or other antenna supporting structures, especially those located near airports or along heavily traveled air routes. The FAA must be petitioned for permission to erect such structures. The agency also specifies tower lighting and painting requirements. Regulations of the FAA are applied to temporary towers as well as permanent towers. When path testing is being done in support of propagation studies, the FAA must be kept advised of when such tests are started and completed if the erection of a temporary tower is involved.

**Local Government Authorities.** When the radio repeater sites are selected, permits must be obtained from local authorities for tower construction, building construction, hoisting, access road construction, and tower guying rights. Zoning and land use laws that regulate such towers must be carefully considered and application must be made for variances from such laws.

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## Chapter 15

# Protection Switching

Where permitted by the Federal Communications Commission (FCC) Rules, microwave radio systems are often provided with protection channels and automatic switching arrangements to minimize loss of service due to atmospheric fading or equipment failure. The protection channels also facilitate maintenance activities and system rearrangements.

Long microwave radio systems are divided into protection switching sections for three basic reasons. First, the administration of the system requires considerable flexibility to accommodate the dropping, blocking, and adding of message channels along the route. Wherever such arrangements are provided, switching sections are conveniently terminated so that the terminal station is not located within a switching section. Second, a long route is sectionalized because there may be simultaneous atmospheric fades in different radio frequency (RF) channels and in different portions of the route. If the entire route were protected from end to end, service on only one of the faded channels would be protected. However, where failures occur simultaneously in different switching sections, the failed channels can be protected. Finally, the outage time due to channel failure for any reason would be excessive if the route were not sectionalized because the propagation time for switching control signals from one end of the route to the other would be excessive. These considerations have led to a recommended maximum of ten repeater hops per switching section; only a small percentage exceed eight hops [1]. Multihop switching sections have the additional advantages of minimizing the required amount of switching equipment and facilitating maintenance activities.

Many different types of switching arrangements are used. In some, channels are switched at intermediate frequencies; in others, they are switched at baseband frequencies or combinations of baseband and intermediate frequencies. In space diversity arrangements, RF channels are switched. Some arrangements are used only to protect against equipment failure and to allow maintenance work to be done. Other arrangements provide protection against both equipment and transmission path (fading) failures.

Most protection switching systems that are designed to protect against atmospheric fading operate as frequency diversity systems; i.e., when a channel fades or fails, service normally carried by that channel is switched to a protection channel in the same band or in another part of the microwave spectrum. Space diversity switching is used to provide fading protection on a per-hop basis. In this arrangement, two antennas are mounted on a radio tower at different heights. These may be at the transmitting end, the receiving end, or both ends of a repeater section. In the Bell System, space diversity antennas are usually used only at the receiving end since this is the simplest and most economical arrangement and, in most cases, provides adequate reliability. Where a further improvement in reliability is required, space diversity may be provided at both ends or, where physical limitations preclude the use of two antennas at the receiver, the two may be mounted at the transmitter only. Where space diversity is used at the receiver only, switching circuits in the receiving portion of the repeater are arranged so that, at threshold, the stronger of the signals from the two antennas is used.\* Since this type of switching provides no protection against equipment failure, it is frequently combined with "hot standby" switching to provide additional protection against repeater equipment failure.

Thus, three kinds of protection switching arrangements are provided in microwave radio systems so that reliability objectives may be met, frequency diversity, space diversity, and hot standby. Frequency diversity arrangements protect against equipment failure in intermediate repeaters and fading in the switching section. Space diversity and hot standby switching arrangements are often combined to protect against both fading and equipment failure.

\*In some arrangements, the two signals are combined; if one becomes noisy, it is suppressed.

## 15-1 CONTINUITY OF SERVICE

Most microwave radio systems carry large numbers of telephone message channels or wideband signals such as television. Therefore, transmission failures have far-reaching effects on message network operations or in terms of public reaction to the interruption of a favorite television program. Considerable effort and expense have been devoted to minimizing the probability of service failures or outages.

The most common cause of channel unavailability in these systems is frequency-selective fading due to multipath transmission in the atmosphere. Fading conditions tend to occur in the evening or early morning hours and cause outages in individual channels. They seldom last more than a few seconds and are often only a small fraction of a second in duration. The frequency of occurrence and the depths of fades are also highly variable; a fade may be hardly noticeable (only a few dB) or it may be 40 dB or more in depth effectively causing complete loss of signal for several seconds, thus requiring transfer of service to a protection channel [2].

Equipment breakdown is another cause of channel unavailability. It occurs less frequently but usually involves a longer outage, perhaps several hours, until personnel can be dispatched to the trouble site and repairs effected. In the meantime, the protection equipment must provide continuity of service. Frequency-diversity switching is favored for long-haul multichannel transmission systems because it is generally less expensive and, unlike space diversity switching, it provides protection against equipment failure. In addition, it provides channels that can be used for emergency network restoration and special event television transmission.

During the early 1970s, FCC rulings limited the number of channels available for protection purposes [3]. As a result, space diversity switching is being used increasingly where it is applicable for protection against multipath fading. A combination of frequency and space diversity systems can be used to improve system reliability beyond that achieved by frequency or space diversity alone. Space diversity switching may also be combined with hot standby switching to protect against equipment failure.

Previous to these rulings, it had been the practice to assign protection channels in the 4-GHz band on the basis of two protection

channels for up to ten working channels in a TD-type radio system. Similarly, two protection channels were used at 6 GHz to protect up to six working channels in a TH-1 or TH-3 system. One protection channel had been assigned for each working channel in 11 GHz systems.

With the amended rulings, common carrier operators are required to reduce the ratio of protection channels to working channels. Only one channel may be assigned in each of the 4- and 6-GHz radio bands for protection purposes and that one may be assigned only if there are at least three working channels. Where it can be demonstrated that a total of three working channels will be required within three years, a protection channel may be authorized simultaneously with the first working channel. In the 11-GHz bands, one protection channel is allowed for each three working channels. A waiver of the FCC Rules must be requested if it is desired to exceed the authorized ratio of protection channels for any reason.

On fully developed routes that utilize both the 4- and 6-GHz bands, this ruling can be satisfied by an arrangement in which two 6-GHz channels are used to protect 18 working channels, twelve at 4 GHz and six at 6 GHz. The 6-GHz channel bandwidth is greater than that of the 4-GHz channels. Thus, 4-GHz channels cannot be used for cross-band protection. These protection arrangements must be adaptable to either or both of the two intermediate frequency (IF) bands centered at 70 and 74.1 MHz. Where necessary, FM terminal pairs are provided to shift the signal to the appropriate IF band. Similar crossband arrangements are also available to include 11-GHz systems.

With these allocations of protection channels, system reliability objectives may not always be fully satisfied by the use of frequency diversity switching alone. In repeater sections subject to excessive multipath fading, service reliability is substantially improved by adding space diversity arrangements. These are usually implemented by a second receiving antenna mounted on the same tower 25 to 50 feet below the primary antenna. With space diversity as a supplement to frequency diversity switching, reliability is significantly improved.

## 15-2 FREQUENCY DIVERSITY SWITCHING IN LONG-HAUL SYSTEMS

The principal Bell System microwave radio systems used for long-haul transmission are TD-2, TD-3, TH-1, and TH-3. When heavily loaded, these systems generally use frequency diversity protection

arrangements in which a protection channel can be switched automatically into service in place of a failed working channel.

The 400A protection switching system is the latest design for long-haul application. It can be used with the TD-2, TD-3, TH-1, or TH-3 systems. The 400A can also be used for crossband diversity switching in which TH-1 or TH-3 channels (at 6 GHz) may be used to protect TD channels (at 4 GHz). This feature is made possible by the large capacity of the 400A relative to systems of earlier design. The 100A can protect TD-2, TD-3, or TH-3 systems. The electron-tube TDAS system, superseded by the 100A, was designed for use with the TD-2 radio system only. The THAS system is used only to protect TH-1 radio systems.

These protection switching systems all operate at intermediate frequencies; stringent loss and crosstalk objectives must be met to assure unimpaired transmission. The initiators (detection circuits) that sense a failure utilize FM receivers to demodulate the IF signal to baseband. The baseband signal spectrum is monitored for excessive noise which is used to initiate a request for transfer of service to the protection channel. Loss of the IF signal also initiates switching to the protection channel.

### The 400A System

The most versatile of the automatic protection switching systems used for long-haul radio systems is the solid-state 400A. It may be used in configurations that cover a range of needs from a simple combination of one regular channel with one protection channel up to a complex arrangement of two protection channels for 22 regular channels that operate in the 4-, 6-, and/or 11-GHz RF bands.

There are a number of features that illustrate the flexibility of the system design. As in other systems, the protection channels may be used to provide temporary or emergency service. When so used, an option is available that allows the protection channel to be preempted by a failed regular channel. The two protection channels are designated X and Y; if the X channel is being used for temporary service, it may be protected by the Y channel. A priority feature permits the designation of one regular channel which may be given protection switching preference over other regular channels. Local and remote manual switching and forced switching are available to facilitate maintenance and troubleshooting activities. Automatic testing of the

switching system is provided by an exerciser circuit which normally operates automatically once every 30 minutes. The receiving switch is not operated during exerciser tests in order to avoid the brief circuit interruption that would occur.

One of the commonly used features, provided in order to satisfy FCC requirements regarding the permissible number of protection channels, is that of providing crossband diversity switching for systems that utilize different IF bands as well as different RF bands. For example, the system may be arranged with two TH-1 channels (with the RF band at 6 GHz and the IF band at 74 MHz) to protect six other TH-1 channels and twelve TD-2 or TD-3 channels. The TD-type systems operate in a 4-GHz RF band and a 70-MHz IF band. The necessary shifting of the IF bands is provided within the 400A system. The TH-1 channels are used as protection channels because they are wide enough to accommodate either TH or TD channels. The difference in IF bands is accommodated by installing FM terminals back-to-back in the path between the 70-MHz regular channel and the 74-MHz protection channel. Thus, the channel signals are actually translated between IF bands by going through baseband frequencies.

As shown in Figure 15-1, switch initiator circuits are connected to each regular and protection channel at the receiving end of the switching section. The connection is made by means of directional couplers which introduce very little loss in the through transmission path and high loss in the pick-off path. The initiator receives the channel signal at IF, translates it to baseband, and monitors channel noise at a frequency near 9 MHz. When the noise exceeds a value equivalent to about 55 dBm in a message channel or when the IF signal power becomes too low, the initiator circuit starts the chain of actions that lead to a transfer of service.

The most common application of the 400A system is the protection of service on a combined TD/TH route in which two TH channels are used as protection channels for twelve regular TD channels and six regular TH channels. Thus, Figure 15-1 illustrates a 2 x 18 arrangement. The basic sequence of operations is similar to that used in most frequency diversity switching systems. Failure of a regular channel is recognized at the receiving end of a switching section by the loss of carrier or an increase in channel noise. Logic circuits then turn on appropriate oscillators to generate signals for transmission over a separate voice-frequency (VF) channel to the transmitting end



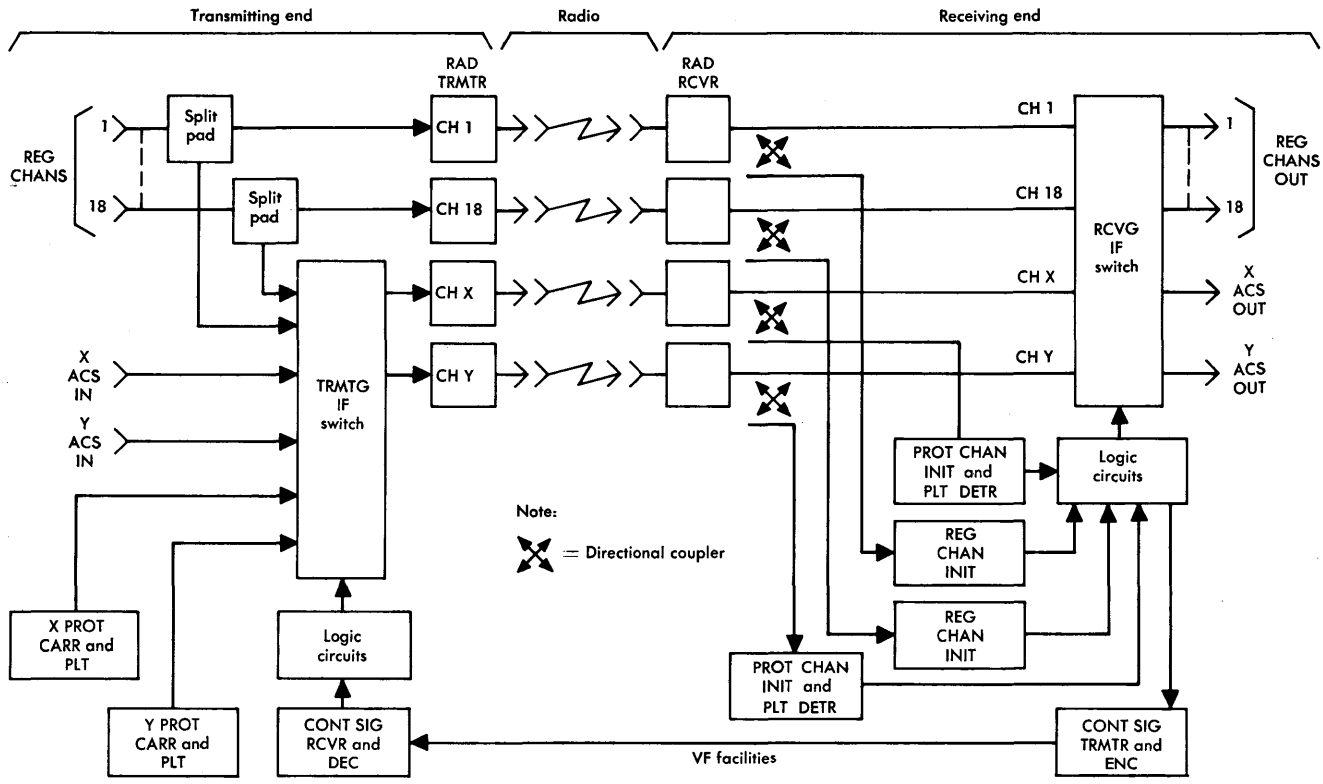


Figure 15-1. Layout of 400A system in one switching section.

of the section. Where two protection channels are used, a separate VF channel is provided for each.

In the 400A system, eight frequencies are used in pairs for regular channel identification: 765, 1615, 1785, 1955, 2125, 2295, 2635, and 2805 Hz. Two other tones are used; one, at 595 Hz, is called the continuity tone for the signalling channel and one, at 2465 Hz, is called the guard tone. One complete set of tone-signal oscillators is provided for each VF channel.

Under normal conditions, the channel identification (or order-tone) oscillators are turned off and continuity- and guard-tone oscillators are turned on. When a failure is detected, the two order-tone oscillators associated with the failed channel and with the first-choice protection channel are turned on. When these signals are detected at the transmitting end of the section, logic circuits cause the protection channel to be bridged to the failed regular channel provided other criteria are satisfied. The continuity tone must be present and its amplitude must be within established limits, the guard tone must be present, and the noise on the VF channel must be below a predetermined value.

An IF carrier, modulated by an 8.6-MHz pilot, is normally transmitted over each protection channel. When a bridging connection is established at the transmitting end, the modulated IF carrier is replaced by a regular channel signal; the loss of the protection channel pilot combined with the failure indication at the receiving end of the regular channel cause the receiving-end logic circuits to operate the transfer switch and to turn off the guard-tone oscillator. The removal of the guard tone causes the bridge at the transmitting end to be locked in the operated condition. If the protection channel remains in service for more than a specified interval, nominally 35 seconds, a prolonged switch alarm is initiated at both ends of the section to alert maintenance personnel to the possibility of an equipment failure.

When the receiving-end circuits check the condition of the regular line and find that it is satisfactory, a switch release sequence is started. After the receiving-end switch is released, an order is sent to the transmitting end to release the bridge and free the protection channel for further use.

In the 400A system, the connections through the transmitting and receiving IF switching circuits, shown in Figure 15-1, are normally made by means of 295-type solid-state switches. Transmission is from

terminal A to terminal AB and from terminal B to terminal BO as shown in Figure 15-2. Provision is made for connecting a 75-ohm termination to the A input of a 295A switch or substituting a termination for the BO output of a 295B switch as shown in the figure. The 295C switch, otherwise similar to the 295A, includes a circuit that monitors the carrier in the channel with which it is associated. Normally, switching actions are initiated by an initiator circuit located at the receiving end of a switching section. However, the monitor circuit in the 295C switch initiates an alarm and a switch if there is a circuit failure (loss of carrier) beyond the initiator application point. Thus, the 295C switch arrangement provides protection against failure within the switch itself.

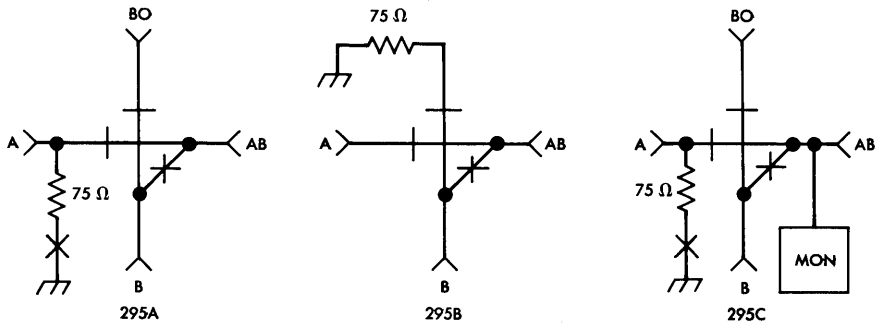


Figure 15-2. Schematics of 295-type IF switches.

Under normal conditions, the 295-type switches operate to transfer service in about 200 nanoseconds. This short service interruption is typical of switching operations in response to atmospheric fading. When there is an equipment failure, the total operating time of the 400A system produces a service interruption typically 30 milliseconds long. If the switching action is not completed within 50 milliseconds, a recycling operation is initiated.

When expansion is planned, the 400A can be used on a route that is already equipped with a 100A protection switching system. The 400A system, partially equipped, then becomes the master system in respect to control and signalling with the 100A slaved to it. If the 100A system has been arranged for 1 x 11 switching, it must be converted to the standard 2 x 10 arrangement. The two former protection channels of the 100A system are then converted to regular

channels. The two 6-GHz protection channels are shared by the two systems. The 400A overbuild arrangement may be combined with the 70- and 74-MHz IF intermix arrangement previously described.

### The 100A System

Technological advances that accompanied the expansion of the TD-2 system from 6 to 12 RF channels and increasing emphasis on system reliability led to the development of the 100A Protection Switching System [4]. This system utilizes solid-state active circuit components throughout (including the switching elements), operates faster than the predecessor TDAS system, and provides the means to replace any one or two of ten regular channels with either or both of two protection channels. The system can also be arranged to operate as a 1 x 11 system to satisfy FCC Rules changes.

The 100A system switches intermediate frequency signals at the transmitting and receiving ends of switching sections usually made up of one to ten repeater hops between main (switching) stations. The two directions of transmission are independently protected. Coded two-tone VF signals are transmitted over an independent VF channel between the ends of the switching section to control the switching operations. A 2465-Hz guard tone is transmitted over each VF channel; the completion of a switch is indicated by logic circuit removal of the guard tone. A one-way VF channel is used for each protection line.

The 100A system can be used to provide protection switching for TD-2, TD-3, and TH-3 transmission systems. The IF switch at the transmitting end of the switching section bridges the protection channel to the regular channel and the IF switch at the receiving end of the section transfers service from the regular channel to the protection channel.

In addition to solid-state IF switches, a 100A system is made up of switching initiators, pilot and noise detectors, logic circuits, tone oscillators and detectors, and a VF communication channel connecting the two ends of the switching section. Amplifiers, alarm circuits, manual control circuits, and an exerciser circuit are also provided to fulfill required system functions.

The basic switching element in the 100A system is the IF gate (8-type) developed initially for use in the THAS system [5]. This gate utilizes solid-state diodes and passive components to act as a

single-pole, single-throw switch. Three 8-type gates and a 1 x 3 combining network are associated with each regular channel as shown in Figure 15-3. Only one path can be closed through the gate at any time.

As shown in Figure 15-3, each protection channel fans out at the receiving end of a switching section through a 4051A network to 12 outputs. One output is connected through an individual 8-type gate circuit to a termination so that the network is always terminated when idle. Another output is connected through an 8-type gate to IF circuits that provide access for the protection channel in the next section or to other equipment in that station. The remaining ten outputs are connected through 8-type gates to the 1 x 3 network of each regular channel. This provides a flexible arrangement capable of switching either of two protection channels, designated X and Y, to replace any of 10 regular channels designated A through J. An inverse arrangement, very similar to that shown, is used at the transmitting end of a switching section.

Each channel is monitored for transmission quality at the receiving end of a switching section. The evaluation of quality is based on carrier amplitude and noise. If the carrier amplitude in a regular channel drops by a predetermined amount, the channel is considered impaired and a switch is required. If the carrier in a protection channel drops by a predetermined amount, no switch is permitted to that channel. Similarly, a fade indicated by an increase in system noise to 55 dBrc0 initiates a switch. If the noise on a protection channel exceeds 52 dBrc0, a switch to that channel is inhibited.

When a failure occurs on a regular channel, the increase in noise or loss of carrier power is detected at the receiving end of the section. A switching sequence is started by the initiator circuits which operate through logic circuits to send coded tone-oscillator signals over one of the two VF channels to the transmitting end of the switching section. The tone oscillators are normally not energized and the result of initiator and logic-circuit actions is to turn on the appropriate oscillators to identify the failed channel in accordance with the code combinations shown in Figure 15-4.

Excessive noise on the VF channel can cause erroneous switch operation because the noise can simulate the coded channel signals. To prevent such errors, a 500-Hz band (900 to 1400 Hz) in the VF channel is continuously monitored at the transmitting end of the switching section. When the noise in this band is excessive, all real

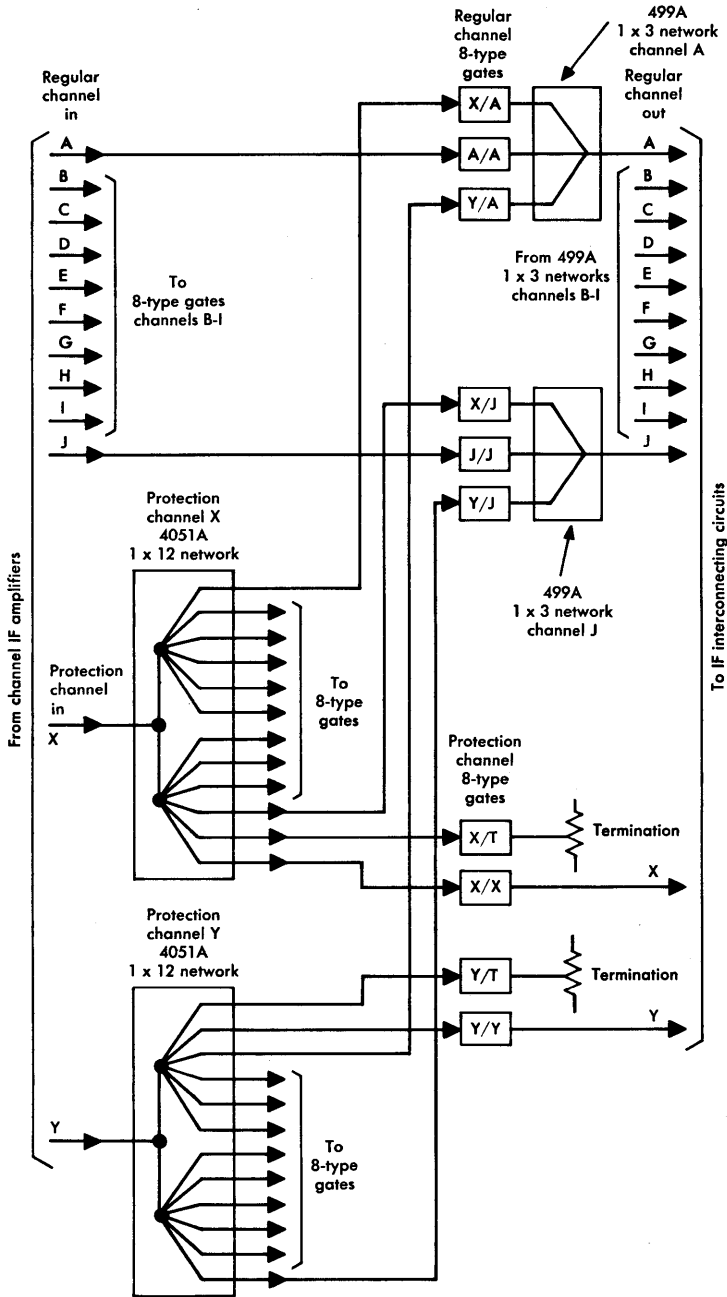


Figure 15-3. Receiving-end switching in 100A system.

SWITCH TO X OR Y	CODE TONE FREQ, Hz				
	1615	1785	1955	2125	2295
A	P	P	O	O	O
B	P	O	P	O	O
C	P	O	O	P	O
D	P	O	O	O	P
E	O	P	P	O	O
F	O	P	O	P	O
G	O	P	O	O	P
H	O	O	P	P	O
I	O	O	P	O	P
J	O	O	O	P	P
No order	O	O	O	O	O

P = tone present; O = tone absent

Figure 15-4. Switching command codes in 100A system.

or false switching orders are ignored; the noise detector generates an inhibiting voltage and initiates an alarm.

The layout of the 100A system for a switching section of 1 to 10 repeater hops and one direction of transmission is shown in Figure 15-5. One or more of the intermediate repeaters may provide a television drop and, where this is done, that station must also be equipped with protection switching facilities as shown.

When the tone-oscillator signals have been detected at the transmitting end of the section, logic circuits cause the appropriate 8-type gate (IF switch in Figure 15-5) to operate. This operation removes the 70-MHz carrier and pilot from the associated protection channel, X or Y, and bridges that channel to the failed regular channel. When the regular channel signal has been substituted for the protection channel carrier and pilot and the order to switch is still present, the receiving-end logic circuits cause the IF switch at the receiving end to operate, thus transferring service from the regular to the protection channel.

The logic circuits are arranged to provide preference switching from any failed regular line to a specific protection channel, X or Y. However, if the designated protection channel is not available for any reason and the other is available, the switch is made to the other protection channel.

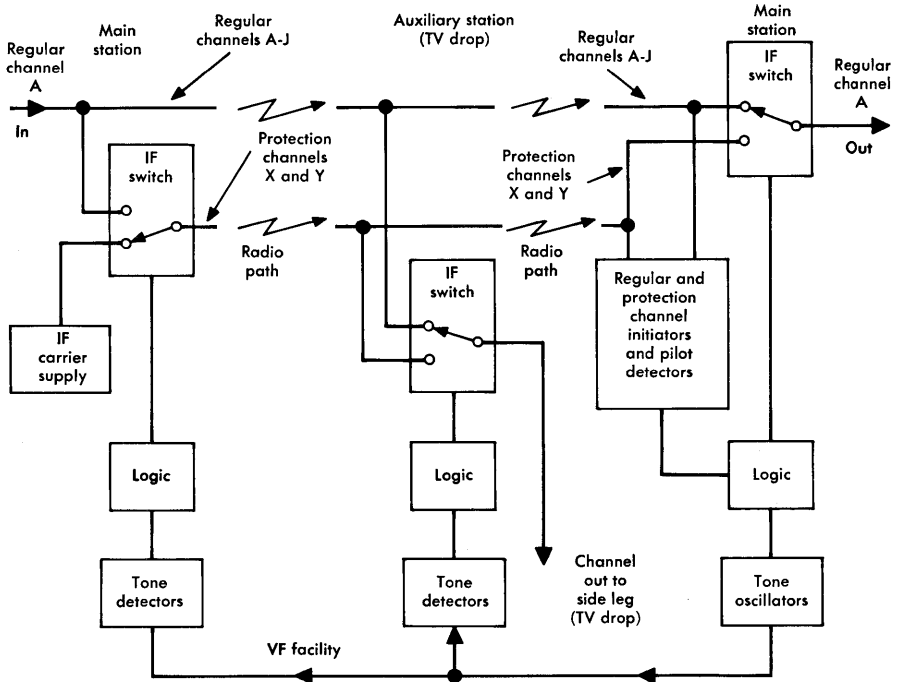


Figure 15-5. One section of a 100A system, one direction of transmission.

Operation of the receiving-end switch initiates a verification signal that causes the guard tone associated with that protection channel to be removed. This action is recognized at the transmitting end where the logic circuits cause the IF switch to be locked in the operated condition. If a switch to a protection channel remains in effect longer than 45 seconds, an alarm is sounded to alert maintenance personnel to the possibility of equipment failure.

The logic circuits at the two ends of the section perform many other functions. When a failed channel recovers, the switches are restored to normal and service is again carried by the regular channel. If a switch is required and cannot be completed to the assigned protection channel within 50 milliseconds, the logic circuits attempt a switch to the alternate protection channel. If both switch attempts fail, an alarm is sounded; several further attempts to switch are made



at 100 millisecond intervals and, finally, at ten-second intervals.\* The logic circuits are also arranged to recognize a failure in a previous section and to inhibit switching attempts in subsequent sections.

The 100A system operations can be checked automatically by an exerciser circuit. A time clock is used to start the automatic test routine, usually once each day. The time is selected so that service is least likely to be affected. The test routine may also be initiated manually to support maintenance and troubleshooting. It is automatically interrupted in about 1 millisecond if a protection switch is required.

Most of the functions of the system are checked in the course of a routine exerciser operation. However, the procedures for previous section failure and transfer from one protection channel to another in the event of protection channel failure are not checked. These operations must be checked during manual routine maintenance operations. The receiving switches are operated during exerciser routines unless the system is equipped with an optional switch control circuit. Receiving switch operation may cause brief service interruptions.

Manual switch controls are provided to permit maintenance and other required operations. These controls may be imposed on individual RF channels. A regular channel trouble condition may be simulated to force a switch to a protection channel and switching may be inhibited by locking out a channel. A regular channel is locked out by simulating a *good* condition in the logic circuits; a protection channel is locked out by simulating a *bad* condition in the logic circuits. Manual controls are imposed only at the receiving end of a section.

Override controls may be imposed manually at either end of a section. These controls are used only when there is a malfunction in the VF control channel or when logic circuits are being maintained.

### The TDAS System

This automatic switching system was the first designed to protect service on the TD-2 radio system. Originally, the TD-2 system provided six two-way radio channels in the RF spectrum between 3.7 and 4.2 GHz. Since one of these RF channels was assigned as a protection channel, the TDAS system was designed to operate as a 1 x 5 switching system [6]. Each direction of transmission was independently protected.

\*The exact sequence depends on how the system is equipped.

The TD-2 system was later expanded to twelve two-way radio channels by placing six additional channels in the guard bands adjacent to the original six channels. Later, because of the reduction in the number of protection channels allowed by the FCC, the TDAS system was redesigned so that, where the switching sections for two 1 x 5 systems were coterminous, the two switching systems could be combined into one 1 x 11 system. However, the 1 x 11 arrangement may not meet outage objectives where electron-tube systems are involved.

The 223-type switching elements used in this system are coaxial structures in which mercury-wetted sealed reed contacts are opened and closed under the magnetic influence of control currents through coils surrounding the glass containers. Each switch consists of four transfer contacts which operate simultaneously when the proper voltage is applied to the series-connected windings. Normally, transmission is from terminal A to AB and from B to OB as shown in Figure 15-6. All transmission paths to and within these switches, including the plug and jack connectors, are coaxial transmission line designs used in order to limit crosstalk by minimizing stray capacitance coupling between paths. Complex interconnections of switches

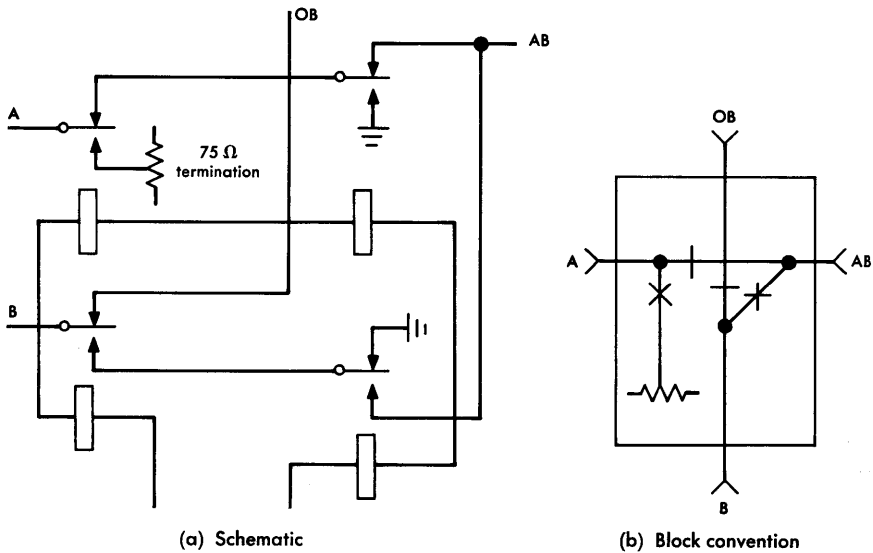


Figure 15-6. The 223-type coaxial switch.

permit the protection channel to be substituted for any regular channel.

A VF channel is used to transmit control signals (guard tones and channel identification tones) to convey the information regarding which switches are to be operated or released. These control signals are converted to appropriate dc signals to operate or release the switches. The five regular channels are identified by 900-, 1100-, 1300-, 1500-, and 1700-Hz single-frequency signals transmitted over the voice-frequency channel. A signal at 630 or 700 Hz is used as a guard tone.

Figure 15-7 shows the principal components of a TDAS switching arrangement applied to one switching section. With all regular channels operative and with channel 1 assigned as a protection channel, the VF channel carries the guard tone from the receiving switching control circuit to the transmitting switching control circuit to indicate the normal condition. Normally, no channel identification signals are transmitted.

Sensing circuits, used to determine the transmission quality of regular channels by monitoring a pilot amplitude and by measuring noise, initiate the switching sequence upon channel failure. The pilot resupply circuit provides 70- and 61.5-MHz signals to the protection channel which are picked off by the protection channel initiator at the receiving end of the section. When the received signals are within established amplitude limits, the initiator indicates to the receiving control circuits that the protection channel is idle and in good working order.

If a regular channel fails, the associated initiator signals the failure to the receiving switching control circuit. If the protection channel is idle and in good working order, the control circuit suppresses the guard tone and transmits the appropriate channel identification signal over the VF channel to the transmitting end of the section. The transmitting switching control circuit operates the appropriate switch, thus bridging the protection channel to the regular channel at the transmitting end, and removes the idle pilot from the protection channel. The protection channel initiator receives the new signal and, if transmission quality is acceptable, signals the receiving switching control circuit to complete the transfer of service by operating the appropriate IF switch at the receiving end of the section. However, if a switch is attempted and the protection line is not available, the receiving switch control circuit inhibits any switching action and generates a service failure alarm.

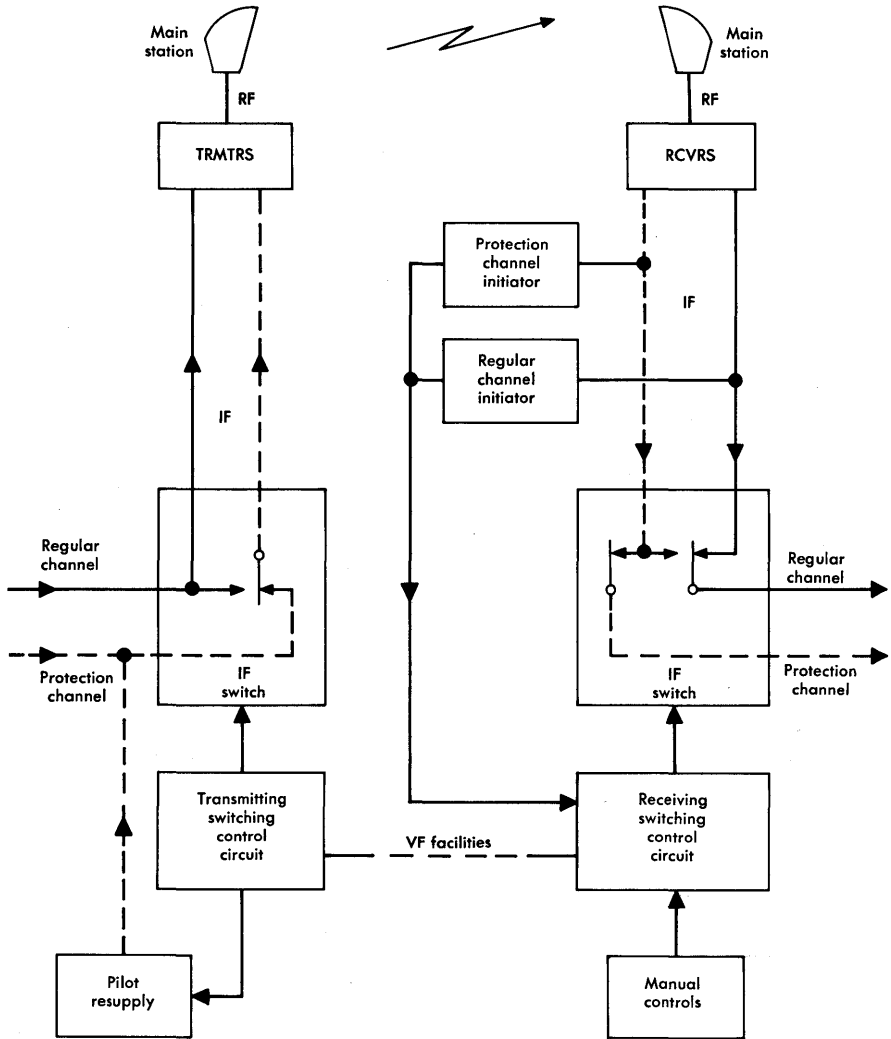


Figure 15-7. One direction of TDAS switching in one switching section.

Figure 15-7 shows only the main stations at the two ends of a switching section. A number of intermediate repeaters are usually included in such a section. Furthermore, it is sometimes necessary to switch at one or more of the intermediate sites in order to protect television drops that might be provided there. The identification signal for intermediate station switching is 2100 Hz.

Manual controls are available at the receiving end of the switching section. They may be used to block switching attempts when the protection channel is being maintained or temporarily used for some part-time service. They may also be used to substitute the protection channel for a regular channel to permit maintenance.

Several other operating features of the TDAS system are of interest. For example, when a failed channel has been cleared the system automatically switches service back to this channel. This is accomplished when the regular channel initiator recognizes satisfactory conditions of carrier amplitude and noise. Another important feature relates to the interaction between a failed section and other sections in tandem with it. The loss of service in the failed section is recognized in all subsequent sections where the protection and failed regular channels are bridged at the transmitting ends. However, since the loss of signal in the failed section is reflected as a loss of signal on both regular and protection channels in subsequent sections, the receiving-end switches are not completed. The protection channels in those sections are then released for further use.

### The THAS System

Two major radio systems have been developed to operate in the 6-GHz band, the TH-1 and the TH-3. The THAS protection switching system operates only with the TH-1 system [6]. Both TH-1 and THAS are no longer manufactured and, therefore, only a brief review is given of the THAS system. The 300A Protection Switching System was developed to operate with the TH-3 system [7]. However, its limitations and changing requirements resulted in the development and use of the more versatile 400- and 401-type systems. Only a few 300A systems are in service.

The needs of the TH-1 radio system for automatic protection switching are well served by the THAS system, the first automatic protection switching system design principally based on solid-state circuits. A few IF amplifiers are based on electron tube technology.

The TH-1 system provides eight 30-MHz wide two-way radio channels in the 6-GHz RF band. In the original design, two of these were reserved for use as protection channels in the THAS system. In the center of the RF band and at the band edges there are four narrowband AM channels allocated for the transmission of voice communication signals between stations and control signals for the THAS system where such signals are required [8]. The control signals

are assigned baseband frequencies 1 kHz apart from 20.5 to 35.5 kHz inclusive. The auxiliary channels are not always used because on some routes, TH-1 and 4-GHz systems are operated together and other auxiliary channel facilities are often available.

The THAS circuits may be arranged to provide 1 x 1 to 1 x 6 or 2 x 2 to 2 x 6 protection; to satisfy changed FCC rules, it is now generally used with just one protection channel. Switching may be done at baseband or intermediate frequencies according to need. Where radio channels only are protected, the switching is organized by switching sections up to ten hops long and only IF switching at 74 MHz is used. In some cases, the switching section may include FM terminals at one or both ends; here, the protection switching may be between baseband points so that the FM terminals are also protected.

Occasionally, the THAS system may be used within a building to protect only FM terminal equipment. In this arrangement, the switching is done at IF at one end and baseband at the other; signalling between the two ends is accomplished by dc over separate wires.

As in other systems, manual switching and override controls are provided and the protection channels may be used for temporary or emergency service. Automatic checks of the switching system functions are made periodically or on demand by an exerciser circuit. The THAS system is unique in that the control logic is at the transmitting end of the switching section and the initiation of switching takes place at intermediate repeater points by monitoring an automatic gain control voltage.

### 15-3 FREQUENCY DIVERSITY SWITCHING OF SHORT-HAUL SYSTEMS

Protection switching of short-haul radio systems differs from that used for long-haul systems for several reasons. Short-haul transmission systems often consist of only one switching section. Where message channels are dropped, blocked, and added along a multiple-section route, each section tends to be short and baseband repeaters are usually employed. Thus, most protection switching systems in the short-haul field are baseband switching systems. Since short-haul routes tend to be lightly loaded and are characterized by a slow rate of growth, the switching was initially provided by 1 x 1 systems. This mode of operation is now restricted under FCC Rules and its use is being discontinued. Short-haul protection switching systems, using noise monitoring as the criterion of channel quality and pilot transmission as the criterion of continuity, are the 400B and the 401-type.

### The 400B Protection Switching System

Baseband signals for microwave radio systems appear at both ends of wire-line entrance links and at the input (or output) of each FM terminal. The 400B system, derived from the 400A, switches at baseband and is used to protect radio channels by a frequency diversity arrangement that includes the FM terminals and may additionally protect the wire-line entrance link at one or both ends of a switching section. The system uses one protection channel to protect up to seven regular channels. The transmission circuits make the 400B compatible with TL-, TM-, TD-, TH-, and TN-type radio systems. Optional features permit its use with television video signals, an intermix of radio channels having different message channel capacities, or channels carrying the 1A Radio Digital System (1A-RDS) signal.

Nearly all circuits in the 400B system are of solid-state design. However, the baseband signal switching is done by 295D-mercury-wetted, sealed-reed contact switches schematically shown in Figure 15-8. This type of switch was selected in order to facilitate the transmission of network television signals which require transmission to very low frequencies. The 400B operates, as do most other protection switching systems, under the control of receiving-end circuits by bridging channels at the transmitting end of the section and by transferring the channels at the receiving end. Switching is initiated by excessive noise in a baseband channel and/or by loss of a pilot signal transmitted at 5.93 or 8.8 MHz.

The 400B offers a number of optional operating features. The protection channel is provided with access so that it may be used for temporary or emergency signal transmission. Manual control then permits preemption of the protection channel by a failed regular channel. A selected regular channel may be designated for priority switching to a busy protection channel. Automatic or manually controlled in-service testing of the switching system is provided through the use of an exerciser circuit. Optional controls are provided for auxiliary switch functions required when the 1A-RDS signal is transmitted. The normal frequency range of the transmission paths through

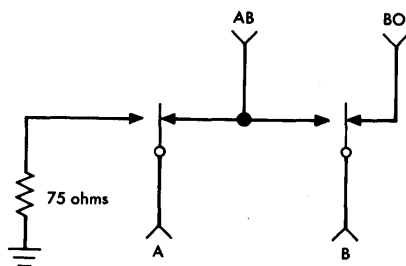


Figure 15-8. Schematic of 295D switch.

the switching system, 60 kHz to 12 MHz, may be extended to zero frequency when required for 1A-RDS or video signal transmission.

Two control signal options are available. One is a separate VF channel with tone signalling similar to that used with the 400A system; the second, which uses digital control signals, was designed specifically for use with the 400B system. This method of signalling is less susceptible to analog system impairments than the tone method of signalling. Receiving-end logic circuits may be controlled manually from the transmitting end of a section if the system is provided with digital control facilities between the two ends.

In the digital mode, a pair of single-frequency signals carry the signalling information from the receiving to the transmitting end of the switching section. The coded signal pair is transmitted simultaneously over radio channels 1 and 2 of the transmission system to protect the signalling system against channel failure. The signals are in the baseband spectrum at 5.91 and 5.93 MHz. Where transmission system operation requires the provision of a wider band (3 master-groups), the 5.91- and 5.93-MHz signals are replaced by 8.80- and 8.82-MHz signals.

Signalling information is transmitted in the form of an 8-bit word. In the idle state, alternate *1*s and *0*s are transmitted. The beginning of a word is indicated by transmitting two successive *1*s, the second of which is the first word bit. The signalling information is coded in the next six bits and the last bit is a parity bit. Even-bit parity is used; i.e., every combination of *1*s in the six information plus parity bit must be an even number. If the number of *1*s is odd, the circuits do not respond.

The two-frequency signalling arrangement is organized as a complementary system. The single-frequency signals are turned on and off to represent *1*s and *0*s, each bit one millisecond long. The two signals (e.g., 5.91 and 5.93 MHz) are turned on and off in a complementary fashion so that a *1* is represented by the presence of 5.91 MHz and a *0* is represented by the presence of 5.93 MHz. If complementary signals are not received, the logic circuits in the signalling receiver do not respond.

### 401-Type Systems

In the design and application of microwave radio systems for short-haul use, there is considerable emphasis on simplicity and economy.



The three systems of the 401 type (401A, 401B, and 401C) have much in common. All utilize noise in a dedicated channel above the normal multiplex band as the criterion of channel quality and a single-frequency pilot as the criterion of system continuity. In all cases, they operate as 1 x 1 frequency-diversity protection switching systems with a permanent bridge connecting the regular and protection channels at the transmitting end of a section. Thus, all switching is by transfer at the receiving end and communication between the two ends is not needed. When a switch is made, the service does not revert to the original channel unless an optional revertive mode is provided. Manual controls are located at the receiving end of the section. Access to the protection channel for temporary or emergency use is provided optionally.

These relatively simple systems may be used with TL-, TM-, TD-, TH-, and TN-type transmission systems. Most of the 401-type systems in service are of the 401B type. These are baseband systems that can protect, in addition to the RF channels, the FM terminals and/or wire-line entrance links. These systems utilize the previously described 295D mercury-wetted sealed-reed relay as the receiving-end switch element.

The 401A is a 1 x 1 IF switching system with operating features generally similar to the 401B system. The switching element used is the solid-state 295A switch. The 401C is a 1 x 1 baseband-to-IF switching system also similar to the 401B in respect to operating features. It utilizes 401B equipment at the baseband end of the switching section. These systems are now seldom used because of FCC Rules which do not now permit the use of 1 x 1 protection except under extenuating circumstances.

#### 15-4 SPACE DIVERSITY AND HOT STANDBY SWITCHING

The augmenting of frequency diversity protection switching of microwave radio channels by different types of protection arrangements has proven to be highly desirable. This is especially evident since the FCC Rules were amended to impose tighter restrictions on the assignment of radio channels for protection use. Two techniques are used in various forms and combinations, (1) space diversity switching of the radio channel and (2) hot standby (powered) repeaters equipped with automatic switching between the regular and hot standby equipment. Both are applied to individual radio channels

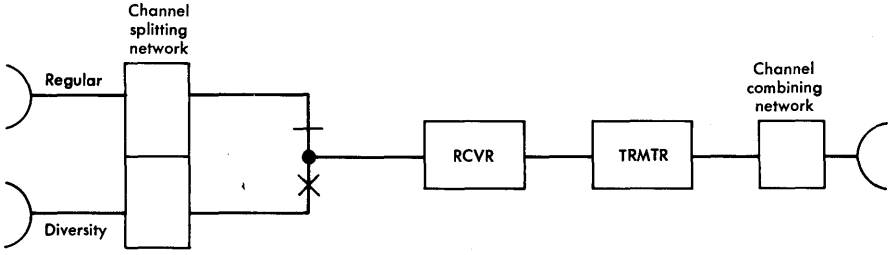
at individual repeaters. Space diversity switching is applied only to repeater sections subject to severe multipath fading. However, if no other form of protection against propagation failure is provided, space diversity switching should be considered even if only a moderate amount of multipath fading is expected.

The effectiveness of space diversity switching depends on the exploitation of the vertical structure of the electromagnetic fields of a radio wave at the receiving point in a point-to-point radio repeater section. Two vertically separated receiving antennas are mounted on the same tower. The regular antenna is usually mounted near or on the top of the tower and the diversity antenna is usually mounted lower on the tower. The nature of fading phenomena is such that only on rare occasions does a signal suffer from destructive multipath interference at both antennas when they are properly spaced [9].

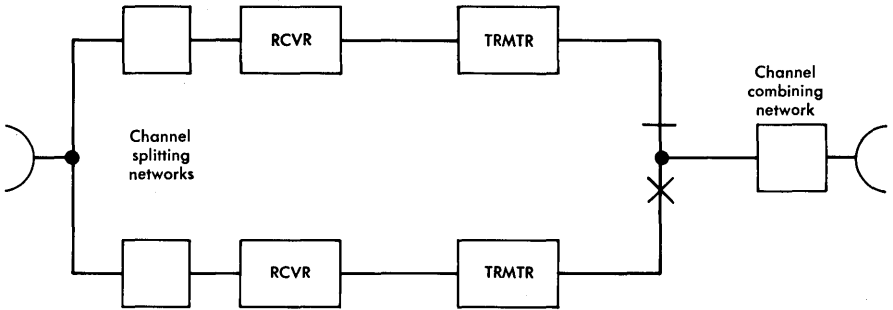
Repeater sections that cross bodies of water or very flat, smooth, and barren countryside are especially subject to atmospheric multipath fading; ground reflections may require the optimization of antenna heights in such sections. In addition, the occurrence of fades is much higher along the Gulf of Mexico and the southern Atlantic coast where stratification of the atmosphere commonly occurs. Although space diversity switching can improve performance, the relatively light loading of most short-haul systems, the costs of the additional antenna system and required tower modifications, and the less stringent outage requirements for short-haul systems make such arrangements less attractive in these applications than on many long-haul systems.

In some repeater sections, where protection against fading alone is required, space diversity switching of the radio path is provided as shown in Figure 15-9(a). In other instances, protection against repeater equipment failure is provided by the hot standby switching arrangement illustrated in Figure 15-9(b). These two configurations are sometimes used in combination as shown in Figure 15-9(c).

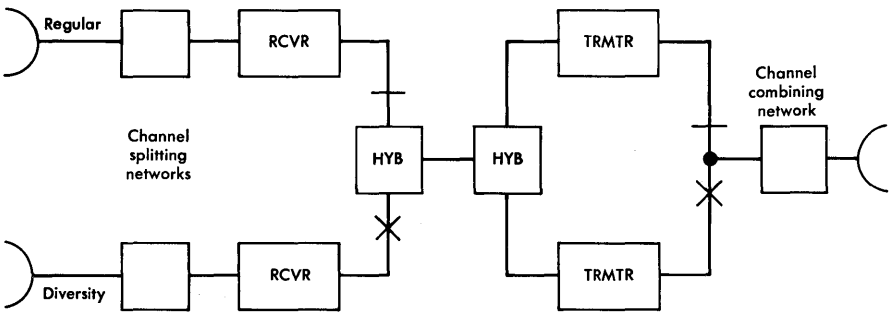
In the configuration of Figure 15-9(a), a waveguide switch is used to transfer the receiver input to either of the two receiving antennas. When carrier power, as measured by the automatic gain control voltage in the main IF amplifier in the receiver, falls below a specified threshold, the switch is activated. This mode of operation, the most commonly used, is called *blind* switching because it is activated without knowledge of the condition of the alternate path. However, most of the time a stronger signal is available because, as previously men-



(a) Space diversity and switching



(b) Hot standby switching



(c) Combined space diversity and hot standby switching

Figure 15-9. Repeater station switching.

tioned, deep fades seldom occur simultaneously on both paths. Space diversity switching can be arranged for nonrevertive (blind) or revertive operation. The correlation of fading on the two antennas of a space diversity system decreases as the distance between them increases. Since this arrangement provides no protection against equipment failure, it is often used in combination with frequency diversity or hot standby arrangements.

The hot standby switching arrangement of Figure 15-9(b) uses either coaxial or solid-state diode-type switches between the transmitters and the channel combining network. The unused transmitter is terminated in a high-power RF termination at all times. The output power of both transmitters is continuously monitored. If the power of the transmitter in use falls below normal by a preset amount, a switch is initiated and, if the standby transmitter power is satisfactory, the antenna connection is switched. This arrangement may be used in either a revertive or a nonrevertive mode. Manual switching and lock-out can be made by means of a switch control circuit.

Space diversity and hot standby switching are combined, as shown in Figure 15-9(c), by including the receiver circuits in the switched diversity paths. Hot standby switching alone is used in the transmitter portion of the repeater in this illustration.

## 15-5 ENTRANCE LINK AND FM TERMINAL SWITCHING

Service on radio systems may be protected against equipment failure in FM terminals and wire-line entrance links by one of several types of automatic protection switching systems. Those commonly found in service include the FM terminal automatic switching (FMAS), THAS FM terminal switch, 200A, and the 200B systems. These systems have many features in common but also differ significantly and thus must be described separately. All have circuits that prevent excessive interactions with previous switching sections in which failures may occur.

Although the FMAS system is no longer manufactured, many are still in service; some of these utilize electron tube circuits and others have more modern solid-state circuits. Switching is accomplished by the use of the previously described 223-type coaxial switches. Baseband signals are switched at one end of the FMAS and IF signals at

the other end. The system may thus be used to protect FM terminal transmitters and receivers alone or, as it is more commonly applied, to protect combinations of FM terminal equipment and the associated wire-line entrance links, such as the A-, B-, or 3-type links.

The system uses one protection channel to protect up to five regular channels. The regular channels may be of various message channel capacities and provision is made in the FMAS system for switching into the protection channel the preemphasis or deemphasis network and level-adjusting pads appropriate to the channels being replaced. Provision is also made for protecting channels transmitting the 1A-RDS signal.

Channel continuity is normally determined by the presence of a single-frequency pilot signal. This pilot can not be used in a channel carrying a television signal. Most FMAS systems initially used a 64-kHz pilot. Newer channel additions and some converted systems use a 512-kHz pilot. The protection channel can accommodate either pilot in the same switching system; however, the latter pilot must be used where 1A-RDS signal transmission is involved. Control signals are transmitted from one end of the system to the other over wire pairs; dc signals are used. Manual controls are provided to switch or to lock out the channel as required.

### The 200A Protection Switching System

Like the FMAS, the more modern and more compact 200A system switches baseband signals at one end of a section and IF signals at the other and is used to protect FM terminal equipment in combination with wire-line entrance links. The most significant differences are that there are no electron tube circuits in the 200A and it is the more versatile system in that the one protection channel is used to protect up to 12 regular channels. Features of the 200A system are otherwise similar in most respects to the FMAS system.

The 200A system can be used to protect radio systems with three different message load capacities: 600, 1200, and 1800 channels. The protection channel must be equipped with suitable preemphasis and deemphasis networks that can be switched in as required.

## The 200B System

In some short-haul system installations, the FM terminal equipment is protected as a part of the radio transmission system. In such cases, it is desirable to provide separate protection switching equipment for the wire-line entrance links. The 200B system may be so used. It switches baseband signals at both ends of 3A wire-line entrance links and may be used only for the protection of links that carry multiplexed telephone message signals. A 64-kHz pilot is used to establish channel continuity. In the 200B system, the preemphasis and deemphasis networks are connected outside the switching section; thus, they are not protected.

Much of the equipment used in the 200B is identical to that in the 200A system. Like the 200A, switching is accomplished on the basis of one protection channel for up to 12 regular channels by means of 223-type switches. Signalling between the two ends is by dc over wire-pair conductors. Manual controls are provided to supplement the automatic switching features.

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## Chapter 16

# Short-Haul Systems

Early designs of microwave radio systems intended for use as end links or spurs for long-haul backbone systems were based on service requirements that were derived from assumptions of short distances and small channel capacities, assumptions that are no longer valid in all respects. In addition, systems of early design no longer meet stability requirements and limitations on protection channel assignments now specified by the Federal Communications Commission (FCC). Operating systems of early design must be upgraded or replaced if they cause interference problems or if it becomes necessary to use frequency bands previously assigned to standby use.

As service demands have increased, the distinction between short-haul and long-haul systems has tended to decrease and systems are used in overlapping applications. Early short-haul systems were designed for a maximum length of about 250 miles and to meet a noise objective of 35 dBrcn0; this is about 3 dB less stringent than would be determined by using a proportion of the objective applied to long-haul systems. Now, it is not unusual to use medium- and long-haul systems in what has been traditionally thought of as the short-haul field. Such systems provide better performance and larger channel capacities.

One of the earliest short-haul systems, the TE, was designed primarily for transmission of television signals. It provided six one-way or three two-way channels in the 4-GHz RF band over as many as six hops in tandem. The system is not used today.

Somewhat later designs include the TJ, TL-1, and TM-1/TL-2 systems. They are no longer manufactured but a number of each type are still in service. In some cases, the performance of these systems has been improved by modification using more modern circuit components. The TM-2, TM-2A, and TN-1 systems are of modern vintage and are economically attractive in many short-haul applications.

## 16-1 THE TJ, TL-TYPE, AND TM-1 SYSTEMS

The first system specifically developed for short-haul telephone and television transmission was TJ. Although the cost of this system was high, it performed satisfactorily. Later, the TL-1 system was developed to fill the needs of short-haul telephone applications more economically than did the TJ system. The TL-1 system met this objective but, even as it was being introduced into service, the needs for improved noise performance, greater channel capacity, and television service became evident. The TL-2 and TM-1 systems were subsequently developed to satisfy these needs.

### The TJ System

Telephone message or television service may be provided on the baseband-repeated 11-GHz TJ microwave radio system [1]. Six two-way RF channels, each about 40 MHz wide, are provided in the 1000-MHz-wide RF band. The system utilizes electron-tube circuits throughout. The baseband signal is applied to the repeller of a klystron tube to generate an FM signal in the appropriate RF channel band. Automatic frequency diversity switching is provided on a one-for-one basis, no longer permitted in most cases by FCC regulations. Only three of the six two-way channels are normally used as regular channels. One antenna is used for both directions of transmission.

Klystron oscillator tubes provide the RF output of the transmitter and the local oscillator signal in the receiver. These oscillators are not sufficiently stable to meet modern FCC requirements. As a result, some systems have been upgraded by using more modern frequency control devices, and others have been removed from service. However, a few of the original design remain in service where they cause no interference problems.



As originally designed, the TJ system could be used on routes up to 250 miles long requiring no more than nine repeaters. The capacity of each RF channel was 240 message channels provided by L-multiplex equipment. The system was also used with ON-2 terminal equipment to transmit 96 message channels. It could also be used to provide television service over distances up to 100 miles. The message channel capacity was later increased to 960 4-kHz channels.

### The TL-1 System

A primary design objective for the 11-GHz TL-1 system was to reduce operating costs relative to those of the TJ system. The effort resulted in a system that required significantly less maintenance effort and operating power than TJ. Installation and engineering costs were also reduced [2].

The circuits in the TL-1 system are all of solid-state design except for the klystron tubes used as the transmitter and receiver local oscillators. The RF channel plan is the same as that used in the TJ system. A common antenna is utilized for transmitting and receiving. Use may be made of a 1 x 1 protection switching arrangement where permitted by the FCC.

The TL-1 system can provide telephone message service over distances up to about 200 miles or ten repeater hops. In each RF channel, the system can carry a load of 48 channels from N-carrier system terminals, 96 channels from ON-carrier system terminals, or, under certain conditions, up to 600 channels of L-multiplexed signals.

### The TM-1/TL-2 System

While designed as two separate systems, the TL-2 and TM-1 systems have been used extensively as a single system incorporating a cross-band frequency-diversity protection switching arrangement. The TM-1 operates in the 6-GHz band and the TL-2 in the 11-GHz band. Many combinations of RF channels, derived from standard frequency plans of the TH-1 (6 GHz) and TJ (11 GHz) systems, may be used.

As in the design of the TL-1 system, the objective of reducing costs relative to those of the TJ system was also applied in the TM-1/TL-2 design [3]. For a 10-hop, 250-mile system, noise performance was improved by about 2 dB, from 37 to 35 dB<sub>rnc0</sub>, relative to the TL-1 system. Provision was also made for television video signal transmission. Power consumption for a transmit-receive panel was reduced from just under 500 watts for TJ to about 170 watts for TM-1 or TL-2. A single antenna is used for both directions of transmission. All circuits, except the klystron oscillators, are of solid-state design.

The crossband frequency-diversity arrangement has the advantage of minimizing the occupancy of the congested 6-GHz band by utilizing a channel in the 11-GHz band for protection. Rain attenuation effects in the 11-GHz band are minimized by using that band primarily to protect against atmospheric fading in the 6-GHz band or when maintenance work is being done. With the changes in FCC regulations, the 1 x 1 switching for which TM-1/TL-2 was originally designed is not allowed on new installations. The 1 x 7 400B protection switching system is now generally used for the crossband arrangement. It should be noted that the TM-1 system has also been used in crossband diversity switching arrangements with the TJ system.

The TL-2 and TM-1 systems both provide an output RF power of 0.1 watt when used for 600 message channels. The capacity of both systems may be increased to 1200 channels by using an IMPATT diode amplifier to increase the klystron output from 0.1 watt to 1.0 watt. When so arranged, the TL-2 system is known as the TL-A2 and the TM-1 as the TM-B1.

## 16-2 THE TM-2 SYSTEMS

Among the modern short-haul radio systems now in common use are the 6-GHz TM-2 and TM-2A. These systems provide message telephone or television video service over distances of about 250 miles with a maximum of 10 repeater hops depending upon topography, geographical location, and other route parameters. The two systems are similar in many respects. However, the TM-2A is a later version that provides greater message circuit capacity, improved performance, and additional features.

The TM-2 system, which normally has a capacity of 1200 message channels in each two-way RF channel, may be modified to provide both improved performance and a capacity of 1800 message channels. The TM-2A incorporates these modifications and provides a capacity of 1800 message channels.

### Frequency Plans

Three RF channel frequency plans are available for use with TM-2 and TM-2A systems. The center frequency allocations for two of these plans are given in Figure 16-1. The two-digit numbering system shown in the figure was chosen as an administrative convenience to designate channels usually equipped in pairs (11 and 21, 12 and 22, etc.). The regular plan provides 16 one-way (eight two-way) channels that correspond to the standard RF channel frequency allocations used in TH-type radio systems. The staggered plan, which provides seven two-way channels, utilizes frequencies that place the TM channels between TH channels and is sometimes used to minimize interference where a TM route crosses a TH route.

CHANNEL NO.	CENTER FREQUENCY (GHz)	
	REGULAR PLAN	STAGGERED PLAN
11	5.9452	5.9600
12	5.9748	5.9897
13	6.0045	6.0193
14	6.0342	6.0490
15	6.0638	6.0786
16	6.0935	6.1083
17	6.1231	6.1379
18	6.1528	—
21	6.1972	6.2121
22	6.2269	6.2417
23	6.2565	6.2714
24	6.2862	6.3010
25	6.3159	6.3307
26	6.3455	6.3603
27	6.3752	6.3900
28	6.4048	—

Figure 16-1. RF channel frequency assignments, TM-2 and TM-2A systems.

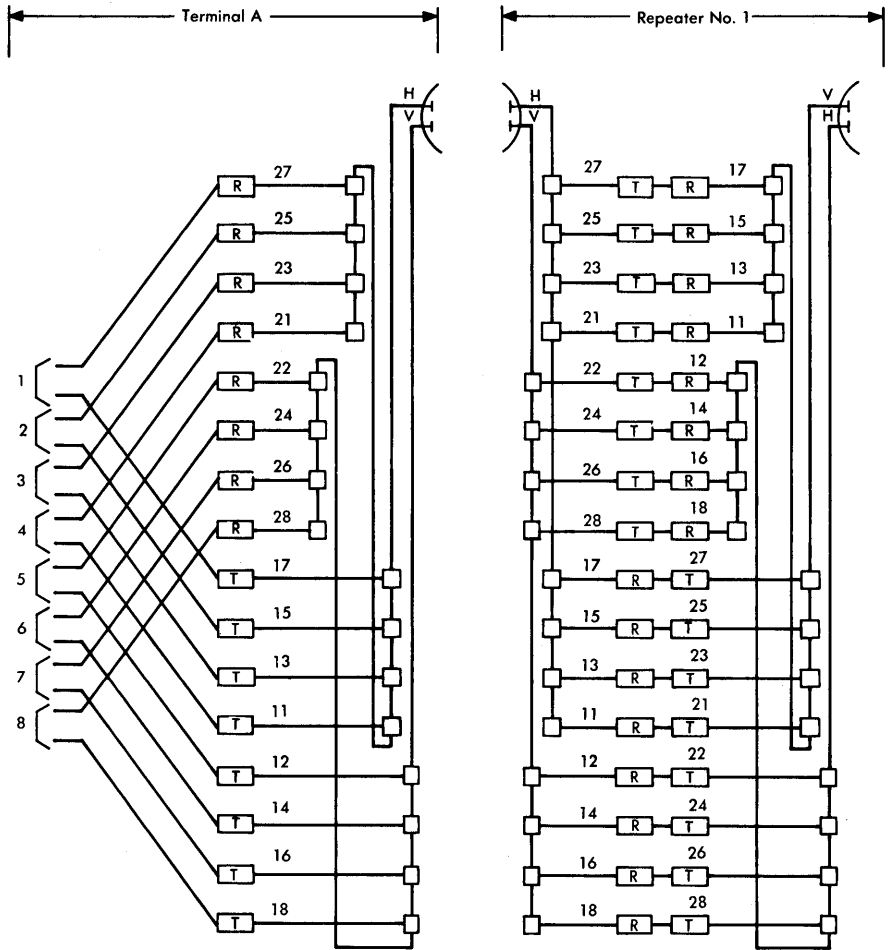
The RF channel allocations are used in TM-2 and TM-2A systems in a so-called two-frequency arrangement using a single antenna for each route direction from a terminal or intermediate repeater station. In the two-frequency arrangement, the same radio channel frequencies, one for transmitting and one for receiving, are used at each station for the opposite directions of a two-way radio channel. Some systems have employed a four-frequency plan in which a different pair of channel frequencies is used for the opposite directions of transmission of a two-way radio channel. Signals in like-numbered channels received from opposite directions at a repeater station are horizontally and vertically polarized to minimize interferences. Channel pairs and polarizations are reversed at successive repeaters. These relationships can be observed in Figure 16-2 where frequency allocations for the two favored frequency plans are shown in terms of channel assignments. The center frequency for each channel is given in Figure 16-1.

In order to control interchannel interference where all RF channels are assigned and heavily loaded, supplementary filters must sometimes be used. In some cases, it is also desirable to operate with two antennas for each route direction, one for receiving and one for transmitting.

The third frequency plan used in these systems, called the split channel plan, was introduced with the TM-1 system and provides two channels in the frequency band allocated to each TH channel. However, it is seldom used because of excessive interference between systems.

## Repeaters

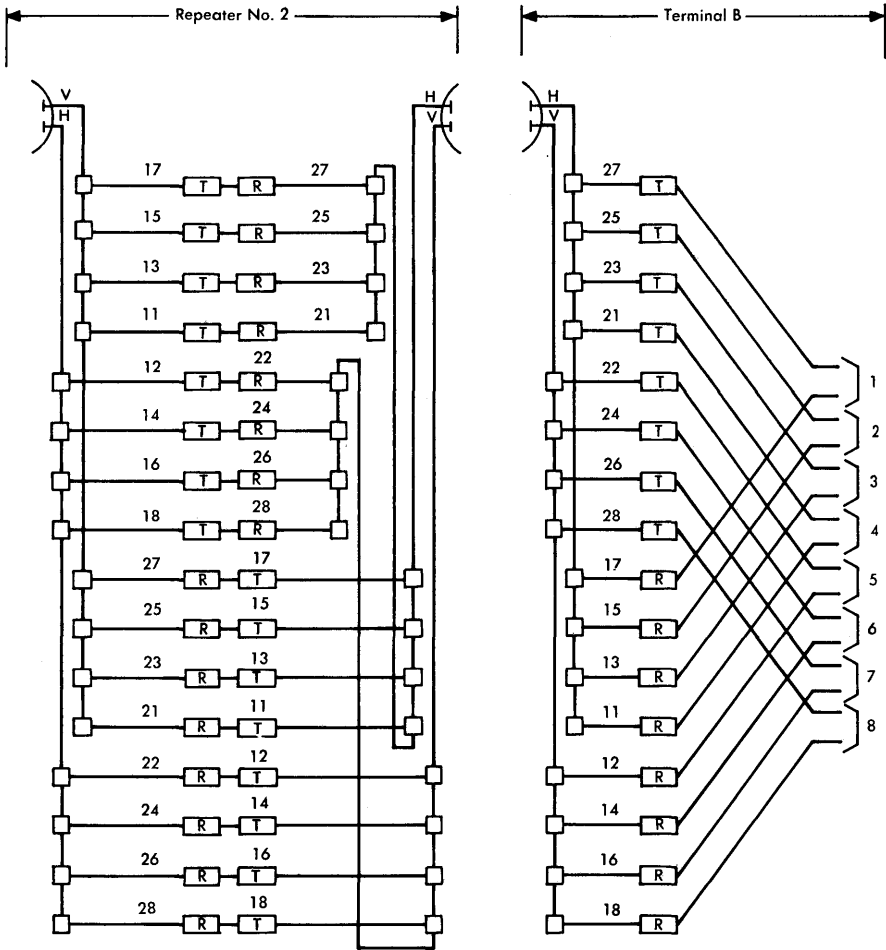
Terminal and intermediate repeaters in TM-2 and TM-2A systems are arranged so that the transmitter and receiver for one route direction from the repeater point (as distinguished from one direction of transmission) are mounted in a single panel as shown in Figure 16-3. This arrangement, similar to that used at main stations in long-haul radio systems, facilitates the use of TM-2A repeaters as baseband or heterodyne (IF) repeaters according to requirements for dropping, blocking, and adding circuits. The TM-2 utilizes only baseband repeaters.



Notes:

1. Designations 1 through 8 show channel pairings for two directions of transmission and recommended order of channel assignments with growth
2. Designations 11 through 18 and 21 through 28 are RF channel numbers
3. T = transmit; R = receive
4. H = horizontal polarization; V = vertical polarization

Figure 16-2. RF channel assignments in TM-2 and TM-2A systems (continued).



Notes:

1. Designations 1 through 8 show channel pairings for two directions of transmission and recommended order of channel assignments with growth
2. Designations 11 through 18 and 21 through 28 are RF channel numbers
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4. H = horizontal polarization; V = vertical polarization

Figure 16-2. RF channel assignments in TM-2 and TM-2A systems.

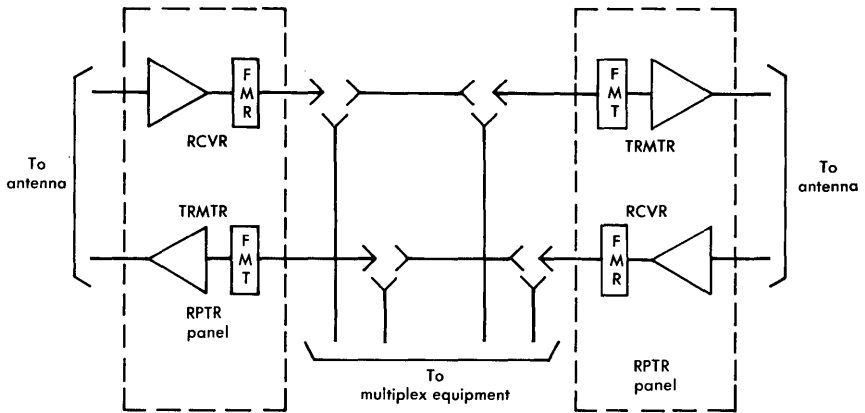


Figure 16-3. Equipment arrangements at TM-2 and TM-2A baseband repeaters.

A block diagram of a TM-2 or TM-2A receiver is shown in Figure 16-4. Radio energy from the antenna is transmitted by waveguide through channel separation networks (which separate horizontally and vertically polarized signals and select the desired channel signal), and through an isolator. The isolator provides an impedance match between the channel separation network and the band reject filter and prevents RF energy reflected by the filter from being returned to the antenna where it might be retransmitted. The band reject filter is tuned to the receiver oscillator frequency and prevents oscillator energy from being transmitted.

The receiver local oscillator produces a single-frequency signal 70 MHz below the nominal carrier frequency of the desired channel. The amplitude of this signal is adjusted by the RF pad. The local oscillator signal then passes through the circulator to reach the band reject filter at which it is reflected; it returns through the circulator to reach the receiver modulator where it is used to demodulate the received RF signal to the IF band.

Unwanted carrier and sideband energy is eliminated by the IF bandpass filter and the desired signal is equalized and amplified as required. If the repeater is to be used as a baseband repeater or as a terminal repeater, the signal is applied to an FM receiver in which the baseband signal is recovered. If a TM-2A repeater is to be used as a heterodyne repeater, the IF signal may be connected to the succeeding transmitter modulator.

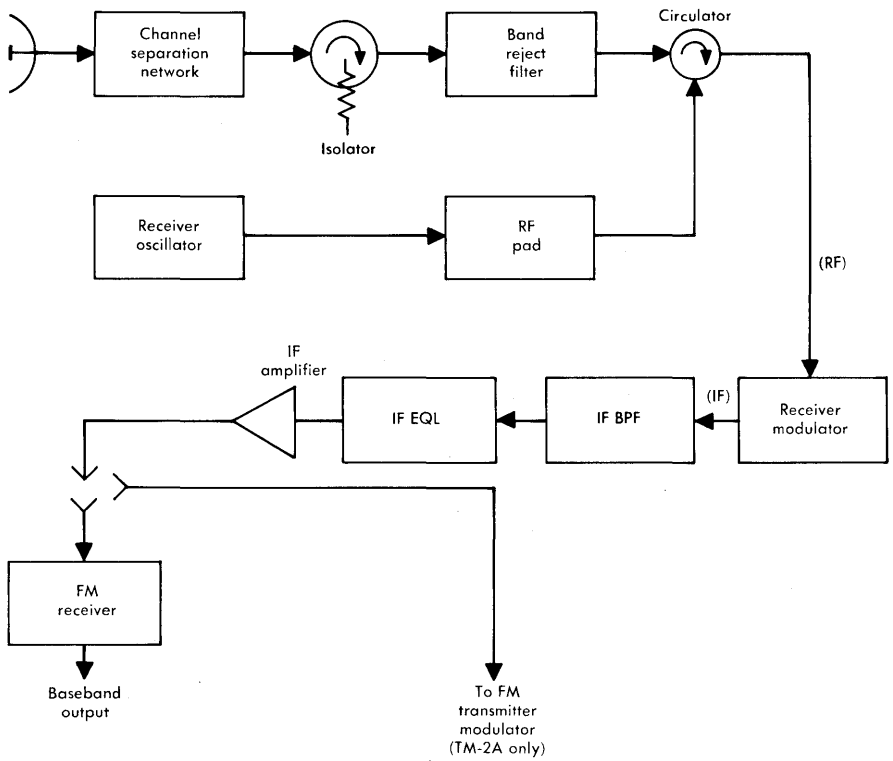


Figure 16-4. Block diagram of TM-2 or TM-2A receiver.

Figure 16-5 is a block diagram of a TM-2 or TM-2A transmitter. The signal at the transmitter input may be at baseband or intermediate frequencies. If the input signal is at baseband, it is connected to the transmitter at the input to the FM transmitter modulator. If the input signal is at IF, an IF limiter transmitter modulator is substituted for the FM transmitter modulator. In either case, the output of the transmitter modulator is an RF signal in the desired frequency band.

The output of the transmitter local oscillator is connected to the circulator through an attenuator used to adjust the signal amplitude. The circulator directs the single-frequency signal to the FM transmitter modulator where it is combined with the IF signal and used as the RF carrier signal. The modulated RF signal then passes through



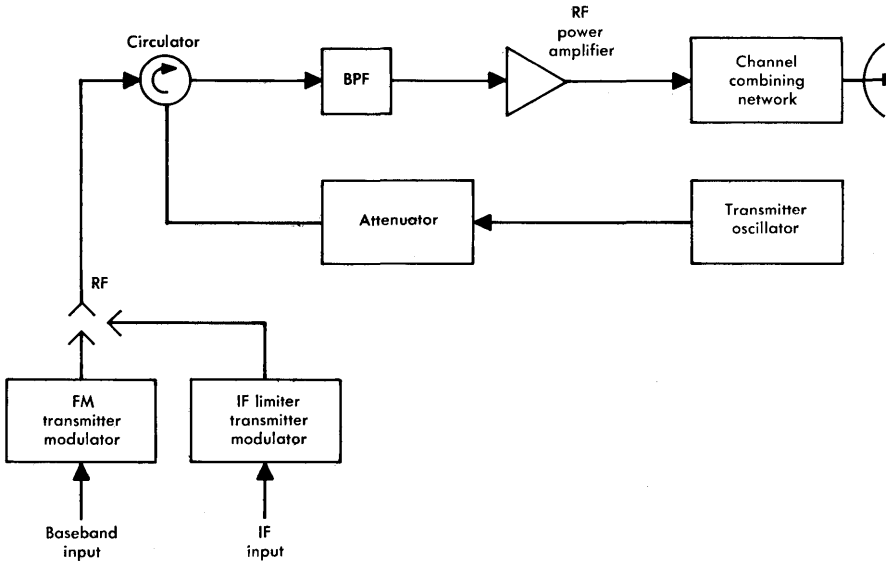


Figure 16-5. Block diagram of TM-2 or TM-2A transmitter.

the circulator to the bandpass filter which removes unwanted sideband components. After amplification in an IMPATT diode amplifier, the signal is combined with other channel signals and transmitted to the next repeater.

The connections between the antenna and the receiver modulator and FM transmitter modulator (including the connections between the circulators and local oscillators) are all made by waveguides. A single parabolic or horn-reflector antenna is used for both transmitting and receiving in one route direction.

In the TM-2 system, the nominal transmitter power output is one watt, +30 dBm. The transmitter may be modified by applying an advanced design of output amplifier to provide 1.6 watts (+32 dBm); this output power is standard for the TM-2A transmitter. The perception loss for these systems is nominally 62 dB. Thus, signals are nominally received in TM-2 at -32 dBm and in TM-2A at -30 dBm. The fade margin for both systems is about 37 dB per repeater hop. Noise in the two systems is about 22 dBm/c0 per repeater hop under normal (nonfaded) conditions. This value applies to a fully loaded

(1200 message channel) unmodified TM-2 system and to a fully loaded (1800 message channel) TM-2A system and a modified TM-2 system.

A number of the protection switching arrangements described in Chapter 15 may be used with the TM-2 and TM-2A systems. Frequency diversity switching is generally used where permitted by the FCC Rules. The 400B Protection Switching System is commonly used. One protection channel may protect up to seven working channels. Space diversity and hot standby switching arrangements may also be used.

### 16-3 THE TN-1 SYSTEM

Designed primarily to provide short-haul microwave radio facilities for local services and as feeder route systems for long-haul backbone routes, the TN-1 system uses standard TL-2 system RF channel assignments. It may provide up to 1800 voice-grade message channels or a broadcast quality black and white or color television circuit over distances up to 250 miles.

Although the TN-1 system is capable of being adapted readily for the transmission of 44.736 Mb/s (3A-RDS) digital signals, only analog applications are covered here. The system operates in the 11-GHz band and utilizes heterodyne repeaters. However, with the addition of a 5A FM terminal, a repeater may be operated as a base-band remodulating repeater. Several types of protection switching systems may be used, the choice depends on the specific application and on local requirements.

In addition to these applications, the TN-1 system may be used to provide protection channels for 4- or 6-GHz systems or an intermix of the two by crossband diversity switching techniques. The system is also used to bridge gaps in 4- or 6-GHz routes where there is heavy frequency congestion and excessive interference at the lower RF bands.

#### Frequency Plans

Several RF channel allocation plans are available for TN-1 analog systems. The *regular plan* provides 12 and the *alternate plan* 11 RF channels, each capable of carrying 1800 message channels. The channel designations, center frequencies, and channel pairings for these plans are shown in Figure 16-6. The frequencies for the two plans are

interleaved but with 1800-channel loading, they cannot be combined because the modulated signal frequencies would overlap. However, if the loading is reduced to 1200 message channels, the two plans can be combined to produce a 23-channel arrangement. The channel center frequencies for this plan are identical to those used in the regular and alternate plans.

REG PLAN, CHAN PAIRS				ALT PLAN, CHAN PAIRS			
CHAN NO.	FREQ (MHz)	CHAN NO.	FREQ (MHz)	CHAN NO.	FREQ (MHz)	CHAN NO.	FREQ (MHz)
1P	10,755	2J	11,685	1E	10,775	1D	11,385
2P	10,955	1J	11,405	2E	10,975	2D	11,665
3P	10,995	4J	11,445	3E	11,015	3D	11,625
4P	10,715	3J	11,645	4E	10,735	4D	11,425
5P	11,155	6J	11,605	5E*	11,175	9D*	11,225
6P	10,875	5J	11,325	6E	10,895	6D	11,585
7P	10,915	8J	11,365	7E	10,935	7D	11,545
8P	11,115	7J	11,565	8E	11,135	8D	11,345
9P	11,075	10J	11,525	9E	11,095	5D	11,305
10P	10,795	9J	11,245	10E	10,815	10D	11,505
11P	10,835	12J	11,285	11E	10,855	11D	11,465
12P	11,035	11J	11,485	12E	11,055	12D	11,265

\*Not normally used

Figure 16-6. RF channel designations, frequencies, and pairings in the TN-1 system.

A recommended pattern of growth (others are possible, depending on objectives) is associated with each of the plans. Specific antenna arrangements must be provided with certain of these plans in order to meet interference objectives. The channels are assigned alphanumeric designations used consistently in all plans applicable to 11-GHz systems. The channels are associated in groups identified by arbitrarily assigned letters D, E, J, and P. Within each group the channels are numbered from 1 to 12.

Although the TN-1 channel designations and frequencies are consistent with other 11-GHz systems, the manner in which they are paired for opposite directions of transmission differs. The TN-1 channel pairings shown in the figure have been selected to achieve the best possible performance with the two-frequency transmission plan made possible by the excellent frequency stability of TN-1 as compared with earlier systems. Note that channels 5E and 9D are

not used because the minimum allowable guard band between transmitters and receivers using the same antenna is 80 MHz. Although the alternate plan can be used alone, it is not normally the first choice because this restriction on channel usage allows only 11 RF channels to be equipped.

Figure 16-7 shows the channel arrangements, polarization pattern, and waveguide interconnections used for the standard frequency plan. This plan can accommodate up to twelve two-way channels with the use of just one antenna for each route direction. Channels that occupy adjacent frequency assignments are transmitted with alternate polarizations in order to achieve the maximum discrimination between channels.

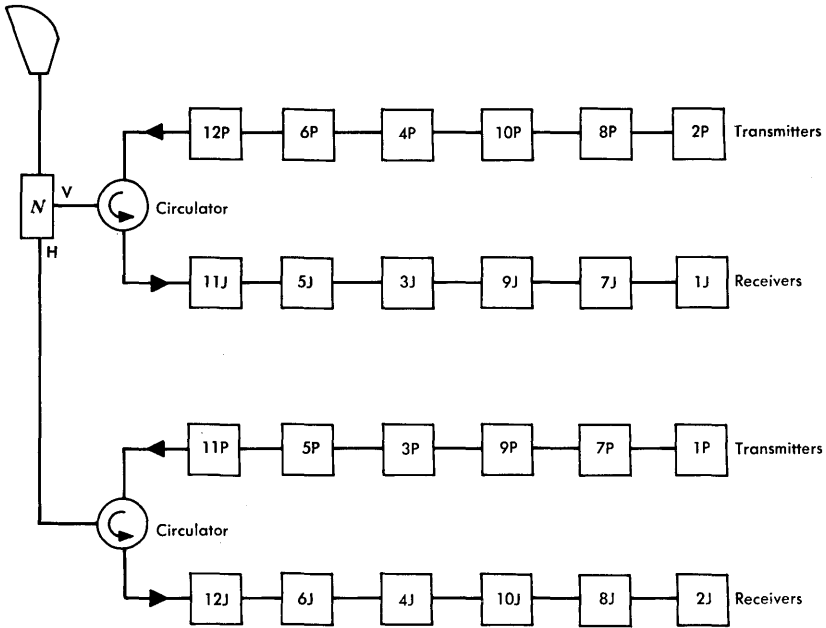


Figure 16-7. TN-1 system, 12-channel arrangement with one antenna.

The single antenna arrangement of Figure 16-7 can only be used with the 12-channel arrangement. In some cases, the performance of a 12-channel system is significantly more reliable if all channel signals are transmitted with the same polarization. This mode of operation, illustrated in Figure 16-8, requires two antennas when more than

six RF channels are equipped. It is especially beneficial where outages caused by rain attenuation are controlling. The channel assignments shown are divided equally between the two antennas and all signals are similarly polarized. Channels in adjacent frequency bands are alternated between the two antennas thus avoiding delay distortion due to adjacent channel bandpass filters. In the presence of rain attenuation, there is an advantage of about 7 dB in fading margin for vertically polarized signals relative to horizontally polarized signals.

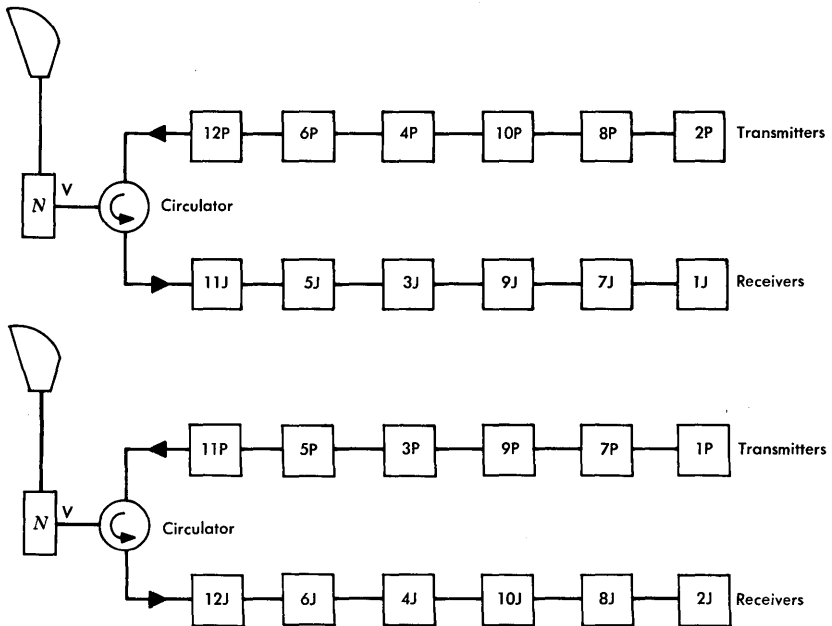


Figure 16-8. TN-1 system, 12-channel arrangement with two antennas.

When TN-1 is to be equipped for 23-channel operation, two antennas must be used for transmission in each direction. Both are used for transmitting and receiving signals. The channel assignments and polarization arrangements are shown in Figure 16-9. The 12-channel plans involve RF channel allocations 40 MHz apart. In the 23-channel plan, the RF channel allocations are only 20 MHz apart. This difference in channel spacing and the greater likelihood of interchannel interference with the closer spacing are the principal reasons for requiring two antennas and separate sets of channel combining networks in the 23-channel plan. In order to separate channels that are

so closely spaced, polarization discrimination and an antenna assignment plan like that described above effectively result in 80 MHz between channels so that channel networks can provide the required selectivity. System combining networks, such as those designated N in Figures 16-7, 16-8, and 16-9, separate 11-GHz from 4- and 6-GHz signals where systems are combined and, in addition, provide for the separation of vertically and horizontally polarized signals where necessary.

The recommended order of channel assignments (growth plan) for each of the frequency plans is illustrated in Figures 16-7, 16-8, and 16-9. In all cases, the recommended sequence of assignment should be read from left to right and from top to bottom of the figures. For example, in the standard plan with one antenna, the channel pairs would be equipped 12P/11J, 6P/5J, . . . 2P/1J. These channels would all be vertically polarized and would be followed by horizontally polarized channels 11P/12J, 5P/6J, . . . 1P/2J. For the 12-channel, 2-antenna arrangement, the same sequence would be followed but with all channels vertically polarized. If the alternate frequency plan with one antenna were to be used (11 channels only), the sequence of assignment would be 12E/12D, 6E/6D, . . . 2E/2D. The channels would all be vertically polarized and would be followed by horizontally polarized channels 11E/11D, 3E/3D, . . . 1E/1D. All would be vertically polarized if two antennas were used. For the 23-channel arrangement of Figure 16-9 the same left-to-right, top-to-bottom sequence would be followed.

Protection channel assignments are recommended according to a pattern consistent with the above growth plans. For  $1 \times n$  switching arrangements, channels 6P and 5J or 6E and 6D are recommended as protection channels. One of these is also used for  $2 \times n$  switching arrangements and, in addition, channel pair 8P/7J or 8E/8D may be used. In any case, where  $2 \times n$  switching is used, the protection channels should be separated by at least 160 MHz.

### Equipment Layouts

The TN-1 circuits and equipment are designed with great flexibility so that the system can satisfy the wide range of applications for which it is intended. Repeaters are normally operated as heterodyne repeaters; however, in combination with a 5A FM terminal, they may also be used as remodulating (baseband) repeaters or to furnish separate transmitting and receiving facilities at terminal points.

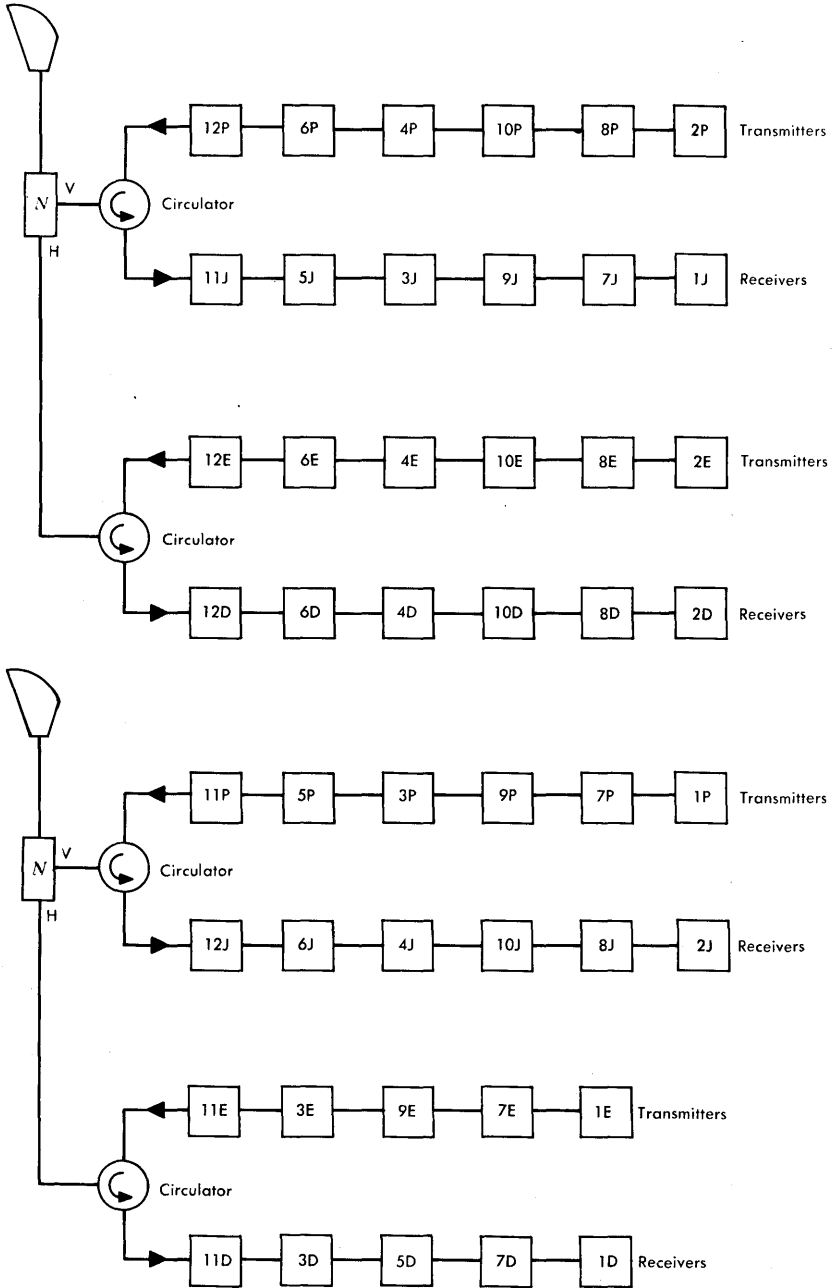


Figure 16-9. TN-1 system arrangement for two antennas and 23 channels.

A number of different protection switching arrangements may be used with the TN-1 system. These include the 100A, 200A, 400A, 400B, and 401B frequency diversity systems and, in addition, space diversity and hot standby arrangements. In most cases, the switching equipment and transmission equipment are intimately related and exert mutual influence on equipment layouts at repeater and terminal points.

The basic transmission unit in TN-1 is a transmitter-receiver (T/R) panel that may be directly interconnected, as shown in Figure 16-10, to form a heterodyne repeater or may be split electrically between the transmitter and receiver for use as a terminal or as parts of a baseband repeater. The panel employs all solid-state electronic components, including an IMPATT diode power amplifier.

The local oscillators for transmitter and receiver are independent and identical except for frequency. The stability-determining portion of the unit is a crystal-controlled transistor oscillator operating at approximately 100 MHz. It phase locks a cavity oscillator operating at approximately 1.4 GHz. The frequency of the cavity oscillator is then multiplied eight times in a diode multiplier. The local oscillator signal is injected in the receiver by use of a directional coupler. A waveguide circulator is used in the transmitter.

The power amplifier in the transmitter makes use of three IMPATT diodes to amplify the microwave signal. It provides an output power of about 3.0 watts to the channel combining filter. The amplifier has its own power supply consisting of an inverter, a rectifier-filter unit, and three current regulators (one for each stage of the amplifier). A control circuit automatically shuts down the amplifier power supply under various trouble conditions.

The receiver channel separating filter and the transmitter channel combining filter are directional filters employing complementary band-rejection and bandpass sections. An additional bandpass filter follows the transmitter modulator and rejects the image signal and other unwanted products from the modulator.

The receiver modulator uses a Schottky barrier diode and, along with the preamplifier, achieves a very low noise figure. The transmitter modulator is driven by a high-level IF limiter-driver amplifier which removes the amplitude modulation from the signal to prevent AM/FM conversion and makes the transmitter output insensitive to input amplitude changes. Two test access ports are provided on the



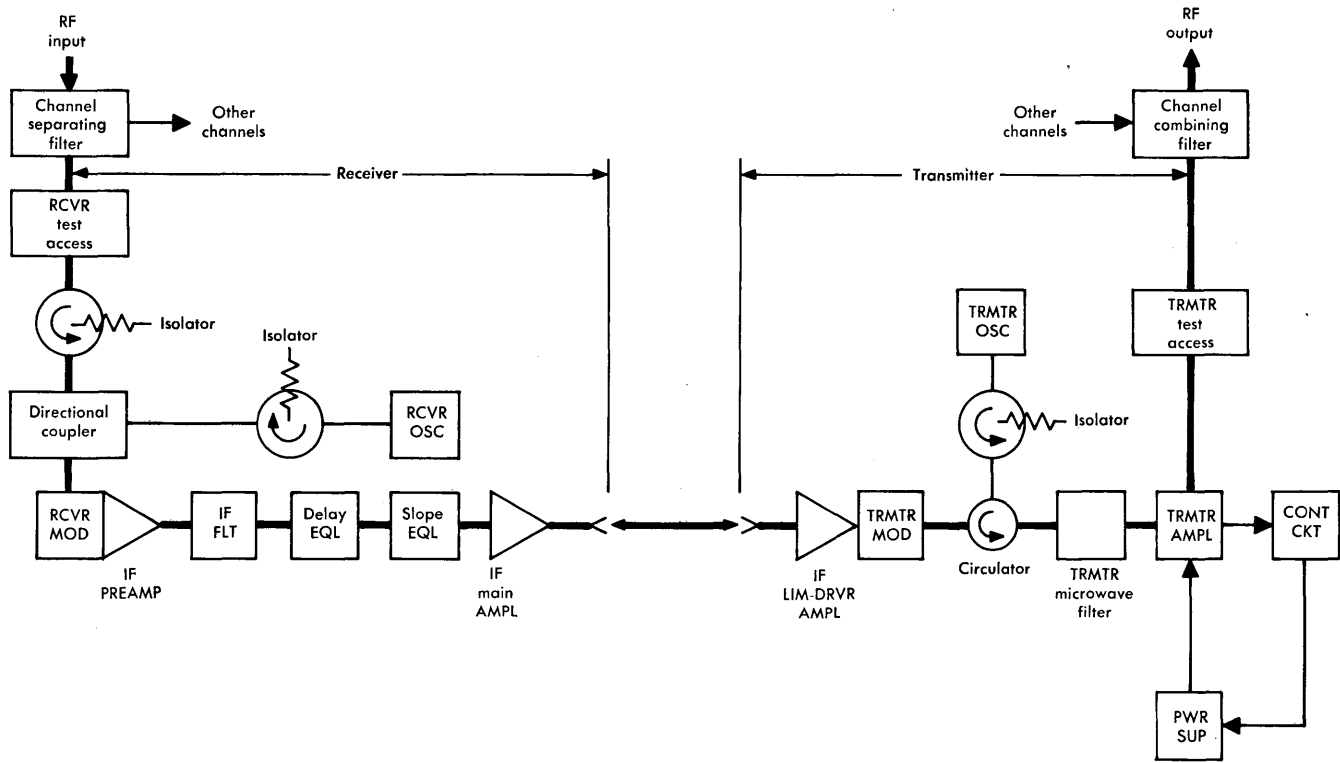


Figure 16-10. Heterodyne arrangement for TN-1 transmitter-receiver.

T/R panel. These devices behave like a section of waveguide in their normal condition. However, insertion of a short-circuiting plate and a coaxial probe converts the unit to a waveguide-to-coaxial transducer. Thus, disassembly of waveguide is unnecessary for normal maintenance. The receiver test access is located after the channel separating filter. The short-circuiting plate may be placed on either side of the probe, allowing the user either to measure received signals or to inject a test signal to the receiver. The transmitter test access follows the transmitter amplifier and provides easy measurement of output power and frequency.

The IF portion of the receiver is very similar to those used in long-haul radio systems. The IF main amplifier, automatic gain control, and carrier resupply are in a single unit.

For hot standby-space diversity switching applications, T/R panels are arranged in pairs (regular and standby) in adjacent bays. The transmitter RF switch is located on the regular panel and the receiver IF switch and hybrid or the baseband switch are located on the standby panel. In both regular and standby transmitters, the transmitter test access is replaced by waveguide-to-coaxial transducers; semi-rigid coaxial cable connects the transducers to a coaxial-type RF switch. The terminated port of the RF switch employs a coaxial pad on the front of the regular panel. This provides both a termination and a convenient test point for the nonworking transmitter.

### Transmission Performance

The TN-1 system meets a noise objective of 35 dBrc0 for a message channel 250 miles long provided there is sufficient signal power at each receiver. For typical loss values, including a 61.5-dB path loss, the received signal power is nominally  $-30.5$  dBm at the receiver test access port when the transmitted signal is 3.5 watts ( $+35.5$  dBm). A received signal amplitude greater than  $-12.5$  dBm would cause excessive noise due to overload in the IF preamplifier of the receiver. With a very short repeater spacing, such an overload condition may exist and the transmitter output or receiver input must be reduced by an RF pad. With signals transmitted at the nominal powers described above, the system operates with a fade margin of about 40 dB which varies with the actual received signal power.

Other performance factors make TN-1 suitable for the applications for which it is designed and for meeting the requirements of the FCC

Rules. For example, the 5A FM terminal and the TN-1 transmitter oscillators are each stable to within  $\pm 0.001$  percent of nominal frequencies over a temperature range of 40 to 120 degrees Fahrenheit. In addition, all single-frequency tones are held to  $-68$  dBm0 or less in any message circuit and envelope delay distortion is controlled in order to limit the generation of intermodulation noise to tolerable values. Differential phase and gain changes meet objectives established for the transmission of color television signals.

### The 5A FM Terminal

Two versions of 5A FM terminal equipment have been developed specifically for use with the TN-1 system. They are both small, inexpensive, solid-state, combined transmitter/receiver units that translate signals between 70-MHz IF bands and baseband frequencies. These versions are called a *modem* and a *deviation shifter*.

The modem is used in baseband remodulating repeater applications to perform the straightforward function of modulation and demodulation between baseband and intermediate frequencies. A feature of this modem design is a carrier spreading circuit that can be activated when voice-grade message signals are transmitted. The circuit supplies a random noise signal in the band from 0 to 1 kHz that is used to deviate the FM carrier at a high modulation index. This carrier deviation spreads the beat frequency of interfering IF- and RF-generated baseband tones over several speech channels and produces a random noise-like interference that is significantly less annoying than tone interference.

The deviation shifter may be used in applications of the TN-1 system where IF interconnection with TD- or TH-type radio systems is required. It is used, for example, at the transmitting end of a TN-1 multirepeater section to increase the FM deviation from the value normally used in the 4- or 6-GHz system to that used in an 11-GHz system. The increased deviation is possible because of the wider RF channel width at 11 GHz. The benefits of the increased deviation are an improvement of the fade margin in the TN-1 system and a reduction of thermal noise. Another deviation shifter must be used to reduce the deviation wherever the signal is to be passed on to a 4- or 6-GHz system. Such arrangements are also used when TN-1 provides a frequency-diversity protection channel for a 4- or 6-GHz system or when it serves as a last-hop connecting link between a 4- or 6-GHz system and a ground station for satellite communications.

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3. Friis, R. W., J. J. Jansen, R. M. Jensen, and H. T. King. "The TM-1/TL-2 Short Haul Microwave Systems," *Bell System Tech. J.*, Vol. 45 (Jan. 1966), pp. 1-95.

## Chapter 17

# Long-Haul Systems

Although the distinction between short-haul and long-haul microwave radio systems is tending to disappear in application, a number of systems have been designed specifically to meet the requirements of 4000-mile transmission. Repeaters for these systems have been designed to satisfy the signal-to-noise objectives established for long network trunks; system layouts have been selected to favor the need for dropping and adding circuits along the route and simultaneously to satisfy reliability criteria by the inclusion of multirepeater protection switching section arrangements.

The first system developed for long-haul transmission was the 4-GHz TD-2. From the time of its introduction in 1950, the performance of this system has been improved steadily and, as improvements were introduced, the message channel capacity has been increased significantly. Initially, each 20-MHz RF channel could accommodate only 480 two-way message channels and the system utilized only six two-way RF channels. Now, there are 12 two-way RF channels and each channel can accommodate 1500 two-way message channels.

Advances in technology, such as solid-state circuit designs, led to the development of the TD-3 system in the early 1960s which, in turn, led to improvements in TD-2 systems. With the exception of a traveling-wave tube output amplifier, the circuits in the TD-3 system utilize solid-state devices throughout. The system is similar to TD-2 in many respects and compatible with it in operation. Modern repeaters, designated, TD-3D, combine TD-2 and TD-3 circuits to provide the most economical use of the 4-GHz band.

Two TH-type systems have been developed for use in the 6-GHz band. The TH-3, the more modern of these, utilizes solid-state technology with the exception of a traveling-wave tube output amplifier. Both systems can accommodate 1800 two-way message channels in each of eight two-way, 30-MHz RF channels. The earlier system, now called TH-1, is similar to TH-3 in many respects but the differences are sufficiently great that the two systems are described separately.

Microwave radio systems are designed to meet noise objectives expressed in terms of the noisiest message channel during the busy hour. The objective used for the design of the TD-2 system was 44 dBrnc0 for a 4000-mile network trunk. For TH-1, the noise objective was 45 dBrnc0 and for the more modern TD-3 and TH-3 systems, 41 dBrnc0. Single-frequency tone interference in TD-3 and TH-3 is not to exceed  $-68$  dBm0 in any voice channel of a 4000-mile system during nonfaded conditions. Performance improvements in TD-2 have been used to increase the load capacity. The system is still engineered to a 44 dBrnc0, 4000-mile objective.

The use of the horn-reflector antenna is among the improvements that made possible the increased message capacity and better performance of long-haul systems. It permits the simultaneous transmission of vertically and horizontally polarized signals in adjacent RF channels, has greater directivity (a sharper beam with low-amplitude side lobes) than earlier designs, and provides better return loss and higher gain. These features are all superior to earlier antenna designs. In addition, it should be noted that the horn-reflector can transmit an extremely broad band of frequencies. It is presently being used at 2-, 4-, 6-, and 11-GHz and has been shown to be satisfactory at 30 GHz [1]. Waveguide connections must be appropriate to the frequency band or bands being transmitted.

## 17-1 THE TD-TYPE SYSTEMS

A majority of long-haul message network trunks are carried by TD-type systems. While these systems are of various vintages, they may be equipped to provide 600, 900, 1200, or 1500 message channels; however, most existing systems are equipped for 1200 or 1500 channel loading. Some systems may not have been modified with upgraded circuits and devices but are suitable for existing light-load conditions.

Most TD-2 systems that have been installed are still in operation although the system is no longer manufactured. As a result of improvements, TD-2 is now very similar to TD-3. As previously mentioned, designs have been combined to provide the most economical repeater, called TD-3D, the only type now being manufactured.

The frequency plans, overall system layout, and repeater spacing are identical in TD-2 and TD-3 systems. An intermediate frequency band extending from 60 to 80 MHz is used for both systems and both use heterodyne repeaters [2, 3].

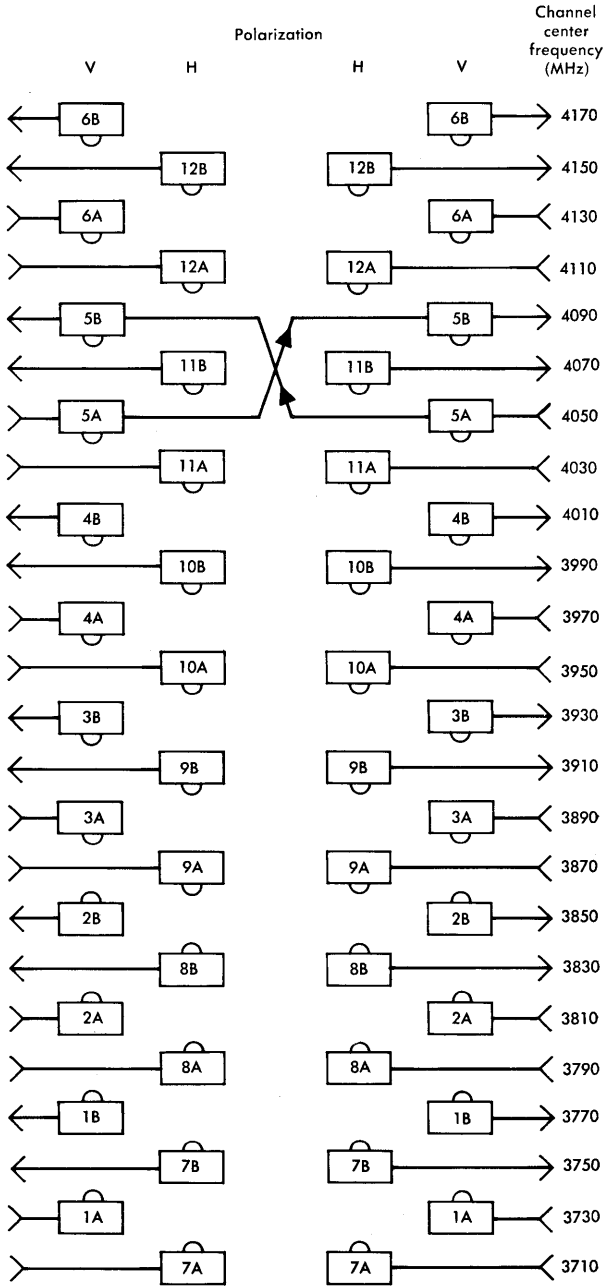
### Frequency Plan

It has been found convenient to divide the 500-MHz band extending from 3.7 to 4.2 GHz into 25 RF channels each 20 MHz wide. In order to provide adequate isolation between the transmitted and received signals, each radio path (or hop) is usually provided with separate transmitting and receiving antennas at each end. The 20-MHz RF channels are allocated in such a manner that two adjacent channels are used for transmitting and the next two adjacent channels are used for receiving. The adjacent channel signals in each pair are transmitted with crossed polarizations. Thus, the channel separating function at a receiver is made somewhat easier because of the cross polarization of signals within each channel pair, which are separated by 20 MHz, and because of the 80-MHz separation between signals of the same polarization [4].

This frequency plan, as applied at a TD-2 or TD-3 repeater, is illustrated in Figure 17-1. Two-way RF channels are numbered 1 to 12. The two frequency bands used for each channel are designated A and B with A always assigned to the lower frequency channel. At adjacent repeaters, transmitter and receiver assignments are interchanged. The frequencies shown at the right of the figure are the center frequencies of the RF channels.

The 25th RF channel assignment, not shown in Figure 17-1, is centered at 4190 MHz. Although this channel is sometimes used for one-way television transmission over single repeater hops, it is widely used for two-way order-wire and alarm transmission. In the latter case, two narrow-band channels, numbered 13A and 13B, are provided at center frequencies of 4190 and 4198 MHz [5].

While the frequency plan of Figure 17-1 is the most efficient and most commonly used, some variations are used where such high



Notes:  
 (1) indicates local oscillator 70 MHz below channel frequency; 70 MHz above channel frequency.  
 (2) In some TD-3 equipment of early vintage, the local oscillator frequency is 70 MHz above the channel frequencies for channels 3 and 9.

Figure 17-1. Frequency plan for TD-type systems (low/high repeater).



efficiency is not required. In some cases, for example, only six channels are provided with all signals similarly polarized. These variations are recommended for use only under unusual circumstances. The four-frequency plan, described in Chapter 16 in connection with short-haul, light-route applications, is not used on long-haul backbone routes. Occasionally on very lightly loaded routes, a single antenna may be used for both transmitting and receiving.

### System Layout

Figure 17-2 is a block diagram of a typical switching section consisting of nine or fewer intermediate repeater stations of a TD-2 or TD-3 radio system. The radio transmitters, receivers, and transmission paths are normally provided with protection switching arrangements such as those described in Chapter 15. The TDAS system may be used with TD-2; the 100A or 400A switching system may be used with either TD-2 or TD-3.

When the route is shared with other systems operating at 6- or 11-GHz, *system networks* must be used to combine or separate the 4-, 6-, and/or 11-GHz signals and to separate the vertically and horizontally polarized signals. These networks feed circular waveguide that carries the signals to or from the antennas. The 4-GHz RF channels are connected to the system networks through *channel combining* and *separating networks*. These are waveguide networks that provide the bandpass and attenuation characteristics to permit combining, in a single rectangular waveguide, all of the vertically or horizontally polarized transmitting or receiving channel signals in the 4-GHz band.

Where required for circuit administration, the system layout may include FM terminals, wire-line entrance links, and terminal switching arrangements as illustrated in Figure 17-2. These system components are often equipped with separate protection switching arrangements.

One or more RF channels may be equipped to transmit television video signals. In such cases, television dropping may be required at intermediate repeater points and additional protection switching arrangements may be provided at those points.

The repeater spacings for TD-type systems are established by transmission line-of-sight requirements, signal-to-noise considerations, and fade margins required in order to meet reliability objectives. The

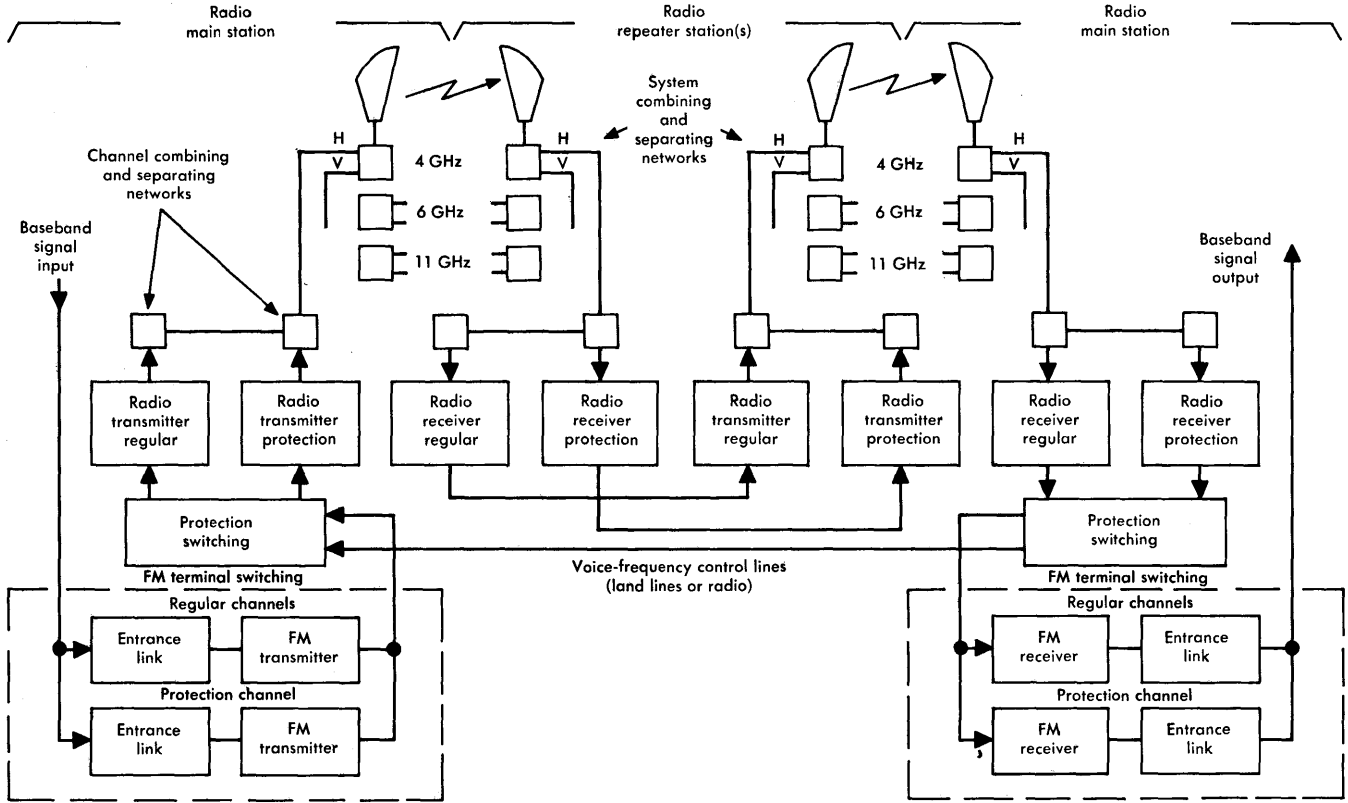


Figure 17-2. Typical TD-type system layout for one direction of transmission in one switching section.

distances between repeaters, together with antenna, waveguide, and channel network gains and losses, are engineered so that section losses between transmitters and receivers are normally about 63 dB. The TD-3 transmitter operates at 5 watts (+37 dBm) output and thus the received signal power is nominally -26 dBm. Initially, the TD-2 system operated with only 0.5 watt (+27 dBm) output resulting in a received signal power of about -36 dBm; thus, a limit was imposed on the number of message channels that could be carried. The transmitter may now be operated at an output of 1 watt, 2 watts, or 5 watts to meet requirements that depend on the type of signal (TV or message), message loading, and path length.

### Repeaters

The TD-type systems utilize heterodyne repeaters with a standard intermediate frequency band centered at 70 MHz. Radio receiving and transmitting equipment for one two-way channel (e.g., 1A and 1B) is mounted in a single transmitter/receiver bay. Where the equipment is used at an intermediate (auxiliary) repeater station, this bay serves one direction of transmission through the station. Where it is used at a main station, at which the protection switching section terminates, the receiver and transmitter are used for the two directions of transmission associated with one route direction [2, 6]. These arrangements are illustrated in Figure 17-3.

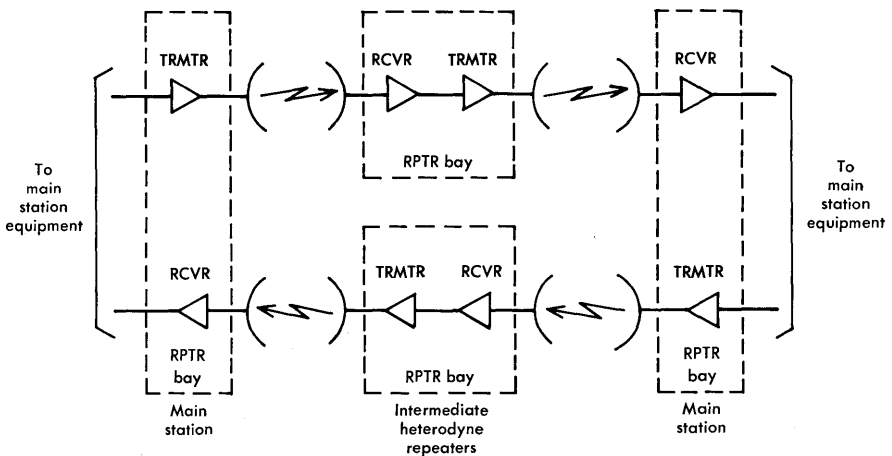


Figure 17-3. Typical long-haul system transmitter/receiver equipment arrangements.

**The TD-3 Repeater.** Figure 17-4 is a block diagram of the receiver portion of a TD-3 repeater. Incoming signals of one polarization in the 4-GHz band are delivered to the receiver where the channel separating network selects the desired channel signal. The channel filter provides additional selectivity to reduce interference from adjacent channels. The directional filter provides the means of combining the RF signal and the local oscillator signal for delivery to the receiver modulator where it is translated to the 70 MHz IF band. The isolator located between the directional filter and the channel filter prevents undesirable signal reflections due to impedance interaction between the filters and, in addition, absorbs many of the unwanted RF products generated in the modulator.

Note in Figure 17-1 that each channel signal is normally shifted by 40 MHz as it passes through a repeater. The microwave generator, isolator, and power splitter in Figure 17-4 deliver an RF carrier to the 40-MHz oscillator-shift modulator which produces a local oscillator signal frequency appropriate to the channel of interest. The generator, isolator, and splitter are shared by the radio receiver and transmitter at intermediate repeaters. At main stations, separate microwave generators are used to supply the required local oscillator signals to the receiver and transmitter. The bandpass filters and isolator that follow the 40-MHz oscillator-shift modulator select the required upper or lower sideband output signal. A number of stages of IF amplification, filtering, equalizing, and automatic gain control circuits follow the receiver modulator and process the signal for transmission to the radio transmitter (at an intermediate repeater) or to terminal circuits at a main station.

The transmitter portion of a TD-3 repeater is shown in Figure 17-5. The signal to be transmitted is connected at IF from the radio receiver at an intermediate repeater or from terminal circuits at a main station repeater. The transmitter output is normally +37 dBm at the desired channel frequency in the 4-GHz band.

The IF limiter removes unwanted amplitude modulation from the input signal. It also furnishes an IF control signal to the IF carrier resupply circuit which generates a baseband tone-modulated carrier in the event of normal IF signal loss. Under these conditions, the carrier resupply circuit also provides a dc bias signal to the limiter that introduces high insertion loss so that noise at the input is attenuated during the period the incoming carrier is absent. The resupplied carrier operates automatic gain control (AGC) circuits at

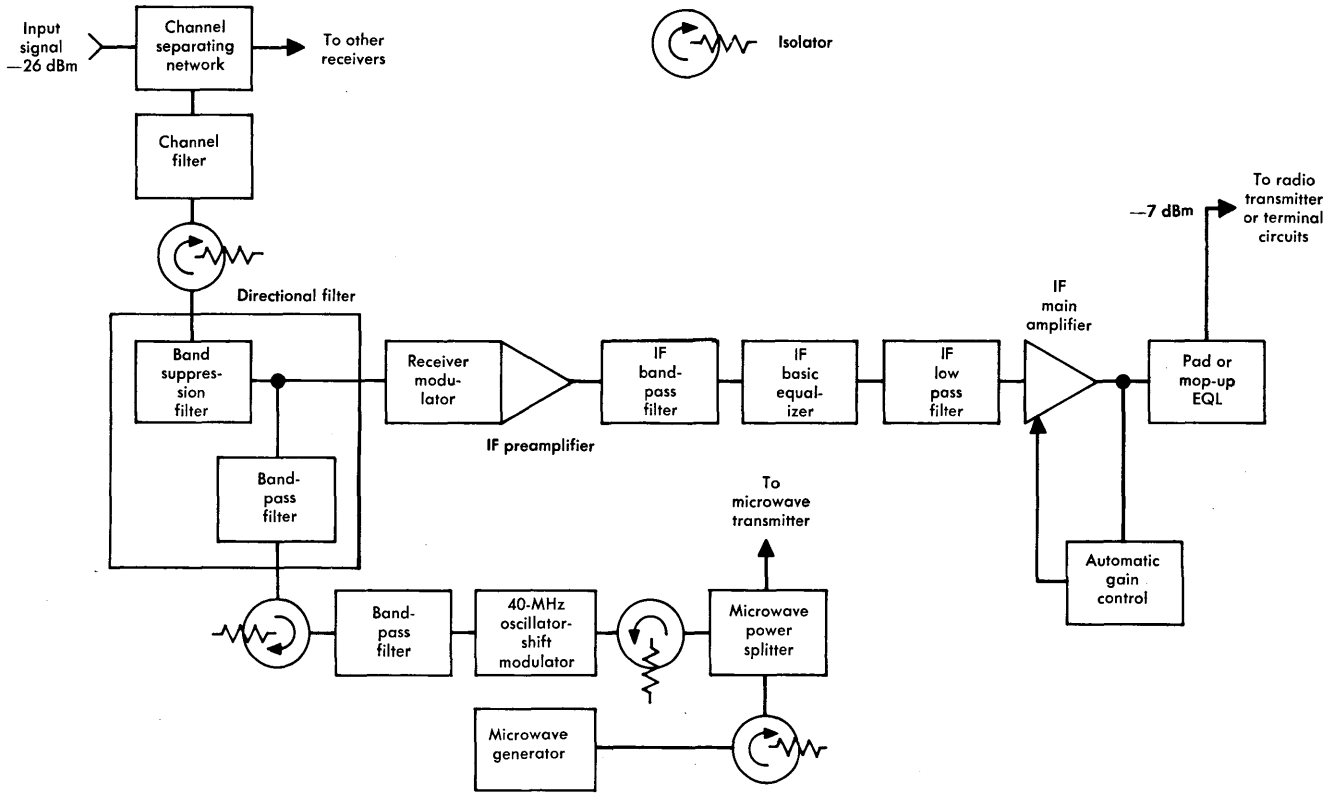


Figure 17-4. Microwave receiver for TD-3 repeater.



subsequent repeaters and thus prevents IF amplifiers from rising to full gain and limiters from band spreading high-amplitude noise signals. The tone modulation on the resupplied carrier is used to initiate the protection switching system.

The IF driver amplifier and transmitter modulator convert the 70-MHz signal to an upper or lower sideband microwave signal in the appropriate channel frequency band by means of a local oscillator signal supplied by the microwave generator. The sideband to be transmitted is selected by the bandpass filter. The unwanted sideband is reflected by the filter and dissipated in the reverse loss of the isolator located between the modulator and the filter. The filter also attenuates the local oscillator leakage signal that appears at the modulator output [7]. By using relatively low selectivity in the sideband selecting filter, inband amplitude and delay distortion in the wanted sideband is kept small, thereby making negligible any cross-modulation noise that might be generated in the traveling wave tube.

The traveling wave tube amplifier produces a signal output power of +37 dBm and a transmission characteristic flat to within  $\pm 0.02$  dB over the channel bandwidth. The low-pass filter following the amplifier suppresses second and third harmonics of the RF carrier by at least 50 dB.

Isolators, tuners, attenuators, and filters are used in the transmitting path. These circuits improve return loss and transmission, adjust signal amplitudes, and provide the necessary selectivity so that other channel and system signals may be combined for application to the common transmitting (circular) waveguide and antenna. Monitoring, control, and alarm circuits are provided at strategic points in the receiver and transmitter. Specially designed power supplies and voltage regulators are used where required.

**The TD-3D Repeater.** While the performance of the TD-3 system has proven to be at least as good as that of the TD-2 system, the initial cost of TD-3 was significantly higher. Relative costs were further affected to the disadvantage of the TD-3 system by the increased capacity of the TD-2 system that resulted from the performance improvements introduced concurrently with the development of TD-3. A more economical version of the TD-3 repeater, designated TD-3A, was introduced as a result of recognizing these cost-performance relationships. Further design effort then led to the introduction of a still more economical repeater, the TD-3D. Although this version of the TD-3

repeater is the only one now being manufactured, most of the TD-3 and TD-3A repeaters produced are still in service.

The TD-3D repeater (as well as the TD-3A) is similar to the TD-3 in terms of functional relationships. The receiver and transmitter portions are shown in Figures 17-6 and 17-7 respectively; the similarity of these units to the corresponding units of TD-3, shown in Figures 17-4 and 17-5, is quite apparent. As shown in Figure 17-7, the TD-3D utilizes a microwave integrated circuit for local oscillator signal distribution. This integrated circuit replaces individual isolators, monitors, attenuators, and other waveguide components used for this purpose in the TD-3 repeater. In addition, the receiver and transmitter IF circuits have been simplified. The three-stage triode electron tube amplifier was substituted for the traveling wave tube amplifier and associated high-voltage power supply used in the TD-3 repeater. Thus, the TD-3D design is a combination of the technologies used in TD-2 and TD-3 adapted to yield an economical repeater capable of meeting the more stringent noise objectives of the TD-3 system.

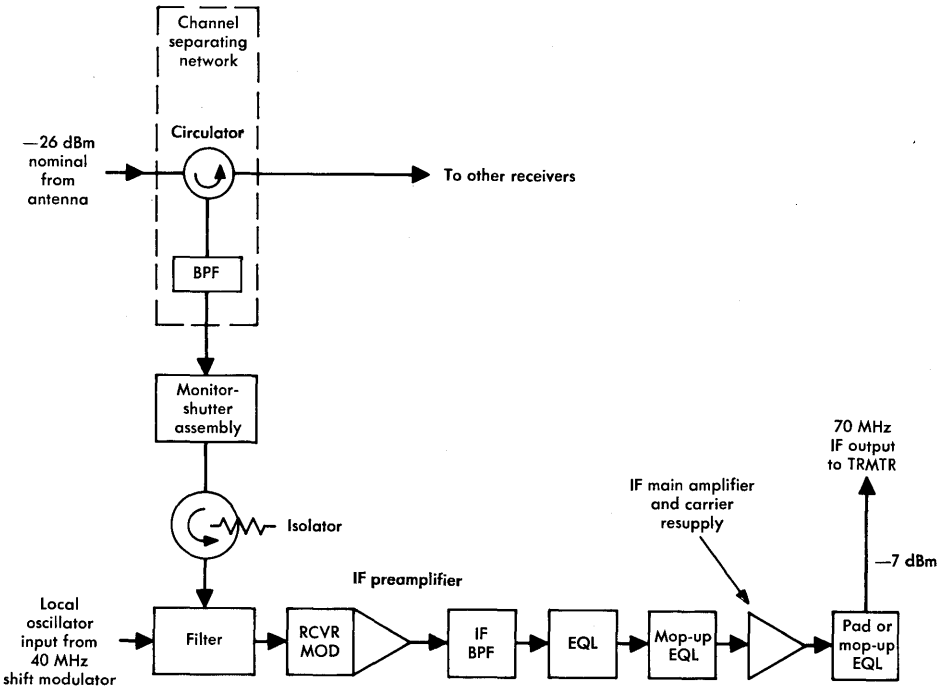


Figure 17-6. Microwave receiver for TD-3D receiver.



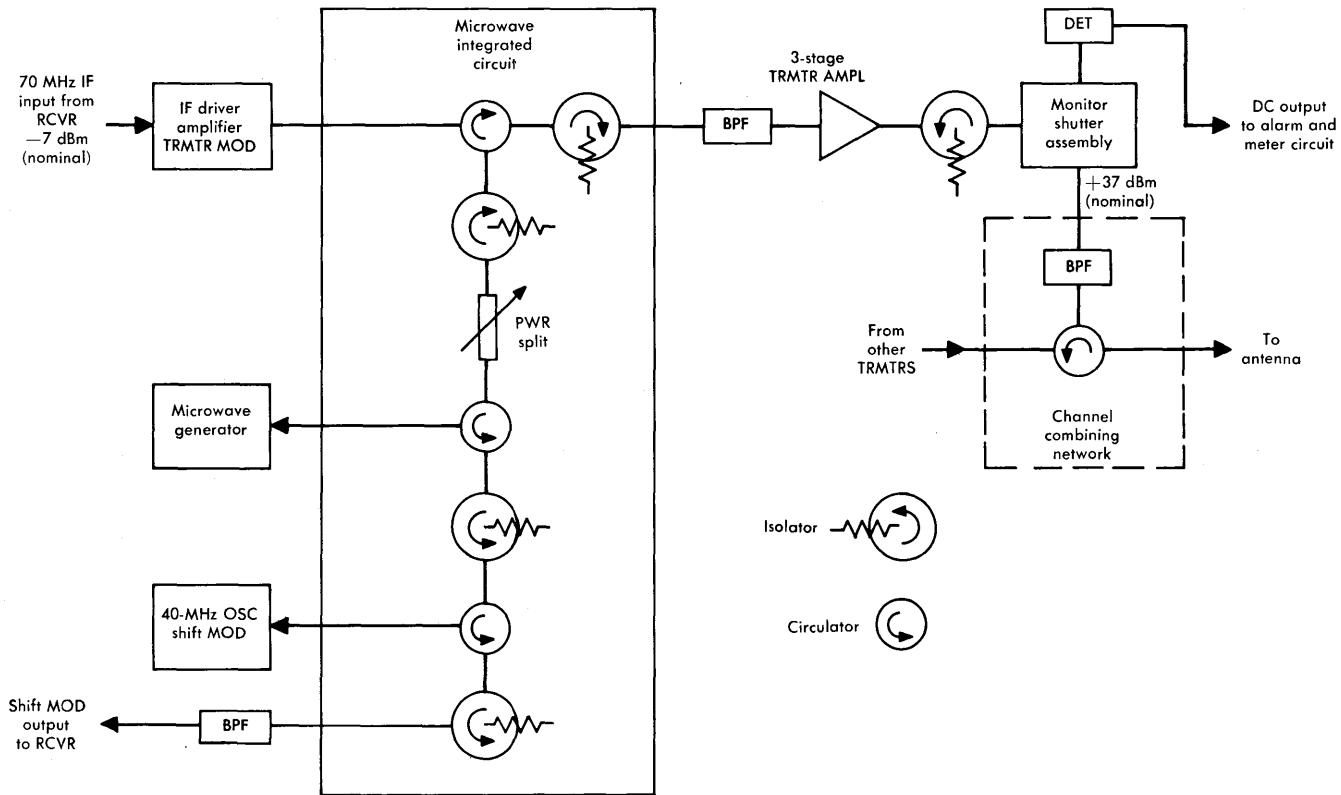


Figure 17-7. Microwave transmitter for TD-3D repeater.

The TD-2 Repeater. Figure 17-8 is a block diagram of a TD-2 intermediate repeater, a design which initially used only electron tube circuits. Many units have been replaced by solid-state equipment but some circuits, such as the transmitting modulator and the transmitting amplifier, still use electron tubes [8].

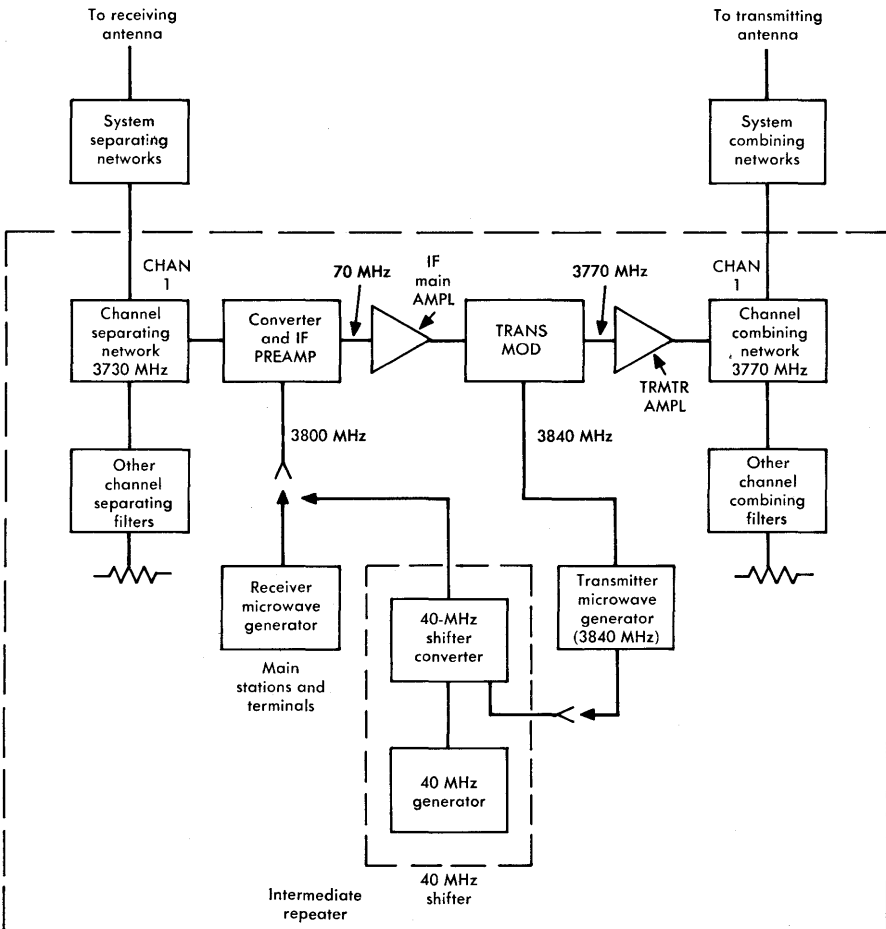


Figure 17-8. Intermediate TD-2 repeater.

The block diagram, applicable in many respects to TD-3 and TD-3D as well as TD-2, shows the frequencies of Channel 1 to illustrate circuit relationships. The received signal, centered in the RF channel at

3730 MHz, is transmitted through system and channel separating networks to the converter and IF preamplifier. A 3800-MHz local oscillator signal translates the signal to the 70-MHz IF band. At an intermediate repeater, the signal is amplified and applied to the transmitter modulator; at a main station, it is transmitted to an FM terminal receiver for demodulation to baseband.

The signal is translated back to the RF band in the transmitter modulator. It is amplified in a three-stage amplifier to an output power of 1, 2, or 5 watts depending on the application. Triode-type electron tubes are used in both the modulator and the transmitter amplifier.

At intermediate repeaters, a common microwave generator is used for receiver RF-to-IF conversion and for transmitter IF-to-RF conversion. In the example of Figure 17-8, the microwave generator frequency of 3840 MHz is used directly in the transmitter but is shifted by 40 MHz to 3800 MHz for use in the receiver. Thus, Channel 1 is transmitted at 3770 MHz, 40 MHz above the received channel frequency. At main stations and repeaters requiring special frequency plan arrangements, separate microwave generators are used for the receiving and transmitting equipment.

After conversion to the desired RF band, the transmitted signal is amplified and combined with other channel and system signals. These are then carried through common waveguide sections to the transmitting antenna.

## 17-2 THE TH-3 SYSTEM

Long-haul capacity in the 4-GHz band may be supplemented by systems operating in the 6-GHz band where the RF channel allocations lie between 5.925 GHz and 6.425 GHz. The most modern system operating in this band, the TH-3, was developed at a time when the majority of operating systems were of the 4-GHz TD-2 type. In many locations, 6-GHz systems are most economical where they can be added to existing 4-GHz routes by overbuilding. In such arrangements, antennas, waveguide connections, buildings, land, and power plants are shared. Thus, the TH-3 system is compatible in as many ways as possible with the TD-type systems [9].

While the principal use of TH-3 has been to provide long-haul services, it may be operated economically over distances in the range of

25 to 1000 miles with the same repeater equipment as that used in long-haul applications. Economy is achieved by the use of less expensive protection switching and maintenance equipment and by adaptation to small equipment shelters rather than the usual repeater station buildings [10].

### System Considerations

With the development of the TH-3 system evolved the system message channel capacity (1800 circuits), the establishment and allocation of signal-to-noise objectives, and the adaptation of existing frequency plans in the 6-GHz band. Each of these problems had to be solved within the context of compatibility with existing 4- and 6-GHz systems.

**Channel Objectives.** Each RF channel in the TH-3 system is designed to carry a baseband signal up to 10 MHz wide. This broad band is suitable for the transmission of a high-definition television video signal or 1800 voice-grade signals typical of those received from L-multiplex equipment. Studies are being made to determine the feasibility of providing a baseband width that can accommodate more than 1800 message channels.

The design objectives for the baseband response are that the attenuation/frequency characteristics in a switching section should be flat to within  $\pm 0.25$  dB from 5 kHz to 8.5 MHz for each radio channel and that there should be no more than 30 degrees phase difference at baseband between the radio channels in a switching section. The latter objective, established to prevent hits on data signals and disturbance to television signals when the protection switching system operates, requires that the absolute delay of all radio channels in a switching section be equal to within ten nanoseconds. This phase equalization objective is difficult to meet economically in TH-3 as well as in other systems for which it has been considered.

**Frequency Plans.** Sixteen RF channels, each 29.65 MHz wide, are developed in the standard 6-GHz frequency plan used by the TH-3 system. These are normally used as eight two-way channels one of which is usually assigned as a protection channel in a 1 x 7 switching arrangement.\* The TH-3 channels are numbered from 11 through

\*Where TH-3 is used in combination with a 4-GHz system, two TH-3 channels may be assigned to protection in a crossband diversity arrangement.

18 and 20 through 28. A *regular* set of frequencies is generally used (designated T) and a *staggered* plan is also available (designated S). The channels are usually identified by a "shorthand" notation such as 8T or 6S; 8T identifies a regular channel received in position 18 and transmitted in position 28 or vice versa. Similarly, 6S identifies a channel in the staggered frequency plan received in position 16 and transmitted in position 26 or vice versa. A two-frequency plan is used at intermediate repeaters; signals received on a channel in the lower portion of the RF band are transmitted in the upper portion of the RF band and vice versa.

The channel frequencies for the two plans are given in Figure 17-9. The figure also illustrates the channel interconnection through the repeater and shows the manner in which channels are assigned for horizontally and vertically polarized signals. The microwave carrier frequencies in TH-3 are all 70 MHz below the RF channel frequencies.

The regular plan of channel assignments coordinates with the plan used for the predecessor TH-1 system and with other users of the 6-GHz common carrier band. However, auxiliary channels, used in TH-1 for the transmission of order-wire, switching, and alarm signals, are not normally provided in TH-3.

The staggered frequency plan has the disadvantage that channel 28S cannot be used for normal video or message service because of insufficient bandwidth in the 6-GHz common carrier band. Thus, a route can be equipped with only seven staggered two-way RF channels. Channel 18S or 20S may be substituted for any other staggered plan channel in isolated hops where interference problems exist. However, these channels can never be used simultaneously.

The standard growth sequence for regular channels is 4T, 8T, 2T, 6T, 3T, 7T, 1T, and 5T, the same sequence as that used for TH-1. It is the reverse of that used for TM-type systems and, as a result, conflicts with short-haul systems are most likely to be postponed. Channels 8T and/or 1T are normally assigned as protection channels. For the staggered plan, the normal growth sequence is 1S, 5S, 3S, 7S, 2S, 6S, and 4S. The even-numbered channels are equipped last because channel 8S cannot be used as a two-way channel.

The staggered plan channel frequency assignments are offset from those of the regular plan by 14.82 MHz, one-half the bandwidth of an RF channel. A third plan is also available for use where interference problems cannot otherwise be solved. It is called the *split* plan.

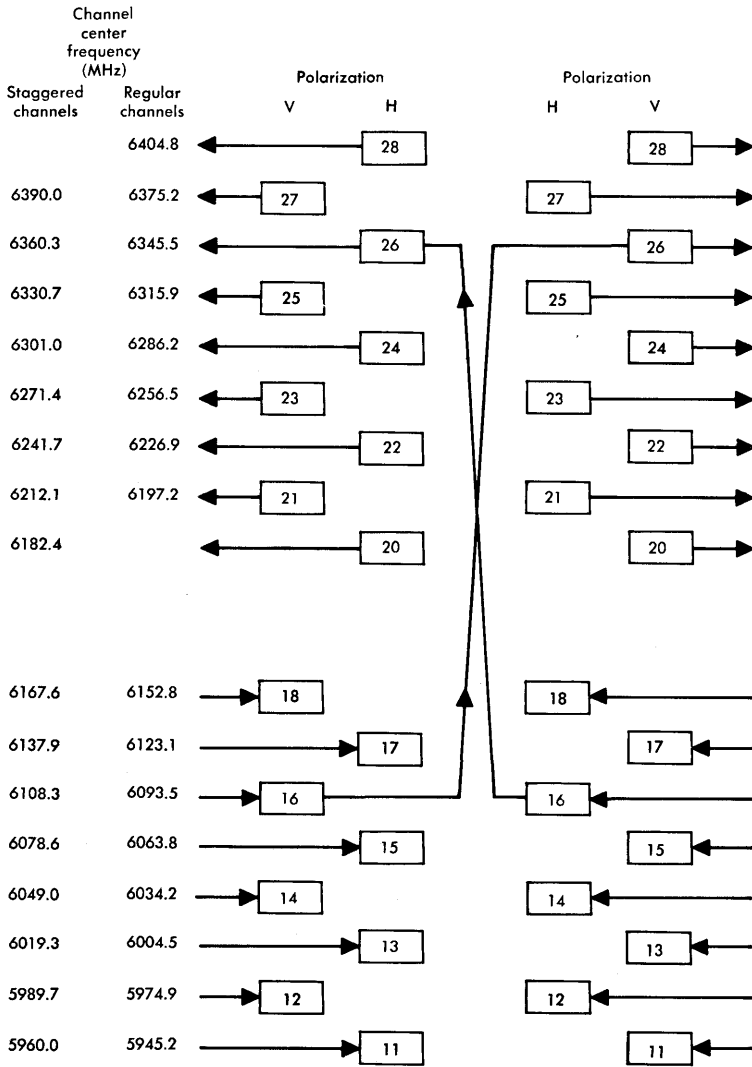


Figure 17-9. TH-3 regular and staggered frequency assignments (low-high station).

The channel frequency assignments are offset by a nominal 7.5 MHz above or below the regular plan channels. These assignments were developed for short-haul systems using four-frequency plans.

The TH-3 system is usually operated with two separate antennas, one for transmitting and one for receiving. However, on lightly loaded routes, the system can be operated with one of the standard two-frequency plans and only one antenna for transmitting and receiving. The arrangement is similar to that described for the TN-1 system in Chapter 16.

### Intermediate Repeater

As in the TD-type systems, the radio receiver and transmitter for one direction of transmission through an intermediate repeater are mounted in a single bay [11]. This arrangement, illustrated in Figure 17-3, provides an efficient physical design layout and permits the sharing of certain equipment items used in both receiver and transmitter, particularly the microwave generator.

**Receiver.** Figure 17-10 is a block diagram of the TH-3 receiver. The received signal is carried from the antenna by waveguide through system separating networks (to select the 6-GHz signal and to separate signals of unlike polarizations) to the channel separation networks shown in the figure. The selected channel is delay equalized within this waveguide network to compensate for the delay distortion of the receiver channel separating filter and the preceding transmitter channel combining filter. The test access port that follows the separation network is the reference point at which the received signal power on a nominal length path is  $-23$  dBm.

The input signal reaches the receiver modulator through an isolator and a directional filter. This filter combines the received signal and the local oscillator signal. It contains a very narrow bandpass filter tuned to the local oscillator frequency and a complementary band rejection filter in the received signal path to prevent the local oscillator signal from reaching the receiving antenna. The narrow bandpass filter also suppresses noise and other spurious signals that may be present in the output of the microwave generator.

The receiver modulator converts the incoming microwave signal to a 70-MHz IF signal. Unwanted output signal components from the modulator are absorbed by the reverse loss of the isolator in the receive signal path; thus, they are prevented from reaching the receiving antenna. The modulator is followed by filters, equalizers, and amplifiers which suppress unwanted out-of-band signal components, equalize delay distortion, and (with an adjustment pad) set the required IF

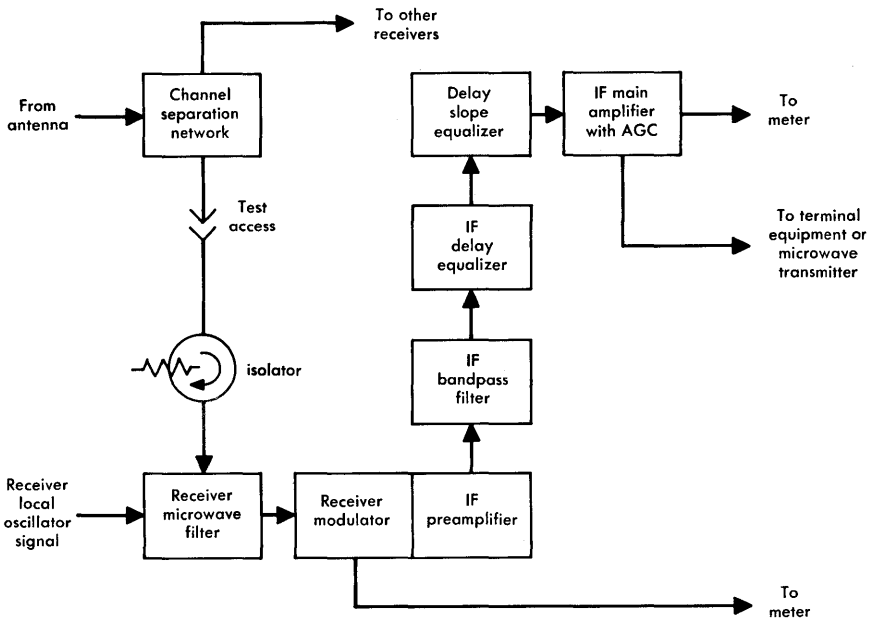


Figure 17-10. TH-3 receiver block diagram.

signal output power. The output signal is delivered to the microwave transmitter at an intermediate repeater or to protection switching equipment at a main station.

**Transmitter.** Figure 17-11 is a block diagram of a TH-3 microwave transmitter. The incoming IF signal is applied to the IF limiter amplifier which removes essentially all amplitude modulation; the transmitter modulator converts the signal from the 70-MHz IF band to the appropriate RF channel frequency.

The output signal from the transmitter modulator passes through the microwave distribution network to reach the transmitter microwave network. This bandpass network passes the upper sideband and reflects the lower sideband as well as other unwanted signal components which are dissipated in an isolator in the microwave distribution network. The transmitter microwave network is delay equalized to prevent the introduction of amplitude modulation which can be converted to signal distortion in the traveling wave tube (TWT) amplifier.



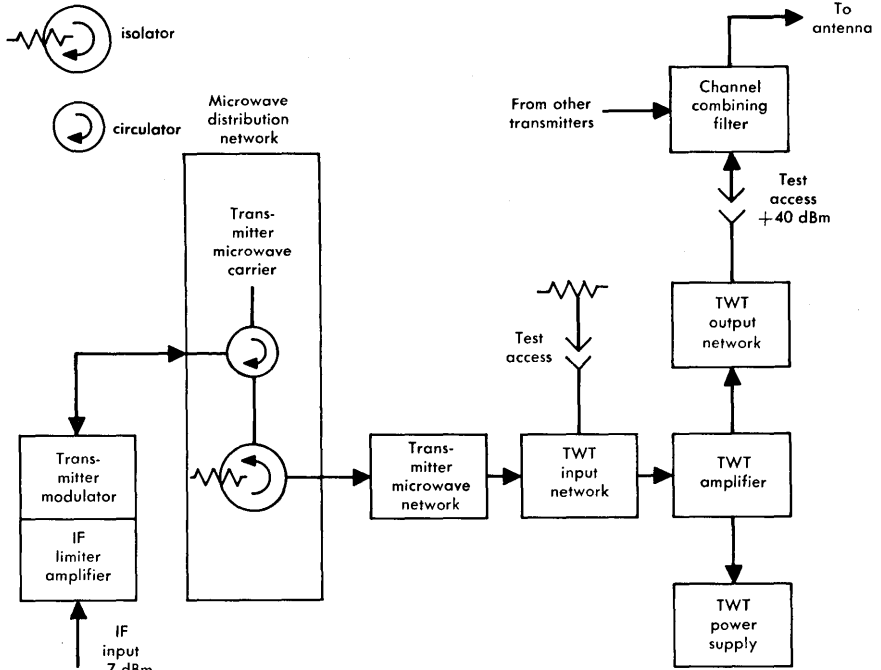


Figure 17-11. TH-3 transmitter block diagram.

The TWT input network provides an impedance match between the transmitter microwave network and the TWT amplifier by the use of an isolator. The input network also contains an attenuator for controlling the TWT input signal power. The test access port is available for measurement during this adjustment.

The TWT amplifier provides a signal power of +40 dBm (10 watts) at the output of the TWT output network, a microwave integrated circuit similar to the TWT input network. The output network contains a low-pass filter to suppress harmonics in the TWT output signal. The amplifier is powered by a dc-to-dc converter that generates all the voltages required by the TWT.

The test access port is used during the measurement and adjustment of output power. The signal then enters the channel combining filter where it is combined with other channel signals for transmission. The output of the channel combining filter is transmitted to the antenna through system combining networks not shown in Figure 17-11.

**Carrier Supply and Distribution.** In the TH-3 system, the received and transmitted channel frequencies differ by 252 MHz; the local oscillator signal is always 70 MHz below the center frequency of the channel. At intermediate repeaters, the microwave generator is shared by the transmitter and receiver in the same bay. This differs from the TH-1 design where a common microwave carrier supply is used for an entire office or repeater station.

A block diagram of the repeater microwave generator signal distribution arrangement is shown in Figure 17-12. The microwave generator delivers a nominal 1-GHz signal as a multiple of a crystal-controlled signal at about 125 MHz. The exact frequencies depend on the required channel frequency. The output of the generator is trans-

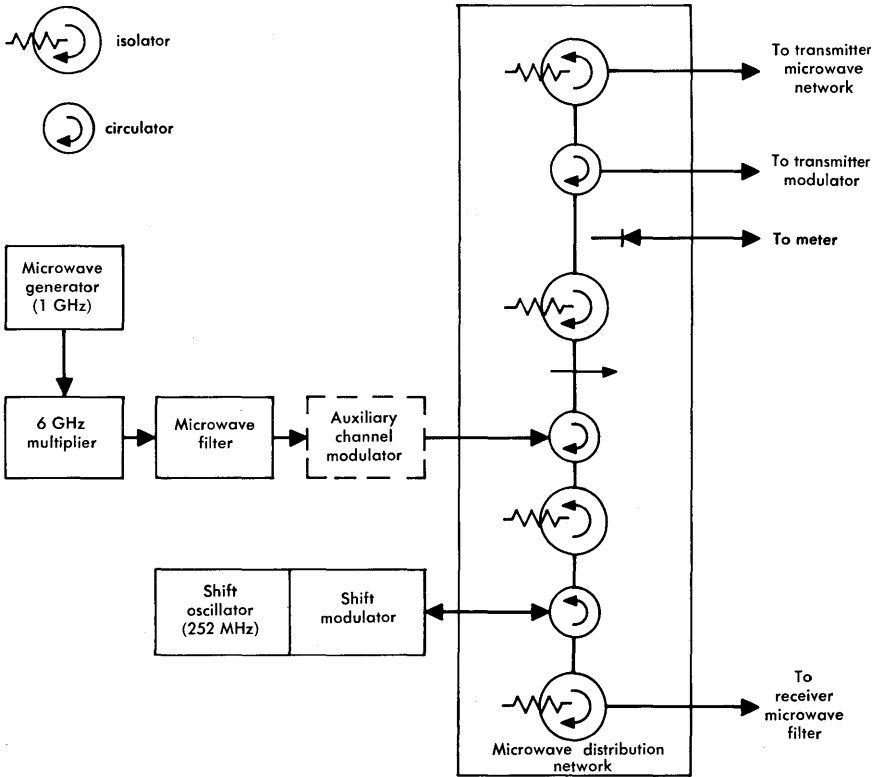


Figure 17-12. Local oscillator signal distribution for TH-3 repeater bay.

lated to the 6-GHz band by a single step of multiplication and passed through the microwave filter to remove unwanted signal components.

The signal passes to the microwave distribution network which is made up of a number of circulators and isolators. One portion of the microwave generator signal is distributed directly to the transmitter modulator by this network. The other portion is provided for the receiver modulator. This signal must be shifted 252 MHz above or below the transmitter frequency depending on whether the repeater is of a low-high or a high-low configuration. The frequency change is accomplished by the shift modulator driven by the 252-MHz shift oscillator.

If the system is provided with an auxiliary channel for the transmission of order-wire, surveillance, control, and other special purpose signals, the signal is transmitted through an auxiliary channel modulator [12]. This unit is used to frequency modulate the microwave carrier with an amplitude-modulated 11.38-MHz carrier.

### Main Station Repeater

The main station microwave receiver and transmitter equipment is identical to that found at intermediate repeaters; however, it is arranged differently. At a main station, the receiver and transmitter for one route direction are mounted in a single bay. This arrangement, shown in Figure 17-3, provides administrative convenience and improved reliability.

The principal equipment change resulting from this difference in layout is that the distribution of the local oscillator signal departs significantly from that used at intermediate repeaters. The signal distribution arrangement, shown in Figure 17-13, involves the separation of the generation and distribution of transmitter and receiver local oscillator signals to improve system reliability. If the single generator used at intermediate repeaters were used at main stations, its failure or removal for maintenance would affect both directions and, as a result, a protection channel would have to be used simultaneously in both directions.

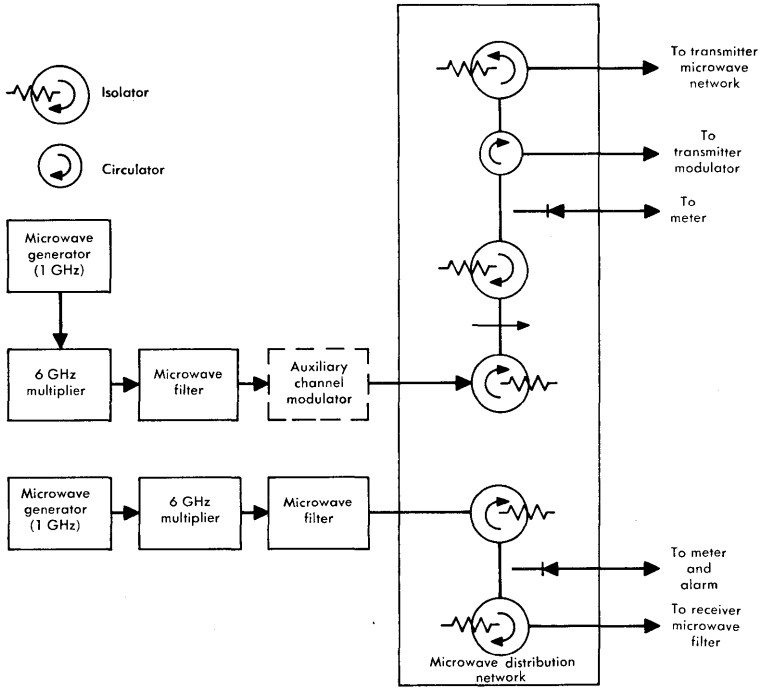


Figure 17-13. Local oscillator signal distribution for TH-3 main station bay.

### 17-3 THE TH-1 SYSTEM

With the intensive use of the 4-GHz common carrier band that built up during the 1950s, it became necessary to exploit the 6-GHz band. The first system designed for 6-GHz application was the TH system, later designated TH-1. While it is no longer manufactured, many systems are in service throughout the United States.

Except for the TH automatic switching (THAS) system described in Chapter 15, the circuits in TH-1 originally were all based on electron tube technology. The solid-state receiver modulator and IF pre-amplifier circuit of the TH-3 system has been incorporated in TH-1 to improve thermal noise performance and increase fade margin. In addition, the original electron tube-type FM terminals have all been replaced by solid-state equipment.

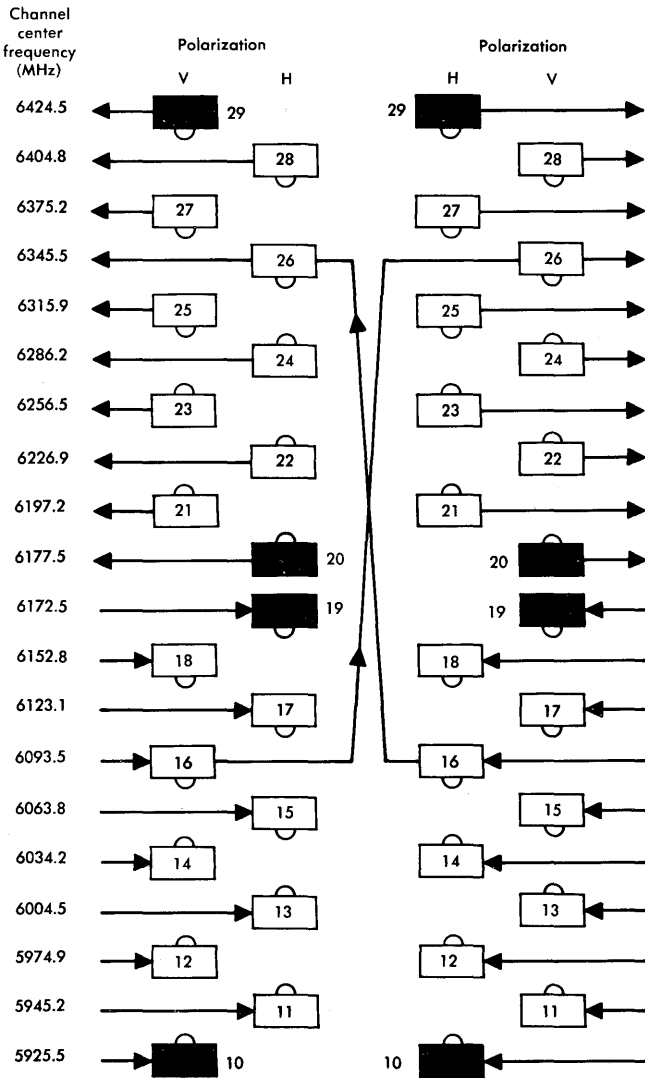
During the development program, every effort was made to optimize the performance of the TH-1 rather than to accommodate its performance to the existing environment of the 4-GHz TD-2 systems. As a result, the intermediate frequency band was established at 74.1 MHz rather than at 70 MHz as in TD-2. Although 74.1 MHz is ideal for easing filter requirements and minimizing intrasystem microwave leakage interferences, experience has shown the overall system administrative desirability of the 70-MHz IF band as standard. If the intermediate frequency of a system provides protection or restoration channels for a system that uses a different intermediate frequency, the IF bands must be shifted accordingly. Such a shift is accomplished by operating FM terminals back-to-back as discussed in Chapter 15.

### System Considerations

The TH-1 system was initially intended to carry theater-grade television signals (10-MHz baseband) or telephone circuits to supplement circuit needs in areas where the 4-GHz spectrum of the TD-2 system had become congested. System objectives were approximately the same as those then applied to other long-haul systems in respect to noise performance and, in addition, were to provide maximum utilization of the 6-GHz spectrum (5.925 to 6.425 GHz) [13].

**System Layout.** A typical TH-1 system consists of transmitter main station equipment, intermediate repeater stations, and receiving main station equipment. A baseband signal source, an entrance link, an FM terminal transmitter, and a radio transmitter comprise the transmitting main station equipment. These units are complemented at the receiving end by the radio receiver, FM terminal receiver, and baseband receiving equipment. Intermediate repeaters are of the IF-heterodyne type. Since the entrance links at the terminal stations operate at baseband, FM terminal transmitters and receivers may be located in close proximity to the radio equipment.

**Frequency Plans.** The frequency plan described previously as the regular plan for the TH-3 system was introduced with the TH-1 system. However, provision was made for additional auxiliary channels for the transmission of order-wire, alarm, and switching system control signals. Figure 17-14 shows the RF channel allocations and, in addition, shows the locations and polarizations of the auxiliary channels.



Notes:

- (1) indicates oscillator frequency is 74.1 MHz below channel center frequency; 74.1 MHz above channel center frequency.
- (2) = auxiliary channels.

Figure 17-14. TH-1 RF channel frequencies (low-high repeater station).

**Auxiliary Channels.** The TH-1 automatic protection switching system (THAS) requires a communication link for signalling from each intermediate repeater to the transmitting end of the switching section. These requirements are fulfilled by the provision of two 100-kHz radio channels which accommodate 16 single-frequency protection switching system control signals and four voiceband channels for each direction of transmission [14]. The latter channels are placed in the auxiliary channel spectrum between 80 and 96 kHz using ON-type carrier terminal equipment. The 16 switching system control signals are spaced 1 kHz apart in the baseband between 20.5 and 35.5 kHz. The RF allocations of the auxiliary channels place them at the high and low ends of the two halves of the 6-GHz band allotted to the two directions of transmission as shown in Figure 17-14.

In combined TD/TH-1 system installations, the TH-1 auxiliary channels may be used to provide voiceband communications for both radio systems. In other installations, the TH-1 needs are filled by voiceband circuits initially supplied for the TD-type system.

**Antennas.** The development of the horn reflector antenna was in part stimulated by the planned introduction of the TH-1 system and by the recognition that substantial radio system economies could be realized if an antenna could be shared by 4-, 6-, and 11-GHz systems. The horn reflector not only achieved this goal but, together with a circular waveguide feed arrangement, also permitted the transmission of cross-polarized signals in each of the bands. The combination of these characteristics permitted close RF channel spacings and adequate discrimination between adjacent channels. Separate antennas are provided for transmitting and receiving.

### Repeaters

Figure 17-15 is a block diagram of the TH-1 radio receiver. The desired incoming RF signal is selected by the channel separation network and, after additional filtering by the channel bandpass filter, it is applied to the receiver modulator. The incoming RF signal is mixed in the modulator with a local oscillator signal to produce an IF signal centered at 74.1 MHz.

The IF signal is amplified, first in an IF preamplifier and then in the IF main amplifier in the receiver. An automatic gain control circuit maintains a constant +8 dBm signal amplitude at the amplifier output for an input signal range of -8 to -43 dBm. The circuit is

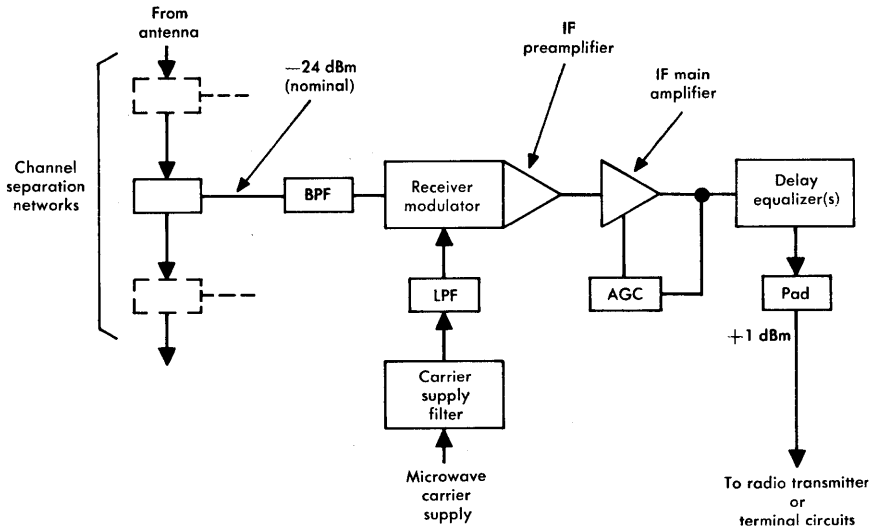


Figure 17-15. TH-1 radio receiver.

also arranged to produce an initiating signal for the protection switching system when the IF signal amplitude exceeds the AGC range by predetermined amounts.

The output signal is delay equalized and then delivered to terminal circuits, if required at that station, or to the radio transmitter, if at an intermediate repeater. The output pad is adjusted in order to deliver the proper signal amplitude at the input to the terminal circuits or radio transmitter.

The nominal signal amplitude of  $-24$  dBm received from the channel separation network at the input to the receiver is based on a typical section loss of 64 dB. If the path is short and the received signal amplitude is too high, it is brought within an acceptable range by a pad (not shown in Figure 17-15) placed either in the common receiving waveguide or in the transmitting waveguide at the preceding repeater, depending on intersystem interference considerations. The local oscillator signal applied to the receiver modulator is received from a common microwave carrier supply, shifted in frequency as required, and filtered by the carrier supply filter and the low-pass filter to remove unwanted signal components.



The radio transmitter is shown in the block diagram of Figure 17-16. A 74.1 MHz IF signal is delivered from terminal equipment (at a terminal station) or from a radio receiver (at an intermediate repeater). It is amplified and limited at the transmitter input in order to remove amplitude modulation from the FM signal.

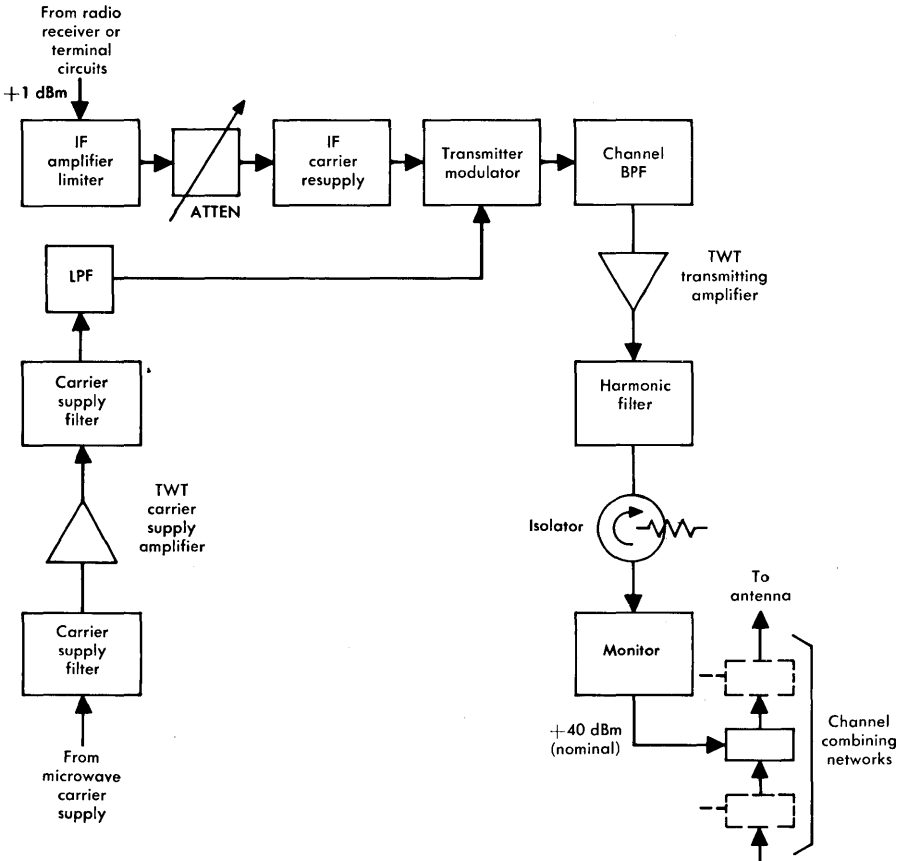


Figure 17-16. TH-1 radio transmitter.

The amplifier limiter has a detection circuit that controls the insertion of a local carrier from the IF carrier resupply circuit. In the event of equipment failure or a deep fade that might effectively remove the input signal, an IF resupply carrier is generated to simu-

late a working signal in succeeding circuits in order to limit the noise resulting from the loss of gain control.

The IF signal from the amplifier limiter is passed through the carrier resupply circuit (with little attenuation) to the transmitter modulator. After it passes through a buffer amplifier, the signal is mixed with the beat-oscillator signal in a low-loss balanced modulator which translates the signal to the appropriate RF channel frequencies. The desired sideband is selected by the channel bandpass filter and applied to the TWT transmitting amplifier. This amplifier typically provides about 32 dB of gain and an output signal power of +40 dBm (10 watts).

After additional filtering, the signal passes through an isolator that provides a termination for the channel combining network where the signal is combined with other channel signals for transmission to the antenna. A power monitor circuit provides a visual indication of the isolator output power and provides an alarm if the signal power drops by more than a predetermined amount.

The local oscillator signal is supplied from the same microwave carrier as that used for the receiver. Since a relatively high oscillator signal power is required, a TWT amplifier is used to provide this power. The local oscillator signal path is filtered to suppress noise and unwanted signal components.

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## Chapter 18

# Domestic Satellite Communications

Communications satellite systems are generally categorized by the type of orbit of the space vehicle and by the type of service provided. The type of orbit most commonly used is the geosynchronous orbit in which the satellite is at a distance of about 22,300 statute miles from the earth so that its orbital period just equals the period of rotation of the earth. The plane of this orbit must have very little inclination with respect to the equatorial plane of the earth and the direction of rotation of the satellite about the earth's axis must be the same as that of the earth.

A special case of the geosynchronous orbit is the geostationary orbit in which the inclination is zero. These terms are sometimes used interchangeably even though it is not practicable to maintain zero inclination. The advantage of the geosynchronous orbit is that the satellites appear to be essentially stationary from any point on the earth. This provides continuous visibility, eliminates the need for tracking by earth stations with small diameter antennas that have relatively wide beam widths, and eases the tracking requirements for even the largest narrow-beam earth station antennas. The disadvantages of the geosynchronous orbit are limited visibility to the higher latitudes and the high satellite altitude. The resulting transmission path length causes long transmission delay and high transmission loss compared to low altitude satellites. Furthermore, the number of orbital position assignments for coverage of the 50 states at 4 and 6 GHz is limited because of interference restrictions.

There are a few cases where other orbits are used to meet special needs. The Russian MOLNIYA satellites, for instance, use an inclined, highly elliptical, 12-hour orbit because of the difficulty in launching an

equatorial spacecraft from Russia. In addition, a geosynchronous satellite would have limited visibility in the northern areas of Russia [1].

Service categories include Fixed Satellite, Mobile Satellite, and Broadcasting Satellite. In Fixed Satellite Service, the satellites are used to interconnect fixed earth stations\* for the purpose of providing any of the types of services normally provided by terrestrial systems, such as telephony, record communications, and television distribution. In Mobile Satellite Service, the satellites are used to connect moving vehicles to a fixed earth station or to other moving vehicles, usually by way of the fixed earth stations. The broad area covered by the transmitted radio waves of orbiting satellites makes them particularly useful for communication with ships on the high seas and with aircraft flying over the oceans. In Broadcasting Satellite Service, satellites receive television and radio program material from one or more earth stations for rebroadcast to receivers in the area covered by the satellites. At the present time, many of the receivers are of the community type; they receive the program material from the satellite for redistribution by over-the-air broadcasting or by cable to a local service region. As the state of the art progresses, direct broadcasting to home receivers using inexpensive antenna systems, inexpensive converters, or both may become practicable.

Fixed Satellite Service is the only one of these services directly involved in providing network telecommunications services. Thus, the remainder of this discussion is devoted to a review of regulatory matters, space vehicle considerations, transmission equipment, and transmission characteristics for Fixed Satellite Service.

## 18-1 INTERNATIONAL AND DOMESTIC REGULATION

The design of communication satellite systems is influenced more than that of any other form of domestic communication system by national and international Radio Regulations and Recommendations of the International Telephone and Telegraph Consultative Committee (CCITT) and the International Radio Consultative Committee (CCIR). As with all radio systems in the United States, frequency bands for satellite services are allocated by the Federal Communications Commission (FCC) in general conformance with the allocations

\*The term earth station is used to designate an earth terminal of a satellite communication system as distinguished from the repeater stations of a terrestrial transmission system.

appearing in the Radio Regulations of the International Telecommunication Union (ITU), a specialized agency of the United Nations.

Many frequencies have been allocated for satellite communications [2]. Some of the frequency bands now used by common carriers for domestic satellite systems are the same as those commonly used for terrestrial systems at 4 and 6 GHz. Although most other frequency bands that have been assigned for satellite systems, including the 11-GHz band, have not yet been exploited, they are being investigated. Experimental satellites that operate at 12 and 14 GHz have been launched and commercial satellites are planned for operation at these frequencies.

Since the frequency allocations are shared with radio systems of other services, it has been necessary to establish certain constraining rules with regard to the operations of communications satellites and associated earth stations. Among these rules, as modified by the FCC, are the following:

- (1) The frequency tolerance of each earth station transmitter shall be  $\pm 0.001\%$ .
- (2) The frequency tolerance of each space station transmitter shall be  $\pm 0.002\%$ .
- (3) Emission originating within but measured outside an RF channel is expressed in terms of the mean power measured in any 4-kHz band outside the RF channel. The limit is a function of the frequency separation between the 4-kHz channel in which the measurement is made and the center frequency of the RF channel in which the emission originates and is expressed in dB below the mean output power of the transmitter in the originating RF channel as follows:

SEPARATION FROM CENTER FREQUENCY OF ORIGINATING RF CHANNEL	MINIMUM ATTENUATION BELOW MEAN OUTPUT POWER OF ORIGINATING RF CHANNEL
50% to 100% of originating channel bandwidth	25 dB
100% to 250% of originating channel bandwidth	35 dB
More than 250% of originating channel bandwidth	$43 \text{ dB} + 10 \log W^*$

\*W is the output power in watts in the originating channel. When emission outside the originating channel causes harmful interference, the FCC may require greater attenuation than that specified above.

- (4) Sites and frequencies for earth stations that operate in frequency bands shared by terrestrial and space services shall be selected to the extent practicable so that the surrounding terrain and existing frequency usage minimize the possibility of harmful interference between the sharing services.
- (5) Within the band between 5925 and 6425 MHz, the mean effective radiated power transmitted in any direction in the horizontal plane by a communications-satellite earth station shall not exceed a value of 45 dB above 1 watt (+45 dBW) in any 4-kHz band.
- (6) Within the band between 5925 and 6425 MHz, earth station antennas shall not normally be authorized for transmission at elevation angles less than five degrees as measured from the horizontal plane to the central axis of the main lobe. (Certain exceptions to this rule are noted in the Rules.)
- (7) The total power flux density (watts per hertz per square meter) at the earth's surface, produced by emission from a communications-satellite space station, where wide-deviation frequency (or phase) modulation is used, shall in no case exceed a value of  $-130$  dBW per square meter for all angles of arrival. This is essentially a limit on the flux density received from an unmodulated RF carrier. If necessary, such signals shall also be continuously modulated by a suitable waveform, so that the power flux density shall not exceed  $-149$  dBW per square meter in any 4-kHz band for all angles of arrival.
- (8) No directional transmitting antenna utilized by a terrestrial station operating in the band between 5925 and 6425 MHz shall be aimed within two degrees of the geostationary satellite orbit, taking into account atmospheric refraction.

These regulations obviously affect system design parameters. Most present-day communications satellites merely amplify and translate the frequency of a received signal for retransmission to earth. In such a system, the only way to control power flux density is by controlling the modulation at the transmitting earth station. In the usual design, the spreading of power flux normally meets the rules when a time or frequency division multiplex signal or a television signal is applied to the earth station transmitter. However, during nonbusy periods with a frequency division multiplex signal or when a tele-

vision signal is all-black, most of the RF energy is concentrated in the region near the carrier frequency and the maximum flux density requirements may be exceeded. In analog FM systems, this problem is usually solved by applying to the earth station carrier a sawtooth modulating signal adequate to meet the flux density requirements during quiescent signal periods.

The elevation angle rules for earth stations establish the limits of visibility of the satellites. This is generally not a controlling factor since very low receiving elevation angles increase the system noise unacceptably.

## 18-2 SPACE VEHICLE CONSIDERATIONS

Communications satellite system design can be divided into two distinct parts, the space segment and earth stations. Although the two parts must be designed together if they are to operate as a system, certain elements of each can be considered independently.

The space segment consists of the satellite(s) and the tracking, telemetry and control (TT&C) station located on the earth. The TT&C station, as the name implies, tracks the satellite(s), receives telemetry information from them, and transmits control signals to them. These stations can be and often are designed and provided by the satellite vendor. They may be incorporated into or collocated with a communication earth station or they may be operated as separate entities. The TT&C functions are not considered further here since the operation of the communication system is not affected when they are properly performed.

The satellites, on the other hand, are a vital part of the transmission path and their physical as well as their electrical performance must be considered. Each satellite is moving and must be stabilized if adequate communications performance is to be realized.

### Satellite Stabilization

Early experimental, active, communications satellites such as Telstar®, Syncom, and Relay were nongeosynchronous low-orbit space vehicles. They were spin-stabilized, as is a bullet, by rotation around an axis that maintained a fixed relation to the earth's axis. This eliminated tumbling and kept the axis properly oriented. However, communications were limited because directional antennas could not be



aimed toward the earth. Since weight and therefore power are precious parameters in space, this mode of satellite operation severely limited transmission system performance. This type of spinning action for stabilization has been replaced by either of two methods that permit highly directional antennas to be employed. These are called the double-spin configuration and the three-axis stabilization technique.

In the double-spin configuration, the satellite is spun at a rate of 50 to 100 revolutions per minute. The antenna platform is motor driven in the opposite direction at the same rotation rate. Depending upon the mechanical design and mass distribution of the satellite, the spin rate necessary to achieve stability can be critical. Damping mechanisms are commonly employed to eliminate "wobble" or nutation. On-board earth sensors are used to control the motor speed. Thus, the antennas appear to be stationary with respect to a given point on the earth. This permits high-gain antennas to be used on board the satellites. Pointing accuracies in the east-west direction (the direction of rotation) much better than 0.1 degree can be obtained easily.

With three-axis stabilization, flywheels on board the spacecraft rotate at high speed to provide stability in all three axes. This makes the exterior of the spacecraft appear to be fixed (within a few hundredths of a degree) with respect to a given point on the earth.

Each of these methods of stabilization has advantages and disadvantages; size and weight of the spacecraft, stability requirements during orbital maneuvers, reliability, cost, and prime power requirements are some of the items that influence the choice of the method used. Even with three-axis stabilization, rotating joints are needed on the solar panels to keep them pointing toward the sun. As long as the satellite meets specified stability requirements and the stability accuracy is known, the communication system design is not directly affected by the stabilization methods employed.

### Station Keeping

Important items of spacecraft design include the ability to keep the station, or satellite, in orbit at its assigned longitude and in the proper inclination. The need for such controls is the result of orbital perturbations that prevent satellites from maintaining geostationary orbits. Corrections to counteract these perturbations, called station keeping, are usually made by firing gas jets on board the satellite.

The fuel most commonly used today for these jets is hydrazine and the life of the satellite is strongly influenced by the amount of fuel required to attain the initial assigned geosynchronous orbital position and to maintain the required orbital position accuracy. Earth station antenna positioning requirements are, of course, keyed to the station keeping accuracy of the satellites.

### Satellite Lifetime

Either of two major factors, depletion or catastrophic failure, may determine the life of a communications satellite. The probability of service outage due to catastrophic failure is minimized by careful design, redundancy, and the selection of subsystems and components by preflight qualification and by thorough testing as the satellite is assembled.

The major depletion components in a satellite are solar cells and the supply of fuel for control purposes. The electrical power used by present-day satellites is derived from solar cells with battery backup for periods of eclipse (i.e. when the satellite is in the earth's shadow). The solar cells deteriorate with time due to solar bombardment. Therefore, the power available from the solar cells is quoted in terms of beginning-of-life and end-of-life watts. The amount required for a given lifetime has an impact on the total weight of the spacecraft. These factors (solar cell life and fuel requirements) are usually balanced against each other within the overall vehicle load requirements and the constraint of the launch vehicle capability to give a predicted lifetime of seven to ten years. So far, most communication satellite failures (total or partial) have been due to component failures rather than exhaustion of fuel or the decay of solar cells.

### Launch Vehicles

The choice of vehicles for placing communications satellites in orbit is limited to those generally available from the National Aeronautics and Space Administration (NASA). Development of a special vehicle for a specific class of satellites would be very expensive; therefore, the satellites are generally designed to fit the weight limits and physical dimensions of available launch vehicles.

At present, the choice is limited essentially to vehicles capable of carrying loads of up to 2000 pounds, with fairing envelopes that can accommodate spacecraft up to 8 feet in diameter and 15 feet long, or up to 4100 pounds with the ability to accommodate spacecraft up to

9 feet 3 inches in diameter and 30 feet long. These weight capacities include the apogee kick motor and fuel needed to achieve a truly synchronous orbit. The fairing envelopes are not themselves cylindrical throughout.

The cost of the launch vehicle is a major portion of the total investment in the space segment of a communication satellite system. There is hope that the space shuttle, now under development by NASA, will reduce launch costs. The shuttle will be a reusable vehicle for inserting very large satellites into a "parking" orbit about 160 miles above the earth. The total load on any mission might be made up of several smaller loads; for instance, it might consist of three communications satellites each with its own propulsion unit. The shuttle is expected to be operational by 1980.

Existing space vehicles are to be phased out gradually. Since the space shuttle essentially replaces only the booster section of the present space vehicles, the equivalent of the second stage (sometimes called a perigee kick motor) must be developed so that a geosynchronous satellite can be placed into a transfer orbit. A third-stage apogee kick motor is required for injection into a synchronous orbit and removal of inclination. Presently, the apogee motor is built into the satellites but there is no compelling reason for this feature.

The space shuttle is expected to have cargo space 15 feet in diameter and 60 feet long with a load capacity of 65,000 pounds. The shuttle will carry several communication satellites and will be capable of being positioned accurately before each satellite is ejected into space from the shuttle.

### 18-3 SATELLITE TRANSMISSION EQUIPMENT

The design and development of satellites and satellite communication systems is a rapidly growing and changing field. Equipment design is subject to stringent requirements derived from the space environment and stresses of launch and orbital adjustment and control.

#### Major Equipment Items

Most present day communication satellites use the 4-GHz common carrier band for downlink transmission from the satellite and the 6-GHz common carrier band for uplink transmission to the satellite.

This mode of operation facilitates signal separation in the two directions of transmission and mitigates intersystem interference. Circuit arrangements are similar in concept to those of terrestrial radio relay stations except for the rather large frequency shift necessary to utilize these frequencies in the manner indicated. The 500-MHz RF channel bands are divided into 40-MHz segments. The equipment used to receive signals at 6-GHz and then to amplify, translate in frequency, and retransmit in a corresponding 40-MHz segment in the 4-GHz band is known as a transponder. Satellites are sometimes classified by the number of transponders they contain.

Most communications satellites have been designed for FM transmission. However, they retransmit multiple carriers or signals of any type of modulation that fall within the pass bands of the transponders. Depending upon the linearity of the major equipment items, transmission of other than FM signals is likely to require some reduction of signal amplitudes to avoid saturation and intermodulation effects. Communication satellite equipment must be qualified to operate in the space environment, light in weight, and equipped with sufficient redundancy and protection switching so that its design life objectives can be achieved.

Communication satellites are equipped with antennas having sufficient gain at superhigh frequencies to cover the land areas of interest. The wideband receivers include a low-noise solid-state RF amplifier, a frequency translator, and a driver amplifier. Light-weight filters with phase equalization are used to separate the receiver output signal into bandwidths that correspond to those of the transponders. Each transponder may have a separate traveling wave tube output amplifier. Command and control receivers and telemetry transmitting equipment for communicating with the TT&C stations are also provided. Separate beacon transmitters for tracking are also often included.

Frequency band utilization and capacity is doubled by the use of orthogonal linear polarization techniques or by using left- and right-hand circular polarization. The former is employed in the 24-transponder Comstar\* (AT&T) and Satcom (RCA) designs. Doubling of the frequency band capacity by the use of spot, or very narrow, beams

\*Comstar, a communication satellite designed and built to AT&T Co. specifications for joint domestic service by AT&T and the General Telephone and Electronics Satellite Corp. (GSAT).

has limitations at 4 and 6 GHz because of launch vehicle fairing-size restrictions (unless antennas which unfold after launch are used) but frequency reuse by the spot-beam technique has been widely advocated for higher frequency satellite design [3].

Ground controlled switching of a number of equipment units, including antenna feed horns, can be used both to increase the flexibility of a communication satellite system and to provide for major component substitution in the event of equipment failure. Ground control of the gain of the satellite receiver is also very desirable to balance the performance of the up- and downlinks over a wide range of earth station antenna sizes and for single- or multiple-carrier operation of the transponders. Such control can greatly increase the capacity and efficiency of a satellite used in several different operating configurations.

Satellites can be designed for many different types of modulation. Today, most employ FM/FDM techniques with either single or multiple carriers per transponder but single channel per carrier (SCPC), demand assignment multiple access (DAMA), and time division multiple access (TDMA) techniques are also used. With the advent of the space shuttle, new digital techniques and new high-frequency active devices and satellite technology can be expected to evolve rapidly.

Redundancy is used to help insure that a communication satellite reaches its design lifetime. However, it does add weight and cost; furthermore, the switches used can be a source of failure. In the Comstar satellite design, redundancy has been provided to protect major equipment items that are common to more than one transponder. It also may be used with equipment items whose mean time between failures would otherwise limit satellite reliability. Redundancy is particularly important to assure reliability of the TT&C system.

### Comstar Satellite Design

The Comstar satellites are designed for a life span of seven years. Their overall length is 20 feet, diameter 8 feet, weight before lift-off 3342 pounds, and weight in orbit 1787 pounds. About 560 watts of direct current power are provided by 17,000 solar cells. Nickel-cadmium batteries power the satellites during solar eclipse periods. As previously mentioned, orthogonal linear cross polarization is used effectively to double the transmission capacity of the satellite.

It can be seen in Figure 18-1 that switches, operated from ground stations, can transfer receivers. Three of the four receivers must fail before any capacity is lost. In addition, the four-step attenuators shown in each transponder can effectively change the gain of the up-link; these attenuators are also controlled from the ground. This is the first use of this principle in a domestic satellite to balance the up- and downlink noise and crosstalk contributions. It permits maximizing the performance and capacity of individual transponders for single or multiple carrier operation and for a wide range of earth station antenna sizes.

As may be seen from Figure 18-1 all 24 transponders can be used between points in the contiguous 48 states (often designated CONUS). The 24 transponders are arranged into four sets of six. Three of these sets are equipped with either S- or T-type switches which allow the associated transponder output signal to illuminate either the CONUS or spot-beam antenna feed systems or both. Spot-beam antenna feed systems can illuminate Alaska, Hawaii, and Puerto Rico. The S-type switches allow the signals to illuminate either the CONUS or a spot-beam antenna feed and provide the same equivalent isotropic radiated power (EIRP) illumination to either coverage area. The T-type switches perform the same function as the S-type switches and have an additional switch position that allows the CONUS and spot-beam coverage areas to be illuminated simultaneously (with a 2-dB reduction of EIRP). Both switch types are controlled by ground commands. They may be individually operated to allow signals from any one of six transponders to illuminate the appropriate spot-beam coverage area.

Each transponder has the capacity for carrying 1500 one-way 4-kHz telephone circuits, two color television signals, or a data signal with a repetition rate in excess of 50 Mb/s. These high signal capacities depend on the use of an AT&T earth station with an antenna 30 meters in diameter.

Circuits are also used (with ground controlled switching) to provide beacon signals for satellite tracking. In addition, there are circuits that provide millimeter wavelength signals to obtain important propagation information needed for the development of a higher capacity and more economical satellite system.

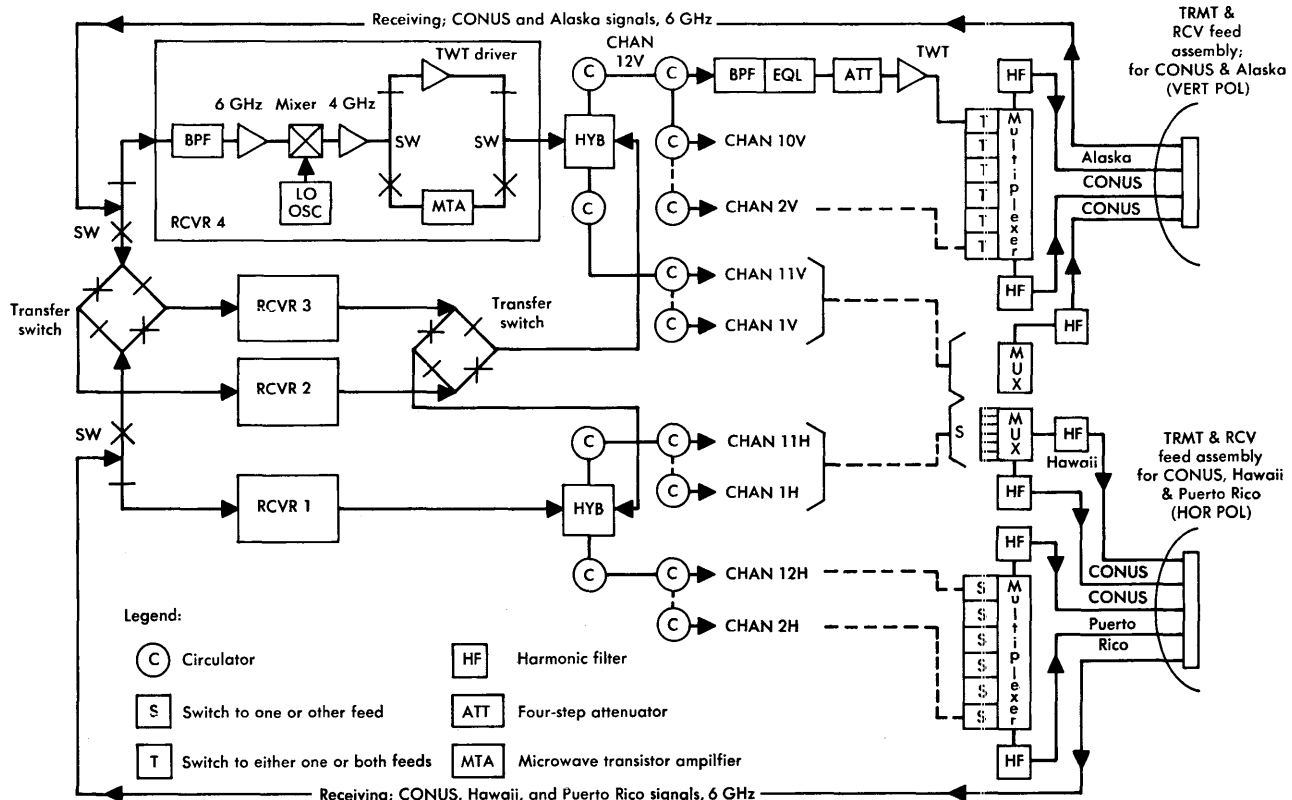


Figure 18-1. Block diagram of Comstar transmission circuits.

## 18-4 EARTH STATION EQUIPMENT

A satellite communication system includes two earth stations, an intermediate satellite repeater, and the links that connect the earth stations with the telecommunications facility network. These links are provided by terrestrial facilities and need not be considered in detail insofar as the satellite system is concerned. They are usually short and thus contribute little impairment to the system but they must be engineered so that intersystem interference requirements are satisfied.

### Frequency Coordination

As previously mentioned, communications satellite systems share frequency allocations with terrestrial common carrier microwave systems. This sharing of frequency bands requires careful coordination to insure that neither service interferes with the other. The FCC Rules relating to satellite communications require that, before an application for an earth station may be filed, the proposed frequency usage must be coordinated with existing terrestrial stations and systems.

In the coordination process, three potential sources of interference must be investigated. First, any earth station and any terrestrial station within 100 kilometers of each other must be coordinated in detail in a manner equivalent to a line-of-sight coordination for terrestrial microwave stations. Second, the FCC Rules prescribe a method for calculating a coordination contour for the proposed earth station. The proposed frequency usage must also be coordinated with all terrestrial stations which fall beyond 100 kilometers but within the contour. The terrain of the interference path determines if a line-of-sight or an over-the-horizon study must be made. The study must include an investigation of the possibility of interference due to tropospheric scatter propagation. Third, the Rules prescribe a method for calculating the potential interference caused by the scattering of energy by precipitation within the volume in space common to the beams of two antennas which intersect each other. The Rules also require that proposed frequency usage in terrestrial services be coordinated with all other users (including satellite systems) in the frequency bands involved prior to the filing of applications.

### Earth Station Transmission Equipment

As in other communications systems, the limitations on satellite system performance are noise and interference. The factors affecting



the performance are the same as those which are of concern in any microwave radio system: antenna gain, receiver noise, modulation noise, and output power. Earth station antenna gain requirements are determined by the transmit power of the satellite, the nature of the service being provided, and the performance objectives. Antenna sizes in practical systems may vary from 30 meters in diameter for large capacity systems designed to meet CCITT noise objectives down to 5 meters or less for those used for receive-only closed circuit video service. Feedhorns may be designed to transmit linear-polarized planar signals or to transmit circularly polarized signals. High-capacity systems may utilize orthogonal linear polarizations.

There is usually a need to track even a stable geostationary satellite. Tracking may be automatic or manual. Large antennas with narrow beams generally require automatic tracking while small broadbeam antennas, which only need to be moved occasionally, may be pointed manually.

The power transmitted by the satellite is often the most restrictive feature of a satellite system; weight limitations in the space vehicle usually limit the size of the battery plant that can be used. For a given satellite transmitter power, the downlink performance is a function of earth station antenna size and receiver noise. The development of new solid-state devices for use in satellite system receivers has led to circuits having extremely low noise figures. Receivers employing such low-noise devices may be used in small or low-capacity earth stations, and, where more exacting noise requirements apply, receiver noise may be reduced to a minimum by cryogenic means. Such techniques are used in broadband satellite systems to achieve system operating noise temperatures as low as 60 kelvins.

Other earth station equipment is typical of microwave receiving equipment in common usage. On the transmitting side, the modulators and up-converters are similar to those used in terrestrial microwave systems. The power amplifier, however, must produce signals of considerably higher output power than those allowed for terrestrial microwave services; output power of several kilowatts is not unusual. Earth station equipment may also include FM deviators, digital RF modulators, analog or digital multiplex equipment, FM deviation converters, and the terminals of a terrestrial transmission connecting link of conventional design.

In the ultimate arrangement planned for the Comstar domestic satellite system, the earth stations will utilize either two or three 30-meter diameter antennas. One (or two) of the antennas are to provide service over one (or two) independently operated satellites. The additional antenna, operating with a separate satellite in orbit, is to provide occasional service and protection against service outages that might be caused by satellite equipment failure or by the sun transit phenomenon, i.e., when the sun appears behind the satellite about the time of the spring and fall equinoxes. This method of service protection is a major factor in obtaining system reliability comparable to that of modern terrestrial transmission systems.

The ground communications equipment at these stations has many advanced features. Among these is an automatic polarization control of transmitted and received signals that is required in order to provide on-axis cross-polarization isolation of at least 25 dB between two orthogonally polarized signals at the same frequency in either band. The stations are arranged for unattended operation during periods when maintenance is not required. Protection switching systems are provided for transmitting and receiving equipment.

Figure 18-2 is a block diagram of the principal transmission circuit components of the earth station in the ultimate format involving three antennas. The deviation converter, upconverter, and high-power amplifier for each RF channel are protected by "hot standby" equipment that can protect up to six working circuits. The receiving circuits, which perform the inverse of the transmitting functions, are arranged in a manner quite similar to that found in the transmitting direction.

The satellite and earth station circuits provide a high degree of isolation between transmitting and receiving directions of transmission and between the two orthogonal linearly polarized signals in both the 4- and 6-GHz bands. However, compensation must be provided for Faraday rotation effects caused by transmission of signals through the earth's magnetic field [4]. Such compensation is provided by the antenna feed system shown in Figure 18-2 and, in somewhat greater detail, in Figure 18-3.

The polarization of signals must be properly aligned with the receiving antennas at the satellite and earth stations. The feed system compensates for the Faraday rotation effects on the 4-GHz downlink signals and adjusts the linearly polarized uplink signals at 6 GHz so

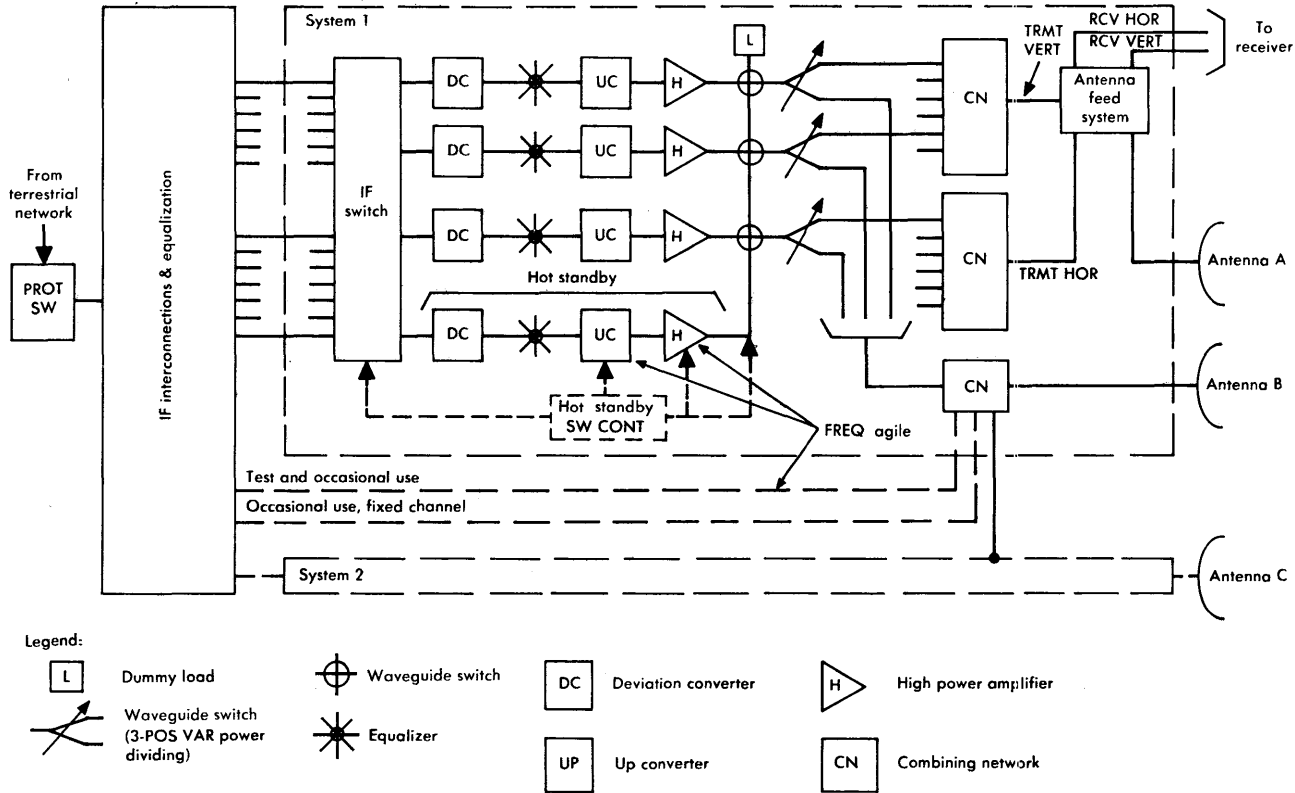


Figure 18-2. Earth station transmitter arrangements.

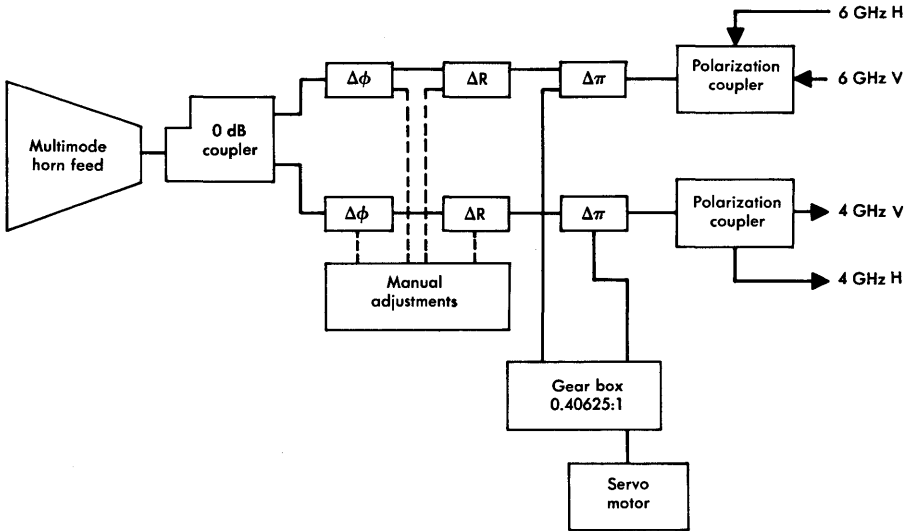


Figure 18-3. Block diagram of AT&T earth station antenna feed system.

that they arrive at the satellite antennas at the proper angles to maintain maximum discrimination.

Because of imperfections in the satellite and earth station antennas, the arriving vertical and horizontal signals are contaminated by a small cross-polarized component, i.e., they are slightly elliptical in polarization. In addition, they are not quite orthogonal to each other. The  $\Delta\phi$  differential phase shifters of Figure 18-3 can be adjusted to remove the ellipticity, the  $\Delta R$  differential attenuators can be adjusted to make the vertical and horizontal signals orthogonal, and the  $\Delta\pi$  phase shifters can be adjusted to make the vertical and horizontal signals conform to the vertical and horizontal outputs of the feed.

Faraday rotation may occur as a result of solar emission and may rotate the 4-GHz signals as much as several degrees. Automatic tracking of  $\Delta\pi$  is provided to follow the received signals and to rotate the transmitted signals in the opposite direction in expectation that they will arrive at the satellite in the proper geometrical relationship. Faraday rotation is inversely proportional to frequency squared, so the transmitting rotation is  $-(3.950/6.175)^2 = -0.40625$  of the observed receiving rotation. The frequencies 3.950 and 6.175 GHz are the center frequencies of the 4- and 6-GHz bands respectively. The

feeds were designed to admit retrofits for ellipticity tracking should this prove necessary.

## 18-5 TRANSMISSION SYSTEM CONSIDERATIONS

The transmission design of a satellite communication system is similar to that of terrestrial microwave radio in some respects but quite different in others.\* The equipment in the satellite may be regarded simply as a microwave repeater. Its functions are to provide gain to compensate for loss between transmitting and receiving earth station antennas and to produce a frequency shift between the 6-GHz band used for uplink transmission and the 4-GHz band used for downlink transmission. As previously mentioned, other radio frequencies allocated to common carrier communication satellite use have not yet been used commercially.

The great distances between earth and satellite repeaters result in high path loss and large transmission delays compared with terrestrial systems. As a result, the control of noise and echo are unique for this type of system and, together with the high cost of satellites, have resulted in the consideration of a number of speech processing techniques for improved performance and cost.

### Link Transmission Characteristics

The up- and downlinks to a satellite are each typically more than 22,300 miles long compared with 25 to 35 miles for terrestrial microwave radio system paths. Attenuation is about 199 dB for the 6-GHz uplink and about 196 dB for the 4-GHz downlink. However, only small portions of the satellite link paths are in the earth's atmosphere and, as a result, problems due to atmospheric attenuation and multipath fading are much less than those in terrestrial systems. However, tracking error must be considered for large antennas since the half-power beam width at 6 GHz for a 30 meter antenna is slightly over 0.1 degree.

Frequency reuse requires a high degree of cross-polarization isolation. When orthogonal linearly polarized signals are transmitted, automatic polarization tracking is necessary to maintain such isolation. This procedure is not necessary with right- and left-hand circularly

\*The computations outlined were transmitted to the FCC as Attachment A of an AT&T submission, "Application for a Domestic Communications Satellite System," March 29, 1973.

polarized systems. However, it appears to be more difficult to achieve a high degree of isolation between signals at the same frequency and having opposite circular polarization.

The determination of transmission performance is dependent on a large number of variables that include the location of the earth station and the orbital position of the satellite. In the following discussion, the satellite system assumed is one that can serve earth stations at San Juan, Puerto Rico; Honolulu, Hawaii; Anchorage, Alaska; and a number of others in the contiguous 48 states. The transmission values given are for a typical pair of links (one up at 6 GHz and one down at 4 GHz) between Los Angeles and New York City.

**Uplink Transmission.** The computation of transmission from an earth station to a satellite repeater requires a knowledge of gains and losses at 6 GHz of the transmitting equipment at the earth station, the transmission path, and the receiving equipment at the satellite. The computations are made on the basis of carrier-to-thermal noise (C/N) ratios. The necessary transmitted power can be calculated from the satellite illumination necessary for the desired EIRP and the saturated flux density in an FM system. Full advantage is taken of the greater flexibility in design of earth station equipment since design restrictions apply to the satellite repeater as a result of limitations on size, weight, and available power.

*Earth Station.* Earth station transmitters operate typically at an output power in excess of 1 kW. For transmission from Los Angeles to New York, for example, the station power of +30.9 dBW, a feed line loss of 4.5 dB, and an antenna gain of 63.3 dB result in a value of +89.7 dBW EIRP for each transmitted carrier [2]. The EIRP is not a true value of radiated power. It is rather an equivalent value stated in terms relative to the power that would be radiated for each carrier by an isotropic antenna. The above values are summarized in Figure 18-4.

PARAMETER	VALUE
Transmitter output power	30.9 dBW
Feed line loss	4.5 dB
Antenna gain	63.3 dB
EIRP per carrier	89.7 dBW

Figure 18-4. Earth station EIRP per carrier for Los Angeles-to-New York uplink transmission.

*Transmission Loss.* The path loss at 6 GHz for the Los Angeles-to-New York uplink is 199.4 dB. In addition, allowance is made for 0.3 dB loss due to earth station tracking error and 0.1 dB for atmospheric attenuation. When these losses are combined with the 89.7 dBW EIRP for the transmitter, the isotropic received power (the power that would be received by an isotropic antenna) is found to be  $-110.1$  dBW, as shown in Figure 18-5. The gain of a one-square-meter antenna is 37.0 dB to give a satellite illumination, or flux density, of  $-73.1$  dBW per square meter. This meets the Comsat General Corporation requirement of  $-72.7 \pm 1.5$  dBW per square meter for the satellite.

PARAMETER	VALUE
EIRP per carrier	89.7 dBW
Earth station tracking loss	0.3 dB
Atmospheric attenuation	0.1 dB
Path loss	199.4 dB
Isotropic received power	$-110.1$ dBW

Figure 18-5. Isotropic received power for Los Angeles-to-New York uplink transmission.

*Satellite.* The signal is received at the satellite by an antenna having a gain of about 31.1 dB. With off-axis and pointing losses totaling about 2.6 dB for the Los Angeles-to-New York uplink and a feed line loss of 3.8 dB, transmission from the antenna to the receiver has a gain of 24.7 dB. (For Hawaiian and Puerto Rican channels, the feed line loss is 6.8 dB; the 3 dB added loss is due to the use of two combiners.)

Satellite system signal-to-noise performance is a sensitive function of temperature. It has been found convenient to express the transmission properties of the receiving portions of the system as a gain-to-temperature ratio,  $G/T$ . The satellite receiving system operates at a noise temperature of 2140 kelvins, referred to the receiver input; it includes a receiver noise temperature of 1850 kelvins. Thus, the receiving system operates at a ratio,  $G/T = -8.6$  dB as shown in Figure 18-6. The Communications Satellite Corporation, Comsat, requirement for this parameter is a minimum of  $-9$  dB relative to 1 kelvin.

PARAMETER	VALUE
Antenna gain	31.1 dB
Off-axis & pointing losses	2.6 dB
Feed line loss	3.8 dB
System noise temperature	33.3 dBK
Receive G/T	-8.6 dB

Figure 18-6. Satellite receiver effects on Los Angeles-to-New York uplink transmission.

*Carrier-to-Noise Ratio.* The thermal noise power at the receiver input may be computed by

$$P_a = 10 \log (kTB \times 10^3) \text{ dBm}$$

where  $k$  is Boltzmann's constant ( $1.3805 \times 10^{-23}$  joule per kelvin),  $T = 2140$  is the noise temperature in kelvins, and  $B = 36 \times 10^6$  is the noise bandwidth in hertz. When all these values are combined with the  $-110.1$  dBW isotropic received power, it is found that for Los Angeles-to-New York transmission, the uplink carrier-to-thermal noise ratio is  $C/N = 34.3$  dB as summarized in Figure 18-7. Although computational details differ somewhat for other earth stations, the system is arranged to produce about the same  $C/N$  value for all uplinks.

PARAMETER	VALUE
Isotropic received power from Figure 18-5	-110.1 dBW
Received G/T from Figure 18-6	-8.6 dB
Boltzmann's constant	228.6 dB
Noise bandwidth	75.6 dB
Uplink carrier-to-noise ratio	34.3 dB

Figure 18-7. Uplink carrier-to-noise ratio for Los Angeles-to-New York transmission at 6 GHz.

**Downlink Transmission.** Similar computations must be performed to determine the transmission over the 4-GHz downlink. The design of this path is also related to the greater flexibility in earth station arrangements relative to those possible in the satellite. Transmitter power from the satellite is much lower than that attainable from the earth station. The design of the earth station results in an extremely low receiver noise figure and higher antenna gain relative to



those of the satellite repeater. The earth station receiver system operates at a low noise temperature of about 60 kelvins.

*Satellite.* The satellite transmitter operates at +7.0 dBW (5 watts) and, with a feed line loss of 1.3 dB, produces a power at the antenna feed of +5.7 dBW (+2.7 dBW for Hawaiian and Puerto Rican transmission due to a 3 dB combiner loss). The antenna gain is 30.3 dB, for Los Angeles-to-New York transmission, which is reduced to 28.1 dB by off-axis loss. Thus, the EIRP per carrier is  $28.1 + 5.7 = 33.8$  dBW as shown in Figure 18-8.

PARAMETER	VALUE
Transmitter output power	7.0 dBW
Feed line loss	1.3 dB
Antenna gain	30.3 dB
Off-axis and pointing losses	2.2 dB
EIRP per carrier	33.8 dBW

Figure 18-8. Satellite transmitting EIRP per carrier for Los Angeles-to-New York downlink transmission.

*Transmission Loss.* The satellite-to-earth path loss at 4 GHz for transmission from Los Angeles to New York is 196.4 dB to which 0.1 dB must be added for atmospheric attenuation. With 33.8 dBW for the EIRP value, the resulting isotropic received power is  $-162.7$  dBW per carrier as shown in Figure 18-9. The gain for an antenna of one square meter is 33.5 dB which results in a satisfactory earth station illumination of  $-129.2$  dBW per square meter.

PARAMETER	VALUE
EIRP per carrier	33.8 dBW
Atmospheric attenuation	0.1 dB
Path loss	196.4 dB
Isotropic received power	$-162.7$ dBW

Figure 18-9. Isotropic received power for Los Angeles-to-New York downlink transmission.

*Earth Station.* The gain to the receiver at the earth station is 60.3 dB, the combination of 60.9 dB antenna gain, an 0.5 dB feed line loss, and an allowance of 0.1 dB loss for an antenna tracking inaccuracy of one tenth of the received beam width. When these values

are combined with the thermal noise of the receiver (calculated for a noise temperature of 60 kelvins), the received G/T is 41.5 dB as summarized in Figure 18-10. Finally, the receive G/T, the isotropic received power, Boltzmann's constant, and the noise bandwidth are combined to give the downlink carrier-to-noise ratio of 31.8 dB as shown in Figure 18-11.

PARAMETER	VALUE
Antenna gain	60.9 dB
Antenna tracking loss	0.1 dB
Feed line loss	0.5 dB
System noise temperature	18.8 dBK
Receive G/T	41.5 dB

Figure 18-10. Earth station receiver effects on Los Angeles-to-New York downlink transmission.

PARAMETER	VALUE
Isotropic received power	-162.7 dBW
Receive G/T	41.5 dB
Boltzmann's constant	228.6 dB
Noise bandwidth	75.6 dB
Downlink carrier-to-noise ratio	31.8 dB

Figure 18-11. Downlink carrier-to-noise ratio for Los Angeles-to-New York transmission at 4 GHz.

**Overall Transmission.** The C/N ratios for uplink and downlink transmission may be combined to yield the overall C/N ratio for the two links. For the Los Angeles-to-New York example, the overall C/N ratio is found, by combining the uplink and downlink values, to be 29.9 dB. Typical values involving transmission between an earth station in the contiguous 48 states and outlying earth stations are 30.1 dB for Anchorage, Alaska; 29.8 dB for Honolulu, Hawaii; and 29.4 dB for San Juan, Puerto Rico.

**Message Circuit Noise**

The message channels in a satellite system accumulate noise from a number of sources. These include the thermal noise just considered, distortion that results from intermodulation and gain and delay distortion, intersystem interference, and certain ancillary circuits and

equipment. The following discussion of noise is based on the use of 1200 message circuits per radio channel. Intermodulation noise is computed on the basis of an average message channel load of  $-16$  dBm0, a peak factor for 1200 channels of 12 dB, and a 4-dB preemphasis factor [5]. Measurements of early Comstar satellites show performance superior to the computed values; satellite and earth stations have both performed better than anticipated. A number of techniques for increasing the circuit capacity are under consideration. These must be applied in a manner that would permit meeting noise objectives and are being considered primarily to permit a reduction in the per-channel costs.

**Noise Allocations.** Satellite system noise is allocated in the manner recommended by international agencies such as the CCITT and the CCIR [6]. The noise is expressed in pWp0 (i.e., picowatts, psophometrically weighted, at 0 TLP). By taking 10 log of the pWp0 value and adding  $-90$  dB, the noise is translated to dBm0 and then, by adding  $+90$  dB, it is translated to dBrc0. A correction of  $+0.5$  dB must then be added to account for the difference between psophometric and C-message weighting.

The thermal noise associated with the 29.9 dB C/N ratio, previously discussed, may thus be translated to a value of 2490 pWp0 for Los Angeles-to-New York transmission. This is made up of 900 pWp0 for the uplink and 1590 pWp0 for the downlink.

The largest component of distortion noise is that allocated to intermodulation with 1100 pWp0 for the satellite and 500 pWp0 for the earth station, a total of 1600 pWp0 [7]. In addition 135 pWp0 and 225 pWp0 are allocated to the satellite and earth station respectively for delay distortion ripple and 40 pWp0 to the satellite for gain slope across a message channel band [8, 9]. These components add together to give 2000 pWp0 for distortion noise.

There are a number of sources of interference that may disturb a satellite channel. These include internal multipath coupling through adjacent satellite filters, adjacent channels in the satellite or earth stations, adjacent satellites, and terrestrial radio systems. These sources have been allocated 100 pWp0 for multipath coupling, 150 pWp0 each for adjacent channel interference in the satellite and earth station, 700 pWp0 for interference from adjacent satellites into the satellite of interest, 300 pWp0 for interference from adjacent

satellites into the earth station of interest, and 1000 pWp0 for interfering terrestrial radio systems. These sources may produce a total of 2250 pWp0.

Other noise sources include end links (1200 pWp0), FM modulators and demodulators, multiplex equipment, and echo suppressors (500 pWp0). These sources total 1700 pWp0.

Altogether, these noise sources should produce a total of  $2490 + 2000 + 2250 + 1700 = 8440$  pWp0. Satellite circuits that just meet this objective would have noise equal to 39.8 dBrc0.

*Intersatellite Interference.* According to CCIR recommendations, the total interference to a satellite from other satellites should not exceed 1000 pWp0. In order to meet this constraint with each station antenna assumed to have a minimum diameter of 32 feet, the minimum spacing between satellites that operate at 4 and 6 GHz has been found by a joint study group under the direction of the FCC staff to be 4 to 5 degrees.\* This conclusion assumed that the services planned for each domestic satellite system would be as visualized when the study was made. Under conditions other than those assumed, spacing may have to be adjusted to bring interference within limits.

*Sun Transit.* For a short period during each of several days about the time of the spring and fall equinoxes, the sun appears behind the satellite. Emissions from the sun into earth station antennas can make satellite circuits very noisy. This phenomenon can be avoided by switching to a protection satellite at a different longitude. A second antenna continuously tracking the protection satellite and appropriate switching equipment must be provided.

**Speech Processing.** The use of compandors and time assignment speech interpolation (TASI) systems appear to offer the capability of reducing per-circuit costs. In addition, compandors may be used to improve the noise performance of voice circuits. Both methods of speech processing are under study. However, they both tend to increase the average load and the effect on the transmission system must be taken into account before either method is used.

\*R. G. Gould "Report of Meeting on Satellite Spacing," FCC Letter dated March 15, 1974.

Intrasatellite system noise introduced by the use of FM/FDM arrangements is reduced by using bandwidth in the form of a large frequency deviation. The use of compandors for noise reduction and a correspondingly smaller frequency deviation to permit the transmission of more signals appears to be quite attractive economically. For example, it appears possible to increase satellite system capacity by a factor of 1.5 to 2.0 by applying compandors to all the speech channels. The channel noise would increase to about 50 dB<sub>rnc0</sub> by use of the additional channels but is reduced by the compandors to the required value of 40 dB<sub>rnc0</sub> or less. Further advantage cannot be taken because the increase in noise on noncompandored circuits would impose signalling limitations and would not allow the operation of many types of data sets at high bit rates.

A TASI advantage of about two to one appears feasible where coterminous circuit groups are large. A digital version of this mode of operation seems feasible because the digital capacity of the system is high since there is only one intermediate repeater (the satellite) in the system.

### Transmission Delay

With one important exception, the transmission characteristics of satellite facilities can be superior to those of terrestrial facilities that require many repeaters. The exception is the round-trip transmission delay; it exceeds 0.5 second and requires the use of split echo suppressors to control echo that would otherwise be very annoying. The CCITT recommends that only one satellite circuit be used in a telephone connection to avoid excessive impairment.

The split echo suppressor most commonly used is the type 4A; however, even when it is used, connections that include a satellite circuit are more likely to be rated unsatisfactory than those that utilize only terrestrial circuits [10]. However, work is proceeding to develop improved and more economical echo suppressors and echo cancelers. An interim arrangement has been implemented for CONUS transmission using "half-hop" circuits. This technique involves the use of a satellite facility for one direction and a terrestrial facility for the other direction of transmission. A significant reduction in customer reaction to echo has been realized on CONUS connections.

In accordance with the CCITT recommendations, the domestic switched message network is arranged to prevent the inclusion of

more than one satellite facility in a telephone connection. Most international traffic routed through the United States is also protected against tandem satellite connections; some exceptions in international routings may occur.

The long delay on satellite circuits also results in problems with the data transmission techniques presently used on the switched message network. In some forms of satellite data transmission, efficiency is low because of the time taken by the transmission of verification signals and of blocked data retransmissions. In addition, the operation of data sets employing half-duplex operation may be impaired or blocked because, with present arrangements, the data set guard interval is short compared with the transmission delay time. The mode of operation by data customers can be changed to mitigate the first problems. Modifications of data sets are being considered to overcome the start-up problems.

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## Chapter 19

# Supplementary Radio Communications

The microwave radio transmission systems used to provide a large proportion of the telecommunications network are supplemented by a number of other radio communications services. Many of the arrangements for these services provide the equivalent of a customer loop to a remote location, normally mobile. The equipment used to provide these loop services may be of General Trade manufacture or may be manufactured by outside suppliers to Bell System specifications. Privately owned and operated arrangements, of which there are many types, are not discussed.

Most of the services under consideration are relatively small-scale in comparison with other services provided by the overall facility network and only a brief survey is warranted here. However, two of these loop-like arrangements, land mobile and personal paging services, are in fairly common use and growing fast enough to justify more thorough descriptions.

Two rather specialized types of transmission systems are used rarely enough to be given only brief descriptions. These are the high-frequency radio systems and the tropospheric scatter systems. These system types have limited and rather specialized fields of application.

### 19-1 LAND-MOBILE COMMUNICATIONS

Domestic public land mobile service provides telecommunications to moving vehicles using the Bell System facility network. In some instances, equipment designed for these purposes is used to provide service to fixed locations that are otherwise inaccessible. Such an

application is called "rural radio" service. There are also many private mobile services relating to police and fire activities, utility maintenance, transportation dispatching, and other activities. Public service is also provided by other radio common carriers that operate competitively on different channel assignments in the same RF bands.

Public demand for such service has grown steadily and in certain locations it has been impossible to satisfy this demand because of the limited frequency band allocated. Only 10 channels are available in the 35-MHz band, 11 in the 150-MHz band and 12 in the 450-MHz band. Early in 1974, the Federal Communications Commission (FCC) allocated a total of 40-MHz in the bands from 825 to 845 MHz and from 870 to 890 MHz for this service. A high-capacity mobile telecommunications system is being developed to utilize these bands by an approach that permits efficient communications by switching the transmission channel automatically as the mobile unit moves about the area [1]. This mode of operation may well provide the means for rapid expansion of land mobile services.

Until the early 1960s, essentially all land-mobile network communications service required a mobile service operator to assist on all calls and push-to-talk operation was required at the mobile stations. With push-to-talk operation, the mobile station user could listen with the telephone handset off-hook and held to the ear. However, to talk over the connection, it was necessary to depress a push-to-talk button on the handset.

Improved mobile telephone service (IMTS) was introduced during the 1960s with the development of two new mobile telephone systems, the MJ system operating in the 150-MHz band and the MK system operating in the 450-MHz band. Except for the frequency bands, these systems are somewhat similar and operate compatibly with step-by-step, No. 1 and No. 5 crossbar, and No. 1 and No. 2 Electronic Switching Systems.

With IMTS, it is possible to dial directly, without operator assistance, from a mobile unit when it is in its home service area. Similarly, incoming calls to the mobile unit are on a direct-dial basis. Each mobile unit is assigned a standard 10-digit telephone number distinct from any other number in the switched message network.

The new systems have a number of features not previously available. These include automatic channel access, automatic number identifica-



tion (ANI) and increased privacy. The system can also be arranged to provide dial service to roamers, i.e., to those mobile units that have left their home areas and desire to operate with systems in the areas in which they are temporarily located.

### System Layout

The principal elements of a land-mobile radio communications system are a control terminal with connections to the switched message network, base station radio transmitter and receivers, and mobile station equipment. The mobile station equipment includes an antenna, transmitter and receiver circuits, supervisory and control circuits, and a telephone station set. The system elements, essentially the same for 150- and 450-MHz systems, are illustrated in Figure 19-1 for an MJ-type system [2].

The area covered by the arrangement of Figure 19-1 is typically 30 to 40 miles in diameter. The base station transmitting equipment may be located some distance from the control terminal and is usually connected by private line facilities. Up to 11 MJ channels and/or 12 MK channels can be assigned within this area. Each channel is equipped with a 50- to 250-watt transmitter at the transmitting antenna site with the output power depending on the area to be covered and FCC radiation restrictions. Base station receivers may be located about the area as required to compensate for the lower output power of the mobile station transmitters, nominally 20 watts.

### Channel Frequencies and Uses

Figure 19-2 shows the channel designations and frequency assignments for the three bands allocated to the Bell System for land-mobile radio communications. Note that four-wire duplex transmission is provided between base and mobile stations.

Signals carried in these channels are phase modulated radio frequency (RF) carriers with a maximum deviation of  $\pm 5$  kHz. The characteristics of the mobile equipment and the applicable performance requirements are explicitly specified [3]. Interference patterns that affect transmission have been studied and much of the system engineering and applications have been related to the results of those studies [4].

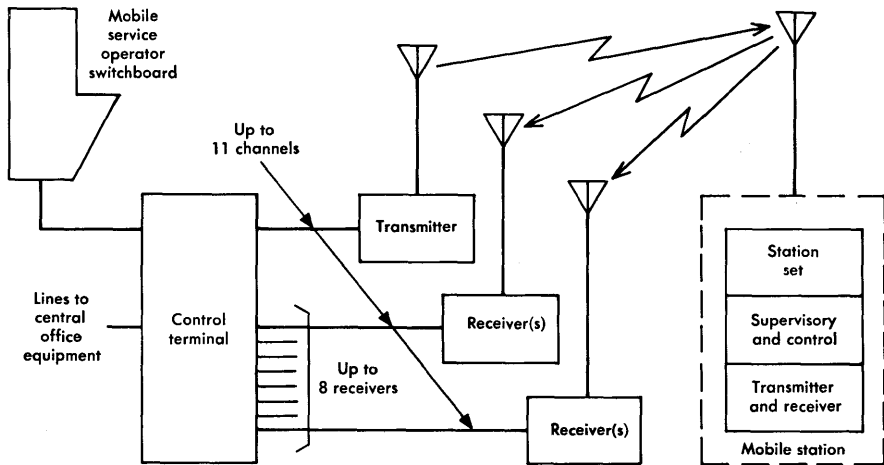


Figure 19-1. Typical IMTS layout for one MJ system service area.

CHANNEL	TRANSMIT FREQ, MHz	
	BASE	MOBILE
ZO	35.26	43.26
ZF	35.30	43.30
ZH	35.34	43.34
ZM	35.38	43.38
ZA	35.42	43.42
ZY	35.46	43.46
ZR	35.50	43.50
ZB	35.54	43.54
ZW	35.62	43.62
ZL	35.66	43.66

(a) 35-MHz band (Not used for IMTS)

CHANNEL	TRANSMIT FREQ, MHz	
	BASE	MOBILE
JL	152.51	157.77
YL	152.54	157.80
JP	152.57	157.83
YP	152.60	157.86
YJ	152.63	157.89
YK	152.66	157.92
JS	152.69	157.95
YS	152.72	157.98
YR	152.75	158.01
JK	152.78	158.04
JR	152.81	158.07

(b) 150-MHz band (MJ)

CHANNEL	TRANSMIT FREQ, MHz	
	BASE	MOBILE
QC	454.375	459.375
QJ	454.400	459.400
QD	454.425	459.425
QA	454.450	459.450
QE	454.475	459.475
QP	454.500	459.500
QK	454.525	459.525
QB	454.550	459.550
QO	454.575	459.575
QR	454.600	459.600
QY	454.625	459.625
QF	454.650	459.675

(c) 450-MHz band (MK)

Figure 19-2. Land-mobile channel frequency assignments.

### Method of Operation

In IMTS operation, the control terminal automatically selects and marks an idle channel (when available) to be used for the next call whether incoming or outgoing. The control terminal marks the channel by applying a 2000-Hz *idle* tone. Under the control of their supervisory and control circuits, all idle mobile stations within transmitter range hunt automatically for this marked channel and camp on it

until a call is established. The first mobile user to go off-hook then seizes this channel and all other station sets again hunt for a newly marked idle channel. This feature makes it unnecessary to monitor channels manually at a mobile station and affords a degree of privacy when in the automatic mode.

The control terminal circuits are responsible for most of the call-handling processes in IMTS though there are some logic circuits at the mobile stations as well. The control terminal provides a transmission, signalling, and switching interface with the central office.

**Base-to-Mobile Station Calls.** When the telephone number of a mobile station is dialed through the message network, the corresponding central office line from the serving central office to the control terminal is seized. The seizure acts as a signal to the IMTS control terminal equipment to interconnect the central office line and a radio channel and to signal selectively the desired mobile unit. The called mobile station logic circuits recognize the connection of an incoming call and respond by transmitting an *acknowledgment* signal. The control terminal then transmits an alerting signal to the mobile station which actuates an audible signal at the mobile station.

When the call is answered at the mobile station, an *answer* signal is transmitted to the base station. This signal trips the ringing and the circuit is cut through for conversation. When the handset is returned to its mounting, a *disconnect* signal is sent to the base station and all circuits are restored to normal.

**Mobile-to-Base Station Calls.** When a call is to be placed from a mobile station, the telephone handset is removed from its cradle. If the unit is not waiting on an idle channel, a busy lamp at the station set is lit and the transmitter cannot be energized. The handset must then be replaced in the cradle and a subsequent attempt must be made. If the unit seizes an idle channel, the mobile station sends a *connect* tone to the base station.

The control terminal at the base station responds to the *connect* signal by removing the idle tone and sends a seize tone to the mobile station. (This causes all other idle IMTS stations to be disconnected from the channel and to hunt for idle tone on another channel.) When the control terminal is ready to receive signals from the mobile station, the seize tone is removed. The mobile station then transmits its IMTS 7-digit number to the base station for automatic number identi-

fication. If the number is valid, the base station transmits dial tone to the mobile station and the desired number can then be dialed [3]. The 7-digit IMTS number transmitted to the base station includes the three numbering plan area (NPA) digits and the four station code digits but does not include the three digits that identify the local central office. This number scheme limits the number of mobile units in an NPA to no more than 10,000.

Dial pulsing involves the transmission of tone spurts to correspond with each dialed digit. Some mobile systems have been equipped to operate with TOUCH-TONE signalling. This permits mobile users to enjoy some of the service features of ESS offices.

On-hook supervision is indicated in the same manner as in base-to-mobile station connections. As pointed out in that discussion, many other features are designed into the system but are beyond the scope of this chapter. Included are a manual mode of operation that may be used in manual areas and a roaming mode used when a mobile unit leaves its normal home area.

**Mobile Station Features.** The transmission and equipment designs of mobile telephone stations are unique. Special requirements are needed to achieve a level of performance that approaches that of standard telephone sets in the switched message network and to provide the features that are unique to land-mobile service.

*Transmission Features.* Two-wire voice circuits from the central office equipment are transformed into four-wire circuits for transmission between the base and mobile stations. A voice-operated gain adjusting device (VOGAD) is used in the transmission path from the base to the mobile station to regulate outgoing speech volume. In the receiving path from the mobile station, a speech-operated noise-adjusting device (SONAD) provides noise suppression during silent intervals.

*Equipment Features.* The mobile station of an MJ system consists of a radio receiver and transmitter, a control unit, and a telephone set with a push-to-talk feature. The control unit includes 11 selector switches labeled to correspond to the 11 channels of the MJ system. Normally, since mobile units may roam into other serving areas, all 11 channels are equipped.

There are three selectable modes of operation designated *H* (home), *R* (roam), and *M* (manual). When the mobile unit is operating in

the home area, the *H* button is depressed. This conditions the station equipment for IMTS operation and causes the equipment to hunt automatically over only the locally-provided channels to find the one marked with idle tone.

The control unit also includes an on-off key switch for the mobile station and two indicator lamps. The *TRANS* lamp lights to indicate that the transmitter is in the operating mode and the *BUSY* lamp lights if a call is attempted when all available channels are busy. An *AUX* pushbutton is used to enable an auxiliary signal to indicate an incoming call when the called person is out of but near the vehicle.

An MK system has many features similar to those provided in MJ. However, the MK system has no channel selector switches since 12-channel selection is automatically programmed. Furthermore, the MK is not equipped for manual operation and the roam mode of operation is preprogrammed to cover only selected channels outside the home area. The push-to-talk feature is not required.

**Operation Beyond the Home Area.** If this mobile unit moves into another area equipped for MJ system operation, the *R* button is depressed as are the channel selection buttons for those channels provided in that area. The set then hunts automatically over only those channels that have been selected. If the locally-provided channels are not known, the selector buttons may be left in the normal condition and the set hunts over all channels.

If the mobile unit moves into an area that is only equipped for manual operation, the *M* button is depressed. This action disables the automatic channel selection and dialing features. The set now must be operated in the full manual mode for channel selection and the push-to-talk button must be used to turn on the transmitter. It can be held depressed during conversation.

## Channel Loading

Demands for land-mobile telephone service far surpass the ability of the relatively few radio channels available to provide adequate service. The development of 150-MHz and 450-MHz IMTS systems has greatly added to the flexibility of use of the available channels. However, mobile systems are engineered to carry heavier per-channel traffic loads than most other facilities in the switched message network with the result that the grade of service is significantly lower than that rendered in other types of services.

A new design of control terminal has recently been introduced. It operates under the control of a small stored-program computer and has many significant operating improvements. A mobile radio automatic message accounting feature permits calls dialed from roaming units to be processed automatically. One version permits one control terminal to serve many remote locations with a combination of dedicated and switched network facilities. Up to 60 channels can be added on one terminal. The new terminals, designated IMTS-B, are compatible with existing IMTS signalling and radio equipment [5].

## 19-2 PERSONAL PAGING SERVICES

Facilities are provided for one-way signalling over the switched network to a pocket-carried radio receiver. When the person using the receiver is alerted by the coded receiver signal, a telephone call must be placed to a previously agreed-upon central location to determine the message involved. This type of service, called BELLBOY®, is furnished by use of General Trade equipment. The principal system components are a control terminal, radio transmission equipment, and pocket-sized receivers. Reliability is stressed in all components [6]. As with land mobile service, personal signalling service is furnished competitively by several common carriers.

Although most personal paging service is provided at frequencies near 150 MHz, there is a limited amount of service provided in the 35-MHz band. Transmitted signal codes can be either unique combinations of single-frequency tones or, in more modern systems, coded digital signals. Upon receipt of the assigned code, the receiver alerts the customer to a call by audible, tactile, or visible means.

A significant proportion of customers subscribe to two numbers, each with a distinctive alerting signal. This permits them to distinguish between routine and priority calls, between group or individual calls, or between sources such as their office or an answering service.

This service is used by people who rely heavily on communications for their usual activities but who are frequently moving about and have no ready access to a telephone for normal service. Personal paging service is growing rapidly.

### Mode of Operation

In most systems, when a paging signal is to be sent, the caller dials a designated telephone number through the message network to reach

the control terminal for the BELLBOY System in that serving area. The control terminal is equipped with an automatic answering feature and, when the call is received, the terminal returns to the caller a distinctive *start*, or *go-ahead*, signal. Upon hearing this signal, the caller transmits a 4-, 5-, or 6-digit address code by TOUCH-TONE signalling procedures to signal the desired receiver (end-to-end signalling). The address code may be transmitted immediately or put into a queue in a memory bank depending on whether the called station is busy and on the details of control terminal design and operation. The control terminal then causes the queued address signals to be broadcast in the order in which they were received. In some systems, all calls are queued and broadcast sequentially every one or two minutes. The caller may disconnect as soon as the address code has been sent and a *call-accept* signal has been received. In some systems, the 7-digit telephone number assigned each paging receiver may be dialed directly and the called person is automatically paged.

### Control Terminal

The BELLBOY control terminal is connected to one or more central offices by trunks very similar to PBX-central office trunks. These must be arranged so that incoming calls to the control terminal can hunt over busy trunks to find an idle trunk to which the connection is made. If 7-digit numbers are used, the connecting circuits may outpulse digits to the control terminal much as if it were a PBX with direct inward dialing. If end-to-end signalling is used, local and/or foreign exchange lines connect the terminal with the central offices. In some small installations, the interconnection logic that determines the flow of address signals from the control terminal to the radio transmitter is built directly into the terminal circuitry but, in most cases, the terminal is controlled by a programmed miniature computer.

**Capacity.** The capacity of a system depends on the calling rate, the holding times for calls through the system, and the number of address codes that can be constructed from the code format used. Most large-capacity systems can provide service to 50,000 or more customers on one radio channel.

The busy-hour calling rate for personal paging systems now in service is approximately 0.1 to 0.2 calls per customer. This calling rate, when combined with the signalling rate for which the system is designed, determines the overall system capacity. Where the signalling



rate is fast, the system capacity is likely to be address limited but where it is slow, capacity is more likely to be calling rate limited.

The coding of address information can limit the system capacity in several ways. The code format must be large and flexible enough to permit the required number of address codes to be constructed. In addition, the memory and logic capacity of the control terminal must be capable of storing such coded information and of retrieving it quickly and accurately as the queued addresses are transmitted to the receivers. Finally, the time required to broadcast the addresses influences the overall capacity of the system.

A system feature that affects the total addressing time significantly is the number of times the address is transmitted. In early system designs, the address was transmitted three times on the theory that the probability of successful transmission would thus be significantly enhanced. However, studies have shown that the enhancement is slight and now the address is broadcast only once.

**Address Formats.** Two forms of address codes are used to signal BELLBOY receivers; one uses a combination of single-frequency tones and the other uses some form of coded digital messages. Where tone signalling is used, the frequencies must be carefully chosen so that (1) tone selection at the receiver is readily achieved, (2) harmonic relationships among the signals are avoided in order to reduce the likelihood of false signalling due to intermodulation, and (3) possible interferences with critical audio-frequency bands used in the switched message network are minimized. Digitally encoded addresses utilize carefully chosen sequences of 1s and 0s to which digital logic circuits in the addressed receiver can respond. These receivers are not vulnerable to intermodulation and usually incorporate error detection and correction features. Both modes of operation are successfully used.

### Transmitter

Address signals are transmitted by frequency- or phase-modulation of an RF carrier. The maximum deviation for the modulated carrier is  $\pm 5$  kHz. The transmitter output power is expressed as an effective radiated power of 500 watts and must be less if the antenna is higher than 500 feet above average terrain.

Most systems are arranged so that address signals are transmitted from the control terminal to several transmitters located strategically

throughout the serving area. Thus, as the receiver is moved from place to place, the received signal is maintained within an amplitude range consistent with the receiver sensitivity and transmitter output power. The several transmitters are operated simultaneously in some systems and sequentially in others. With simultaneous operation, the interconnecting facilities from the control terminal to the transmitters may have to be delay equalized to provide efficient operation in areas where the transmitter coverage overlaps. If these facilities are not delay equalized, signalling tones in overlapping areas may cancel resulting in no receiver contact. With sequential transmission, the principal penalty is the total time that must be allotted to the transmission of one address signal by all the radio transmitters. This penalty can be overcome in digital systems by operating at a high signalling rate.

### Receiver

The range of operation of a personal paging system transmitter depends heavily on the sensitivity of the pocket receivers, the nature and size of surrounding buildings, and the power output and placement of the radio transmitters. Typically, a range of 4 to 5 miles has been found feasible in city business districts; this may be reduced to as little as 1 to 1.5 miles where building construction methods utilize large amounts of metal and reception is desired inside the buildings [7].

The receiver sensitivity is a design parameter controlled by the manufacturer. Its value must be known when a new paging system is being engineered for service. Sensitivity specifications must include the method of suspending the receiver, an allowance for body effects, temperature variations, and other detailed requirements. Measurements with transmitter frequency deviations appropriate to normal operations must be made.

The receiver must be highly selective in order to function properly in an environment of strong RF signals from other services. The selectivity must be maintained over a wide range of environmental temperatures.

Radiation of RF energy from the local oscillator in the receiver must meet FCC requirements. In addition, two receivers should not interfere with one another when separated by a distance of two feet.

A number of receiver features are offered by manufacturers. For example, a receiver may respond immediately to a paging signal or it may store the signal until interrogated by the called person. This feature is valuable to people who may not want the alerting signal to disturb them or others at certain times. As previously mentioned, receivers may also provide acoustic, visual, or tactile response.

### 19-3 MARINE, AIRCRAFT, AND RAILROAD CUSTOMER SERVICES

In addition to land mobile and personal paging services, several other telecommunications customer services use radio as a transmission means and may be classified according to the locations of the station equipment. These include ships at sea and on inland waterways, aircraft, and railroad trains. The following survey includes a brief description of each of these services, the field of application, and the range of frequencies used for transmission.

#### Marine Services

Public telephone services, designated by the suffix B, between ships and between ship and shore stations are divided into three classes [8]. Public Class I-B stations provide long-range, high-seas, radio-telephone service to ships almost anywhere in the world by the same high-frequency (HF) land facilities as those used for overseas service. Public Class II-B stations (coastal harbor service) provide communications in the medium-frequency (MF) band between shore stations and ships over distances up to about 150 miles. Public Class III-B service operates in the very high-frequency (VHF) band over distances of up to 50 miles maximum. It is used primarily for service between land stations and vessels close to shore or on inland waterways and is often called VHF maritime service.

**Coastal Harbor Service.** Although Public Class II-B service can be provided over distances of up to a maximum of about 300 miles under certain conditions of transmission, coastal harbor service ranges vary widely and are often limited to less than 100 miles. Service along the Atlantic, Pacific, and Gulf coasts is provided by channels in the MF band. A limited amount of service is also available in the Mississippi valley and on the Great Lakes. Under the Rules of the FCC, all MF and HF double-sideband equipment used for coastal harbor service was converted to single sideband operation on January 1, 1977; the 2182-kHz calling and safety channels may still be used as double-sideband channels.

**VHF Maritime Service.** Reliable operation and good transmission quality is provided by frequency-modulated signals at VHF when the marine station is within about 20 miles of the land station. Channels for this service, sometimes also called VHF-FM service, are located between 157 and 162 MHz. Under the FCC Rules, VHF-FM capability on a vessel is a prerequisite to granting a license to operate in other frequency ranges and the use of other frequency ranges is prohibited when the VHF range is adequate.

**Calling and Safety Channels.** Two channels, channel 51 at 2182 kHz and channel 16 at 156.8 MHz, are used for voice communications during calling intervals. After initial contact has been established, the stations shift to other channels for continued operation. Communication on the calling and safety channels may be continued only in the case of distress situations.

Three classes of spoken emergency signals are recognized and, by law, must be given priority over other types of signals at all times. The call signal, MAYDAY, has highest priority and is used if there is immediate danger of loss of life or property. The second priority signal, PAN, is used when the safety of a vessel or person is in jeopardy. For example, a "man overboard" call signal would be transmitted as a PAN signal. The third priority signal, SECURITY, is used to convey messages concerning the safety of navigation or to transmit important meteorological information. The appropriate word, MAYDAY, PAN, or SECURITY, is spoken three times to attract attention before the rest of the message is transmitted. The calling and safety channels are monitored continuously by many Coast Guard and public coast stations and by many vessels while they are at sea.

### **Aircraft and Railroad Services**

Radio-telephone communication between land stations and moving private aircraft is available throughout most of the country. The radio equipment operates in the 460-MHz region of the frequency spectrum. With this service, communication is established through the switched message network by manual methods similar to those previously used for public land-mobile communications.

The only public radio-telephone service supplied to moving trains is that used with the Metroliner trains that operate between New York City and Washington, D. C. Six two-way channels are provided

in the 400-MHz region of the spectrum. Nine land-based stations are located along the route. Access to the switched message network and control of transmission and reception from these stations are centered in Philadelphia, Pennsylvania [9].

#### 19-4 SUPPLEMENTARY LONG-HAUL RADIO FACILITIES

While the line-of-sight microwave systems discussed in Chapters 16 and 17 are the most commonly used radio systems among network transmission facilities, tropospheric methods of transmission and high-frequency radio transmission are also used for some overseas service and to fill certain other special long-haul needs. Neither of these is used extensively and only brief discussion is warranted here.

##### Tropospheric Transmission Beyond Line of Sight

Microwave radio transmission is usually considered reliable only between antennas that have an unobstructed line-of-sight path between them. However, transmission has been found to be practicable over paths longer than the line-of-sight path by taking advantage of reflection, refraction, and diffraction phenomena in the troposphere (up to 7 to 10 miles above the earth's surface) [10].

Systems of this type are usually called tropospheric scatter systems but are also referred to as troposcatter, forward scatter, UHF scatter, over-the-horizon, or beyond-the-horizon systems. They use large, highly directive antennas, and high-powered transmitters. Satisfactory transmission is achieved over hops of up to 300 miles. As a result, such systems are attractive for providing service to off-shore islands where traffic is not sufficient to justify installation of an undersea cable system or a satellite system and where a line-of-sight radio system would be blocked by the curvature of the earth. They are also used in the Arctic where the maintenance of line-of-sight systems would be costly and where message channel capacity requirements are low. A major installation of this type, called the White Alice System, provides military and commercial telecommunications services in Alaska [11].

Transmission of RF energy from one antenna to another depends primarily on the reflection and refraction of radio waves from atmospheric irregularities and on diffraction of the waves as they pass over the earth's surface [12]. The latter phenomenon is most effective

when the obstacle that blocks the line of sight approaches the characteristic of a knife edge. Thus, where possible, tropospheric system antennas have been located so that relatively sharp mountain ranges provide the needed knife-edge terrain contour.

Selective fading is a principal source of impairment in tropospheric scatter systems. Both slow and fast fading phenomena occur. Slow fading occurs over periods of hours or days and the range of fading is greater than for line-of-sight systems; this is probably caused by changes in atmospheric refraction. However, it is not a sensitive function of frequency and can be compensated by automatic gain control circuits in the receiver. Fast fading is a nearly continuous phenomenon with a Rayleigh distribution; it is related to multipath interference from a multitude of scattering sources at high altitude and is more serious than in line-of-sight systems. The fades are frequency sensitive to such a degree that the number of voice circuits per radio channel is limited to about one tenth as many as for a line-of-sight system. Systems are operated with various combinations of frequency and space diversity automatic switching arrangements and combiners at the receiver site [13].

The tropospheric scatter method of transmission can be used in the VHF (30 to 300 MHz), UHF (300 MHz to 3 GHz), and SHF (3 to 30 GHz) bands. Weak but usable signals may be detected several hundred miles beyond the horizon. The White Alice System operates in the 400 to 900 MHz portion of the UHF band. The choice was made as a compromise; lower frequency operation would require impractically large antennas and higher frequencies would involve excessive transmission loss and fading.

A typical terminal is made up of transmitter and receiver circuits and a complex arrangement of antennas. Two 30- or 60-foot diameter antennas, one for receiving only and one diplexed for transmitting and receiving, are used. The transmitter uses a high-power klystron output stage with bandwidth accommodating the equivalent of 30 to 130 voice channels. A relay station consists of two such terminals back-to-back.

### Overseas Radio Facilities

Three Bell System coastal stations, one each in New Jersey, Florida, and California, are equipped with high-power transmitters and elaborate antenna systems for operation at a large number of channel

frequencies in the HF band between 4 and 23 MHz. Similar non-Bell System stations are located at Honolulu, Hawaii and Mobile, Alabama. Single-sideband transmission is used for communications with vessels at sea and with transoceanic land stations. Propagation problems make it necessary to use channels at different frequencies during various seasons and times of day and to different ship positions.

This mode of transmission has been largely replaced by submarine cable and satellite systems for communications with major countries overseas. As the channels have been released, they have been re-assigned to the developing nations where circuit demand is still low. In addition, HF circuits are commonly used for communications between land stations and ships on the high seas. Radio waves in the HF band are reflected between the ionosphere and the earth and tend to follow the earth's curvature. With high-power output and large antennas, it is possible to communicate with nearly all locations around the world.

Transmission in the HF band is used for long-range, point-to-point communication. The transmitters are sometimes arranged for independent-sideband operation where an upper-sideband signal and a different lower-sideband signal are transmitted at the same carrier frequency. Speech channels are inverted for privacy and some of them are bandshifted to permit a single transmitter to carry as many as four voice channels simultaneously [14].

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**Telecommunications  
Transmission  
Engineering**

*Section 5*

*Digital Systems*

The high-speed operating characteristics, low power consumption, small size, and low cost of solid-state components have made possible the development of a wide range of new electronic systems. These include a number of high-speed digital transmission systems that operate over paired wire cables, coaxial cable, or microwave radio. The repetition rates used in these systems range from 1.544 to 274.176 megabits per second. The various systems and repetition rates have been organized into a hierarchy of time division multiplex arrangements that is the time domain analogy of the frequency division multiplex arrangements previously described. The many digital transmission systems being manufactured by General Trade suppliers and used by the operating telephone companies are not described herein.

The design of digital transmission systems and terminal equipment is critically affected by the characteristics of the transmission media used and by the unique demands of pulse transmission. Chapter 20 examines the relationships among the parameters and describes, in general terms, the processing carried out to prepare digital signals for transmission over metallic media. The effects of signal impairments along transmission lines and methods of dealing with these impairments are discussed. Some aspects of digital system maintenance are also considered.

Chapter 21 gives more detailed consideration to various types of terminal equipment used with digital transmission systems. The digital multiplex hierarchy and the various types of equipment used to generate the hierarchical signals are discussed. Descriptions of a number of types of channel banks (signal processing equipment) are given to show how analog signals are processed to make them satisfactory for transmission.

Chapter 22 covers the transmission lines and equipment used to transmit digital signals between terminals. The processes of reshaping, retiming, and regeneration are described as are some of the unique coding schemes that are used to facilitate transmission. Some line maintenance problems are also briefly discussed.

Chapter 23 examines the transmission of digital signals on microwave radio systems. Digital signal transmission requires some system engineering work that differs from that applied to analog radio systems. The three principal Bell System digital radio systems (the 1A-RDS, the 3A-RDS, and the DR 18A) are described. The 1A-RDS utilizes existing analog radio systems to transmit a 1.544 Mb/s signal simultaneously with a normal analog message load. The 3A-RDS utilizes TN-1 microwave radio equipment to transmit a 44.736 Mb/s DS3 signal and the DR 18A system utilizes regenerative repeaters throughout to transmit a 274.176 Mb/s DS4 signal.

## Chapter 20

# Cable System Design Features

A pulse transmission system may be defined as a carrier system in which the carrier is a series of regularly recurrent pulses. Modulation of the carrier may take the form of varying any of several pulse parameters such as amplitude, duration, position in time, or presence. Thus, the modulation methods are called pulse amplitude modulation (PAM), pulse duration modulation (PDM), pulse position modulation (PPM), and pulse code modulation (PCM). Only PCM lends itself well to the technique of regeneration used in the line repeaters of a digital system. This technique is used to reconstruct pulses that have been impaired by transmission over an imperfect medium and requires the line input pulses to be discrete in amplitude and duration. Although the ability to regenerate the transmitted signal is a requirement imposed by transmission line parameters, the signal processing needed to achieve a suitable format takes place in the terminal equipment.

In PCM, the carrier is modulated by the insertion or removal of pulses in time slots that correspond with the time slots of the pulses in the unmodulated carrier to form a code that represents some characteristic of the modulating signal. Message signals are processed in terminal equipment, called D-type banks, designed to transform each signal from an analog to a digital format (coding), to multiplex a number of such coded signals into a line pulse stream by time division multiplex (TDM) techniques, and to provide timing and synchronization so that the individual message signals can be extracted and restored to their original forms at the receiving terminal.

Most digital systems are designed so that the line signals are re-generated at every repeater; i.e., they are amplified, equalized, retimed, and reshaped to eliminate the effects of noise and distortion. However, a mixture of analog and digital repeaters may be used. In these cases, the signal is amplified and equalized at analog repeater points and regenerative repeaters are used only where required to eliminate the signal impairment accumulated over several analog repeater sections.

The regenerative nature of digital line facilities produces one of the major advantages of PCM transmission, i.e., the noncumulation of line impairments. Message signal characteristics are represented by a coded stream of binary pulses all of which are identical in amplitude, shape, and duration. This pulse stream may be further processed (coded) to make it more suitable for transmission over the repeatered transmission line. Although large on a per-line-section basis, the attenuation, distortion of shape or duration, and induced interference are all virtually eliminated by each regenerative repeater thus producing an unimpaired line signal for transmission to the next repeater. Exceptions are random phase modulation (jitter), which can accumulate in successive repeaters and must be kept small by design, and errors in pulse regeneration.

As digital transmission systems have come into common use, the administration of network signals has led to the development of a digital signal multiplex hierarchy analogous to that found in analog systems. In addition, there is evolving an integration of digital transmission and switching technology which interacts in many ways with the digital multiplex hierarchy.

## 20-1 DIGITAL TERMINAL SIGNAL PROCESSING

The terminal equipment in a digital transmission system must perform a number of functions in processing input analog or digital signals. These functions include filtering, amplitude sampling, coding, timing, framing, synchronization, and multiplexing. As parts of the sampling and coding processes, quantizing and instantaneous companding functions are performed on voice signals. In addition, signaling functions are incorporated. Where appropriate, digital data signal processing is included to enable the simultaneous transmission of various combinations of processed speech and data signals. The terminal equipment processes one or more input analog and/or digital signals to produce a composite digital signal suitable for transmission

over the digital line to a distant terminal where the inverse processes are carried out.

The terminal equipment associated with specific digital transmission systems should not be confused with M-type multiplex equipment which converts signals from one level in the digital hierarchy to another and multiplexes several low-rate signals into one of higher rate and demultiplexes a signal of high rate into several low-rate signals. Of concern here is the equipment in which the primary function is the conversion between analog and digital signal formats.

### Sampling, Quantizing, and Companding

It can be shown that a band limited signal can be represented by amplitude samples taken at regular time intervals at a rate equivalent to at least twice the bandwidth. Furthermore, it can be shown that the original signal can be recovered from these samples with no loss of information [1].

Figure 20-1 illustrates the sampling process as applied to a simple sinusoidal signal waveform. In the figure, the pulses occur at accurately timed intervals and have a finite time duration. They are designated in Figure 20-1 (b) as natural pulses because they depict the amplitude variation of the signal during the time the pulse is present. However, a single value is used to represent the signal amplitude since the sampling time is very short compared to the sampling interval. The total amplitude range is divided into increments (quantized) to be used for signal representation from sample to sample. The number

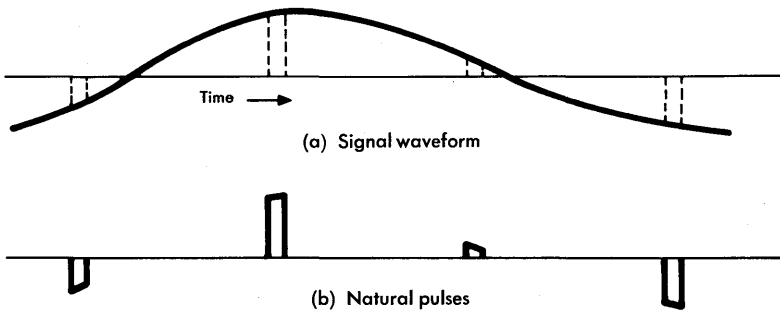


Figure 20-1. Sampling at timed intervals with pulses of finite duration

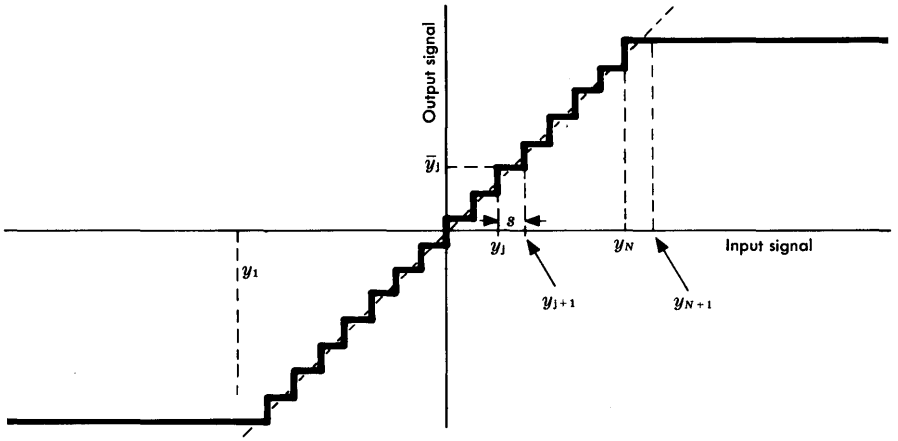
of increments selected is a significant parameter in the accuracy of the representation.

Figure 20-2 illustrates the action of a quantizer in which the total amplitude range is divided into sixteen equal incremental values. The transfer characteristic of such a quantizer is illustrated in Figure 20-2(a). The diagonal dashed line shows the linear input/output signal relationships that would exist without quantization. The heavy "stair-step" shows that for a range,  $s$ , of input signal amplitudes between  $y_j$  and  $y_{j+1}$ , the output signal has a constant value  $\bar{y}_j$ . As shown, the incremental values for the output signal represent uniform quantization steps between the minimum and maximum values that the output signal can attain.

The difference between the quantized output signal and the output signal without quantization, represented as the error signal in Figure 20-2(b), is called quantization noise. The power contained in this error signal may be determined and used for evaluating the resulting signal-to-distortion ratio for this noise.

Figure 20-2(c) shows how a full-load sine-wave signal would be represented with such a uniform quantizing arrangement. For any sine wave having an amplitude in excess of the full-load value, distortion due to overload would be observable at the peak values of the wave. For signals smaller than full-load, the signal-to-distortion ratio would also deteriorate because the quantizing steps would represent a larger proportion of the total signal amplitude. The latter observation suggests a method, called instantaneous companding, be used for improving the signal-to-distortion ratio for low-amplitude signals since these are more prevalent.

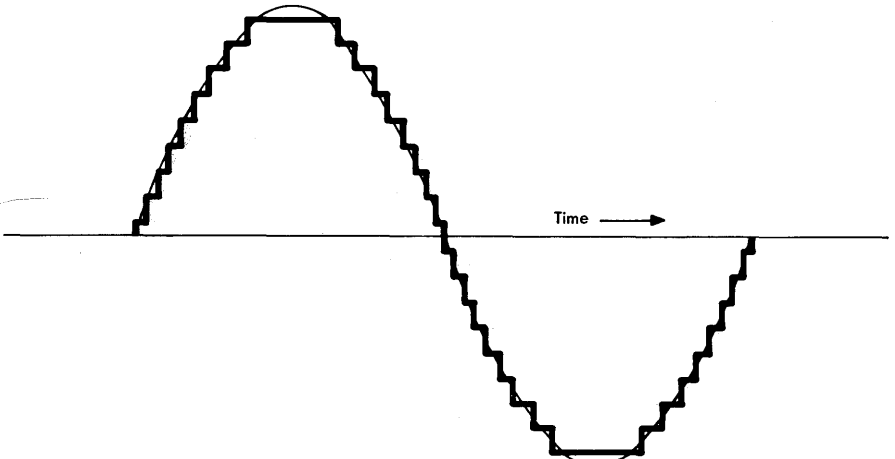
The transfer characteristic of a nonuniform companding quantizer is chosen so that more amplitude steps are used to represent small-signal amplitude variations than are used to represent large-signal amplitude variations. Such a quantizer, illustrated in Figure 20-3(a), would appear to have more nearly equal steps of amplitude if plotted to a logarithmic scale on the ordinate. Figure 20-3(b) shows that less quantizing noise is generated by small signals than by large signals. The selection of a quantizer characteristic to satisfy the signal-to-distortion objectives for the types of signals to be transmitted is made during the design of the system. Where speech is the signal type of greatest interest, a near-constant signal-to-distortion ratio in dB is desirable over a wide range of speech signal amplitudes. Such a



(a) Uniform quantizer transfer characteristic



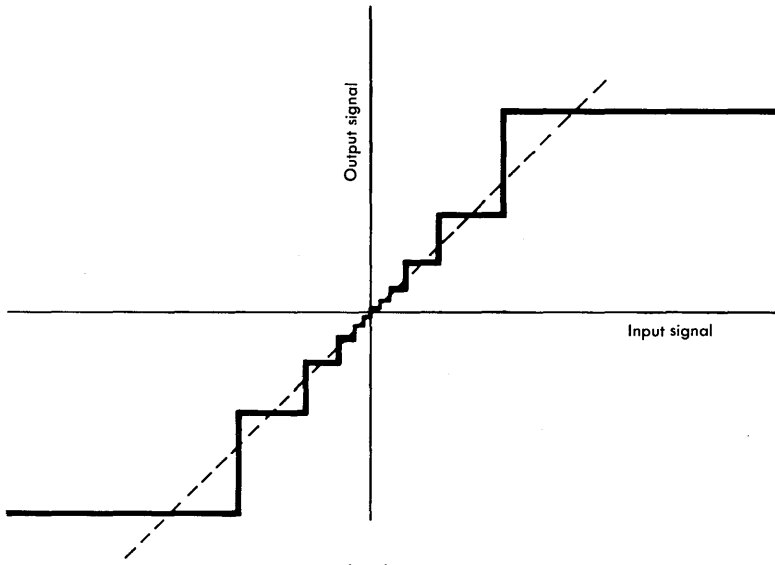
(b) Error signal



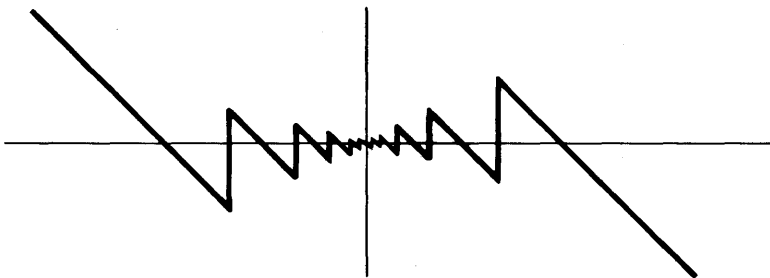
(c) Quantized full-load sine wave

Figure 20-2. Characteristics of a uniform quantizer.

condition is theoretically achievable by the provision of a logarithmic compression characteristic which may be closely approached in practice by the use of modern solid-state circuits [2]. An improvement of about 30 dB in signal-to-distortion ratio for small signals is practicable.



(a) Transfer characteristic



(b) Error signal

Figure 20-3. Characteristics of a nonuniform quantizer.



## Coding

To facilitate the line repeater regeneration process, the amplitude samples just described must be transformed into a format that permits regeneration. For this purpose, it is desirable to transmit a stream of pulses identical in amplitude, shape, and duration. In addition, the pulses must appear in the signal at predictable times and must be controlled in a manner that permits them to be interleaved with other signal pulses, i.e., time division multiplexed. Therefore, the amplitude of each sample is converted to a series of fixed-amplitude, precisely-timed pulses (a binary word) by the process of pulse code modulation.

**Pulse Code Modulation.** The number of quantizing steps used in pulse amplitude sampling has a direct effect on the selection of the PCM coding arrangement. A unique binary code must be used to represent each quantized amplitude. The number of binary digits necessary is thus directly dependent on the number of amplitude steps to be represented over the total range of the quantizer.

For local speech transmission, it has been found satisfactory to provide 128 amplitude steps\*. If each amplitude is to be represented by a binary number, seven bits is the minimum word length that can be used to represent all possible amplitude steps. The process of coding an amplitude sample as a binary word may be accomplished in many ways and by a variety of circuit arrangements. In all cases, the quantizing may be nonuniform, to provide companding, or uniform [2].

A simplified illustration of the entire PCM process is given in Figure 20-4. A very short segment of a speech wave and the PAM pulse samples of the segment are shown in Figures 20-4(a) and (b). In Figure 20-4(c), a 4-bit binary PCM code is illustrated as representing the amplitudes of the PAM pulses. Figure 20-4(d) shows how the binary signal is commonly converted to a bipolar signal for line transmission; 0s in the binary signal are 0s in the bipolar signal but 1s in the binary signal are transmitted as alternate positive and negative pulses in the bipolar format. Figures 20-4(e), (f), and (g) show the processes necessary to recover the original signal from the line signal.

\*To satisfy toll requirements and to allow for the accumulation of noise in tandem terminals, about 256 amplitude levels must be provided.

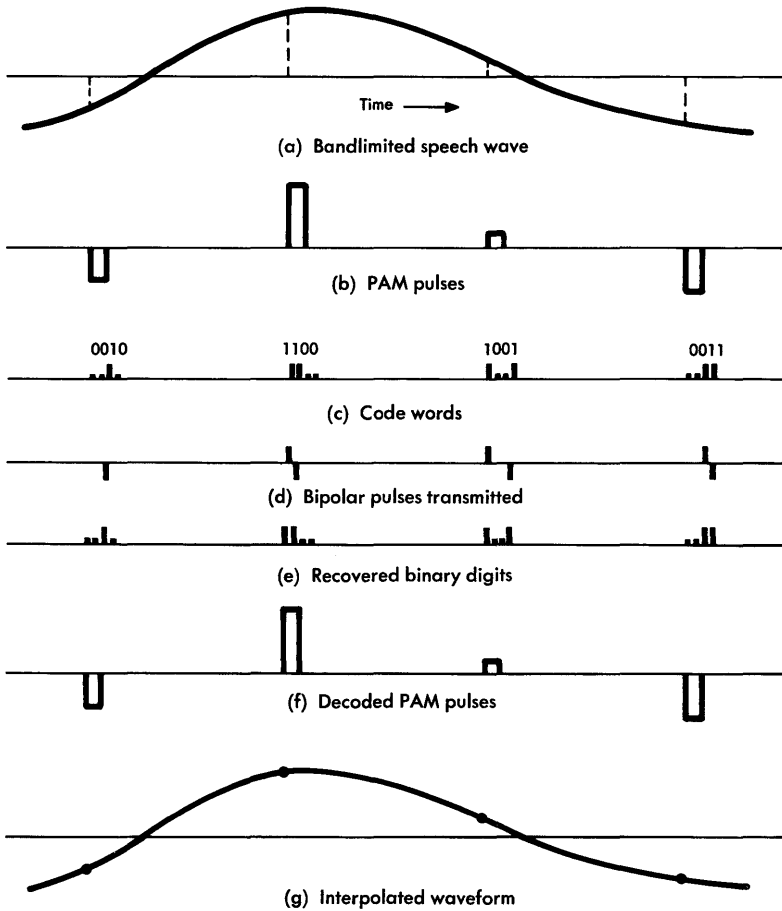


Figure 20-4. Signal processing steps in digital transmission.

**Differential PCM.** Signal coding in PCM requires sampling and the representation of the sample amplitude by a binary code. In differential PCM (DPCM), used in some loop transmission systems, the *changes* in signal amplitude are measured and coded rather than the amplitude values. In some situations, either of the two methods may be used with equivalent performance, thus allowing the method that requires the lower digital rate to be used.

Several special types of DPCM may be used. In one type, the size of the step change is made constant and the difference signal between samples may be coded into one binary digit to convey the polarity of the difference. This method of coding is called *delta modulation*. Large error signals result when the slope of the input exceeds one step per sample. For a smaller input signal slope, the error resembles quantizing noise.

Coding arrangements may also be provided in DPCM with two or three binary digits to represent difference signal polarities and amplitudes. Such systems are called two-bit or three-bit DPCM systems.

**Signalling.** Although 7-bit encoding generally satisfies quality requirements for local speech transmission, the performance improvement realized with 8-bit encoding is great enough that most modern systems use a modified form of 8-bit encoding of input signals. One such 8-bit word is transmitted in succession for each of 24 channels to make up a sequence of 192 time slots. A framing bit is added to form a 193-bit frame. In the modified method of encoding, the least significant digit in each 8-bit word representing a speech sample is used for signalling in one frame out of six. In the remaining five-sixths of the frames, the least significant digit is used to encode additional levels in the input signal waveform. Thus, the encoding is the equivalent of 7-5/6 bits per word. The coding of the signalling bit is adequate to represent all required signalling states.

The simplicity of providing for signalling in digital systems is one of the reasons digital terminal equipment is more economical than analog terminal equipment. This has been a significant factor in the rapid growth of digital systems in the local portion of the facility network.

**Data Signal Processing.** In order to provide flexibility of use for digital transmission systems, the terminal equipment must provide for the processing of digital data signals as well as voice signals. The required processing does not include amplitude sampling or companding but the digital signals must be coded in a manner that satisfies data signal transmission requirements and, at the same time, is compatible with digital line transmission requirements. Furthermore, if the digital signals are to be multiplexed with other digital signals or with digitized speech signals, they must be processed so that the format is compatible with multiplexing, framing, timing, and synchronization functions throughout the system.

A number of types of terminal equipment that meet these complex requirements are available. The designs cover a wide range of input signal characteristics that include synchronous and nonsynchronous signals, serial and parallel data streams, and many different data signalling rates. Some of these equipment types have also been adapted for use with the Digital Data System (DDS) [3].

In some cases, voiceband data signals that can be carried by standard voice-grade message channels may be transmitted over a digital transmission system without processing. In these cases, the signals are treated as analog signals insofar as terminal processing is concerned.

### Multiplexing

The interleaving of pulses that represent the signal amplitudes of different channel signals into a single continuous stream is called time division multiplexing (TDM). The process involves the three major functions of timing, framing, and synchronization.

**Timing.** All of the major logical processes in a digital system terminal depend on accurate timing of the pulses associated with each signal and with the multiplexing of the coded signals into a single pulse stream. In most terminals, the timing is provided by or derived from a single clock circuit that distributes a stream of pulses with a highly precise and stable repetition rate. The sampling and coding functions are controlled by this timing signal so that all pulses are properly related in respect to repetition rate, width, and position in a time sequence.

**Framing.** Detailed methods of multiplexing and demultiplexing digital signals vary from system to system. However, one feature is shared by all. The pulse stream of multiplexed signals must be organized so that the pulses associated with each specific signal can be identified and separated from the other signals in the stream. This is accomplished by organizing the pulse stream into *frames*. The separation of one signal from the others is then accomplished by counting pulse positions relative to the beginning of a frame. In this manner, code words representing the elements of each signal can be extracted from the combined bit stream and reassembled into a single stream of pulses associated with a particular channel signal. This procedure also permits the identification of the most significant digit in a code word.

In D-type banks, the 193rd pulse position in each frame is dedicated to the framing function. A specific and unique sequence of pulses is transmitted in this pulse position to identify the frame length. Since the frame length consists of 193 pulse positions, there are 193 different phases that the receiver circuits can assume but only the one corresponding to the frame format is correct. When this is accomplished, the receiver is said to be in frame.

Deterioration of framing performance may be caused by line errors which alter the framing pattern and cause the receiver to react falsely as if it were out of frame. This condition is called a *misframe*. The mean time between misframes even under conditions of high error rate must be made long to prevent excessive loss of information. The time required to reframe must be kept very short.

**Synchronization.** For satisfactory performance, terminal circuits must be properly synchronized with one another. In the originating terminal, this function is fulfilled by the timing signal previously discussed. Where the function of the equipment is to multiplex digital signals from different sources, it is necessary to assure that all sources are in synchronism or to adjust the rates of the incoming signals before multiplexing. Because of the importance of synchronization, the clock circuits in both cases must be extremely reliable and must produce timing signals with great precision.

**Formation of Line Signals.** The 50-percent duty cycle, bipolar, 1.544 Mb/s, DS1 line signal of a digital transmission system is made up of the elements discussed above, i.e., coded information pulses, signaling pulses, and framing pulses. In addition, signals at higher line rates include control bits, parity bits for error detection, and communication bits for administrative uses. The format of this combined signal must satisfy the requirements of the transmitting and receiving terminal equipment as well as those of the repeatered line.

The basic need is to establish the line repetition rate. This requirement involves the entire system, line, and terminal equipment, and establishes or influences many of the other basic system interrelationships. The factors that most influence the line rate are (1) the number of channels to be provided, (2) the need to sample input signals at a rate equivalent to twice the highest frequency to be transmitted, (3) the number of quantization levels to be provided in the sampling process, (4) signalling requirements, and (5) framing requirements.

The most economical terminal equipment design at present is accomplished, in part, by combining the amplitude samples of all channel signals into a single pulse stream. The coding process can then be applied to this multichannel pulse stream by the use of common equipment. Alternatively, each channel signal sample could be coded by PCM equipment and the separate code words could then be multiplexed into a single bit stream. Since coders must be provided on a per-channel basis in this case, costs may be higher. However, technological economies resulting from the large numbers involved may make costs comparable.

Other system requirements must also be satisfied. To avoid unwanted variations in average signal voltage (baseline wander) while keeping the regenerative repeaters simple and inexpensive, it is often found desirable to form the line signal into a bipolar or similar format [as illustrated in Figure 20-4(d)] in which the dc and low-frequency components are negligible. It is also necessary to restrict the number of consecutive 0s transmitted. This restriction helps to limit baseline wander but it is primarily required to guarantee the transmission of a minimum proportion of 1s to sustain regenerative repeater timing circuit operation. The manner of satisfying these requirements is tailored to each specific system.

**Demultiplexing and Decoding.** At the receiving end of a digital transmission system, the inverse of the processes used at the transmitting end must be provided. Logic circuits, operating on information contained in the framing code, steer the pulses associated with each channel through appropriate gates to separate them from the other channel signal pulses.

The signalling pulses are also removed from the pulse stream and directed to signalling conversion circuits. The PCM pulses are converted to PAM sample pulses which are then passed through low-pass filters to recover the original analog signal. The received signal decoding process, in general, tends to result in a simpler circuit design task than that of the transmitter coding process.

## 20-2 DIGITAL TRANSMISSION LINE

Digital transmission systems have been designed to operate over wire-pair cables or coaxial cable facilities. The signal format is a stream of discrete pulses, generated in the terminal equipment, that must satisfy certain requirements imposed by the repeatered transmission line. In all cases, the line signals are impaired by loss, distur-

tion, and noise introduced by the transmission medium. These impairments are overcome by repeaters placed at regular intervals along the transmission path. In addition, the line equipment must be arranged so that impairment limits are not exceeded.

### Signal Characteristics

Most digital systems transmit bipolar or modified bipolar signals because average values of dc and low-frequency components are minimum and the design of repeater circuits are thus facilitated.

**Line Repetition Rate.** Digital systems involve the transmission of a signal having a fixed repetition rate. This rate is determined by the number of speech channels to be provided, the sampling rate, the number of quantizing levels, the number of bits required to encode each amplitude, and the number of bits assigned to miscellaneous functions, such as framing and channel signalling. For signals above DS1 in the hierarchy, the rate is determined by limitations imposed by the transmission medium and by the number of bits added for framing, synchronization, and other administrative functions. Multiple signals from the lower levels of the hierarchy or other sources are then fitted into the bit stream as efficiently as possible.

These considerations have led to standard line repetition rates which were originally derived to satisfy the requirements of a particular transmission system type. These rates, now designated DS1 (1.544 Mb/s), DS1C (3.152 Mb/s), DS2 (6.312 Mb/s), DS3 (44.736 Mb/s), and DS4 (274.176 Mb/s), form the digital multiplex hierarchy. They are not integrally related because bits are added to each signal to control the multiplexing process and for other service functions.

**Signal Coding Format.** A number of different coding techniques may be used for the line signal of a digital transmission system. The bipolar format, or some code modification such as bipolar with zero suppression, is usually used because dc and very low-frequency signal components are virtually eliminated and because the concentration of energy in the signal is shifted to one-half the baud-rate frequency. The shift of energy to the lower frequency reduces crosstalk coupling, reduces the required bandwidth, and makes the design of timing recovery circuits more practical. In many other types of signal formats, the energy may be concentrated at much higher frequencies or might exhibit a nearly flat spectrum to very high frequencies. The elimina-

tion of dc components permits transformer coupling between transmission conductors and repeaters and facilitates the design of threshold decision circuits by controlling baseline wander.

There are many factors that enter into the choice of code for the transmitted signal for a specific system. Code characteristics may be used to measure the performance of the repeatered line, to derive timing information, to minimize crosstalk, and for a number of other functions. The optimum for each system is that code which provides satisfactory performance most economically and coordinates most practicably with other systems that might operate in the same cable.

### Transmission Line Signal Impairments

The transmission of digital signals from one repeater to another introduces a number of impairments that must be corrected at each repeater. These impairments include loss, distortion, random noise, impulse noise, crosstalk, and echo. In addition, jitter introduced by the regenerative repeaters tends to accumulate from repeater to repeater.

**Distortion.** As in any transmission system that uses wire pairs or coaxial conductors as the transmission medium, the principal impairments are the loss and attenuation/frequency and delay distortions introduced by the cable conductors. These impairments attenuate and distort the pulses and make them unrecognizable. The pulses must be restored at least to the point where detection circuits can recognize the presence or absence of a pulse in each time slot. The impairments are overcome at repeater points by an amplifier/equalizer that introduces attenuation/frequency and delay characteristics that are approximately the inverse of the impairments produced by the transmission conductors. These corrections must be made before the regeneration process is implemented.

**Noise.** As with any other type of system, digital system design and development must be considered from the point of view of thermal noise, impulse noise, and crosstalk. These impairments are controlled by specification of repeater spacings and cable pair usage for the two directions of transmission. However, since the regenerative process eliminates noise accumulation from repeater to repeater, it is possible to consider these phenomena on a per-repeater basis to a far greater extent in digital system design than in analog system design. A characteristic of digital systems is that they perform extremely well up



to a critical value of the signal-to-noise ratio and then deteriorate rapidly when that critical value is passed. Thus, adequate margin must be provided to preserve a satisfactorily low error rate.

These qualitative statements regarding error impairment in digital signal transmission apply quite well where the noise has predictable characteristics and is of a known amplitude. However, these attributes are not always applicable where impulse noise is controlling. Impulse noise consists of large amplitude peaks that occur unpredictably in infrequent bursts against a relatively quiet background. The most common sources of impulse noise are lightning and the switching transients that occur in telephone central offices.

Impulses caused by lightning surges tend to be longitudinally induced in the cable pairs. Thus, the effects of such surges are minimized by maintaining a close impedance balance from each conductor to ground.

Switching transients are most interfering in those sections of cable closest to central offices. They are induced, by cable-pair crosstalk mechanisms, in digital system pairs from voice-frequency pairs where they originate. Control of such transients is achieved by maintaining balance to minimize the effects of longitudinal induction and by designing the repeater sections adjacent to central offices to be shorter than nominal. Thus, signal attenuation is reduced and a higher signal-to-noise ratio is maintained. Also, the digital system and voice-frequency circuits are usually segregated in different cables or in different cable units (binder groups) to reduce the probability of induced transients.

**Crosstalk.** Crosstalk between cable pairs is a limiting impairment in the design of digital transmission systems for use over wire-pair cables [4]. For systems with the two directions of transmission in the same cable sheath, near-end crosstalk (NEXT) is the major interference and, for systems where the two directions of transmission are isolated in separate cables or by shielding, far-end crosstalk (FEXT) is dominant [5]. Therefore, careful studies must be made of the distributions of crosstalk and crosstalk coupling loss.

Because regenerative repeaters are used in digital systems, crosstalk impairments do not accumulate from one repeater section to the next. Averaging techniques used in the design analysis of analog systems cannot be used in the design of digital systems. In such a system, a single repeater section with a slightly lower than acceptable

signal-to-noise ratio can significantly degrade the error performance of the entire chain of repeater sections.

The distribution of the pair-to-pair equal level coupling loss (ELCL) in cables has been found to be log normal. Capacitance balance between pairs is measured during manufacture and, when limits are exceeded, cables are rejected. Since there is a correlation between capacitance unbalance and crosstalk coupling, the distribution of coupling losses tends to be truncated at the low-loss end. A representative distribution of pair-to-pair ELCL for pulp cable measured at 3 MHz is shown in Figure 20-5. Crosstalk coupling loss at frequencies other than 3 MHz can be inferred from known relationships between crosstalk loss and frequency. Crosstalk loss decreases with frequency at 6 dB per octave for FEXT and approximately 4.5 dB per octave for NEXT.

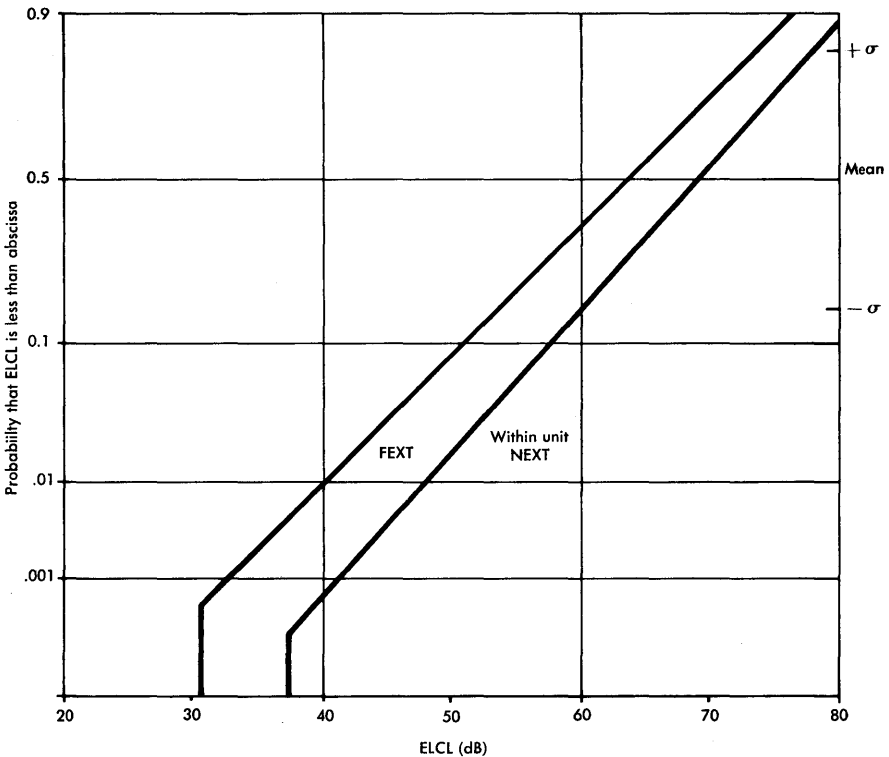


Figure 20-5. Pair-to-pair ELCL at 3 MHz for 1000 feet of 50-pair unit of 22-gauge pulp cable.

In a multipair cable, a given pair receives crosstalk interference from many other energized pairs. Probability theory can be used to obtain the distribution of crosstalk coupling as if it were the power sum of many interferers. The resulting distribution is again log normal. Figure 20-6 illustrates the distributions of NEXT and FEXT when 49 pairs of a 50-pair cable unit crosstalk into one pair. Because of the effect of transmission level point differences, NEXT is far worse than FEXT.

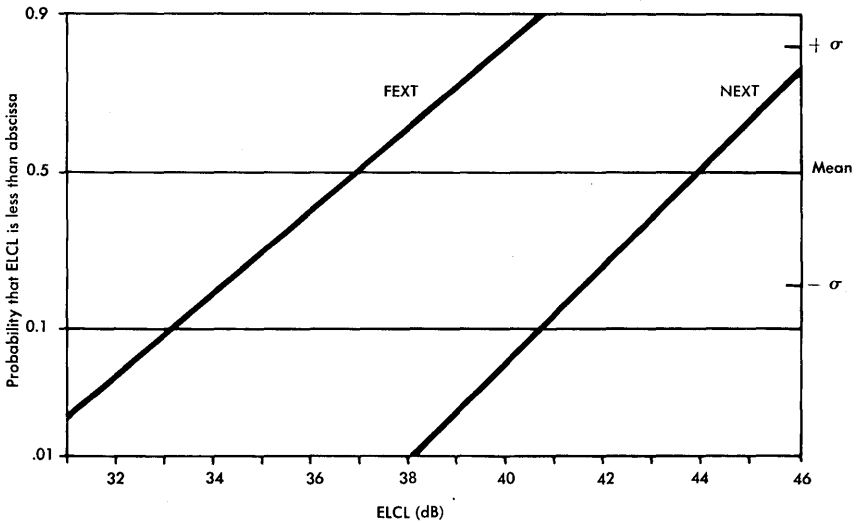


Figure 20-6. Power sum of crosstalk interference from 49 pairs.

Figure 20-7 illustrates the relationship between crosstalk coupling loss and the number of interferers. Because of random addition, the effective coupling loss decreases about 3 dB when the number of interferers doubles. The minimum FEXT shown represents the 99.9 percent limit of the distribution and does not reflect the truncation of the original pair-to-pair ELCL distribution.

Because crosstalk depends on the statistical nature of the paired cable manufacturing process, extensive pair-to-pair coupling loss measurements must be made on new cable designs so that statistical distributions can be established for engineering digital transmission systems.

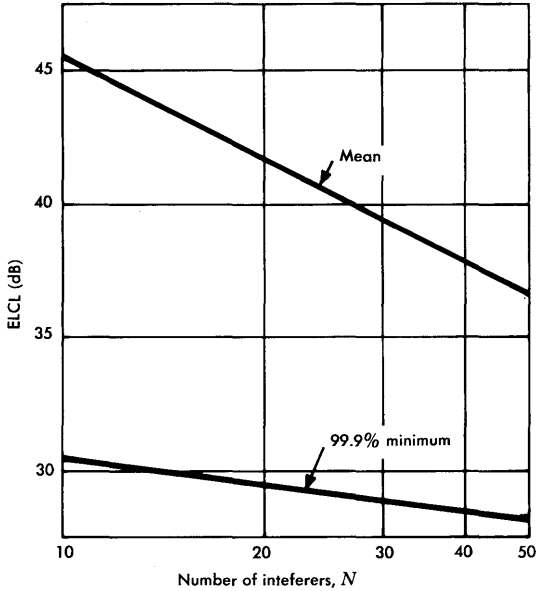


Figure 20-7. Power sum of interfering signals due to FEXT.

**Echo.** The transmission distortions that occur in digital systems all tend to produce intersymbol interference. Signal echoes, which contribute to this type of impairment, are a result of impedance discontinuities that may arise from many sources. To prevent the generation of echoes, the terminating impedances of repeater and terminal circuits are designed to match the impedances of connecting transmission lines or other equipment. However, there are many other sources of echo, such as gas plugs and splices, that must be carefully controlled if system performance is to be satisfactory.

Gas plugs are used in wire-pair cables at points where they enter central office buildings and at maintenance area boundaries. A gas plug is an airtight seal, usually formed from epoxy resin forced into the cable sheath, that allows application of gas pressure between plugs to prevent moisture accumulation. The electrical effect of the plug is to add capacitance concentrated at the plug thus creating a discontinuity in the impedance of the cable pairs. Repeater spacings are made short where gas plugs are used in order to accommodate the added capacitance. Splices in cable pairs also introduce impedance

discontinuities and capacitance unbalance in the transmission paths which can enhance echoes and crosstalk.

Gauge and insulation changes at points where different types of cable are spliced together may also cause impedance discontinuities and echoes. In addition, bridged taps, used extensively in the loop plant but not much in the trunk plant, can also produce echoes. These potential sources of echo impairment must be examined carefully when a proposed new system is being engineered for installation.

### Repeater Characteristics

The regenerative repeaters placed along a digital transmission line perform a sequence of operations which result in an output signal that is an authentic replica of the signal transmitted from the previous repeater or system terminal. These functions include amplification and equalization of the received signal, the generation of an internal timing or clock signal, the slicing of the incoming signal and decision-making as to the presence or absence of a pulse in each time slot, and the regeneration of discrete pulses in the proper time slots to form the original line signal. To support these functions, there must also be circuits to power the repeater and to protect the repeater from lightning or other unwanted power surges [6].

**Amplification and Equalization.** At the input to a regenerative repeater, signal pulses have low amplitude due to the loss of the preceding section of transmission line. The pulses are also badly distorted by the frequency characteristic of the line. Thus, the input circuits to such a repeater provide both gain and equalization as illustrated by the block diagram of Figure 20-8.

The amplification function of the repeater input must provide sufficient gain to compensate for the losses of the transmission line and equalizer. The amplitudes of signal pulses at the output of the amplifier are typically held constant by an automatic line build-out circuit.

The equalization function of the repeater input may be implemented in two steps. A fixed section provides compensation for the attenuation/frequency characteristic of a nominal length of transmission line. A variable section is used to compensate for departures such as differences between actual and nominal repeater section length and loss variations due to temperature.

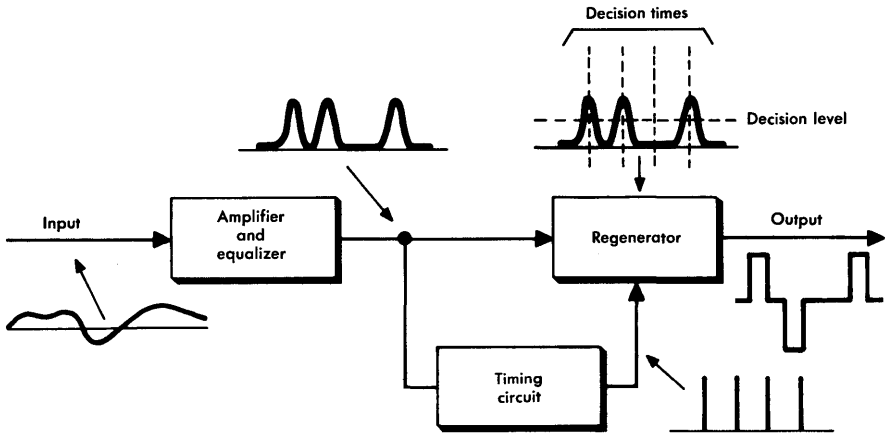


Figure 20-8. Regenerative repeater block diagram.

The design of the attenuation/frequency characteristic of an equalizer for a digital transmission system differs significantly from that for an analog system. The analog system design objective is to produce a constant attenuation/frequency characteristic over the passband of the system. In a digital system, the objective is to optimize the characteristic for pulse transmission. The problem is one of finding a suitable compromise bandwidth which would minimize pulse distortion but not allow too much noise to enter the channel.

The adjustable equalizers, called automatic line build-out (ALBO) networks, now used in most digital system repeaters are automatically adjusted in accordance with the characteristics of the received signal. The equalizer characteristic combined with the line characteristic should result in an overall channel characteristic between the two repeater points that approximates a raised cosine characteristic and, with the transmitted pulse characteristic, meets the Nyquist I criteria for pulse signal transmission [7].

A regenerative repeater is usually ac-coupled to the transmission line by transformers or capacitors. This type of coupling permits the powering of the repeater from direct current carried on the transmission conductors and isolates the repeater somewhat from low-frequency noise on the line. However, it effectively removes the dc and low-frequency components from the signal and thus causes base-line wander which makes it difficult to establish the presence or

absence of pulses. The most common technique used to deal with baseline wander is to place restrictions on the coding of the transmitted signal to reduce the dc and low-frequency content. Another technique, quantized feedback, involves the incorporation of circuits in each repeater to restore the dc and low-frequency signal components. Only weak coding restrictions are imposed.

**Timing.** The regenerated signal transmitted from a repeater must be accurately timed to maintain the proper intervals between pulses and pulse width. As shown in Figure 20-9, the timing information is usually extracted from the line signal after it has been equalized and amplified.

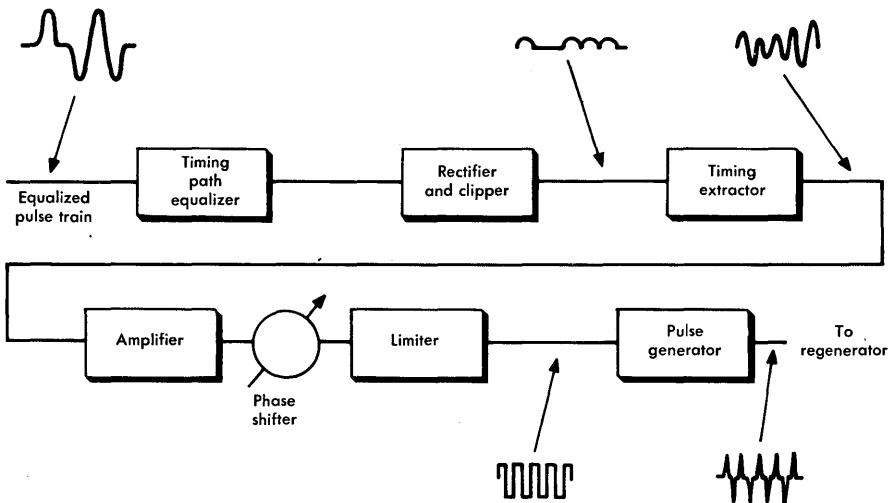


Figure 20-9. Typical repeater timing path.

After additional equalization, used in some systems to optimize the operation of the timing circuits, the incoming signal is rectified and clipped in order to derive a discrete signal component at the line repetition rate. The rectified and clipped signal is then applied to the timing extractor, a circuit tuned to the timing frequency. The  $Q$  of this circuit must be high enough to permit satisfactory timing action during a sequence of 0s in the transmitted signal. The design must be a compromise between circuit performance and signal coding to limit the number of consecutive 0s. The desired sinusoidal timing

component is amplified and limited to produce an approximate square wave at the signalling rate. This signal is then used to control a clock-pulse generator which produces narrow pulses that are alternately positive and negative at the zero crossings of the square wave. A phase-shift circuit in the timing path adjusts the phases of the timing pulses so that they occur at the middle of each signal pulse interval. This method of deriving a clock signal is called forward-acting timing; a digital repeater that uses this type of timing is called self-timed [4].

The narrow positive clock pulses are used to gate the incoming pulse stream into the regenerator. The negative clock pulses are used to turn off the regenerator. Thus, the combination is used to control the width of the regenerated pulses.

The processes of timing and regeneration lead to a signal impairment called *jitter*, the appearance of pulses at timing intervals different from ideal. Jitter, which can be regarded as a random phase modulation of the pulse stream, can lead to crosstalk and distortion in the reconstructed analog signal. From some sources, jitter adds systematically while from others it adds randomly or nonsystematically. Systematic effects degrade the pulse train in the same way at all tandem repeaters. Examples are intersymbol interference, pulse width differences, and clock threshold offsets. Nonsystematic jitter sources include the mistuning of clock circuit filters and crosstalk from other systems. In a long chain of repeaters, jitter performance is usually dominated by systematic effects.

**Regenerator Circuits.** A fundamental function of the regenerator is to examine the incoming signal during each pulse interval and to determine if a pulse is present in that interval. This function is carried out after the signal has been amplified and equalized.

Most regenerative systems transmit bipolar signals such as that illustrated in Figure 20-4(d). Such signals can have (in a pulse interval) one of three states: positive, zero, and negative, usually designated  $+$ ,  $0$ ,  $-$ . The threshold circuits are gated to admit the line signal at the middle of each pulse interval. If the signal is positive and exceeds a positive threshold, it is recognized as a positive pulse. If it is negative and exceeds a negative threshold, it is recognized as a negative pulse. If it has a value between the positive and negative thresholds, it is recognized as a  $0$  (no pulse).



When either threshold is exceeded, the regenerator is triggered to generate a pulse of the appropriate duration, polarity, and amplitude. In this manner, the distorted input signal is reconstructed as a new output signal for transmission to the next repeater.

**Surge Protection and Power.** Operating power for line repeaters is generally supplied by direct current transmitted over the signal conductors. The dc and ac signals are separated and recombined at the repeater terminals. A dc voltage is derived from the dc line current as it passes through power circuit diodes in the repeater.

In many locations with aerial, buried or underground cable, it is necessary to protect the repeater circuits against damage by lightning or other power surges. Primary protection is provided by gas tubes or by standard carbon blocks that limit longitudinal surges to a maximum of about 600 volts peak. Secondary protection is provided by a series connection of parallel, oppositely-poled diodes bridged across each conductor pair. With a current-limiting resistor in series with each conductor, surge currents are limited to a peak value of about 50 amperes.

### Transmission Line Layout

Regenerative repeaters are distributed along a transmission line at distances that are determined by a number of interrelated phenomena. With the initial designs of digital systems, a 6000-foot objective was established for repeater spacings so that manholes and other facilities previously used for loading coils could be reused for regenerative repeaters. The achievability of this objective depended on the control of signal impairments incurred along the line such as thermal noise, crosstalk, impulse noise, loss, distortion, and jitter. When this objective was met, the 6000-foot repeater spacing became near-standard and most digital systems utilizing wire-pair media are designed for this nominal spacing.

Most systems are organized so that up to 25 repeaters can be housed in one apparatus case at each location. This arrangement affords efficient space utilization in manholes or on telephone poles and provides a large enough cross-section of voice channels so that several systems can be operated in one cable and most route capacity requirements can be fulfilled economically. Recent studies indicate that it may be economically desirable to increase the capacity of apparatus cases to perhaps 50 repeaters.

System lengths have been generally constrained by maintenance considerations. In most cases, the overall length is divided into spans that are defined as the maximum allowable distances between central office buildings. These spans must be specified in terms of the maximum distance over which repeaters can be powered from central office power supplies. In addition, it is convenient to regard such spans in terms of maintenance and operating functions and the related equipment in the central office buildings at the ends of the spans.

### 20-3 MAINTENANCE

Manual and computer-aided administration, maintenance, and surveillance systems are now available. These receive trouble reports, direct the transfer of service to standby facilities, and perform diagnostic routines to aid in isolating the trouble.

Most digital transmission system terminals are equipped with carrier group alarm (CGA) arrangements. When a system fails, the network trunks carried by the failed system are processed so that false charges do not accrue. The trunks are usually made busy as long as the failure persists so that they cannot be seized and thus tie up common switching equipment. They are automatically restored to service when the system is repaired.

The basic maintenance requirements for a digital transmission system are filled by equipment capable of detecting errors in or loss of the line signal, of determining the location of a faulty repeater, and of transferring service (manually or automatically) from a failed line to a standby line. These functions are fulfilled by equipment of various degrees of sophistication depending on the length of the systems and on the number of voice circuits that can be affected by failure.

The error-detection function is usually related to the basic characteristics of the transmitted signal. For example, the 1s that are encoded into the bit stream of a bipolar signal are transmitted alternately as positive and negative pulses. When two successive pulses are of the same polarity, the bipolar characteristic is violated and recognized by bipolar violation detectors. Other forms of error detection are used for other types of signals.

In some systems, when a complete loss of signal is detected, service is switched automatically to another line and an error-free test signal

is substituted on the defective line; thus, subsequent spans do not respond to the trouble condition. This procedure, in effect, provides isolation of gross troubles to a span.

Fault location procedures usually take the form of inserting a signal in the defective span with intentional violations of the code format. These violations are introduced at an audio rate and a voice-frequency signal is returned on a maintenance pair in such a manner that the defective repeater can be identified.

Most installations of short digital systems are operated with one or more powered standby systems, called maintenance systems, on the same route. When a working line fails, service may be switched or patched to a maintenance system. Automatic switching is sometimes provided for exceptionally long systems and for those carrying 96 or more circuits.

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## Chapter 21

# Digital Terminal and Multiplex Equipment

Digital transmission and switching facilities are being used increasingly throughout the telecommunications network. When this network began to take form, T1 was the only digital transmission system. One type of terminal equipment, called D1 banks, was used to transform voice-frequency signals to a digital format compatible with the line signal required by the T1 carrier system. Now, there are a number of transmission system types together with a variety of terminal and multiplex equipment to operate with each type.

The digital network is evolving in a manner similar to that of the analog network. A hierarchy of transmission rates, called digital levels, has been established and will undoubtedly expand as the digital network expands in flexibility and size. These levels are designated by digital signal (DS) numbers that increase with the rates from DS0 to DS4. The rates are not integral multiples of lower rates because, at each level, bits are added to facilitate multiplexing and other service functions.

The digital multiplex units used to translate from one digital level to another are designated by a prefix M (for multiplex) followed by two digits that designate the steps in the translation process. For example, M13 multiplex equipment is used to multiplex several DS1 signals into the DS3 stream and to demultiplex the DS3 signal into its constituent DS1 signals.\* The M1C multiplex unit, an exception to this numbering plan, combines two DS1 signals to form a DS1C signal.

\*In this case, the process is called "skip level multiplexing" because level 2 is omitted from the process.

The terminal equipment units are referred to as D-type banks and provide the interface between analog circuits and digital multiplex equipment and/or transmission lines. Analog signals are processed into a digital form and multiplexed for digital system transmission in one direction and demultiplexed and processed for analog transmission in the other direction. Other types of banks are used at the terminal locations of digital systems for processing digital data signals. In some cases, these banks are arranged to multiplex a number of data signals into a single bit stream for transmission. In other cases, the data signals are multiplexed with various combinations of processed analog signals.

A number of equipment arrangements are available to provide the interface between transmission systems and electronic switching systems (ESS). The processing of signals for time division switching by the No. 4 ESS is so similar to that used in D-type banks that in some of these arrangements signals may be switched without processing to an analog format. In other arrangements, analog circuits similar to those of the D-type bank have been used directly as the trunk circuit terminations at an analog ESS. Both of these arrangements have resulted in substantial cost savings at the point of interconnection between digital transmission systems and electronic switching systems.

The flexibility that has been provided in the digital hierarchy permits future expansion to include higher transmission rates and a number of other features. For example, an experimental coder-decoder (codec) has been developed to permit the translation from an analog to digital (and digital to analog) format of 720 telephone channels. This digital mastergroup signal is transmitted at the DS3 rate [1]. The mastergroup and other broadband codecs will permit the efficient use of new technology such as waveguide and optical fiber (lightwave) communications systems by providing economical means for interconnecting these and existing analog systems.

## 21-1 THE DIGITAL MULTIPLEX HIERARCHY

Just as the development of J- and K-type carrier systems established the 12-channel group as the first and basic building block in the frequency division multiplex (FDM) hierarchy, the development of the 24-channel T1 carrier system established the basic building block in the time division multiplex (TDM) hierarchy. In TDM, the basic unit is the DS1 signal with a digital transmission rate of 1.544 Mb/s,

a rate suitable for the time division multiplexing of 24 digitally-encoded voice-frequency signals. Other levels of the hierarchy are related to the basic DS1 rate but, as previously mentioned, not by integral multiples. However, all the rates are integral multiples of 8 kb/s. The hierarchical levels and the types of multiplexing equipment used for the translation of signals between levels are shown in Figure 21-1.

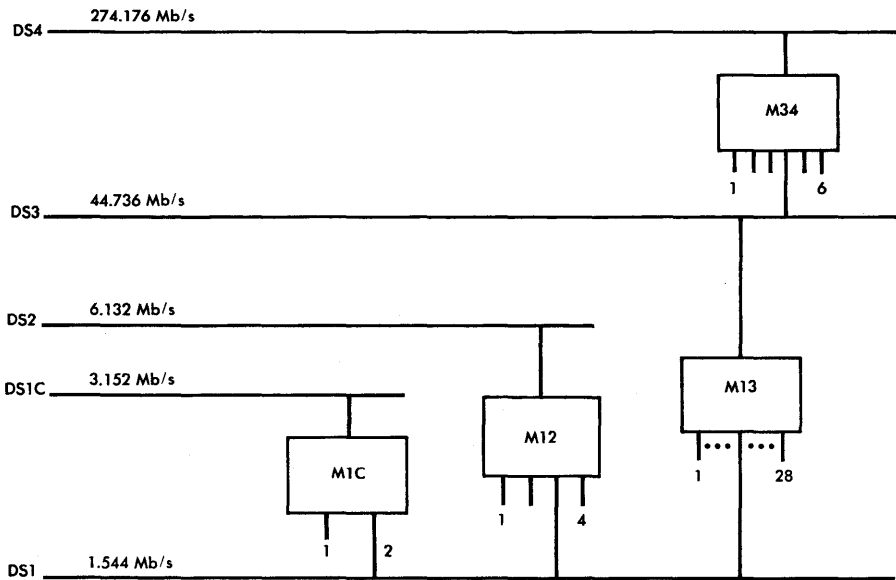


Figure 21-1. Digital hierarchy and multiplexing plan.

The organization of the bit stream and the format of the transmitted signal must simultaneously satisfy two sets of criteria at any level in the hierarchy. First, the signal must satisfy interconnection and transmission requirements imposed by the transmission facility to be used. These requirements are expressed in terms of signal characteristics observed at a cross-connect frame. Included are such parameters as the transmission rate, the signal format (i.e., whether the signal is polar, bipolar, or multilevel), the location in the bit stream of parity bits required by the transmission system, pulse amplitude, allowable number of consecutive zeroes, etc.

The second set of requirements imposed on the bit stream is a function of the methods of multiplexing and the message signal, fram-

ing, and signalling formats. They are imposed to assure compatibility of the signal with terminal equipment used at the ends of the facility.

### The 24-Channel DS1 Signal

The DS1 is a bipolar 50-percent duty cycle signal made up of 1.544 million time slots per second in each of which one bit, a 0 (no pulse) or a 1 (pulse), may be transmitted. This signal may be processed in a number of ways to make it suitable for transmission over a particular type of facility or for multiplexing with other DS1 signals.

The 1.544 Mb/s transmission rate for the DS1 signal was originally derived to satisfy transmission constraints imposed by repeater design and cable characteristics for the T1 carrier system. The objective was to provide a transmission rate that could accommodate a number of voice-frequency (VF) signals that had been suitably processed for digital transmission. The number of VF channels that was shown to be feasible was 24, sometimes called a digroup. The basic requirement is that of sampling an analog signal at a rate at least twice that represented by the channel bandwidth in hertz. Thus, each 4-kHz channel signal had to be sampled at a rate of 8000 per second to produce a pulse amplitude modulated (PAM) signal.

The next requirement to be satisfied was derived from the combination of processes in pulse code modulation (PCM), i.e., the representation of each amplitude sample by a quantized voltage and the conversion of that voltage into a pulse code in which a constant number of bits were assigned to represent the various quantized voltages. To satisfy initial local trunk transmission quality and signalling requirements, each of 128 quantum levels and the signalling state of the channel being sampled are portrayed by an 8-bit code word. In channel banks of later design, 256 quantum levels are coded 5/6 of the time. Signalling information is carried in the 8-bit code word 1/6 of the time.

The third requirement to be fulfilled is that of providing a pulse sequence that can be used to decode the received signal. For this purpose, the line signal is organized in blocks of pulse positions called frames. Each frame is defined as a sequence of time slots made up of one 8-bit code word for each of the 24 channel signals. Thus, a frame consists of 24 channel samples  $\times$  8 bits per sample = 192 bits. At the end of each frame, an extra bit is added to the signal to

identify the frame sequence and to synchronize the channel bank circuit operations. When the frame rate is combined with the sampling rate of 8000 per second, the DS1 signalling rate is determined to be  $193 \times 8000 = 1,544,000$  bits per second, 1.544 Mb/s.

In a complete signal, the eight bits representing each VF signal amplitude sample and signalling state are random sequences of 1s and 0s. Thus, each sequence of 192 bits in a frame is made up of random 1s and 0s. In early equipment designs, the framing bits that follow each 192-bit sequence are transmitted as alternate 1s and 0s thus providing a coded sequence of framing pulses (1 0 1 0 1 0 . . .) that can be recognized by the receiving terminal. In later designs, the framing pulses are coded as a repeating sequence the basic combination of which is the series 1 1 0 1 1 1 0 0 1 0 0 0.

Coding is sometimes modified for improved performance and, when other than speech signals are to be transmitted, the code format is modified as necessary for the particular signals involved. However, the basic rate of 1.544 Mb/s is maintained in all cases in order to satisfy the requirements for transmission over T1 repeatered line facilities.

### The DS1C Signal

Two DS1 signals are combined to form a DS1C signal but, as received, they are generally not synchronized with one another nor with the new DS1C signal. The transmission rate for each of the DS1 signals is nominally 1.544 Mb/s while the transmission rate for the DS1C signal is 3.152 Mb/s. Thus, there are approximately  $3152 - 2 \times 1544 = 64$  kb/s used for synchronization and framing of the DS1C signal. The synchronization of the two DS1 signals to make them alike in repetition rate and of a rate suitable for incorporation into a single DS1C bit stream is accomplished by a process called *pulse stuffing*. In this process, time slots are added to each signal in sufficient quantity to make the signal operate at a precise rate controlled by the clock circuit in the transmitter. Pulses are inserted (or stuffed) into these time slots but carry no information. Thus, it is necessary to code the signal in such a manner that these noninformation bits can be recognized and removed at the receiving terminal. This coding is incorporated at the point where the two DS1 signals are multiplexed together to form the DS1C signal. For convenience, the two signals are designated No. 1 and No. 2.



The DS1 signals, received from the DSX1 cross-connect frame as bipolar signals, are first converted to unipolar signals. Before the two signals are multiplexed, signal No. 2 is inverted logically (all 0s are converted to 1s and all 1s are converted to 0s) in order to control the signal statistics of the transmitted pulse stream. After stuffing and the inversion of signal No. 2, the two signals are multiplexed by interleaving them bit-by-bit according to the input numbering sequence assigned to the two signals.

The multiplexed bit stream is next scrambled in a single-stage scrambler. Each scrambler output bit is the modulo two sum of the corresponding input bit and the preceding output bit [2]. This signal is now combined (multiplexed) with a control bit sequence that permits the proper demultiplexing of signals No. 1 and No. 2 and the deletion of stuffed bits from the two signals at the receiving terminal.

Each control bit precedes a block of 52 bits from the multiplexed DS1 signals, 26 bits from each. The control bits form a repetitive sequence 24 bits long which, with the information bits associated with each control bit, defines a 1272-bit block called an  $M$  frame. This control bit sequence may be regarded conveniently as a digital word the individual bits of which are dispersed in the composite signal pulse stream. Each 24-bit control sequence (or word) is made up of three sub-sequences designated  $M$ ,  $F$ , and  $C$ . The entire sequence is shown in Figure 21-2. The symbol,  $\emptyset$ , is used with subscripts to show how the information bits from the two DS1 signals are interleaved.

The  $M$  sequence consists of four bits designated  $M1$ ,  $M2$ ,  $M3$ , and  $M4$ . They are the first, seventh, thirteenth, and nineteenth bits in the 24-bit sequence and define the start of four 318-bit subframes in the 1272-bit  $M$  frame. The  $M$  sequence may be written  $0\ 1\ 1\ X$ . The first three bits,  $0\ 1\ 1$ , are used to identify the  $M$ -frame format and the fourth bit,  $X$ , is used as a maintenance signalling channel to indicate receiving terminal alarm conditions at the transmitting terminal. A  $1$  indicates no alarm while a  $0$  indicates the presence of an alarm at the receiving terminal.

The  $F$  sequence is made up of alternate 1s and 0s ( $F1 = 1$  and  $F0 = 0$ ) that appear at the beginning of every third 52-bit information sequence, i.e., as every third bit in the 24-bit control sequence. This code is used at the receiving terminal to identify the scrambled input signals and the control bit time slots.

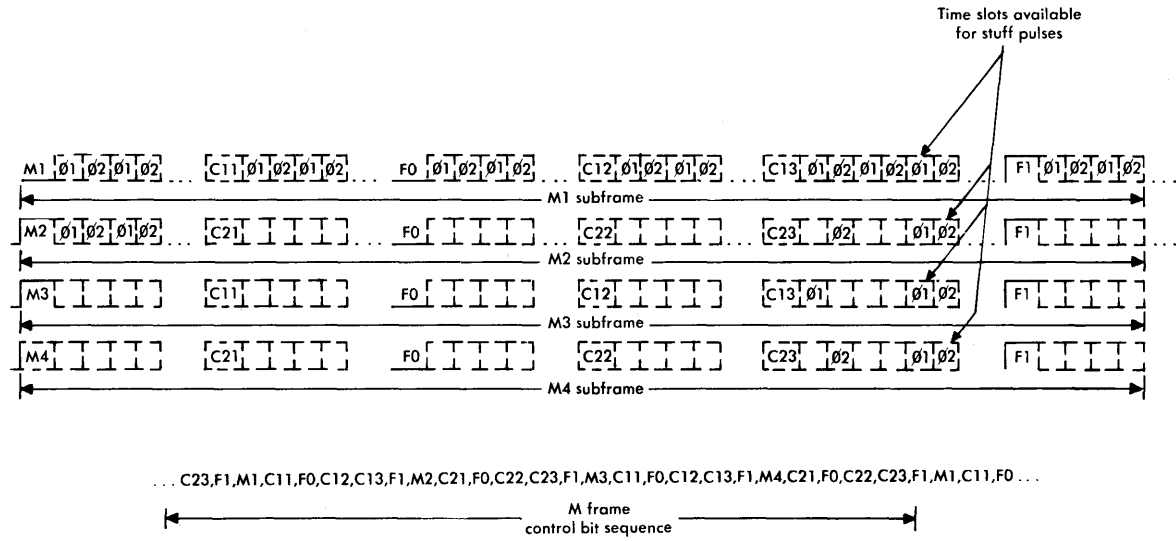


Figure 21-2. Organization of DS1C signal bit stream.

The *C*-bit sequence is used to identify the presence or absence of stuff pulses in the information bit positions of each subframe. There is a sequence of three *C* bits in each subframe. If a stuff pulse is to be inserted during the subframe, the *C* bits are all 1s. If a stuff pulse is not inserted, they are all 0s. The stuffed time slot is the third information bit following the third *C* bit in the subframe. Stuffing for DS1 signal No. 1 occurs during the first and third subframes and for signal No. 2 during the second and fourth subframes of an *M* frame. The maximum stuffing rate is 4956 bps for each DS1 signal; the nominal rate is 2264 bps.

The processes described above are carried out in the transmitting terminal. All must be reversed at the receiving terminal in order to restore the DS1 signals to their original conditions.

In its transmitted form, the DS1C signal is bipolar with a 50-percent duty cycle. The component DS1 signals and the DS1C signal are converted to a binary (unipolar) form for processing within the multiplex equipment. Thus, bipolar violations in any of these signals are eliminated.

### The DS2 Signal

An M12 multiplex unit is used, as indicated in Figure 21-1, to combine four DS1 signals into a single bit stream [3]. The 6.312 Mb/s DS2 signal is made up of the combination of these four DS1 signals and a number of control, framing, and stuff bits.

Synchronization of the four DS1 signals is necessary because these signals may originate in different sources having independent and unsynchronized timing clocks. As in the M1C, this synchronization is accomplished by adding stuff pulses to each signal so that all four are of the same rate which is determined by a common timing clock at the multiplex unit.

All of the control information for the far-end demultiplexer is carried within an 1176-bit frame which is divided into four 294-bit subframes. The control-bit word, disbursed throughout the frame, begins with an *M* bit as shown in Figure 21-3. The four *M* bits are transmitted as 0 1 1 *X* where the fourth bit, which may be a 1 or a 0, may be used as an alarm indicator bit. When a 1 is transmitted, no alarm condition exists at the transmitting end of the section; when a 0 is transmitted, an alarm is present. The 0 1 1 sequence for the first three *M* bits is used in the receiving circuits to identify the frame.

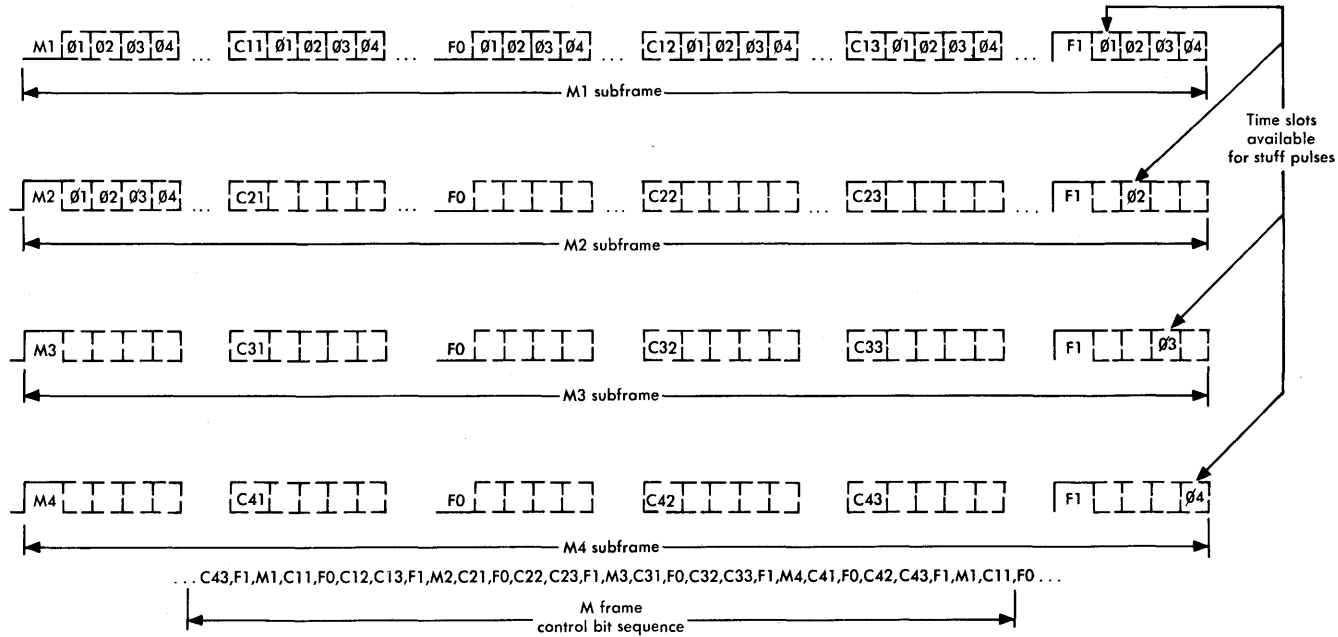


Figure 21-3. Organization of DS2 signal bit stream.

Within each subframe two other sequences are used for control purposes. Each control bit is followed by a 48-bit block of information of which 12 bits are taken from each of the four DS1 signals. These are interleaved sequentially in the 48-bit block. The first bit in the third and sixth block is designated an  $F$  bit. The  $F$  bits are a  $0101\dots$  sequence used to identify the location of the control bit sequence and the start of each block of information bits.

The stuff-control bits are transmitted at the beginning of each of the 48-bit blocks numbered 2, 4, and 5 within each subframe. When these control bits, designated  $C$ , are  $000$ , no stuff pulse is present; when the  $C$  bits are  $111$ , a stuff pulse is added in the stuff position.

The stuff bit positions are all assigned to the sixth 48-bit block in each subframe. In subframe No. 1, the stuff bit is the first bit after the  $F1$  bit; in subframe No. 2, the stuff bit is the second bit after the  $F1$  bit, and so on through the fourth subframe. The nominal stuffing rate is 1796 bps for each DS1 input signal. The maximum is 5367 bps.

Prior to multiplexing at the M12 multiplex unit, input signals 2 and 4 are logically inverted. This is done to improve the statistical properties of the output DS2 signal.

At the output of the M12 unit, the multiplex signal is unipolar and must be converted for transmission to a bipolar format with a 50-percent duty cycle. The format used at the DS2 level is called bipolar with six-zero substitution (B6ZS). If there is no sequence of bits longer than five that is composed of all 0s, the signal is true bipolar. However, if a sequence of six 0s occurs, the format is modified. If the last pulse before the six 0s was positive, the code substituted for the six 0s is  $0+-0-+$ ; if the last pulse before the six 0s was negative, the code substituted for the six 0s is  $0-+0+-$ . In both cases, bipolar violations occur in the second and fifth bit positions of the substitution. These violations are recognized at the receiver so that the proper sequence of six 0s can be substituted.

### The DS3 Signal

Presently, the DS3 signal is generated within the M13 by two steps of multiplexing. As indicated above, combinations of up to four DS1 signals are processed to form a DS2 signal. Then, as many as seven DS2 signals may be multiplexed to form the DS3 signal. In de-

multiplexing, the inverse two-step process is carried out. Internally, these signals are all in a polar format so that there can be no bipolar violations. The output DS3 signal is in a modified bipolar format with three zeroes substitution (B3ZS) and a 50-percent duty cycle.

The pattern of subframe, frame, and control bits for the 44.736 Mb/s DS3 signal is formed in much the same manner as that described for the DS1C and DS2 levels in the hierarchy. The DS3 signal is partitioned into frames of 4760 bits. Each frame is divided into seven subframes each having 680 bits. Note that the number of subframes corresponds to the number of DS2 signals formed within the multiplex unit. Each subframe, in turn, is divided into eight blocks of 85 bits. The first bit in each block is used as a control bit with the remaining 84 bits available for information. This format is outlined in Figure 21-4.

The initial bits in successive subframes are *X*, *X*, *P*, *P*, *M0*, *M1*, and *M0*. The first time slot in each of the first two subframes, designated as an *X* bit, may be used for alarm or other operation or maintenance purpose. However, the two *X* bits in a frame must be the same, either *00* or *11*.

The first time slots in the third and fourth subframes are designated as *P* bits. These are used to convey parity information relating to the 4704 information time slots following the first *X* bit in the previous frame. If the modulo two sum of all information bits is *1*,  $PP = 11$  and if the sum is *0*,  $PP = 00$ .

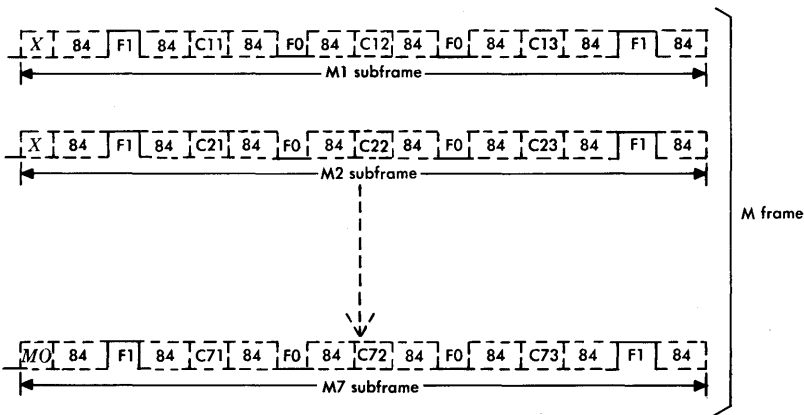


Figure 21-4. Organization of DS3 signal bit stream.

The first time slots in subframes 5, 6, and 7 are designated  $M$  bits. These three time slots always carry the code  $0\ 1\ 0$  which is used as a multiframe alignment signal.

In each subframe, blocks 2, 4, 6, and 8 carry  $F$  bits. These are transmitted in the first time slot of each of these blocks as a  $1\ 0\ 0\ 1$  code that is used as a frame alignment signal to identify all control bit time slots.

The first time slots in subframes 3, 5, and 7 carry bits to indicate the presence or absence of a stuff pulse in the subframe. The bits designated  $C_{i1}$ ,  $C_{i2}$ , and  $C_{i3}$  are the stuffing indicator bits for the  $i$ th subframe where  $i$  is any number from 1 to 7. In the  $C$ -bit positions, a  $1\ 1\ 1$  code indicates that a stuff pulse has been added and a  $0\ 0\ 0$  code indicates that no stuff pulse has been added. One stuff pulse per subframe may be added in the eighth block. The stuffing time slot is the first information time slot in that block for the DS2 signal that corresponds numerically to the subframe, i.e., the  $i$ th time slot in the eighth block of the  $i$ th subframe. The nominal and maximum stuffing rates per 6.312 Mb/s input are 3671 bps and 9398 bps respectively. The 6.312 Mb/s signals appear internally in the multiplex unit. Each is a DS2 signal made up of four multiplexed DS1 signals in a manner similar to that used in the M12.

The B3ZS format is one in which any three consecutive  $0$ s in the polar signal are replaced by a sequence that produces a bipolar violation. Each block of three consecutive  $0$ s is removed and replaced by  $B\ 0\ V$  or  $0\ 0\ V$  where  $B$  represents a pulse conforming with the bipolar rule and  $V$  represents a pulse violating the bipolar rule. The choice of  $B\ 0\ V$  or  $0\ 0\ V$  is made so that the number of  $B$  pulses between consecutive  $V$  pulses is odd.

Following is an illustration of B3ZS coding that assumes the polarity of the last pulse transmitted previous to the three successive  $0$ s was negative. If the last pulse had been positive, the resulting B3ZS signals would be the inverse of those shown. Case 1 assumes that an odd number of pulses have been transmitted since the last bipolar violation; Case 2 assumes that an even number of pulses have been transmitted since the last bipolar violation.

Binary Signal: 1 0 1 0 0 0 1 1 0 0 0 0 0 0 0 1 0 0 0 1 ...

B3ZS Signal

Case 1 (odd): + 0 - 0 0 V + - B 0 V B 0 V 0 0 + 0 0 V - ...  
 + 0 - 0 0 - + - + 0 + - 0 - 0 0 + 0 0 + - ...

Case 2 (even): + 0 - B 0 V - + B 0 V B 0 V 0 0 - 0 0 V + ...  
 + 0 - + 0 + - + - 0 - + 0 + 0 0 - 0 0 - + ...

### The DS4 Signal

Six 44.736 Mb/s DS3 signals are multiplexed, using pulse stuffing synchronization, to form the 274.176 Mb/s DS4 signal. The DS3 signals are of the modified bipolar B3ZS type previously described. The DS4 signal is a polar binary signal. Logical 1 bits are 100-percent duty cycle positive voltage pulses and logical 0 bits are 100-percent duty cycle negative voltage pulses. These voltages are measured from the center conductor to the outer conductor of the coaxial tube used for transmission.

In DS4, the basic signalling block consists of 4704 time slots called a superframe. Each superframe is divided into 24 frames of 196 time slots each and each frame is divided into two subframes of 98 time slots each. In each subframe, the first two time slots are used for control bits and the remaining 96 time slots are used for information bits.

This organization of the bit stream is shown in Figure 21-5. The symbol,  $\emptyset$ , is used with subscripts to show how the information bits from the six DS3 signals are interleaved on a bit-at-a-time basis according to the input numbering order.

In the time slots designated  $M$  and  $\overline{M}$ ,  $X$  and  $\overline{X}$ , and  $C$  and  $\overline{C}$ , collectively called  $S$  bits, each of the bits with an overscore is the complement of the companion bit without overscore. Bits  $M_1$ ,  $M_2$ , and  $M_3$  are used to align the superframe and are always coded 1 0 1. Thus,  $\overline{M}_1$ ,  $\overline{M}_2$ , and  $\overline{M}_3$  are always coded 0 1 0. The bits designated  $X$  and  $\overline{X}$  may be used in the transmission system for the purpose of signalling, maintenance, and operations information but they are not used in the multiplex and demultiplex (muldem) equipment. The  $X$  bits must be coded 0 0 0, 1 1 1, 0 0 1, or 1 0 0 but may be changed within that constraint to convey system information. The bits  $C_i$   $\overline{C}_i$   $C_i$



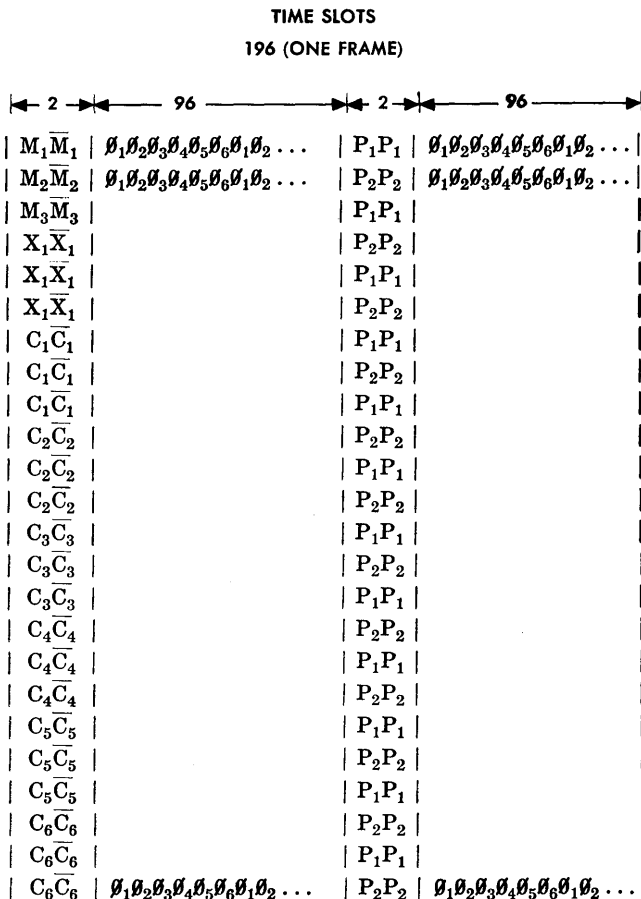


Figure 21-5. Organization of one superframe of the DS4 signal bit stream.

are used as a stuffing indicator word for each DS3 input  $i$ . The word  $111$  indicates that the  $i$ th input has been stuffed in that superframe and  $000$  indicates that there has been no stuffing in that superframe. The complementary  $C$  and  $\overline{C}$  bits are used at the demultiplexer for two-bit error correction. The time slot used for stuffing DS3 input  $i$  is the eighth  $\theta_i$  slot occurring after the last  $C_i$  bit in the superframe. The nominal stuffing rate is 27,429 bps per DS3 signal and the maximum is 58,286 bps per DS3 signal.

The bits designated  $P$  are parity bits used in error detection. Bit  $P_1$  is a parity bit taken over all odd-numbered information bits in the two frames immediately preceding  $P_1$ . Bit  $P_2$  is a parity bit taken over all even-numbered information bits within the same two frames. Bit  $P_1$  or  $P_2$  is a 0 if the number of counted 1s is even and 1 if the number of counted 1s is odd. The  $P$  bits are transmitted as identical pairs.

The information bits of the DS4 signal designated  $\emptyset_i$  are scrambled before being combined with control bits. This is accomplished by modulo two addition of the information bits to the bits of a pseudorandom sequence. Each bit of the pseudorandom sequence, which has a signalling rate of 137.088 Mb/s (one-half the DS4 rate), is used to scramble two information bits. The even numbered information bits are added (modulo two sum) to the corresponding pseudorandom bits and the odd numbered information bits are added to the complement (logically inverted sequence) of the pseudorandom bits.

## The Digital Data System

A separate digital hierarchy, related to and coordinated with the hierarchy previously discussed, has evolved to accommodate the transmission of DATA-PHONE® Digital Service signals on standard digital facilities at rates of 2.4, 4.8, 9.6, and 56.0 kb/s. These signals may be multiplexed in various combinations by stuffing and packing techniques into a bipolar, 100-percent duty cycle pulse stream at 64 kb/s. After suitable processing, this multiplexed signal, designated DS0, can be transmitted over the equivalent of one voice channel (64 kb/s) in a DS1 signal [4].

## 21-2 DIGITAL MULTIPLEX EQUIPMENT

Digital signals are translated from one level of the hierarchy to another by equipment designed to multiplex a number of lower rate signals together to form a higher rate signal. At the receiving end, the equipment separates the individual signals and processes each into the format required at the lower rate. The multiplex equipment now available is designated M1C, M12, M13, and M34. These units translate signals between levels in the hierarchy as indicated by the numerals in the designation. Another unit, designated MX3, is under development. It will provide flexibility in translating signals between the DS3 level and the DS1, DS1C, or DS2 levels by selection of interchangeable circuit plug-in units.

### Signal Characteristic Specifications

In the previous discussion of the digital hierarchy, many of the signal characteristics are specified in order to satisfy interconnection or transmission facility requirements and to satisfy compatibility of terminal equipment. In some cases, these requirements apply equally to the multiplex equipment at all levels of the hierarchy and, in other cases, they differ somewhat with the level. Some line transmission systems utilize framing, parity, and other bits provided in the format so that only signals having the specified formats can be transmitted.

### Line Rates and Codes

The signal descriptions for the several levels in the hierarchy are summarized in Figure 21-6. Among the requirements imposed on all of these signals is a limit on the number of consecutive 0s that may appear. These requirements must be satisfied because the regenerative repeaters of various transmission systems depend on the statistics of the signals for timing extraction and, for DS4 signals, to limit the variation in the dc component of the signal (baseline wander).

SIGNAL	REP. RATE, Mb/s	TOLERANCE PPM*	FORMAT	DUTY CYCLE, PERCENT
DS0	0.064	†	Bipolar	100
DS1	1.544	±130	Bipolar	50
DS1C	3.152	±30	Bipolar	50
DS2	6.312	±30	B6ZS	50
DS3	44.736	±20	B3ZS	50
DS4	274.176	±10	Polar	100

\*Parts per million.

†Expressed in terms of slip rate. See reference 4.

Figure 21-6. Summary of repetition rates and codes in digital hierarchy.

In the T1 Carrier System, the 0 sequence restriction is that there may be no more than 15 consecutive time slots carrying 0. As the line signal is formed by channel signal sampling and coding and by combining information, signalling, and framing signals, it is monitored so that successive 0s of each 8-bit code word can be counted. When the number of 0s reaches 7, the circuits are arranged so that a 1 is inserted in the pulse stream in the position corresponding to

the least significant information bit of the channel sample code in the sequence. Thus, a tolerably small impairment is introduced in the pulse code for the channel voltage sample at that instant. These operations are performed just before the line signal is converted from a unipolar to a bipolar format for transmission.

Somewhat similar modifications of the line signal are used when the T1 carrier system is used for data transmission. The details depend on individual data bank design and on the sensitivity of various types of data signals to the subsequent impairment [5].

The M-type multiplex units must also control the number of consecutive 0s in the higher-rate output signals. This is accomplished by 0 substitution as previously described (B6ZS and B3ZS codes) and by the use of scrambling techniques also previously described.

### Synchronization

Two forms of synchronization must be considered at each level of the digital hierarchy. The first is the synchronization of a bit stream to some specific value of repetition rate. This form of synchronization is expressed by stating the nominal bit rate and adding a tolerance to that expression. The requirements on this form of synchronization are given in Figure 21-6.

The second form of synchronization is the timing of one bit stream relative to another when the two are to be time division multiplexed into one bit stream at a higher rate. For this purpose, the relative timing must be precise and is accomplished above the DS1 level by pulse stuffing. As previously described, all signals to be multiplexed can be made to have precisely the same rate in bits per second by adding stuff pulses to the slower signals. When the signals are demultiplexed, the stuff pulses are removed. The resulting gaps in the pulse stream are closed to restore the original bit stream timing except for a small residual jitter. The gap closure made necessary by the removal of stuff pulses is usually accomplished by the use of an elastic store.

### Elastic Stores

In digital multiplex equipment, problems of synchronizing multiple bit streams are often solved by the use of elastic stores [6]. These are circuits that permit the repetition rate of a digital pulse stream

to be changed. The output pulse stream may have considerable jitter due to the process of change; it can be smoothed by combining the store circuitry with a phase locked loop which controls the output pulse stream repetition rate.

The number of binary digits that can be held in an elastic store is limited to the number of storage cells provided in the design. Incoming information digits are entered into the store (write in) under control of the incoming timing clock and are extracted (read out) under the control of an independent local clock. Thus, the store must be designed for the specific application.

If the read-out rate of a store is lower than the write-in rate, the read-out circuits will lag behind the write-in and eventually will be overtaken by the write-in sequence. A block of digits equal to the store size is thus lost. Conversely, if the reading rate is higher, reading overtakes writing and a block of digits may be repeated. In both situations, the store is said to have spilled. The indiscriminate spilling of a store may be avoided by synchronization.

Pulse stuffing may be regarded as controlled spilling that allows recovery of the original sequence of digits. For this type of control, the reading clock rate must be higher than the writing clock rate and the extra digits must be inserted at specified times to permit ultimate removal. The first condition is satisfied by the assignment of appropriate nominal clock rates and allowable variations or tolerances. The second is satisfied by a periodic monitoring of the delay between writing and reading operations.

### Pulse Parameters

Pulses transmitted to and from digital multiplex equipment must meet a number of specifications to assure proper equipment operation. These specifications relate to pulse amplitude, width, rise and decay times, permissible overshoot, jitter, and format. The specifications are applied at carefully defined measuring points for each of the hierarchical levels, usually a cross-connect frame designated DSX1, DSX1C, etc., according to the level at which it operates.

In most cases, pulse amplitude, width, rise and decay times, and permissible overshoot are specified by an oscilloscope template that provides a display of the ideal or nominal pulse and tolerances on each of the parameters. Generally, the tolerances have been estab-

lished to limit impairments due to the lengths of cable between multiplex equipment and cross-connect frames. Where cable length limits cannot be met, plug-in equalizers are used to permit longer lengths of cable.

Some approximate or nominal values of these parameters and some specifications of parameters other than those covered by the use of templates may be considered for each of the signal repetition rates. In some cases, specifications have not been finalized.

**The DS1 Signal.** The template for DS1 signals is designed to show a nominal pulse width of 324 ns with a tolerance of  $\pm 30$  ns as measured at half amplitude. The rise and decay times must be less than 80 ns between the 10- and 90-percent amplitude points. A trailing edge overshoot of 10 to 30 percent of the pulse amplitude is acceptable with a decay to less than 10 percent of the peak overshoot required within 400 ns. In addition to the template-controlled specifications, signal power in DS1 signals is specified to be such that the ratio of the power in positive pulses to that in negative pulses shall be no more than 0.5 dB. These specifications generally allow for up to 750 feet of cable between the DSX1 frame and the source of DS1 signals although, in some applications, the cable length is restricted to 655 feet.

**The DS1C Signal.** A nominal pulse width of 160 ns is specified for the DS1C signal. The trailing edge overshoot should not exceed 10 percent of the pulse amplitude. Up to 400 feet of cable may be used between the DS1C output of a multiplex terminal and the DSX1C cross-connect frame. Somewhat greater lengths are permissible between the DSX1C cross-connect frame and a D4 channel bank.

**The DS2 Signal.** The power in the DS2 signal is specified at two frequencies when an all 1s pattern is transmitted. The power at 3.156 MHz is to be between 0.2 and 7.3 dBm and, at 6.312 MHz, it is to be  $-20.0$  dBm or less as measured at the DSX2 cross-connect frame. For an all 1s pattern, the template-controlled specification on pulse width is adjusted so that, at the multiplex unit, the power measured in a 2-kHz band at 3.15 MHz is 18.2 dBm  $\pm 0.1$  into 110 ohms. Allowance is thus made for 1000 feet of cable from the multiplex unit to the DSX2 cross-connect frame.

**The DS3 Signal.** The power in a DS3 signal is specified as measured at the DSX3 cross-connect frame when an all 1s signal is trans-

mitted. The power measured in a 2-kHz band at 22.368 MHz should be between  $-1.8$  and  $+5.7$  dBm and, at 44.736 MHz, it should be at least 20 dB below that measured at 22.368 MHz. The template-controlled pulse width is specified as  $11.2 \pm 1.1$  ns with rise and decay times of  $4.5 \pm 1.4$  ns. The overshoot and undershoot must be less than 10 percent of the pulse amplitude. These values permit the use of up to 450 feet of solid-dielectric coaxial cable between the multiplex equipment and the DSX3 cross-connect frame.

**The DS4 Signal.** This 100-percent duty cycle polar signal has a power that is specified in terms of the transmission of an alternating *1 0 1 0 . . .* pattern. As measured at the DSX4 cross-connect frame, the power in a 2-kHz band at 137.088 MHz should be between  $-3.68$  and  $+4.35$  dBm. At 274.176 MHz, the power should be at least 15 dB below that measured at 137.088 MHz. The pulse width is approximately 3.65 ns. Allowance is made in these specifications for up to 150 feet of solid-dielectric coaxial cable.

### Multiplex and Cross-Connect Operations

The initial multiplexing of signals takes place in channel banks as one of several functions that include the translation from analog to digital format, companding, and coding. The result of these processes is the formation of the DS1 signal that forms the basic building block for the digital hierarchy. The succeeding steps of multiplexing in the M-type multiplex equipment are carried out as required to form the higher level DS1C, DS2, DS3, and DS4 signals each of which appears, for administrative purposes, at the appropriate cross-connect frame. The signals at any frame may originate at a number of different sources.

At the DSX1 cross-connect frame, the DS1 signals may originate in a D-type channel bank, a T1 line, a 1A-RDS radio link, an M1C, M12, or M13 multiplex unit, one of several types of data banks or data multiplex units, or a terminating unit at an electronic switching system. At the DSX1C cross-connect frame, DS1C signals may be fed from an M1C multiplex unit, a D4 channel bank, or a T1C line. Similarly, the DS2 signals found at a DSX2 cross-connect frame may originate in an M12 multiplex unit, a D4 channel bank, or a T2 line. At a DSX3 cross-connect frame, signals may be present as a result of connections to an M13 multiplex unit, an M34 multiplex unit, or a 3A-RDS microwave radio link. Finally, at a DSX4 cross-connect

frame, there may be signals from an M34 multiplex unit, a T4M line, or a DR 18A radio link. In each case, flexibility is provided to permit additional types of signal sources to deliver signals to a cross-connect frame provided interface and interconnection specifications are satisfied.

To each of the multiplex units is applied a stringent set of specifications relating to *reframe time*. The reframe time is defined as the sum of the waiting time required to determine that an out-of-frame condition exists, the search time during which the framing circuits search for the framing signal code, and the time to reestablish frame alignment after the framing signal is identified. In the M1C multiplex unit, the maximum allowable reframe time is 17 ms; in the M12, it is 15 ms. In the M13 multiplex, two steps of multiplexing and demultiplexing are used. Signals are stepped through the DS2 level internally in the equipment. The maximum reframe time allowed for the first demultiplexing step, from DS3 to DS2, is 2 ms and, for the step from DS2 to DS1, it is 7 ms. The combined time should not exceed 9 ms. The maximum reframe time for the M34 unit is 0.2 ms.

A number of maintenance features are provided in the multiplex equipment. These always include alarms generated at demultiplexer units to indicate loss of signals or excessive time out of frame. In some cases, these alarms are extended back to the corresponding multiplexer at the far end. Many multiplex units are also equipped with monitors to detect any multiplexer or demultiplexer malfunction and to switch in a standby unit automatically. In addition, some units are equipped with circuits that substitute an idle signal upon loss of input so that trouble indications are not extended beyond that unit.

### 21-3 PCM CHANNEL BANKS

The processing of analog signals, primarily speech, for transmission over digital facilities is accomplished in equipment designated as D-type channel banks. The functions of these banks include filtering, sampling, compressing, coding, multiplexing, synchronizing, and framing at the transmitter and the inverse of most of these processes at the receiver. A succession of D-type banks has been developed, each to improve performance, reduce costs, and/or satisfy requirements that were not applicable in earlier designs.

The D-type banks have been designated D1 through D4. In addition, design improvements have been introduced (especially in the D1



banks) to upgrade the performance or to make them compatible with later designs. In D1 (later designated D1A), the improved designs have been designated D1B and D1D. The D1C is a special adaptation of the D1 bank for use with the Traffic Service Position System No. 1 (TSPS-1).

Although the various D-type channel banks differ somewhat in detail, they all perform the same basic functions. Each of one or more groups of 24 channel signals is processed into one or more 1.544 Mb/s DS1 pulse streams. Each channel signal is sampled 8000 times per second and, after quantization, the PAM samples are converted by PCM techniques into eight-bit words. In each design, instantaneous companding is used in order to improve the signal-to-distortion performance. However, the companding characteristic is not the same in all designs.

Most of the information contained in the eight-bit words relates to the speech signals being processed. However, certain bits are used for channel signalling. The manner in which these signalling bits are assigned differs somewhat in the various designs.

As previously discussed, the eight-bit word for each PAM sample and the 24 channels per DS1 pulse stream combine to make up what is called a frame of  $8 \times 24 = 192$  pulse positions. In all designs, one pulse position is added to each frame to identify the beginning of the frame. With 8000 samples per second, the bit stream is made up of  $193 \times 8000 = 1,544,000$  bits per second. This signal is binary (unipolar) within the channel bank equipment but is converted to a bipolar format before it is transmitted from the channel bank equipment.

### Channel Units

The interface between analog signal transmission circuits and digital transmission circuits in channel banks is provided by plug-in units called channel units. Two interfaces are provided, one for information signals and one for signalling. Many different types of channel units are available to provide for the many types of signalling arrangements used, for the many types of trunks and special services circuits, and for two-wire or four-wire operation. Channel units for all D1-type banks are compatible but D1, D2, D3, and D4 channel units are generally not compatible with one another.

Figure 21-7 illustrates a two-wire channel unit and a four-wire channel unit with E and M lead signalling. The two-wire unit contains a hybrid coil to provide the conversion from two-wire to four-wire transmission and fixed and adjustable pads for line-up use. In the four-wire unit, adjustable-gain amplifiers are provided in both paths. The adjustment range of about 1.5 dB is sufficient to provide the standard transmission level points of  $-16$  dB and  $+7$  dB at the input and output respectively.

In both units, the signalling information in the transmitting direction is passed to a scanning gate. When the transmitting counter enables the gate, the signalling state is transmitted to the transmitting common signalling unit for encoding. Similarly, the received signalling information from the receiving common signalling unit is passed through a selecting gate enabled, at the proper times, by the receiving counter. The reconstruction circuit transforms the received signalling pulses to the signalling state corresponding to that at the distant transmitting terminal.

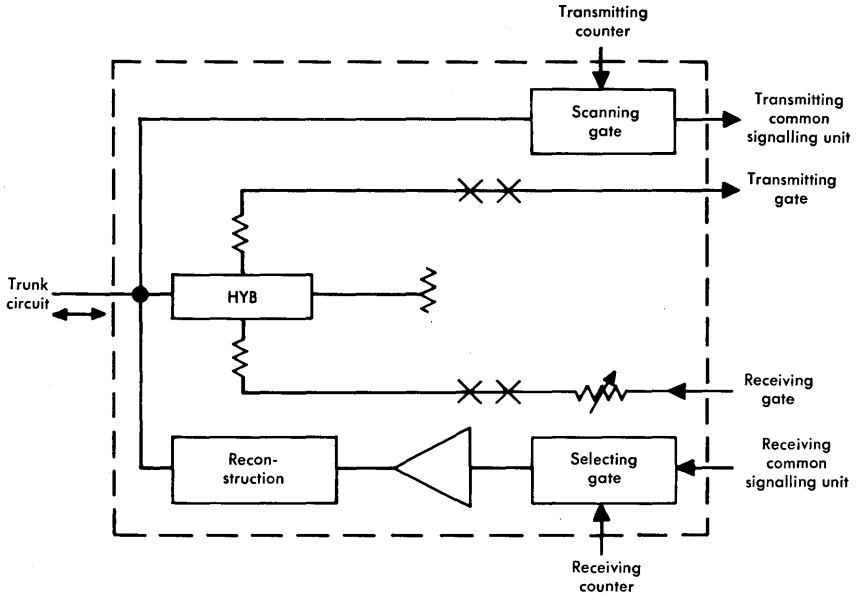
### The D1 Channel Banks

The terminal equipment for the T1 Carrier System was initially provided by the D1 channel bank, later designated the D1A bank [7]. Although it is no longer manufactured, there are still many D1A channel banks in service.

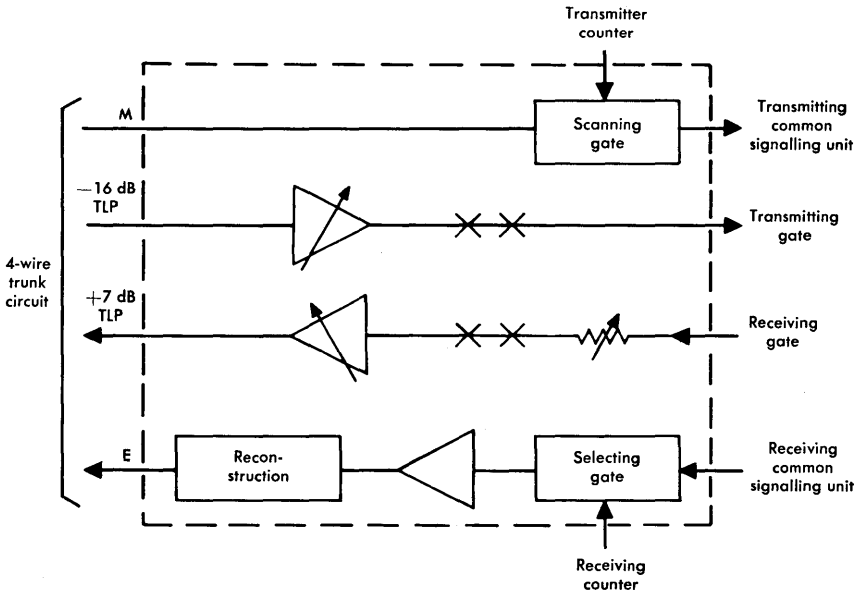
The required signal processing within the channel bank is achieved by circuits that utilize a number of unique pulse trains. These pulse trains provide timing and logic functions to effect the sampling, expanding, coding and decoding, multiplexing and demultiplexing, synchronization, and framing required in the transmitting and receiving portions of the bank.

Channel banks are made up of a number of plug-in units which are in two general classifications. *Channel units*, previously discussed, must be furnished on the basis of one plug-in unit for each channel. All other plug-in units are classified as *common units* that perform functions for more than one channel.

**Internal Pulse Trains.** Figure 21-8 illustrates the principal pulse streams in the D1 channel bank. The circuit units alluded to in Figure 21-8 are shown in Figure 21-9, a block diagram of the transmitting portion of the common equipment of the D1 bank.



(a) Two-wire channel unit



(b) Four-wire channel unit

Figure 21-7. Typical D1 bank channel units.

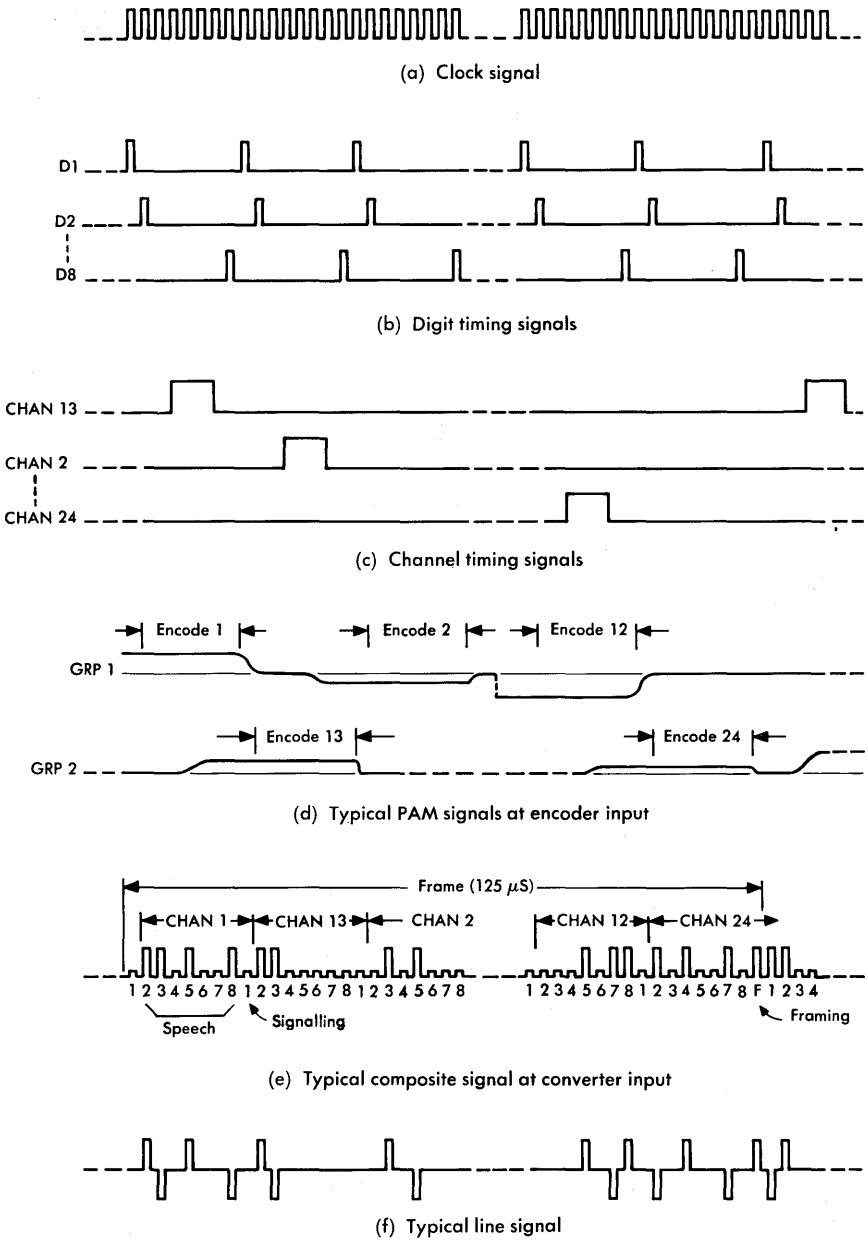


Figure 21-8. Pulse trains within a D1 channel bank.

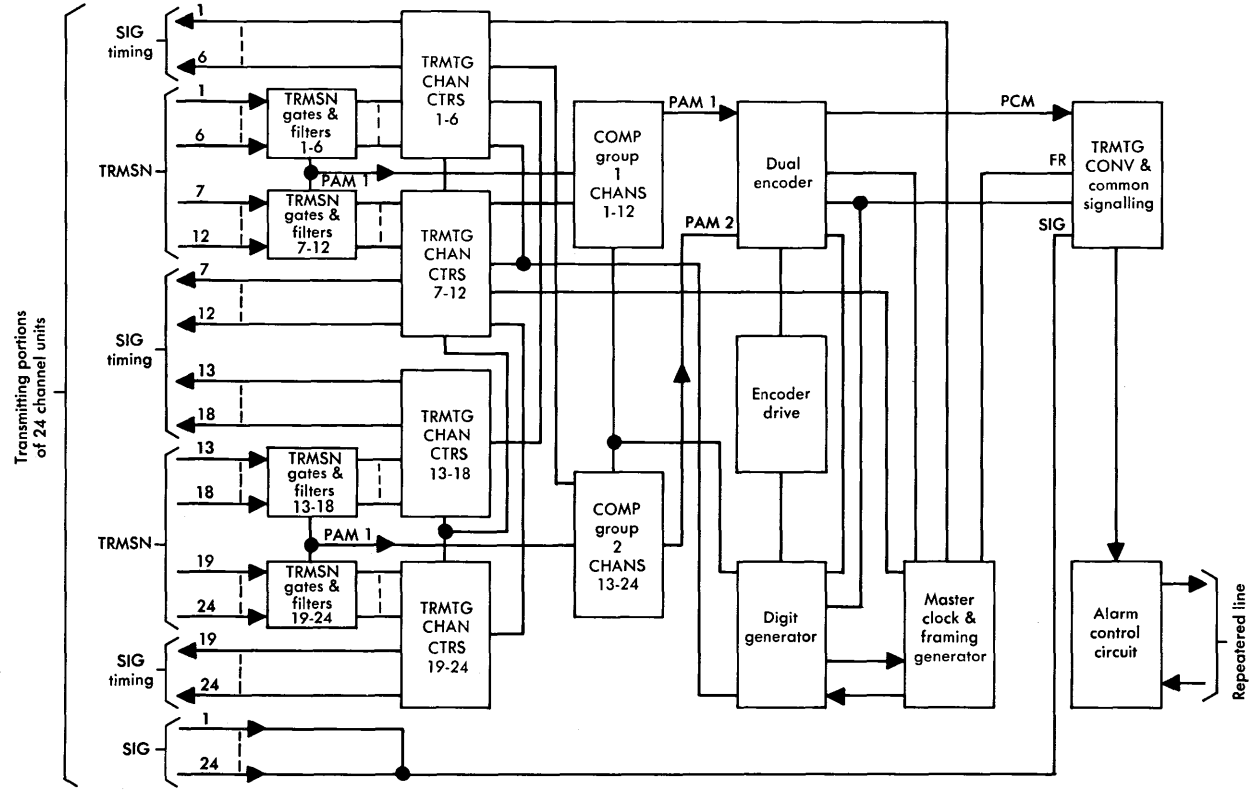


Figure 21-9. Transmitting portion of D1 bank common equipment.

The fundamental timing signal for the terminal is shown as the clock signal in Figure 21-8(a). It is generated by a crystal-controlled oscillator in the master clock and framing generator. The pulse train is a 50-percent duty cycle binary signal of square-topped pulses having the basic repetition rate of 1.544 Mb/s.

The digit generator provides sequences of pulses on eight separate leads for use in encoding and other timing functions. These digit timing signals are illustrated in Figure 21-8(b). A ninth stage in the ring counter provides a pulse at the end of each frame for control of the framing generator, a part of the master clock unit.

Digit pulses are fed from the digit generator to the transmitting channel counter circuits which generate channel pulses as shown in Figure 21-8(c). These pulses are used to activate a sampling gate in each channel unit to allow a PAM sample pulse from each such unit to be passed at the proper instant for coding. In D1A, D1B, and D1C banks, the channel counters are blocking oscillators turned on by one digit pulse and turned off by another. Each counter accommodates six stages; thus, for a completely equipped bank, four units are required as shown in Figure 21-9.

The PAM pulses, shown in Figure 21-8(d), are transmitted in two independent pulse streams from the outputs of the transmission gates and filters to the group compressors. One compressor acts on channels 1 through twelve; the other acts on channels 13 through 24. The sampling times of the channels in the two groups are interleaved so that group 1 channels are sampled at odd-numbered times, group 2 channels at even-numbered times. Thus, the channel signals appear at the input to the encoder in the order: 1, 13, 2, 14, . . . 23, 12, 24, 1, 13, 2, 14, . . . as illustrated in Figure 21-8(e). The range of input amplitudes of about 1000 to 1 is reduced to a range at the output of about 63 to 1 in a modified logarithmic-to-linear conversion so that the output variation in volts is approximately proportional to the input variation in dB over most of the range. The two compressor outputs are connected to the dual encoder in which two summing amplifiers and comparison networks, under the logic control of the encoder drive unit, encode the two pulse trains alternately into a single stream of PCM time slots made up of a random succession of 0s and 1s. In this binary stream, seven of each group of eight pulses are used to represent the amplitude of the associated PAM sample. This would permit the coding of 128 amplitude values. However, the

all-0s code is inhibited in order to guarantee the presence of at least one 1 in each seven-bit code word. Thus, 127 amplitude values may be represented by this coding arrangement.

The unipolar PCM signal, occupying seven of the eight pulse positions assigned to each channel sample, is one of three signals fed into the transmitting converter and common signalling unit. A second signal, processed by the common signalling portion of this unit, consists of signalling state information from the scanning gate of each of the 24 channel units in turn. Each pulse is reshaped and timed to interleave with the PCM pulses in the unipolar train. The third signal is the framing signal from the framing generator. The combined unipolar signal is illustrated in Figure 21-8(e).

The final steps of processing in the transmitting converter and common signalling unit involve a regeneration of each unipolar pulse and the conversion of the pulse train to a bipolar format. Alternate pulses are inverted as shown in Figure 21-8(f). The resulting bipolar signal is sent to the transmission line by way of an alarm control unit which is plugged into the shelf with the receiving portion of the terminal.

A block diagram of the receiving circuits is given in Figure 21-10. Timing for the receiving circuits is quite similar to that for the transmitting circuits. However, the main clock signal is derived from the incoming signal pulse train rather than from a master clock circuit as in the transmitting portion of the terminal.

The signal from the repeatered line is received by the alarm control unit. After the pulse amplitude has been adjusted by appropriate padding, the signal is applied to the receiving converter and common signalling unit where it is converted to a unipolar format and regenerated. The unipolar signal is then applied simultaneously to the framing detector, signalling circuit, and decoder circuit which select appropriate pulses from the combined pulse train for further processing.

The decoder scans the seven pulse positions allocated to each sample and synthesizes a compressed PAM pulse from the sample code. The resulting train of PAM pulses passes through the expander which restores the samples to their original amplitudes and transmits them to the receiving gates. These operate one at a time in rotation and route each pulse through an individual low-pass filter to the receiving portion of the associated channel unit.

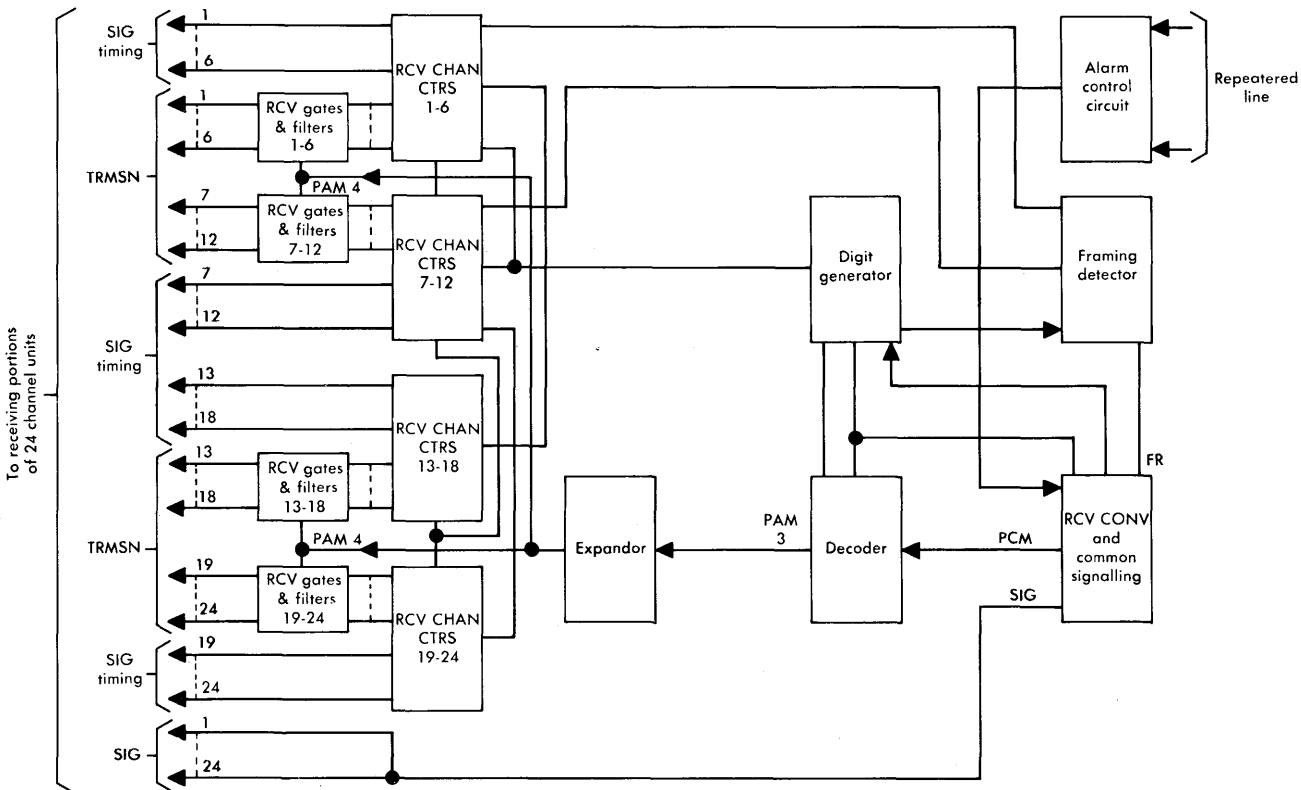


Figure 21-10. Receiving portion of D1 bank common equipment.



The eighth digit associated with each seven-digit PCM code word [digit 1 in Figure 21-7(e)] is used to transmit signalling information. These signalling digits are selected, amplified, and passed to the receiving signalling gates in the appropriate channel units where the signalling states corresponding to those at the distant terminal are reproduced. As designed, this method of transmitting signalling information can represent only two signalling states. Some signalling systems (revertive pulsing and foreign exchange trunk signalling) require more than two states. To accommodate these systems, the D1A bank is arranged so that digit 8 may be "borrowed" for signalling during times when the circuit is inactive, i.e., not carrying speech. Thus, three effective signalling states may be represented part of the time by the two code-word digits, 1 and 8.

The timing signal in the receiving portion of the terminal is generated in the receiving converter and common signalling unit from the unipolar pulse stream derived from the incoming signal. The dissipation of the tuned circuit, resonant at the expected frequency, is low enough that oscillation of a slave clock is maintained over moderately long blank intervals in the incoming signal. The clock signal drives a digit generator like that used in the transmitting portion of the terminal.

Framing may be lost due to errors in the pulse stream that may result from malfunction of the receiver or the transmitter at the distant end or from interference picked up along the repeated line. When this occurs, synchronism is restored under the control of the framing signal generated in the receiving timing circuits. The framing signal consists of alternate 1s and 0s in every 193rd pulse position, a pattern seldom duplicated for more than two or three frame intervals in any other pulse position. When the framing detector recognizes a number of violations of the  $1\ 0\ 1\ 0\ \dots$  pattern, a hunting action is started. An additional pulse position per frame is inserted in the locally generated framing signal until the framing position is reached. When the two patterns match, the hunting action ceases.

**The D1B Channel Bank.** Functionally, the D1B channel bank is the same as the D1A except for the manner in which signalling information is processed. Because of these differences, the D1A and D1B banks are not compatible although equipment may be transformed from D1A to D1B by changing specified plug-in units and making

minor bay wiring changes. For both, the same bank type must otherwise be used at both ends of a digital system.

The eighth digit of each code word is "borrowed" in D1A to provide additional signalling information when required. While the use of this digit in D1A for revertive pulse signalling and foreign exchange circuits does not affect transmission quality because it is used while the circuit is inactive, the loss of the eighth digit on some no-charge calls does represent a slight degradation of quality. This is overcome in the D1B bank by the revised method of signalling used.

In the D1B bank, the signalling information is all carried by digit 8 of each code word. The logic circuit arrangements of the common signalling circuit are programmed so that a signalling sequence of four frames contains the required information. Digit 1 in the first two of these frames is used to provide up to four signalling states, the maximum required. Digit 1 in the third and fourth frames of the sequence are always 0s. This code has been adopted to avoid the possibility of signalling information producing a 1 0 1 0 repeated sequence since this would be confused with the standard framing signal sequence.

**The D1C Channel Bank.** Transmission between a base unit and a remote operator position of the TSPS-1 may be provided by a digital transmission facility equipped at both ends with D1C channel banks. These banks, which provide data transmission capability and 24 speech channels, were designed specifically for this type of service. The PCM voice signals are processed by seven-digit encoding in exactly the same manner and by use of the same circuitry as in the D1A channel bank. However, bit 1 of each eight-bit channel code word is used to transmit data used by the TSPS-1. Data transmission requirements bear no relationship to the signalling requirements in a D1A bank, and therefore, the two types of bank are not compatible.

A spare D1C bank is always provided for use with one, two, or three regular banks to permit alternate bank operation and for standby operation when a regular bank is out of service. Thus, a minimum installation requires two complete D1C banks. While the D1A and D1B banks are furnished in 7-, 9-, and 11-1/2 foot bay arrangements, the D1C bank is available only in a 7-foot bay.

**The D1D Bank.** By replacing a number of plug-in common units with newly designed units, D1A and D1B channel banks may be made

compatible with the D3 and D4 channel banks. Conversion from D1A to D1D also requires minor bay wiring changes. Channel banks so converted are designated D1D [8]. The changes affect speech, signalling, and framing code formats.

For speech signal coding, all eight bits of a channel word are used in five out of every six frames. In the remaining frame, digit 1 is used for signalling. To accommodate these changes, it is necessary to change the framing format so that frames containing signalling information can be identified. The overall effect of these changes is an improvement in speech signal transmission performance since 256 amplitude values (instead of 128) are represented in five of every six frames, thus reducing the quantizing noise. A second modification involves the companding characteristic used in the D1D bank. With the new characteristic, the signal-to-noise ratio is improved significantly over a wide range of input signals.

The D1D framing format is a code carried in each 193rd bit position of the composite signal. The code consists of a *1 0 1 0 1 0* sequence carried in odd-numbered frame positions interleaved with a *1 1 1 0 0 0* sequence carried in the even-numbered frame positions. This combination of sequences, producing a composite framing sequence *1 1 0 1 1 1 0 0 0 1 0 0 0*, forms a time-shared combination of a terminal frame pattern and a signalling frame pattern. The terminal frame pattern, *1 0 1 0 . . .*, is used for rapid frame pulse identification. The signalling frame pattern, *1 1 1 0 0 0 . . .*, is used to identify signalling bits carried in the sixth and twelfth of each sequence of frames.

The encoder in the D1D bank has a nonlinear characteristic to provide the signal compression necessary for the desired compandor action. The characteristic, designated  $\mu = 255$ , differs considerably from that used in the D1A and D1B banks where  $\mu = 100$  [9]. (The parameter,  $\mu$ , determines the degree of compression and expansion used in the compandor.) The encoder also includes a 0 code suppression circuit to prevent the loss of line synchronization. When an all-0s code occurs at the encoder network, a 1 is substituted for digit 7 of the code word. The signal format follows that used in the D2 channel bank.

The clock generator may be driven by an internal crystal-controlled oscillator which generates a 6.176 MHz sine wave. This sine wave is

divided by four and converted to yield a 1.544 Mb/s square wave. The clock may also be driven by an external source or it may be derived from the incoming signal.

A number of other changes in circuit, operating, and maintenance details were made in D1D banks to improve their performance and to make them compatible with D3 banks. However, none of these changes resulted in functional differences as notable as those described.

### The D2 Channel Bank

As in all D-type channel banks, the plug-in circuits used in the D2 bank are of two general classes. Channel units are furnished on a per-channel basis to satisfy the operating requirements of the particular type of trunk or special service circuit with which it is associated. Common units are used to process all of the channel signals applied to the bank and are independent of the types of trunks or circuits applied to the bank. While other D-type banks are arranged to process the signals of 24 channels, the D2 bank processes 96 channels simultaneously [10, 11]. Thus, the common units are used somewhat more efficiently in the D2 bank. A block diagram of the bank is given in Figure 21-11.

The 96 input channel signals are processed by the D2 transmitting bank circuits to deliver four DS1 signals at the bank output. Each of these signals is identical in format to the output of other D-type banks in that the composite signal represents the pulse coding of 24 channels in a frame of 192 bits with a framing signal carried in the 193rd bit position. Each channel is sampled 8000 times per second and each amplitude sample is processed into an eight-bit code in five out of every six frames. In the sixth frame, digit 1 is used for channel signalling as in the D1D bank previously described. Zero-code suppression is used in the D2 bank as in other D-type banks. The D2 bank is compatible with D3 banks although adapters must be provided at the D3 bank to assure complete channel sequencing compatibility. The function of these adapters is to adjust channel number counters, an adjustment made necessary by the fact that channel processing sequences are different in the two bank designs. Otherwise, the framing signal sequence is the same as that previously described for the D1D channel bank. However, the D2 and D1D banks are not considered compatible because channel counting sequences cannot be made to correspond.

Signal processing in the D2 bank transmitter circuits, shown in Figure 21-11, involves a number of steps some of which are similar to those described for other bank types and some of which are quite different. If necessary, a voice-frequency circuit is transformed from two-wire to four-wire in the hybrid coil. The attenuators and amplifiers in the transmitting path are used to adjust the transmission level point to  $-16$  dB. The signal in each channel is filtered, sampled, and combined with 11 other channel signals to form a *group*. After additional amplification, two groups are combined by means of transfer gates to form a *digroup*. The digroup signal is amplified and combined with three other digroups to form a PAM stream consisting of pulse samples from 96 channel signals. These sample pulses are then coded by a nonlinear coder to provide the compressor portion of a compander with  $\mu = 255$ , similar to that of the D1D bank. The PCM signal is combined in the digital processor with signalling and framing pulses to form a 6.312 Mb/s signal from which four independent DS1 signals are extracted. These signals, which have been in a binary format up to this point, are also converted into a bipolar format. The receiving circuits of the bank perform functions inverse to those of the transmitting circuits and produce 96 analog signals at the  $+7$  dB TLP.

### The D3 Channel Bank

Among the D-type channel banks now most commonly found in service is the D3 [12, 13]. This bank was developed in the early 1970s to replace the D1A and D1B banks in new installations. A greater than 2-to-1 reduction in size, lower cost, improved performance, and a wide range of circuit and equipment options have made the D3 a successful design.

The reduction in size was achieved primarily by the use of hybrid integrated circuits (HIC) in the plug-in units of the bank. The economies of HIC manufacture also contributed significantly to the lower cost of this bank relative to earlier designs.

Performance improvements resulted primarily from the application of a new compander characteristic and from the assignment of eight bits for the encoding of each PAM sample pulse in five of every six frames. These improvements are identical to those described previously for the D1D channel bank.

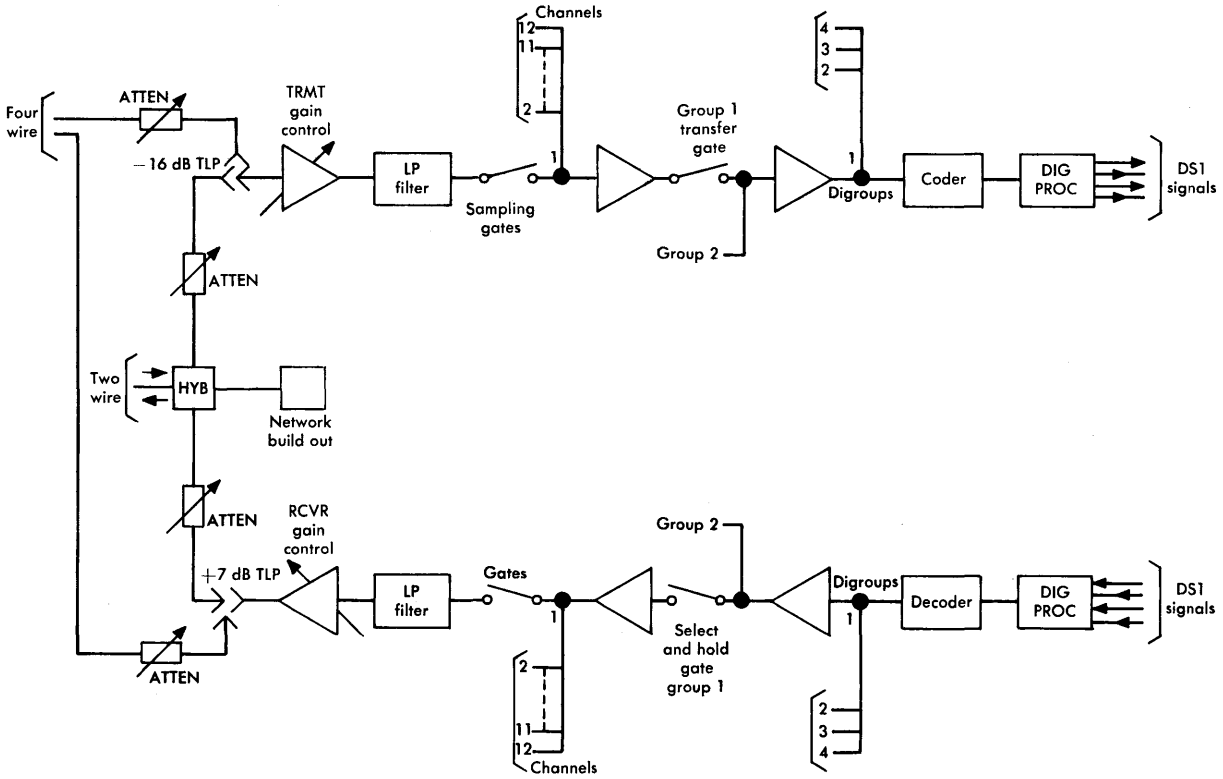


Figure 21-11. Simplified block diagram of the D2 channel bank.

Among the options that are provided in the D3 bank are access arrangements for the Common Channel Interoffice Signalling (CCIS) System and for maintenance and operations by the use of the E-type telemetry systems. The clock circuits in the D3 bank may be synchronized internally or externally.

A monitored set of common plug-in units may be furnished optionally as part of a maintenance shelf in the D3 bank. This arrangement provides a method of quick service restoral by substituting plug-in units from the maintenance bank to the failed bank. A variety of bay arrangements are available in D3 that include 7-, 9-, and 11-1/2-foot bays.

### The D4 Channel Bank

The latest and most versatile of the D-type banks is the D4. It provides basically the same functions as those described for other D-type banks but is arranged to operate in any one of four different line formats (modes) that permit its use with T1, T1C, or T2 lines; i.e., it is capable of generating DS1, DS1C, or DS2 signals by the selection of appropriate plug-in equipment. Each D4 bank provides for the transmission of up to 48 channel signals. About a 2-to-1 reduction in size and per-channel power dissipation has been realized in the D4 bank relative to the D3 bank.

**Operating Modes.** Figure 21-12 illustrates the four operating modes of the D4 channel bank. Mode 1 is used with a T1C line facility operating with D4 channel banks at both ends. For this mode, the T1C line interface units, LIU-1, are used to multiplex two DS1 binary signals and then transform the composite binary signal to the bipolar format required for transmission. They also include the bank clock circuits and the looping circuits used for single-ended testing and insert control bits required at the distant receiving bank. The mode 1 signal cannot be demultiplexed to DS1 signals by an M1C multiplex unit nor can it be multiplexed to the DS3 level in a proposed multiplex unit called the MX3.

Mode 2 may be used with a T1C line having a D4 bank at one end and an M1C (or the proposed MX3) multiplex unit at the other. The T1 terminals of the M1C multiplex unit may be connected to either a D1D, D2, D3, or D4 bank, or to a digroup terminal at a No. 4 ESS machine. The LIU-2 performs functions similar to those of the LIU-1 in mode 1 but operates with a synchronizer-desynchronizer

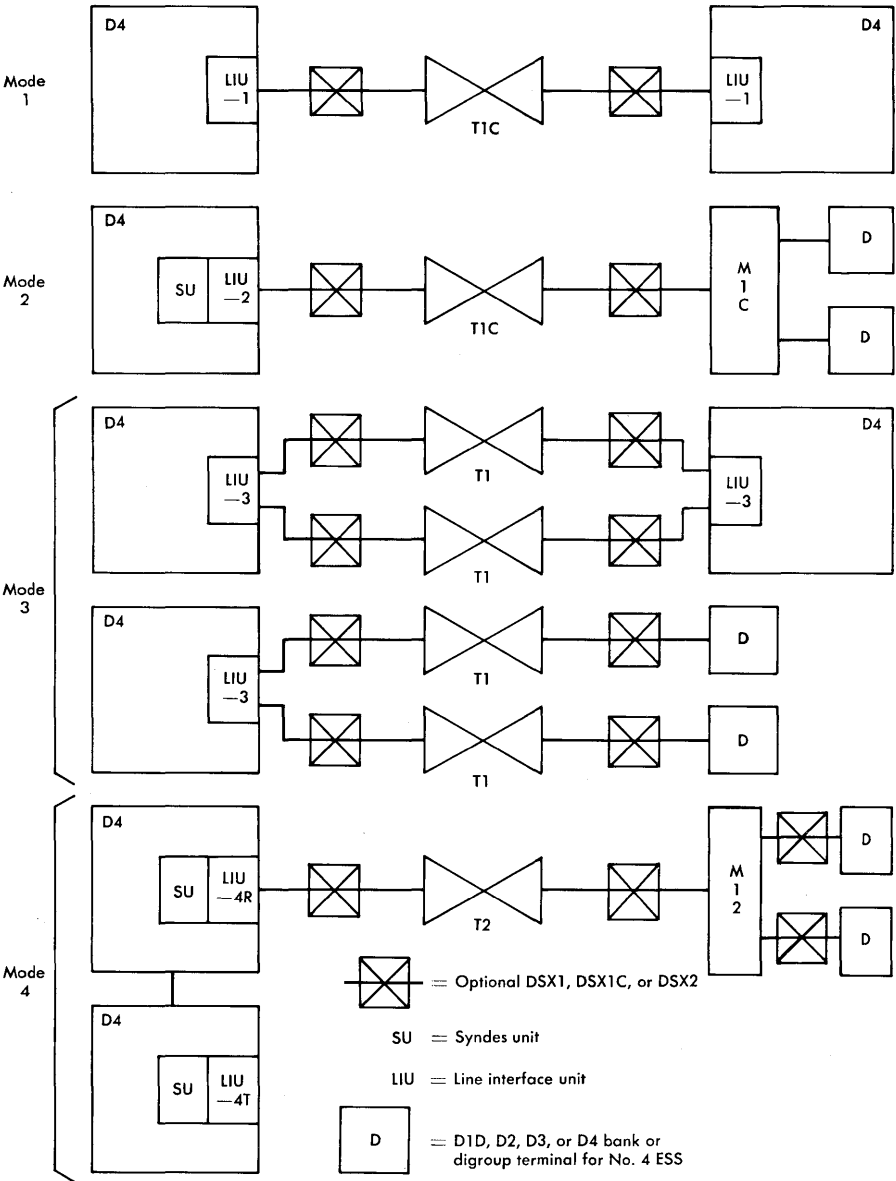


Figure 21-12. D4 channel bank applications.



(syndes) unit to add or delete control and stuff pulses in the same manner as that used in the M1C multiplex unit.

In mode 3, the D4 bank can be used with two T1 lines or with one of the multiplex units such as M12 or M13. The interface with the lines is provided by LIU-3 circuits which deliver DS1 signals to the lines for transmission. In one case, the mode 3 operation terminates in another D4 bank at the far end while the other case illustrates D4 compatibility with D1D, D2, D3, and D4 banks and a digroup terminal at a No. 4 ESS machine.

Mode 4 operation requires a combination of two D4 banks to form a 96-channel bit stream for transmission over a T2 line. The far end of the transmission line may terminate in another D4 bank arranged for mode 4 operation or, as shown in Figure 21-12, it may terminate in an M12 multiplex unit which may, in turn, be connected to any of a variety of channel banks. In the D4 banks, an LIU-4T unit must be used to control the transmitting circuits in the two banks and an LIU-4R unit must be used to control the receiving circuits in the two banks. Each line interface unit must operate with a syndes unit.

**Operating Features.** Signal processing within the D4 bank is based on the use of two digroups of 24 channels each. These are designated A and B and the channels for each are designated 1A through 24A and 1B through 24B. These channels are sampled in any of three optional sequences. The selection is based on the sequence in the channel bank used at the far end of the line. Where only D4 banks are involved, the preferred sequence is the same as that used in D3 banks. The coding of speech, signalling and framing information, and the companding characteristic used are the same as those in the D1D, D2, and D3 channel banks. Timing is accomplished by clock circuits in the line interface units and may be controlled internally or externally or derived from the incoming bit stream.

A D4 maintenance bank consists of channel bank equipment which is kept operating in a looped condition. It is monitored for alarm conditions and tested for tone transmission by a maintenance bank test set. These and other tests ensure the availability of replacement plug-in units known to be in good working order. The bank also provides channel unit test capability for use in isolating troubles and for ensuring channel unit integrity when a channel is to be added to a working bank. The maintenance bank may be supplied as optional equipment.

### Special Purpose Terminal Arrangements

A number of data bank and multiplex terminal arrangements are available. Some of these are designed to process data signals only, others process a combination of data signals and pulse code modulated speech signals, and others are designed to transmit signals of the digital data system [5, 14, 15]. A number of these arrangements are described in Chapter 6.

The development of electronic switching systems and the proliferation of digital transmission systems has brought about an increasing interaction between and combining of the two technologies. For example, the signal format used in D1D, D2, D3 and D4 channel banks is the same as that used by the digroup terminal of the No. 4 ESS, a time division switching system [16]. A digroup terminal may be used to terminate DS1 signals at a No. 4 ESS to permit channel switching without processing the signals to voice frequencies. The digroup terminal removes framing pulses, extracts the signalling information from each channel, and then steers the pulse code modulated speech information into the logic processes of the ESS operations.

Trunk circuits used with No. 1, 2, and 3 ESS machines have many functions that overlap those of the channel units in D-type channel banks. Methods are under development to combine these units to make the interface between the switching and transmission systems more economical. Units of this type, called direct interface channel units, are now available for D3 channel banks terminating at No. 2 ESS machines.

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## Chapter 22

# Digital Transmission Lines

A number of wire-pair and coaxial transmission media are used to transmit the various signals of the digital hierarchy. In each case, regenerative repeaters are installed at specified intervals along the line to amplify, retime, and regenerate the pulses for transmission to the next repeater or to a terminal.

The facilities developed for this mode of operation have all been designated as T-type systems. Those presently in use include the T1 and T1/OS, T1C, T2, and T4M Digital Transmission Systems which transmit signals at the DS1, DS1C, DS2, and DS4 rates respectively.

Most of these systems provide trunk facilities in metropolitan and suburban areas; there are also some applications in the loop plant. The distances over which these systems can operate economically are being increased and some systems now in service extend well beyond metropolitan and suburban areas.

The layout of digital lines is based on repeater spacings established by line loss, interference, bandwidth, and the provision of adequate margins. Line spans that encompass a number of repeater sections are based on operations and maintenance considerations and on the limitations of supplying power to remote repeaters over the transmission conductors. The provision of fault locating facilities, maintenance spare lines, and protection switching arrangements are other aspects of digital line layout that must be considered.

### 22-1 THE T1 DIGITAL TRANSMISSION SYSTEM

The first digital system to find acceptance and the one that is in most common use is the T1 Digital Transmission System. The field

of application is primarily to provide switched network trunks between central offices up to about 50 miles apart [1]. Some systems are as short as five miles but, in general, T1 systems are more economical than voice-frequency facilities at distances of 10 miles or more. The T1 line equipment has also been found economical for loop applications such as those described for the SLC-40 system discussed in Chapter 3 [2].

While T1 was initially limited to a maximum length of about 50 miles by operating and maintenance considerations, it may now be used over distances of up to about 200 miles. A maximum of 200 regenerative repeaters comprising several power spans may be connected in tandem. This increase has been realized by applying more stringent engineering rules to ensure meeting performance objectives and by the addition of operating and maintenance features needed for longer routes. Also, improved features and equipment needed for small installations and more economical central office equipment arrangements are provided. In such applications, the system is called T1 Outstate (T1/OS) [3].

The signal transmitted over a T1 carrier line must have a repetition rate of 1.544 Mb/s, a bipolar, 50-percent duty cycle format, and contain no more than 15 consecutive 0s. These constraints on signal characteristics must be applied in the system terminal equipment but are necessary in order to assure satisfactory operation of regenerative repeaters located along the line.

### Transmission Media

A wide variety of multipair exchange cables may be used for T1 systems. These include polyethylene-insulated conductor (PIC) cables, pulp-insulated copper-pair cables of 19, 22, 24, and 26 gauge, and aluminum conductor cables of 17 and 20 gauge. In most cases, the two directions of transmission can be carried in the same cable provided they are in different cable units, or binder groups, in order to control crosstalk between systems. Engineering rules specify the manner in which such separation must be accomplished but, even within these rules, a limit is imposed on the number of pairs that can be used as T1 lines.

In some cases, the crosstalk between cable pairs is excessive due to the assignment of too many T1 lines per cable. It is then mandatory that the two directions of transmission be carried in separate cables

or in cables with shielding between binder groups to provide sufficient isolation so that cable fill of T1 lines is equivalent to that obtained by using separate cables. Such cables are called screened cables. Some systems are operated with the two directions of transmission in the same binder group but with reduced repeater spacing.

Metropolitan area trunk (MAT) cable was designed to optimize performance for T1 systems and to minimize costs for all types of metropolitan area circuits. This cable is most useful in heavily populated areas requiring large cross-sections of circuits between central offices. [4].

In addition to trunk applications, T1 system line equipment is used in the loop plant to carry SLC-40 signals using standard loop plant cables. Great care must be taken in all applications to be sure that cable pairs have been checked for satisfactory operating conditions. All bridged taps, load coils, and line build-out networks must have been removed. In many cases, voice-frequency equipment will have been used on the pairs involved for some previous service and all of this equipment must also be disconnected.

The standard administration of cables in the loop plant is not as well suited to T1-system transmission as that in the trunk plant. Loop cables are generally not operated under gas pressure and are therefore more prone to impairment due to moisture. A cable route from the central office to a remote area may be made up of mixed gauges. Binder group integrity may be lost since it is less important in the loop plant than in the trunk plant. All of these factors must be examined carefully and the cable condition upgraded where deficient if the T1 line equipment is to operate satisfactorily.

### Regenerative Line Repeater

The T1 system utilizes two general types of repeaters called line and central office repeaters. Line repeaters, designed for use in man-holes or on telephone poles, have circuits which include two regenerators arranged for either one or two directions of transmission. These repeaters are generally assembled in apparatus cases that house 25 repeaters (50 regenerators). The other type, designed for use in central office repeater bays, contains circuits to regenerate the signals on only one line. Thus, two such regenerators must be used at each intermediate central office repeater point for a complete two-way

system. However, a single central office repeater is used in the receiving direction where a T1 line terminates. Other differences between line and central office repeater designs relate to powering and maintenance features. Power is fed from central offices to the remote repeaters and the office repeaters may be powered locally or from the line power loop.

In the years since T1 systems were introduced, significant technological advances have been made and incorporated in the repeaters. A general description of these repeaters may apply to all vintages but detailed improvements in design must be discussed individually. The most significant changes have involved the introduction of automatic line build-out networks to replace the earlier fixed networks, the use of integrated circuit techniques in many of the circuits, and the reduction in power consumption. These advances have resulted in significant reductions in size and heat dissipation problems.

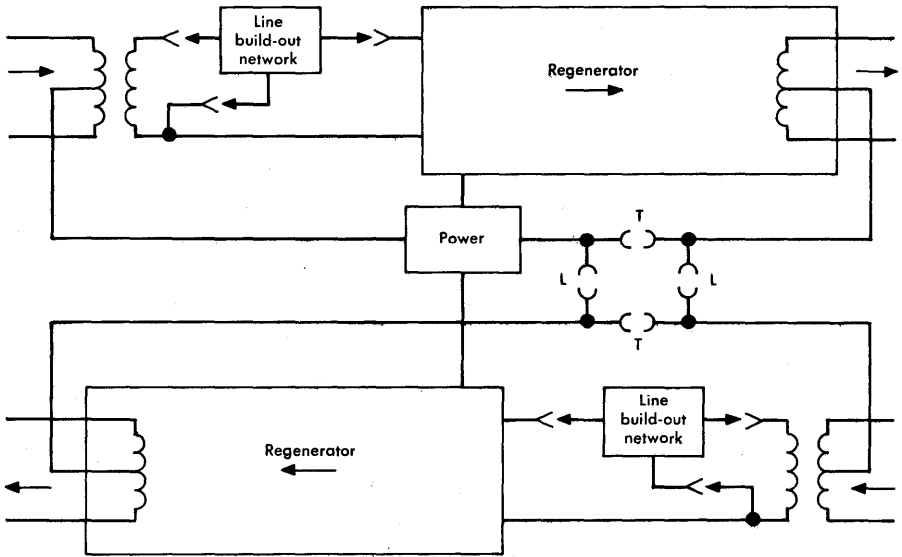
**General Description.** Figure 22-1 is a block diagram of a typical T1 regenerative line repeater and also shows a schematic drawing of the regenerator used in the initial repeater design.

In the original regenerator design, coded 201 and 205 types,\* the build-out networks had fixed attenuation/frequency characteristics and had to be selected for each repeater site and direction of transmission. The selection was based on the measured or calculated loss to the previous repeater site. The function of the network was to build out the cable attenuation/frequency characteristic to approximate that of 6000 feet of 22-gauge cable.

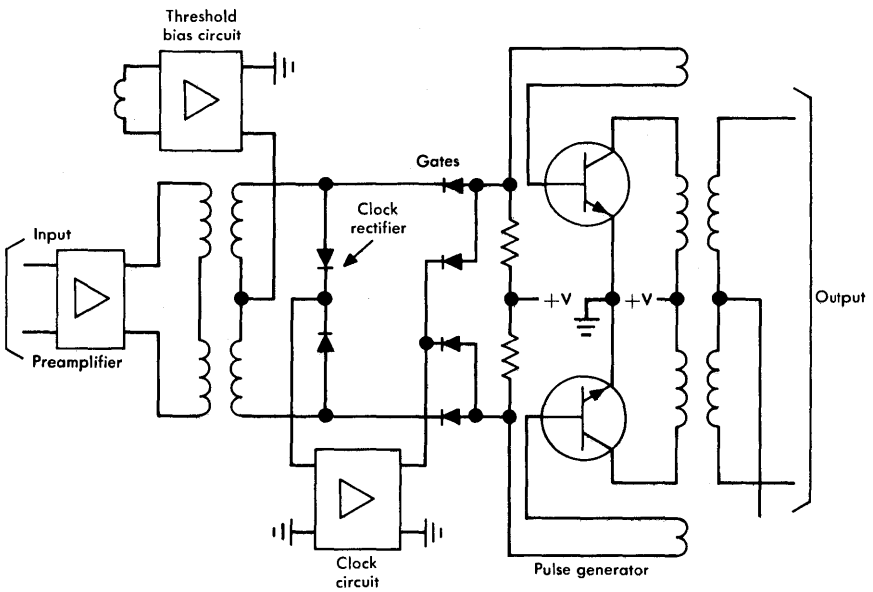
Direct current from the cable conductors flows through the power circuit which provides regulated voltage to operate the active transmission circuits. Screw-type switches are used to loop the dc path or to connect it through as required. The direct current is applied at the central office repeater through a simplex transformer arrangement.

In the regenerator circuits, illustrated in Figure 22-1(b), a preamplifier amplifies and equalizes the incoming signal to reshape the pulses and to reduce intersymbol interference. The preamplifier output signal drives the threshold bias, clock, and pulse generator circuits.

\*The 201 repeater contains no electrical surge protection circuitry. The 205 repeater includes surge protection and is therefore somewhat larger.



(a) Two-way repeater configuration



(b) Regenerator circuit

Figure 22-1. Regenerative repeater for T1 line.



The threshold bias circuit sets the decision voltage level which determines for each time slot whether a pulse is present. The decision level is optimized over a moderate range of variation of the incoming signal amplitude. The clock circuit rectifies the incoming bipolar signal. The resulting unipolar pulse train contains a strong periodic component at the original repetition rate of 1.544 Mb/s which is selected by a tuned circuit, amplified, and shaped to provide timing pulses for the decision circuit and to time the output pulses. The clock circuit also gates the decision circuit so that the digital stream is examined at the center of each time slot for the presence or absence of a pulse.

The output circuits of the repeater include two gate circuits, one corresponding to each polarity of pulse in the input signal. When an incoming signal pulse of either polarity coincides with the timing pulse, the pulse generator (blocking oscillator) of the same polarity is triggered to send out a new pulse.

**Circuit Improvements.** The T1 system line repeaters have been redesigned to achieve improved performance as technology has advanced [5]. The new repeaters, coded 208 and 209 (corresponding to the predecessor 201 and 205 types) are about one-third the size of the earlier versions. In addition to the reduction in size, the new designs achieved lower costs, a wider operating temperature range, and improved performance, especially in respect to equalization.

The reduction in size was an important factor because space for repeater mountings in manholes was becoming congested. With the reduction in repeater size, it became possible to reduce significantly the size of the 25-repeater apparatus cases as well; mounting and access arrangements made the effective volume reduction even more valuable.

In the initial repeater design, discrete components were used throughout. Line build-out (LBO) networks had to be selected at each repeater point. In the 208 and 209 repeaters, a large part of the circuitry is provided in the form of tantalum capacitors, thin-film resistors, and silicon integrated circuits. In addition, an automatic line build-out (ALBO) network was developed to allow the repeater to operate at a wide range of cable loss and thus to compensate for variations in cable characteristics due to departures of length and temperature from nominal values.

Further improvements in repeater performance have been realized in the most recent repeater design. The improvements result primarily from the extended use of silicon integrated circuit techniques. The new line repeaters, coded 238 and 239 types, require significantly less line current (60 versus 140 mA) and repeater voltage (6.8 versus 10.9 volts) than the earlier types. Advantage may be taken of these lower values by reducing the power feed voltage or by extending the lengths of power spans. Because of the lower repeater voltage and line current, these repeaters are not compatible with earlier designs; the same type repeater must be used for replacement or all repeaters in an entire power span must be changed to the new design.

All of the more recent designs (208, 209, 238, and 239 types) include the ALBO feature. In addition, they have been designed so that they do not free run when there is no signal present. Free running, or spontaneous oscillation, is a characteristic of the 201 and 205 types that made maintenance difficult and added undesirable interference in working systems in the same cable. The later designs are also relatively insensitive to impedance discontinuities at or near the output of the repeater. In addition, the 238- and 239-type repeaters have much greater immunity to induced 60-Hz line current impairments.

**Office Repeaters.** For each of the line repeater vintages discussed above, comparable designs have been provided for use in central offices. In general, remote line repeaters contain two regenerators in each assembly. However, terminal office repeaters provide for two directions of transmission only one of which includes a regenerator. In the receiving direction, a regenerator is used because all of the functions of a line repeater, i.e., equalization, timing, and regeneration, must be provided. The transmitting portion of a terminal office repeater is made up entirely of passive components which comprise an artificial line and power feed circuitry to carry operating current from the central office power supply to the transmission conductors for use at remote repeaters.

An express office repeater panel is available to provide regenerators for lines that pass through an office without connection to terminal equipment and without the ability to feed power to remote repeaters. In this arrangement, line repeaters are mounted in central office bays in a manner that is less costly than standard office repeater bays or central office mounted apparatus cases.

**Repeater Options.** Repeaters for both line and office applications are designed with many options some of which are exercised by selection of the proper repeater code, some by switch operation, and some by the installation of appropriate networks within the repeaters.

Repeaters located along a T1 route must be capable of feeding direct current through to the next repeater or of looping the current back to the originating terminal. The choice is made at the time of installation by operation of a switch or by selection of the proper repeater. In the original T1 repeater design, it was also necessary to install the proper LBO network according to the type of cable and the length of the preceding line section. This is not required in later designs that incorporate ALBO networks.

In systems operating in a single cable, the two regenerators of a repeater assembly are normally bidirectional, i.e., they transmit in opposite directions. These regenerators are then associated with one transmission system. Where two-cable operation is used, the two regenerators transmit in the same direction (a unidirectional repeater) and the two systems are unrelated.

An option is offered in the 238 and 239 types of bidirectional line repeaters in respect to fault location capabilities. The fault location function may be carried out from either end of the span. Connection to separate fault location lines is selected by a switch on each repeater.

Line repeaters that incorporate surge protection circuits are somewhat larger than those that do not. Thus, it is necessary to select proper apparatus cases as well as the proper repeater codes for installation where surge protection may be required. Apparatus cases for protected repeaters also incorporate gas tubes for protection against very high-voltage surges.

Most of the designs of repeaters may be used with any of the PIC or pulp-insulated cables normally found in the local trunk plant. However, special codes of the low-power repeaters (238 and 239 types) are used where the transmission medium is the new MAT cable.

Some of the options mentioned above for line repeaters are also available for office repeater applications but surge protection and one- or two-way fault location are not available. However, office repeaters have other options appropriate to the various line power feed situations.

### Line Layout

The repeatered lines in T1 are laid out as span lines, i.e., the transmission lines from a DSX1 cross-connect frame (or an office repeater bay) in one power-feed central office to a DSX1 cross-connect frame (or an office repeater bay) in the next power-feed central office. A span line is required for each direction of transmission. The span lines between two offices are collectively called a span. With this concept, it is possible to provide maintenance lines, order wires, and fault location equipment between central office buildings without regard to system terminal locations. The arrangement also provides a convenient administrative unit for circuit assignment, maintenance, and powering.

With 22-gauge cable, the maximum distance between power feed points is approximately 17 miles when repeaters of early design are used and approximately 36 miles when the newer low-power repeaters are used. Many factors, such as cable gauge, aerial or below-ground installation, and length of end sections, affect the exact spacing of power feed points. In some cases, remote power feed points are located in other than central office buildings.

Regenerative repeaters are housed in apparatus cases located along the cable. These cases may be mounted in manholes or on pedestals or telephone poles. They are usually arranged to contain 25 repeaters in a 5 x 5 equipment matrix, a fault locating filter, and an order-wire terminal. The repeaters and apparatus cases serve up to 25 two-way systems for bidirectional operation or 50 one-way systems for unidirectional operation. Stub cables are connected to the apparatus cases at the factory and connections are made to transmission cables by splicing. Single-cable and two-cable operations require different splicing patterns.

Repeaters are designed for optimum performance at a cable loss of approximately 31 dB at 772 kHz which is equivalent to a cable length of about 6000 feet for 22-gauge pulp-insulated cable and other commonly used cable types. When a new system is engineered and repeater locations established, the loss of the cable to be used must be known and allowance must be made for the actual loss and for increased loss with higher than normal temperatures. Engineering rules specify the allowable departures from the nominal spacings that are permitted in order to accommodate environmental conditions along

the route. For example, repeater spacings adjacent to central offices are made short to overcome the effects of impulse noise originating from switching transients.

Cables are designed and manufactured in various ways as described in Chapter 2. Some are made up of bundles of conductor pairs called binder groups and others are made up of layers of conductor pairs. Splicing rules determine the extent to which the integrity of the binder groups and layers is maintained. The intersystem crosstalk performance of the cable is very dependent on these factors; engineering rules specify which conductor pairs may be used under various circumstances. System performance objectives can be assumed only when these rules are rigidly applied in the layout of systems.

One or more powered span lines may be reserved as maintenance lines. These are used to carry service while maintenance is being performed on working lines or to restore service in the event of working line failure. Service restoral is usually achieved by patching although some T1 systems are equipped with automatic protection switching.

System lengths are generally limited to a maximum of 50 miles, a limit imposed primarily by maintenance and fault location procedures. This limit has been extended to about 200 miles for T1/OS systems.

### Maintenance Considerations

Two rules are applied to the generation of a T1 line signal. One is that the signal must have a bipolar format, i.e., successive pulses must alternate in polarity. The other is that there must be no more than 15 consecutive 0s and an average density of one pulse in every eight signal time slots. These two characteristics are used by monitoring equipment to evaluate T1 line performance. Signal irregularities demonstrated by violations of either rule are detected and indicated by a special test set, called a line monitor [6]. When violations are excessive, an office alarm may be sounded. The monitor can be used to initiate protection line switching where this function is provided.

A line monitor is usually connected to a specific maintenance line or to a critical working line. However, it can be used to monitor any line by patching between the monitor and the office repeater of the line to be checked. Thus, it is valuable in seeking the cause of inter-

mittent trouble. Separate lamps are provided to indicate the nature of the violation observed, bipolar or absence of 1s. The lamps flash to indicate the degree of the line trouble detected and the way in which they flash can be used to diagnose line troubles. Special plug-in units are available for use with the line monitor to provide additional trouble diagnosis such as average violation rate and variable alarm threshold conditions.

Another significant aid to T1 system maintenance is the fault location system used to identify which repeater section is causing line troubles. A loaded pair is required for lines accommodated by each set of apparatus cases (25 repeaters) in each span to provide fault locating facilities for up to 12 repeater locations. Each location is assigned an interrogation frequency which corresponds to the passband of a common filter connected to each repeater in an apparatus case. A fault location pair must be used for each apparatus case at any location.

Span lines having more than 12 tandem repeaters are not unusual. The longer spans may be equipped for fault location in either of two ways. Separate fault location pairs and sets of filters may be used for separate portions of longer spans. With this method, fault location in a given direction is performed from one end of the span only. Otherwise, the fault location testing must be carried out from opposite ends of a span with the fault location pair split at the midpoint. In both cases, the same set of frequencies is used to identify faulty repeater sections.

When fault location is carried out, the line under test must be removed from service. A fault location test set is used to transmit a test signal from the terminal. This test signal includes many bipolar violations and has a strong voice-frequency component which passes through the repeaters and is picked off by the fault-location filter at each repeater point. The test signal must be changed to correspond in frequency with the passband of the filter at the repeater under test. The voice-frequency signal is returned to the test location over the fault location pair and is measured by the test set. The faulty repeater section is identified when its single-frequency signal is not returned or when it is impaired by a marginally operative repeater.

A number of other tests are required for T1 system maintenance. These include measurements of transmission pair losses and bipolar

violations as well as tests of repeater performance. Test instruments are available for each of these measurements.

An order wire must be provided to supplement other maintenance facilities and procedures. It requires a loaded pair that parallels the digital line for each span. Typically, the order-wire pairs are loaded with 88-mH coils installed in repeater apparatus cases or spliced into the line, as required. Access to the order wire is provided at each repeater location and at one or both ends of the span. A subscriber access line is used to provide access to the switched message network to aid in maintenance activities. Battery for talking and signalling on the order wire is provided through the order-wire panel located in the central office at one end of the span. This panel may be located at the DSX1 cross-connect frame, the office repeater bay, or the span terminating bay. Intermediate amplification may be provided where necessary.

### The T1 Outstate Digital Transmission System

The T1/OS system utilizes standard T1 carrier equipment but permits the installation of much longer systems than are possible with conventional applications [3]. The increased length is made possible by the development of new engineering rules, the provision of features to enhance reliability and improve maintenance procedures, and the development of central office equipment arrangements that provided more economically the variety of combinations needed for small installations.

According to the new engineering rules, up to 200 repeaters may be connected in tandem. The maximum length of a system is a function of the quality of individual repeater sections and the permissible repeater spacings. These spacings are dictated by the need to maintain signal amplitudes at values that permit processing by the repeaters and to maintain an adequate signal-to-interference ratio so that errors are few. Screened cables or dual cables are used whenever possible to minimize the effects of near-end crosstalk.

Transmission quality is assured by the application of a *design number* to each line section, span, or terminal-to-terminal system. The overall engineering design objective is that at least 95 percent of all properly engineered and installed systems have an error rate of less than one error in  $10^6$  bits. The probability of exceeding this

error rate is allocated on a section-by-section basis. For T1/OS, 5 percent is allocated as the design number for the maximum allowable system length of 200 repeater sections. Hence, each repeater section is allocated a design number or maximum probability of  $5/200 = 0.025$  percent of exceeding the error rate of one error in  $10^6$  bits. The design number for a span or a system is the sum of the design numbers for the component parts.

Remote repeater powering rules are the same as for conventional T1 systems. The low-power repeater, previously described, permits wider spacing between power feed points and its use is therefore favored in the T1/OS system.

The improved fault locating capability is achieved by providing amplification for the fault locating signals. In addition, the outgoing or incoming regenerator can be tested from one end of the span by controlling the fault-line power supply polarity. The transmission facility used for these signals must be constructed according to a separate set of engineering rules. These rules include the use of a computer program for analyzing fault location problems associated with the rather complex system layouts that are a feature of T1/OS installations.

To improve system reliability, T1/OS systems are provided with a protection switching arrangement. A number of span lines may be connected in tandem to form a maintenance span. Switching is implemented at the ends of such maintenance spans. Alarms and trouble indications are displayed at the ends of maintenance spans and may also be transmitted to a centralized maintenance center.

The central office equipment arrangements for T1/OS are designed for flexible combinations required to satisfy a wide variety of operating needs. These arrangements include office repeater, order wire, fault locating, span terminating, and switching equipment as well as D-type channel banks. The same order-wire arrangements are used as those described for the T1 system.

## 22-2 THE T1C DIGITAL TRANSMISSION SYSTEM

The central office and outside plant environments for which the T1C system was developed are similar to those of the T1 system. As a result, there are many similarities between the two systems. The repeater spacings of T1 may be used for T1C, thus facilitating the



conversion from T1 to T1C. In addition, the bipolar 50-percent duty cycle signal format is used by both systems and the same transmission media can be used. Regeneration, powering, and maintenance functions are also similar [7].

While the signal format in the T1C system is similar to that in the T1 system, as mentioned above, it differs in one major respect, repetition rate. The T1C system is designed to provide 48 voice-grade channels. To accommodate these channels, the line repetition rate in T1C is 3.152 Mb/s, more than twice the 1.544 Mb/s repetition rate of the T1 system. This greater channel capacity is the main advantage of the T1C system over T1 since much more efficient use is made of cable conductors, ducts, and manholes.

### Transmission Media

The T1C system can generally be used with all of the same media as those used for T1 systems although fewer pairs can be equipped in single cables that provide both directions of transmission. However, with the greater channel capacity of the T1C system, a net gain of more than 50 percent can be realized over T1 operation. With two-cable or screened cable operation, cable pairs can be fully utilized (with some pairs reserved for order wires and fault locating functions) and the two-to-one increase in capacity per system can be realized with T1C operation. The MAT cable can be used with T1C as well as with T1 systems [4].

Crosstalk is controlled by strict application of engineering rules regarding segregation of cable pairs and selection of binder groups. Crosstalk performance has also been improved by a redesign of the apparatus case for T1C repeaters. The low-amplitude input signals are separated from high-amplitude output signals by separate cable stubs and by careful control of internal wiring.

### Regenerative Repeater

Figure 22-2 is a block diagram of a T1C regenerator. It can be seen that this regenerator is functionally similar to a T1 regenerator. As with the latest versions of T1 repeaters, the T1C repeaters were designed for small size and low cost. Hybrid integrated circuits are used. An automatic line build-out network is used and the equalizing amplifier can compensate for cable loss from about 10 to 53 dB as measured at 1.576 MHz. Timing is accomplished by extracting the 3.152 MHz component from the signal by means of a crystal filter.

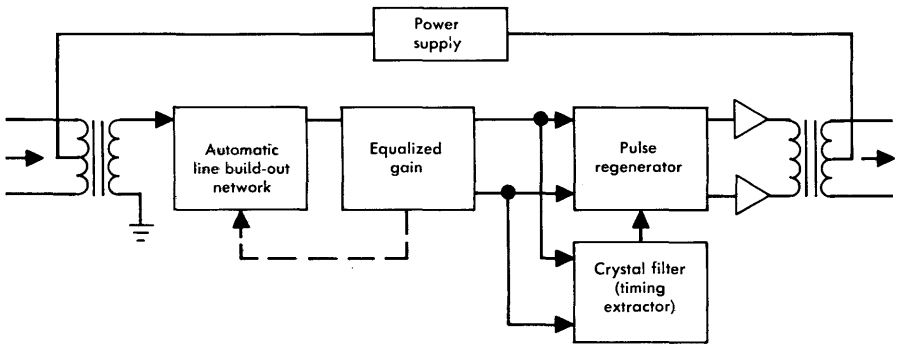


Figure 22-2. Regenerator for a T1C line repeater.

### Line Layout

The layout of T1C systems is basically the same as that of T1 systems. Repeater spacing rules, maximum route distances, and the number of repeaters housed in an apparatus case are all similar but T1C rules are more restrictive in setting repeater spacings adjacent to central offices.

The apparatus cases for T1C repeaters are somewhat larger than those for T1 repeaters but are similar in construction. Where a route is expected to grow and ultimately to require the capacity of T1C systems, the initial T1 installation can be made in T1C apparatus cases. Cable splicing rules for T1C must be used. Adapters are available to make it possible to plug T1 unidirectional repeaters into the positions designed for T1C. At the time of conversion, the T1 repeaters and adapters are removed, T1C repeaters are plugged in, and relatively simple changes must be made in power feed arrangements. Additional channel banks and appropriate multiplex equipment, such as the M1C, must be provided in the terminal. Many of the options described for T1 line and office repeaters are available for T1C operation. Order-wire arrangements like those described for the T1 system may be used with T1C systems.

### 22-3 THE T2 DIGITAL TRANSMISSION SYSTEM

The extension of digital transmission techniques to distances well beyond a metropolitan area was first realized with the development of the T2 system which is capable of providing 96 4-kHz channels

for transmission over distances up to about 500 miles [8]. The required terminal equipment includes D-type channel banks and an M12 multiplex unit or D4 channel banks operating in mode 4 as described in Chapter 21.

There are a number of facets of T2 system design that make it similar to the T1 system design. However, there are also substantial differences in signal format, transmission media, repeater design, line layout, and maintenance procedures.

### Signal Format

The T2 line transmits a modified form of the bipolar 50-percent duty cycle signal called bipolar with six zero substitution (B6ZS). The repetition rate is 6.312 Mb/s. The substitution of a special code for any succession of six 0s guarantees the presence of sufficient pulses in the signal to maintain repeater clock operation but introduces bipolar violations that are used at the receiving terminal as an indication that the special code is to be removed from the signal. This coding method is efficient from the point of view of terminal operation but maintenance problems are somewhat increased because means must be provided to recognize the intentional bipolar violations. This is accomplished, together with an evaluation of transmission quality, by a violation monitor and remover. When the monitor senses a violation, it removes the violation so that it is detected only once, transmits a violation free signal to isolate the trouble to the span preceding the monitor, and activates an alarm lamp. However, the monitor is designed to recognize and pass a zero substitution code which contains intentional bipolar violations.

### Transmission Media

Although certain of the cables used for T1 and T1C transmission could be used for T2, the higher losses due to the higher repetition rate and the excessive crosstalk would make repeater spacings uneconomically short. To overcome this problem, a special low-capacitance (LOCAP) cable was designed specifically for use with the T2 system [9]. Cables of this design are available with 27, 52, or 104 conductor pairs. The conductors are dual expanded polypropylene-insulated 22-gauge copper. Separate cables must be used for opposite directions of transmission. These cable pairs exhibit lower capacitance, lower loss, and higher crosstalk coupling losses than do conventional cable pairs.

### Regenerative Repeater

A regenerator for one direction of transmission is mounted in an apparatus case separate from that used for the opposite direction. Unlike T1 and T1C, each regenerator is assembled separately as an independent plug-in unit. Two regenerators, one for each direction of transmission, are considered a repeater.

As with other systems, a T2 regenerator performs the functions of pulse reshaping, retiming, and regeneration. A selection of plug-in equalizers must be made to match repeater gain to the LOCAP cable loss in the preceding repeater section. The timing circuit operates on the basis of the characteristics of the pulse stream. A monolithic crystal filter with a very narrow passband extracts the clock signal. If the signal is lost, the clock disappears and there is no regenerator output, thus preventing free-running oscillation.

### Line Layout

The T2 system operates over distances of up to about 500 miles on LOCAP cable. Repeaters are housed in apparatus cases that may be manhole or pole mounted. Each apparatus case can house up to 24 one-way regenerators. A protection switching system is provided in which one protection line can protect up to 23 working (or service) lines. The two directions of transmission are independently protected.

At each repeater location, there are three apparatus cases used for each complement of 24 T2 lines. Two cases are used to house the regenerators, one for each direction of transmission. The third case houses maintenance facilities required for the 48 one-way lines.

Normally, the maximum repeater spacing with underground or buried air-core LOCAP cable is 15,000 feet. This maximum spacing must be adjusted downward for sections adjacent to a central office, for those containing aerial cable, and where environmental temperatures are excessive. Individual repeater sections are engineered to meet a design number objective similar to that described for the T1/OS system. The objective for a maximum length system of 250 repeaters is that the error rate should not exceed one error in  $10^7$  bits in 95 percent of all lines.

Each T2 line installation is divided into maintenance spans which include up to 44 repeaters, intermediate power stations, and the terminal locations. A span terminating bay provides mounting space for

regenerators, power feed units, violation monitors and removers, and protection switching apparatus for one protection group of 24 systems. In addition, the span terminating bay has alarm indicators and access to all lines for fault location activities.

### Maintenance

The fault location system used for T2 lines is similar to those used for T1 and T1C lines. Each regenerator is connected to a common narrowband pick-off filter the output of which is connected to a fault locating line. A digital test signal with a high voice-frequency component corresponding to the passband of the filter is transmitted from the span terminating bay. The voice-frequency signal is returned to the office over the fault locating pair. Absence of this signal indicates a fault at the corresponding repeater or in the preceding line section; marginal failures can be determined from abnormalities in the returned signals. Each regenerator location along the line is assigned a different frequency for identification purposes. In T2, all regenerators in a maintenance span of up to 44 repeaters can be tested from the maintenance offices; each office tests the lines in the direction of transmission away from the office.

The violation monitor and remover is the principal unit for checking the quality of transmission. When errors are few, unwanted bipolar violations are corrected and the trouble is indicated by the flashing of an indicator lamp designated LOW. When the error rate is high or in the absence of a signal, another lamp, designated HIGH, is also lit. The violation monitor and remover also initiates action of the automatic protection switching system.

Verification of trouble conditions or transmission quality at remote repeater locations may be made by means of a portable battery-powered bipolar violation detector. An audible "beep" signal is used to indicate bipolar violations. The instrument beeps continuously when no signal is present.

## 22-4 THE T4M DIGITAL TRANSMISSION SYSTEM

Presently, the digital line having the largest channel capacity is the T4M which is designed to operate as an intercity and metropolitan area facility [10]. This system differs in many respects from other

digital systems now in operation. The signal format, repetition rate, and the transmission medium are different. In addition, the regenerator has many different features because of the signal format and higher repetition rate.

### Signal Format

The T4M transmits the DS4 signal of the digital hierarchy, 274.176 Mb/s; this rate can accommodate 168 multiplexed DS1 signals or 4032 4-kHz channels. Figure 22-3 shows unipolar, bipolar, and polar binary signals for comparison. The T4M uses the 100-percent duty cycle (nonreturn to zero) polar binary signal because it is more efficient in the use of the information-carrying capacity of the digital line. An analytical comparison of the bipolar and polar binary formats has shown significantly more margin in respect to error-rate performance for the latter [11]. However, scrambling is necessary to make it suitable for system use.

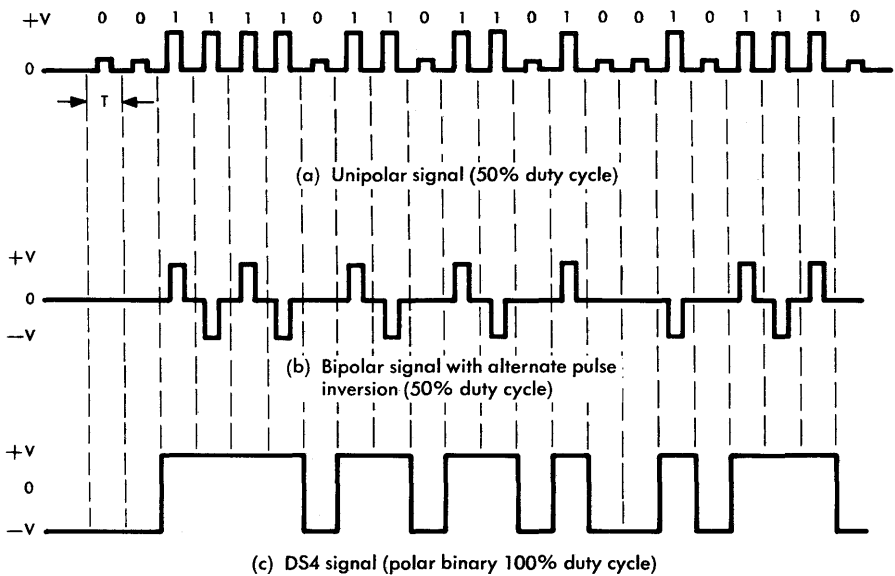


Figure 22-3. Signal waveform comparison.

### Transmission Medium

The T4M system is designed to operate over standard 0.375-inch diameter coaxial cable units. Cables are manufactured with up to 22 of these coaxial units. An 18-unit cable is suitable for use in 3-1/2 inch cable ducts, commonly found installed under city streets and the 22-unit cable can be used in 4-inch cable ducts. Thus, very large channel requirements can be fulfilled by T4M systems.

Much of the hardware used for T4M is identical to that used in the L5 analog transmission system. For example, the apparatus case for line regenerators utilizes much of the same hardware (base plate, cable terminals, and mounting details) as those used in L5. The apparatus case contains four regenerators for two 2-way systems and provides access to the output of each regenerator for in-service error monitoring. A separate apparatus case houses the wire-pair conditioning circuits and fault locating electronics which serve up to 22 regenerators.

### Regenerative Repeater

In the T4M system, the regenerative repeater is made up of two separately mounted regenerators in which the most critical functions are fulfilled by hybrid integrated circuits. A block diagram of a regenerator is shown in Figure 22-4.

In this regenerator, only a small percentage of the information capacity is used for error monitoring and other administrative functions. Quantized feedback is used to control dc wander and phase-locked loop timing provides for spanning long periods in the scrambled data stream during which there are no signal transitions.

After information signals and power have been separated at the input, an equalizer compensates for gross signal distortion introduced by the transmission medium. An automatic line build-out circuit then compensates for temperature changes and for variations in regenerator spacing within a broad range defined by the regenerator code being used. Four codes cover spacings of 0 to 5700 feet.

The decision circuit recognizes the presence of positive or negative pulses and produces new undistorted pulses. These functions can only be carried out with the help of the timing and control circuit to provide accurate sampling of the pulse stream in the decision circuit.

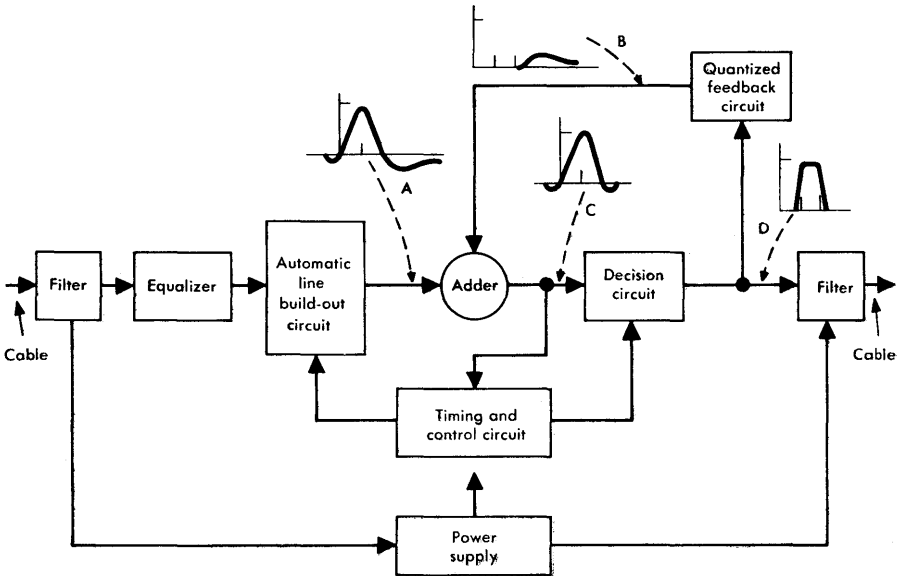


Figure 22-4. Regenerator for a T4M repeater.

The quantized feedback circuit completes the reshaping of the signal prior to the decision circuit. Preliminary signal processes result in a prescribed attenuation of low-frequency components which produce a pulse tail as shown at A in Figure 22-4. The missing signal component is generated in the quantized feedback circuit, as shown at B, and fed back to the decision circuit input to cancel the unwanted tail [12]. The resulting signal, at C, contains only a negligible amount of intersymbol interference and permits the generation of a new pulse of the desired characteristics as shown at D. The pulse stream and power feed current are recombined at the output for transmission to the next regenerator.

### Line Layout

The spacing between T4M regenerators, nominally one mile, may be up to 5700 feet. Exact spacing is not critical within the code range but, near the boundaries between codes, selection may depend on the accuracy of the route map. System length is limited primarily by powering and maintenance considerations.



Automatic protection switching increases system reliability and facilitates maintenance on working lines. Service is switched from a working to a protection line when the error rate exceeds one error in  $10^6$  bits. The span between protection switching points may be up to 111 miles long and spans may be connected in tandem to form systems up to 500 miles long. In one direction, up to ten working lines may be protected by a single protection line. Powering and maintenance activities are organized within maintenance spans which normally correspond with a protection switching span. Each maintenance span terminates in a span terminating frame which contains essentially all the operating equipment including office regenerators, violation monitors and removers, protection switching, alarm indicating, and fault locating circuitry.

### Maintenance

The maintenance plan is based on fault isolation and identification. In-service monitoring isolates the fault to the troubled line and protection switching removes the line from service. A fault locating test set operated from the span terminating frame at the transmitting end of the line isolates the trouble to a particular regenerator. A portable violation monitor complements the fault locating equipment by permitting violation rate measurements at the span terminating frame and at many access points in the line including the output of every regenerator.

Other test sets available for aiding in the installation and maintenance of a T4M line are:

- (1) A regenerator test set used with a portable signal generator to determine the performance of regenerators prior to installation
- (2) A portable signal generator used as the signal source for regenerator and line testing
- (3) A transmission test set used to measure the suitability of the coaxial units for T4M transmission.

These test sets were specifically developed for use with T4M installations. Several test sets are also used during cable installation for testing corona performance, insulation resistance, and conductor resistance.

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## Chapter 23

# Digital Transmission on Radio Systems

The processing of signals to prepare them for transmission over microwave radio systems is different from that used for cable facilities. These differences arise in part from the stringent limitations on radio system bandwidth imposed by the Federal Communications Commission (FCC). In addition, impairments and methods of overcoming them are quite different in the two types of systems.

Where existing radio routes are to be adapted to digital signal transmission, the route engineering is generally not seriously affected and most of the engineering problems considered are those inherent in the existing system. However, engineering of a new all-digital radio route is somewhat different in detail from that applied to conventional analog microwave systems.

Three facilities of Bell System design are available as digital carrier systems that use microwave radio as the transmission medium. The 1A Radio Digital System (1A-RDS) provides for the transmission of a 1.544 Mb/s DS1 signal in combination with a standard frequency division multiplexed message load. The digital signal, after suitable processing to limit its spectrum to the band from 0 to about 470 kHz, is placed in the spectrum below the message signal thus providing a guard band between 470 and 564 kHz, the lowest frequency in the message spectrum. The 3A Radio Digital System (3A-RDS) provides the capability for transmitting a 44.736 Mb/s DS3 signal in the 11-GHz common carrier band. The DR 18A Digital Radio System operates at the DS4 rate, 274.176 Mb/s, to provide metropolitan trunk facilities in the 18-GHz band. All repeaters in this system are fully regenerative. The 3A-RDS and the DR 18A

both utilize four-phase modulation of a carrier signal, a transmission mode that is favorable for microwave radio transmission. The modulated signal is of nearly constant amplitude and highly immune to the types of impairment normally found in microwave radio transmission.

### 23-1 THE 1A RADIO DIGITAL SYSTEM

Although the 1A-RDS may be used to provide any service that can be fulfilled by a DS1 pulse stream, it was developed primarily to provide a long-haul digital facility for the Digital Data System (DDS). Analog microwave radio systems are widely used for intercity telecommunications. Most of these systems provide voice circuits by the use of U600 frequency division multiplex equipment in which the lowest transmitted frequency is 564 kHz. Thus, there is a frequency band approximately 500 kHz wide within which a digital signal may be placed [1, 2].

#### Terminal Equipment

As discussed in Chapter 21, the DS1 signal is a 1.544 Mb/s, bipolar, 50-percent duty cycle pulse stream the spectrum of which requires more than the available 500 kHz. Terminal equipment must be provided to transform the signal into a format compatible with this bandwidth. This equipment, called the 1A Radio Digital Terminal (1A-RDT), performs all the necessary functions including regeneration, when required [3].

Figure 23-1 is a block diagram of the transmitting portion of the 1A-RDT. At the input, the DS1 signal enters an elastic store which removes any jitter that may have been accumulated. In this circuit, the signal is "written" into a memory and then "read" out as a binary signal at a uniform rate. It is then scrambled to suppress high-amplitude discrete components. With scrambling, the output spectrum is noise-like and affects the radio system in a manner similar to that of an additional message load.

The most significant step of processing takes place in the converter where the binary signal is coded into a seven-level, partial response signal [4]. In this converter, the binary signal is grouped into pairs of bits and the information contained in each pair is converted to one of seven voltage values. Theoretically, only four levels are required

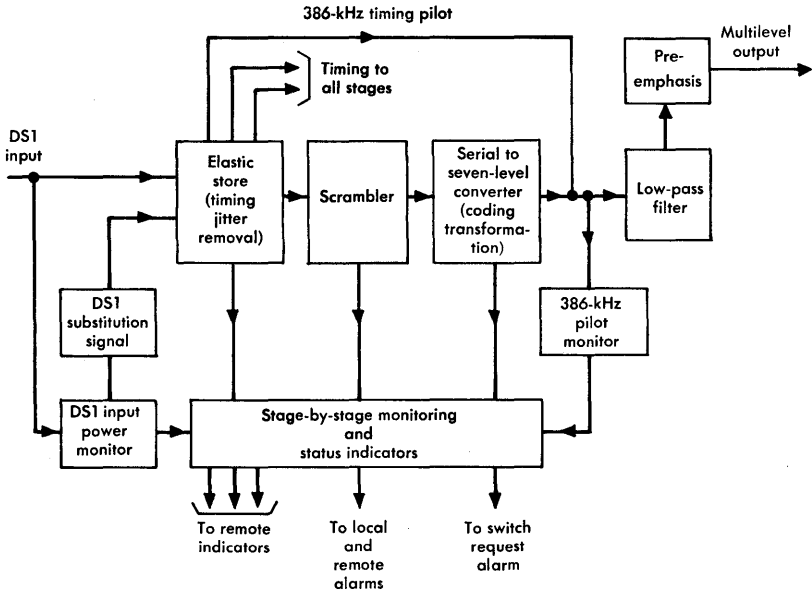


Figure 23-1. Transmitting portion of the 1A-RDT.

for this coding but seven are required to achieve the desired spectrum shaping; the additional three levels are used for error detection and to minimize impairments due to departures from ideal characteristics of filters and equalizers. The required bandwidth for the modified signal is less than 500 kHz, thus providing for a guard band between the digital signal and the analog U600 signal.

At the output of the transmitting terminal, a low-pass filter is used to shape the spectrum and suppress redundant energy above 386 kHz that might impair 512-kHz pilot transmission or any of the analog message channels above 564 kHz. In addition, other terminal circuits are provided for various aspects of system maintenance. The monitoring and status indicator circuits provide in-service monitoring and failure indications of terminal operations. In the event of loss of the input signal, the DS1 substitution signal, consisting of all 1s, is transmitted in its place. A 386-kHz pilot, synchronized to the DS1 signal, is transmitted to the receiver for synchronization of its circuits. A manually controlled protection switching arrangement permits the substitution of a protection terminal for any one of up to eight working terminals. Frequency allocations for the 1A-RDS signal, pilot signals, and message signals are illustrated in Figure 23-2.

The receiving portion of the 1A-RDT is shown in Figure 23-3. The processes in the receiver are the inverse of those in the transmitter resulting in an output signal that is a replica of the DS1 input signal at the transmitter. The low-pass filter separates the desired multilevel digital signal from the remainder of the radio system message signals. The signal amplitude is adjusted by the automatic gain control amplifier and the 386-kHz pilot is extracted for control of the timing recovery circuits.

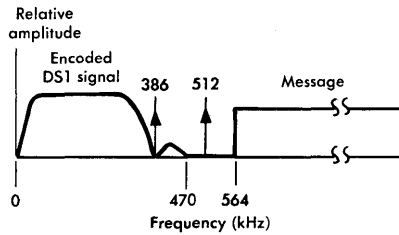


Figure 23-2. Microwave radio system spectrum with 1A-RDS signal.

The multilevel signal is sampled once during each symbol period to determine which amplitude value was sent and the scrambled binary signal is recovered by the decoder. After the descrambler recovers the original data sequence of 1s and 0s, the bipolar converter restores the signal to the DS1 format.

As in the transmitter, signal monitoring and status indicators are provided to show the status of receiver performance. Many of the circuits used for these purposes are identical to those used in the transmitter. A manual protection switching arrangement similar to that used at the transmitter is also used in the receiver.

### System Layout

The manner in which the 1A-RDS signal is combined with message signals for transmission over a microwave radio system is illustrated in Figure 23-4. The signal from a DSX1 cross-connect frame is processed in the transmitting portion of the 1A-RDT. The 1A-RDS signal is transmitted over an access trunk to a message-data combiner where it is added to the message signal. This combined signal is transmitted over the radio system to the receiving terminal where the 1A-RDS signal is separated from the message load in another message-data combiner. The link between office A and office B may be a multihop microwave radio channel in which the combined signal is demodulated to baseband through FM terminals at the end stations but not at intermediate stations.

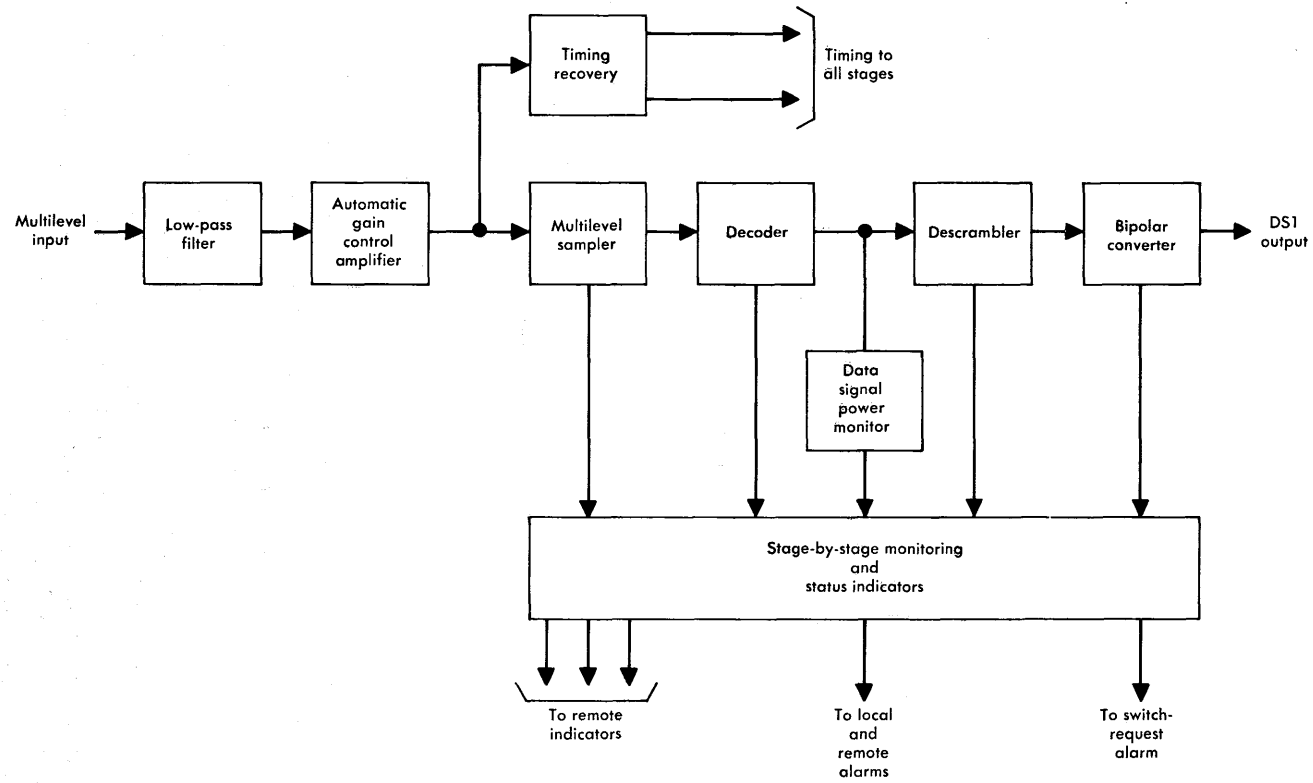


Figure 23-3. Receiving portion of the 1A-RDT.

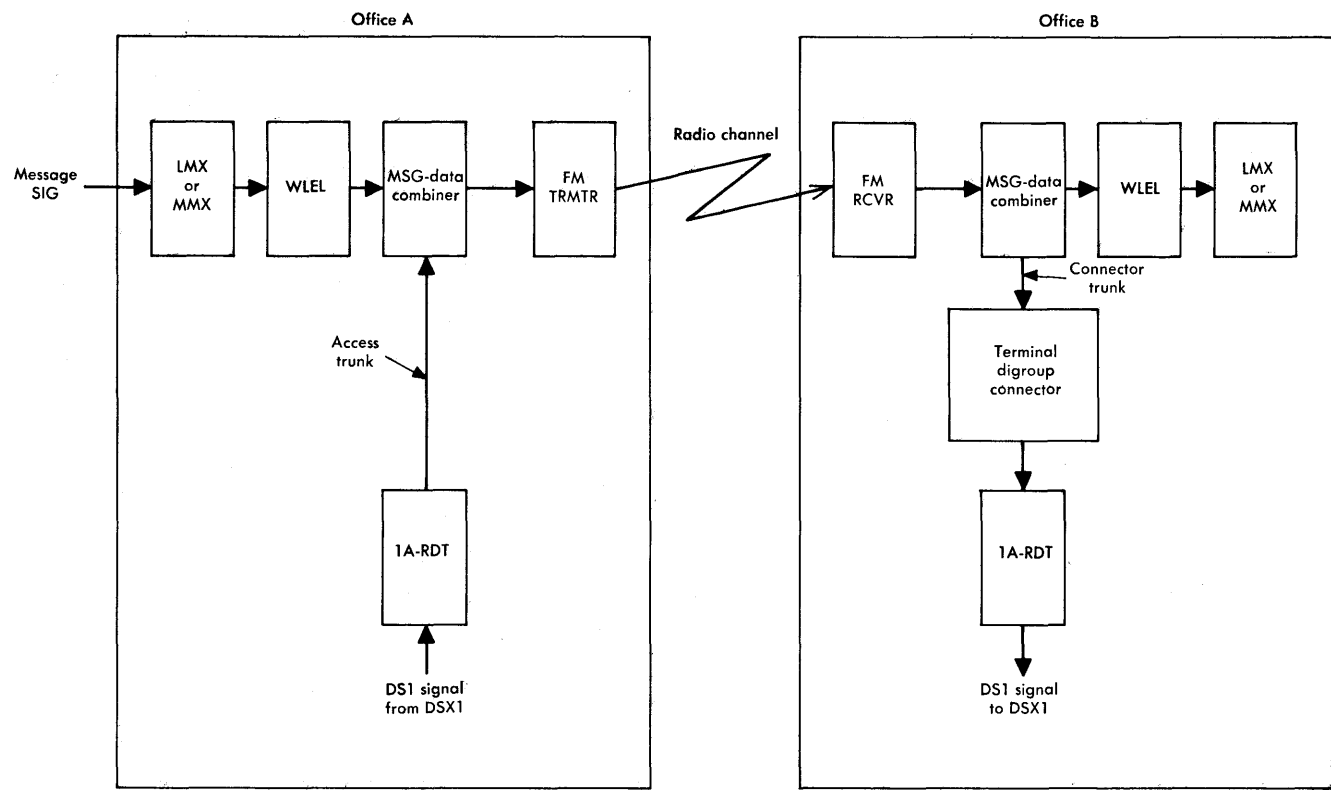


Figure 23-4. Simplified 1A-RDS block diagram.



The analog message and digital signals are split into two paths by the message-data combiner. The digital signal is then separated from the telephone message signal by a digroup connector. This unit provides gain, filtering, and equalization for the 1A-RDS signal before it is applied for processing to the receiving portion of the 1A-RDT or combined with a new message signal from transmission over another link.

In most cases, a 1A-RDS signal may be transmitted over as many as three tandem links without regeneration. Where regeneration is required, partly as a result of distortion contributed by intermediate digroup connectors, a 1A-RDT operating back-to-back must be used. Equipment arrangements for both types of intermediate terminal stations are shown in Figure 23-5.

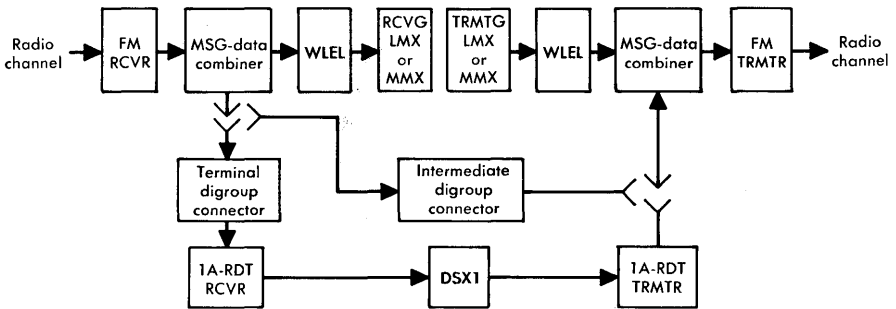


Figure 23-5. Intermediate terminal stations with and without regeneration.

System layouts of the types described are available for most long- and short-haul microwave radio systems. However, they differ somewhat in detail according to the needs of the particular radio system. Standard radio protection switching arrangements are used to protect 1A-RDS service as well as the standard message service carried by the radio system.

**Engineering**

In most applications, the 1A-RDS is installed to add digital transmission capability to an existing analog microwave radio system. As a result, there is little to be done in terms of route engineering. However, a number of tests must be made to be sure the spectrum to be occupied by the 1A-RDS signal is not contaminated and preparations

must be made to provide the necessary interconnections between the new digital system and the existing analog system. Before these connections can be made, a number of changes in the existing equipment may be necessary. For example, if the existing multiplex equipment is L600, it must be replaced by or modified to be equivalent to the U600. The low-frequency cutoff of the L600 spectrum, 60 kHz, is far too low to accommodate the 1A-RDS signal.

Features of the existing radio system must also be examined carefully for possible modification or elimination. For example, some systems use pilots at 64 and/or 308 kHz, frequencies that fall within the 1A-RDS signal spectrum. In this case, the existing system must be modified to use a pilot at 512 kHz, a frequency that falls above the 1A-RDS signal spectrum and below the multiplex spectrum. In some systems, carrier spreading is used to reduce the interfering effect of single-frequency interference. With the 1A-RDS, the carrier spreading feature must be turned off or otherwise disabled. However, the benefits of carrier spreading are not lost; the 1A-RDS signal provides a carrier spreading effect.

In engineering the 1A-RDS, consideration must be given to the location of the 1A-RDT. For best performance, it should be as close as possible to the FM terminals but, for administrative purposes, it should be as close to the frequency division multiplex equipment as possible. Compromise is sometimes necessary. It is also necessary that the terminals be located within cable run distance limits of the DSX1 cross-connect frame. In addition, 1A-RDS signal leads must be separated from leads carrying ac power or high-amplitude dc signalling.

Performance of the radio system may cause marginal error-rate performance in the 1A-RDS. For example, radio-frequency interference near the RF carrier may be troublesome during periods of fading. However, if the radio system meets its interference objectives, 1A-RDS transmission is usually satisfactory. In some situations, it may be desirable to install protection switch initiators that would respond to interference near the carrier.

## 23-2 THE 3A RADIO DIGITAL SYSTEM

The 3A-RDS satisfies a need for economical interconnection of T1 systems in metropolitan and short-haul applications [5]. Signals are transmitted at the DS3 rate, 44.736 Mb/s, in the 11-GHz microwave

radio band. The 3A Radio Digital Terminal (3A-RDT) operates by four-phase modulation of a 70-MHz IF carrier. The system has a capacity of up to 22 channels (20 working and 2 protection) each of which can carry 672 voice circuits. The 22 radio channels are in 11 different frequency bands. Two signals are carried in each band, one polarized horizontally and one vertically.

### Terminal Equipment

The 3A-RDT equipment provides the interface between a DSX3 cross-connect frame and the transmitter/receiver equipment of a TN-1 system. In the transmitting direction, the DS3 signal is received from the cross-connect frame and processed in the 3A-RDT transmitter for radio transmission. At the 3A-RDT receiver, the radio signal is received from the TN-1 receiver, transformed back to the original DS3 format, and transmitted to the DSX3 cross-connect frame at that location.

**Transmitter.** The incoming DS3 signal is used by the line receiver circuit to derive timing information and to generate a clock signal for use throughout the transmitter as shown in Figure 23-6. The signal format is also changed at this point from a bipolar to a polar format and any bipolar three zero substitution (B3ZS) patterns are removed from the signal to restore the original succession of zeroes.

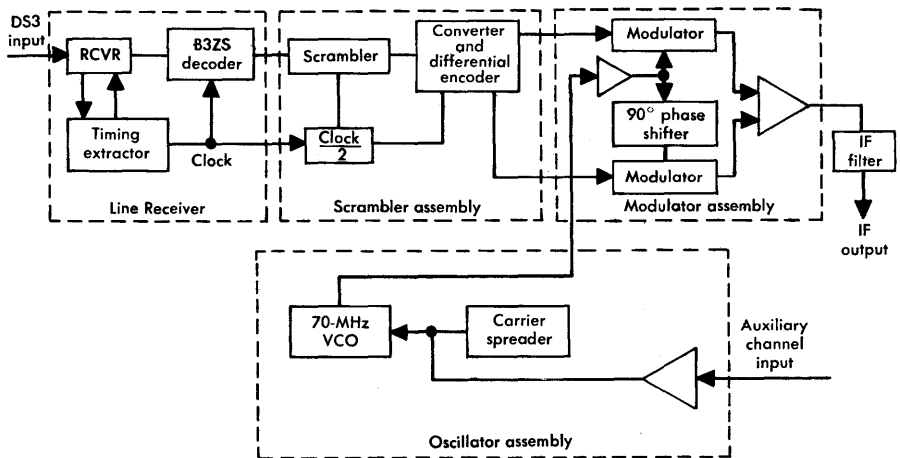


Figure 23-6. Block diagram of 3A-RDT transmitter.

Next, the polar signal is scrambled to ensure that repetitive pulse patterns, which might produce discrete spectrum lines, do not appear in the pulse stream. The scrambler rearranges the pulses in a prescribed manner so that the descrambler in the receiver can restore the signal to its original form. In the scrambler assembly, the signal is separated into two pulse streams called rails. Odd bits are transmitted on one rail and even bits on the other. The two rails operate at 22.368 Mb/s, one-half the DS3 rate. The pulse stream on one rail is offset in time (delayed) from the pulse stream on the other by one-half a baud interval so that pulse transitions do not occur simultaneously in the two signals. The signals on the two rails are next differentially encoded to facilitate receiving terminal design and to accommodate phase ambiguity in the recovered carrier. In differential encoding, the transmitted signal is modulated to reflect phase changes in the modulating signals rather than to reflect any absolute values of phase.

The modulators are supplied digital modulating signals from differential encoders and 70-MHz carrier signals from the oscillator assembly with the phase of one carrier signal shifted 90 degrees relative to the other. Each digital signal independently phase modulates one IF carrier and, after modulation, the two are summed to produce the composite IF signal.

A voltage-controlled oscillator (VCO) generates the required 70-MHz carrier signal, the center frequency of which is stabilized by a crystal oscillator. The VCO is frequency modulated by a 60-Hz carrier spreading sawtooth signal and by an auxiliary channel signal consisting of four 4-kHz channel signals frequency division multiplexed into the 4- to 20-kHz band. These 4-kHz channels carry order-wire, alarm, and protection switching system control signals. The auxiliary channel signals are transmitted simultaneously over working radio channel No. 1 and the protection channel to provide reliability for the auxiliary channel.

**Signal Format.** The signal format resulting from the processes described above is called offset keyed four-level phase-shift-keyed (PSK) modulation. The development of the signal is illustrated in Figure 23-7. The differentially encoded signals on the two rails and the half-baud interval ( $\tau/2$ ) offset of the rails is illustrated in Figures 23-7(a) and 23-7(b). The noncoincidence of transition times for the two signals is evident in these figures. Note that, as a result

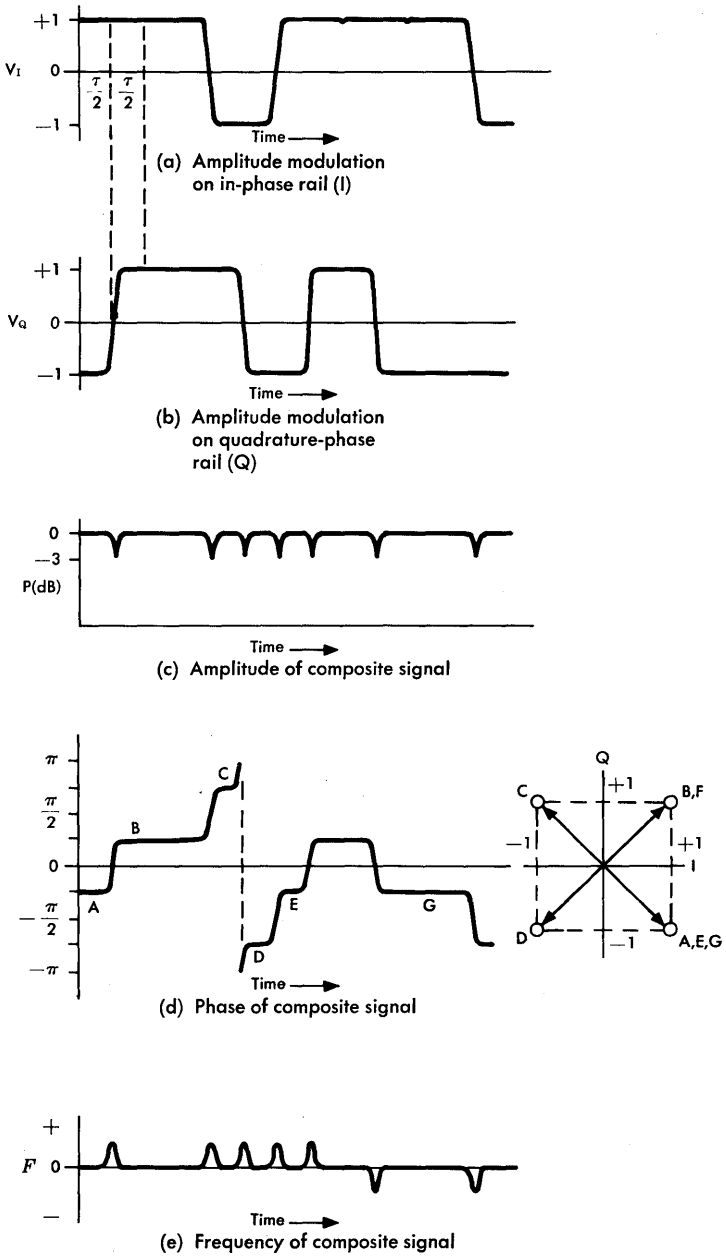


Figure 23-7. Signal processing in the 3A-RDS.

of this noncoincidence, simultaneous phase changes on the two rails can not occur.

Figure 23-7(c) shows the amplitude of the composite signal after the two modulated rail signals have been summed. During steady-state conditions, when no phase changes occur, the amplitude is constant and represented as a reference value of 0 dB. During the rise or decay time of a pulse on either rail, the phase of the associated carrier shifts by 180 degrees. During the time of this phase shift, the amplitude of the combined signal drops to a value of  $-3$  dB and then returns to the reference value. This mode of transmission, where the signal amplitude changes only slightly, is more tolerant than others of microwave circuit nonlinearities.

Figure 23-7(d) shows the phases of the composite signal in two related representations. At the left, the phase is shown as a function of time. Each amplitude transition of a rail signal from one polarity to the other causes a corresponding change in carrier phase of the modulated signal on that rail of 180 degrees. During interval A, the sum of the carrier phases corresponding to  $+1$  on the in-phase rail and a  $-1$  on the quadrature-phase rail is depicted arbitrarily as  $-\pi/4$  radians. The first transition shown is that in the signal on the quadrature-phase rail from  $-1$  to  $+1$ . This causes a phase shift of 180 degrees in the associated carrier on that rail and produces a shift of  $+\pi/2$  radians from the previous position of the composite signal. The changes of phase may be followed in the time-function representation of Figure 23-7(d) and may also be visualized in the phase-progression diagram to the right. As the phase changes by 90 degrees, it can be seen that the amplitude of the combined signal passes through unity and then again increases to 1.42. This illustrates the 3-dB drop shown in Figure 23-7(c).

Figure 23-7(e) shows how the frequency of the composite signal varies as the input signal varies. As the phase of the composite signal varies, the frequency temporarily increases or decreases during the time of transition.

The combined signal, then, is one of nearly constant amplitude and frequency with the phase constantly shifting among four possible values. The  $\tau/2$  offset between the two independent rail signals guarantees that phase changes in the composite signal occur only in positive or negative 90-degree increments and that the amplitude never is zero.

**Receiver.** The input to the 3A-RDT receiver, Figure 23-8, is a 70-MHz IF signal from a TN-1 microwave radio receiver. This signal is used in the carrier recovery phase locked loop (PLL) circuit where the carrier component is extracted and used as inputs to the demodulator. These inputs, 90 degrees apart in phase, are combined with the modulated input signal to produce two-rail polar signals like those in the transmitter. These pulse streams are regenerated, decoded from their differential format, recombined into a single 44.736 Mb/s pulse stream, and descrambled. Parity checks are made and where errors are found by the violation monitor and restorer (VMR) parity is restored under its control. At the output of the receiver, the signal is reconverted to the B3ZS format used in DS3 signal transmission.

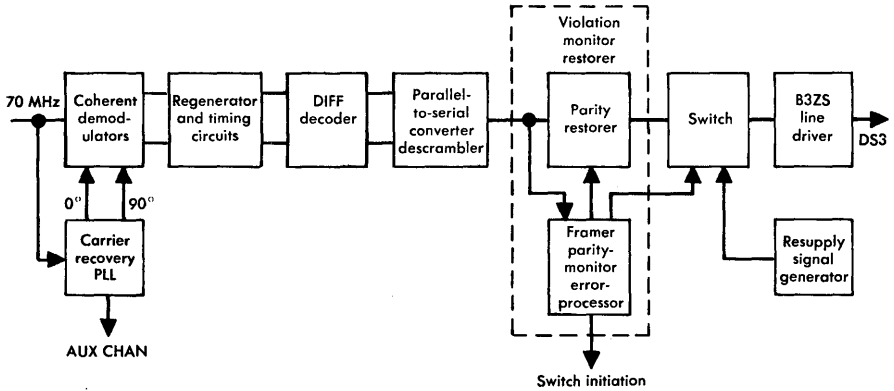


Figure 23-8. Block diagram of 3A-RDT receiver.

The resupply signal generator produces a signal which may be substituted for the incoming signal under control of the violation monitor restorer. This signal is an alternating *1 0* code in the DS3 format used to prevent unnecessary protection switching when a trouble occurs in a preceding section of line or piece of equipment.

The carrier recovery circuit is also used to recover and amplify the auxiliary channel signals. These signals are transmitted to auxiliary channel equipment for further processing and, as previously mentioned, to fulfill order-wire, alarm, and protection switching functions.

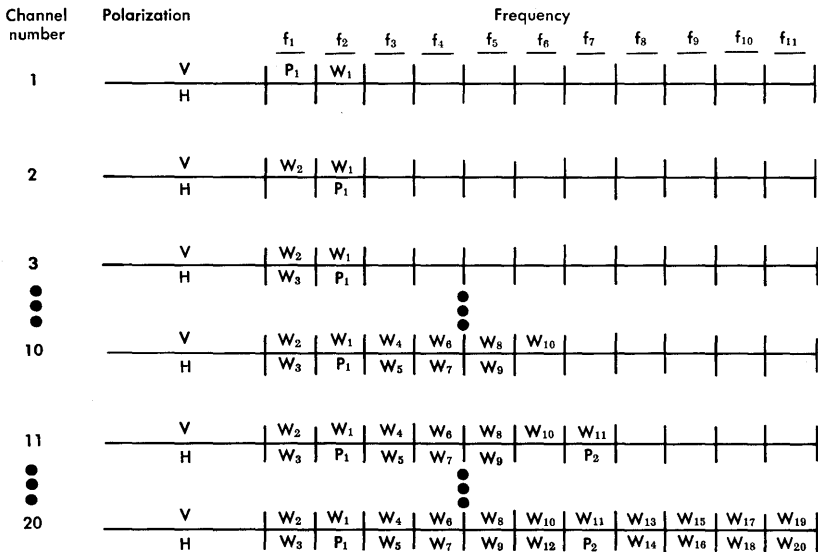
**Regenerator.** Carrier recovery, demodulator, and regenerator circuits from the 3A-RDT receiver of Figure 23-8 are used with modulator and oscillator circuits from the transmitter of Figure 23-6 to form a

3A-RDT regenerator. Interconnections between the two sets of circuits are made where signals are in the two-rail mode. Differential coding, scrambling and descrambling, and conversion to or from the B3ZS format are not available at a regenerator point.

**System Layout**

Up to 22 radio-frequency channels may be utilized in the 3A-RDS for the transmission of DS3 signals. This high channel capacity is provided by transmitting signals of both horizontal and vertical polarization on 11 different channel frequencies as shown in Figure 23-9. Protection channels and automatic protection switching are provided. In a fully loaded system, two independent 1 x 10 protection switching systems are used to provide 20 working channels and 2 protection channels. The channel frequency allocations are generally the same as those for the TN-1 radio system.

An illustrative layout of a 3A-RDS is shown in Figure 23-10. Signals are received from and delivered to a DSX3 cross-connect frame.



Notes: P indicates protection channel  
 W indicates working channel

Figure 23-9. Polarization plan for 3A-RDS.



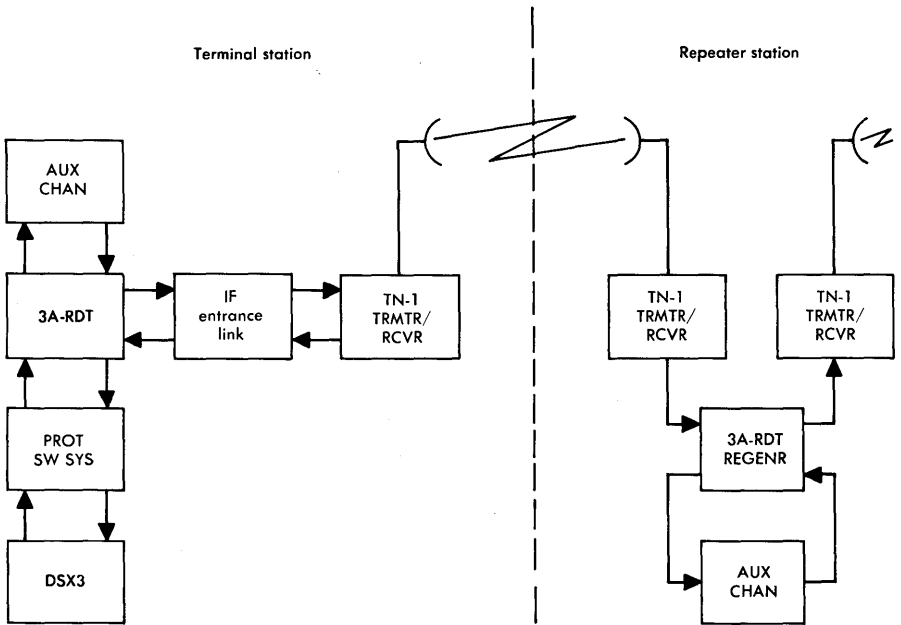


Figure 23-10. Block diagram of 3A-RDS.

Automatic protection switching is provided by 400H or 401H systems which are similar in design to the 400- and 401-type systems but respond to switch initiator signals generated by the violation monitor and restorer circuits. With the 400H system, a group of up to ten working channels is protected by one protection channel. Where desirable and permitted by the FCC Rules and Regulations, the 401H system may be used to provide one protection channel for one working channel.

At a terminal station, the 3A-RDT equipment is used to translate between the DS3 signals and the offset keyed four-level PSK signals. Where these terminals are located close to the TN-1 radio transmit/receive bays, a direct connection may be made. If cable length limitations are exceeded, an IF entrance link may be used for interconnection.

A 3A-RDT regenerator is normally used at repeater sites; however, where desired, an IF repeater (without regeneration) may be used subject to certain restrictions and a slight performance degradation. The 3A-RDS systems are otherwise engineered by standard methods.

## Maintenance

Items of test equipment designed specifically for maintenance of the 3A-RDS include a portable test terminal made up of standard 3A-RDT plug-in circuits, a DS3 error rate test set (ERTS), and a noise generator. These units are assembled in a carrying case and may be used in troubleshooting procedures at a terminal or repeater station.

Violation monitors and restorers are built into the 3A-RDS to provide continuous monitoring of transmitted signals and to give alarm indications when the error rate is excessive. These units also provide signals to initiate protection switching operations and, as illustrated in Figure 23-8, to substitute a resupply signal to replace the normal signal during periods of excessive fading or upon other loss of signal.

During periods of normal operation, when no protection switching is required, an all *1s* signal is transmitted over the protection line. This signal provides for performance monitoring of the protection line.

## 23-3 THE DR 18A DIGITAL RADIO SYSTEM

Regenerative repeaters are used throughout the DR 18A system which operates in the nominal 18-GHz common carrier frequency band (17.7 to 19.7 GHz). The system transmits DS4 signals (274.176 Mb/s) in each of eight RF channels, one of which is assigned as a protection channel. Each DS4 signal can provide up to 4032 4-kHz circuits; thus, the capacity of a fully loaded DR 18A system with seven working RF channels is 28,224 two-way 4-kHz voice circuits. The principal field of application is on high-density metropolitan trunk routes.

The major components of the system are radio line terminating frames (RLTF), regenerative repeaters housed in canisters mounted in enclosed platforms on top of tapered antenna masts, a protection switching system (incorporated in the RLTF), and a repeater power system with reserve batteries. The antenna system consists of a feed assembly that projects through a 45-degree mirror to illuminate a horizontally-mounted parabolic dish antenna. The radio signals are reflected from the antenna to the mirror and are again reflected for transmission to the next repeater. The route engineering and layout of DR 18A systems are similar to such factors in other microwave systems but some details are unique because of the 18-GHz operating

frequency. As with all digital transmission systems, special attention was given to maintenance features in the DR 18A system.

### Terminal and Repeater Arrangements

The DS4 signals transmitted by this system are generated in M13 and M34 multiplex units. They are fed through a DSX4 cross-connect frame to the RLTF where they are processed for radio transmission. In the opposite direction, the received radio signals are processed into DS4 signals in the receiving portion of the RLTF and delivered to the DSX4 frame for further transmission.

**Transmitter.** The DS4 signal is a two-level (polar) signal having a repetition rate of 274.176 Mb/s. It is processed in the transmitter circuits into a four-phase differentially-coded phase-shift-keyed RF signal in the 18-GHz transmission band. In the RLTF, each successive pair of bits is encoded into one of four discrete phase changes. In order that the transmitted signal may be represented by phase changes rather than by absolute values of phase, it is necessary that the input polar signal be processed by some form of differential coding that represents the change in information from one pulse interval to the next. As indicated in the functional diagram of Figure 23-11, the

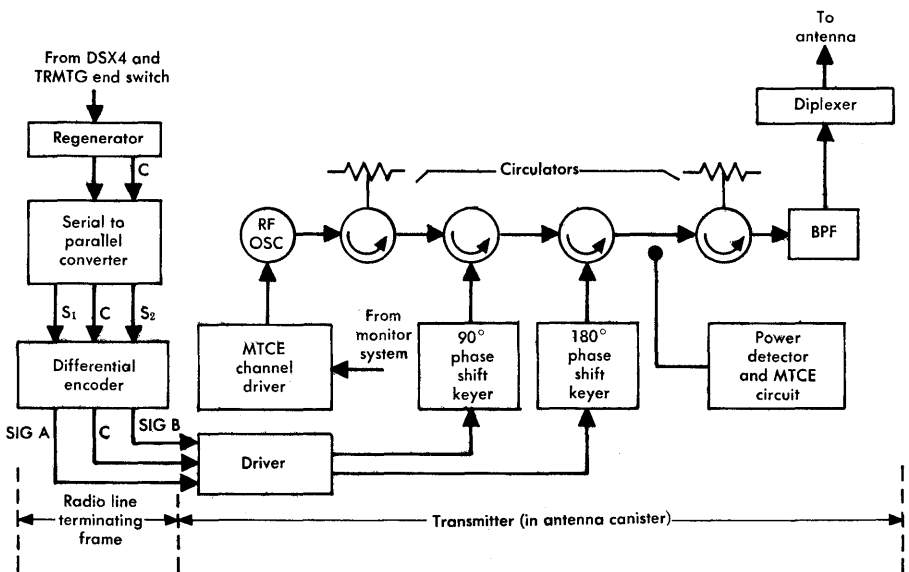


Figure 23-11. Functional block diagram of DR 18A transmitting circuits.

logic circuits at the transmitting end of the DR 18A are divided between the RLTF and the radio transmitter. The signal from the DSX4 cross-connect frame passes through the transmitting portion of the 400D Protection Switching System to the regenerator. The diagram also shows that the DS4 signal is converted to a two-rail format from a single pulse stream at the input. The two rails are designated  $S_1$  and  $S_2$ . The signals on these leads are polar signals with a repetition rate of 137.088 Mb/s; they are made up of alternate pairs of bits extracted from the input signal. The serial-to-parallel converter also transmits on the  $C$  lead a clock signal derived in the regenerator from the incoming pulse stream. This clock signal is used as a timing signal for the RLTF and radio transmitter circuits.

The information signals are processed in the differential encoder so that the encoder output signals, SIG A and SIG B, represent the changes in information from one pulse interval to the next rather than the absolute value of the information in each pulse interval. The information carried by SIG A and SIG B is used to operate logic circuits in the transmitter driver stage and to operate the phase-shift keyers which produce the proper phase shifts in the transmitted RF signal. The manner in which the RF phase changes are accomplished may be visualized by referring to Figure 23-12.

The logic designations, such as  $1/0$ ,  $0/0$ , etc., represent the logic states of the signals on the  $S_1$  and  $S_2$  leads with the state of the signal on lead  $S_1$  always the first value. The nodes ( $P$ ,  $R$ ,  $S$ , and  $T$ ) represent the RF phase position in any given bit position and the logic designations show the amount and direction of phase change that correspond to the designated change in logic. To provide guidance in understanding the processes, assume that the RF signal rests at  $+90$  degrees from reference, node point  $R$ , in a given bit interval. To have arrived at that point, assume that the  $90^\circ$  phase-shift keyer, shown in Figure 23-11, is operated and that the  $180^\circ$  phase-shift keyer is released.

Consider now the four conditions that may exist in the next interval and what these conditions imply in respect to the operation or release of the phase-shift keyers. The four possible conditions in the next interval are  $0/0$ ,  $0/1$ ,  $1/0$ , or  $1/1$ .

If the logic state on leads  $S_1$  and  $S_2$  in the next interval is  $0/0$ , the phase must not change between intervals, the condition of the phase-

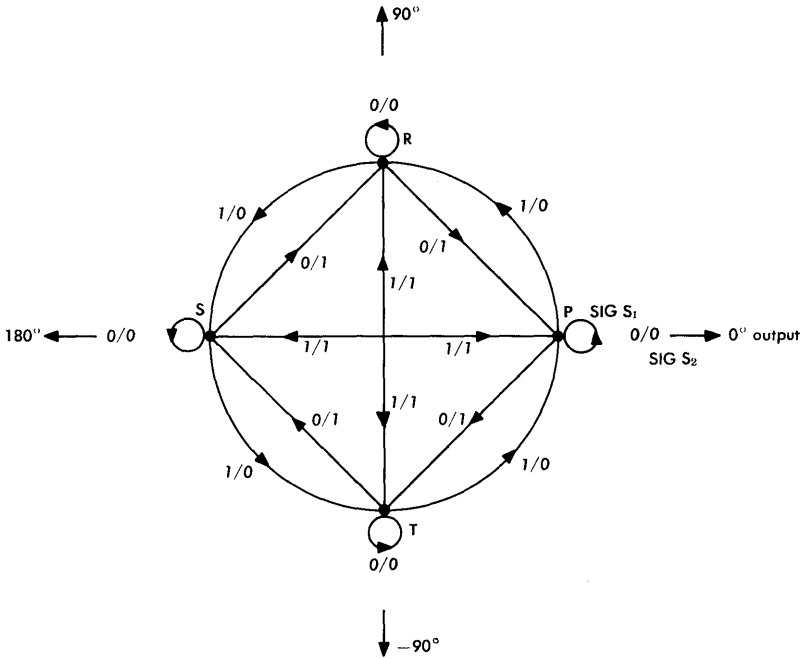


Figure 23-12. Phase-progression diagram for DR 18A.

shift keyers remains unchanged, and the RF signal phase remains as it was at node point *R*. This is indicated by the small circle above the phase vector circle at point *R*.

Now, suppose the logic state on leads *S*<sub>1</sub> and *S*<sub>2</sub> in the next interval is a *0/1*. The phase-progression diagram shows that the RF signal phase should be changed to that represented by node point *P*, a change of  $-90$  degrees. The logic circuits of the differential coder and the driver must operate to release the  $90^\circ$  phase-shift keyer to achieve the new RF phase condition.

Then, assume that the RF phase is again represented by node point *R* and that the next interval is represented by a *1/0* condition on leads *S*<sub>1</sub> and *S*<sub>2</sub>. The phase progression diagram shows that this change of state is represented by a phase change of  $+90$  degrees from point *R* to point *S*. To accomplish this phase change requires that the  $90^\circ$  phase-shift keyer be released to produce a  $-90$  degree shift and, simultaneously, the  $180^\circ$  phase-shift keyer must be operated to produce a net advance of  $+90$  degrees.

Finally, assume that the RF phase rests at node point *R*, as before, and that the next pulse interval is represented by a 1/1 condition on leads *S*<sub>1</sub> and *S*<sub>2</sub>. This change in phase requires a move to node point *T*, a change that may be achieved by operation of the 180° phase-shift keyer. Similar logic and phase changes may be deduced from any given phase position on the phase-progression diagram; logic circuit operations leading to the operation or release of the phase-shift keyers follow from the required logic sequences. The logic states that relate the polar signals on *S*<sub>1</sub> and *S*<sub>2</sub> to the appropriate phase shifts of the RF signal are given in Figure 23-13.

LOGIC STATE		CHANGE IN RF PHASE, degrees
LEAD <i>S</i> <sub>1</sub>	LEAD <i>S</i> <sub>2</sub>	
0	0	0
1	0	+90
0	1	-90
1	1	180

Figure 23-13. Logic-to-RF phase changes.

The impatt diode RF oscillator of Figure 23-11 is frequency modulated by a 100 kb/s signal from the monitor system to provide for the transmission of maintenance information. In addition, the transmitted power is monitored and detected to provide maintenance information regarding the transmitted signal.

The outgoing signal is transmitted over waveguide to the antenna. The signal is first filtered, to eliminate unwanted energy outside the assigned channel frequency band, and then transmitted to a channel combining network (diplexer) which combines (and separates in the receiving direction) the seven working channels and one protection channel.

**Receiver.** As in the transmitting direction, the logic functions used to recover the DS4 signal are divided in the receiving direction between the radio receiver and the RLTF. The radio receiver portion of the terminal equipment is shown in Figure 23-14.

The received signal is transmitted from the antenna through the channel diplexer to a down converter. An impatt diode RF oscillator is used to translate the signal to a 1.7-GHz intermediate frequency

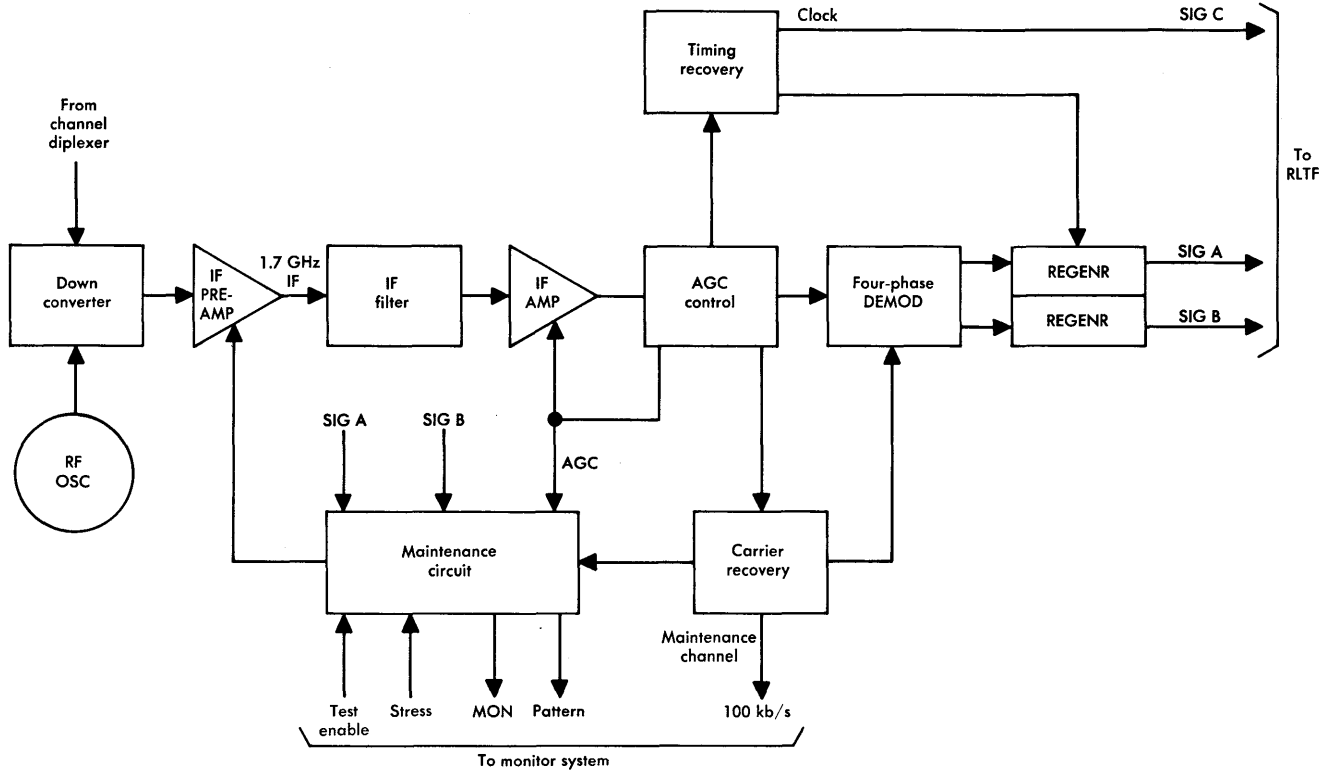


Figure 23-14. The DR 18A radio receiver.

band where it is filtered and amplified. For coherent detection of the four-phase signal, a reference carrier must be recovered. The carrier recovery circuit regenerates a carrier signal suitable for coherent detection; the 100 kb/s maintenance signal is recovered as a by-product of the carrier recovery process.

After detection by the four-phase demodulator, the digital signal is regenerated as two parallel bit streams. With timing controlled by the carrier recovery circuit, the regenerated two-rail signal is delivered to the following transmitter or, at a main station, to the RLTF for further processing as shown in Figure 23-15.

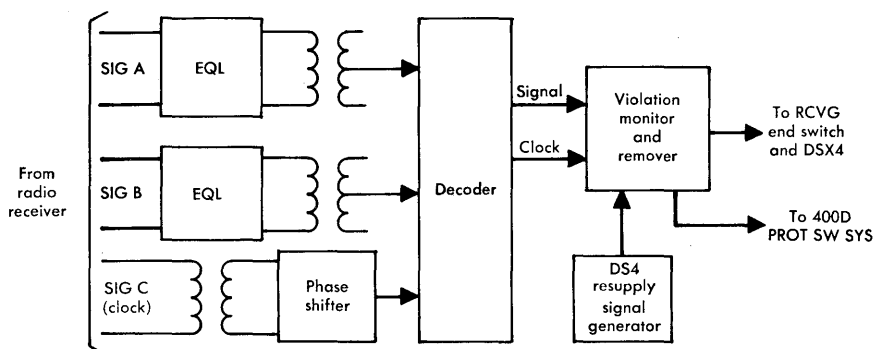


Figure 23-15. Receiving path through RLTF.

When the two-rail signals have been equalized and a proper phase adjustment has been made in the clock signal, the DS4 signal is reconstituted in the decoder. To guarantee satisfactory operation of the decoder circuit, the RLTF must be located within 500 feet of the radio receiver and 150 feet of the DSX4 cross-connect frame.

The RLTF contains a violation monitor and remover which measures the bit error rate of the received signal. At error rates in excess of one error in  $10^5$  bps, a protection switch request is initiated. When the error rate exceeds one error in  $10^3$  bps, a resupply signal is substituted on the failed line. Thus, previous section failures do not propagate and the M34 multiplex unit does not reframe.

**Regenerative Repeaters.** The transmitting circuits of Figure 23-11 and the receiving circuits of Figure 23-14 are combined (without using an RLTF) to make a regenerative repeater. These units are mounted,



independent of interconnections with an RLTF, in the antenna canister of an intermediate repeater.

### System Engineering and Layout

Many aspects of DR 18A system engineering and system layout problems are related to some of the unique features of digital signal transmission at 18 GHz. Channel assignments, transmitted signal polarizations, and protection switching arrangements have been specified to conform to the FCC Rules and Regulations.

**Protection Switching Arrangements.** The 400D Protection Switching System provides protection primarily against equipment failure in a multihop DR 18A radio link. The system operates on the basis of one protection channel for up to seven working channels. The general design features are similar to those of other systems of the 400-type. Switch initiation is based on error rate criteria derived from the violation monitor and restorer.

**System Layout.** Figure 23-16 is a partial representation of a typical system layout which shows the configuration of three commonly used stations. At the left is a terminal station with a roof-mounted antenna. In the center is a pole-mounted repeater and at the right is a roof-mounted repeater that may be on a telephone company owned or leased building roof. The radio transmitter and receiver units are mounted inside the antenna canisters, A, in order to minimize the length of waveguide runs between the repeater units and the antennas, thus minimizing waveguide losses. Each canister is mounted on a platform, B, on top of a roof mast, C, or pole mast, E. At the base of each mast, a cabinet, D, contains power and maintenance equipment. As shown at the repeater sites, two antenna canisters are required to provide transmission in the two directions.

A pole-mounted repeater station utilizes a mast up to 120 feet high. At such a site, access to the radio equipment is provided by a portable service car which carries a craft person to a height convenient for access to the equipment through hinged doors at the bottom of the platform. The cable car ascends the mast on a steel cable using a built-in winch system that operates on commercial ac obtained from the maintenance cabinet. A roof-mounted repeater arrangement is similar to a pole-mounted arrangement except that a mast only six feet high is used. No service car is required.

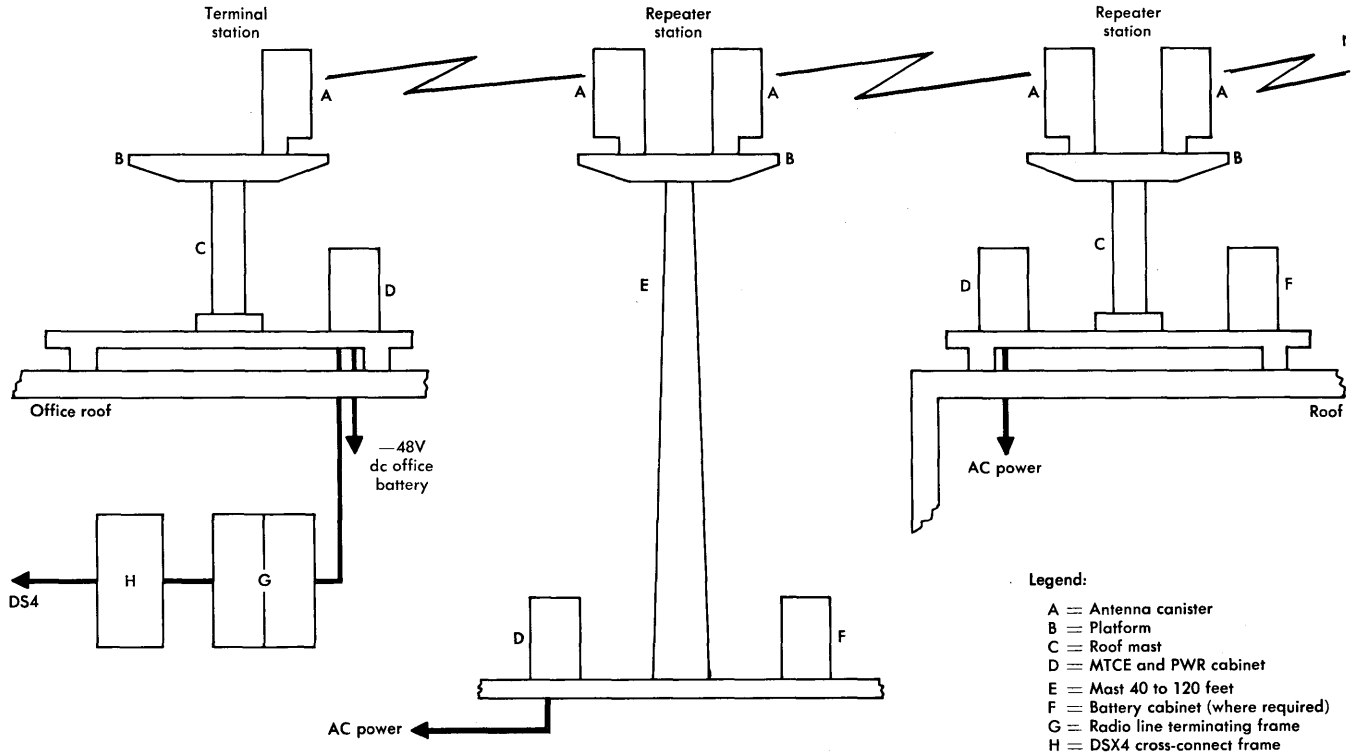


Figure 23-16. Typical DR 18A system layout.

A second cabinet is provided at remote repeater stations. This cabinet contains a battery back-up power plant to provide emergency power to protect against a service failure caused by a commercial ac outage.

**Repeater Spacing and Site Selection.** The repeater spacings in the DR 18A system are established by environmental conditions relating primarily to the intensity of rainfall in the vicinity. Fading at 18 GHz is almost entirely due to rainfall. Permissible repeater spacings vary from approximately 1.8 miles in areas of high rainfall intensity to about 5.0 miles in areas of light rainfall.

Site selection for DR 18A is based on considerations similar to those that apply to other microwave radio systems but generally somewhat simpler. The conventional obstacle clearance requirements are recommended: 1.0 times the first Fresnel zone clearance for  $K = 4/3$  and 0.3 times the first Fresnel zone clearance for  $K = 2/3$ . In coastal areas, more clearance is required and routes are engineered for  $K = 1/2$ . The clearance tends to be small because of the high frequency of operation and short repeater spacing.

**Channel Assignments.** The frequency plan for DR 18A provides eight two-way RF channels. As shown in Figure 23-17, the common carrier band between 17.7 and 19.7 GHz is divided into an upper and a lower band similar to those assigned in the 6- and 11-GHz frequency plans. Cross-polarized cochannel operation is used to obtain the eight two-way channels. Channels 1A and 1B, 2A and 2B, etc., are used for opposite directions of transmission for one two-way RF channel. In most cases, the first working channel is assigned to channel 1 with the protection channel assigned to channel 2. Subsequent assignments are usually made in numerical order.

**RF Interference.** The transmission format and antenna design for DR 18A are such that interference problems should not limit its application in dense metropolitan areas. Eight or more directions of operation are possible at a junction station.

The cochannel carrier-to-interference objective is 25 dB for 0 degrees interfering angle between channels. This objective is based on the assumption of correlated fading between the channels. As the interfering signal angle increases, the correlation in fading is reduced and more stringent objectives apply. The function is linear from 25 to 55 dB and between 0 and 40 degrees of angle.

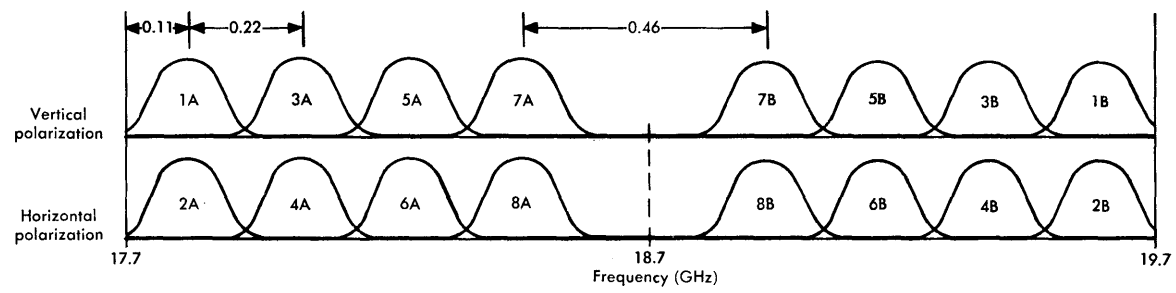


Figure 23-17. The DR 18A channelization plan.

## Maintenance

Maintenance operations such as performance monitoring and fault location are performed from the RLTF at either end of a system. A radio line monitoring system performs a continuous check of the status of up to 13 remote repeater stations and the two terminal stations; it can report status information to both ends. This system is also used for fault location by transmitting test patterns and commands to remote stations and by observing the status response from each. Failed units are not repaired locally; they are replaced and returned to the factory.

Alarms and status indications are displayed on a panel associated with the RLTF. Some alarms, such as a prolonged switch to the protection channel, are initiated by the protection switching system.

Remote repeater status signals and control signals are transmitted over the 100 kb/s maintenance channel. Polling time for a fully equipped system of 15 stations is about 0.1 second. Many operational and transmission tests can be performed by remote control with this maintenance system.

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**Telecommunications  
Transmission  
Engineering**

*Section 6*

*Transmission Maintenance*

Those operations that are concerned with the problems of keeping transmission facilities operating so that Bell System grade-of-service objectives are met may be considered as transmission maintenance. Maintenance can be classified as consisting of three major functions: surveillance, evaluation and analysis, and repair, all of which must be carried out in an expeditious, efficient, and economical manner.

Chapter 24 shows how network growth and complexity have made necessary new approaches to transmission maintenance. Two major trends are noted. One is toward centralization of maintenance and operations control and the other is toward mechanization through the use of digital computers. Centralized maintenance systems that illustrate these trends are described and the manner in which maintenance capability is designed into some transmission systems is also discussed.

In spite of these trends toward centralization and mechanization, a large number of mobile, independently-mounted, fixed and portable test sets are still required for use by maintenance personnel. Chapter 25 describes selected examples of modern test sets in these classifications.

## Chapter 24

# Maintenance Systems

Transmission maintenance involves a wide range of activities that include the testing and adjustment of circuits and facilities during installation and preparation for service as well as during the time they are in active service. Maintenance activities are designed to prepare a facility for initial operation, to locate sources of trouble, and to repair the troubles so that transmission performance is held as nearly as possible to the high standards of performance that have been established. Maintenance activities also include the ability to remove failed circuits from service, to make them appear busy, to apply restoration and temporary repair methods, to support trouble reporting activities, and to implement standard record keeping and administrative procedures. These procedures must be efficient and must provide a wide range of accurate information about circuits and facilities. When systems and circuits are properly installed, tested, and adjusted before they are put into service, the incidence of trouble during the service period is significantly lower and, as a result, maintenance costs are lower.

Maintenance equipment, systems, and methods have undergone the same patterns of expansion and innovation that have featured the growth of the entire telecommunications network. Factors that have influenced these changes include the necessity of keeping pace with network growth and of applying new technology in order to make maintenance economical and compatible with the technical advances being applied to facility and circuit designs. These effects have been felt in the maintenance of loops, trunks, and special services circuits as well as in local and toll facilities.

The changes that have taken place in the design and operation of maintenance systems have been accompanied by two notable trends: centralization of maintenance control and mechanization through the application of computers. These trends have produced major changes in methods of operation, have led to the need for new training methods, and have resulted in a broadening of computer software applications throughout the operating organizations.

In many cases, a transmission facility is monitored, tested, and adjusted by equipment that is designed as an integral part of the facility. In other cases, maintenance systems are designed to be shared by a number of different types of transmission facilities. For both, the trend toward centralization is quite notable. Modern maintenance systems are capable of remote testing, evaluation, and control of transmission systems over many hundreds of miles from a central point.

Loops, trunks, and special services circuits are dispersed over wide areas and utilize a large variety of facilities. Furthermore, their maintenance is more directly related to the satisfactory operation of traffic networks than to the maintenance of a specific transmission system or facility. When an individual circuit fails, it is usually not the result of a facility failure. However, if it is a trunk or special service circuit, it may seriously affect service in the network in which it is used. Thus, circuit maintenance systems are not designed as integral parts of specific transmission systems but are generally tailored to meet the needs of specific types of circuits.

Maintenance activities cannot be carried out efficiently without a large amount of support equipment. This equipment includes arrangements for gaining access to the transmission facilities to be maintained, order-wire and alarm arrangements, record keeping, and provisions for remote control and telemetry.

## 24-1 NETWORK EFFECTS ON MAINTENANCE

Network growth and the implementation of direct distance dialing have had remarkable effects on the methods and procedures that are used to maintain the telecommunications plant. These effects have been especially notable in trunk maintenance activities. Increasing demands for service have brought about a tremendous growth in the number of trunks and the ways in which they can be interconnected.



With direct distance dialing, the trunk surveillance that was formerly provided by operators involved in establishing connections has been lost. As a result, there has been a reduction in manual testing and a great increase in centralization and mechanization of trunk testing.

### Surveillance

Transmission facilities are subjected to continuous surveillance in a number of ways. In analog transmission systems, single-frequency pilots are transmitted at carefully controlled frequencies and amplitudes; they are monitored and applied to feedback circuits called regulators to maintain transmission level points at the required values. When pilot amplitudes vary beyond established limits, alarms are initiated to alert maintenance personnel to the existence of real or incipient trouble conditions such as excessive system gain or loss. In digital systems, monitoring circuits make continual checks of error performance and when the error rate is excessive, alarms are initiated. Power circuit fuses and circuit breakers are equipped with alarm features that alert maintenance personnel in the event of power system failure.

To supplement these and other built-in surveillance systems, many routine tests are made periodically to verify the satisfactory operation of both facilities and circuits. In the past, such testing was performed manually and much manual testing of this sort is still being carried out. However, the factors discussed earlier that are leading toward the mechanization of maintenance procedures are affecting surveillance testing as well. Loops, trunks, and special services circuits are increasingly being tested by automatic means and/or by remote control. Output data usually include a printout of only those circuit tests that fail to meet requirements.

### Test Procedures

Initially, testing involved the coordination and cooperation of two testers, one to connect transmitting test signals and the other to measure the results at the other end of the circuit. Such procedures are time consuming and difficult to schedule efficiently because the testers must be available simultaneously. It is often difficult to schedule such simultaneous action, even under trouble conditions, because maintenance activities and routine testing programs are conducted autonomously in each office.

The problems of coordinating maintenance activities have been greatly mitigated by the development of arrangements that can be controlled remotely and thus permit one-person testing. With such remote control arrangements, a single tester can make many measurements of overall performance and, with suitable controls, can sectionalize the circuit to assist with trouble location and isolation procedures. Test lines have been made available to further simplify trunk testing which, in many cases, can be carried out in both directions of transmission by one person; a wide range of transmission and operational tests can be performed. Access to these test lines is provided by dialing through the switched message or private network. Single-person testing with remote control and loop-back circuit arrangements are proving to be efficient and economical.

In many cases, it is now efficient to test circuits automatically with no test personnel involved. This type of testing may be regarded as a form of surveillance in that large numbers of loops and trunks and some special services circuits may be tested automatically and failures recorded. Generally, no record is provided of circuits that pass all tests.

### Test Equipment

A wide variety of test equipment is required in the maintenance of circuits and facilities. Measurements must be made to establish circuit continuity and to determine gains, losses, noise, impedance, delay and attenuation/frequency distortion, return loss, and other parameters. The test equipment that is now available for these tasks has evolved in sophistication with the advance of technology; measurements can be made under remote control from a centralized maintenance center that may be many miles distant from the point of measurement.

Although mobile or portable test sets are still used for manual testing, maintenance equipment has become more centralized and less mobile as techniques for testing by one person have been introduced. Loop-back circuits, test lines, and computer-controlled test equipment have all tended to be mounted in equipment bays, in consoles permanently located in areas of central offices most convenient to the circuits under test, or at a centralized location that provides convenient access to the circuits to be tested. The shift to computer control of maintenance activities has introduced the necessity for emphasis in plant operations on the development and control of computer software.

### Preventive Maintenance

In the past, considerable emphasis was placed on preventive maintenance. In such activities, adjustments of electronic equipment, cleaning, adjustment and replacement of mechanical parts, and replacement of electronic components were accomplished at specified intervals in an attempt to prevent trouble conditions and to anticipate failure. These activities were generally carried out by one person but sometimes required the coordination of two or more people.

It was found that these activities were costly and often introduced troubles that would otherwise have not occurred. As a result, there is now less emphasis on preventive maintenance than was formerly the case. This lack of emphasis does not apply to such routine maintenance activities as adding water to batteries, pruning of tree limbs, and other routines that must be followed to keep equipment in proper working order and to prevent damage.

### Trouble Identification and Location

The rapid growth of the network, the large number of facilities and circuits that now comprise the network, and the interactions of various parts of the plant under trouble conditions have all led to increased automation of test facilities for identifying and locating service-affecting troubles. Even when a trouble can be identified with a specific system, it is often expensive and difficult to locate the source of trouble without adequate fault locating facilities. Many of these fault locating facilities can be operated remotely under the control of a centralized maintenance center. The accuracy of fault location arrangements has a strong impact on the cost of repairs since maintenance crews can be dispatched more efficiently when troubles are accurately located.

### Operating Centers

The centralization of maintenance activities mentioned previously can be seen in nearly all the maintenance systems and procedures in common use. Loops from many different central office switching machines can now be tested from a single, centralized automatic repair service bureau. Trunks serving the toll portion of the network can be tested over hundreds of square miles by a single test center. Similarly, many special services circuits can be subjected to mechanized test procedures from a central location.

The centralization of maintenance activities can also be seen in carrier system operations. Some systems can be tested and adjusted over hundreds of miles by remote control from a centralized point. This type of capability has also been extended to the remote control of tests and adjustments of transmission system terminal and multiplex equipment.

## 24-2 FACILITY MAINTENANCE SYSTEMS

The maintenance of transmission facilities (media and line and terminal equipment) is administered, controlled, and implemented by systems and equipment of two general classifications. In the first classification, maintenance capability is designed as an integral function of a transmission system. In the second classification, maintenance systems are designed as independent entities with functions that may be utilized by a number of different transmission systems. The functions in both classifications include surveillance, the identification, evaluation, and location of troubles, and the alerting of personnel to the existence of trouble conditions. The remote control of certain operations and maintenance activities may also be provided in some systems.

### System-Integrated Maintenance Arrangements

Essentially all carrier transmission systems have some built-in maintenance equipment. Some of this equipment is relatively simple and consists of little more than some form of surveillance. In other systems, the equipment is quite extensive and includes many operational features as well as maintenance features.

**Analog Transmission Systems.** Maintenance of analog transmission systems is based primarily on the transmission and measurement of single-frequency pilot signals. In most cases, these signals are applied to the system at carefully controlled frequencies and amplitude. Variations in amplitude are used at the receiving end of a system or section to adjust automatically the gains or losses of regulating equalizers. Circuits are also provided at the receivers to respond to variations of the received signal that exceed established limits. These circuits actuate visual and/or audible alarms and initiate the switching of service to protection facilities, where available.

*N-Type Carrier Systems.* The single-frequency signals that are used in N-type systems for regulation are the real or reinserted channel carriers. In the double sideband N1 and N2 terminals, these carriers are modulated by channel signals but, even with this modulation, the total power of these transmitted carriers is sufficiently constant that system regulators operate on the basis of this power. In the N3 terminals, the operating mode is single-sideband, suppressed carrier with 12 of the carriers reinserted after suppression. They are transmitted with the complex message signal at amplitudes and frequencies equal to the amplitudes and frequencies of the carriers in N1 and N2.

When system failure is indicated by the loss of carrier power, detection circuits initiate carrier failure alarms and a trunk processing sequence. In this sequence, all calls that had been established over the affected network trunks are disconnected and the trunks are taken out of service and made to appear busy so they cannot be seized by the switching machine while the trouble exists. The disconnection of the trunks terminates customer charges that might otherwise accumulate. When the trouble is cleared, the circuits are automatically tested for continuity and noise; if found to be acceptable, the circuits are automatically restored to service.

Other forms of maintenance in N-type systems are performed by the use of mobile or portable test equipment. This work includes transmission and noise measurements, fault location, equalizer adjustments, troubleshooting, etc.

*Analog Multiplex Equipment.* The broadband analog coaxial and microwave radio systems transmit multiple signals that are combined by frequency division multiplex (FDM) techniques. The multiplex equipment has maintenance features that include the transmission of pilot signals, the use of regulators, alarms, and some protection switching arrangements. These features have been described in Chapter 9 and are simply summarized here.

In analog channel bank equipment, the only built-in maintenance feature is the provision of fuse alarms to indicate loss of power. Such alarms are used throughout the FDM equipment.

All modern group and supergroup multiplex equipment utilizes pilot-controlled regulators designed to maintain transmission loss to within 0.1 dB of the design value. In the LMX-2 equipment, these

pilots are automatically and continuously scanned to indicate the power of the incoming pilots and the deviations from output design values. These indications provide a measure of the amount of regulation range being used. Alarms are initiated when pilots exceed established limits.

This scanning function is not provided in the later LMX-3 multiplex design. In this equipment, the only alarm feature associated directly with transmission is a loss-of-pilot alarm. In most large modern offices, the scanning function is performed by the Carrier Transmission Maintenance System described later in this chapter.

Equipment that operates at mastergroup or multimastergroup levels of the multiplex hierarchy is equipped, without exception, with pilot-controlled regulators and loss-of-pilot alarms. In addition, this equipment is generally provided with automatic protection switching arrangements and with patching facilities that permit flexible use of spare equipment for service protection, broadband restoration, and maintenance.

*Analog Coaxial Systems.* The three principal coaxial transmission systems now in service, the L3, L4, and L5, all utilize pilot-controlled regulators to maintain line transmission characteristics within acceptable limits. Each system is also equipped with an automatic protection switching system to protect service against equipment failure. In addition, these systems also have specialized equipment for equalizer adjustment, trouble analysis, and fault location.

In the L3 system, two general types of equalizers are used [1]. The first is a set of pilot-controlled equalizers (regulators) with attenuation/frequency characteristics designed to compensate automatically for system transmission variations due to identifiable causes. To prevent these equalizers from interacting in adverse ways, the pilots (after conversion to direct current) are passed through a small analog computer that has outputs which control the amount of change in each equalizer characteristic.

The second type of equalizer used in the L3 system is known as a *cosine equalizer*. These equalizers are adjusted on out-of-service lines by passing a sweep-frequency signal over the line and reading a power meter. Service is transferred to the protection line while these adjustments are being made. The sweep-frequency oscillator and the power

meter are mobile units mounted on rolling bays for use in central offices. There is also a portable power meter for use at remote repeaters.

The identification and location of faulty L3 repeaters (those that have completely failed, have improper gain, or have an excessively nonlinear input/output characteristic) is accomplished by a fault location system called Performance Evaluation of Amplifiers from a Remote Location (PEARL) [2]. The PEARL measuring equipment is mobile for central office use. However, at each repeater point, it is necessary to install an oscillator, an attenuator, two pads, and a phase shifting network. An oscillator with a frequency in the range of 214 to 260 kHz is installed at each repeater to be evaluated. The oscillator frequencies are 1 kHz apart and each repeater is associated with a specific frequency.

The oscillator output signal is simultaneously applied at the input and the output of the repeater. The amplitude and phase of the signal to the amplifier input are adjusted so that the two signal components cancel at the output. When the gain of an amplifier changes, the balance of the two signal components is disturbed and a measurable signal is transmitted to the test location. The location of the trouble is identified by the frequency of the signal. If an amplifier produces excessive nonlinear distortion, it is found by an out-of-service measurement. A high-amplitude single-frequency signal is transmitted over the line in the normal transmission band. This signal cross-modulates with the oscillator signals in all repeaters to produce a unique spectrum of modulation products. When a repeater produces excessive cross-modulation, the product resulting from the test procedure has an excessive amplitude compared with the products from other repeaters.

In the L4 system, a remote control center located at a manned main station provides a central control point for equalizer adjustment and fault location on an in-service basis [3, 4]. The "bump shape" equalizer design is one in which the adjustment of one equalizer network affects only a relatively small portion of the frequency band. A single-frequency test signal, transmitted near the center of each equalizer band, provides an indication of the amount of correction being introduced by that network. The setting of each network depends on the amount of current passing through a thermistor. This current is controlled remotely from the control center.

Commands are transmitted from the control center over single-frequency command channels located in the L4 spectrum between 316 and 492 kHz. Each remote equalizing repeater is assigned a unique command channel frequency in this band thus permitting each to be addressed individually from the control center. Each command channel carrier can be modulated by pairs of signals between 600 and 1000 Hz. A total of 62 different command signals can be transmitted. These commands are used to select the desired route and line for tests and adjustment. The command signals turn on or off the test oscillators located at equalizing repeaters for equalizer setting evaluation, connect the test oscillators to the equalizing repeater input or output, and adjust individual equalizers. In addition, the command signals turn on or off the power supply to monitoring oscillators used for fault location.

The monitoring oscillators are located at each remote repeater. A different frequency in the band between 18.500 and 18.560 MHz is assigned to each repeater point. The frequencies, 4 kHz apart, are assigned consecutively to repeaters along the line to facilitate repeater identification during fault locating procedures. The oscillators are powered over interstitial pairs in the cable from a nearby equalizing repeater. The power supply can be turned on, energizing the oscillators, from the control center. The received oscillator signals are displayed on a spectrum analyzer in the control center. Analysis of this display is used for identifying and locating faulty repeaters.

In the L5 system, a centralized and automated Transmission Surveillance System (TSS) with remote transmission surveillance auxiliary (TSA) stations controlled from a transmission surveillance center (TSC) were developed as an integral part of the L5 transmission system [5]. Digitally operated test equipment makes desired measurements under local or remote programmed or manual control. Data are collected and analyzed at the TSC where all operations, including remote repeater fault location, are controlled by a small general-purpose computer. However, there is no remote control of equalizer adjustment as in the L4 system. Experience with L4 showed that the equalizers and system are so stable that the cost of the remote control circuitry could not be justified.

**Microwave Radio Systems.** The maintenance facilities that are integrated with microwave radio systems are those of surveillance, protection switching, and alarms. In the analog systems, surveillance



takes the form of single-frequency pilot signals which control flat-gain regulators.

The regulators correct the system gains to compensate for changes due to atmospheric fading or other causes and initiate protection switching system operations when limits are exceeded. The digital radio systems use violation monitors and restorers. When violations exceed established limits, these circuits also initiate protection switching operations.

All radio systems are equipped with alarm arrangements that indicate signal power loss and deteriorated transmission performance. These alarms are displayed locally and may also be extended to a centralized maintenance location over a remote alarm and control system.

**Digital Systems on Metallic Media.** A comprehensive maintenance plan for the digital transmission network is evolving with the network. In some cases, maintenance features and functions are incorporated in the transmission systems; in other cases, maintenance is provided by external systems that may include record keeping and operational features as well.

*Terminology.* To facilitate discussion of digital system maintenance, it is desirable to define several commonly-used terms: *red alarm*, *yellow alarm*, *upstream*, *downstream*, and *resupply signal* (sometimes called a "blue signal"). When failure occurs in one direction of transmission, a loss-of-service alarm is initiated at the affected receiving D-type channel banks. Since loss of service is involved, a red alarm light is lit and an audible alarm is sounded; the alarm is called a red alarm. When such an alarm is initiated, the associated transmitting D-type banks are usually signalled automatically to indicate the failure. At the transmitting end, a yellow alarm light is lit and the alarm is called a yellow alarm. The red and yellow alarm convention is maintained throughout most of the digital network. Loss-of-service alarms are also initiated at intermediate multiplexer units.

Upstream and downstream describe transmission phenomena relative to some reference point in a transmission path. Points downstream are those to which signals are being transmitted from the reference point and points upstream are those from which signals are being received at the reference point.

A resupply signal is substituted for a failed signal to prevent or minimize protection switching or the sounding of alarms in equipment located downstream from a failed link or piece of equipment. A resupply signal satisfies line format specifications at the hierarchical level at which it is inserted but carries no message or framing information for lower hierarchical levels.

*Digital Terminals.* The principal maintenance feature of D-type channel banks is a circuit that recognizes a loss of signal or a loss of framing in the receiving terminal equipment. When such a service failure occurs, this circuit initiates a red alarm and transmits a yellow alarm signal to the channel banks at the other end of the system.

The presence of these alarm conditions also initiates trunk processing functions where supplied. In this process, all busy network trunks involved in the failure are released, removed from service, and made to appear busy. Customer charges on the disconnected calls are terminated and the trunks are held out of service and in the busy condition until repairs are completed. The circuits involved in trunk processing are called carrier failure alarm or carrier group alarm circuits.

Maintenance and surveillance of multiplex units are controlled in much the same manner as that used for channel banks. Circuits are provided to monitor the received signal. These circuits register an out-of-service alarm when the incoming signal is lost or when the multiplex unit loses synchronism and the signal goes out-of-frame.

To prevent a loss of signal or framing from affecting downstream multiplex equipment and channel banks, a resupply signal is substituted for the regular signal in some multiplex units. Such a signal maintains downstream equipment in working order or allows it to recognize the failure as upstream so that unnecessary maintenance activity is avoided. No message or D-bank framing information is transmitted.

*Digital Lines.* Surveillance of repeatered line performance and location of faulty repeaters on digital transmission facilities are performed from central offices at the ends of or along the route of each system. Performance is evaluated by violation monitors that examine the signal for code violations. Signals are commonly monitored for bipolar violations and equipped to recognize valid violations such as those introduced by B6ZS and B3ZS formats. They are also

generally monitored for violations of successive 0s restrictions and for loss of signal. Appropriate alarms indicate the nature of any observed impairment. As in multiplex units, some lines provide a resupply signal in case of total failure.

The repeated lines of all digital systems are equipped with fault location circuitry so that a defective repeater can be identified from the central office before maintenance personnel are dispatched. The fault location arrangements commonly used require the transmission of a specially coded signal from the central office. This signal contains a high concentration of energy at specific voice frequencies which are assigned to correspond to specific repeater locations. At each remote repeater, a bandpass filter selects the frequency associated with that location; circuits are provided to transmit the voice-frequency signal back to the central office over a separate wire pair. Missing or distorted signals identify faulty repeaters.

*Cross-Connect Frames.* Equipment frames made up of jack panels serve as cross-connection points and as common locations in the central office for the interconnection of digital system channel banks, multiplex equipment, and transmission facilities. These cross-connect frames also serve as access points for service restoration, rearrangements, and testing for trouble identification, isolation, and location.

Cross-connect frames are designated separately (DSX0, DSX1, DSX1C, DSX2, DSX3, and DSX4) for each of six digital rates. Each frame is used to interconnect equipment that operates at the corresponding rate. The six frames can be grouped into three types, each with different features, although all except the DSX0 are equipped with tracer lamps for convenient identification of the two ends of a cross-connection.

The DSX0 is the only frame of the first type. It is used only for interconnecting terminal and multiplex equipment to furnish DATA-PHONE digital service over the Digital Data System. Quad terminals on the cross-connect panels are interconnected by quad jumpers equipped with quad connectors.

The second type includes the DSX1, DSX1C, and DSX2 frames. These feature monitoring jacks and interconnection jacks for patching. Access to the 100- or 110-ohm circuits is obtained by use of 310-type telephone plugs.

The DSX3 and DSX4 comprise the third type of frame. These frames have no monitoring jacks although such jacks are provided in connecting equipment for patching between working, standby, and protection equipment and lines. The jacks, plugs, and cross-connect cords are of a 75-ohm coaxial type.

### System-Independent Maintenance Arrangements

The complexity of modern transmission systems and of the network has made it difficult to provide maintenance by manual methods. As a result, an increasing number of automated maintenance systems are being provided. Among these systems are the Carrier Transmission Maintenance System (CTMS), the Surveillance and Control of Transmission Systems (SCOTS) equipment, the Telecommunications Alarm Surveillance and Control (TASC) System, the T-Carrier Administration System (TCAS), and the Cable Pressure Monitoring System (CPMS). These systems are designed to provide surveillance and maintenance functions over a variety of transmission systems in a portion of the facilities network. They all feature some form of computer control [6].

**Carrier Transmission Maintenance System.** Automatic, in-service testing of coaxial carrier systems, microwave radio systems, and associated multiplex equipment is provided by the CTMS [7]. Access to carrier system test points is provided by a broadband switching and control network that uses coaxial cable and coaxial switches. The central installation contains a minicomputer, a cassette-tape or disk memory unit, switch control circuits, and a teleprinter; the measuring equipment consists of very precise, digitally controlled 90-type test equipment [8].

The CTMS monitors pilot amplitudes and noise and scans the transmission band of the facility under test for unwanted high-amplitude signals (hot-tone scan). The system can be used to identify, sectionalize, and isolate troubles and to determine whether troubles are inside or outside the central office building.

When used at a No. 4 crossbar switching office, the CTMS can be coupled with automatic trunk measuring equipment under the control of a single computer. This combined arrangement is called a Trunk and Facility Maintenance System (TFMS). Trunks may be measured at carrier system line frequencies thus providing an additional meas-

uring point for maintenance personnel to sectionalize and isolate trunk troubles.

Measurements are automatically made by the CTMS on a programmed basis and on any desired schedule. Tests may also be initiated by operator command from a remote control and display unit or from distant offices by command from a data set. The remote control and display unit can be plugged into access connectors at trunk testboards, private line test centers, and other bay locations in the office. Test results are displayed in the form of a numerical readout.

**Surveillance and Control of Transmission Systems.** Remote, automated surveillance, control, and maintenance administration of broadband transmission facilities may be provided by SCOTS [9]. This system uses E-type telemetry systems to scan unstaffed remote repeater points and toll offices for alarms. If an alarm is detected, the nature of the problem is analyzed by the system and alarm center personnel are alerted. The system can interface with the C1 alarm system and with existing E-type telemetry systems. A SCOTS control station has the capacity for monitoring and controlling 128 remote locations. Thus, in the broadband plant, one or more operating areas or states may be monitored from a single centralized operating center.

Functions remotely controlled by SCOTS include protection switching system operations and the sequencing of emergency restoration procedures. The system may also be used to control temporary facility arrangements that might be required for major sports or other events.

**Telecommunications Alarm Surveillance and Control System.** The general-purpose TASC system provides mechanized and centralized alarm reporting, status surveillance, and remote control of a large variety of telecommunications equipment. The TASC equipment can analyze failures and present processed information to the TASC central operators. It also maintains a log of all operating events, provides for selective log retrieval, and administers trouble tickets and other operational support tasks.

The TASC centralized location utilizes standard channels to connect the central location with remote control terminals and/or computers which may monitor and control selected portions of the plant. These features permit the TASC system to function simultaneously as an independent alarm center and an integral component of a multisystem

control center. A computer connection can be used to link TASC and Automatic Trouble Analysis (ATA) computers to support an electromechanical switching control center.

**The T-Carrier Administration System.** The exceptional growth in the use of T1 carrier systems in many metropolitan areas has led to a need for centralized and automated facilities for the control of administration and maintenance of the digital network facilities [10]. A large metropolitan network may include 10,000 or more T1 carrier systems made up of over 50,000 span lines. The complexities of operations and interconnections in such a network can only be solved by a centralized administration system such as TCAS.

Maintenance and operation activities in a network of T1 carrier systems are controlled from a centralized T-carrier restoration and control center (TRCC). Such activities are augmented in large networks by the use of TCAS to provide surveillance of system performance and analysis of system failures. The TCAS also provides automatic trouble isolation to a faulty channel bank or a specific span, provides reports on the current status of the digital network, periodically monitors the performance of each working system, and maintains a log of the status and use of maintenance lines.

A minicomputer is used at the TRCC for control of TCAS operations. Connections are made from the TRCC to remote offices by dedicated E-type telemetry systems.

The functions of the TCAS can be implemented by stages so that the administration system may grow as the network increases in size and complexity. Such a planned implementation of TCAS growth also provides a means for introducing the system gradually and economically.

**Cable Pressure Monitoring System.** Although it is not devoted to transmission measurements, the CPMS is important to transmission maintenance. The quality of transmission performance deteriorates significantly when moisture enters transmission cables. Many cables are maintained under gas pressure to impede the entrance of water through small holes or breaks in the cable sheath and to provide indications of such breaks by changes in gas pressure.

Pressure transducers and contactors are installed in cable sheaths, status indicators are used on air dryer and pipe alarms, and flow monitoring devices are used to measure gas flow. These devices are

all monitored by the CPMS using E-type telemetry systems to transmit status information to terminals in each wire center. This data is collected by the CPMS central computer by automatic polling of the wire-center terminals via switched network connections. The system generates trouble reports which are printed at the central terminal and transmitted by teletypewriter to the appropriate maintenance center. Special measurements and data may be requested from the central location by teletypewriter.

### 24-3 CIRCUIT MAINTENANCE SYSTEMS

Message network loops and trunks and some types of special services circuits are now maintained on the basis of measurements made by computer-controlled test equipment and maintenance systems. Many of these systems also incorporate large-scale computer memory capabilities that are being used increasingly to replace manual methods of record keeping.

#### Loop Maintenance

The high rate of station movement and the complexities of loop feeder and distribution cable layouts make loop maintenance and record keeping procedures difficult. Loop operations are centered in the repair service bureau (RSB) which is responsible for maintenance of station equipment as well as loops.

Since most loops are provided over cable pairs, a large part of loop maintenance work pertains to cable testing and cable maintenance. Most of this type of work was performed manually in the past but automatic testing and analysis of results is increasingly being used. Since outside plant cables terminate in the central office at a main distributing frame (MDF), testing and other loop operations must be carried out with adequate concern for the complexities that exist at the MDF.

**Cable Testing.** Much cable testing is still performed by manual methods using frame-mounted test equipment or portable sets that can be carried into the outside plant environment [11]. The frame-mounted test equipment is usually assembled into a repair service bureau test arrangement. In either case, manual test methods are slow and expensive and, as a result, mechanized test arrangements are finding increasing use here as in other parts of the plant.

An effective measure of cable pair quality is the line insulation resistance. Thus, tests are made in which the resistance between the conductors of a pair or from conductor to ground is measured and compared with expected values. Automatic Line Insulation Test (ALIT) equipment is being used to make such tests economical. A time-shared computer program has been made available for the Analysis of Automatic Line Insulation Tests (ANALIT). The combination of ALIT and ANALIT has made possible efficient and effective means for the improvement of plant quality and the elimination of some customer service complaints.

**Repair Service Bureau.** Loop maintenance activities are centered at the RSB where records of station locations, cable assignments, and customer services are maintained and where personnel and test facilities are located. Repair service attendants are stationed at the bureau to receive customer trouble reports. Until recent years, all activities at RSBs were carried out manually; many test procedures required coordination between test desk personnel and other maintenance personnel responsible for activities at the main distributing frame, at customer premises, or along the cable. Much of this work is being mechanized and subjected to computer control [12].

Station maintenance is not currently adaptable to mechanization. Many station tests can be made from the RSB but when trouble has been established as station trouble, a visit to the customer premises by repair personnel is required.

As various RSB functions are adapted to mechanization, the bureau is becoming known as an Automated Repair Service Bureau (ARSB). The major objectives in mechanizing RSB operations are (1) to improve efficiency and reduce the cost of repair operations, (2) to improve customer service by reducing the time required for detecting, locating, and repairing troubles, and (3) to improve the handling of customer contacts by repair service attendants.

An important component of an ARSB is the Loop Maintenance Operations System (LMOS). This computer system mechanizes RSB customer line card records by storing them in computer memory and can produce a variety of management reports. Among its functions are customer trouble report processing, control of mechanized testing, analysis of past trouble reports by referring to the trouble report evaluation and analysis tool (TREAT) program, and the provision



of equipment utilization reports. A maximum of five million customer line records can be accommodated by one LMOS installation.

A number of automated test systems are available for use with an ARSB and LMOS. These include a line status verifier (LSV), automated line verification (ALV) equipment, and mechanized loop testing (MLT) equipment. The LSV and ALV, now available, have limited capability; the MLT system provides mechanization of essentially all ARSB test functions.

The TREAT program may be used with LMOS or may function alone to provide analyses and reports of a variety of loop operations. These include customer-provided equipment summaries, customer trouble reports, special services inventories, and coin telephone operation reports. The program can also be used for repair force administration.

### Trunk Maintenance

Two major functions are provided by most network trunks. They provide transmission paths between switching entities; in addition, most trunk circuits provide address and signalling functions associated with setting up a wide variety of connections. Thus, trunk maintenance must include tests to evaluate both transmission and operating performance.

The switched message network has grown to such a degree that the maintenance of trunks, now numbering in the millions, must be mechanized in order to provide a satisfactory grade of service economically. As trunk testing has progressed from manual to computer-assisted methods, many intermediate stages of development have produced semi-automatic equipment with limited capabilities. Many of these intermediate maintenance systems and equipment types may still be found in use.

The manual testboards still in operation, such as the 17C and the 17D, depend on close association with large jack fields of voice-frequency trunk appearances to gain access by patching to the trunk desired for testing. These testboards have been modernized from time to time by the installation of new and improved test sets, display units, and test signal generators.

One transmission measuring set, manufactured by outside suppliers to Bell System specifications, is coded KS-20805. This system provides rack mounted test equipment and several types of digital display units capable of being viewed from various distances. The system is arranged to measure and display noise in dB<sub>rnc</sub>, frequency in kHz, and power in dB<sub>m</sub>.

Outgoing trunk (OGT) test frames are often found in older electro-mechanical switching offices. These frames provide jack access and test facilities for all outgoing trunks. They may operate manually or in conjunction with automatic or semi-automatic systems some of which are designed as maintenance support systems for specific switching systems. The intertoll manual test frame (IMTF) is an arrangement for use in No. 4 crossbar offices to replace the 17C test-board and the OGT test frame. The IMTF is also required to test the circuits of the Common Channel Interoffice Signalling (CCIS) System in No. 4 crossbar offices. In addition, several vintages of semi-automatic test frames have been employed. For example, the automatically directed outgoing intertoll trunk (ADOIT) frame operates to test outgoing trunks at a No. 4 crossbar office. Also, the automatic outgoing trunk test (AOTT) frame may be installed at No. 4 crossbar offices to test originating toll connecting trunks. A similar arrangement may be installed to test trunks that originate at a step-by-step machine [13]. These arrangements are being replaced by newer mechanized test arrangements.

Many phases of trunk and facility maintenance work relating to No. 4 crossbar offices may be automated by the TFMS. As previously mentioned, a fully equipped TFMS includes the Outgoing Trunk Testing System (OTTS) bay, CTMS equipment for carrier measurements, and a minicomputer for program control of both systems. The TFMS provides routine trunk and facility testing and may be used in demand testing for trouble identification and location.

One of the most versatile systems for testing network trunks is the Centralized Automatic Reporting on Trunks (CAROT) System [14]. The principal components of a CAROT System are a centralized, computer-operated controller, remote office responders, remote office test lines (ROTL) for use with most types of switching machines, and miscellaneous other test lines for communications between ROTLs and responders and for connecting appropriate test equipment to the trunk under test.

The system that preceded CAROT, called the Automatic Transmission Measuring System (ATMS), was capable of testing trunks between two central offices automatically [15]. The principal components of that system were the ATMS director and the ATMS responder, one similar to that now used in CAROT. To increase the flexibility of ATMS testing, ROTLs were developed so that tests could be performed between a ROTL and a ROTL responder without the necessity of using a test frame and ATMS director. This simplification made it unnecessary in small office installations to purchase an ATMS director but testing and test control were still confined to trunks between offices directly involved in the tests. The CAROT system, with its central controller, combines these features in such a way that tests can be performed on trunks between any two offices in the area controlled by CAROT; the central controller may be located at any convenient location within or near that area. From the central location, a CAROT controller can use ROTLs, responders, and test lines to perform transmission loss and noise tests and operational tests on trunks between surrounding central offices. If measured values fall outside established limits, the trunks are considered impaired and test results are presented in a form suitable for troubleshooting.

Tests by CAROT are controlled by a minicomputer. Trunks within the served area are identified and their designations entered into disk files which are updated regularly to reflect changes in the network. Trunks are tested in regular sequence during nonbusy hours. During more active periods of the day, the system may be used, on demand, to test trunks that are being serviced because of troubles indicated during the routine tests. A single CAROT system can serve up to approximately 100,000 trunks. Additional features, such as those that enhance circuit order and other administrative operations, are being added to the CAROT system by revising the computer program that controls its operations.

The advent of digital switching with the No. 4 ESS led to the need of further mechanization in operation and administration services to plant, clerical, and management personnel. Various work centers are provided with interfaces to the Circuit Maintenance System (CMS 1B) through interactive keyboard and cathode ray tube displays [16]. The system mechanizes much of the work distribution, circuit-order administration, and many types of reports. The system has very large capability that can be exercised through interactive connections with

the No. 4 ESS processor, CAROT, CTMS, and other maintenance and administration systems.

### Special Services Circuit Maintenance

With the great diversity of functions and the wide range of circuit types involved, centralized and mechanized testing of special services circuits has developed somewhat more slowly than that used for network trunks. There has been a tendency to develop specialized test centers for each major classification of special services: the television operating center (TOC) for television services, wideband test and service bays for wideband data services, serving test centers (STC) for the digital data system (DDS) and other services.

Many of these test centers are being merged into a special service center (SSC) to provide centralized and mechanized control of special services operations. New Circuit Maintenance Systems (CMS-2A and CMS-3A) mechanize much of the administrative and record-keeping aspects of the centralized operations control centers. The Switched Access Remote Test System (SARTS) provides the SSC with remote access and test capability for a large number and variety of special services circuits. Enhancements to these systems will expand their application to even more diverse fields [17]. The SARTS, CMS, and the Automatic Data Test System (ADTS) provide the principal SSC operations supports systems.

**The Switched Access Remote Test System.** As implied by its name, SARTS combines two functions to provide one-person testing of special services circuits from the SSC. The first function, switched access, is implemented by the use of any of several versions of the Switched Maintenance Access System (SMAS) at central offices remote from the SSC. The second function is that of a Remote Test System (RTS) capable of performing transmission and operational tests on a wide variety of special services circuits. Remote operation of the SMAS and the RTS is controlled from the SSC over data communications circuits which are also used to transmit test results from the remote location to the SSC.

Access and test commands are initiated at the SSC by use of a minicomputer process controller and test positions equipped with DATASPEED® 40 terminals. These terminals use cathode ray tube displays to guide the test processes and to indicate test results. The initial program for SARTS permits testing of up to 50,000 circuits

among as many as 50 remote offices, the use of up to 24 test positions at the central location, and up to 10 test ports (local and/or remote) per SMAS/RTS combination. Enlarged SMAS/RTS combinations that provide up to 20 test ports are being introduced.

**Circuit Maintenance System.** The CMS is a multiprocessor system that mechanizes administrative and record-keeping functions. DATA-SPEED 40 terminals are used, as in SARTS, to provide convenient and interactive person-machine interfaces for operations personnel in SSCs, STCs, and central offices.

Two versions of the CMS are available for special services support. The CMS-2A provides mechanized record keeping and administration in support of STCs. The CMS-3A serves as a communications hub in an SSC to coordinate all plant activities required to install and maintain special services circuits in operating telephone companies.

**Automatic Data Test System.** The ADTS is a computer-controlled system that mechanizes most data set and data terminal testing functions performed at data test centers [18]. It can perform both dynamic and static tests on data stations designed for the switched network and, in conjunction with SARTS, for those used on private lines. Communication with ADTS by maintenance personnel is made possible by the use of TOUCH-TONE signals. Thus, a one-person test operation, either from an SSC or from a remote station, is made possible. The system also provides programs for system test and maintenance and for storing and retrieving information from a variety of data-service-related files.

#### 24-4 MAINTENANCE SUPPORT

The trend toward mechanization and computer control of operations and maintenance equipment and methods has not lessened the need for many items of support equipment. Some of these facilities provide efficient means of access to circuits for test. In other cases, the support is in the nature of equipment to enable maintenance personnel to communicate with one another efficiently and conveniently or to permit remote control and surveillance of transmission systems and circuits from centralized locations. Some support items, such as protection channels, are needed for service protection and for the temporary repair and restoration of failed transmission facilities.

### Access for Maintenance

All electronic equipment must be designed so that the equipment can be tested. In some cases, the necessary test access is provided by pin jacks. In some systems that employ plug-in equipment, "extenders" are used to permit the circuit cards or boards to remain in the operating environment and yet to make all the components available for test and observations. Often, jacks are mounted in a convenient manner so that test equipment can be plugged in for maintenance testing.

In many central offices, voice-frequency patch bays are set up with many thousands of jacks to provide access for testing loops or trunks. Patch cords can be used to interconnect such circuits and are also used to connect the desired circuit to the test desk for convenient access to test equipment and test signal sources.

Distributing frames often provide access for maintenance testing as well as for circuit installation and rearrangement work. Connectors, called shoes, may be used to make contact with selected terminals and to extend the connection by test cords to jacks that carry the circuit test connection to a testboard.

With the increased emphasis on automatic and semi-automatic trunk and special services circuit testing by SARTS and CMS, a need developed for easy access to a large number of circuits. The Switched Maintenance Access System, which is displacing jack and plug access equipment, is a switching arrangement that provides for connections between test facilities and any one of thousands of trunks and/or special services circuits [19]. The switches may be operated under computer control or by manual operation to select the circuit to be tested.

### Communications for Maintenance

Two general types of communications facilities are used for operations and maintenance work. Order wires provide voice communications for maintenance personnel. Data communications links are used to extend alarms and other status indicators from unmanned and remote locations to centralized points where maintenance and operations are controlled. They are also used to transmit control information from centralized points to remote points.

**Order Wires.** Voice communications facilities are used to permit maintenance personnel to communicate with one another between remote locations or between a remote location and a centralized location. The facilities may be no more than a connection to the switched message network, a point-to-point connection with direct and uncomplicated signalling arrangements, or a complex communication system with selective signalling arrangements. Order wires are usually routed over facilities separate from those with which they are associated for maintenance.

Order-wire appearances are provided wherever needed. Such appearances, in the form of telephone headset jacks, are commonly found at all remote repeater points along transmission routes. Jack or station set appearances may also be found in a central office at distributing frames, transmission bays, multiplex bays, etc.

**Data Communications.** It is often desirable to provide arrangements to extend alarm and other status indications from remote to central locations. Two major systems are available for this purpose; both are also capable of transmitting control information from the central location to remote points.

*The C1 Alarm and Control System.* Initially, the C1 system was designed to support maintenance activities on microwave radio systems [20]. The C1 functions include the transfer of detailed alarm and supervisory information at unattended radio stations to an attended point, called an alarm center, and the transmittal of orders for controlling operations at the unattended stations from the alarm center. Order-wire facilities are part of the C1 system.

An alarm section is made up of an alarm center and up to 12 remote locations. The section is served by one or two alarm circuits with a maximum of six remote stations on each. A specific single-frequency signal is assigned to each remote location. When there are no alarms present, the single-frequency signal is continually transmitted. When an alarm occurs, the single-frequency signal is removed from the line to alert the alarm center. A command signal is then transmitted to the station to request a scan of its alarm circuits. The status of each, up to a maximum of 882 in a fully equipped radio station, is then transmitted to the alarm center. A total of 490 separate command signals can be sent from the alarm center to each remote location.

Radio or cable line facilities separate from those of the radio system monitored by the C1 system are used for alarm, command, and order-wire transmission. A two-wire alarm line is used to transmit alarm and status information to the alarm center. A four-wire line is used for command and order-wire transmission.

*The E-Type Telemetry Systems.* Data transmission for alarm, status, and control for many of the systems previously discussed, such as the L4 and L5 coaxial systems, TASC, TCAS, SCOTS, and for many others is provided by E-type telemetry systems [21]. Status inputs at remote locations are represented by two-state (binary) information from alarm circuits or relays; commands from a central location are similarly coded in a binary form. Thus, the system is designed to transmit binary coded signals to and from the central location.

Considerable flexibility has been designed into the E-type systems. They operate economically over a wide range of systems and are particularly adaptable to computer control and interaction. Standard four-wire data transmission facilities and 202-type data sets are used for communication between E2 central and remote locations.

### Service Protection

Many transmission systems and some multiplex equipment are provided with protection switching and transmission facilities. These protection systems are described with the systems with which they are associated. Generally, they protect service by switching from a working to a protection facility when there is an equipment failure or loss of transmission for some other reason such as multipath fading of microwave radio systems.

In addition to their service protection functions, these arrangements also are used to facilitate maintenance. When maintenance of a working system is required, service may be transferred by manual control of the switching system (or by patching, in some instances) to the protection line or equipment. When maintenance work is completed, service is restored to the regular facility.

Protection facilities are also used for emergency restoration. Service interruption due to a major route failure can sometimes be temporarily restored by rerouting channels over protection facilities of other systems. After repairs have been made, service is restored to the regular facilities.



Service restoral is sometimes accomplished by temporary repairs. Emergency equipment is stored for this purpose. For example, a microwave radio route might fail due to the destruction of a repeater tower. A temporary tower might be delivered by truck and erected near the sight of the original tower to carry service while a new permanent tower is being constructed. Repeaters and jumper cables for coaxial lines are similarly stored and may be used to effect a temporary repair while a major cable break is being restored. Many other examples of such temporary service restoral might be cited.

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## Chapter 25

# Test Equipment

Testing of circuits, systems, and facilities for transmission evaluation and trouble location requires the use of test equipment that may be installed in fixed locations or which may be provided more economically in the form of mobile test sets. For example, a specific type of set may be essential for occasional use but too expensive to be provided in many fixed locations, only to lie idle most of the time. Other sets are designed to be hand carried for use in field locations. Some portable sets are arranged so that they may be conveniently and permanently mounted in a fixed or mobile bay. Some mobile sets are designed to operate on commercial power only, some on batteries only, and others on either commercial power or internal batteries. A few need only the incoming signal that is to be measured.

Solid-state techniques have made it practicable to reduce the size and weight of test sets and to include superior capabilities. Innovations are being introduced at an unusually rapid pace as a result of advancing technology. Many sets do more than indicate electrical values on meters. They quickly process and store information and display the results in the form of illuminated readouts or cathode ray tube traces. Such capability eliminates human errors in reading meters and switch settings and in making calculations. Some sets display instructional readouts to guide the user through successive test procedures.

Essentially, the types of measurements made are those of loss, gain, return loss, longitudinal balance, impedance, background noise, impulse noise, phase jitter, and intermodulation distortion. In digital transmission systems, peak-to-average ratio (P/AR) of the signal

voltage, channel delay distortion and bandwidth, and pulse timing jitter are measured.

A comprehensive discussion of test equipment is made difficult by the large number of parameters that must be measured and the wide range of types of circuits, systems, and facilities that must be evaluated. Many transmission parameters must be measured on voiceband and wideband circuits, on analog and digital transmission systems, and on systems that employ amplitude or frequency modulation. In addition, requirements differ in respect to measurements of station equipment, loops, trunks, the many types of special services circuits, and the various media that are used. As a result of these factors, there are many different types of test sets.

Much of the portable test equipment used for transmission measurements is manufactured outside the Bell System, some to meet Bell System specifications. However, several test sets are still manufactured within the Bell System to satisfy specific needs.

The unprecedented growth of the switched message network and of the variety of services provided have had a major impact on transmission maintenance methods and procedures. The large increase in data transmission and in types of data services has perhaps had the greatest single influence. The increasing emphasis on digital data transmission has made it necessary to examine the capabilities of the message network to transmit digital data signals and to specify a consistent set of requirements on maintenance equipment [1]. As a result, a set of guidelines has been applied to test equipment of General Trade manufacture as well as to equipment of Bell System manufacture [2].

Test equipment for transmission maintenance must meet stringent electrical and physical design requirements. Electrical requirements include the transmission parameters to be measured and the method of measurement. Accuracy, range, displays of results, and many other features and characteristics are also specified. Physical features are specified in terms of size, weight, portability, mounting arrangements, identification, and many others. The degree to which these electrical and physical requirements are met determines the usefulness and cost of the equipment. Thus, these factors must be known in great detail if economic choices are to be made in the provision of maintenance test equipment.

## 25-1 VOICEBAND LOSS AND DELAY MEASURING EQUIPMENT

The most significant parameters that determine the quality of a voiceband channel are the attenuation/frequency and delay/frequency characteristics. Thus, many test sets are designed to measure transmission loss (or gain) at specific frequencies or over certain frequency bands and to measure the delay distortion in the channel.

Oscillators and detectors are the fundamental types of test sets used for measuring circuit losses or gains. Within the frequency range for which an oscillator is designed, the important characteristics are the output impedance, the accuracy and stability of output frequency and amplitude, and the purity of output signal wave shape. Important characteristics of a detector, or transmission measuring set, are input impedance, frequency range, amplitude measuring range, and accuracy. Longitudinal balance, stability, high-voltage protection, and other parameters must also be specified.

Test signal amplitudes may typically be between  $-40$  and  $+10$  dBm at the points of measurement. Circuits that normally carry speech or voiceband data signals must be measured from below 60 Hz to above 4000 Hz. The frequency range of interest in program circuit measurements is from 20 Hz to 20 kHz. Gain (or loss) measurements to determine slope across the VF band are normally made at frequencies near 400, 1000, and 2800 Hz. Envelope delay distortion, defined as the derivative of the phase shift in a circuit (in radians) versus frequency (in radians per second), is measured as a deviation of phase from that at some reference frequency, usually 1800 Hz.

### Test Signal Generators

There are many general purpose and specialized signal generators used to provide test signals at appropriate frequencies and to have special characteristics, where required. Among these are the 71G tone generator and the KS-19353 Oscillator. While the operation of the 71G is confined to the VF band, the KS-19353 Oscillator may be used for the VF band and for carrier-frequency testing up to a maximum frequency of 560 kHz.

**The 71G Tone Generator.** Precise sine-wave signals are provided at 404, 1004, and 2804 Hz by the portable 71G Precision Tone Generator to permit gain-slope measurements to be made over the VF band. In

addition, this generator may be used as a replacement for the older 71-types usually called *milliwatt supplies*. The frequency reference in the 71G is a highly accurate crystal oscillator signal from which all frequencies used in the set are derived. The output is stable to  $\pm 0.03$  dB of any of three selectable output powers, 0,  $-10$ , or  $-16$  dBm. The output impedance may be selected to be 600 or 900 ohms.

The output frequencies are all offset from 400, 1000, and 2800 Hz in order to favor transmission testing of T-type digital facilities. A test signal at an integral submultiple of the 8-kHz sampling frequency used in D-type channel banks can cause harmonically related interferences to fall back into the VF band. These can result in variations, or "beats," of the measured signal amplitude or of noise measurements that depend on the use of 1004-Hz signal as a "holding tone," the so-called C-notched noise measurement. If the holding-tone frequency is a rational submultiple of the 8-kHz sampling rate, the quantizing noise power is concentrated at a few frequencies rather than spread over the VF band.

**The KS-19353 Oscillator.** This portable oscillator is a general-purpose source of test power in the frequency range of 50 Hz to 560 kHz and power range of  $-40$  to  $+10$  dBm. In the frequency range of 50 Hz to 20 kHz, the output impedance is optionally 600 or 900 ohms; in the 5-kHz to 560-kHz range, it is 135 ohms. The output frequency is adjustable by means of a stepped multiplier switch and a continuously adjustable dial. Frequency accuracy is  $\pm 3$  percent and the output is stable to  $\pm 0.1$  percent for one hour and for a temperature change of  $\pm 5$  degrees Fahrenheit. The output power is adjustable by decade switches in steps as small as 0.1 dB. Dialing and line-holding are provided in the 600- and 900-ohm mode to permit network connections to be established for test.

### Test Signal Measuring Instruments

Test signal power must often be measured with great accuracy in order to evaluate transmission gains and losses and to provide calibration of test signal sources. Many types of meters, detectors, and analyzers are available for such measurements. Some are frequency-selective, some are wideband, and some are designed to fulfill only specialized measurement functions.

**The 22A Milliwatt Reference Meter.** Calibration of the output power of 1-kHz test signal sources of either 600- or 900-ohms impedance with errors no greater than 0.03 dB may be accomplished by the use of the portable 22A Milliwatt Reference Meter. It includes a calibration standard the accuracy of which is not affected by normal handling. The 22A can be calibrated to show deviations from power levels in the range  $-16$  to  $0$  dBm in 1-dB steps and from power levels of  $+0.5$ ,  $+4$ , and  $+7$  dBm. Although a number of these meters are still in use, they have been largely replaced by more modern instruments of General Trade manufacture.

**The 23D Transmission Measuring Set.** Test signal power may be measured in 600- and 900-ohm voice-frequency circuits on a terminating basis by the portable 23D Transmission Measuring Set (TMS). The frequency range is 300 to 5000 Hz and the power measurement range is  $-25$  to  $+10$  dBm. The 23D is energized by the incoming signals and requires neither battery nor commercial ac power.

The circuit to be measured is connected to the set through either jacks or binding posts. Direct current blocking is provided and circuitry is included to permit dialing and line-holding. Power in dBm is measured by adjusting a rotary switch in 5-dB steps to bring the meter pointer on scale and adding the switch and meter readings.

### Combined Signal Generator and Measuring Instruments

The test signal generation and measurement functions are sometimes conveniently combined in a single measuring instrument. Two examples of such test sets are the 25B Voiceband Gain and Delay Set and the 27F P/AR Transmitter and Receiver which comprise a rating system for VF circuits used for data signal transmission. While the 27F provides an overall evaluation of a VF circuit, it does not provide a useful identification of impairment components. Other sets, such as the 25B Voiceband Gain and Delay Set, must be used to determine the effect of individual impairments.

**The 25B Voiceband Gain and Delay Set.** The gain and envelope delay characteristics of VF transmission channels may be measured in the range of 300 to 3000 Hz by the 25B Voiceband Gain and Delay Set. With an external oscillator, measurements may be extended to 25 kHz. Transmitting and receiving impedance is either 600 or 900 ohms, switch selected. Frequency, received amplitude, and delay are shown

on meters for point-by-point measurements and corresponding dc outputs may be used to drive X-Y recorders when graphs are required. The transmitter output is adjustable from  $-30$  to  $0$  dBm, receiver measurement range is  $-30$  to  $+10$  dBm, and accuracy is  $\pm 0.2$  dB at  $1$  kHz. Delay error below  $300$  Hz is approximately  $\pm 20$   $\mu$ s, and above  $300$  Hz,  $\pm 10$   $\mu$ s. Dialing and line-holding features are provided. When used on two-wire circuits, a return path must be provided to obtain a phase reference for the measurements.

**The 27F P/AR Transmitter-Receiver.** The overall suitability of a voice-frequency channel for data transmission may be evaluated by the P/AR system which is designed to measure the simultaneous effects of envelope delay distortion, bandwidth reduction, and poor return loss (producing gain and phase distortion) which cause intersymbol interference in voiceband data signals [3]. The P/AR measurement is largely insensitive to noise, phase jitter, gain slope, intermodulation distortion, frequency shift, or transient phenomena.

The P/AR technique consists of transmitting a train of precisely shaped pulses having a known ratio of peak-to-average full-wave rectified voltage into one end of a channel and observing at the other end, on the receiving section of another 27F, the extent to which that ratio has changed. Thus, a rapid, weighted, straightaway measurement is made of channel impairments.

The P/AR receiver indicates the change on a meter calibrated from  $100$  to  $0$ , giving the P/AR rating. A rating of  $100$  means that the ratio in the received pulses is the same as that in the transmitted pulses, while a rating of  $0$  means that the ratio in received pulses is only half of that in the transmitted ones. Intermediate ratings and ratios are linearly related.

## 25-2 NOISE MEASURING EQUIPMENT

Any interference in a communication channel may be considered as noise. Some types of noise arise in channels as a result of natural physical phenomena. Some are generated by mechanisms within the channel and may be functions of the signals transmitted as well as of the channel characteristics. Other types are introduced in the channel from outside sources by some form of induction or crosstalk mechanism.



The measurement of various types of noise on communication circuits in terms that express their relative interfering effects is not a simple matter. The design of measuring equipment must take into account the subjective effects of noise on human listeners as well as electrical and mechanical effects on inanimate receivers such as data terminal equipment. For acoustic noise measurement, the test equipment response must be frequency-dependent, not only because the human hearing system is similarly dependent but also to allow for loss-frequency distortion between the point of electrical measurement and the acoustic output at the telephone receiver. The equipment must also allow for inertia in the human hearing system which does not sense the full intensities of sounds until they have persisted for about 0.2 second. A burst that does not last that long is subjectively evaluated in approximate proportion to its intensity and duration. For impulse noise, the measuring equipment must be capable of registering all noise impulses that are strong enough to be accepted as data signal elements. Such impulses are typically too short in duration to be sensed by ear and cannot be evaluated by means of acoustic noise measurements; separate mechanisms are needed to gather information for evaluating impulse noise.

Any specific pattern and intensity of voiceband noise has different interfering effects on different persons and for various amplitudes of the speech with which it is interfering. Thus, the objective measurement of acoustic noise with a noise-measuring set gives only a rough average of the interfering effect of that noise under various conditions. Interfering effects under specific conditions can vary by several dB. On the other hand, since the variability among data transmitting and receiving sets is comparatively small and since the data transmission levels are comparatively well controlled, the meaning of impulse noise measurements is more definite. However, variability in the types and amplitudes of noise may render short-period measurements of little value in trouble detection.

Noise measurements on VF channels used for digital data signal transmission are valid only if a holding tone is present. The signal in current use for such measurements is a single-frequency, 1004-Hz tone. Beyond the point in the transmission path where it is needed but before it reaches the noise-measuring circuitry, this signal is suppressed by a sharply tuned band-elimination filter in the weighting network known as a C-notched network. The probability of significant noise components falling in the eliminated band (995 to 1025 Hz) is

small, and the effect of the filter in measurements of flat Gaussian noise is to reduce the reading by less than 0.5 dB.

### The 3C Noise Measuring Set

All types of background noise that can interfere with the ease and satisfaction of listening on voice and program circuits may be measured by the 3C Noise Measuring Set. This portable instrument can measure both noise-to-ground and metallic circuit noise. The former is measured across 100,000 ohms; the latter is measured either on a bridging basis or across an internal termination. Noise readings require corrections when circuits bridged are not of 600-ohm impedance and when the circuits terminated are not of 600- or 900-ohm impedance. The 3C can measure metallic noise in the range 0 to 95 dBrn and longitudinal noise from 40 to 135 dBrn; both ranges apply before any corrections are made.

The major frequency-dependent part of the 3C response is provided by weighting networks in plug-in units. Weightings are defined by loss-frequency curves that show overall loss, relative to that at 1 kHz, from the input of the set to the noise reading device. In general, the object of having different weightings is to take account of the various interference-versus-frequency relations in the several types of service. The 3C weights each frequency component of a given noise in proportion to its interfering effect, adds those weighted components on a power basis and shows the result on a meter having suitable dynamic characteristics.

Weighting networks for the 3C include C-message, C-notched, program, 3-kHz flat, and 15-kHz. The C-message characteristic is fairly flat between 700 and 3000 Hz but has about 28 dB attenuation at 180 and 5000 Hz relative to the 1000-Hz loss. The C-notched characteristic combines the C-message characteristic and a sharp elimination band (notch) centered at 1010 Hz having at least 50 dB attenuation between 995 and 1025 Hz. Program weighting is designed to take into account the relative interfering effects of various frequencies on program material in the 8-kHz band. It rolls off below 1 kHz, but not as rapidly as C-message weighting, and emphasizes the response between 1 and 8 kHz. The 3-kHz flat weighting is flat from below 60 Hz to 2000 Hz, is down about 3 dB at 3000 Hz, then rolls off at 12 dB per octave. It is useful for detecting low-frequency noise induced from power lines or from ringing signals on other telephone circuits. The weighting

known as 15-kHz flat is used for top quality, wideband program circuits. The frequency characteristic is the same as that of the 3C set circuitry, exclusive of plug-in networks, and is achieved simply by using a frequency-insensitive plug-in unit. It is flat up to 5 kHz, rolls off gradually above that point, and is 4 dB down at 15 kHz.

### The 7A Carrier-Frequency Noise Measuring Set

Means for measuring noise on AM carrier channels in the range of 10 to 552 kHz are provided by the solid-state 7A set. Upon being connected to the line, tuned to the carrier frequency of the desired channel, and set for the upper or the lower sideband as required, the 7A demodulates the line noise to baseband channel noise, weights it as desired, and feeds that output to the measuring circuitry. The latter consists of an attenuator adjustable in 10-dB steps and a dBrn meter marked in 1-dB steps. The sum of the attenuator setting and the adjusted meter reading is the noise measurement.

When the 7A is used in the bridging mode, it does not interfere with operation of the carrier system but, before it is used in the terminating mode, the system must be taken out of service. The mode is selected and adjustments in dB are made with the FUNCTION switch. The measuring ranges of the 7A are shown in Figure 25-1.

FUNCTION SWITCH POSITION	RANGE, dBm
135-ohm terminating	-40 to +92
Bridging, add 10	-30 to +102
Bridging, add 20	-20 to +112
Noise-to-ground	-10 to +122

Figure 25-1. Measurement range of 7A Noise Measuring Set.

The 7A also provides a narrowband (120 Hz) tuning option which permits precise tuning to desired channels and accurate measurement of carrier, pilot, or test signals by suppressing all extraneous noise and signals. Auxiliary jacks on the front panel permit acoustic monitoring of the noise on the demodulated carrier band as well as connections to noise recorders and impulse-noise counters.

### The 6-Type Noise Measuring Sets

A number of test sets, coded 6-type, have been developed to measure noise of various types and to cover a number of different frequency bands. The primary use for these sets is the evaluation of circuits for data signal transmission.

**The 6F Voiceband Noise Measuring Set.** Message circuit background noise and the distribution of noise impulse amplitudes may be measured by the portable 6F Voiceband Noise Measuring Set. This set is designed primarily for the evaluation of noise on voiceband data circuits but does not evaluate the interfering effect of noise on speech transmission as accurately as does the 3C Noise Measuring Set.

Several plug-in weighting networks are provided for C-notched and flat measurement of voiceband noise. Another network permits measurement of noise in a 50 kb/s data circuit. Terminating, bridging, or noise-to-ground measurements may be selected by means of a switch on the front panel. A monitoring jack permits aural observations.

The distribution of impulse amplitudes in a given channel is determined by means of four counters, each of which indicates on a register all impulse peaks which exceed the specific threshold setting. Such a distribution is required in order to determine the error performance in digital signal transmission as a statistical function of the interference. The lowest of the four dBrn settings is that of the lowest counter on the front panel plus 30 dB. The other three thresholds may be set to exceed the first in successive equal steps of 2, 4, or 6 dB. The total spread of thresholds may thus be 6, 12, or 18 dB. This arrangement provides flexibility for bracketing both narrow and wide ranges of impulse amplitudes and for centering the thresholds so that all four counters can provide significant information. A timer in the set can be preset to stop the counting after any chosen interval up to 60 minutes or the counters may be allowed to run until stopped manually. Each counter has a capacity of 9999 and can operate up to 7 times per second.

**The 6G Wideband Noise Measuring Set.** Continuous noise within the range of 4 to 560 kHz and, alternatively, the number of noise impulses that exceed a chosen threshold during a selected time interval, or until stopped manually, may be measured by the portable 6G Wideband Noise Measuring Set. For terminating measurements of circuit noise, the input impedance is either 75 ohms unbalanced or 135 ohms bal-

anced. For longitudinal noise on 135-ohm balanced circuits, the input impedance is 10,000 ohms to ground and 1000 ohms tip-to-ring. Two weighting networks are provided in a single plug-in unit. A flat network is provided by a resistive pad permitting measurement over the full frequency range of the set, 4 to 560 kHz. The second network, which provides 10 to 50 kHz weighting, is essentially flat in that range but rolls off rapidly outside it.

The 6G was designed primarily for making measurements on wide-band data channels of various bandwidths between 4 and 560 kHz either on baseband cable or on carrier facilities. When it is counting impulses, the threshold between countable and noncountable magnitudes is set by adjusting the dials on the front panel. The same dials are used for bringing the meter needle on scale in the preferred range when continuous noise is being measured. The range for continuous noise is from 0 to 100 dBm and for impulse thresholds, from 30 to 110 dBm in 1-dB steps.

The internal mechanical counter can register up to 6 impulses per second and has a counting capacity of 999. Counting rates up to 5000 per second can be attained with an external electronic counter connected at the FAST CTR jack.

**The 6H Impulse Counter.** The number of impulse noise peaks that exceed a selected threshold on voice-frequency circuits during a chosen test period may be determined by use of a 6H Impulse Counter. The threshold and test period can be set, the former at any whole number of dB from 40 to 99 dBm and the latter at any value up to 15 minutes.

Plug-in networks with C-notched and flat weightings are provided with the 6H counter. The C-notched network permits measurement of impulse noise on compandored circuits. Input impedance is about 735 ohms, a compromise between 600 and 900 ohms. The maximum counting rate is 7 per second and the highest registerable total is 9999, which exceeds the highest possible 15-minute count.

### 25-3 IMPEDANCE-RELATED MEASURING EQUIPMENT

The effect on transmission performance of noise and echoes is significantly influenced by circuit impedances. This is true especially where circuit interfaces may introduce impedance discontinuity, series-impedance unbalance, or impedance-to-ground unbalance be-

tween the conductors of a transmission pair. In addition, impedance discontinuities may be introduced along a transmission medium by cable damage or by omission or improper placement of load coils. Such discontinuities can produce transmission echoes that impair transmission.

A large variety of portable, mobile, and bay-mounted test equipment is available for the measurement of impedance and impedance-related parameters. These include sets designed to measure return loss and longitudinal balance and to evaluate by simulation the impedance of a transmission line.

### Return Loss Measurement

Control of echoes, essential to good transmission, depends upon maintenance of adequate return loss within the transmission medium at points of transition between four-wire and two-wire facilities and at junctions of any medium with a repeater or a terminal [4]. Return loss is a measure of the composite reflections from irregularities within a medium. It is generally a function of frequency but its effective value within a specific frequency band can be obtained in a single measurement by using appropriately weighted thermal noise as test power and a power-summation detector as a measuring device. Another method is the use of a sweep-frequency generator for test power.

**The 54C Return Loss Measuring Set.** Accurate and rapid impedance matching of an E6 repeater to connecting cable facilities may be made by use of a 54C Return Loss Measuring Set and by adjustment of the intervening line build-out (LBO) network. The greatest return loss attainable indicates the best impedance match. This portable set has also been found useful in making rapid echo structural return loss measurements as part of the conformance and completion tests on new or rearranged cables.

The 54C set consists essentially of a sweep-frequency generator, hybrid transformer, bandpass filter, and meter circuit. One-way sweeps of the selected frequency band are made at a rate of ten per second without significant pause between sweeps. Each frequency band is selected for adjusting specific components in the LBO network of the E6 repeater. When the 54C set is used for cable-conformance tests, the 500 to 2500 Hz band is selected.

Because return losses vary throughout the frequency sweep, the meter needle usually moves in a pattern that may cover a range of a dB or more. However, since the motion of the needle is periodic rather than random, it is easy to tell when return loss has been optimized. In reading the meter, it is customary to estimate the midrange position of the needle. Return loss is read as the sum of a dial switch setting and meter indication.

Jacks are provided for using the 54C set with an external oscillator, if desired. Other jacks are provided for using the set with an external balancing network that is required when measuring structural return losses of cable pairs.

**The KS-20501 Return Loss Measuring Set.** The functions of evaluating echo and singing return losses on either two-wire or four-wire circuits are combined in the portable KS-20501 Return Loss Measuring Set. It generates a wide band of noise which may be passed through any one of three weighting networks by means of internal circuitry and used as a signal for return loss measurements. Return loss is indicated by the sum of a dial-switch setting and a meter reading on the front panel. An external oscillator may be connected to the set for measuring return loss versus frequency from 200 to 5000 Hz. The set is used primarily for making through and terminal balance and singing point tests.

The echo return loss (ERL) weighting network frequency characteristic has 3-dB points at 560 and 1965 Hz. On the other hand, the singing return loss (SRL) weighting, having 3-dB points at 260 and 500 Hz, emphasizes the influence of frequencies in the lower part of the voice band. Readings obtained with SRL weighting correspond closely to those obtained with other singing point test sets when the singing points are in the lower part of the voice band. The singing return loss high (SRL-HI) weighting, having 3-dB points at 2200 and 3400 Hz, emphasizes the influence of frequencies in the upper part of the voice band. Readings obtained with SRL-HI weighting correspond closely to those obtained with the singing-point test sets when the singing points are in the upper part of the voice-frequency band.

### Balance Testing

The degree of impedance balance between each conductor of a wire pair or of an equipment unit and ground is a measure of immunity to

noise induced from extraneous sources such as power lines, power conductors of electric railroads, etc. A measure of this balance can be approximated by using a noise measuring set to obtain separate readings of noise to ground and message circuit noise on the same facility. The longitudinal balance is calculated as a function of the difference between the two readings. Such determinations are dependent upon the frequency spectrum of the noise induced in the facility at the time of the measurements. Single-frequency measurements of longitudinal balance can also be made by energizing the longitudinal circuit at the desired frequency and measuring message circuit noise with a frequency analyzer having an adjustable narrowband filter.

One longitudinal balance test set, designed and furnished by General Trade manufacturers to meet IEEE standards, measures the balance on either a one-port or a two-port basis with self-supplied power. The measurement may be made with an adjustable single-frequency or on a broadband basis. Controls that permit achievement of an internal balance of 120 dB make practicable the measurement of balances as high as 100 dB. Each port is provided with its own dc supply for optional use on the circuit under test to determine the effect of dc bias on balance. Each supply is capable of furnishing up to 120 mA to an external resistance of up to 450 ohms.

### Level Tracers

A test set for measuring electrical characteristics of facilities and equipment as functions of frequency and for displaying them graphically on a cathode ray tube screen is called a level tracer. It may supply internally a sweep-frequency signal or, for measurements of characteristics such as attenuation, may receive a sweeping signal from the far end of a transmission facility. In either case, it continuously monitors the frequency of the signal it is sensing and places the horizontal coordinates of the graph in proportion to those frequencies while placing the vertical coordinates in proportion to the measured characteristics. Level tracers are commonly used in displaying loss, return loss, and impedance magnitude.

In early level tracers, the cathode ray tube beam was controlled directly by the measured X (frequency) and Y (magnitude) coordinates and produced on a retentive screen a trace that faded out gradually within a sweep cycle. In later designs, the measured coordinates are stored in memories which are swept rapidly to produce nonfading



traces that change only as the coordinates are updated in the memories as a result of adjustment of the entity being measured. Some of the late designs can generate in turn, and update alternately, two traces comparing the same or different properties of the same or different telephone circuits or equipment items. That ability is useful in locating and diagnosing impedance irregularities in cable pairs by using simulation with artificial cable modules. Some level tracers provide auxiliary dc outputs, proportional to horizontal and vertical coordinates of the graph, for driving X-Y plotters when permanent records of characteristics are wanted. For such use, means are also provided for slowing the sweep and reducing to acceptable amounts the plotting errors caused by inertia of the moving parts of the plotter.

### Measurement of Line Impedance

A major use of impedance measurements is to diagnose and locate impedance irregularities in cable pairs. A commonly-used technique is to terminate the pair under investigation with a nonreflecting network (one having the characteristic impedance of the line) at the far end and to obtain a graph of impedance magnitude versus frequency at the near end by using a level tracer as the measuring instrument. The level tracer applies a small constant ac to the pair as the frequency range is swept and uses the voltage drop across the pair at each frequency as a measure of the impedance magnitude. Amplification of that voltage drop coordinated with the choice of the impedance scale on the cathode ray tube graticule results in a direct indication of impedance magnitude. Deviations in the graph provide data for deducing the nature of the irregularity (e.g., an omitted or mislocated loading coil) and computing its distance from the measuring end.

A different empirical method of procedure after the graph has been obtained involves imitation of the layout of the real pair, including the irregularity, by means of an artificial cable kit. A group of graphs of simple irregularities at various distances from the measuring end provides initial guidance for setting up the artificial layout. Successful imitation of the irregularity is indicated by close agreement of the graphs of the real and artificial pairs as shown simultaneously by the level tracer. Sets used for this purpose include the 1A Artificial Cable Kit and several kits manufactured by the General Trade.

The 1A Artificial Cable Kit permits simulation of the transmission characteristics of cable circuits at voice frequencies. It consists of a

number of cable modules and loading coils, all similarly packaged in small plastic boxes equipped with jacks and plugs for direct interconnection. The modules simulate the impedance and propagation characteristics of 19-, 22-, 24-, 25-, and 26-gauge cable pairs in lengths of 6000, 3000, 1500, 750, and 250 feet. Loading coils of 88, 44, and 22 mH are included.

The kit simulates a cable circuit from 10 to 7000 Hz with errors no greater than  $\pm 2$  percent in either impedance or propagation constant; it is thus well within the performance range of actual cable. When ground resistance, which is too variable in the field to be included in the kit, is added externally in series with the ground line, the kit simulates the longitudinal circuit (pair-to-ground) up to about 300 Hz, a range that is of interest for signalling purposes. In the laboratory, the kit provides means for measuring in advance the transmission performance of proposed layouts and for answering a variety of questions; for example, the transmission penalties to be expected if performance is sacrificed for cost reduction. In the field, the kit provides means for identifying and locating irregularities in cable pairs by adjusting the simulated layout to exhibit the same shortcomings as those of the real cable.

#### 25-4 HIGH-FREQUENCY MEASURING EQUIPMENT

Many types of transmission measurements must be made on broadband analog channels and systems in order to determine performance quality and to carry out operating and maintenance functions. In some cases, test equipment available for these purposes is designed for use with specific systems or types of channels. In other cases, the equipment is of a general-purpose nature and can be used for measurements on a wide variety of channels and systems.

The parameters of interest in broadband channels and systems are similar to those in voiceband channels. Loss/frequency and delay/frequency characteristics and noise of all types are the most important impairments to be considered.

##### Test Sets for Analog Channel Measurements

A large number and variety of high-frequency test sets are required for the maintenance of the many channels and systems that are now in service. These sets cover an extremely wide range of frequencies and bandwidths as required by the various types of systems.

**The 70A Spectrum Generator.** A number of test signals are provided simultaneously for aligning multichannel analog cable-carrier line facilities by the 70A Spectrum Generator. The output impedance is  $135 \pm 10$  ohms within the range 10 to 300 kHz. The signal frequencies have been selected to extend throughout the range of types K, N, and ON carrier systems and to avoid interference with pilot frequencies. Inserting the appropriate plug-in networks assures that the frequency spacing, amplitudes, and slope are matched to the system being aligned. After the generator has been set up at the transmitting end of the carrier line, the alignment can be completed by one person at the receiving end using a receiver such as the KS-15872 Spectrum Analyzer.

**The KS-15872 Spectrum Analyzer.** The display of signal amplitudes as a function of frequency is conveniently accomplished by a spectrum analyzer [5]. The KS-15872 Spectrum Analyzer is used to determine the frequency and magnitude of each of several test signals received simultaneously on a K, N, or ON cable carrier system and to display the results on a cathode ray tube. This analyzer is especially useful in making equalizer adjustments at the receiving end of such a carrier line when the 70A Spectrum Generator is used at the transmitting end to provide the test signals since the effects of adjustments are evident as soon as they are made. The overall frequency range is from 5 to 300 kHz and the width of sweep is adjustable from 10 Hz to 200 kHz within that range. Full-scale amplitude indications are adjustable from 250 microvolts to 25 volts with an accuracy of  $\pm 0.5$  dB. Input impedance is either 55,000 ohms unbalanced or 135 ohms balanced.

### General Purpose Test Equipment

A number of different types of test sets are available for analog system maintenance. Some of these have a wide range of capabilities and may be regarded as test and maintenance systems. Others are designed on a modular basis with individual units having specialized functions but capable of being incorporated into maintenance systems under manual or automatic control.

**The 34A Transmission Measuring Set.** Tests and maintenance of 75-ohm carrier circuits in the range 35 Hz to 20 MHz and of 135-ohm balanced circuits from 10 kHz to 1 MHz may be performed by the use of the 34A Transmission Measuring Set (TMS). It is essentially a detector

with a variable attenuator, an indicating meter, and a thermocouple with means for calibration. The set is designed for fixed or mobile bay mounting.

The range for gain measurement is 0 to 91 dB, the same as that of the attenuator. Loss measurements in the same dB range can be made by using an external amplifier or high-gain detector. The set can measure power in the range of  $-10$  to  $+30$  dBm. When a source of test power is required at the same location an external oscillator must be used.

**The 37B Transmission Measuring Set.** Noise, intermodulation, pilot amplitudes, and transmission characteristics on L-carrier and TH- and TD-type microwave radio systems may be measured by the use of the 37B TMS. It functions normally as a decade-tuned selective detector, mainly on a 75-ohm unbalanced terminating basis but can also be used on a bridging basis by connecting an attenuator between the bridging point and the set; thus, sensitivity is reduced. Most sets are used in mobile bay arrangements.

In the normal mode, the 37B measures signal power of  $-120$  to 0 dBm in the frequency range of 50 kHz to 11 MHz. External repeating coils may be used to modify the input impedance for terminating measurements on 124- and 135-ohm balanced circuits.

Signal power is measured by adjusting two rotary decade switches to bring the meter reading on scale. The signal power is the sum of the decade switch readings and the meter reading. Selectivity is such that signals are 3 dB down at  $\pm 0.25$  kHz from the tuned frequency and 60 dB down at  $\pm 5$  kHz.

**The 90-Type Test Equipment.** A number of test equipment units are available for manual or mechanized transmission measurements on wideband facilities [6]. Some of these units, coded individually as 90-type test equipment, are available as portable and mobile instruments. In other cases, these units have been incorporated in complex maintenance systems such as the Transmission Surveillance System of the L5 Coaxial Transmission System and the Carrier Transmission Maintenance System.

*The 90A Carrier Frequency Oscillator.* Test signals required for long-haul carrier system maintenance may be provided by a 90A

Carrier Frequency Oscillator. A decade-type frequency control provides steps as small as 1 Hz from 10 kHz to 60 MHz. A similar type of output amplitude control provides steps as small as 0.1 dB from -99.9 dBm to 0 dBm. Frequency is displayed on an 8-digit readout while output amplitude is shown on a 3-digit readout. Frequency accuracy is  $\pm 50$  Hz  $\pm 2$  parts per million; output amplitude stability is  $\pm 0.01$  dB. Temperature-compensated oscillators eliminate the need for warm-up. Harmonic distortion is at least 50 dB below the fundamental for frequencies below 20 MHz and at least 40 dB below the fundamental for frequencies above 20 MHz. Spurious signals are 65 dB below the fundamental. The 90A includes three sets of output jacks for 75-ohm unbalanced circuits and for 124-ohm and 135-ohm balanced circuits.

*The 90D Level Control Unit.* A precise output power of 0 dBm into a 75-ohm load is provided by the 90D Level Control Unit. An input sinusoidal signal of -24 to -36 dBm and between 10 kHz and 70 MHz is amplified by the unit to achieve this output. Short-term variations from 0 dBm are within  $\pm 0.01$  dB up to 60 MHz. This control unit may be used with nonsinusoidal inputs but the output accuracy is reduced.

The 90D is used principally at offices where adjustable frequency oscillators are not available to provide test power for transmission measurements. Power at the desired frequency is sent from an adjacent office by way of a transmission facility and patched to the input of the 90D. Test power at 0 dBm is then available for transmission measurements.

*The 90G Oscillator.* Sinusoidal test signals for maintaining carrier systems, accurate in both frequency and output power, may be obtained from a 90G Oscillator designed primarily for the L5 carrier system. The 90G can also be used with other system types and as a standby in connection with the L5 surveillance system.

The frequency of the output signal is based on temperature-compensated reference oscillators and frequency synthesis by means of phase-locked loop oscillators. The temperature compensation obviates warm-up time. Output frequency is selected by means of a series of rotary decade switches adjustable from 20 kHz to 100 MHz in steps as small as 1 Hz. The frequency is displayed on an 8-digit readout. The output amplitude is similarly displayed and is adjustable from 0 dBm to -90 dBm in steps as small as 0.1 dB. Frequency error

is not more than  $\pm 50$  Hz  $\pm 2$  parts per million and amplitude error varies from  $\pm 0.1$  dB to  $\pm 0.6$  dB depending upon frequency.

Output impedances are 75 ohms unbalanced, 124 ohms balanced, and 135 ohms balanced. Harmonic distortion is more than 40 dB below the signal amplitude up to 60 MHz and more than 35 dB below from 60 to 100 MHz. Nonharmonic spurious signals are more than 50 dB below the signal amplitude.

*The 90H Selective Detector.* Although it was designed primarily for L5-carrier maintenance, the 90H Selective Detector can also be used for maintenance of other carrier systems. In accuracy of tuning and amplitude indications, it is a suitable complement to the 90G Oscillator for making measurements in the frequency range of 20 kHz to 100 MHz. The 90H oscillator is similar to that of the 90G and requires no warm-up to attain stability. Its tuned frequency is selected by a series of rotary decade switches and is displayed on an 8-digit readout. Bandwidths of 200 Hz, 2500 Hz, or 3100 Hz are selectable by means of a rotary switch. The 3100-Hz bandwidth is used for channel noise measurement in either the lower or upper sideband with respect to the tuned frequency.

The 90H measures the sum of the power at all frequencies in the selected band and displays it in dBm as the sum of a digital readout and a meter indication. The available impedances and the range and accuracy of frequency settings are the same as those of the 90G Oscillator. Harmonic distortion is normally 50 dB below the signal amplitude and can be reduced to 60 dB below for some purposes, by means of a switch on the front panel.

*The 74A Wideband Power Meter.* The need for a reference standard to establish a precise oscillator output of 0 dBm into a 75-ohm load at any frequency up to 240 MHz is filled by the 74A Wideband Power Meter. It is intended primarily for calibration of the 90A Oscillator and other carrier-frequency test equipment. The accuracy, provided by a thermocouple and a rugged meter, lies between  $\pm 0.02$  dB and  $\pm 0.3$  dB depending on frequency and the return loss of the signal source. A protection circuit for the thermocouple is disabled by operation of a nonlocking key when a measurement is being made. In addition to the precise measurement of oscillator outputs of approximately 0 dBm, the 74A includes an output jack for calibration of 75-ohm measuring sets. Output power is 0 dBm  $\pm 0.01$  dB into a 75-ohm load.

### System-Related Test Sets

A large number of test sets are available for the maintenance of specific transmission systems or of types of transmission systems or channels. Several are described briefly in order to illustrate these categories of sets.

**The 98B Portable Pilot Test Set.** An example of a type of instrument used for special-purpose measurements in a specific transmission system is the 98B Portable Pilot Test Set designed for line maintenance work on L4 coaxial systems. It can be used at any remote repeater location since it is powered from the coaxial line. The set includes an oscillator for calibration, a meter for pilot power indication, a lamp to indicate any momentary interruption of the line pilot, and a switch to connect the measuring circuit to either the repeater input or output, as desired.

The 98B is connected through high-impedance probes to both the input and output of a repeater. Its functions are (1) to measure the input and output power of the 11.648-MHz temperature pilot, thus indicating repeater gain, (2) to provide visual indication of pilot interruptions exceeding 50 microseconds, and (3) to maintain line continuity during replacement of a repeater so that line power need not be turned down. The first two functions do not require taking the repeater out of service.

**The 26A Gain and Delay Measuring Set.** Gain and delay characteristics of group and supergroup facilities in the range of 5 to 600 kHz may be measured with the 26A Gain and Delay Measuring Set. Frequency, received amplitudes, and delay are shown on three meters. Direct current outputs for driving recorders are provided on the front panel. Output impedance of the transmitter and input impedance of the receiver are either 75 ohms unbalanced or 135 ohms balanced, jack-selectable. Transmitter output at the 75-ohm port may be selected from  $-45$  to  $-30$  dBm in 5-dB steps; at the 135-ohm port, transmitter output may be selected from  $-50$  to  $-40$  dBm or from  $-15$  to 0 dBm in 5-dB steps. The sensitivity range of the receiver is from  $-50$  to 0 dBm.

**The KS-20548 Test Sets.** Maintenance tests of FM terminal transmitters and receivers for microwave radio systems may be performed with KS-20548 Test Sets. The sets are available in two versions, one for intermediate frequency (IF) and baseband modes and the other for the baseband mode only. The former version permits input at

either IF or baseband and output at either IF or baseband, regardless of which input is selected. The latter permits measurements in the baseband only. These sets measure amplitude linearity and system group delay. They also provide means of accurately setting the 70-MHz center frequency and adjusting the deviation sensitivity of an FM transmitter. One of the two units that make up each test set generates the test signals and the other one receives and measures test signals.

The unit designed for operation at intermediate or baseband frequencies can measure the attenuation/frequency characteristic of FM terminals on a sweep-frequency basis, compare the center frequency of the terminal passband with an internal crystal-controlled standard, and provide for the deviation sensitivity of the terminal. An IF marker can be supplied by the set for use in an oscilloscope display. Remote monitoring at one end of a radio link is possible and a crystal-controlled signal is provided to facilitate the measurement of noise or spurious signals without using the FM terminal transmitter.

**The 70B Power Meter.** This portable instrument provides the means for measuring signal amplitudes in the frequency range from 0 to 20 MHz on video transmission facilities. The 70B is a nonselective thermocouple device having a 75-ohm unbalanced input and a 124-ohm balanced input. Measuring range is  $-10$  to  $+3$  dB with respect to either a 0 dBm or a 0 dBV reference selected when the set is calibrated. Maximum error in the range  $-1$  to  $+1$  dB is  $\pm 0.1$  dB.

### Test Sets for T1-Carrier Systems

The T-type carrier systems are based on pulse transmission, a mode subject to all of the same forms of distortion that affect analog systems and to impulse noise which usually has no noticeable effect on analog transmission. Test equipment for these systems must be capable of detecting deformations or displacements of pulses that would prevent correct interpretation by receiving equipment. Portable test sets for T1 Digital System lineup and maintenance include a line error detector and an error rate test set. These illustrate the types of test sets used to maintain T-type systems. In most cases, maintenance equipment for digital systems is incorporated within the system.

**Line Error Detector for the T1 System.** A portable Line Error Detector is used for monitoring bipolar signals at repeater points on T1 lines and for determining whether errors exist in those signals. If errors



exist, the set determines whether they originate ahead of the repeater output or result from repeater malfunction due to reflections from the outgoing line.

Access to the line is gained by withdrawing the repeater from its mounting, plugging the detector into the mounting, and mounting the repeater in the detector. Tests may be made with the output line either normal or replaced by a 100-ohm termination. After switches have been set for the desired test conditions, the results are indicated by a lamp which lights, flashes, or remains unlighted.

**The KS-20775 Error Rate Test Set.** This portable instrument counts either logic errors or bipolar violations that occur on a 1.544 Mb/s transmission facility during a selected time period and displays the total on a digital readout. The transmitting section generates a 1,048,575-bit, quasi-random test pattern. For a self-test or for identification of the system under test a fixed number of errors can be inserted into each cycle of the test sequence. Either logic errors or bipolar violations may be selected for the purpose. The receiving section uses two different switch-selected methods for measuring errors. For logic errors, the set compares the incoming data, which originated in the quasi-random word generator of another set, with the output of a similar generator in the receiver, after synchronizing the two bit streams. Each disagreement of the two streams is counted as an error. For bipolar violations, the set monitors the signal to verify that consecutive 1s are alternated in polarity regardless of the presence or absence of intermediate 0s. Each failure of polarity reversal is counted as an error.

## 25-5 DATA SET AND DATA LOOP TEST EQUIPMENT

Analog voiceband circuits are often used to transmit digital data signals. Such circuits are most conveniently evaluated for digital transmission by test instruments specifically designed for that purpose. In addition to circuit evaluation, it is also often necessary to evaluate the performance of data sets used as terminal equipment at the ends of analog data loops.

### The 911NA Data Test Set

A signal source and distortion measuring set for testing data terminal equipment, such as teletypewriters, are provided by the portable 911NA Data Test Set. It uses integrated circuits, light emitting diodes,

diode matrices, and other advanced techniques to provide convenient means for making distortion measurements. A signal source generates either a 5-element or an 8-element code, each with selectable test message lengths. Transmission rates range from 45.5 to 1800 bauds. The set can continuously repeat certain test signals and can generate distortion up to 49 percent in 1 percent steps indicating with lamps the type of distortion. It can show in a two-digit readout the highest distortion for each group of 16 characters, count distortion peaks for threshold values of 5 percent to 40 percent, and count the parity errors received. Self-test by an output-to-input connection is provided to verify correct test set operation.

### The 914C Data Test Set

The operation of voiceband data sets in digital or analog systems may be tested with the 914C Data Test Set. It operates in duplex with either series or parallel data signals. In the transmitting mode, it generates a dotting signal (alternate 1s and 0s), a 63-bit quasi-random word, and a 511-bit quasi-random word conforming to the CCITT standard. The internally-established bit rates range from 150 to 2400 bits per second. With external clock signals, the set is capable of repetition rates of 10 to 20,000 bps. The transmitting circuit generates control signals to condition the data set being tested to the desired operating mode. Interface connections are made by inserting short-circuiting pins in a crosspoint matrix.

In the receiving mode, the 914C compares a received data signal with an internally generated signal and counts errors. An adjustable pulse sampling width permits measuring the distortion in received signals and a loudspeaker permits listening to line signals. Built-in dc and ac voltmeters may be used either bridging or across a 600-ohm termination. Fixed and adjustable reference voltages permit testing of analog systems.

### The 921A Data Test Set

General-purpose serial data test capability for installation and maintenance testing at data stations is provided by the 921A Data Test Set [7]. It also introduces the convenience of luggage-type packaging since it must often be carried to test sites by public transportation. When set up for use, it exposes an 18 x 13 inch panel on which the controls, an alphanumeric display, and connection ports are located.

A microprocessor converts the input to the set into easily-read information, administers overall system control, and sets up required interconnections for the desired measurements when the operator enters the proper two-digit code on a 20-button keyboard. The set makes use of a 32-character alphanumeric display to show processed data and to communicate with the operator. Through its capability of setting up preprogrammed tests and of processing input data, the microprocessor minimizes setup and adjustment time and reduces operator errors. A memory-based controller and plug-in interface modules provide flexibility for adding new test features.

The 921A is used for end-to-end and station-to-serving-test-center tests. Synchronous and nonsynchronous data sets, data service units (DSU), and channel service units (CSU) used in the Digital Data System (DDS) can be tested. It may be used with other data test sets in the 900 series for end-to-end testing.

Plug-in modules are provided to meet a number of interface standards. Interface lead status is monitored and shown by light emitting diodes. Access to 37 interface leads is provided to accommodate existing and planned data sets. A bridging mode can be used for on-line tests. Data rates up to 56 kb/s for synchronous applications and fifteen bit rates for asynchronous applications are available. Operation is either duplex or half-duplex.

With the built-in microprocessor, the 921A test set has been preprogrammed to carry out a number of tests automatically. Steady-state synchronous services may be tested for bit and block error rates and for proper start-up and synchronization functions. Start-stop distortion measurements for 202-type data set operation, parity error measurements, and specially coded message tests may be performed for asynchronous services. Isochronous distortion measurements may be made on DDS circuits and CSUs. In addition, the 921A can perform a number of general purpose tests including tests of its own performance.

### Data Test Sets for the DDS

A transmitter-receiver pair of portable test sets is used to test 64 kb/s signals in the DDS. The KS-20909 Data Test Set provides either balanced bipolar or logic-level signals at the 64 kb/s level. The set produces signals to any of the four data rates offered to the customer: 2.4, 4.8, 9.6, or 56 kb/s. Output data words of either 511 or

2047 bits are provided singly or repeatedly. The set is designed to generate signals toward either an office channel unit (OCU) or a multiplexer. It furnishes discrete control codes to which DSUs and OCUs respond. It can also generate loopback test patterns for those units.

The KS-20908 Digital Test Set is a digital signal receiver designed to monitor signals at the 64 kb/s level. It can perform error tests between a serving test center and loop terminations and can provide loopback at a DSU, an OCU, and a CSU. The receiver demultiplexes signals at any of the DDS substrates and can destuff stuffed signals at any of those rates. It accepts either 511- or 2047-bit test-word lengths of bipolar or logic-level signals. Light emitting diodes display the detected control codes and the byte patterns. The bit-error or block-error count is displayed on a 3-digit readout. The KS-20908 accepts signals originating from KS-20909 or one of several other data test sets after those signals are processed by the digital data system.

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**Telecommunications  
Transmission  
Engineering**

*Section 7*

*Transmission System Integration*

In the previous sections of this volume, circuits, systems, and equipment of various types have been described as elements of the telecommunications facility network. Little attention has been given to the manner in which these elements interact when they are connected together or used in close proximity to one another or to other kinds of facilities. In this section, the limitations on certain types of simultaneous operation are discussed and the way in which systems and circuits are interconnected are described in order to show how the overall facilities network is integrated into a working telecommunications system.

In Chapter 26, system compatibility and coordination are considered. Some systems and circuits do not coordinate well because of interferences induced in one from another. In other cases, coordination is satisfactory and there are few, if any, constraints on their operation over the same or nearby facilities. Where problems exist, there may be methods of mitigating the interference. Some attention is given to these mitigation means.

Chapter 27 shows how systems of different characteristics are interconnected to provide a network that can grow and be rearranged in a flexible and economic manner. Certain aspects of network operation involve the use of equipment that is common to many systems. Outstanding in this respect is the network of equipment and circuits that synchronize the frequencies and repetition rates of most of the analog and digital carrier systems used in the switched message network and in private switched networks. A number of other points of interaction and overlap are also discussed.

## Chapter 26

# System Compatibility and Coordination

The design, application, and simultaneous use of transmission systems and circuits using the same or proximate facilities in such a manner as to prevent excessive cross-coupled interference is often called coordination. The interferences that must be controlled include crosstalk and inductive interference (power hum).

Basically, coordination consists of the understanding and control of interference coupling phenomena. The elements of these phenomena are influence, coupling, and susceptibility. A thorough understanding of these elements requires definitions of (1) signals transmitted in disturbing channels, (2) disturbing channel characteristics, (3) coupling path characteristics, (4) disturbed channel characteristics, and (5) susceptibility of signals in the disturbed channels to the interferences.

Interference problems may be conveniently considered in terms of loop facilities and circuits or trunk facilities and circuits. These two aspects of the interference problem have some common attributes but the predominant use of carrier systems in the trunk plant creates a significantly different environment from that of the loop plant. In the trunk plant, the problems are largely those of determining whether systems of different types coordinate with one another, i.e., whether they are compatible. The increasing use of subscriber line carrier systems is closing the gap between the loop and trunk portions of the plant. Common to both is the interaction with other utilities, especially with power transmission and distribution facilities. Control of interferences from power lines into communications circuits is generally regarded as inductive coordination.

## 26-1 COUPLING CONSIDERATIONS

Coordination and crosstalk coupling are, in reality, the same problem but the two are regarded somewhat differently. When crosstalk coupling is under consideration, specific interfering and impaired channels and signal types are of primary concern as in the case of intelligible crosstalk between voice circuits. When inductive interference is under consideration, a wide variety of interfering and disturbed channels must be considered together with a number of coupling paths. The challenge is to take into consideration all possible combinations and to determine which is limiting. A review of the controlling parameters is desirable in order to visualize them in relation to one another and to show how they may interact under various circumstances [1].

Where interference between transmission systems or circuits is a problem, it is essential that the characteristics of signals that may be carried in the disturbing system or circuit be well-defined. The characteristics of importance are the amplitude, power spectral density, occupied frequency band and the nature of single-frequency components (frequencies, amplitudes, consistency, intermittancy, etc.) of the signal. The statistics of disturbed and disturbing channel occupancy are also significant [2]. All of these parameters are established by the nature of the signals transmitted and by the design of the circuits or systems being used. There is little control that can be exercised in the operating environment except to be sure that design limits imposed on the signals and channels are not exceeded.

The characteristics of the disturbing channel have less effect on coordination problems than transmitted signal characteristics but cannot be ignored. The normal power spectral density of the signal at different points in the channel may be modified significantly by the channel characteristics. The nature of the low- and high-frequency channel cutoff characteristics must also be taken into consideration.

The parameters of the coupling paths between disturbing and disturbed systems and circuits have a major effect on the magnitude of the coordination problem. The transfer function (loss/frequency characteristic) of the coupling path and the disturbing signal magnitude and power spectral density determine the effect of the interference in the disturbed channel.

Finally, the signals and channel characteristics of the disturbed systems or circuits must also be considered in terms of coordination

problems. The susceptibility of these signals to the types of interference introduced and the manner in which the channel may change the characteristics of either signals or interferences or both must be evaluated. Susceptibility of signals varies widely. For example, if the interference has high-amplitude impulse components and the disturbed channel carries digital signals, the signals are more subject to impairment than would be the case with voice signals.

In some cases, interference problems can be solved by imposing limitations on the use of facilities. For example, one type of system produces excessive interference in another type of system when an excessive number of the disturbing systems are carried in the same cable or in the same binder group. Satisfactory operation can be achieved by limiting the number of systems of the disturbing type in the cable or binder group. Physical separation of transmission facilities is sometimes necessary to solve such problems.

## 26-2 COORDINATION IN THE LOOP PLANT

Transmission in the loop plant is primarily on wire-pair cables which have been engineered and installed to satisfy voice transmission and station set signalling requirements. However, many other types of signals are transmitted and carrier techniques are increasingly being used when found to be economical. Each time a new signal type is added or a new type of loop carrier system is made available, coordination of the new service or system with the existing loop plant and the environment within which it is to operate must be considered carefully; i.e., loop plant signal spectra must be carefully controlled.

In many locations, loops and trunks are intermixed. Thus, particularly where carrier techniques are employed, more combinations of systems and/or circuits may coexist. Furthermore, pole line and underground facilities are shared by communications and power distribution circuits to a greater extent in the loop plant than in the trunk plant. As a result, intercompany coordination of these situations is more intensive in the loop plant.

### Inductive Coordination

The problems of inductive interference are classified as those of *influence*, *coupling*, and *susceptibility*. These problems all relate to the introduction of interference in communications channels from power circuits. A number of techniques are used to control interfer-



ences. These include the careful balancing and shielding of communications circuits to reduce susceptibility, the physical separation of power and communications circuits to reduce coupling, and the transposition and load balancing of power line conductors to reduce influence. Generally, the transposition of power line conductors is undertaken only as a last resort.

In some cases, apparatus and equipment may be added to circuits to reduce power line induction. Four classes of mitigation are possible: (1) reduction of longitudinal current, (2) reduction of longitudinal voltage, (3) reduction of longitudinal voltage and current, and (4) reduction of susceptibility. In all cases, care must be taken to ensure that such action does not introduce new transmission problems while solving the initial problem of hum.

The susceptibility of individual circuits to inductive interferences is greatly enhanced when terminations are not well balanced. Thus, an effective and more permanent form of interference reduction is the improvement of circuit balance where required. Such improvements may be effected on party lines and coin lines by the application of new technology and the use of modern circuit components especially designed to achieve balanced circuits.

The performance of individual voice-frequency circuits that exhibit an excessive amount of power interference can sometimes be improved by the use of longitudinal choke coils. These devices, inserted in series with the line to increase the longitudinal impedance of the line at interference frequencies, present a low metallic impedance to the desired signals. The impedance increase has the effect of reducing longitudinal currents that comprise the interference. At frequencies as low as 60 Hz, this method is difficult to apply. Resonance of the inductor and the capacitance to ground may exist and cause an increase in longitudinal current. The choke coil can also have an adverse effect on the transmission of 20-Hz ringing current on party lines. However, in some cases, choke coils can be advantageously used; each case must be analyzed separately. Usually this form of treatment is practical on only a small percentage of cable pairs.

Another method of reducing longitudinal currents is by the use of neutralizing transformers. These are, in effect, another form of longitudinal choke. A neutralizing transformer is constructed by winding a telephone cable, sometimes several hundred feet long, on a ferromagnetic core. The cable may consist of 6 to 50 pairs one or two of

which may be designated as the "primary winding." The pairs of this primary winding are connected in parallel and grounded at both ends. Longitudinal current induced in the primary winding is coupled into the "secondary windings." The coupled voltages and the voltages of induced currents in the secondary windings are oppositely phased and cancel. Substantial improvement can be realized but there are major limitations. As a result, the use of such transformers is recommended only as a temporary solution until coordination efforts to satisfactorily reduce influence are completed.

Longitudinal currents may be eliminated as sources of interference by the use of isolation transformers. However, dc continuity is interrupted and this method cannot be used where dc transmission is required for transmitter current or for signalling. Even where it can operate satisfactorily, such as on carrier circuits, testing and maintenance problems may be introduced.

Longitudinal voltages can sometimes be controlled by the use of a well-balanced two-winding coil, called a drainage reactor, with a high mutual inductance between windings. The two windings are connected in series across the line and the center tap is grounded. The windings are polarized so that equal and opposite currents cause cancellation of the longitudinal inductance. The windings provide a low-impedance path from each side of the line to ground. The effect of the shunt impedance is minimized because of the series-aiding inductance across the line. Well-balanced capacitors are frequently used in series with each winding to prevent the completion of a dc path across the line. As with other forms of line-by-line control of induced interference, drainage reactors have limitations and can be used only with great care.

### Transmission Level Point Coordination

Voice-frequency circuits that provide similar services coordinate best when they are laid out in such a manner that transmission level points (TLP) have equal values at the same physical points along the common route. When this is done, crosstalk effects are minimized because there is no high TLP producing crosstalk by coupling into a low TLP of another circuit. Such an ideal layout is often not achievable. Different directions of transmission sometimes result in different TLPs at the same point in a two-wire circuit and at highly correlated points in a four-wire circuit. Furthermore, the signal amplitudes at

a given TLP may vary considerably according to the type of signal transmitted. Nevertheless, crosstalk can best be controlled by making the TLPs in different circuits as much alike as possible.

In the design and development of broadband carrier systems, the coordination of TLPs across the system frequency band is an important consideration in achieving satisfactory system signal-to-noise performance. This is a complex problem that involves many system parameters including the types of signals transmitted, the design of repeaters, the attenuation/frequency and delay/frequency characteristics of the medium and repeaters, and the nature and amount of feedback in the repeaters.

In all cases, signal amplitudes in disturbed and disturbing circuits at the point of coupling determine to a large extent the seriousness of any coordination problems. If the circuits involved are message network or voiceband special services circuits and if the coupling characteristics are known, the TLP concept is useful in establishing coordination relationships. Where grossly unlike signals are involved, other criteria must be used to judge the interactions that may exist.

### Data Loops

Loops must be provided for the transmission of voiceband, group-band or supergroup-band data and for the various customer data speeds (2.4, 4.8, 9.6, or 50 kb/s) in the Digital Data System. It has been found that data loops for these services coordinate satisfactorily with each other, with voiceband circuits, and with the T- or N-type carrier systems some of which are found in the loop plant. However, these data signals may cause excessive interference in wideband program circuits. When such a difficulty is encountered, it is considered as a special coordination problem to be resolved by the application of an engineering solution. The disturbing signal amplitude may have to be reduced, coupling losses increased, or disturbed circuit signal amplitude increased. In some cases, it may be necessary to reassign service to different cable pairs.

### Loop Carrier Systems

Loop transmission needs are being served increasingly by digital and analog carrier systems. Coordination problems have been studied extensively and such systems have been found to coordinate satisfactorily in loop cables provided certain restrictions are observed. Any number of analog loop carrier lines may be used with up to five

T1-type lines in 6-, 11-, 16-, and 25-pair PIC cables and in 8-, 9-, 12-, 13-, and 25-pair binder units of larger PIC cables. For different binder units in PIC cables and in all types of PULP-insulated cable, there are no interference constraints and standard engineering rules apply.

### 26-3 COORDINATION IN THE TRUNK PLANT

As previously mentioned, coordination problems are basically crosstalk between carrier systems, between large numbers of circuits carried in the same or nearby facilities, or between combinations of such systems and circuits. In addition, there are a number of intrasystem phenomena that may be regarded as coordination problems that, in general, must be solved during the design and development of each system type. These include TLP and frequency coordination so that intrasystem interferences are held within acceptable limits.

Among the factors that must be examined in intersystem coordination are frequency allocations, modulation methods, application of companders, and system regulation methods. Multiplex equipment for all analog carrier systems utilizes single or double sideband amplitude modulation. Carriers are placed at multiples of 4-kHz (or 8-kHz in double sideband systems) so that crosstalk interference tends to be intelligible unless the interfering sideband is inverted in frequency. The frequency inversion depends on details of modulation processes and the use of single sideband versus double sideband processing. If the interfering signal is offset in frequency, the interference is less disturbing than if the overlap is exact. These factors and the use of companders in either or both of the systems involved must be examined carefully in considering intra- and intersystem coordination.

Most analog carrier systems are regulated by holding the transmitted signal power constant or by the transmission of single-frequency pilot signals that are used to control gain regulators. Intersystem or intrasystem crosstalk may produce interference in the passband of the regulator to cause fluctuations or constant errors in the regulation system.

#### Short-Haul Carrier Systems

The short-haul systems most commonly used are the N- and T-types. These systems must be considered from the point of view of their coordination with each other, with systems of similar types, and with

video and wideband data transmission facilities. Some problems of coordination have grown out of methods of cable plant administration; engineering rules have been written in some cases to account for those methods of administration.

Generally, any type of interference in a digital transmission system results in a deterioration of the error rate. This may result in excessive errors in data transmission, an increase in noise in PCM speech transmission, or, when framing is affected, a temporary loss of service. Interference from one analog system into another is most likely to be evidenced by intelligible crosstalk; interference from a digital system to an analog system is most likely to result in excessive noise in the disturbed circuits.

In the past, rules had to cover coordination of a number of carrier systems now obsolete, such as the C-, H-, J-, and K-type systems. These rules still apply but there are so few of these systems still in service that discussion here of these problems is not warranted.

**The N-Type Carrier Systems.** When early N-type carrier systems were installed, cable splicing methods, called random splicing, were such that the integrity of the binder groups was not maintained. As a result, most of these cables have limited usefulness for the application of T1 Digital Systems and essentially do not coordinate when both N- and T-type systems are required. The interference of T-type signals into N-type systems is excessive. As a result, the two systems are seldom used simultaneously in any cable even where the cables have been spliced with binder group integrity maintained.

Some wideband data signals also coordinate poorly with N-type systems. However, in cables where binder group integrity is maintained, wideband data and N-type systems may be operated simultaneously provided the systems are segregated in separate binder groups.

**The T-Type Digital Systems.** Coordination of T-type systems is primarily a problem of meeting crosstalk requirements between combinations of T-type systems. For the most part, the T-type systems do not coordinate well with other systems or circuits such as the N-type systems, program circuits, and wideband data circuits. Such circuits should be segregated as much as possible from T-type systems. Where alternate facilities are not available, special engineering is usually necessary to make transmission satisfactory.

Engineering rules specify the manner in which T-type systems may be assigned pairs in cables. The rules vary according to type of system, type of cable and apparatus case, mode of operation (i.e., one-cable or two-cable), and other parameters. These rules are designed to permit a maximum number of systems to be assigned to a cable within the constraints of crosstalk and other interference criteria.

**Central Office Cabling.** In many cases, the routing of cables through central offices is carefully specified in such a manner as to control crosstalk between systems and circuits. Separate cables are specified for different types of systems and circuits and, in many cases, spacing between cables is specified as well. Sometimes the spacing specified causes cables to be run in different cable ducts or racks or to be routed in different ways through an office.

### Frequency Coordination

Intrasystem and intersystem interferences can sometimes be reduced or eliminated by proper selection of carrier frequencies, channel bandwidths, and channel placements in the spectrum. In allocating frequencies during the design and development of a new analog carrier system, guard bands must be provided between channels so that the channel signals can be separated by the use of realizable filters having finite cutoff characteristics. Often, the allocation process can be carried out so that undesirable interferences are made to fall into these guard bands. Also, these frequency bands are sometimes provided for the transmission of special-purpose signals such as regulating pilots or protection switching signals.

An analogous situation exists in the design and development of a digital transmission system. In this case, time slots must be provided in the digital pulse stream so that special-purpose signals may be transmitted. Functions that are provided include framing, synchronization, error detection and correction, and maintenance and alarm indications. This analogy does not apply in any comparison of interference effects.

The engineering of microwave radio systems and routes always involves careful consideration of frequency coordination problems. In the design of such systems, frequency allocations and the achievability of appropriate band-edge cutoff characteristics must optimize per-

formance within the system and, simultaneously, must satisfy the Rules and Regulations of the Federal Communications Commission regarding channel assignments and frequency stability.

The layout of radio system routes must satisfy intersystem requirements. Consideration must also be given to intersystem interferences between Bell System radio routes as well as to interferences between Bell System and other common carrier routes using the same or similar microwave frequencies.

Such coordination problems tend to be trivial where potential interference is between two systems using widely different frequency bands but become most significant where the same frequency bands are involved. Such problems have been multiplied since satellite systems have come into service because they use the 4- and 6-GHz bands predominantly. Interferences between satellite and terrestrial systems must be avoided. The problems become more complex because of the wide areas covered by microwave beams in satellite systems.

#### REFERENCES

1. American Telephone and Telegraph Company. *Telecommunications Transmission Engineering*, Volume 1, Second Edition (Winston-Salem, N. C.: Western Electric Company, Inc., 1977), Chapter 17.
2. American Telephone and Telegraph Company. *Telecommunications Transmission Engineering*, Volume 1, Second Edition (Winston-Salem, N. C.: Western Electric Company, Inc., 1977), Chapters 12-16.

## Chapter 27

# Common System Facilities

In order to function as an integrated network, the many different types of transmission systems, with the different circuits and media, must be capable of being flexibly interconnected. Each network element must operate compatibly with all the others in order to provide a full range of communications services economically and with satisfactory performance. The requirement for interconnection and compatibility makes necessary the availability of many special equipment units and creates a need for a number of circuit and equipment designs common to a number of systems.

Among the most important features of the network in respect to interconnection and compatibility are the hierarchical structures of the analog and digital portions of the multiplex arrangements. The resulting relationships among frequency bands in the analog equipment and among repetition rates in the digital equipment make possible relatively simple and straightforward translation between multiplex levels, provide standard interfaces, and facilitate maintenance and administration.

In addition to the need for interconnection, there are a number of ways in which systems tie together through the use of common equipment. In this category of equipment, the most significant is the signal generation and distribution facilities used to synchronize analog and digital system operations. Of nearly equal importance is the equipment provided for emergency restoration of service that may be required in the event of major route failure.



## 27-1 CIRCUIT AND SYSTEM INTERCONNECTION

Interconnections between various parts of the facility network may take place directly, where full compatibility exists, or through appropriate interface equipment that may modify signals only slightly or may produce significant transformations from one format to another. The various types of interconnection equipment may be grouped conveniently in categories that relate them to the frequency bands or to the types of carrier systems involved. There are interconnections of voice-frequency circuits, of group, supergroup, and mastergroup channels of the frequency division multiplex hierarchy, of digital channels transmitting signals at defined repetition rates, and of some mixed digital-analog channels.

### Voice-Frequency Interconnections

Since the largest number of circuits in the telecommunications plant are voice-frequency (VF), the largest number of interconnections must also be made at VF. These include VF-to-VF connections and connections between VF circuits and the channel banks of analog or digital carrier systems. In addition, interconnection points must provide signalling compatibility and adequate maintenance access to each circuit.

**Switching Systems.** Voice-frequency circuits are interconnected flexibly and frequently by the many types of switching systems most of which are organized in public or private switched networks or provide Business Communications Systems in the form of PBXs and key telephone sets. These interconnections are made in switching networks according to the needs of the users as indicated by address signals generated by dial or TOUCH-TONE pad operations and extended through the networks by a variety of signalling systems.

**Distributing Frames.** There are many types of distributing frames. Most are arranged with cable pairs connected to terminals organized in vertical rows on one side of the frame and in horizontal rows on the other. Connections are made between appropriate pairs of terminals by means of jumper wires between the vertical and horizontal sides of the frame.

The most common and most important of these frames is the main distributing frame (MDF). Trunk or loop cable pairs are terminated on the vertical side of the MDF and equipment cables are terminated

on the horizontal side. The distant ends of the equipment cables are connected to line or trunk circuits at switching machines or to other types of equipment used in the central office. Jumper wires, called cross connections, are used to connect a specific loop or trunk to the assigned switching machine termination or other type of equipment.

Interconnections can be made at the MDF with nearly as much flexibility as those made by switching machines. However, the operations are extremely slow, by comparison, and the connections are semipermanent. Although many of these connections are soldered, most are made by wire-wrapping techniques or by high pressure causing the terminal device to cut through the insulation of the cross-connect wires.

**Voice-Frequency Patch Bays.** Mounting arrangements are provided for large numbers of jacks that may be used for test access or for patch-cord connections between voice-frequency circuits. Loops, trunks, and special services circuits may be connected to such patch bay facilities by cross-connection at the MDF. Some of these patch bay arrangements are of standard design but there is a great deal of flexibility in the manner in which jack terminations and circuits are associated. The patch cord method provides great flexibility in the manner in which circuits may be interconnected.

**Facility Terminals.** All the features required to terminate a transmission circuit are consolidated in a facility terminal [1]. Plug-in units which provide the needed transmission and signalling functions are mounted in standard shelf or bay arrangements. In addition to providing these functions for circuits operating exclusively at voice-frequencies, facility terminal designs provide interface functions between voice-frequency and analog or digital carrier systems. Thus, they may be regarded as another type of equipment designed for interconnecting voice-frequency loops, trunks, and special services circuits.

### Analog Carrier Systems

The principal analog carrier systems currently in service include the N-family (utilizing wire cable pairs), the L-family (designed for operation over coaxial cables), and microwave radio systems. The N-type systems utilize multiplexing equipment designed specifically for them. All of the other systems utilize equipment based on the

group, supergroup, and mastergroup frequency assignments of the frequency division multiplex (FDM) hierarchy.

In order to satisfy service requirements along major coaxial cable and microwave radio routes, blocks of channels must be dropped, blocked, and added in many combinations. These functions, collectively called branching, are fulfilled by various combinations of filters which pass or suppress those portions of the spectrum involved.

Where transmission systems are interconnected, the signals of all circuits of one system could be demultiplexed to voice frequency and then reassembled for transmission over the other route or system. Such interconnections are sometimes necessary especially for special services circuits. However, they are unacceptably complex and expensive in many situations. Thus, connecting arrangements are provided at group, supergroup, and mastergroup levels of the hierarchy in the form of equipment units called connectors. Another unit, called the N3-to-L junction, allows interconnections to be made between N3 systems and the group band of the FDM hierarchy.

Interconnection of the communications networks of the Bell System and foreign countries is accomplished to a large extent by undersea cable systems. At points where these systems terminate in North America, a number of interface and interconnection problems must be resolved at the terminating stations.

**Branching.** Broadband transmission systems, especially those that carry long-haul circuits, must be equipped with facilities that permit dropping, blocking, and adding circuits in a flexible manner along the route. These branching functions can be fulfilled by using multiplex equipment and the various types of connectors but, for very large systems, they can be realized more economically by the use of various combinations of high-pass and low-pass filters. Branching arrangements of this type are accomplished primarily at the mastergroup and multimastergroup levels in the FDM hierarchy.

The most comprehensive mastergroup branching arrangements are those developed for the 6-mastergroup L4 Coaxial System [2]. In L4, any combination of contiguous mastergroups may be blocked or passed by the application of appropriate combinations of high-pass and low-pass branching filters. These are used at main stations where multiplex equipment may be conveniently located to complete the addition

and/or deletion of mastergroups from the high-frequency line. These arrangements also include facilities for blocking, inserting, or passing line pilot signals as required.

Similar arrangements have been designed for jumbogroup signal administration in an L5 Coaxial System [3]. These facilities may be combined with L4 mastergroup branching filters to provide flexible mastergroup arrangements for L5 systems. The L4 filters are also used for branching in some long-haul microwave radio systems.

**Connectors.** Blocks of 12, 60, and 600 channels, corresponding to the group, supergroup, and mastergroup levels of the FDM hierarchy, are conveniently administered in providing trunks and special services circuits between communities of different sizes and different traffic flow patterns. Such administrative flexibility is provided by the use of connectors which permit various kinds of system interconnection in an efficient and economic manner.

*Group Connectors.* The principal function of a connector is to provide an undistorted passband for the desired signal and to provide high attenuation to all signals outside the passband. A typical loss characteristic of a group connector is shown in Figure 27-1. Note that the inband (60 to 108 kHz) transmission characteristic is flat within  $\pm 0.2$  dB and that out-of-band signals are attenuated relative to the passband by at least 85 dB. A separate connector must be used for each direction of transmission.

In some applications, group connectors must also fulfill a number of optional functions that depend on the signals to be transmitted and on the requirements for the particular application. These include adjustment of transmission loss or gain to achieve the required transmission level points, equalization of delay distortion caused by the sharp filter cutoff characteristics, and the suppression (or nonsuppression) of pilot signals associated with the channel group. In some cases, these optional features are built into the group connectors; in other cases, the options are provided by ancillary equipment connected in tandem with the connector. Among older systems, group connectors have been used to interconnect group bands of J- and K-type systems as well as the more modern L-multiplex equipment.

Group connectors cannot be used indiscriminately. If delay equalization is not provided, the inband delay distortion is excessive and

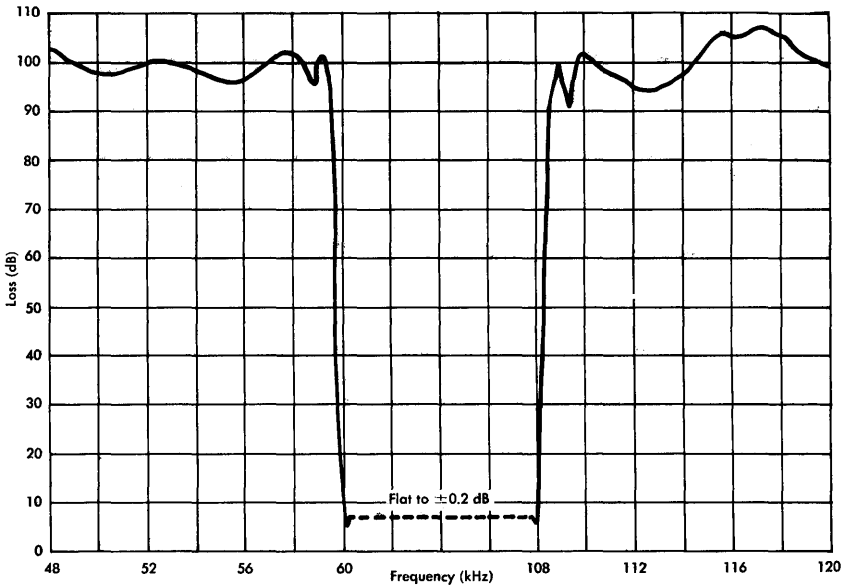


Figure 27-1. Typical group connector loss characteristic.

wideband data signals cannot be transmitted. Even with gain and delay equalization, accumulated distortion imposes a limit on the number of connectors that may be used in tandem.

*Supergroup Connectors.* The principal function of these connectors is to pass signals in the band from 312 to 552 kHz (five 12-channel groups) with minimum distortion and to suppress all signals outside that band. The 60-channel supergroup is often convenient to administer as a single block between remote metropolitan areas. Thus, many system interconnections are made by means of supergroup connectors. Figure 27-2 illustrates a typical supergroup connector loss characteristic.

The passband is flat to  $\pm 0.2$  dB and all signals at frequencies outside the band are attenuated by at least 90 dB. Special precautions were taken in the design to suppress signal energy at 308 and 556 kHz to make these frequencies suitable for pilot signal transmission. A separate connector must be used for each direction of transmission.

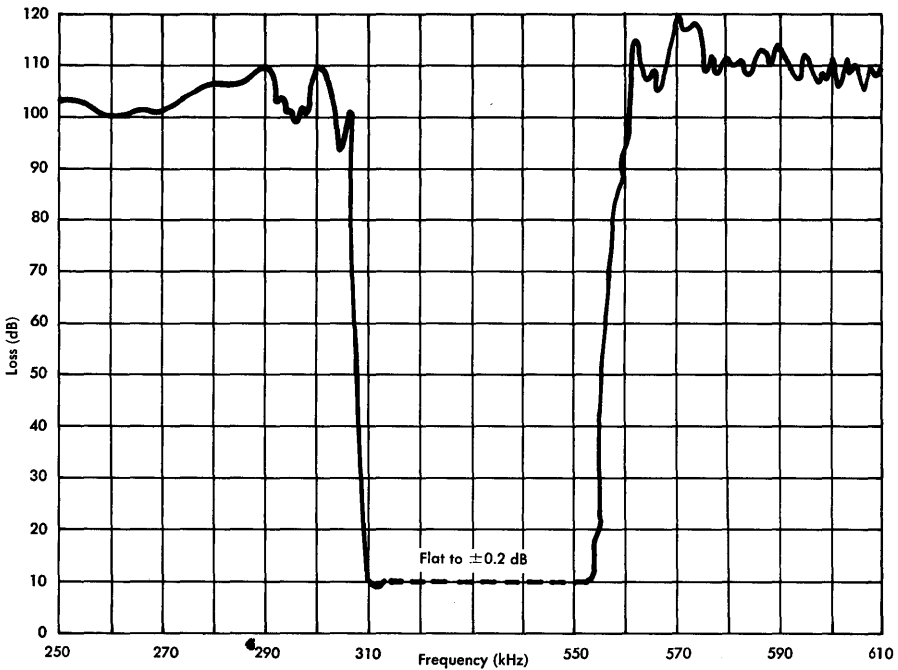


Figure 27-2. Typical supergroup connector loss characteristic.

An optional delay equalizer is available for wideband data transmission. The supergroup connector also contains an adjustable equalizer to compensate the dominant attenuation/frequency distortion characteristic of the previous supergroup section; as many as four connectors may be operated in tandem.

*Mastergroup Connectors.* The provision of interconnecting capability for analog mastergroup bands (600 channels) is made complex because of the necessity for interconnecting various combinations of mastergroup translator (MGT) and mastergroup multiplex (MMX-1 and MMX-2) equipment. As a result, there are four different types of mastergroup connectors. One is used to connect MMX-1 to MMX-1 equipment; one connects MMX-2 to MMX-2; one interconnects MMX-1 and MMX-2 multiplex units. The fourth is a passive connector (no gain elements) that is used in certain situations to interconnect MGT and MMX or other MGT units.

In all cases, the basic function of the connector is to pass all frequencies between 564 and 3084 kHz and to suppress signals at all frequencies outside that band. Equalizers are provided to correct deviations in the attenuation/frequency characteristic caused by the bandpass filter and by office cables used for connections between the connectors and the mastergroup multiplex equipment. Other features and functions vary from connector type to connector type.

The unit used for MMX-1 to MMX-1 connections provides a one-way transmission path for the mastergroup band. Thus, two connectors must be used at each interconnection point. Where necessary, narrow band-elimination filters may be installed in the connector to suppress pilot signals; the frequencies of these signals vary with the type of system involved. Optional connections are also provided so that, where needed, a supergroup connector can be used in parallel to pass the low-end combined spectrum of one supergroup and one mastergroup in L3 coaxial or TH-1 microwave radio system interconnection. Adjustable gain is available to help establish the proper transmission level points. A parallel output port facilitates external connections that may be required for surveillance or broadband restoration access.

The unit normally used to interconnect MMX-2 mastergroups is a two-way connector that provides adjustable gain in order to achieve the proper transmission level points. It includes narrow band-elimination filters to suppress the 2840-kHz mastergroup pilots in the two directions of transmission. Where required, such pilots must be reinserted for use in the circuit after the connector. Jacks are provided at the input and output in each direction of transmission to permit a spare connector to be temporarily connected in the circuit when maintenance must be performed on the working unit.

The third type of mastergroup connector, used to interconnect MMX-1 and MMX-2 multiplex units, provides two directions of transmission in one unit. In one direction, a receiving MMX-1 multiplex unit is connected to a transmitting MMX-2 unit and in the other direction, a receiving MMX-2 unit is connected to a transmitting MMX-1 unit. Narrow band-elimination filters are used optionally to suppress unwanted pilot signals in the two directions of transmission. Each path contains an adjustable attenuator and amplifier used to establish desired transmission level points. Although maintenance jacks are provided in regular working connectors, they are not pro-

vided in connectors of this type used for connections to a restoration patch bay.

The passive mastergroup connector permits two-way interconnection between mastergroup translators, MGT-A and MGT-B, or between these translators and any other mastergroup multiplex facility. The passive connector includes filters to suppress the 2840-kHz mastergroup pilot signals and energy outside the mastergroup pass-band. A variable attenuator is provided to adjust the transmission level point to the desired value.

**The N3-L Junction.** Inherent incompatibilities between N3 and L-multiplex systems must be resolved if these systems are to be interconnected at group frequencies. These incompatibilities are resolved by use of the N3-L junction, a transmission arrangement that takes into account the differences in group-band frequencies, transmitted carriers versus low-amplitude pilots, and compandored versus non-compandored speech-channel operation. Thus, group-band interconnection is implemented by means which are less expensive and more efficient than if all circuits were demodulated to voicefrequencies for interconnection.

*System Incompatibilities.* The basic group in the L-multiplex hierarchy consists of 12 4-kHz channels in a single-sideband format which occupy the frequency band between 60 and 108 kHz. In addition, a low-amplitude pilot signal is transmitted at 104.08 kHz for use in regulating the gain of the receiving terminal and as an alarm initiator.

The N3 carrier signal consists of two 12-channel groups of single-sideband channels occupying either the band between 36 and 132 kHz or the band between 172 and 268 kHz. Within the N3 terminals, the two groups are derived from 12-channel groups occupying the band from 148 to 196 kHz. In addition, the N-carrier line signal includes 12 high-amplitude single-frequency carrier signals that are used for line regulation, channel regulation, frequency correction, and demodulation at the receiving terminal. If transmitted over facilities using L-type multiplex, these carrier signals could cause overload and interference problems. Thus, they must be attenuated for transmission over the L-equipped facility and then must be enhanced to their proper amplitudes for further transmission over N-type facilities.

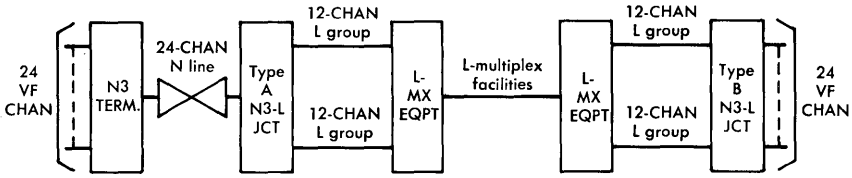


Companders are used in all N-type systems. Thus, the amplitude range of signals in each voice channel is compressed for line transmission and restored to its normal range by expansion at the receiving terminal. The adjustment of transmission level points must be provided in N3-L junction design so that the compressed signals from an N-type system cannot create overload in the system utilizing the L-multiplex. Several varieties of N3-L junctions are provided; the use of each depends on its location in a composite system.

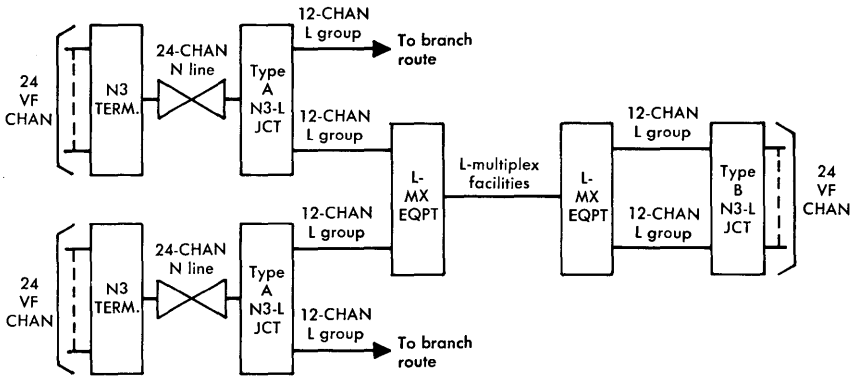
Since some incompatibilities cannot be overcome economically, N3-to-L interconnections cannot be made universally. For example, the N3-L junction cannot be used with group No. 1 of any L-multiplex supergroup. A 152-kHz carrier, used in N3 and partially suppressed for transmission over facilities using L-multiplex equipment, falls at 104 kHz in the L-multiplex group band. When the group band is translated to the group 1 position in the supergroup band, this carrier falls at 316 kHz, only 80 Hz from the 315.92-kHz supergroup pilot. These two signals then cause an intolerable mutual interference problem. For somewhat similar reasons, group No. 2 of certain L-multiplex supergroups cannot be used with N3-L junction arrangements. Care must also be taken in using partially equipped N3-L junction arrangements so that adequate carrier power is supplied for N-carrier line extensions.

*Junction Types.* The N3-L junctions are designated as types A, B, and C. The A-type junction provides a direct translation between N-type line signals and L-type group signals. The B-type junction is used to terminate two 12-channel N3 groups that have been formed into two L-multiplex groups. The line side of this junction is made up of two L-type channel groups and the drop side consists of 24 voice-frequency channels. The C-type junction is an arrangement for terminating one 12-channel group of a composite system and extending the second group over L-type facilities. Typical applications of these three junction types are shown in Figure 27-3.

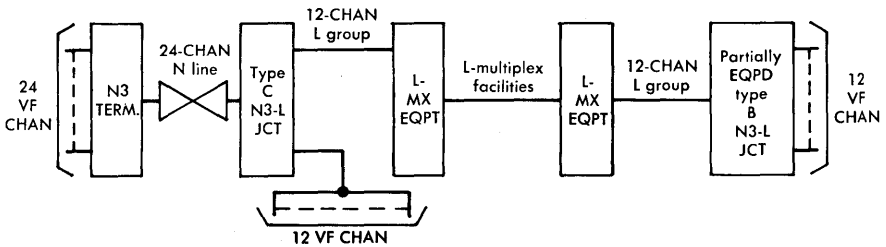
*Junction Functions.* All types of N3-L junctions utilize many standard N3 equipment units and also use many junction units in common. In addition, standard L-multiplex group connectors are used in many of the N3-L interconnection arrangements in order to guarantee the suppression of any out-of-band energy that might produce interferences in the connecting system.



(a) Application of A- and B-type junctions



(b) Alternative application of A- and B-type junctions



(c) Application of B- and C-type junctions

Figure 27-3. Some typical arrangements of N3-L junctions.

In an A-type junction unit, the principal functions are most conveniently described in terms of the two directions of transmission. In transmission from N3 to L, the 24-channel N3 signal is first separated into two 12-channel groups. Standard N3 frequency correction is then applied to each group to correct any shift in frequency that may have occurred in the N-carrier line. These channel-group signals are passed through alarm, squelch, and restoral circuits. The squelch function is provided to prevent overload of the L-type facilities in the event of failure of the N-carrier line. The carrier signals normally present in an N3 signal are attenuated by 15 dB relative to the speech channel signals and the amplitude of the entire group signal is adjusted downward by 8.5 dB to account for the higher average volume in the compressed N3 signals. The two channel-group signals, each occupying the band from 148 to 196 kHz, are finally translated into the 60 to 108 kHz band for transmission over two L-multiplex groups.

In the opposite direction of transmission, inverse processes are carried out. The basic group signals are translated from the 60 to 108 kHz band to the 148 to 196 kHz band. The N3 carrier signals are amplified by 15 dB; these carriers and the sideband signals are then adjusted to the proper N-carrier transmission level points. The two groups are then translated and combined to form an N-carrier line signal.

The B-type junction utilizes N3 terminal equipment, modified to operate on the reduced carrier power, to translate the 24 VF channels to and from the N-carrier operating frequencies. It uses A-type junction equipment to translate two 12-channel N-type groups into two basic L-multiplex groups. The N3 carrier signals are attenuated and, since compandors are used in N3, signal amplitudes are adjusted for use in L-multiplex. Thus, the distant end of the L-multiplex system can be connected to an N-carrier line through an A-type junction as shown in Figure 27-3 (a).

The C-type junction is essentially made up of one-half of a standard N3 terminal and one-half of an A-type junction. This arrangement permits flexibility in interconnecting N3 and L systems as depicted in Figure 27-3 (c).

**Distributing Frames.** The complexities and the dynamic nature of circuit administration have led to the development and use of distributing frames for interconnecting basic groups, supergroups, and

mastergroups. Their use reduces the intervals and costs of engineering and implementing plant additions and changes.

*Group and Supergroup Distributing Frames.* Two vintages of group and supergroup distributing frames (GDF and SGDF) are in use. The older versions consist of terminal blocks (GDF) and panels equipped with individual, miniature, coaxial fittings (SGDF) to which are connected cables from channel banks, group connectors, group banks, supergroup connectors, and other group band and supergroup band equipment. Cross-connection panels may be bay-mounted or contained in a cabinet. The number of circuits that can be accommodated is sometimes limited by the cabling density. The maximum number of one-way cross-connections that can be made is 1260 in the GDF equipment and 500 in the SGDF equipment. The GDF cross-connections are made at the front of the panels with unshielded pairs that are wire-wrapped to the terminals. These arrangements sometimes result in difficulties with circuit identification when changes are to be made, especially in GDFs that are loaded to near capacity. In the SGDF, cross-connections are made with miniature coaxial cable with a snap-on connector at each end.

The new designs of GDF and SGDF, introduced with the LMX-3 multiplex equipment, also consist of individual panels that can be conveniently mounted in cabinets. Cabling density limits the number of circuits that can be accommodated to a maximum of 1000 one-way group cross-connections or 500 supergroup cross-connections. Color coding and alphanumeric designations are used to identify terminals and cross-connections. The GDF cross-connections are made by means of shielded pairs terminated in small connectors that plug into the cross-connect frame sockets. In the SGDF, miniature coaxial cable is used with snap-on connectors. Connector sockets are multiplied in pairs to permit in-service rearrangements. Transmission level points are standardized to permit flexible interconnection of group and supergroup facilities.

*Mastergroup Distributing Frames.* Centralized cross-connect arrangements for basic mastergroup facilities (LMX, MMX, mastergroup translators, mastergroup connectors, and single mastergroup wire-line entrance links) are provided by the mastergroup distributing frame (MGDF). This equipment also provides access for other functions such as basic mastergroup restoration and maintenance by the Carrier Transmission Maintenance System. Cross-connections are

made by means of miniature coaxial cables with standard coaxial plugs at each end. All connecting points are multiplied so that in-service reassignments can be performed. Cable loss and slope equalizers are included for all line-side connections. A separate panel may be used with the cross-connect frame to terminate restoration trunks and other types of restoration equipment. Typically, an MGDF can provide cross-connections for a maximum of 85 one-way mastergroups.

**Undersea Cable System Interconnections.** International communications by undersea cable circuits is administered from a number of *gateway* cities insofar as traffic flow is concerned. These gateways are at Denver, Col., Jacksonville, Fla., New York, N. Y., Oakland, Cal., Pittsburg, Pa., and White Plains, N. Y.

A distinguishing characteristic of undersea cable systems is that they utilize 3-kHz voice channels instead of the 4-kHz channels that are otherwise standard. Facilities carrying a mixture of 3-kHz and 4-kHz channels would produce undesirable intermodulation products and other interferences. Therefore, all undersea cable VF channels are transformed to 4-kHz channels at the first central office location encountered in the United States.

### Digital Systems

Although analog transmission technology has matured and still forms the basis for much of the facility network, digital techniques are being introduced rapidly. As new digital transmission and switching systems are added and as new digital services are introduced, provision must be made for the same type of flexibility and interconnection as are provided in the analog portions of the network. Presently, the principal interconnection elements of the digital network are the multiplex units used to translate signals between the various levels of the hierarchy, the DSX-coded cross-connect frames, and various interface units used for the direct interconnection of digital transmission and switching systems. These types of equipment are all described in Chapter 21.

### Digital-Analog Interfaces

The existence of both analog and digital facilities makes necessary the development of suitable interfaces that permit interconnection of the two types. Most such interfaces occur in voice-frequency channels in the form of D-type channel banks where VF signals are processed

into digital formats for transmission over digital transmission facilities. The reverse processes are used to translate digital signals into the analog format.

The use of digital switching systems such as the No. 101 ESS and the No. 4 ESS also have made it necessary to process analog signals into a digital format so they may be properly switched by time division methods. These and the inverse functions, similar in many respects to those of D-type channel banks, are carried out at the switching machine.

## 27-2 COMMON SYSTEMS EQUIPMENT

The coordination of the numerous analog and digital systems now in service is satisfied in several respects by the use of common equipment and facilities. The most important of these common facilities are those relating to synchronization, pilot signal generation, and restoration.

### Synchronization

The frequencies of control and operating signals (such as pilots and carriers) used in frequency division multiplex equipment must be precise and stable. If they are not, serious transmission impairment may result. For example, an offset in frequency of as little as 2 Hz causes an undesirable distortion of program signals [4]. In some cases, signals might drift out of the passband of a filter and signal components may be significantly attenuated. There is an equally urgent need for accurate and stable timing signals for digital transmission and switching systems.

In the United States, the needs for such accurate frequency and timing signals are filled by the *Bell System Reference Frequency Standard* (BSRFS) and a nationwide network of facilities and equipment called the Bell System Carrier Synchronization Network [5]. In addition to the stringent requirements on accuracy and stability, the BSRFS and the distribution network must be highly reliable.

**Carrier Synchronization Network.** The nationwide distribution of synchronization signals is over a tree-like network with many branching points and with no closed loops. The center of the BSRFS network is located in an underground station on an L5 Coaxial Carrier System route at Hillsboro, Missouri. Coaxial and microwave radio facilities are used to carry reference frequency signals from the BSRFS to

regional synchronization centers scattered conveniently throughout the country. Regional frequency supplies (RFS) are located at the regional centers. The RFSs are highly stable and accurate signal generators that are quasi-frequency locked to the signal received from the BSRFS. The quasi-frequency lock technique provides buffering from incoming hits, for example due to line switching, and thus prevents distribution of hit effects throughout the reference frequency network. The RFSs provide frequencies used directly or indirectly by every central office in the region that requires synchronizing signals for proper operation. These offices are generally equipped with primary frequency supplies (PFS) whose signal frequencies are synchronized to the incoming signal.

Two frequencies are generally used for transmission from the BSRFS to the RFS locations, 2.048 MHz and 20.480 MHz. These frequencies were chosen so that they would fall in guard bands in the commonly-used frequency spectra of broadband analog transmission systems. The 20.48-MHz signal is used for transmission over L5 Coaxial Carrier Systems and the 2.048 MHz signal is transmitted over L1, L3, L4, and L5E Coaxial Carrier Systems and over most microwave systems. A two-frequency synchronizing signal is to be used with the new AR6A Microwave Radio System. Reference frequency signals are to be transmitted at 11.200 and 11.264 MHz. Due to transmission system characteristics, the frequencies of these signals may drift somewhat but it is expected that they drift alike and the difference frequency (originally derived from an RFS signal) is expected to remain constant at 64 kHz.

Regional frequency supplies have output signals at 64 and 512 kHz which are used for distribution of frequency control signals to central offices within the region. These synchronizing signals may be transmitted independently over coaxial or microwave facilities to central offices within the region or they may be used simultaneously as line pilots in the systems over which they are transmitted. Within each region, these signals (or one at 308 kHz) are extended throughout the region for synchronization of the more remote offices.

**Reference and Synchronizing Frequency Signal Generators.** A number of types of signal generators are used in the various locations of the synchronizing network. These are controlled in various ways to serve somewhat different purposes. All signals are controlled to extremely close tolerances and all are made reliable by design and by the provision of automatic protection switching among signal generators.

*Bell System Reference Frequency Standard.* The BSRFS consists of three cesium frequency standards and associated monitoring, alarm, and switching equipment [6]. As shown in Figure 27-4, the A or B cesium standard generates the desired 2.048 and 20.480 MHz signals and supplies them to distribution buses. The C cesium standard is used as a reference source for frequency monitoring circuits. The frequency offset among the three standards is normally less than one part in  $10^{11}$ . The two reference signals are dedicated for reference frequency purposes and must be transmitted without modulation throughout the reference frequency network.

A failure of output power or a frequency offset of more than eight parts in  $10^{11}$  between the in-service (A or B) standard and the idle (A or B) standard or between the in-service standard and the C reference standard causes a switch to the idle standard. A failure of the idle standard or of the C standard causes the switching function to be inhibited until the defective unit is replaced. If a second standard fails while one is already out of service, the BSRFS is automatically disconnected from the reference frequency network since the accuracy of the remaining unit cannot be determined.

*Regional Frequency Supply.* Where regional frequency supply locations are L5 coaxial system main stations, the regional frequency supplies are jumbogroup frequency supplies (JFS) which supply reference frequencies for the jumbogroup multiplex equipment [7]. Where the location is not an L5 main station, a regional frequency supply equivalent to a JFS is used. Distribution within a region is over coaxial cable or microwave radio facilities.

Should the incoming reference signal fail for any reason, the JFS runs free and the RFS continues to supply synchronization signals to that regional network. The frequency stability of the JFS without an input reference signal is such that synchronization signal degradation should not occur for several weeks. Thus, the JFS acts as a buffer to protect the region from phase and other discontinuities.

*Primary Frequency Supplies.* Although there are several vintages of PFS in service, the version commonly used is known as the PFS-2B. This unit operates on the basis of internal 1024-kHz crystal oscillators which are phase-locked to a 64- or 512-kHz synchronizing signal received from the line.



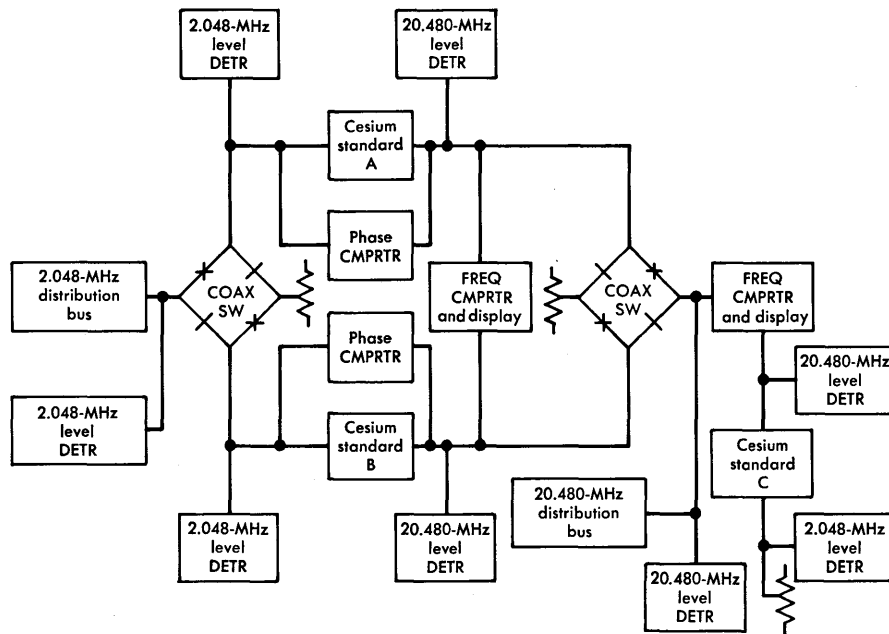


Figure 27-4. Bell System reference frequency standard.

Primary frequency supplies transmit 64-, 308-, and 512-kHz synchronizing signals within a regional synchronizing network. These units may be operated as a master, submaster, or controlled PFS. The master PFSs synchronize submaster PFSs which, in turn, are used to synchronize controlled PFSs. Within a region, no more than four signal regeneration points are used.

Most offices containing PFSs are equipped with redundant units and protection switching arrangements to provide the necessary reliability and to allow maintenance to be performed without affecting service [8].

**Office Master Frequency Supply.** The frequency accuracy requirements of FDM equipment used with the AR6A Microwave Radio System are met by using an office master frequency supply (OMFS). This unit is quasi-frequency locked with an incoming 2.048-MHz reference signal and the frequency offset is normally less than five parts in  $10^{10}$ . As in the JFS, the quasi-frequency lock provides buffering against hits on the incoming reference signal. Output frequencies of the OMFS, 64 and 512 kHz, are derived in redundant generators and distributed over two independent bus systems.

In addition to the synchronization of AR6A FDM carrier and pilot supplies, the OMFS is used as the office reference for all PFSs and for 64- or 512-kHz line pilot supplies in the office. It may also be used in offices without AR6A or JFS/RFS equipment to extend the reference frequency network regionally.

### Pilot and Carrier Supplies

In most systems, pilot and carrier supplies are designed as harmonic generators or crystal-controlled phase-locked oscillators. Designs and applications vary considerably but in most cases the supplies may feed more than one system or more than one piece of equipment to make the system costs as low as possible.

Usually, large numbers of circuits can be affected by carrier or pilot supply failure. Therefore, there is considerable emphasis on reliability; most carrier and pilot supply arrangements include redundancy and some form of automatic protection switching.

In order to achieve benefits of economy and consistency of operation and administration, there has been some effort to utilize the same regulating pilot frequencies in new system designs wherever possible.

Thus, the 64-kHz pilot frequency is used in L1 coaxial systems and in most radio systems. The 308-kHz pilot is used in L3 coaxial systems and in early TH-1 microwave systems. The 2064-kHz and 3096-kHz pilots are used in both L1 and L3 systems. All master-group multiplex arrangements that include regulation utilize a 2840-kHz pilot. In the lower multiplex levels, 104.08 kHz is used as a group pilot; the same frequency is translated to 315.92 kHz to be used as a supergroup regulating pilot.

The 512-kHz synchronizing signal, used in the synchronization network previously described, serves a dual purpose in the L4 Coaxial Carrier System. In addition to providing a synchronizing signal for the multiplex equipment, it provides a regulating pilot for the L4 line. It is also used as a line and synchronization pilot on radio channels carrying 1A-RDS signals.

A unique signal is used to provide continuity information needed in broadband restoration procedures. This signal is transmitted at 560 kHz. It is pulsed on and off at a one-second rate to make it easy to identify. Measuring equipment, used to identify this signal, is also capable of giving a qualitative evaluation of the validity of the restoration path and of the failed path after repair.

### Restoration

Most of the equipment and facilities used to restore service that has been lost due to a major route failure consist of protection lines on other routes that have not been affected by the failure. Restoration procedures involve the use of such facilities by direct interconnection when the failed and restoration facilities are of the same type. Where the facilities are incompatible, the failed systems are often connected to maintenance mastergroup equipment; the signals are demultiplexed and restored mastergroup-by-mastergroup to the extent possible.

To facilitate these procedures a restoration patch bay is generally provided. All working systems and mastergroups are brought into this bay by restoration trunks which are terminated in jacks on the front of the patch bay. Protection lines and maintenance multiplex equipment are also trunked into this bay. The restoration trunks are equalized and proper TLPs are established at the bay. In both protection and working lines, the trunks are wired from dual, parallel jacks at the equipment units. Thus, service is not carried through the patch bay except when restoration patches are established.

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## INDEX

- Absorption, microwave rain, 51
- Access arrangement, data, 141
- Access facilities, data, 134
- Adaptive equalizer, 145, 149, 272
- Adding, channel, 708
- Add-on channel, 81
- Administration
  - line, 339
  - main station, 338
- Aircraft services, 517
- Alarm
  - carrier failure, 651
  - carrier frequency, 254
  - carrier group, 253, 275, 310, 547, 651
  - polling, 343
  - red, 650, 651
  - yellow, 650, 651
- Alternate use panel, LWA-1, 163
- Amplifiers, 227-type, 114
- Analog carrier systems, 4
  - coaxial, 317
  - short-haul, 277
- Analog facility terminal, 121
- Analog interface, data station, 143
- Analog loop-back testing, 151
- Analog transmission system maintenance, 645
- Analyzer, spectrum, 684
- Answering systems, telephone, 205, 218
- Antenna
  - delay loss, 56
  - diversity, 419
  - gain, 48
  - horn-reflector, 53, 55, 356, 447, 472
  - microwave, 53
  - mobile radio, 59
  - parabolic, 53, 54, 356
- Armorless cable, 347
- Artificial cable kit, 682
- Atmosphere, standard, 381
- Attendant facilities, PBX, 214
- Attenuation, rain, 355
- Automatic call distributors, 205, 217
- Automatic Identification of Outward Dialing, 213
- Automatic line build-out circuit, 608
- Automatic line build-out networks, 594, 602
- Auxiliary channel, 462, 468, 470, 472
- Back-to-back coupling loss, 53
- Balance testing, 680
- Banks
  - analog channel, 226
  - digital channel, 569
  - group, 229
  - supergroup, 229
- Baseband entrance link, 365
- Baseband repeaters, 358, 429, 439
- Baseline wander, 535, 544, 564
- Basic group, 6, 224
- Basic jumbogroup, 224
- Basic mastergroup, 224
- Basic repeater, 330
- Basic supergroup, 224
- Battery, 274
  - feed circuit, 189, 210
  - noise, 201
  - voltage, 202
- Beam bending, 381
- BELLBOY service, 512
- Bell System Reference Frequency Standard, 249, 719, 721
- Belltap, 94
- Bifilar winding, 36
- Bipolar violations, 168
- Bit error rate, 139
- Blind switching, 358, 419
- Block error rate, 139
- Blocking, 708
  - earth, 392
- Blue signal, 650
- Branching, 708
- Breakdown, high-voltage, 319
- Breaking, FM, 369
- Break-in, echo suppressor, 128
- Bridge lifter, 78
- Broadband restoration, 323
- Broadcasting satellite service, 478
- Building construction, telephone, 21

- Build-out
  - automatic line, 594, 602
  - capacitor, 38
  - lattice, 38
  - line, 270, 592
- Business communications systems, 204
- Cable
  - armorless, 347
  - coaxial, 44
  - core, 28
  - low-capacitance, 604
  - metropolitan area trunk, 33, 591, 596, 602
  - pair-twist, 35, 43
  - pitch, 35
  - quad-twist, 43
  - screened, 591
  - testing, 656
  - toll, 40
  - unit, 28
- Cable kit, artificial, 682
- Cable laying, undersea, 349
- Cable systems, undersea, 317
- CALL DIRECTOR telephone set, 206
- Call distributors, automatic, 205, 217
- Calling and safety channels, 517
- Call sequencing, 196
- Carrier
  - failure alarm, 646, 651
  - frequency alarm, 254
  - frequency oscillator, 685, 686
  - group alarm, 253, 275, 310, 547, 651
  - spreading, 619
  - supplies, 723
  - synchronization network, 720
- Center, television operating, 199
- Channel
  - add-on, 81
  - capacity, microwave system, 372
  - group, N3 carrier, 312
  - networks, 450, 464, 472
  - service unit, 167
- Channel bank, 226
  - digital, 569
  - pulse trains, 571
- Channel unit, 570
  - office, 169
  - 0-type, 280
- Characteristic impedance, 319
- Choke coils, longitudinal, 698
- Circuit
  - automatic line build-out, 608
  - battery feed, 189, 210
  - coupling, 202
  - junctors, 189, 192
  - line, 184
  - transcontinental, 3
  - trunk, 185
- Coastal harbor service, 516
- Coaxial cable, 44
  - crosstalk, 46
  - unit, 318
- Coaxial carrier systems, 317
  - L5, 326
  - repeater designs, 328
  - system conversion, 325
  - systems engineering, 318
- Codec, 550
- Coding, 530, 536
  - sliding index, 164
  - transition, 164
- Common carrier supply, N3-carrier, 315
- Common control switching system, 181
- Communications for maintenance, 663
- Communications Satellite Corporation, 496
- Communications Systems, Business, 204
- Companding, 526
- Compandors, 267
- Compensator, impedance, 108
- Comsat, 496
- Comstar, 485, 486, 500
- Concentrators, line, 80
- Connectors
  - digroup, 618
  - group, 709
  - mastergroup, 712
  - supergroup, 710
  - trunk, 618
- Constants
  - primary, 32
  - secondary, 32
- Contact noise, 201
- Continuity of service, 356
- Convergence, 387

- Conversion, Coaxial System, 325
- Coordination, 696
  - data loop, 700
  - frequency, 489, 703
  - inductive, 697
  - intersystem, 701
  - transmission level point, 699
- Core, cable, 28
- Corona, 319
- Corrosion, electrolytic, 31
- Counter, impulse, 678
- Coupling, 696, 697
  - circuits, 202
  - ringer, 97
- Coupling loss
  - back-to-back, 53
  - side-to-side, 53
- Crossband diversity switching, 400, 401
- Crossbar switching system, 181
- Cross-connect facilities, N-carrier, 301
- Cross-connect frames, 652
- Cross ring, 94
- Crosstalk, 201, 538
  - coaxial cable, 46
  - coupling, 35
- Customer premises facility terminal, 121
- Data
  - access arrangement, 141
  - access facilities, 134
  - auxiliary set, 141, 155
  - banks, 165
  - communications for maintenance, 664
  - loop coordination, 700
  - loop, wideband, 157
  - modems, 162
  - scrambler, 147, 150
  - service unit, 167
  - service, voiceband, 141
  - System, Digital, 166
  - technical support, 140
  - terminal, N2WT-1, 163
  - test set, 690, 691, 692
  - under voice, 364
- DATA-PHONE data sets, 142
- DATA-PHONE digital service, 166
- Data set
  - 303-type, 154
  - 404-type voiceband, 155
  - DATA-PHONE, 142
  - DATA-PHONE types, 144
  - equalizers, 149
  - holdover option, 146
  - new sync option, 146
  - timing, 149
  - training sequence, 145
  - training interval, 146
- Data signal
  - descrambler, 157
  - processing, 532
  - scrambler, 156
- Data station
  - 303-type, 154
  - analog interface, 143
  - digital interface, 142
  - wideband, 154
- DATEC, 140
- Decoding, 535
- De-emphasis, 365
- Delay distortion, 140
- Delay-lens antenna, 56
- Delay measurement, 670
- Delay measuring set, gain and, 688
- Delta modulation, 532
- Demultiplexing, 535
- Descrambler, data signal, 157
- DESIGN LINE telephone, 93
- Design number, 600, 605
- Detector, 670
  - error, 689
  - selective, 687
- Deviation
  - equalizer, 271
  - shifter, 444
- Dial
  - control, 179
  - long line unit, 75
  - long trunk unit, 75
  - PBXs, 211
- Differential circuit, echo suppressor, 128
- Differential pulse code modulation, 531
- Diffraction, 386
  - knife-edge, 387

- Digital
  - Data System, 166, 613
  - facility terminal, 121
  - interface, data station, 142
  - loop-back testing, 151
  - line signals, 534
  - mastergroup, 550
  - multiplex hierarchy, 525
  - multiplex units, 549
  - service, DATA-PHONE, 166
  - signal characteristics, 564
  - signals, types of, 138
  - system interconnection, 718
  - system maintenance, 547
  - transmission system maintenance, 650
- Digital-analog interface, 719
- Digital channel banks, 569
  - D1, 571
  - D1B, 578
  - D1C, 579
  - D1D, 579
  - D2, 581
  - D3, 583
  - D4, 584
- Digital signal numbers, 549
  - DS1, 552, 567
  - DS1C, 553, 567
  - DS2, 556, 567
  - DS3, 558, 567
  - DS4, 561, 568
- Digroup, 552, 583
  - connector, 618
  - terminals, 198
- Dimension PBX, 212
- Direct formed supergroup, 229
- Direct inward dialing, 213
- Direct outward dialing, 213
- Direct wiring, 179
- Disabler
  - echo suppressor, 132
  - repeater, 109
- Distortion
  - delay, 140
  - pulse, 537
  - telegraph, 138
- Distributing frame
  - group, 233, 717
  - main, 178, 706
- Distributing frame (*cont*)
  - mastergroup, 233, 717
  - supergroup, 233, 717
- Diversity antenna, 419
- Domestic public land mobile service, 504
- Double-spin stabilization, 482
- Downlink transmission, 484, 497
- Downstream, 650
- Drainage reactor, 699
- Dropping, 708
- Ducting, 382
- DUV, 364
- Earth blocking, 392
- Earth station, 478, 495, 498
- Echo, 541
- Echo suppressor, 502
  - break-in, 128
  - differential circuit, 128
  - disabler, 132
  - enabler, 132
  - full, 126, 128
  - sensitivity, 126
  - split, 126
  - types, 129
- Efficiencies, station set, 91
- Elastic store, 565, 613
- Electrolytic corrosion, 31
- Electronic switching system, 182
- Electronic Industries Association, 142
- End section, 40
- Engineering
  - coaxial route, 324
  - coaxial systems, 318
  - microwave system, 371
- Entrance facilities, 362
- Entrance link
  - baseband, 365
  - intermediate frequency, 367
  - switching, 421
  - wire-line, 364
- Envelope delay distortion measurement, 670, 672
- Equalization, 268, 339, 542
  - N1 line, 294
  - N2 line, 300
  - pre- and post-, 274
  - strategy, 272



- Equalization (*cont*)
  - wideband loop, 160
- Equalizer
  - 359-type, 115
  - adaptive, 145, 149, 272
  - adjustment, 647
  - data set, 149
  - deviation, 271
  - fixed, 270
  - tapped delay line, 149
  - variable, 271
- Equalizing repeater, 334
- Equivalent four-wire N-carrier, 302
- Equivalent four-wire transmission, 348
- Equivalent isotropic radiated power, 487, 495
- Error detection, 689
- Error rate, 139
  - bit, 139
  - block, 139
  - test set, 690
- Exchange, private branch, 204, 209
- Express office repeater, 595
- Extended area service, 18
- Extension networks, 4182-type, 119
  
- Facilities, loop, 64
- Facility terminals, 707
  - analog, 121
  - customer premises, 121
  - digital, 121
  - metallic, 120
  - repeater, 121, 124
- Fading
  - frequency-selective, 398
  - microwave, 51
  - multipath, 355
  - selective, 382
- Faraday rotation, 491
- Fault location, 340, 343, 599, 601, 606, 610, 638, 644, 648, 649, 652
- Federal Aviation Administration, 394
- Federal Communications Commission, 393
- Feedback, quantized, 609
- Ferreed switch, 182
- Fixed satellite service, 478
- FM breaking, 369
- FM receiver, 361
- FM system modulation noise, 369
- FM terminal, 444
  - switching, 421
  - test set, 688
  - transmitter, 361
- Forecasting, 19
- Four-wire terminating sets, 118
- Frame, 552, 556, 559, 561
  - cross-connect, 652
  - distributing, 706, 717
  - group distributing, 717
  - main distributing, 178, 706
  - mastergroup distributing, 717
  - radio line terminating, 627
  - supergroup distributing, 717
- Framing, 533, 569
- Free-space loss, 386
- Frequency
  - allocations, microwave system, 371
  - control unit, N3-carrier, 314
  - coordination, 489, 703
  - diversity switching, 357, 397, 399, 415
  - division multiplex, 6, 223
  - plan, 388, 428, 435, 448, 461, 470, 636
  - shift, 140
- Frequency-selective fading, 398
- Frequency standard, reference, 249
- Frequency supplies
  - jumbogroup, 721
  - office master, 723
  - primary, 720, 723
  - regional, 249, 720, 721
- Fresnel zone, 49, 385
- Frogging, 27
- Full-bucking repeater station, 390
- Full echo suppressor, 126, 128
  
- Gain
  - antenna, 48
  - measurement, 670, 672
  - repeater, 259
- Gain and delay measuring set, 688
- Generator
  - spectrum, 684
  - test signal, 670
  - tone, 670
- Geostationary orbit, 477
- Geosynchronous orbit, 477, 484
- Ground return circuit, 3

- Group
  - banks, 229
  - basic, 6, 224
  - connector, 709
  - distributing frame, 233, 717
  - units, 0-type, 283
- Half-bucking repeater station, 390
- Hardening, 318, 323
- Height-loss run, 386
- Heterodyne repeater, 432, 439
- Hierarchy, time division multiplex, 550
- High-capacity mobile telecommunication service, 505
- High-voltage breakdown, 319
- HIL0 switching, 194
- Holdover option, data set, 146
- Horn-reflector antenna, 53, 55, 356, 447, 472
- Hot standby switching, 397, 418
- Hot-tone scan, 653
- Hybrid integrated network devices, 277
- Identification, tip party, 96
- Idle circuit termination, 196
- Idle tone, 508
- IF repeaters, 360
- Impairment, noise, 139
- Impairments, radio system, 355
- Impedance
  - characteristic, 319
  - compensator, 108
  - measurement, 682
- Improved mobile telephone service, 505
- Impulse counter, 678
- Impulse noise, 140, 200, 538
  - measurement, 677
- Induction, power line, 698
- Inductive coordination, 697
- Inductive loading, 3, 36, 43, 45, 65, 103
- Influence, 697
- Interchange, time slot, 198
- Intercom, 206
- Interconnection
  - digital system, 718
  - undersea cable system, 718
  - voice-frequency, 706
- Interface, digital-analog, 719
- Interface unit, voiceband, 198
- Interference
  - intersatellite, 501
  - intersystem, 392
  - intrasystem, 391
  - overreach, 391
  - radio-frequency, 388
- Intermediate frequency, 354
  - entrance link, 367
  - repeaters, 360
- Intermodulation, 261
  - ceiling, 261
  - noise, 261, 265
- International Telecommunication Union, 9, 394
- Intersatellite interference, 501
- Interstitial radio channels, 377
- Interstitial wires, 45
- Intersystem
  - coordination, 701
  - interference, 392
- Intrasystem interference, 391
- Inward dialing, direct, 213
- Isolation
  - ringer, 97
  - transformers, 699
- Isotropic radiated power, equivalent, 487, 495
- Jitter, 140, 545
- Jumbogroup
  - basic, 224
  - frequency supplies, 249, 721
  - multiplex, 241, 327
- Junctions
  - N3-L, 713
  - ON, 305
- Junctor circuit, 189, 192
- Key service units, 208
- Key telephone
  - systems, 204, 206
  - units, 207
- Knife-edge diffraction, 387
- Launch vehicles, 483
- Lead designations, 187
- Level
  - control unit, 686
  - points, transmission, 263
  - tracer, 681
  - video signal, 172

- Lifter, bridge, 78
- Line administration, 339
- Line
  - circuit, 184
  - concentrators, 80
  - connecting equipment, L5, 242
  - maintenance, 339, 598
  - monitor, 598
  - signals, digital, 534
- Line build-out networks, 105, 108, 270, 592
  - automatic, 594, 602
- Line-of-sight microwave transmission, 47
- L-multiplex wideband data equipment, 162
- Load capacity, 260
- Loading, inductive, 3, 36, 43, 45, 65, 103
- LOCAP cable, 604
- Long-haul transmission systems, 6
- Longitudinal choke coils, 698
- Long route design of loops, 68
- Loop, 64
  - facilities, 64
  - long route design of, 68
  - maintenance, 656
  - multiplexer, subscriber, 85
  - repeater, wideband, 158
  - resistance design of, 65
  - unigauge design of, 66
- Loop-back
  - circuits, 643
  - testing, analog, 151
  - testing, digital, 151
- Loop carrier systems
  - multichannel, 84
  - single channel, 82
  - subscriber, 88
  - wideband data, 157
- Loss, 202
  - free-space, 386
  - measurement, 670
  - mobile radio path, 58
  - path, 387
  - return, 202
  - talk through, 207
  - via net, 103
- Low-capacitance cable, 604
- Main distributing frame, 178, 706
- Main station
  - administration, 338
  - repeater, 335
- Maintenance, 275
  - access, 663
  - analog transmission system, 645
  - communications, 663
  - digital system, 547
  - digital transmission system, 650
  - line, 339
  - lines, 598
  - loop, 656
  - preventive, 644
  - span, 601, 605
  - special services circuits, 661
  - trunk, 658
- Manual PBXs, 210
- Marine services, 516
- Maritime service, VHF, 517
- Mastergroup
  - basic, 224
  - connector, 712
  - digital, 550
  - distributing frame, 233, 717
  - L600, 235
  - multiplex, 236
  - translator, 228, 327
  - U600, 236
- MAT cable, 33, 591, 596, 602
- MAYDAY, 517
- Measurement
  - envelope delay, 670, 672
  - gain, 670, 672
  - impedance, 682
  - impulse noise, 677
  - loss, 670
  - noise, 673
  - P/AR, 673
  - return loss, 679
  - structural return loss, 679
  - test signal, 671
  - transmission, 342
- Measuring set
  - gain and delay, 688
  - noise, 675, 676, 677
  - return loss, 679, 680
  - transmission, 670, 672, 684, 685
  - wideband noise, 677

- Metallic facility terminal, 120
- Meter
  - power, 689
  - wideband power, 687
- Metropolitan area trunk cable, 33, 591, 596, 602
- Microwave
  - antennas, 53
  - fading, 51
  - polarization, 53
  - propagation paths, 47
  - radio repeaters, 429, 439
  - radio route selection, 376
  - radio systems, 8
  - rain absorption, 51
  - reflections, 48
  - repeater, 464
  - repeaters, 452, 472
  - system channel capacity, 372
  - system engineering, 371
  - system frequency allocations, 371
  - systems short-haul, 424
  - transmission, line-of-sight, 47
- Milliwatt reference meter, 672
- Milliwatt supply, 671
- Minimum acceptable performance, 141
- Misalignment, 266, 268
  - penalties, 273
- Misframe, 534
- Mobile radio
  - antennas, 59
  - path loss, 58
  - systems, 8
  - transmission, 58
- Mobile satellite service, 478
- Mobile telecommunication service,
  - high-capacity, 505
- Mobile telephone service, improved, 505
- Modems, 162
- Modulation
  - delta, 532
  - differential pulse code, 531
  - noise, FM system, 369
  - phase shift keyed, 147
  - pulse code, 10, 524, 530, 552
- MOLNIYA satellite, 477
- Monitor
  - line, 598
  - violation, 651
- Monitor and remover, violation, 604, 606, 633
- Monitor and restorer, violation, 624, 627, 650
- Muldem, 562
- Multichannel loop carrier systems, 84
- Multimastergroup
  - multiplex, 241
  - translator, 244, 327
- Multipath fading, 355
- Multiple wiring, 179
- Multiplex
  - bandwidth utilization, 247
  - combining and separating, 251
  - common equipment, 248
  - efficiency, 247
  - frequency division, 6, 223
  - jumbogroup, 241, 327
  - mastergroup, 236
  - multimastergroup, 241
  - program terminals, 254
  - reliability, 253
  - signal-to-noise, 252
  - stability, 251
  - synchronization, 249
  - time division, 10
  - transmission response, 251
  - twin channel, 278
  - units, digital, 549
- Multiplex hierarchy
  - digital, 525
  - frequency division, 224
  - time division, 550
- Multiplexing, time division, 533
- National Aeronautics and Space Administration, 483
- National Television System Committee, 12
- Natural slope engineering, 310
- N-carrier
  - cross-connect facilities, 301
  - equivalent four-wire, 302
  - wideband data equipment, 163
- Negative impedance repeater, 105, 136
- Network
  - automatic line build-out, 594, 602
  - carrier synchronization, 720
  - channel, 450, 464, 472
  - line build-out, 105, 108, 592

- Network (*cont*)
  - switched services, 205
  - switching, 179
  - system, 450, 464
  - tandem tie trunk, 205
- Neutralizing transformer, 198
- New sync option, data set, 146
- Noise, 537
  - battery, 201
  - contact, 201
  - floor, 260
  - impairment, 139
  - impulse, 140, 200, 538
  - intermodulation, 261, 265
  - loading, 370
  - objectives, 477
  - quantization, 527
  - random, 140
  - thermal, 260, 265
  - weighting, 675, 676
- Noise measurement, 673
  - impulse, 677
- Noise measuring set, 675, 676, 677
  - wideband, 677
- N-type analog carrier systems, 288
- Number, design, 600, 605
- Objectives
  - noise, 447
  - transmission, 461, 470
- Office
  - channel unit, 169
  - master frequency supplies, 723
  - repeater, express, 595
  - repeaters, 595
- ON junctions, 305
- ON terminals, 305
- Open-wire lines, 27
- Operating centers, 644
- Orbit
  - geostationary, 477
  - geosynchronous, 477, 484
- Order wires, 343, 600, 664
- Oscillator, 670
  - carrier frequency, 685, 686
- O-type
  - analog carrier systems, 278
  - channel units, 280
  - group units, 283
  - line repeaters, 286
- O-type (*cont*)
  - twin channel units, 283
- Outward dialing
  - automatic identification of, 213
  - direct, 213
- Overbuilding, 375, 385, 460
- Overload, 266
  - ceiling, 260
  - margin, 260
- Overreach, 379
  - interference, 391
- Overseas radio, 519
- Pad sockets, 11C, 119
- Pair-twist, cable, 35, 43
- PAN, 517
- P/AR measurement, 673
- Parabolic antenna, 53, 54, 356
- Parameters; pulse, 566
- Party identification, tip, 96
- Patch bay
  - restoration, 724
  - voice-frequency, 707
- Path loss, 387
  - mobile radio, 58
- Path profile, 383
- Path testing, 385
- PBX
  - attendant facilities, 214
  - dial, 211
  - Dimension, 212
  - manual, 210
  - station lines, 209
  - tie trunks, 210
- Performance, minimum acceptable, 141
- Personal paging services, 512
- Personal signalling service, 512
- Phase-progression diagram, 623, 630
- Phase shift keyed modulation, 147
- PICTUREPHONE signal transmission, 13
- Pilot supplies, 723
- Pilot test set, portable, 688
- Pitch, cable, 35
- Polarization
  - microwave, 53
  - signal, 377
- Polar signal, 155
  - restored, 156
- Portable pilot test set, 688

- Power
  - factor, 319
  - feed, 328
  - line induction, 698
  - meter, 689
  - meter, wideband, 687
  - supplies, 274
  - system, 344
- Pre-emphasis, 365
- Pretripping, 95
- Preventive maintenance, 644
- Primary constants, 32
- Primary frequency supplies, 249, 720, 723
- PRINCESS telephone, 93
- Private branch exchange, 204, 209
- Profile path, 383
- Program services, 80
- Program terminals, multiplex, 254
- Progressive control, 179
- Propagation paths, microwave, 47
- Propagation, velocity of 40, 44
- Protection
  - surge, 546
  - switching, 275, 322, 356
  - switching of WLEL, 367
  - switching system, 340, 396
- Public land mobile service, domestic, 504
- Pulse
  - distortion, 537
  - parameters, 566
  - stuffing, 553, 556, 560, 562, 565
  - trains, channel bank, 571
  - transmission systems, 10
- Pulse code modulation, 10, 524, 530, 552
  - differential, 531
- Push-to-talk, 505, 510
  
- Quad-twist, cable, 43
- Quantization, 552
  - noise, 527
- Quantized feedback, 609
- Quantizing, 526
  
- Radiated power, equivalent isotropic, 487, 495
- Radio
  - interstitial, channel, 377
  - line terminating frame, 627
- Radio (*cont*)
  - path testing, 385
  - regular, channel, 377
  - repeater site selection, 377
- Radio-frequency interference, 388
- Radio system
  - engineering, terrain profile studies, 380
  - impairments, 355
  - repeater spacing, 369
  - route layout, 376
  - selection, 374
  - signal-to-noise, 368
- Railroad services, 517
- Rain
  - absorption, microwave, 51
  - attenuation, 355
  - scattering, 355
- Random noise, 140
- Range extender
  - signalling, 75
  - type 2A, 76
  - with gain, 68, 72
- Range extension, ringing, 97
- Reactor, drainage, 699
- Receiver, FM, 361
- Red alarm, 650, 651
- Reference Frequency Standard, Bell System, 249, 719, 721
- Reference meter, milliwatt, 672
- Reflection, 386
- Reflections, microwave, 48
- Reframe time, 569
- Regenerative repeater, 542, 591, 605, 608, 633
- Regenerative repeater, wideband, 158
- Regenerator, 545, 591, 605, 608, 624, 626
- Regional frequency supplies, 249, 720, 721
- Regular radio channels, 377
- Regulating repeater, 272, 331
- Regulation, 272
  - N1 line, 294
  - N2 line, 300
  - wideband loop, 161
- Regulators, 272
- Relay satellite, 481
- Reliability, 275, 322, 323, 338
- Remreed switch, 182

**Repeater**

- baseband, 358, 429, 439
- basic, 330
- designs, coaxial, 328
- disabler, 109
- E6, 105, 123
- E7, 136
- equalizing, 334
- express office, 595
- facility terminal, 121, 124
- gain, 259
- heterodyne, 432, 439
- intermediate-frequency, 360
- main station, 335
- microwave, 452, 464, 472
- microwave radio, 429, 439
- N1 line, 291
- N1A system line, 297
- N2 line, 298
- negative impedance, 105, 136
- office, 595
- options, T1, 596
- 0-type line, 286
- powering, N1 line, 297
- powering, N2 line, 301
- regenerative, 542, 591, 605, 608, 633
- regulating, 272, 331
- replacement, 339
- spacing, 450
- spacing, DR 18A, 636
- spacing, radio system, 369
- spacing rules, 328, 338
- station, full-bucking, 390
- station, half-bucking, 390
- wideband loop, 158
- wideband regenerative, 158
- V4, 111, 124
- Resistance design of loops, 65
- Resistors, 89-type, 119
- Restoration, 323, 724
- Restoration patch bay, 724
- Restored polar signal, 156
- Resupply signal, 624, 650, 651, 652
- Return loss, 38, 43, 202
  - measurement, 679
  - measurement, structural, 679
  - measuring set, 679, 680
  - structural, 36, 43
- Reverse battery supervision, 194

**Right-of-way, 325**

Ring, cross, 94

**Ringer**

- biasing, 96
- coupling, 97
- isolation, 97
- station set, 96

**Ring, 94**

Ringing range extension, 97

Ring tripping, 94

Ring-up circuits, 97

Roam, 511

Roamer, 506

**Route**

- engineering, coaxial, 324
- layout, radio system, 376
- microwave radio, selection, 376
- selection, coaxial, 324

Rural Electrification Administration,  
81, 84

Rural radio service, 505

**Sampling, 526**

Satcom satellite, 485

**Satellite**

- fuel, 483
- launch vehicles, 483
- life, 483
- stabilization, 481
- system design rules, 479
- transponder, 485

**Satellite service**

- broadcasting, 478
- fixed, 478
- mobile, 478

Scattering, rain, 355

Scrambler, 148, 150, 156, 554, 563, 607,  
613, 615, 621

Screened cable, 591

Sealing current, 169

Secondary constants, 32

Section, end, 40

SECURITY, 517

**Selection**

- radio system, 374
- route, 324

Selective detector, 687

Selective fading, 382

- Sensitivity, echo suppressor, 126
- Sequence of switching system operations, 196
- Service bay, wideband, 161
- Service continuity, 356, 398
- Service speed, DDS, 166
- Service unit
  - channel, 167
  - data, 167
- Shielded conductors, 44
- Short-haul
  - analog carrier systems, 277
  - microwave systems, 424
  - transmission systems, 6
- Side tone, 89
- Side-to-side coupling loss, 53
- Signal polarization, 377
- Signal-to-noise, radio system, 368
- Signalling in PCM systems, 532
- Signalling range extender, 75
- Single channel loop carrier systems, 82
- Site selection
  - DR 18A, 636
  - radio repeater, 377
- Sliding index coding, 164
- Solar cells, 483
- SONAD, 510
- Space diversity switching, 357, 397, 418
- Space shuttle, 484
- Spacing, repeater, DR 18A, 636
- Spacing rules, repeater, 328, 338
- Span, 597
  - lines, 597, 601
  - maintenance, 601, 605
- Special services circuit maintenance, 661
- Spectrum analyzer, 684
- Spectrum generator, 684
- Speech-operated voice adjusting device, 510
- Spilling, store, 566
- Split echo suppressor, 126
- Split pairs, 35
- Spreading, 361
  - carrier, 619
- Stabilization
  - double-spin, 482
  - satellite, 481
  - three-axis, 482
- Standard atmosphere, 381
- Station lines, PBX, 209
- Station keeping, 482
- Station set
  - efficiencies, 91
  - ringer, 96
  - telephone, 89
- Step-by-step switching system, 179
- Store, elastic, 565
- Store spilling, 566
- Stored program control switching system, 182
- Stranding factor, 319
- Structural regularity, 37
- Structural return loss, 38, 43
  - measurement, 679
- Stuffing, pulse, 553, 556, 560, 562, 565
- Submastergroup, 231, 236
- Subscriber loop carrier system, 88
- Subscriber loop multiplexer, 85
- Sun transit, 501
- Superframe, 561
- Supergroup
  - banks, 229
  - basic, 224
  - connector, 710
  - direct formed, 229
  - distributing frame, 233, 717
- Supervision, reverse battery, 194
- Suppression
  - hangover time, 127
  - operate time, 127
  - pickup time, 127
- Surge protection, 546
- Surveillance, transmission, 341, 642
- Susceptibility, 697
- Switched services network, 205
- Switched transmission operations, 196
- Switching
  - blind, 358, 419
  - crossband diversity, 400, 401
  - entrance link, 421
  - FM terminal, 421
  - frequency diversity, 357, 397, 399, 415
  - hot standby, 397, 418
  - network, 179
  - protection, 275, 322, 356
  - sequencing, 196
  - space diversity, 357, 397, 418
  - span, 329



- Switching system
  - common control, 181
  - crossbar, 181
  - electronic, 182
  - protection, 340, 396
  - step-by-step, 179
  - stored program control, 182
- Synchronization, 534, 553, 565, 719
  - multiplex, 249
  - network, carrier, 720
- Syncom satellite, 481
- Synchronizer-desynchronizer, 584
- Syndes unit, 584
- System networks, 450, 464
- Systems
  - carrier, 5
  - microwave radio, 8
  - mobile radio, 8
  - pulse transmission, 10
  
- Talk-through loss, 207
- Tandem tie trunk network, 205
- Tapped delay line equalizer, 149
- T-carrier wideband data equipment, 164
- Technical references, 142
- Telegraph distortion, 138
- Telephone
  - answering systems, 205, 218
  - building construction, 21
  - DESIGNLINE, 93
  - PRINCESS, 93
  - station set, 89
  - systems, key, 204, 206
  - TRIMLINE, 93
- Telephotograph signal transmission, 12
- Television
  - facility test position, 199
  - operating center, 13, 199
  - signal transmission, 12
  - System Committee, National, 12
- Telstar satellite, 481
- Terminal
  - digroup, 198
  - facility, 707
  - FM, 444
  - N1, 303
  - Terminal (*cont*)
    - N2, 308
    - N2WT-1, 163
    - N3, 311
    - ON, 305
- Terminating frame, radio line, 627
- Terminating sets, 118
- Termination, idle circuit, 196
- Terrain profile studies, radio system engineering, 380
- Test
  - equipment, 643
  - lines, 643
  - signal generators, 670
  - signal measurement, 671
- Test set
  - data, 690, 691, 692
  - error rate, 690
  - FM terminal, 688
  - portable pilot, 688
- Testing, balance, 680
- Thermal noise, 260, 265
- Three-axis stabilization, 482
- Tie trunks, PBX, 210
- Time Assignment Speech Interpolation System, 267
- Time division multiplex, 10
  - hierarchy, 550
- Time division multiplexing, 533
- Time slot interchange, 198
- Timing, 533, 544
  - data set, 149
- Tip party identification, 96
- Toll cable, 40
  - transmission characteristics, 43
- Tone generator, 670
- Tracking, telemetry and control station, 481
- Traffic Service Position System, 113
- Training interval, data set, 146
- Training sequence, data set, 145
- Transcontinental circuits, 3
- Transformer
  - neutralizing, 698
  - isolation, 699
- Transition coding, 164
- Translator
  - mastergroup, 238, 327
  - multimastergroup, 244, 327

- Transmission
  - characteristics, toll cable, 43
  - equivalent four-wire, 348
  - level point coordination, 699
  - level points, 263
  - measurements, 342
  - measuring set, 670, 684, 685
  - media, 318
  - mobile radio, 58
  - objectives, 461, 470
  - operations, switched, 196
  - plan, wideband loop, 159
  - surveillance, 341, 642
- Transmission systems
  - long-haul, 6
  - short-haul, 6
- Transmitter, FM, 361
- Transponder, 485
- Tribits, 148
- TRIMLINE telephone, 93
- Tripping, ring, 94
- Tropospheric transmission, 518
- Trunk
  - circuit, 185
  - connector, 618
  - maintenance, 658
  - PBX tie, 210
- Twin-channel
  - multiplex, 278
  - units, O-type, 283
- Underbuilding, 375, 385
- Undersea cable
  - laying, 349
  - system, interconnection, 718
  - systems, 317
- Unigauge design of loops, 66
- Unit, cable, 28
- Universal service connection, 215
- Uplink transmission, 484, 495
- Upstream, 650
- Velocity of propagation, 40, 44
- VHF maritime service, 517
- Via net loss, 103
- Video
  - pairs, 44
  - signal level, 172
- Video (*cont*)
  - transmission systems, 170
- Violation monitor, 651
  - and remover, 604, 606, 633
  - and restorer, 624, 627, 650
- VOGAD, 510
- Voiceband data service, 141
- Voiceband data set, 404-type, 155
- Voiceband interface unit, 198
- Voice-frequency interconnection, 706
- Voice-frequency patch bay, 707
- Voice-operated gain adjusting device, 510
- Voltage, battery, 202
- Waveguides, 56
- Weighting, noise, 675, 676
- White Alice, 518
- Wideband
  - data loop, 157
  - data station, 154
  - data terminals, 255
  - loop equalization, 160
  - loop regulation, 161
  - loop repeater, 158
  - loop transmission plan, 159
  - noise measuring set, 677
  - power meter, 687
  - regenerative repeater, 158
  - service bay, 161
- Wideband data equipment
  - L-multiplex, 162
  - N-carrier, 163
  - T-carrier, 164
- Winding, bifilar, 36
- Wired music, 80
- Wire-line entrance link, 364
- Wiring
  - direct, 179
  - multiple, 179
  - plans, 207
- WLEL, 364
- WLEL protection switching, 367
- World Administrative Radio Confer-ences, 9
- Yellow alarm, 650, 651

