Bandpass Sampling (2B)

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Please send corrections (or suggestions) to youngwlim@hotmail.com.

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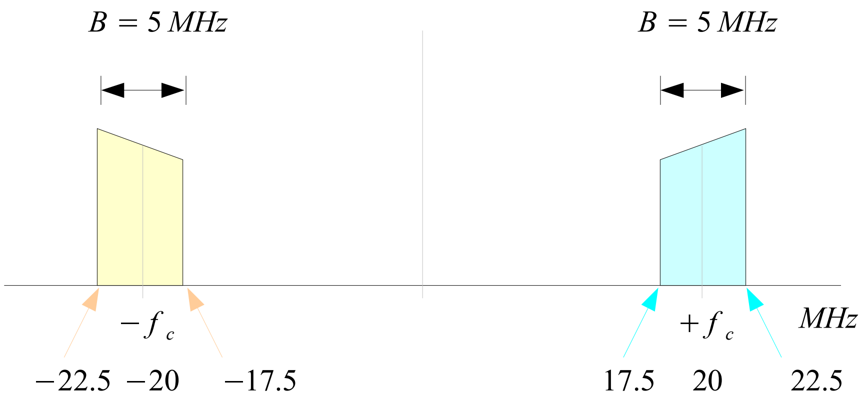
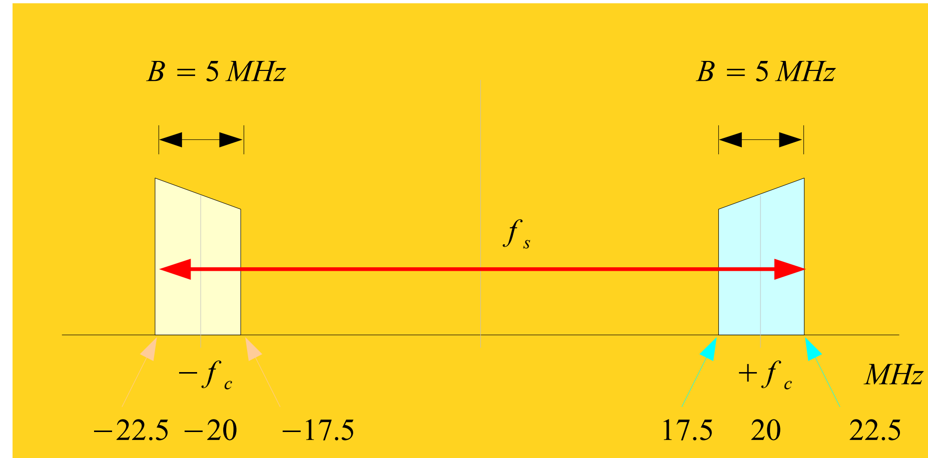
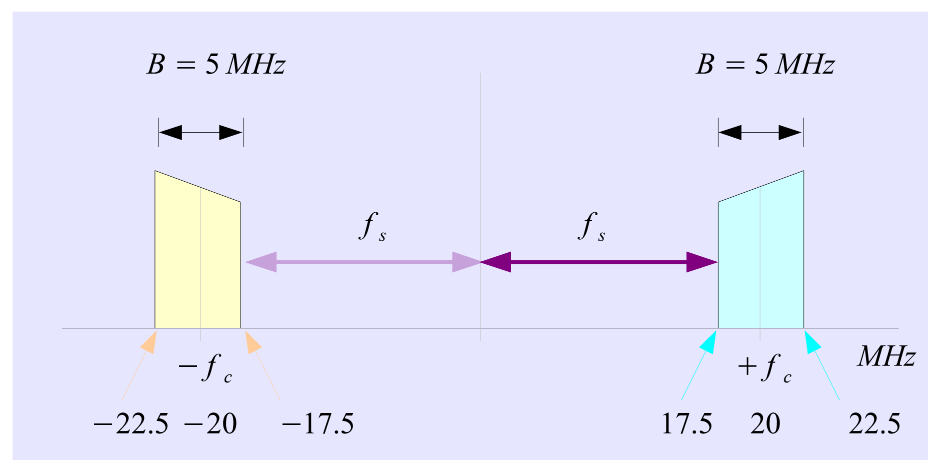
Band-limited Signal



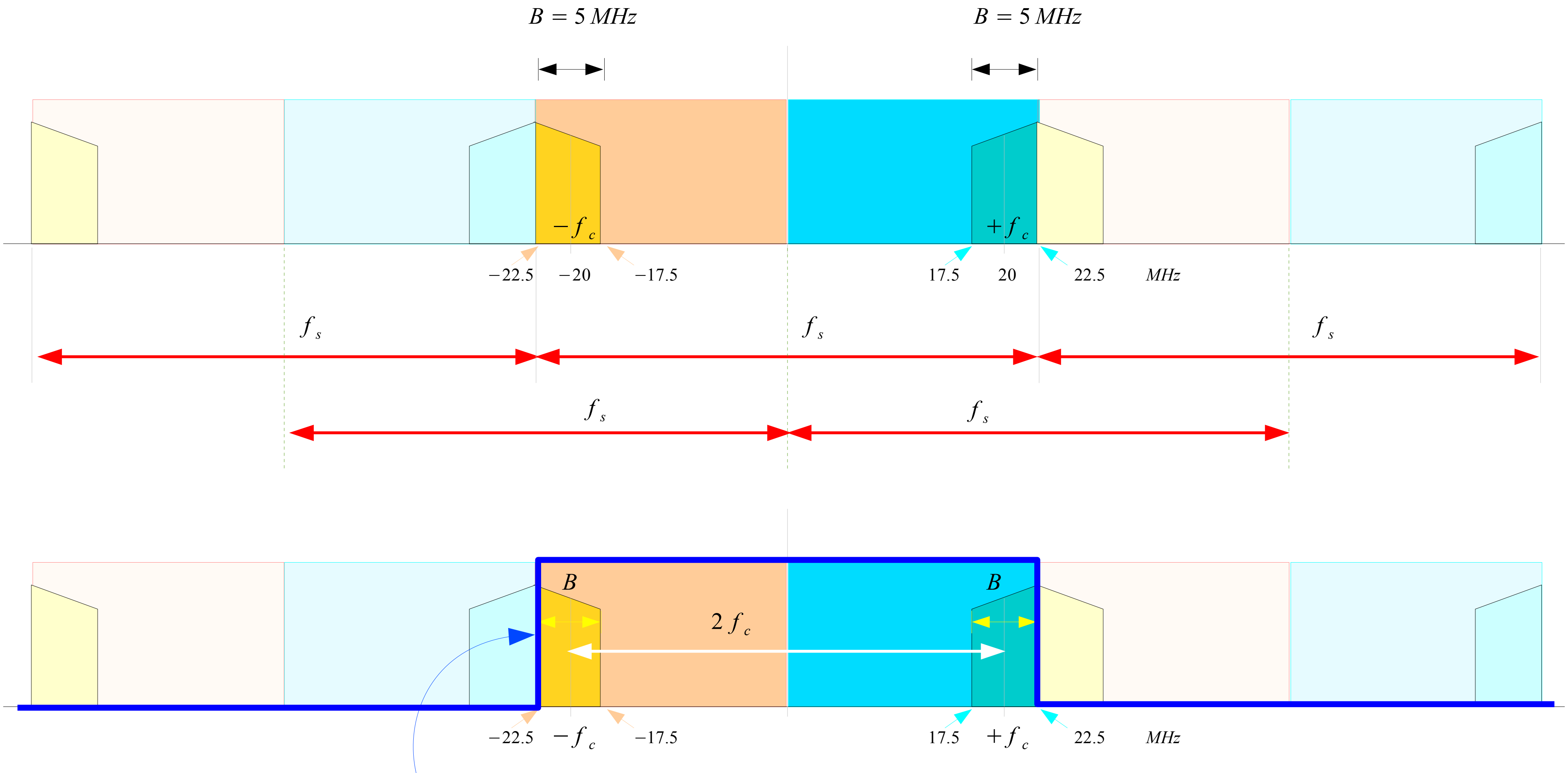


- Lowpass Sampling

- Bandpass Sampling
- IF filtering
- Harmonic Sampling
- Sub-Nyquist Sampling



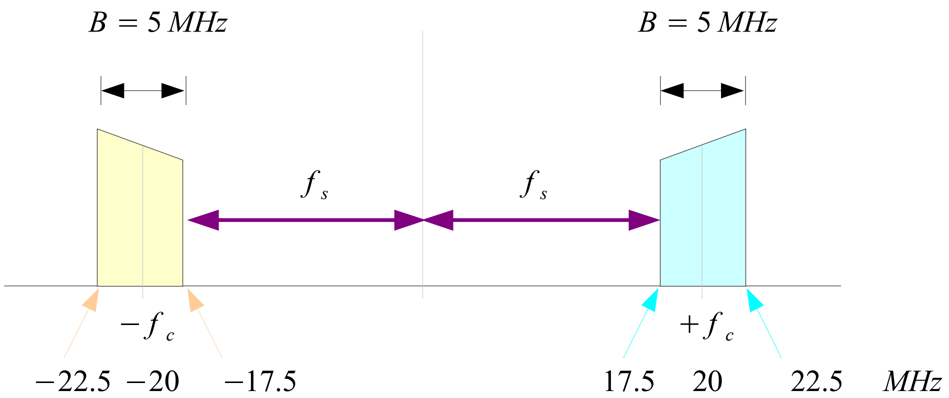
Low-pass Signal Sampling



Nyquist Criterion

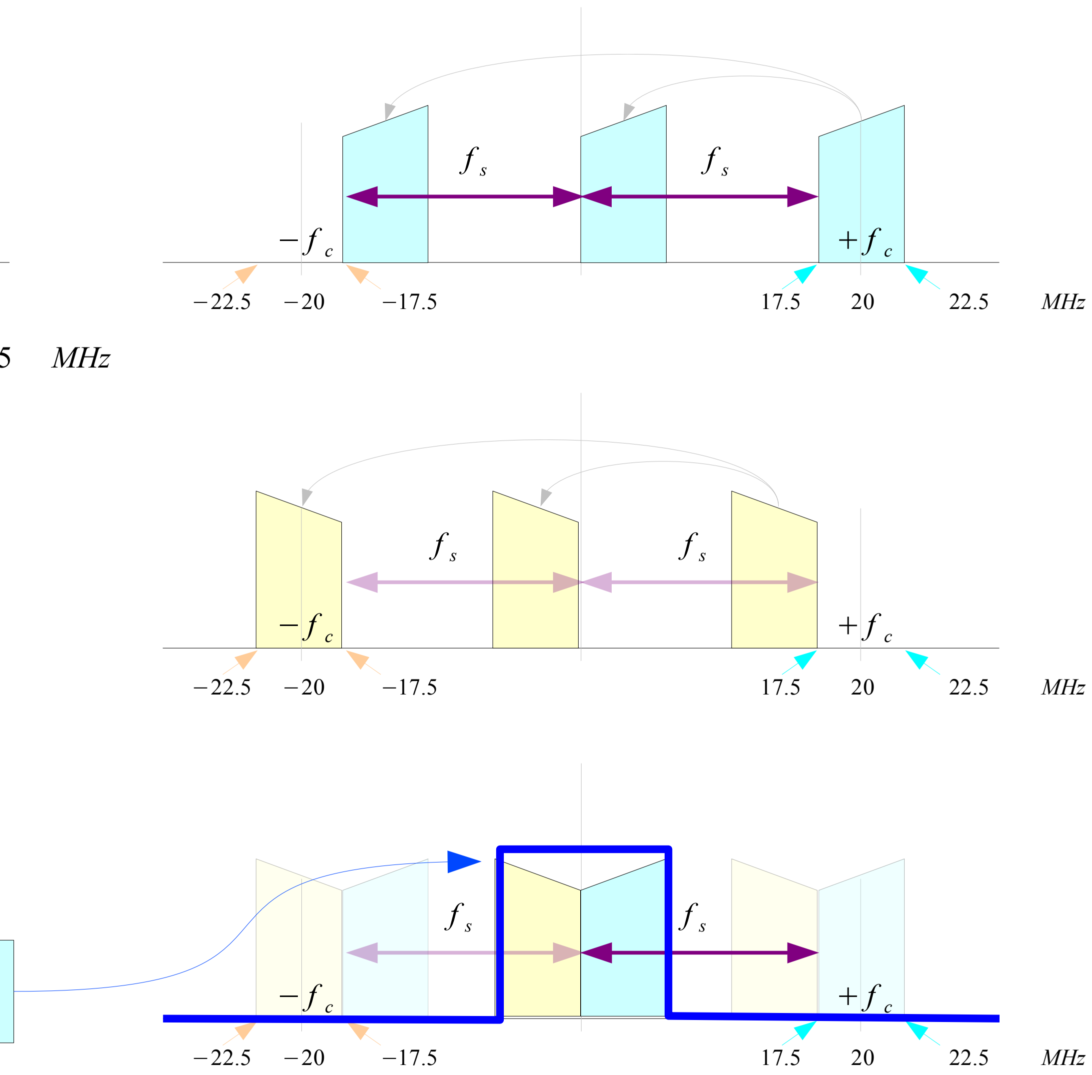
$$2f_c + B \leq f_s$$

Band-pass Signal Sampling



- **Bandpass Sampling**
- **IF filtering**
- **Harmonic Sampling**
- **Sub-Nyquist Sampling**

Nyquist Criterion	$2B \leq f_s$



Sampling Frequency f_s (1)

Assume there are m multiples of f_s

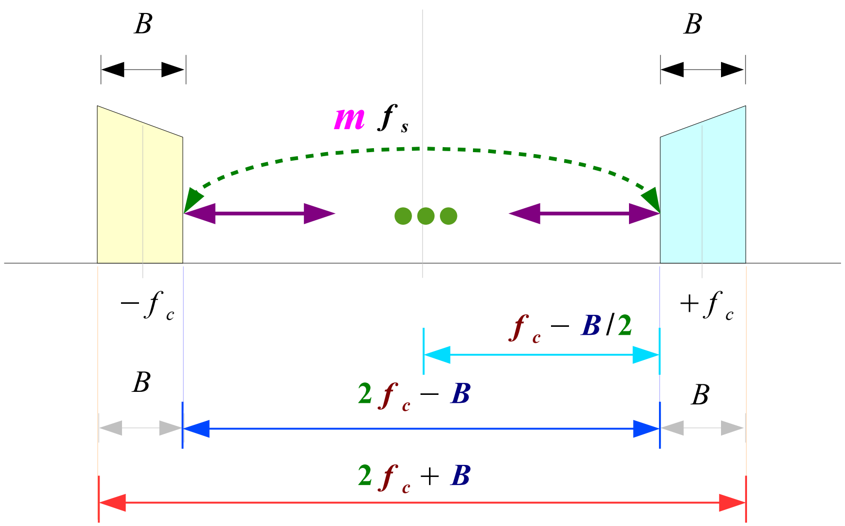
$$2f_c - B = m \cdot f_s$$

Given an integer m — **Max f_s condition**

f_s *can be decreased according to the following condition without introducing aliasing problems*

$$2f_c + B = (m+1) \cdot f_s$$

Min f_s condition



Given Band-pass Signal is characterized by

- *Bandwidth* B
- *Carrier Frequency* f_c

$$\frac{2f_c + B}{m+1} \le f_s \le \frac{2f_c - B}{m}$$

Sampling Frequency f_s (2)

$$\frac{2f_c + B}{m+1} \le f_s \le \frac{2f_c - B}{m}$$

Given Band-pass Signal is characterized by

- ***Bandwidth B***
- ***Carrier Frequency f_c***

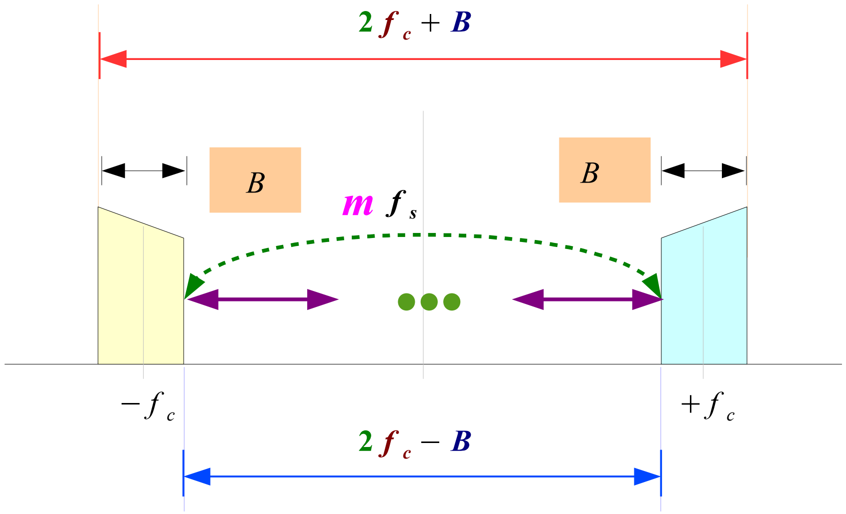
➡ ***Normalization by B***

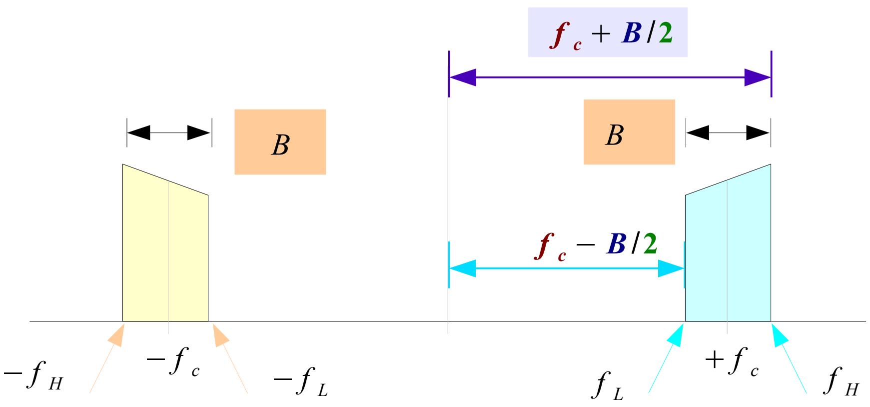
$$\frac{2f_c + B}{(m+1)B} \le \frac{f_s}{B} \le \frac{2f_c - B}{mB}$$

$$\frac{2f_H}{(m+1)B} \le \frac{f_s}{B} \le \frac{2f_L}{mB}$$

$f_H = f_c + B/2$ ***Highest frequency***

$f_L = f_c - B/2$ ***Lowest frequency***





$$\frac{2f_c + B}{m+1} \le f_s \le \frac{2f_c - B}{m}$$

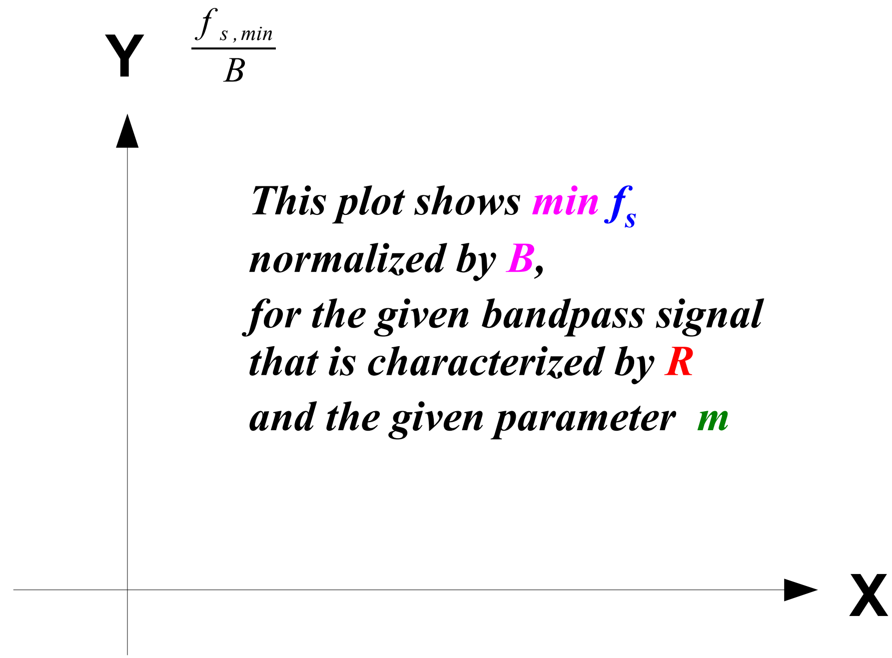
$$\frac{f_c + B/2}{B} = R \rightarrow X$$

→ highest signal frequency / bandwidth B

$$\frac{2f_c + B}{(m+1)B} = \frac{f_{s,min}}{B} \rightarrow Y$$

→ minimum sampling rate / bandwidth B

X-Y Plot



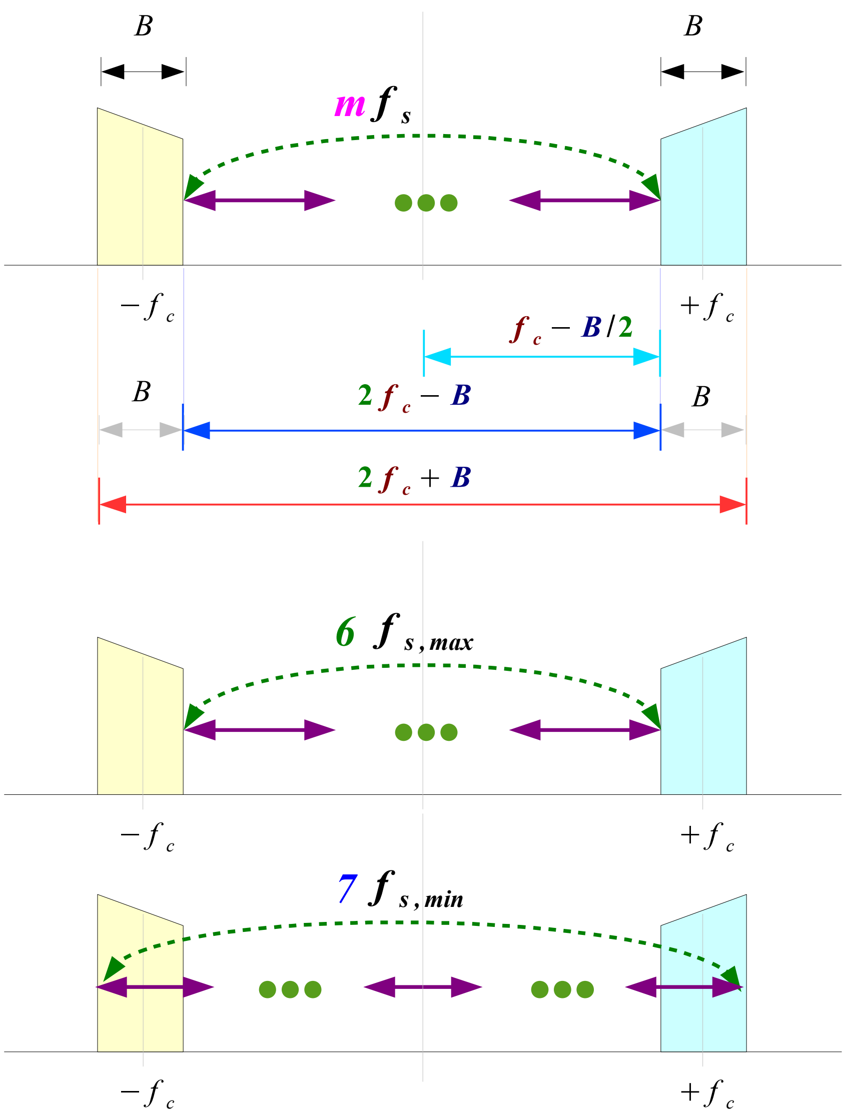
This plot shows min f_s normalized by B, for the given bandpass signal that is characterized by R and the given parameter m

Characterized by

- ***Bandwidth B***
- ***Carrier Frequency f_c***

$$R = \frac{f_H}{B} = \frac{f_c + B/2}{B}$$

Example m=6 (1)



$$\frac{2 f_c + B}{m + 1} \le f_s \le \frac{2 f_c - B}{m}$$

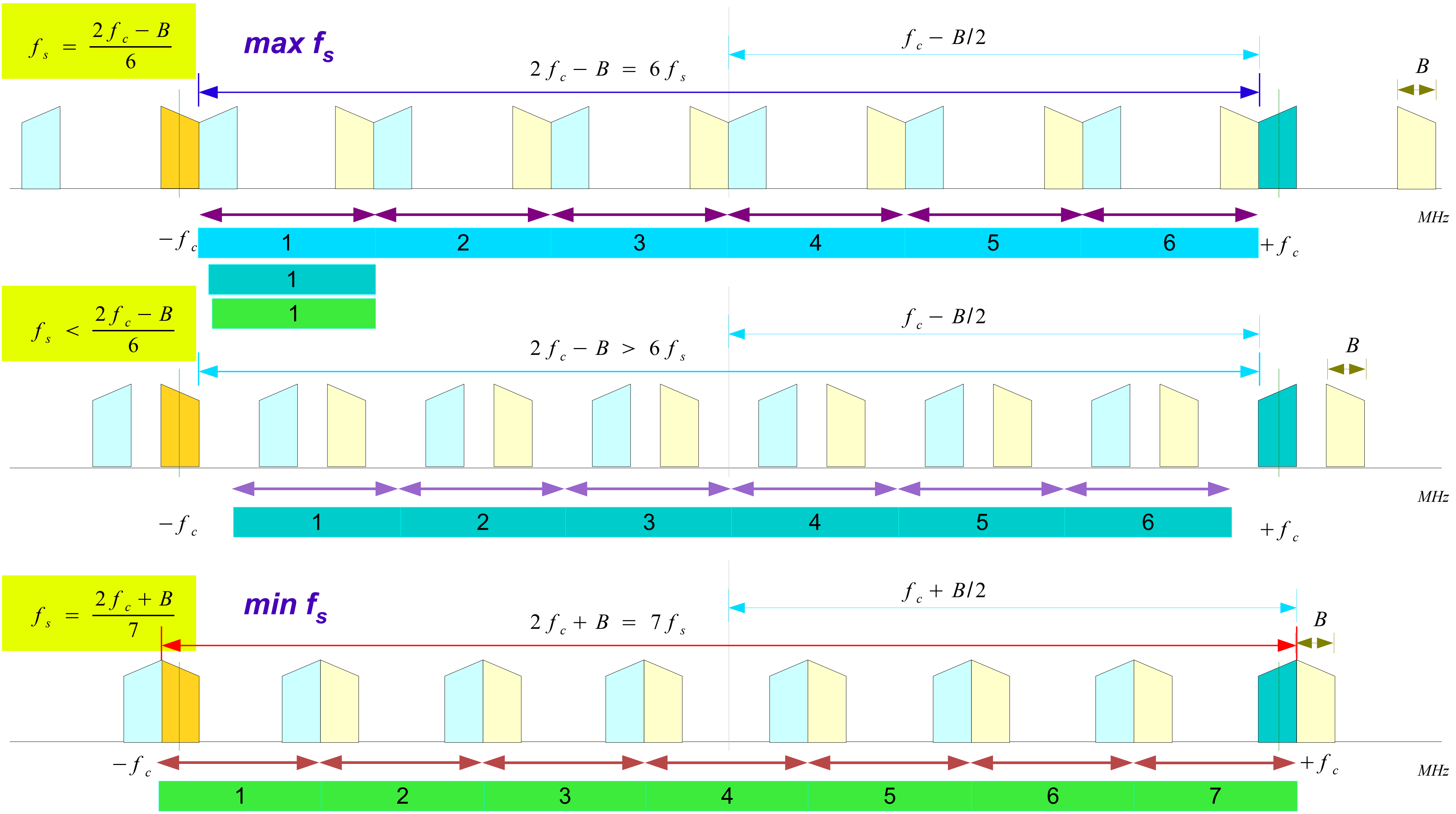
When $m = 6$

$$\text{min } f_s \quad \frac{2 f_c + B}{7} \le f_s \le \frac{2 f_c - B}{6} \quad \text{max } f_s$$

$$\text{max } f_s = \frac{2 f_c - B}{6}$$

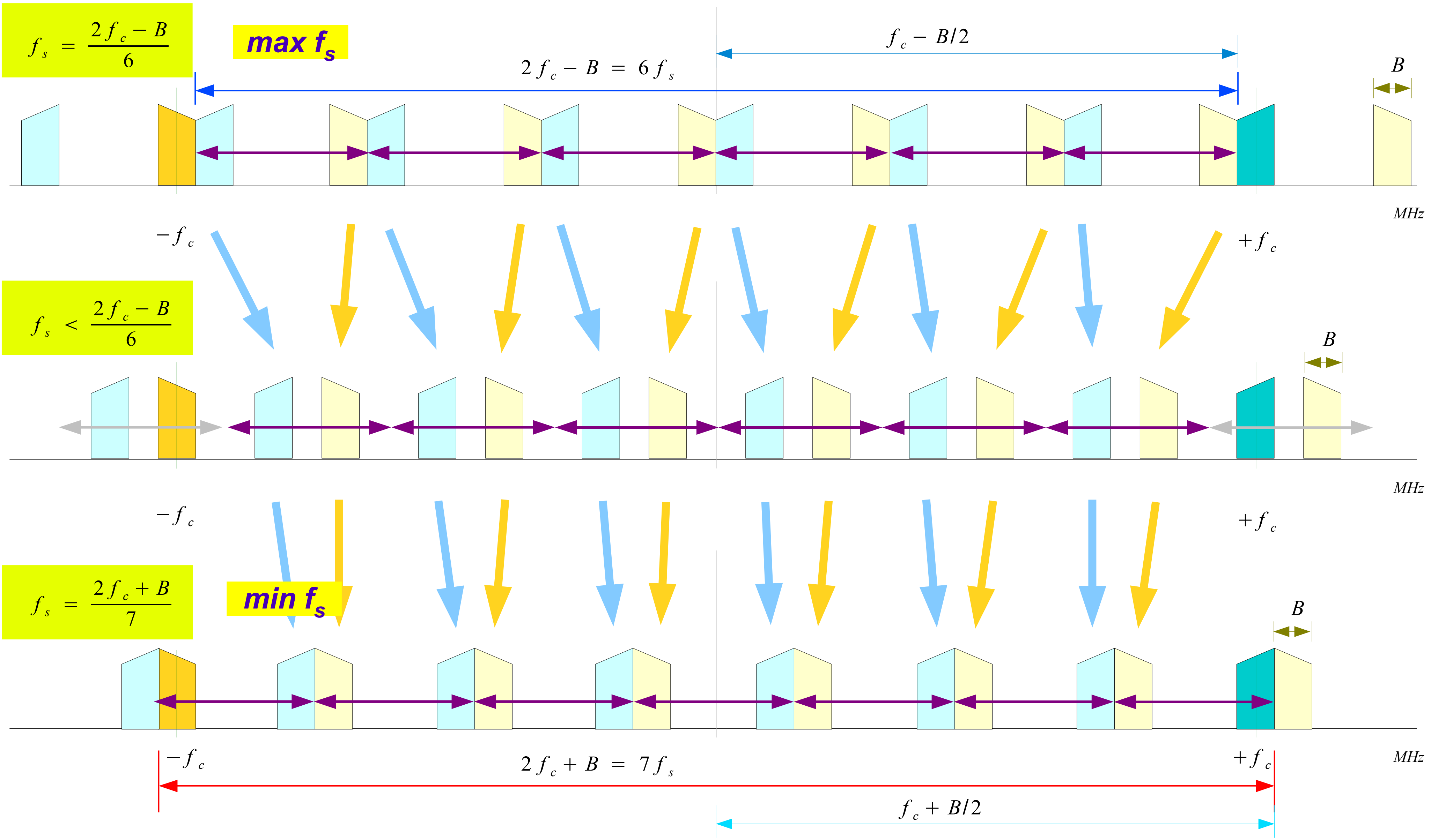
$$\text{min } f_s = \frac{2 f_c + B}{7}$$

Example m=6 (2)



$f_s = \frac{2f_c - B}{6}$
max f_s
$f_c - B/2$
$2f_c - B = 6f_s$
B
MHz
$-f_c$
1
2
3
4
5
6
$+f_c$
1
1
$f_s < \frac{2f_c - B}{6}$
$f_c - B/2$
$2f_c - B > 6f_s$
B
MHz
$-f_c$
1
2
3
4
5
6
$+f_c$
$f_s = \frac{2f_c + B}{7}$
min f_s
$f_c + B/2$
$2f_c + B = 7f_s$
B
$-f_c$
$+f_c$
MHz
1
2
3
4
5
6
7

Example m=6 (3)



$f_s = \frac{2f_c - B}{6}$
max f_s
$f_c - B/2$
$2f_c - B = 6f_s$
B
MHz
$-f_c$
$+f_c$
$f_s < \frac{2f_c - B}{6}$
B
MHz
$-f_c$
$+f_c$
$f_s = \frac{2f_c + B}{7}$
min f_s
B
$-f_c$
$+f_c$
$2f_c + B = 7f_s$
MHz
$f_c + B/2$

Range of f_s (1)

For a given m	$\frac{2f_c + B}{m+1} \le f_s \le \frac{2f_c - B}{m}$	Nyquist Criterion	$2B \le f_s$

$f_c = 20\,MHz$

$B = 5\,MHz$

	min f_s		max f_s	Optimum Sampling Frequency
$m = 1$	$\frac{2\cdot 20 + 5}{1+1} = 22.5$	$\le f_s \le$	$\frac{2\cdot 20 - 5}{1} = 35$	$f_s = 22.5\,MHz \quad (10 \le f_s)$
$m = 2$	$\frac{2\cdot 20 + 5}{2+1} = 15$	$\le f_s \le$	$\frac{2\cdot 20 - 5}{2} = 17.5$	$f_s = 17.5\,MHz \quad (10 \le f_s)$
$m = 3$	$\frac{2\cdot 20 + 5}{3+1} = 11.25$	$\le f_s \le$	$\frac{2\cdot 20 - 5}{3} = 11.67$	$f_s = 11.25\,MHz \quad (10 \le f_s)$
$m = 4$	$\frac{2\cdot 20 + 5}{4+1} = 9$	$\ge$	$\frac{2\cdot 20 - 5}{4} = 8.75$	X
$m = 5$	$\frac{2\cdot 20 + 5}{5+1} = 7.5$	$\ge$	$\frac{2\cdot 20 - 5}{5} = 7.0$	X

Range of f_s (2)

$$\frac{2f_c + B}{m+1} \le f_s \le \frac{2f_c - B}{m}$$

$$\frac{f_c + B/2}{B} = R$$

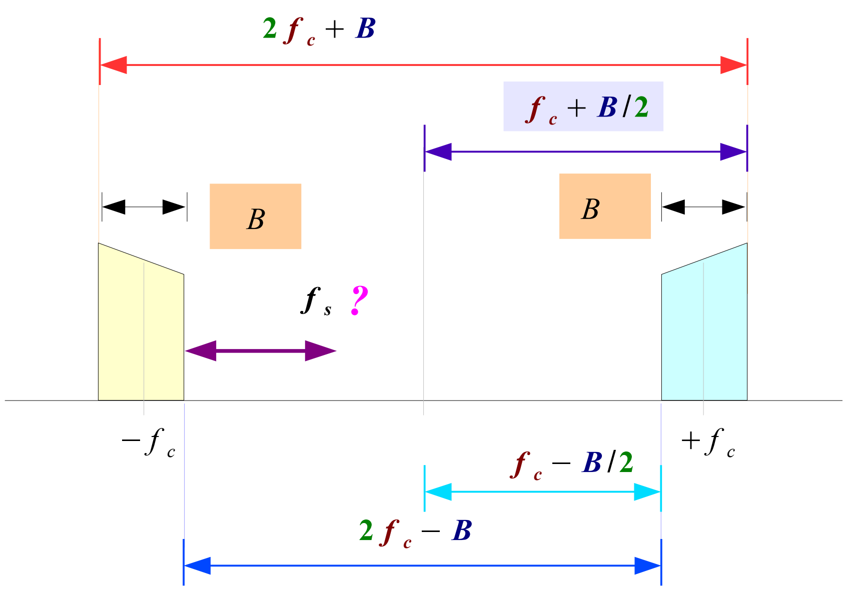
➡ $\dfrac{\text{highest signal frequency}}{\text{bandwidth B}}$

$$\frac{2f_c + B}{(m+1)B} = \frac{f_{s,min}}{B} = g(m,R)$$

➡ $\dfrac{\text{minimum sampling rate}}{\text{bandwidth B}}$

$$\frac{2(f_c + B/2)}{(m+1)B} = \frac{2R}{m+1} = g(m,R)$$

$m = 0$	$g(0,R) = 2R$		
$m = 1$	$g(1,R) = R$	$m = 5$	$g(5,R) = \frac{1}{3}R$
$m = 2$	$g(2,R) = \frac{2}{3}R$	$m = 6$	$g(6,R) = \frac{2}{7}R$
$m = 3$	$g(3,R) = \frac{1}{2}R$	$m = 7$	$g(7,R) = \frac{1}{4}R$
$m = 4$	$g(4,R) = \frac{2}{5}R$	$m = 8$	$g(8,R) = \frac{2}{9}R$



Range of f_s (3)

$$\frac{2f_c + B}{m+1} \le f_s \le \frac{2f_c - B}{m}$$

$$\frac{f_c + B/2}{B} = R$$ → **highest signal frequency / bandwidth B**

$$f_H = f_c + B/2$$

$$R = f_H / B$$

$$\frac{2f_c + B}{(m+1)B} = g(m, R)$$ → **minimum sampling rate / bandwidth B**

$$f_{s,min} = \frac{2f_c + B}{m+1} = \frac{2f_H}{k}$$

$$\frac{2f_c + B}{(m+1)B} = g(m, R) = \frac{2R}{m+1} = \frac{2R}{k}$$

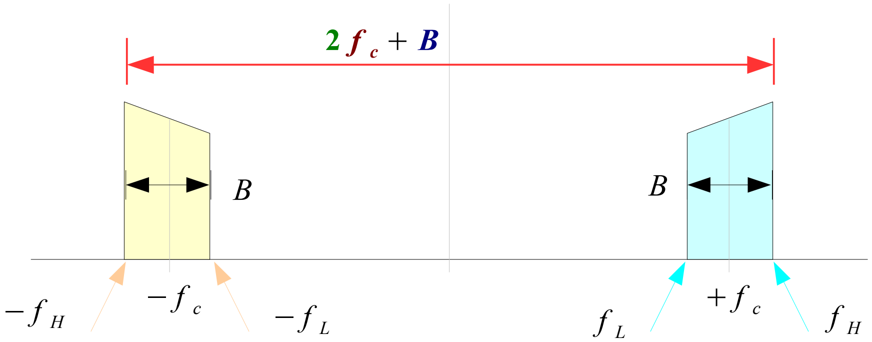
$$m + 1 = k$$

$$g(m, R) = \frac{2f_H}{kB} = \frac{2R}{k}$$

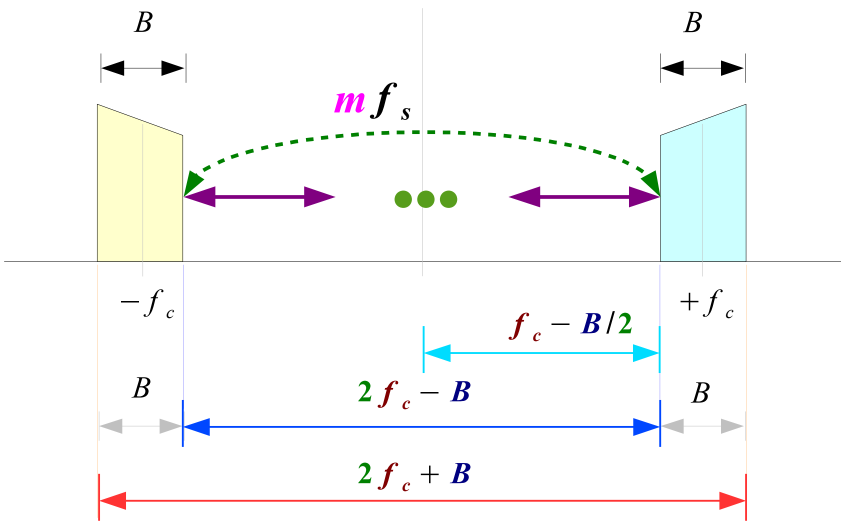
k represents how many f_s are in $2f_c + B$ in

Min f_s condition

$$2f_c + B = (m+1)\cdot f_s = k \cdot f_s$$



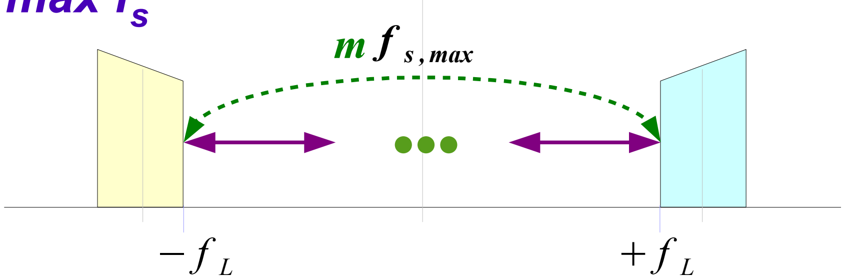
Range of f_s (4)



$$\frac{2f_c + B}{m+1} \le f_s \le \frac{2f_c - B}{m}$$

$$m + 1 = k$$

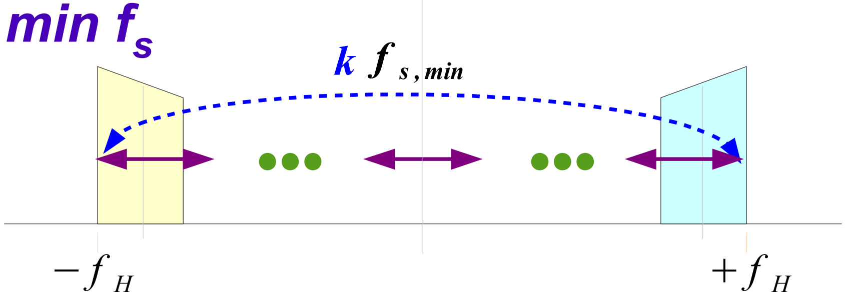
max f_s



m represents how many f_s are in $2f_c - B$ in **max f_s**

$$\textbf{max } f_s = \frac{2f_c - B}{m} = \frac{2f_L}{m}$$

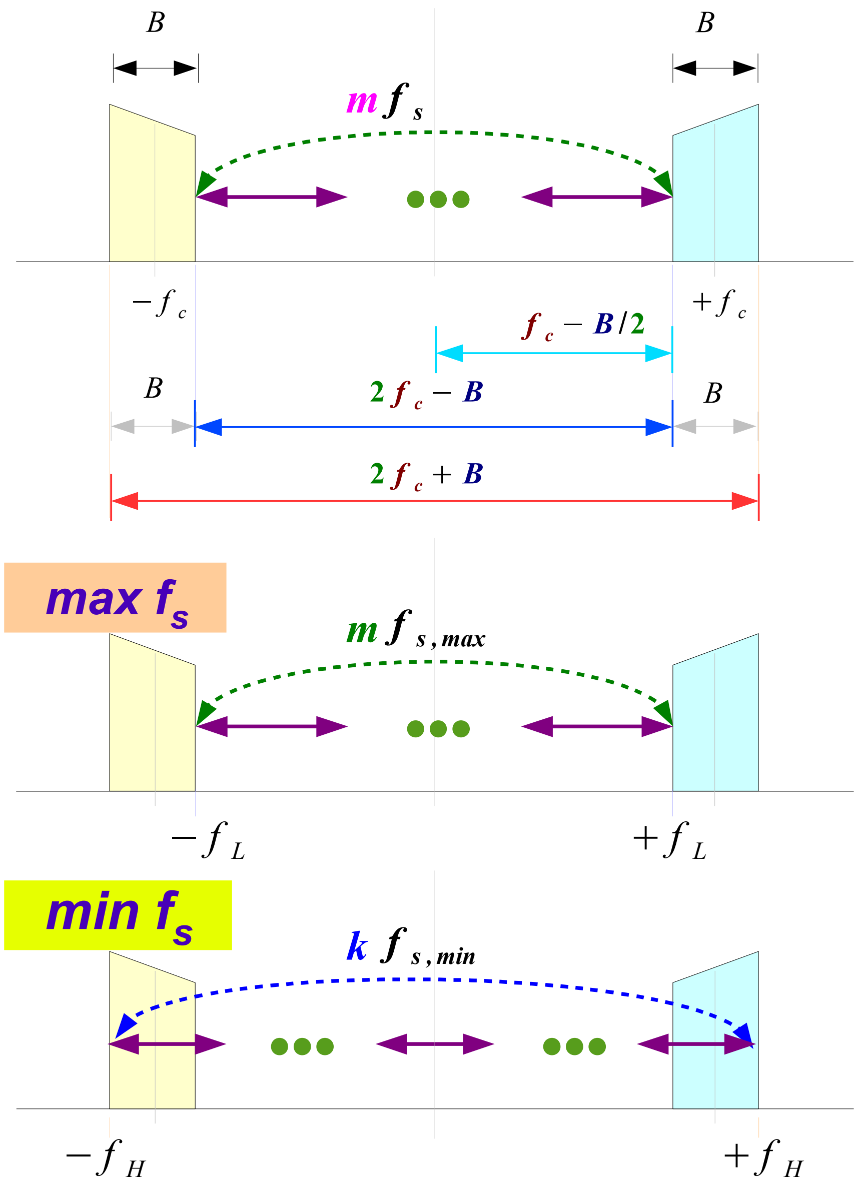
min f_s



k represents how many f_s are in $2f_c + B$ in **min f_s**

$$\textbf{min } f_s = \frac{2f_c + B}{k} = \frac{2f_H}{k}$$

Range of f_s (5)



$$\frac{2 f_c + B}{m+1} \le f_s \le \frac{2 f_c - B}{m}$$

$$\frac{2 f_c + B}{k} \le f_s \le \frac{2 f_c - B}{k-1}$$

$$\frac{2(f_c + B/2)}{k} \le f_s \le \frac{2(f_c + B/2) - 2B}{m}$$

$$\frac{2 f_H}{k} \qquad \frac{2(f_H - B)}{m}$$

min f_s max f_s

$$\frac{2 f_H}{k} \le f_s \le \frac{2 f_L}{m}$$

$$k = 2 \qquad f_H \le f_s \le 2 f_L \qquad m = 1$$

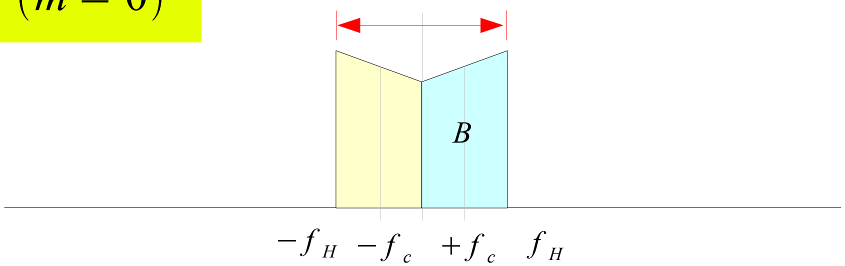
$$k = 3 \qquad \frac{2}{3} f_H \le f_s \le f_L \qquad m = 2$$

$$k = 4 \qquad \frac{1}{2} f_H \le f_s \le \frac{2}{3} f_L \qquad m = 3$$

Example k=1

$k = 1$
$(m = 0)$

$f_H = f_c + B/2 = 1B$



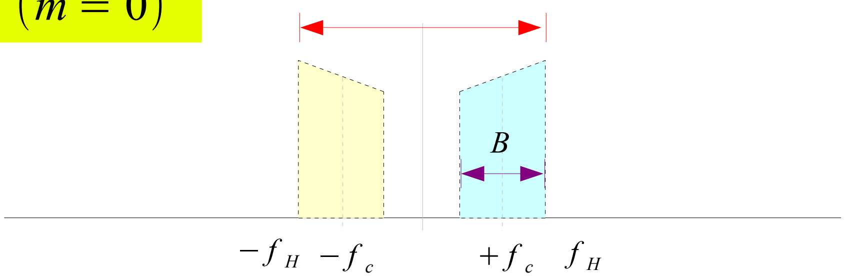
$R = f_H / B = 1$

$$\frac{f_{s,min}}{B} = \frac{2 f_H}{k B} = \mathbf{2}$$

$$\frac{f_{s,max}}{B} = \frac{2(f_H - B)}{(k-1)B} = +\infty$$

$k = 1$
$(m = 0)$

$f_H = f_c + B/2 = 1.5B$



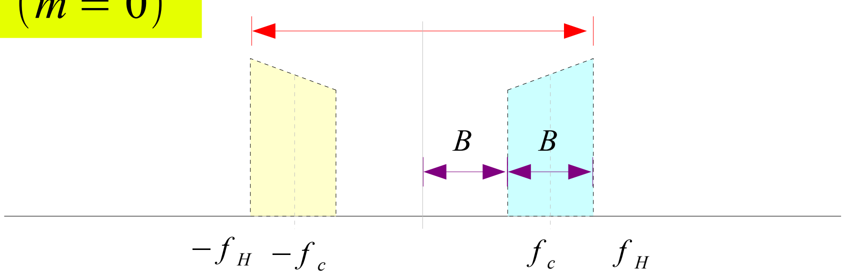
$R = f_H / B = 1.5$

$$\frac{f_{s,min}}{B} = \frac{2 f_H}{k B} = \mathbf{3}$$

$$\frac{f_{s,max}}{B} = \frac{2(f_H - B)}{(k-1)B} = +\infty$$

$k = 1$
$(m = 0)$

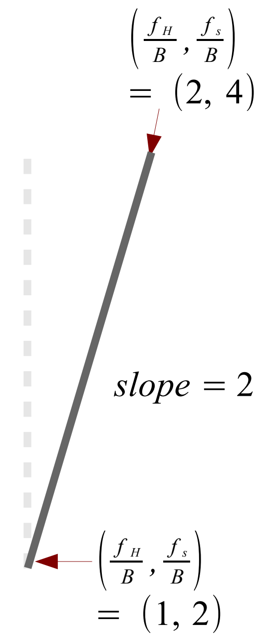
$f_H = f_c + B/2 = 2B$



$R = f_H / B = 2$

$$\frac{f_{s,min}}{B} = \frac{2 f_H}{k B} = \mathbf{4}$$

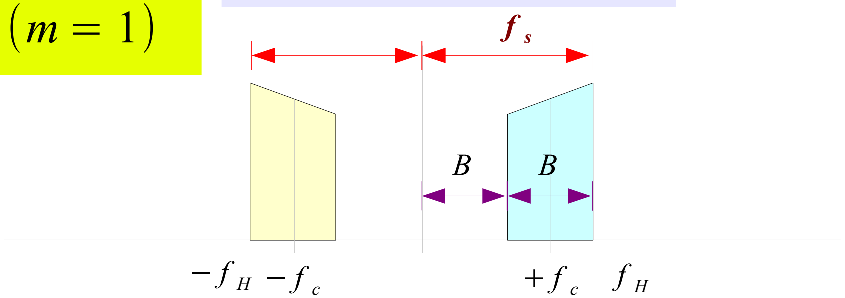
$$\frac{f_{s,max}}{B} = \frac{2(f_H - B)}{(k-1)B} = +\infty$$



Example k=2

$k = 2$
$(m = 1)$

$f_H = f_c + B/2 = 2B$



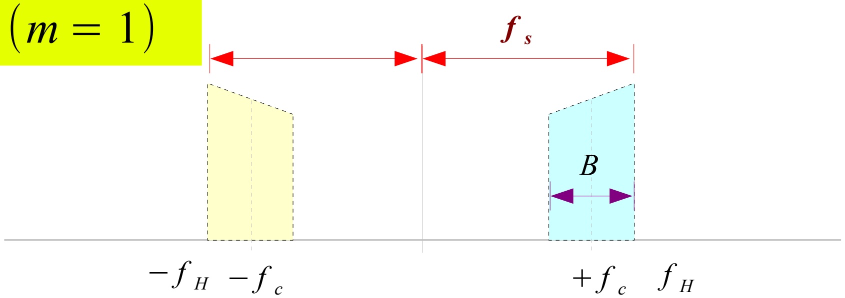
$R = f_H / B = 2$

$$\frac{f_{s,min}}{B} = \frac{2 f_H}{k B} = \mathbf{2}$$

$$\frac{f_{s,max}}{B} = \frac{2(f_H - B)}{(k-1) B} = \mathbf{2}$$

$k = 2$
$(m = 1)$

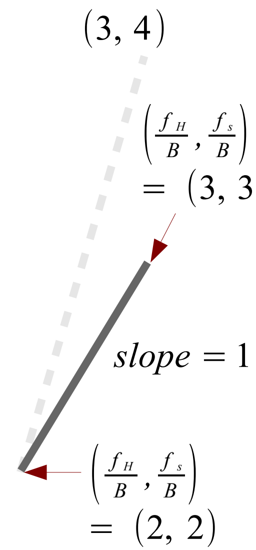
$f_H = f_c + B/2 = 2.5B$



$R = f_H / B = \mathbf{2.5}$

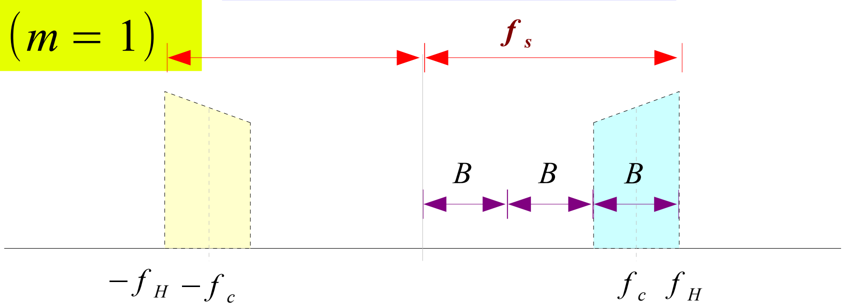
$$\frac{f_{s,min}}{B} = \frac{2 f_H}{k B} = \mathbf{2.5}$$

$$\frac{f_{s,max}}{B} = \frac{2(f_H - B)}{(k-1) B} = \mathbf{3}$$



$k = 2$
$(m = 1)$

$f_H = f_c + B/2 = 3B$



$R = f_H / B = 3$

$$\frac{f_{s,min}}{B} = \frac{2 f_H}{k B} = \mathbf{3}$$

$$\frac{f_{s,max}}{B} = \frac{2(f_H - B)}{(k-1) B} = \mathbf{4}$$

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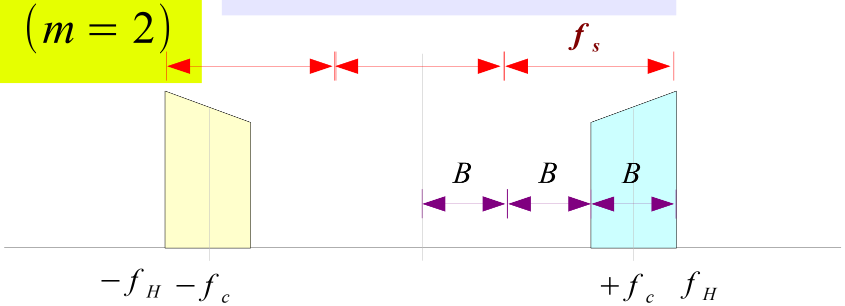
Example k=3

$k = 3$
$(m = 2)$

$f_H = f_c + B/2 = 3B$



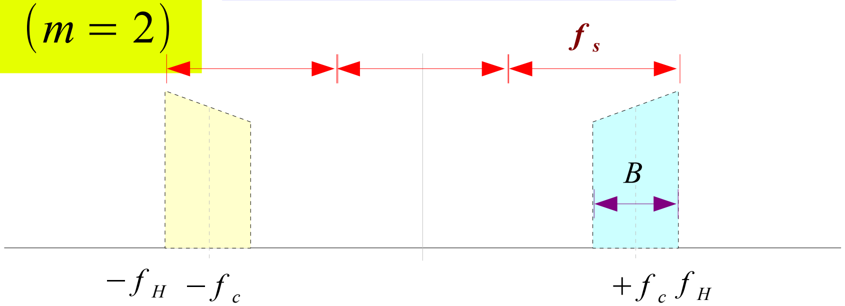
$$R = f_H / B = 3$$

$$\frac{f_{s,min}}{B} = \frac{2 f_H}{k B} = \mathbf{2}$$

$$\frac{f_{s,max}}{B} = \frac{2(f_H - B)}{(k-1) B} = \mathbf{2}$$

$k = 3$
$(m = 2)$

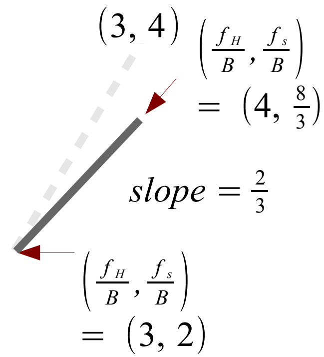
$f_H = f_c + B/2 = 3.5B$



$$R = f_H / B = 3.5$$

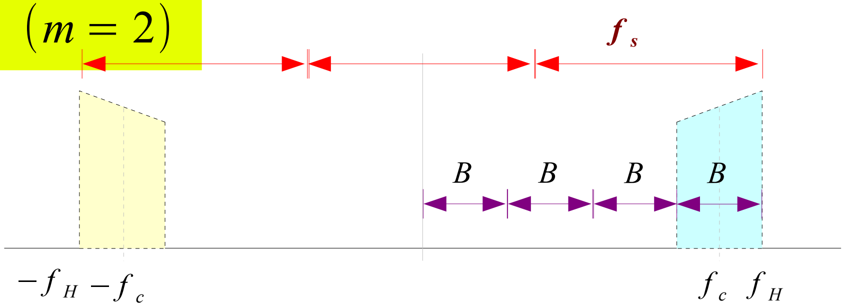
$$\frac{f_{s,min}}{B} = \frac{2 f_H}{k B} = \frac{\mathbf{7}}{\mathbf{3}}$$

$$\frac{f_{s,max}}{B} = \frac{2(f_H - B)}{(k-1) B} = \mathbf{3}$$



$k = 3$
$(m = 2)$

$f_H = f_c + B/2 = 4B$



$$R = f_H / B = 4$$

$$\frac{f_{s,min}}{B} = \frac{2 f_H}{k B} = \frac{\mathbf{8}}{\mathbf{3}}$$

$$\frac{f_{s,max}}{B} = \frac{2(f_H - B)}{(k-1) B} = \mathbf{4}$$

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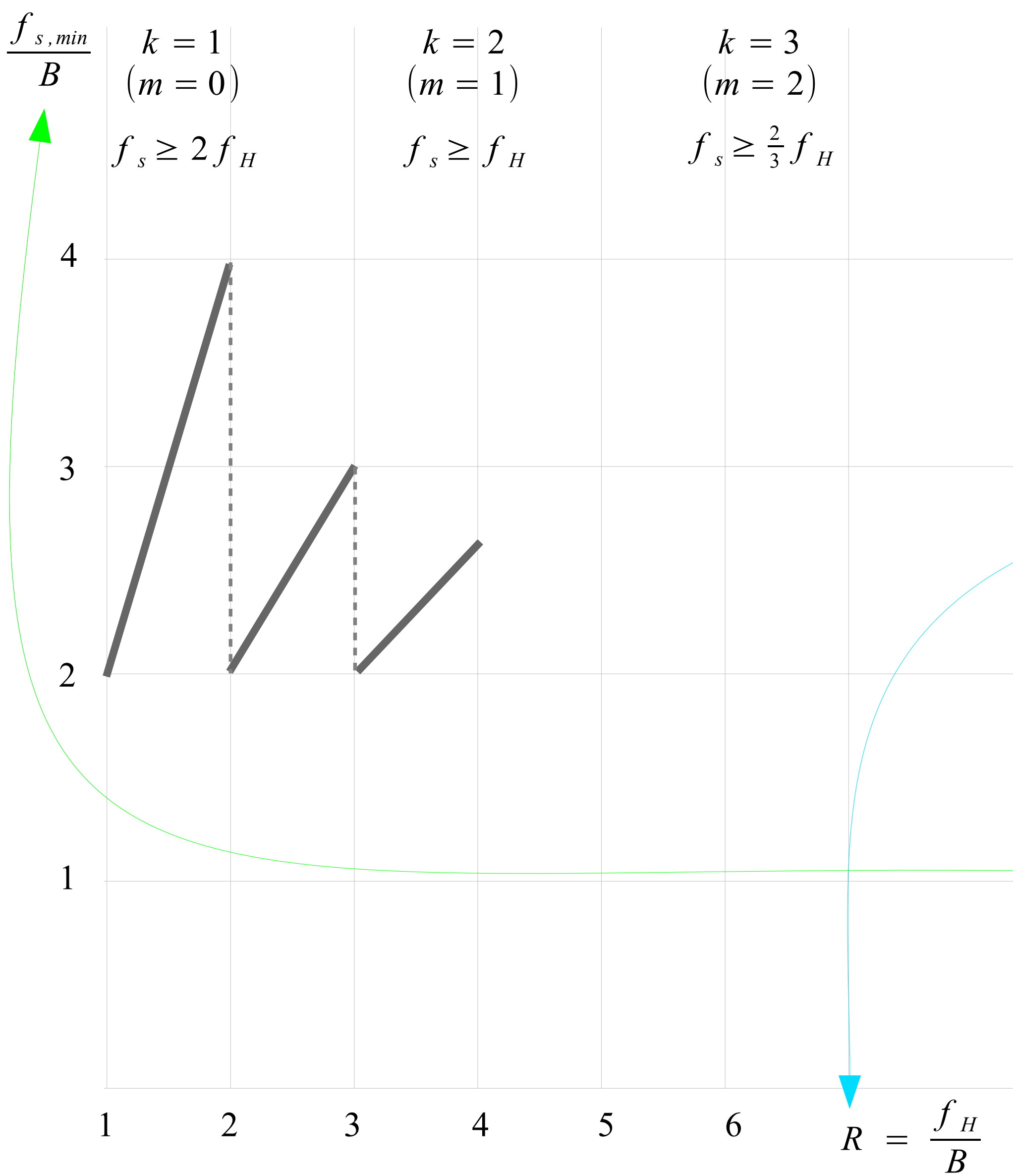


$$\frac{2f_c + B}{m+1} \leq f_s \leq \frac{2f_c - B}{m}$$

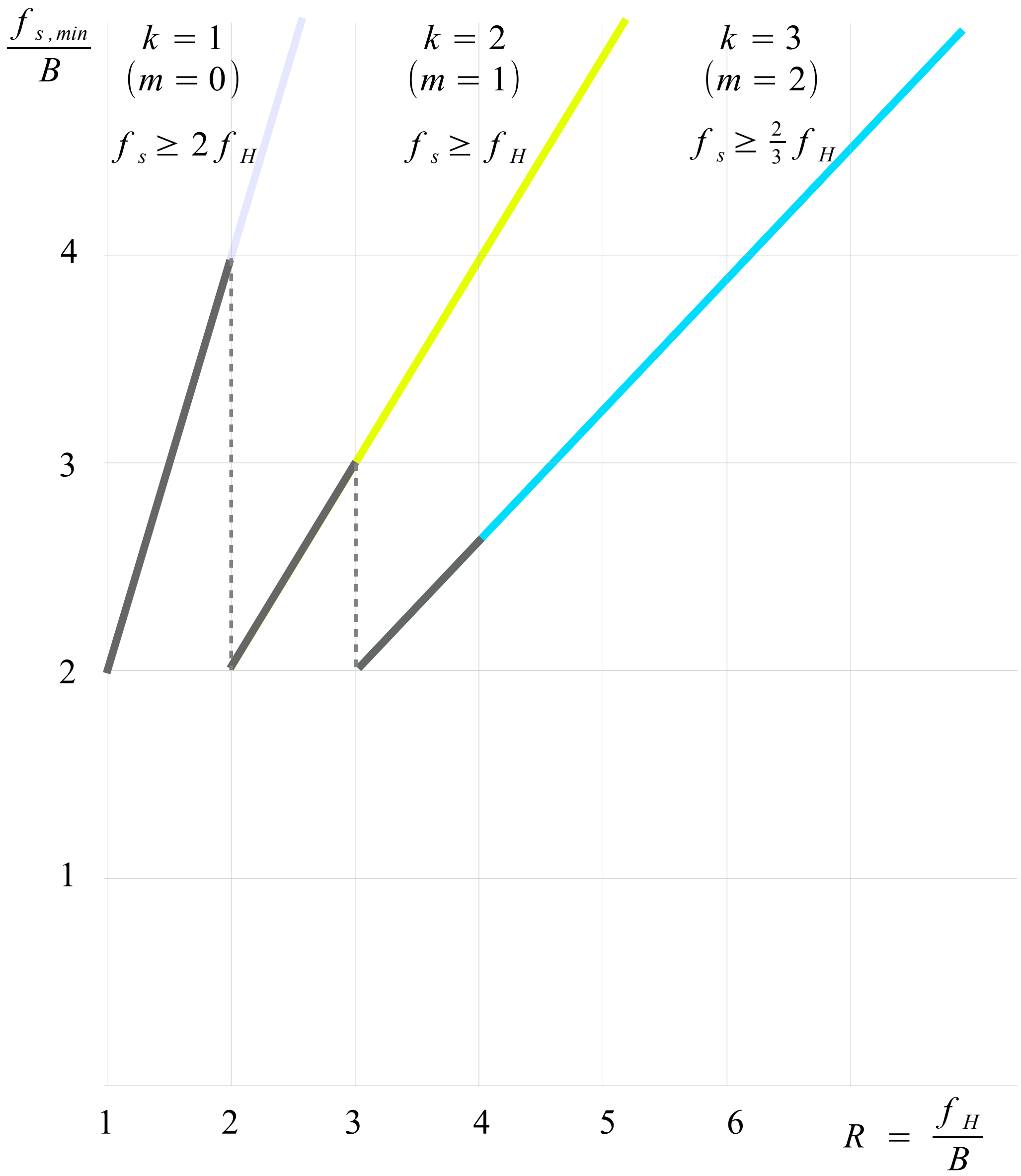
$$\frac{2f_c + B}{k} \leq f_s \leq \frac{2f_c - B}{k-1}$$

$$\frac{f_c + B/2}{B} = R$$

➡ highest signal frequency / bandwidth B

$$\frac{2f_c + B}{(m+1)B} = \frac{f_{s,min}}{B} = g(m, R)$$

➡ minimum sampling rate / bandwidth B



$$\frac{2f_c + B}{m+1} \leq f_s \leq \frac{2f_c - B}{m}$$

$$\frac{2f_c + B}{k} \leq f_s \leq \frac{2f_c - B}{k-1}$$

$$\frac{f_c + B/2}{B} = R$$

➡ $\frac{\text{highest signal frequency}}{\text{bandwidth B}}$

$$\frac{2f_c + B}{(m+1)B} = \frac{f_{s,min}}{B} = g(m, R)$$

➡ $\frac{\text{minimum sampling rate}}{\text{bandwidth B}}$

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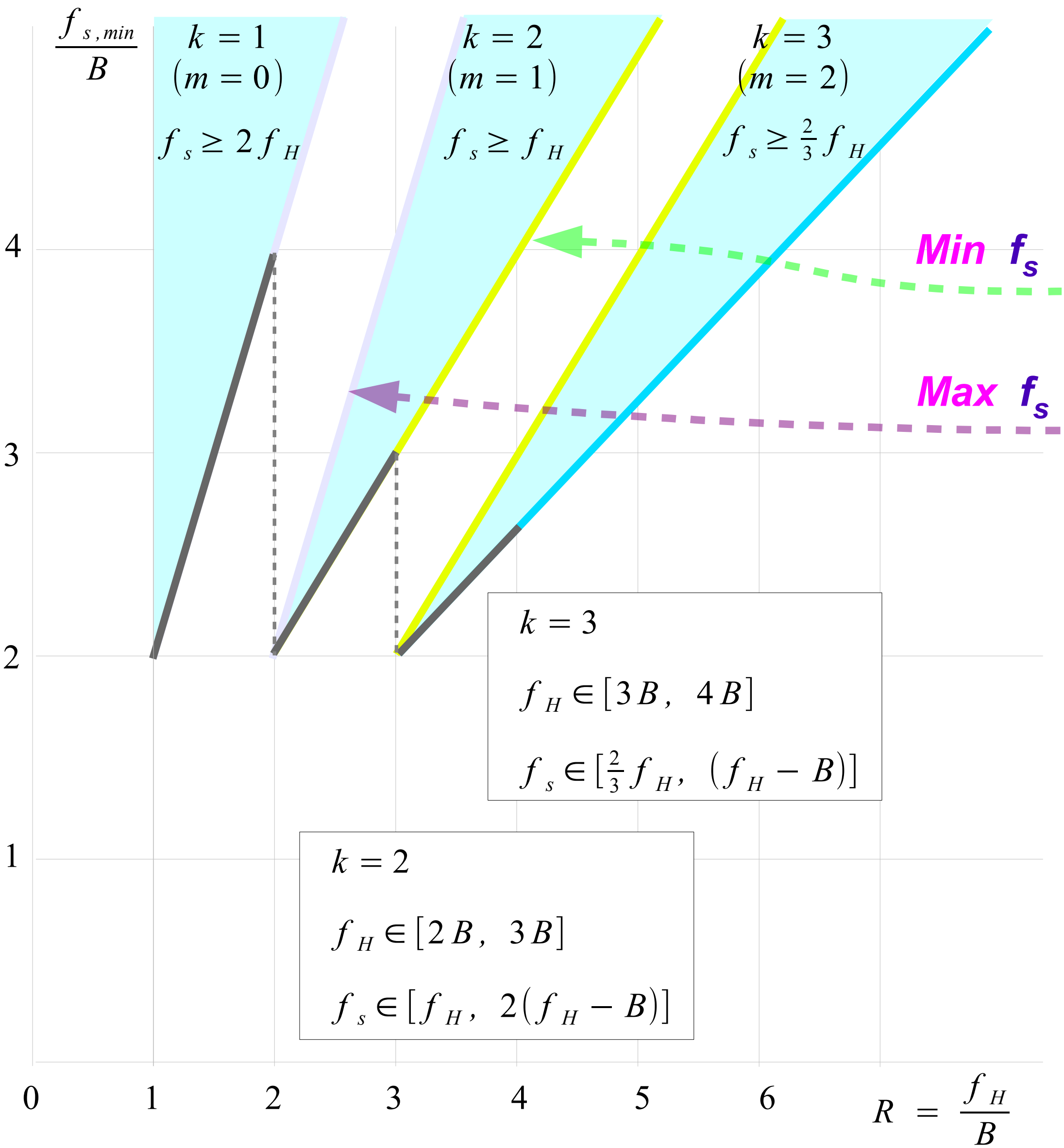

$$\frac{2f_c + B}{m+1} \leq f_s \leq \frac{2f_c - B}{m}$$

$$\frac{2f_c + B}{k} \leq f_s \leq \frac{2f_c - B}{k-1}$$

Min f_s

Max f_s

	Max f_s	**Min f_s**
	$y = 2(x-2)+2$	$y = 1(x-2)+2$
$k = 2$	$y = 2x-2$	$y = x$
	$y = 1(x-3)+2$	$y = \frac{2}{3}(x-3)+2$
$k = 2$	$y = x-1$	$y = \frac{2}{3}x$

References

[1] http://en.wikipedia.org/
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[3] A “graphical interpretation” of the DFT and FFT, by Steve Mann
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