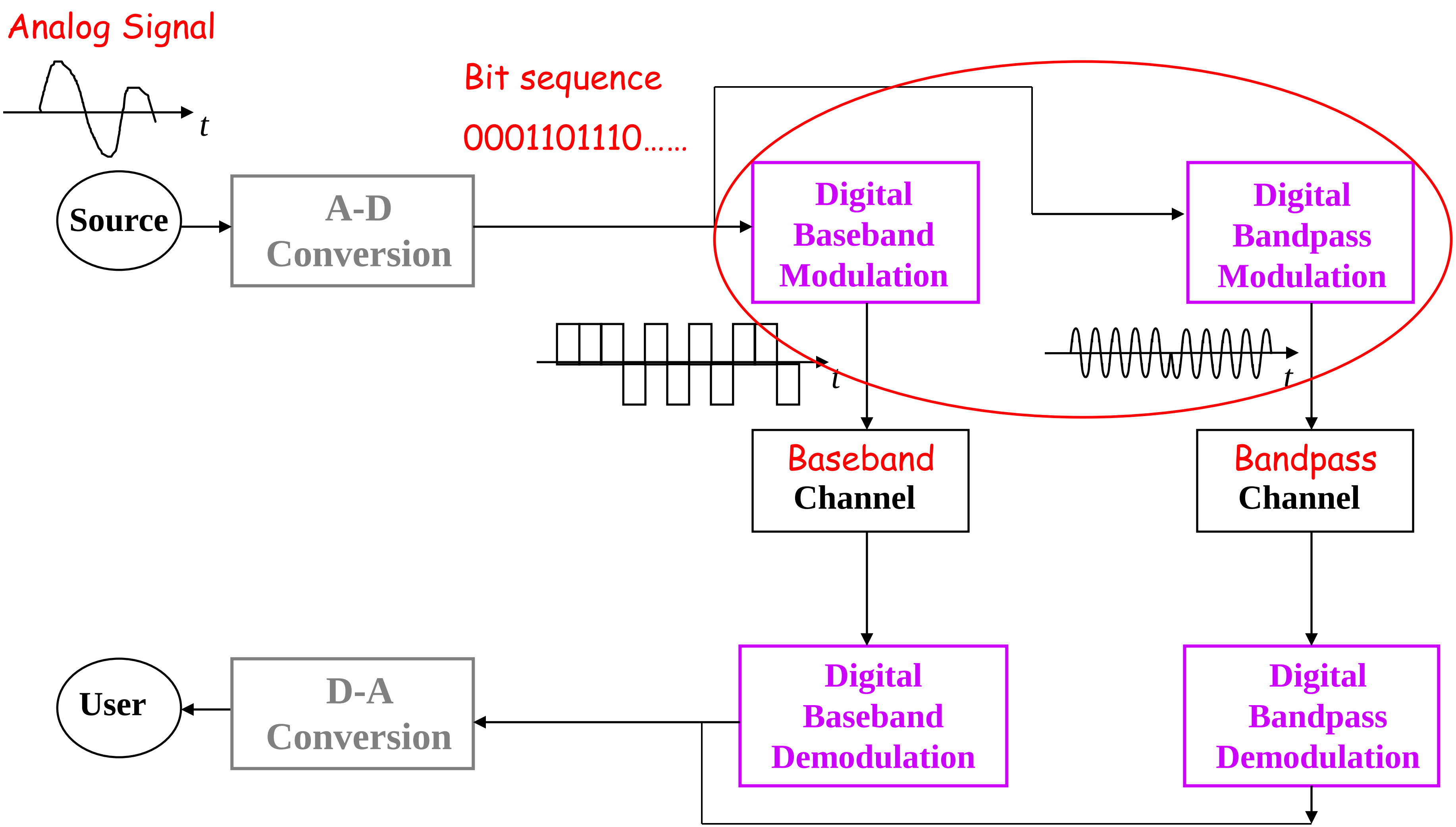
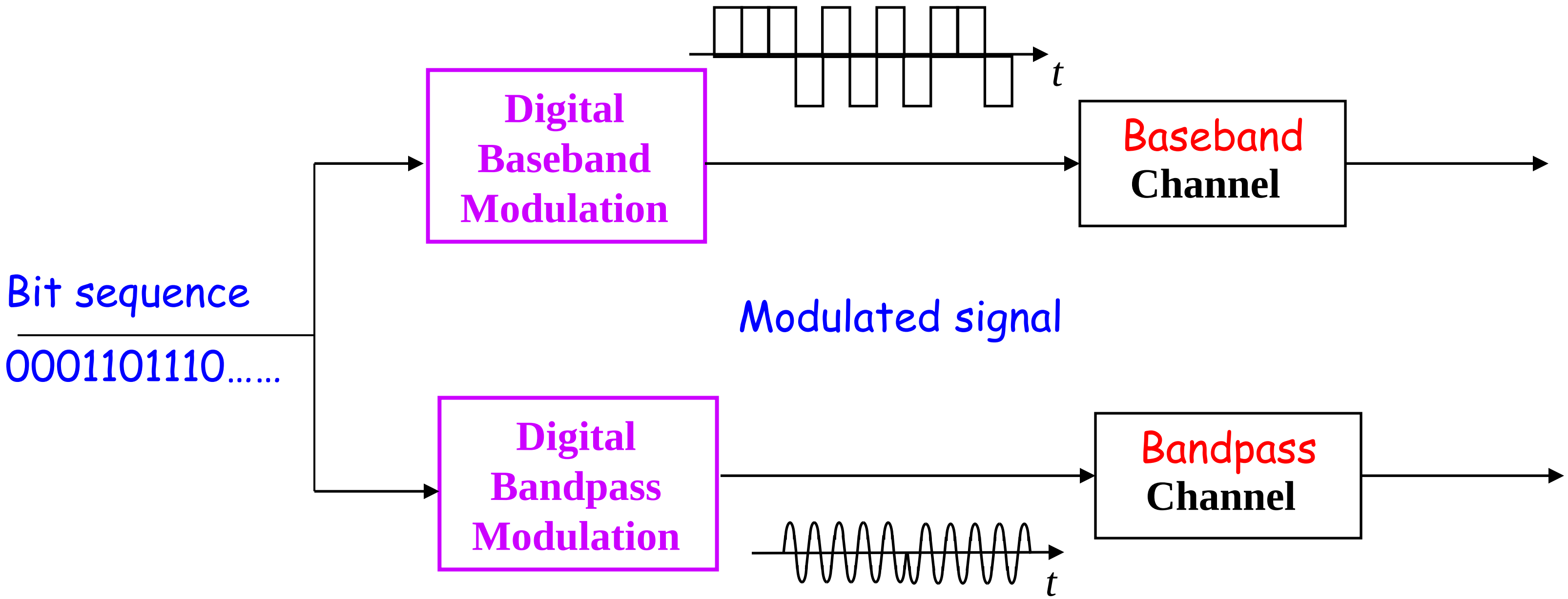
Lecture 7. Digital Communications
Part II. Digital Modulation

- Digital Baseband Modulation
- Digital Bandpass Modulation

Digital Communications

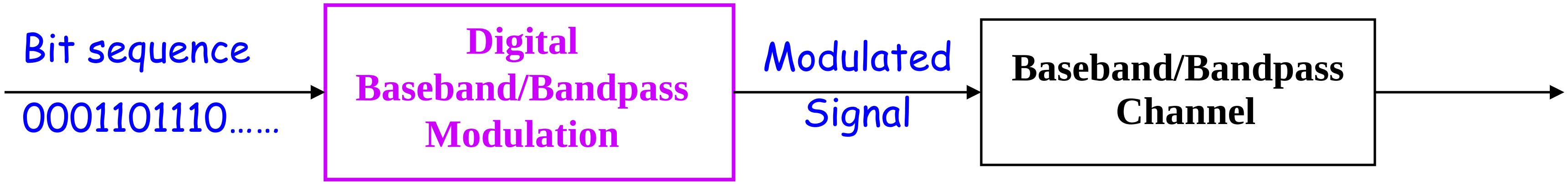


Digital Modulation



- How to choose proper digital waveforms to "carry" the digits?

Digital Modulation



- Bit Rate: number of bits transmitted in unit time
- Required channel bandwidth: determined by the bandwidth of the modulated signal.
- Bandwidth Efficiency:

$$\gamma \triangleq \frac{\text{Information Bit Rate } R_b}{\text{Required Channel Bandwidth } B_h}$$

Digital Baseband Modulation

- Pulse Amplitude Modulation (PAM)
- Pulse Shaping

Digital Baseband Modulation

- Choose baseband signals to carry the digits.
  - Each baseband signal can carry multiple bits.

Binary

- Each baseband signal carries 1 bit.
- Bit Rate: $R_b = 1/\tau$
- Totally 2 baseband signals are required.

M-ary

- Each baseband signal carries a symbol (with $\log_2 M$ bits).
- Symbol Rate: $R_s = 1/\tau$ Bit Rate: $R_b = (\log_2 M)/\tau$
- Totally M baseband signals are required.

Digital Baseband Modulation

- Focus on “amplitude modulation”
  - The baseband signals have the same shape, but different amplitudes.
  - Time-domain representation of the modulated signal:

$$s(t) = \sum_{n=-\infty}^{\infty} Z_n \cdot v(t - n\tau)$$

where Z_n is a discrete random variable with $\Pr\{Z_n = a_i\} = 1/M,\ i = 1,\ldots,M,$

$v(t)$ is a unit baseband signal.

  - Power spectrum of the modulated signal:

$$\boxed{G_s(f) = \frac{1}{\tau}|V(f)|^2 \cdot \left(\sigma_Z^2 + \frac{\mu_Z^2}{\tau}\sum_{m=-\infty}^{\infty}\delta\left(f - \frac{m}{\tau}\right)\right)}$$

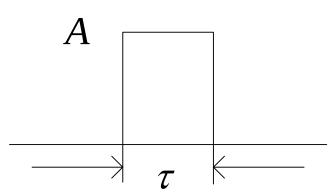
Read 3008_Lecture7_Supplemental.pdf for details.

Pulse Amplitude Modulation (PAM)

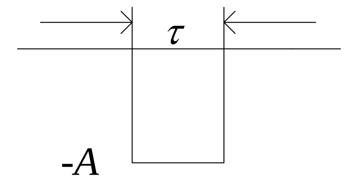
- Binary PAM
- Binary On-Off Keying (OOK)
- 4-ary PAM

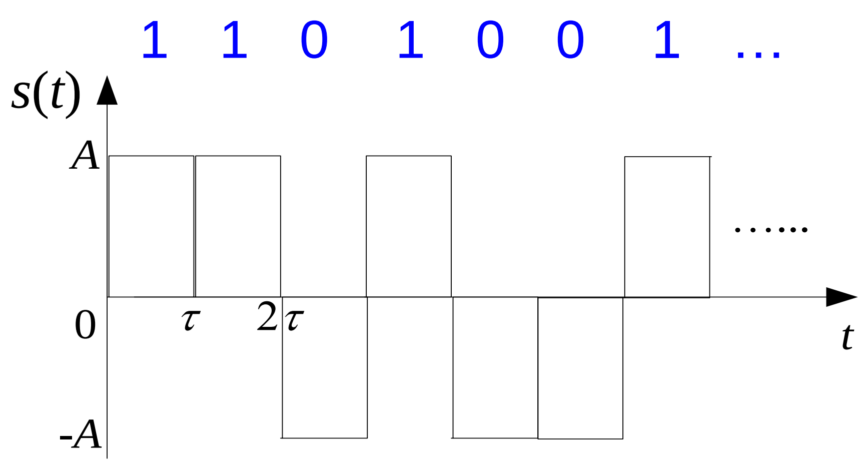
Binary PAM

1: a positive rectangular pulse with amplitude A and width τ



0: a negative rectangular pulse with amplitude $-A$ and width τ





$$s(t) = \sum_{n=-\infty}^{\infty} Z_n \cdot v(t - n\tau)$$

✓ $\Pr\{Z_n = \pm 1\} = 1/2$

✓ $v(t) = \begin{cases} A, & 0 \le t \le \tau \\ 0, & \text{otherwise} \end{cases}$

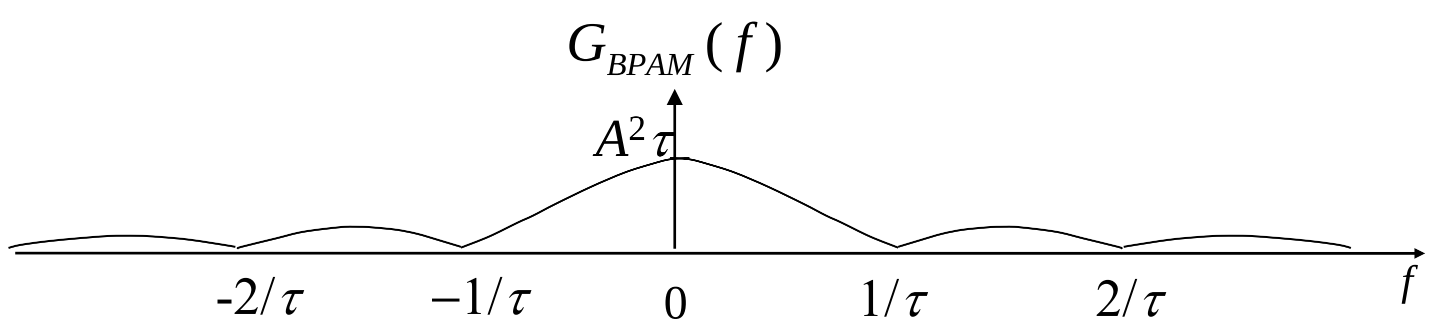
Power Spectrum of Binary PAM

$$G_s(f) = \frac{1}{\tau}|V(f)|^2 \cdot \left(\sigma_Z^2 + \frac{\mu_Z^2}{\tau} \sum_{m=-\infty}^{\infty} \delta\left(f - \frac{m}{\tau} \right) \right)$$

With Binary PAM: $V(f) = A\tau \operatorname{sinc}(f\tau)$

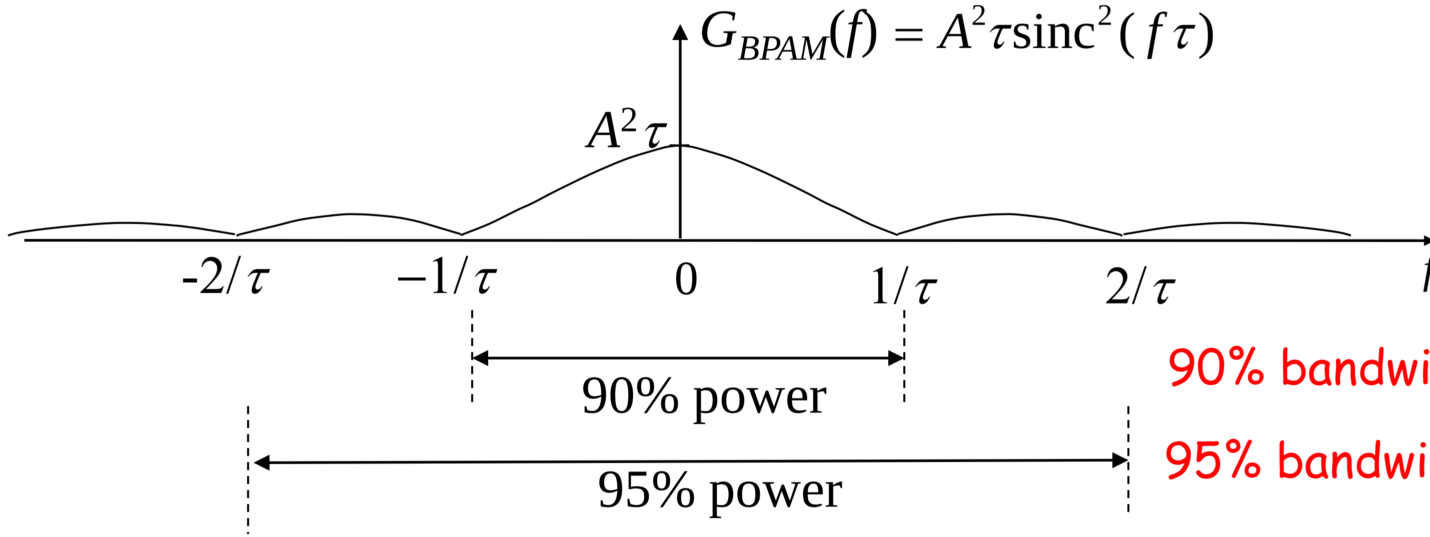
$$\mu_Z = 0, \ \sigma_Z^2 = 1$$

$$G_{BPAM}(f) = A^2 \tau \operatorname{sinc}^2(f\tau)$$



See Textbook (Sec. 3.2) or Reference [Proakis & Salehi] (Sec. 8.2) for more details.

Effective Bandwidth of Binary PAM



90% bandwidth: $1/\tau$

95% bandwidth: $2/\tau$

- Suppose 90% of signal power must pass through the channel (90% in-band power):

Required Channel Bandwidth: $B_{h\_90\%} = 1/\tau$

Bit rate: $R_b = 1/\tau$

$$B_{h\_90\%} = R_b$$

- Suppose 95% of signal power must pass through the channel (95% in-band power):

Required Channel Bandwidth: $B_{h\_95\%} = 2/\tau = 2R_b$

Bandwidth Efficiency of Binary PAM

- Bandwidth Efficiency : $\gamma = \dfrac{\text{Information Bit Rate } R_b}{\text{Required Channel Bandwidth } B_h}$

- Bandwidth Efficiency of Binary PAM:

$$R_b = 1/\tau$$

$$B_{h\_90\%} = 1/\tau$$

$$B_{h\_95\%} = 2/\tau$$

$\Rightarrow$

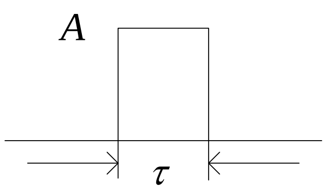
$\gamma_{BPAM} = 1$ with 90% in-band power

$\gamma_{BPAM} = 0.5$ with 95% in-band power

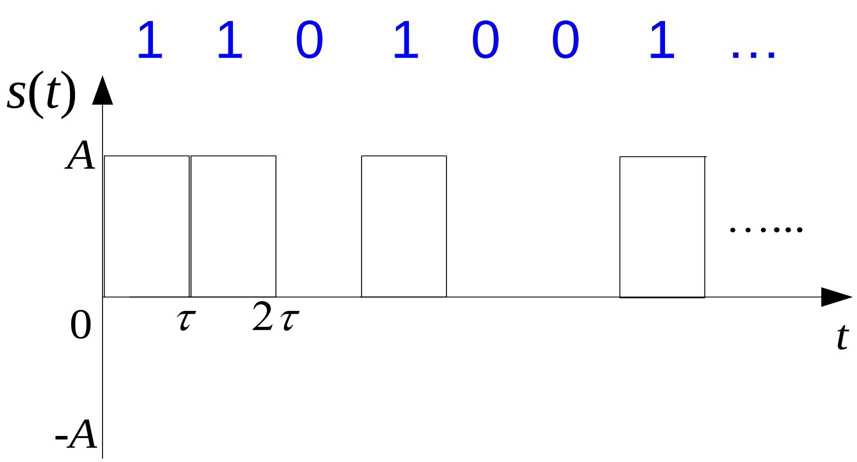
What if the two pulses have unsymmetrical amplitudes?

Binary On-Off Keying (OOK)

1: a positive rectangular pulse with amplitude A and width τ



0: nothing (can be regarded as a pulse with amplitude 0)



$$s(t) = \sum_{n=-\infty}^{\infty} Z_n \cdot v(t - n\tau)$$

✓ $\Pr\{Z_n = 1\} = \Pr\{Z_n = 0\} = 1/2$

✓ $v(t) = \begin{cases} A, & 0 \le t \le \tau \\ 0, & \text{otherwise} \end{cases}$

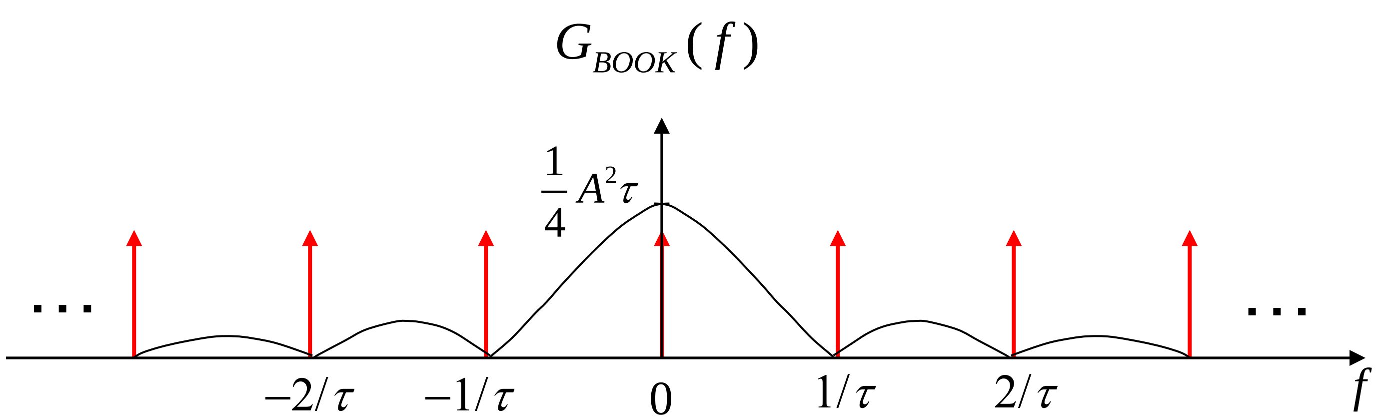
Power Spectrum of Binary OOK

$$G_s(f) = \frac{1}{\tau}|V(f)|^2 \cdot \left(\sigma_Z^2 + \frac{\mu_Z^2}{\tau} \sum_{m=-\infty}^{\infty} \delta\left(f - \frac{m}{\tau} \right) \right)$$

With Binary OOK: $V(f) = A\tau \mathrm{sinc}(f\tau)$

$$\mu_Z = 1/2, \ \sigma_Z^2 = 1/4$$

$$G_{BOOK}(f) = \frac{1}{\tau}\left(A\tau \mathrm{sinc}(f\tau) \right)^2 \cdot \left(\frac{1}{4} + \frac{1}{4\tau} \sum_{m=-\infty}^{\infty} \delta\left(f - \frac{m}{\tau} \right) \right)$$



Bandwidth Efficiency of Binary OOK

- Bandwidth Efficiency : $\gamma = \dfrac{\text{Information Bit Rate } R_b}{\text{Required Channel Bandwidth } B_h}$

- Bandwidth Efficiency of Binary OOK:

$$R_b = 1/\tau$$

$$B_{h\_90\%} = 1/\tau$$

$$B_{h\_95\%} = 2/\tau$$

$$\Rightarrow$$

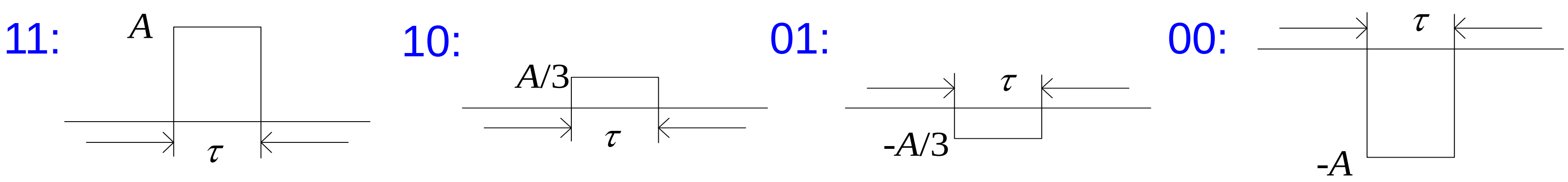
$\gamma_{BOOK} = 1$ with 90% in-band power

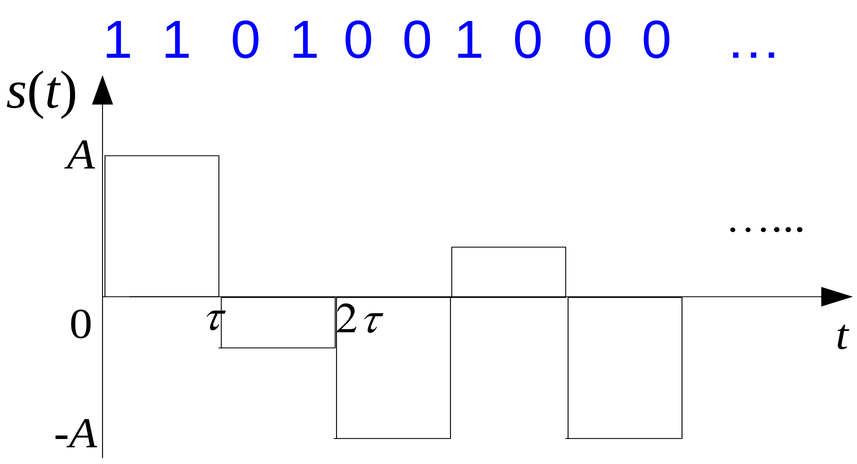
$\gamma_{BOOK} = 0.5$ with 95% in-band power

Can we improve the bandwidth efficiency without sacrificing the in-band power?

4-ary PAM

- 4-ary PAM: Each waveform carries 2-bit information.





$$s(t)=\sum_{n=-\infty}^{\infty} Z_n \cdot v(t-n\tau)$$

✓ $\Pr\{Z_n=1\}=\Pr\{Z_n=1/3\}$
$=\Pr\{Z_n=-1\}=\Pr\{Z_n=-1/3\}$
$=1/4$

✓ $v(t)=\begin{cases} A, & 0\le t\le \tau \\ 0, & \text{otherwise}\end{cases}$

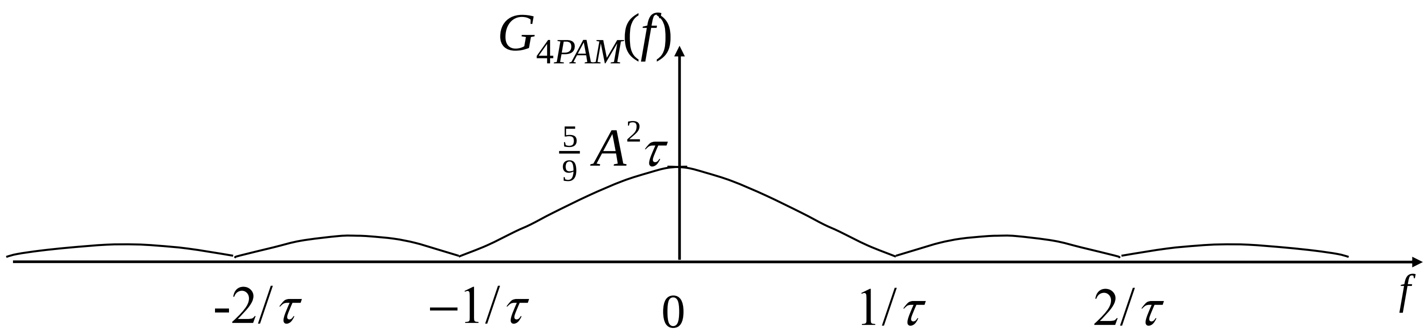
Power Spectrum of 4-ary PAM

$$G_s(f) = \frac{1}{\tau}|V(f)|^2 \cdot \left(\sigma_Z^2 + \frac{\mu_Z^2}{\tau}\sum_{m=-\infty}^{\infty}\delta\left(f - \frac{m}{\tau}\right)\right)$$

With 4-ary PAM: $V(f) = A\tau\text{sinc}(f\tau)$

$$\mu_Z = 0, \ \ \sigma_Z^2 = 5/9$$

$$\Rightarrow G_{4PAM}(f) = \tfrac{5}{9}A^2\tau\text{sinc}^2(f\tau)$$



- Required channel bandwidth with 90% in-band power: $B_{h\_90\%} = 1/\tau$
- Required channel bandwidth with 95% in-band power: $B_{h\_95\%} = 2/\tau$

Bandwidth Efficiency of 4-ary PAM

- Symbol rate: $R_S = 1/\tau$
- Bit rate: $R_b = 2 \cdot R_S = 2/\tau$
- Require channel bandwidth:

with 90% in-band power: $B_{h\_90\%} = 1/\tau = R_S = \frac{1}{2} R_b$

with 95% in-band power: $B_{h\_95\%} = 2/\tau = 2R_S = R_b$

$\Rightarrow$

$\gamma_{4PAM} = 2$ with 90% in-band power

$\gamma_{4PAM} = 1$ with 95% in-band power

4-ary PAM achieves higher bandwidth efficiency than binary PAM!

Bandwidth Efficiency of M-ary PAM

- Suppose there are totally M distinct amplitude (power) levels.
- How many bits are carried by each symbol?

$$M = 2^k \Rightarrow k = \log_2 M$$

- What is the relationship between symbol rate R_S and bit rate R_b?

$$R_S = R_b / k \quad \text{or} \quad R_b = kR_S$$

- What is the required channel bandwidth with 90% in-band power?

$$B_{h\_90\%} = R_S = R_b / k$$

- Bandwidth Efficiency of M-ary PAM

Tradeoff between bandwidth efficiency and fidelity performance

$$\boxed{\gamma_{MPAM} = k = \log_2 M \quad \text{with 90\% in-band power}}$$

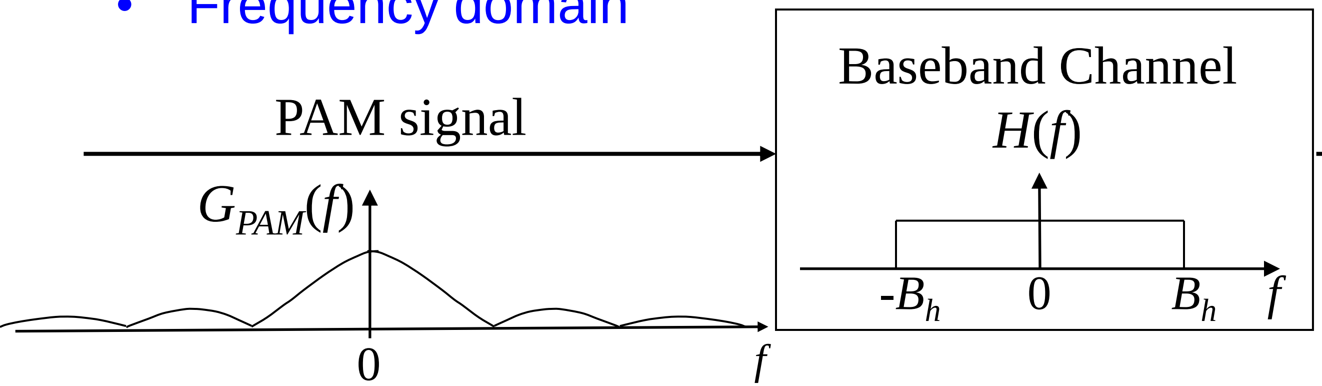
- A larger M also leads to a smaller minimal amplitude difference – higher error probability (to be discussed).

Pulse Shaping

- Inter-Symbol Interference (ISI)
- Sinc-Shaped Pulse and Raised-Cosine Pulse

Transmission over Bandlimited Channel

- Frequency domain



$$G_Y(f) = G_{PAM}(f)\,|H(f)|^2$$

The signal distortion incurred by channel is always non-zero!!

- Time domain

PAM signal → Baseband Channel $h(t)$

$$s(t) = \sum_{n=-\infty}^{\infty} Z_n \cdot v(t - n\tau)$$

$$y(t) = s(t) * h(t) = \sum_{n=-\infty}^{\infty} Z_n \cdot x(t - n\tau)$$

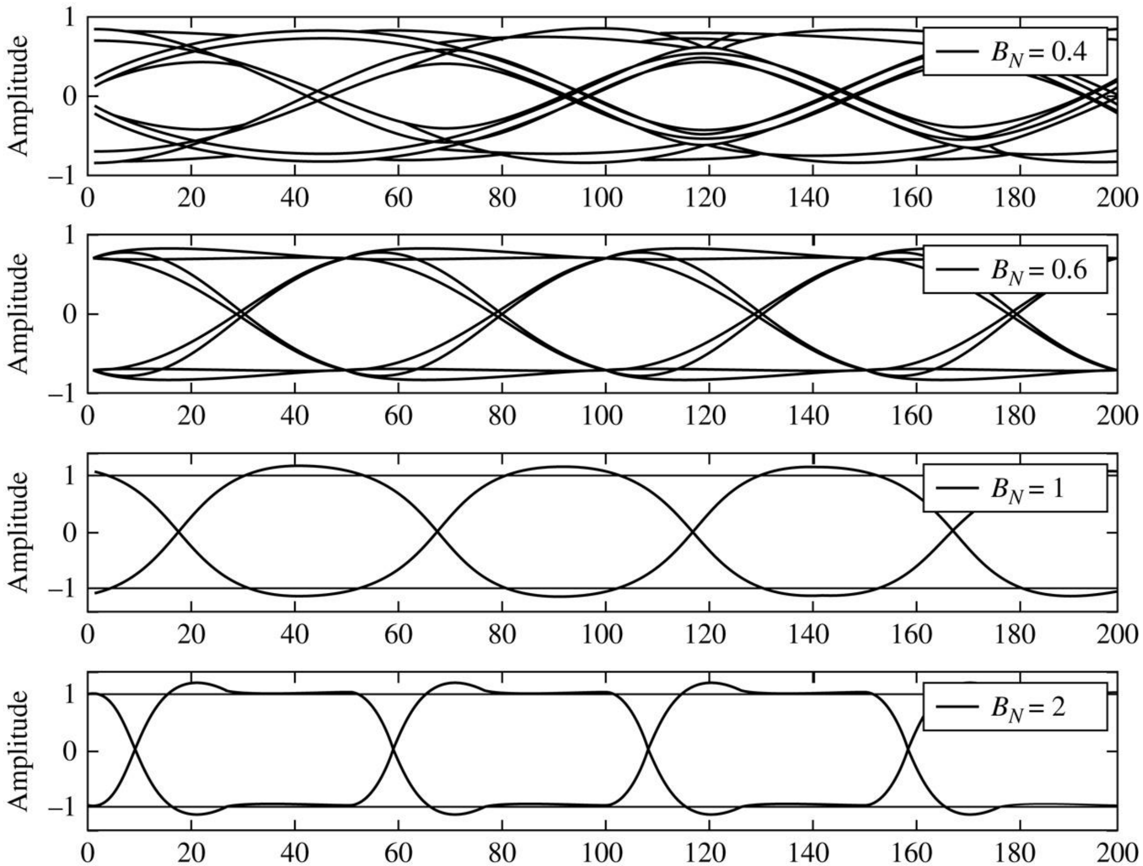
$$x(t) = v(t) * h(t)$$

Sample $y(t)$ at $m\tau$, $m=1,2,\ldots$, we have

$$y(m\tau) = \sum_{n=-\infty}^{\infty} Z_n \cdot x(m\tau - n\tau) = Z_m \cdot x(0) + \sum_{n \neq m} Z_n \cdot x(m\tau - n\tau)$$

Inter-symbol Interference (ISI)!

ISI and Eye Diagram



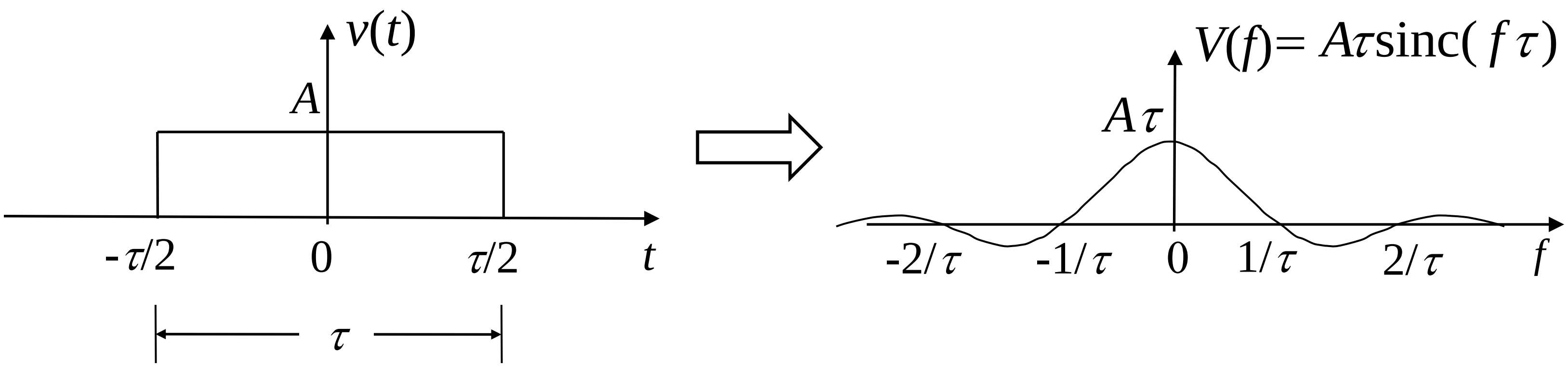
- An eye diagram is constructed by plotting overlapping k-symbol segments of a baseband signal.
- An eye diagram can be displayed on an oscillo-scope by triggering the time sweep of the oscilloscope.

See Reference [Ziemer & Tranter] (Sec. 4.6) for more details about eye diagram.

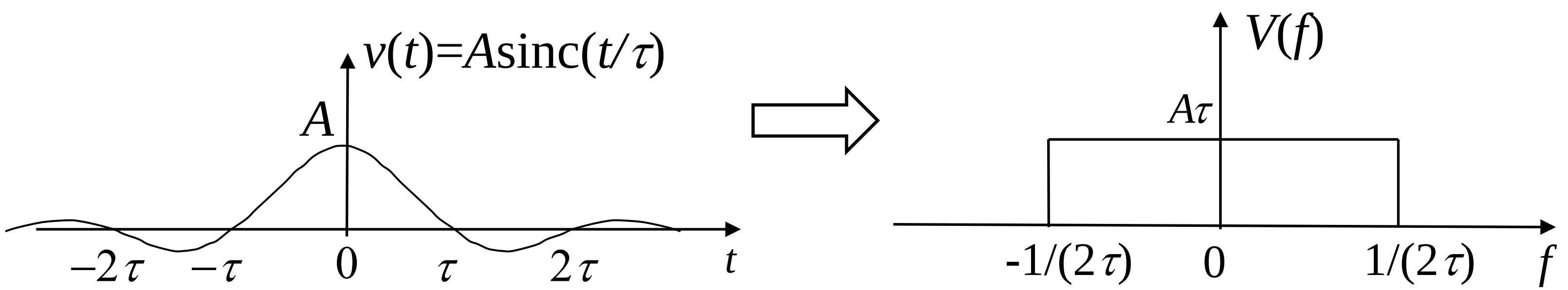
- ISI is caused by insufficient channel bandwidth.
- Any better choice than rectangular pulse?

Sinc-Shaped pulse

Sinc-Shaped Pulse



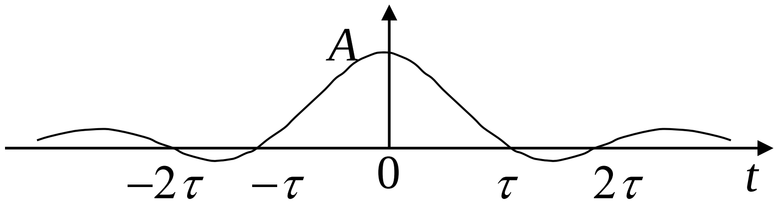
Rectangular Pulse



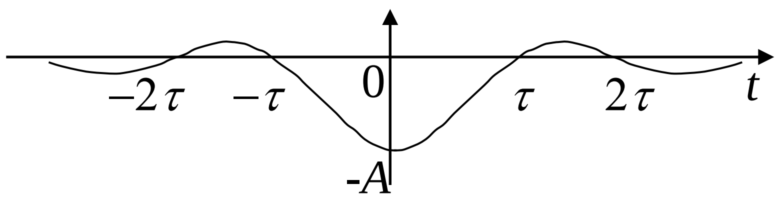
Sinc-Shaped Pulse

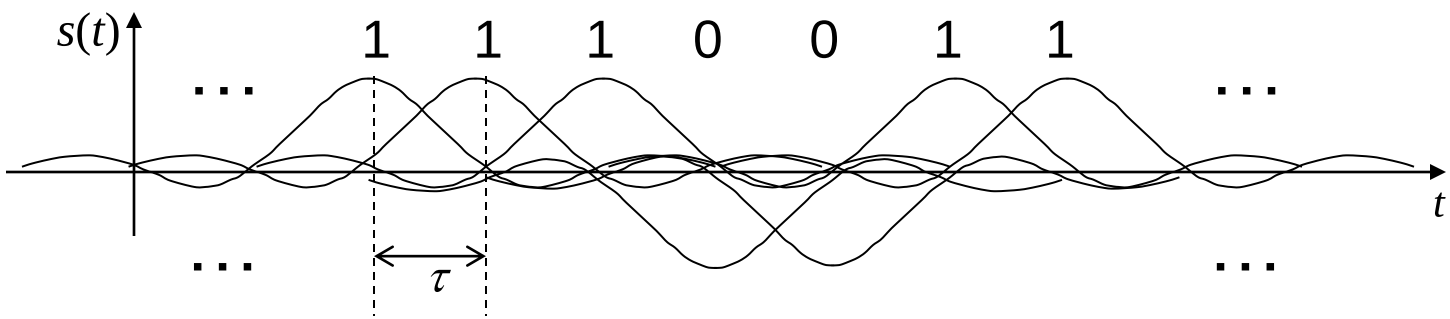
Binary Sinc-Shaped-Pulse Modulated Signal

1: a positive sinc-shaped pulse with amplitude A and first crossing-zero point $\pm\tau$



0: a negative sinc-shaped pulse with amplitude -A and first crossing-zero point $\pm\tau$





$$s(t) = \sum_{n=-\infty}^{\infty} Z_n \cdot v(t - n\tau)$$

✓ $\Pr\{Z_n = \pm 1\} = 1/2$

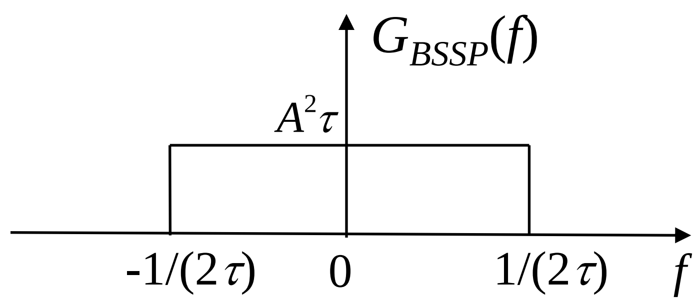
✓ $v(t) = A\mathrm{sinc}(t/\tau)$

Power Spectrum of Sinc-Shaped-Pulse Modulated Signal

$$G_s(f) = \frac{1}{\tau}|V(f)|^2 \cdot \left(\sigma_Z^2 + \frac{\mu_Z^2}{\tau} \sum_{m=-\infty}^{\infty} \delta\left(f - \frac{m}{\tau} \right) \right)$$

With Binary Sinc-Shaped-Pulse Modulated Signal: $\mu_Z = 0,\ \sigma_Z^2 = 1$, $V(f) = A\tau, \quad |f| \le \frac{1}{2\tau}$

$$G_{BSSP}(f) = A^2\tau, \quad |f| \le \frac{1}{2\tau}$$



Bit Rate: $R_b = 1/\tau$

Required channel bandwidth: $B_h = 1/(2\tau) = R_b/2$

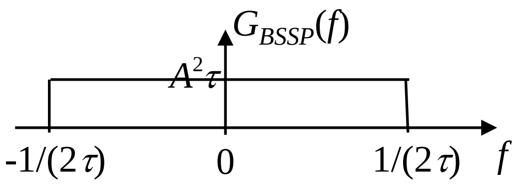
$\gamma_{BSSP} = 2$

(with 100% in-band power)

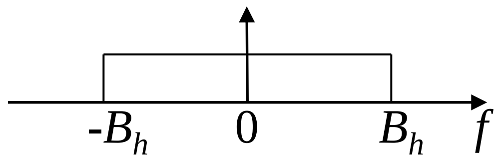
Sinc-Shaped-Pulse Modulated Signal over Bandlimited Channel

- Frequency domain

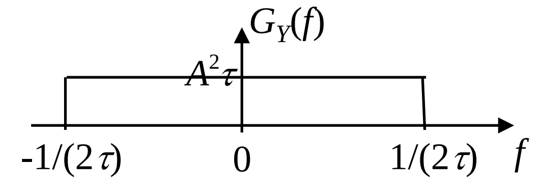
Binary Sinc-Shaped-Pulse signal



Baseband Channel $H(f)$



$$G_Y(f) = G_{BSSP}(f)\,|H(f)|^2$$



- Time domain

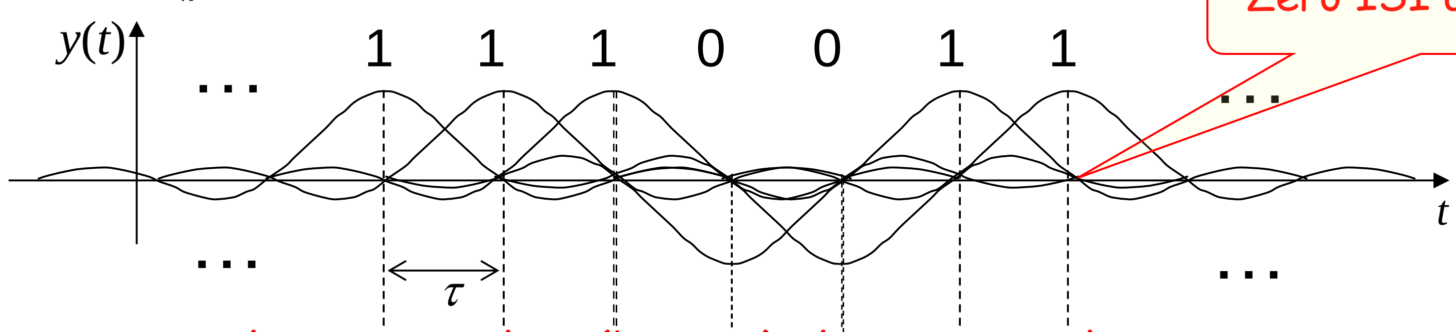
Binary Sinc-Shaped-Pulse signal

$$s(t) = \sum_{n=-\infty}^{\infty} Z_n \cdot v(t - n\tau)$$

Baseband Channel $h(t)$

$$y(t) = s(t) * h(t)$$

Zero ISI at $t=m\tau$!



Are there any other (better) choices to achieve zero ISI?

Nyquist Pulse-Shaping Criterion for Zero ISI

Nyquist pulse-shaping criterion for zero ISI

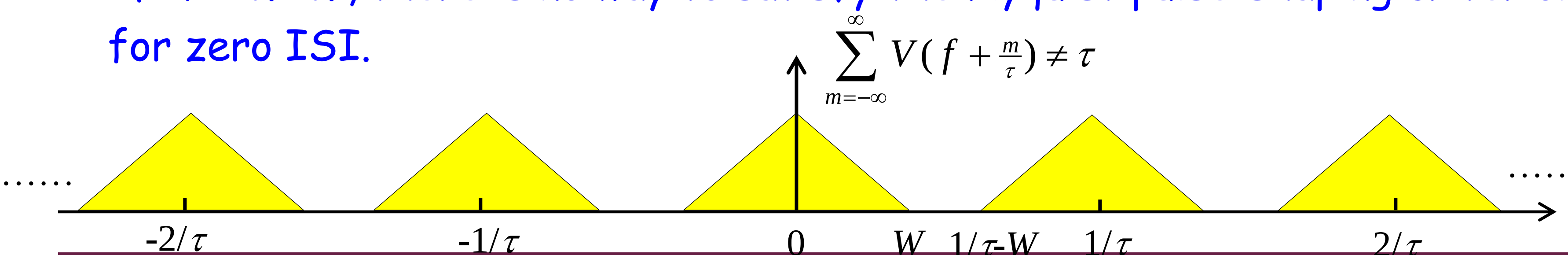
A necessary and sufficient condition for pulse $v(t)$ to satisfy

$$v(n\tau) = \begin{cases} 1, & n = 0 \\ 0, & n \neq 0 \end{cases}$$

is that its Fourier transform $V(f)$ satisfies $\sum_{m=-\infty}^{\infty} V(f + \frac{m}{\tau}) = \tau$.

Suppose that the bandwidth of unit pulse v(t) is W, which is also the required channel bandwidth. To pass the digital modulated signal with symbol rate $1/\tau$ through the channel:

- If $1/\tau$-W>W, there is no way to satisfy the Nyquist pulse-shaping criterion for zero ISI.



Nyquist Pulse-Shaping Criterion for Zero ISI

Nyquist pulse-shaping criterion for zero ISI

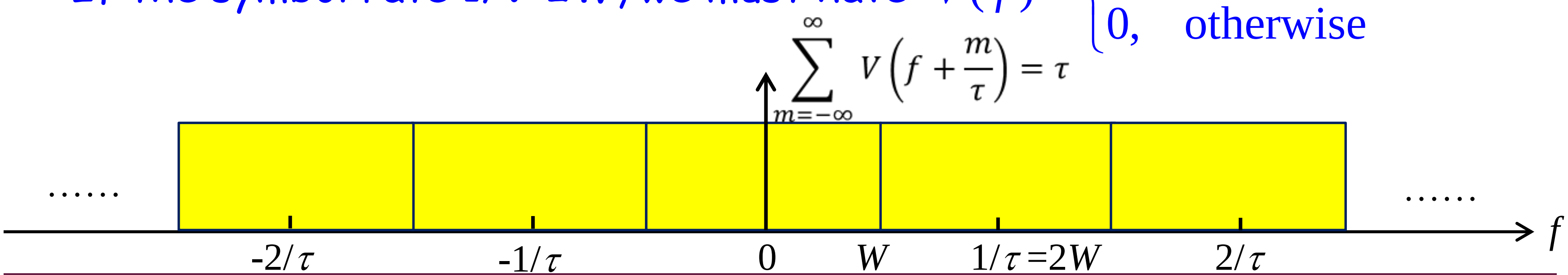
A necessary and sufficient condition for pulse $v(t)$ to satisfy

$$v(n\tau) = \begin{cases} 1, & n = 0 \\ 0, & n \neq 0 \end{cases}$$

is that its Fourier transform $V(f)$ satisfies $\sum_{m=-\infty}^{\infty} V(f + \frac{m}{\tau}) = \tau$.

Suppose that the bandwidth of unit pulse v(t) is W, which is also the required channel bandwidth. To pass the digital modulated signal with symbol rate $1/\tau$ through the channel:

- If the symbol rate $1/\tau = 2W$, we must have $V(f) = \begin{cases} \tau, & |f| < W \\ 0, & \text{otherwise} \end{cases}$



Nyquist Pulse-Shaping Criterion for Zero ISI

Nyquist pulse-shaping criterion for zero ISI

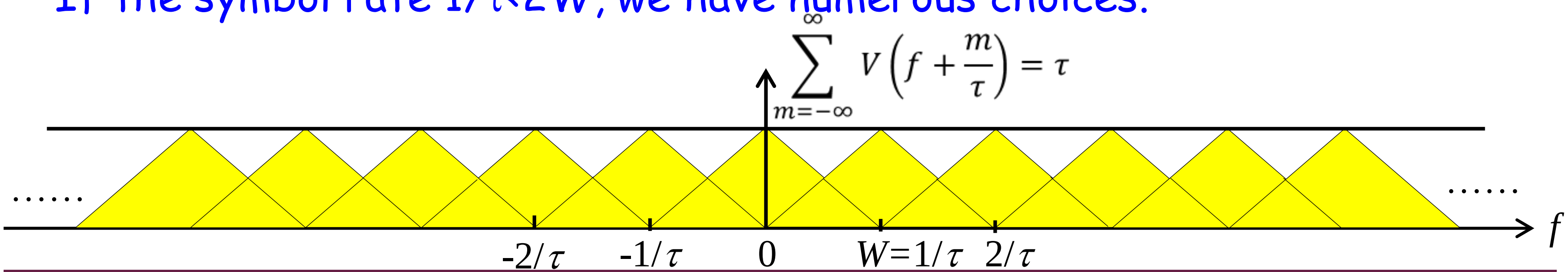
A necessary and sufficient condition for pulse $v(t)$ to satisfy

$$v(n\tau) = \begin{cases} 1, & n = 0 \\ 0, & n \neq 0 \end{cases}$$

is that its Fourier transform $V(f)$ satisfies $\sum_{m=-\infty}^{\infty} V(f + \frac{m}{\tau}) = \tau$.

Suppose that the bandwidth of unit pulse v(t) is W, which is also the required channel bandwidth. To pass the digital modulated signal with symbol rate $1/\tau$ through the channel:

- If the symbol rate $1/\tau < 2W$, we have numerous choices.



Nyquist Pulse-Shaping Criterion for Zero ISI

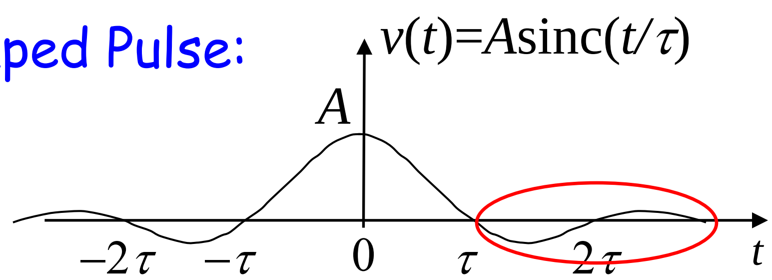
According to Nyquist pulse-shaping criterion for zero ISI:

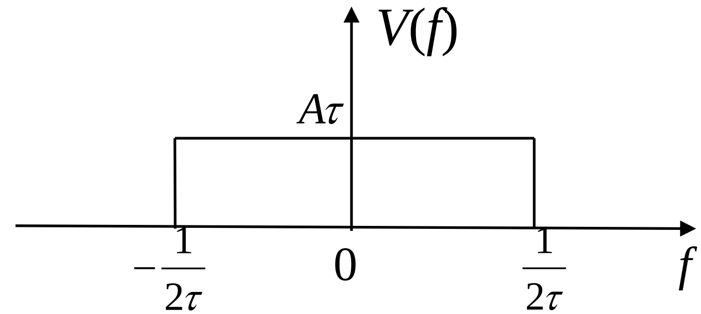
- ✓ If the symbol rate $1/\tau > 2W$, there is no way that we can design a system with zero ISI.
- ✓ If the symbol rate $1/\tau = 2W$, we must have $V(f) = \begin{cases} \tau, & |f| < W \\ 0, & \text{otherwise} \end{cases}$
  - The maximum symbol rate for zero ISI is 2W.
  - In the binary case, the highest bandwidth efficiency for zero-ISI is 2, which is achieved by the binary sinc-shaped-pulse modulated signal.
- ✓ If the symbol rate $1/\tau < 2W$, we have numerous choices. One of them is called Raised-Cosine Pulse.

$\boxed{\text{See Textbook (Sec. 4.4) for more details.}}$

Raised-Cosine Pulse: Tradeoff between Bandwidth Efficiency and Robustness

Sinc-Shaped Pulse:

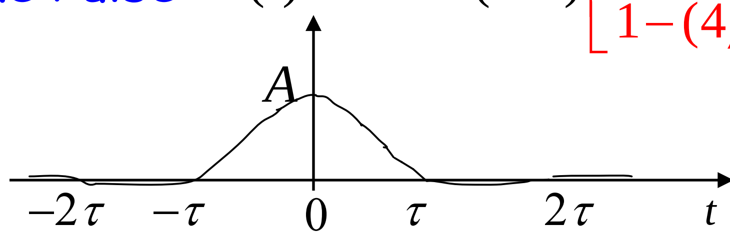


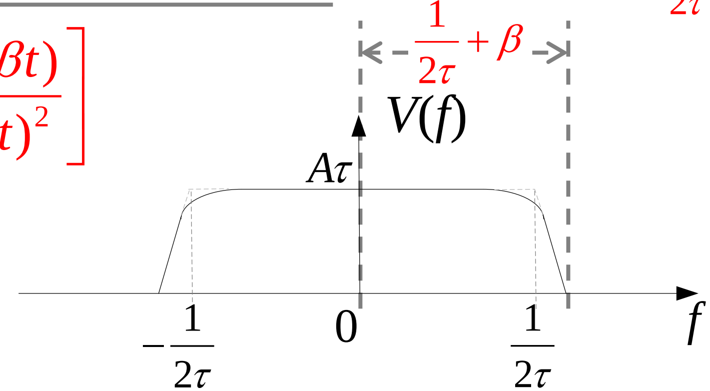


- Strong ISI at $t \neq n\tau$.
- Perfect synchronization is required at the receiver side.

Raised-Cosine Pulse: $v(t) = A\mathrm{sinc}(t/\tau)\left[\dfrac{\cos(2\pi\beta t)}{1-(4\beta t)^2}\right]$

$0 \le \beta \le \dfrac{1}{2\tau}$





- Larger β → More robust; Larger bandwidth

Summary I: Digital Baseband Modulation

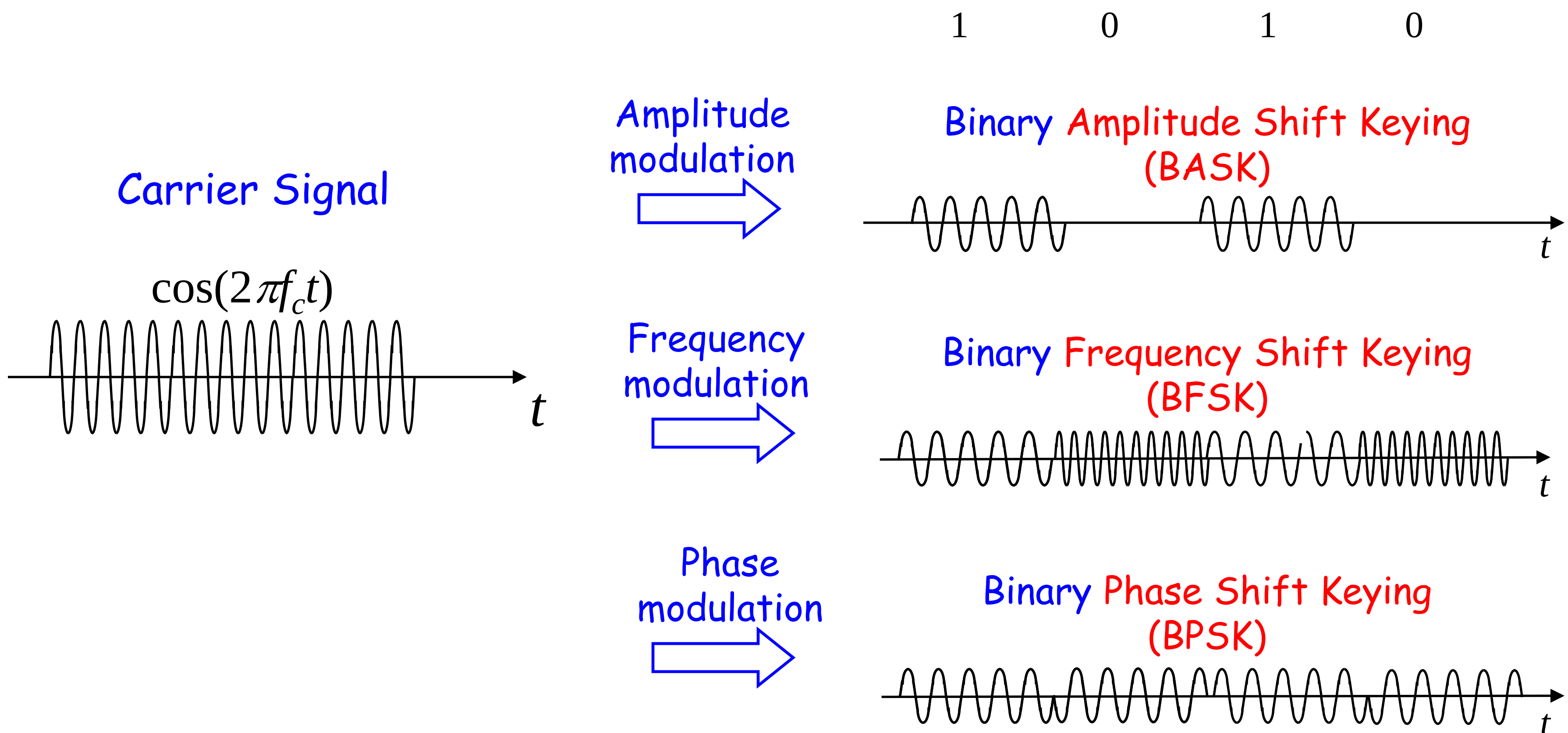
<table>
<tr><th colspan="2"></th><th>Complexity</th><th>Bandwidth Efficiency</th></tr>
<tr><td rowspan="2">PAM</td><td>Binary PAM</td><td>Low</td><td>1 (90% in-band power)</td></tr>
<tr><td>4-ary PAM</td><td>Low</td><td>2 (90% in-band power)</td></tr>
<tr><td colspan="2">Binary Sinc-Shaped-Pulse Modulation</td><td>High (Susceptible to timing jitter)</td><td>2 (100% in-band power)</td></tr>
<tr><td colspan="2">Binary Raised-Cosine-Pulse Modulation</td><td>Moderate</td><td>$1 < \frac{R_b}{\frac{1}{2}R_b + \beta} < 2$
(100% in-band power)</td></tr>
</table>

Digital Bandpass Modulation

- Binary ASK
- Binary FSK
- Binary PSK
- Quaternary PSK

Digital Bandpass Modulation

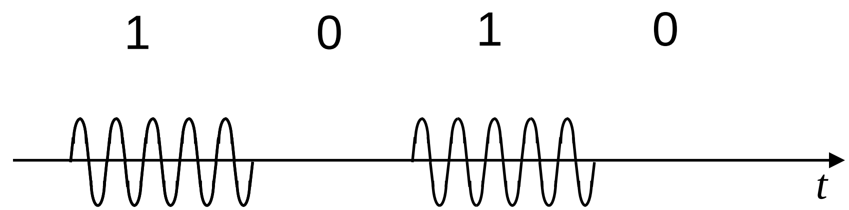
- How to transmit a baseband signal over a bandpass channel?



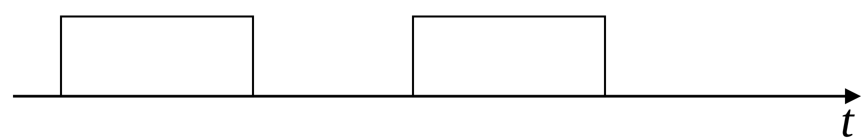
Binary Amplitude Shift Keying (ASK)

- Generate a binary ASK signal:
  - Send the carrier signal if the information bit is “1”;
  - Send 0 volts if the information bit is “0”.

$$s_{BASK}(t) = s_{BOOK}(t)\cos(2\pi f_c t)$$

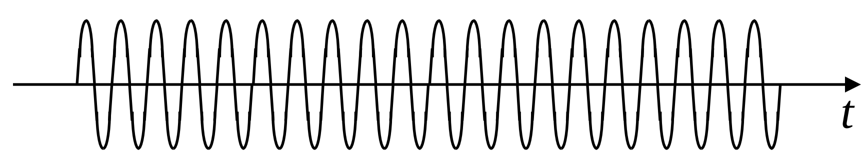


Binary On-Off Keying $s_{BOOK}(t)$



X

$\cos(2\pi f_c t)$



Power Spectrum of BASK

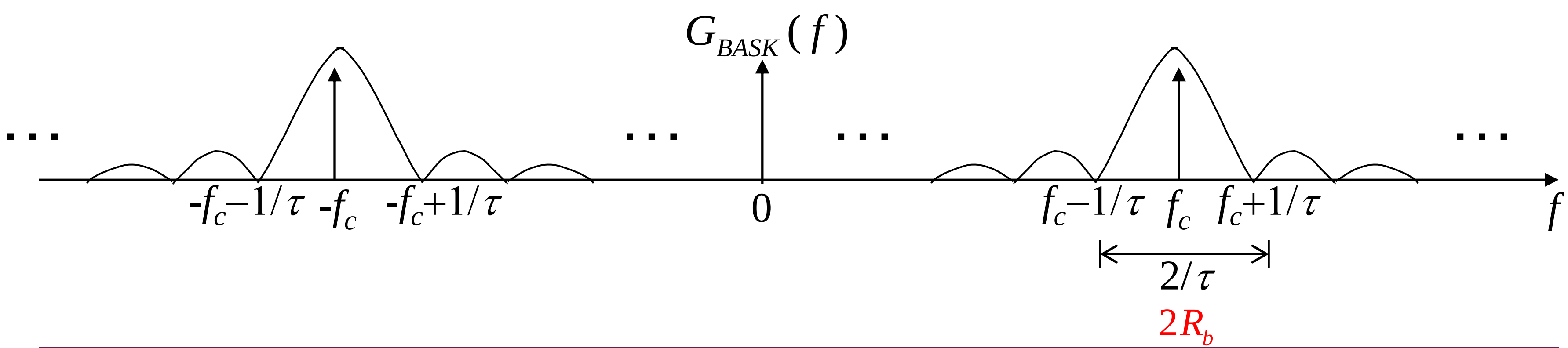
- Power spectrum of Binary OOK:

$$G_{BOOK}(f) = \frac{1}{\tau}\left(A\tau \operatorname{sinc}(f\tau)\right)^2 \cdot \left(\frac{1}{4} + \frac{1}{4\tau}\sum_{m=-\infty}^{\infty}\delta\left(f - \frac{m}{\tau}\right)\right)$$

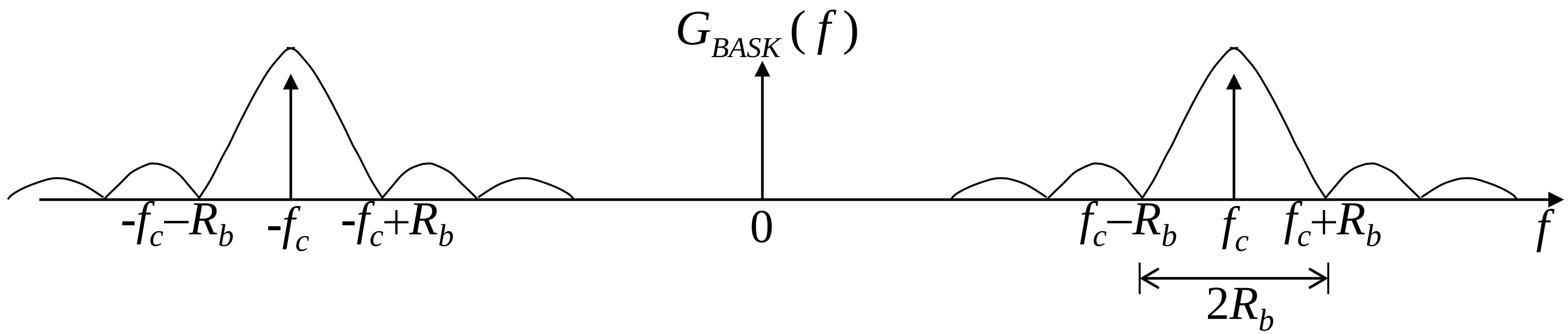
- Power spectrum of Binary ASK:

Read the supplemental material for details.

$$G_{BASK}(f) = \tfrac{1}{4}[G_{BOOK}(f - f_c) + G_{BOOK}(f + f_c)]$$



Bandwidth Efficiency of BASK



The bandwidth of BASK signal is twice of that of its baseband signal (binary On-Off Keying)!

- The required channel bandwidth for 90% in-band power:

$$B_{h\_90\%} = 2R_b$$

- Bandwidth Efficiency of BASK:

$\gamma_{BASK} = 0.5$ with 90% in-band power

$\gamma_{BASK} = 0.25$ with 95% in-band power

Binary Frequency Shift Keying (BFSK)

- Generate a binary FSK signal:
  - Send the signal $A\cos(2\pi(f_c+\Delta f)t)$ if the information bit is "1";
  - Send the signal $A\cos(2\pi(f_c-\Delta f)t)$ if the information bit is "0".

Frequency offset

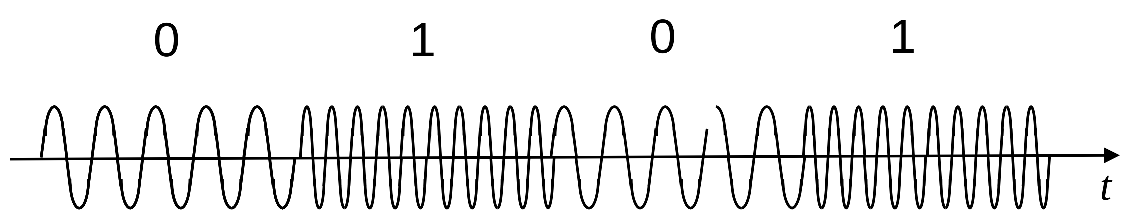
$$s_{BFSK}(t) = \underbrace{s_{b1,BFSK}(t)}\cos(2\pi(f_c+\Delta f)t) + \underbrace{s_{b2,BFSK}(t)}\cos(2\pi(f_c-\Delta f)t)$$

$$s_{b1,BFSK}(t) = \begin{cases} A & b_i = 1 \\ 0 & b_i = 0 \end{cases}$$

Binary On-Off Keying

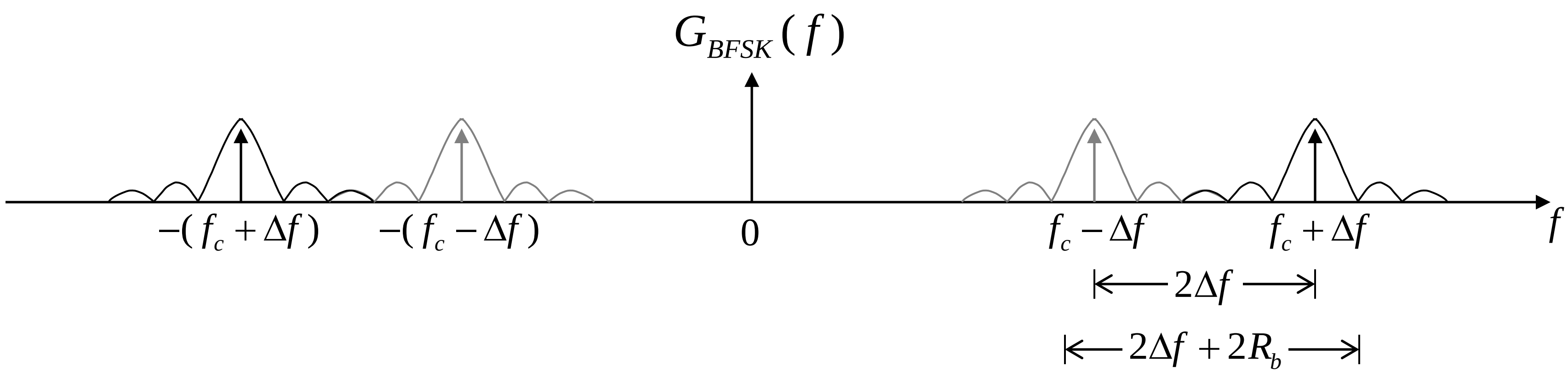
$$s_{b2,BFSK}(t) = \begin{cases} 0 & b_i = 1 \\ A & b_i = 0 \end{cases}$$

Binary On-Off Keying



Bandwidth Efficiency of BFSK

$$G_{BFSK}(f) = \tfrac{1}{4}[G_{b1,BFSK}(f-(f_c+\Delta f)) + G_{b1,BFSK}(f+(f_c+\Delta f))]$$
$$+\tfrac{1}{4}[G_{b2,BFSK}(f-(f_c-\Delta f)) + G_{b2,BFSK}(f+(f_c-\Delta f))]$$



- The required channel bandwidth for 90% in-band power:

$$B_{h\_90\%} = 2\Delta f + 2R_b$$

- Bandwidth efficiency of BFSK:
  (with 90% in-band power)

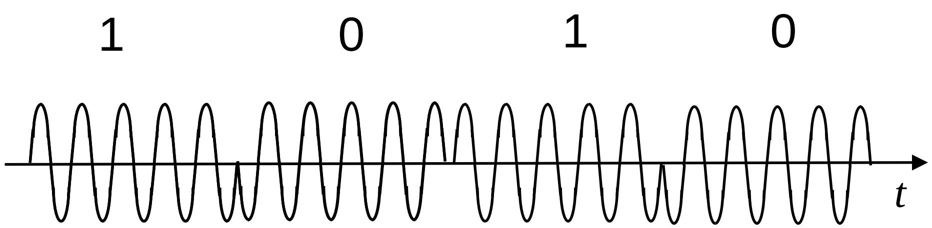
$$\gamma_{BFSK} = 0.5 \cdot \frac{1}{1+\Delta f / R_b} < 0.5 = \gamma_{BASK}$$

The bandwidth efficiency of BFSK signal is lower than that of BASK signal!

Binary Phase Shift Keying (BPSK)

- Generate a binary PSK signal:
  - Send the signal $A\cos(2\pi f_c t)$ if the information bit is "1";
  - Send the signal $A\cos(2\pi f_c t+\pi)$ if the information bit is "0".
    $=-A\cos(2\pi f_c t)$

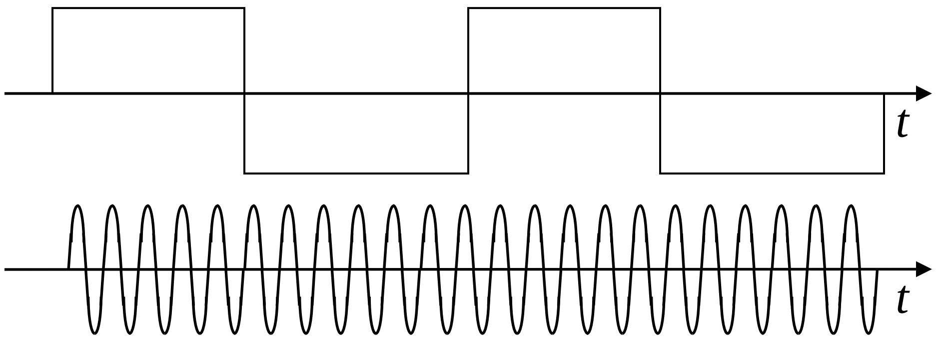
$s_{BPSK}(t) = s_{BPAM}(t)\cos(2\pi f_c t)$



Binary PAM $s_{BPAM}(t)$

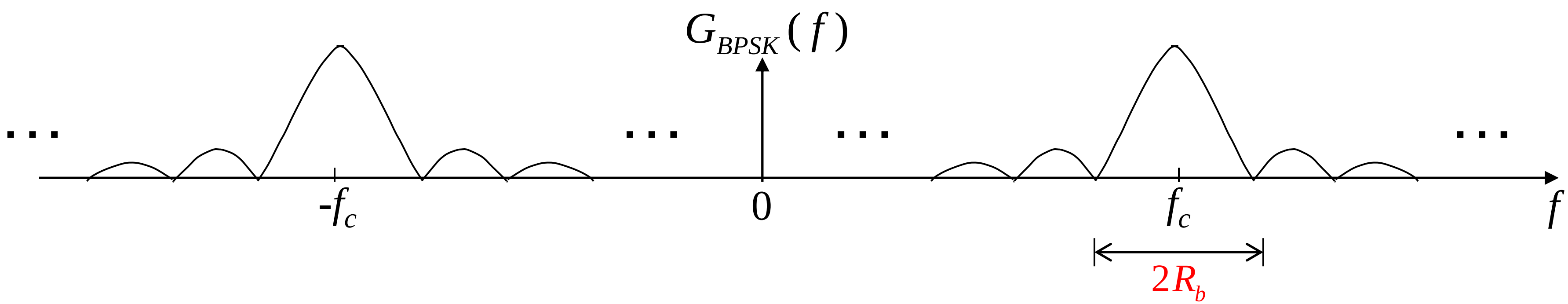
X

$\cos(2\pi f_c t)$



Bandwidth Efficiency of BPSK

$$G_{BPSK}(f) = \frac{1}{4}[G_{BPAM}(f - f_c) + G_{BPAM}(f + f_c)]$$



- The required channel bandwidth for 90% in-band power:

$$B_{h\_90\%} = 2R_b$$

- Bandwidth Efficiency of BPSK:

$$\boxed{\begin{array}{l} \gamma_{BPSK} = 0.5 \text{ with 90\% in-band power} \\ \gamma_{BPSK} = 0.25 \text{ with 95\% in-band power} \end{array}}$$

The bandwidth efficiency of BPSK signal is the same as that of BASK signal!

M-ary PSK

- M-ary PSK: transmitting pulses with M possible different carrier phases, and allowing each pulse to represent $\log_2 M$ bits.

✓ Binary PSK:

"1" $s_1(t) = A\cos(2\pi f_c t)$

"0" $s_2(t) = A\cos(2\pi f_c t + \pi)$

✓ Quaternary PSK: (QPSK)

"11" $s_1(t) = A\cos(2\pi f_c t + (-\pi/4))$

"10" $s_2(t) = A\cos(2\pi f_c t + \pi/4)$

"00" $s_3(t) = A\cos(2\pi f_c t + 3\pi/4)$

"01" $s_4(t) = A\cos(2\pi f_c t + 5\pi/4)$

QPSK

"1 1" $s_1(t) = A\cos(2\pi f_c t - \pi/4)$

"1 0" $s_2(t) = A\cos(2\pi f_c t + \pi/4)$

"0 0" $s_3(t) = A\cos(2\pi f_c t + 3\pi/4)$

"0 1" $s_4(t) = A\cos(2\pi f_c t + 5\pi/4)$

A QPSK signal can be decomposed into the sum of two PSK signals: an in-phase component and a quadrature component.

$$s_{QPSK}(t) = d_I \frac{A}{\sqrt{2}} \cos(2\pi f_c t) + d_Q \frac{A}{\sqrt{2}} \sin(2\pi f_c t)$$

$$d_I = \begin{cases} 1 & \text{if } b_{2i-1} = 1 \\ -1 & \text{if } b_{2i-1} = 0 \end{cases}$$

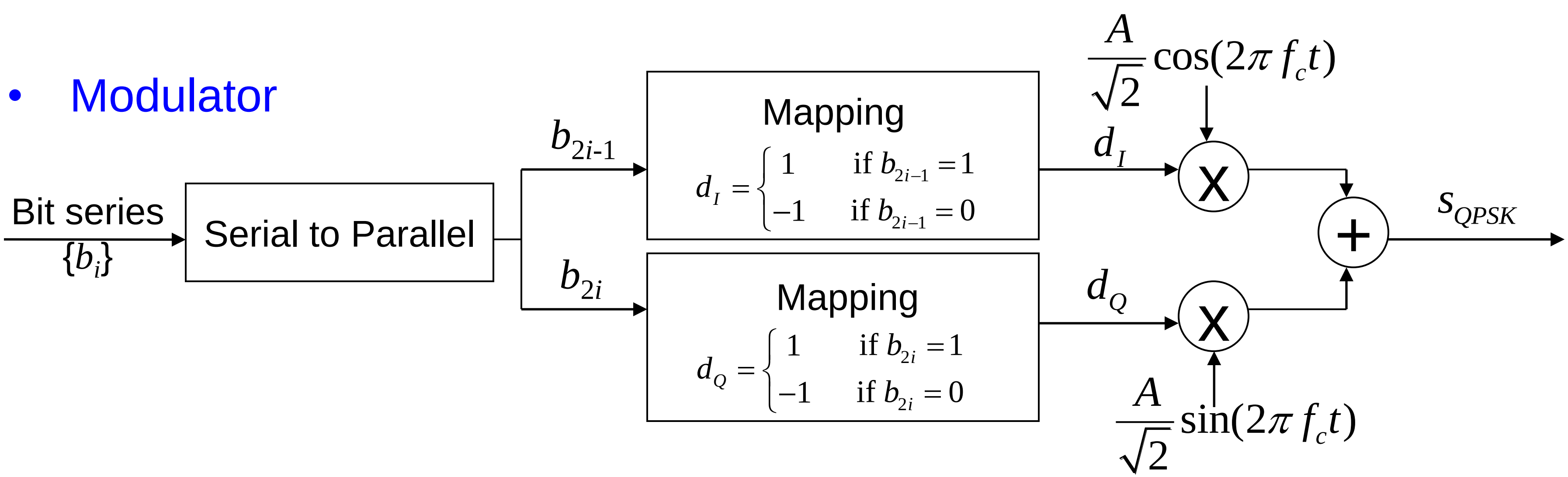
$$d_Q = \begin{cases} 1 & \text{if } b_{2i} = 1 \\ -1 & \text{if } b_{2i} = 0 \end{cases}$$

QPSK Modulator

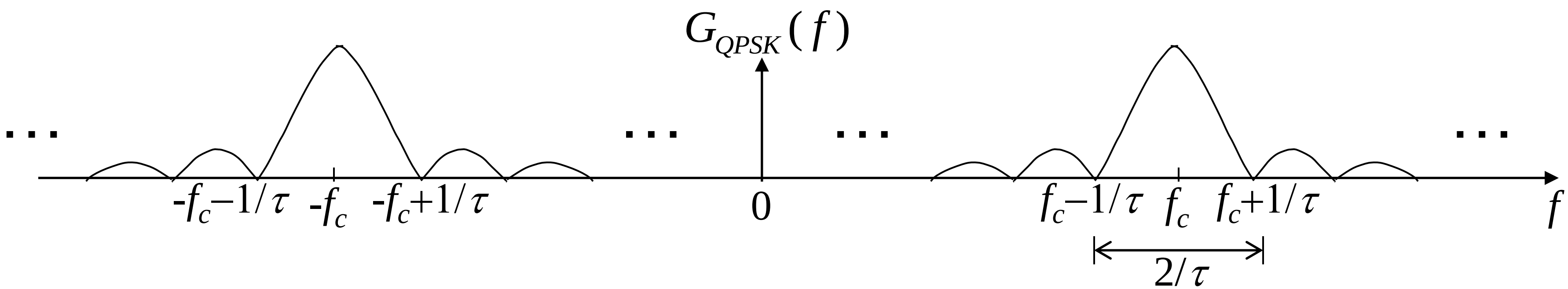
$$s_{QPSK}(t) = d_I \frac{A}{\sqrt{2}} \cos(2\pi f_c t) + d_Q \frac{A}{\sqrt{2}} \sin(2\pi f_c t)$$

$$d_I = \begin{cases} 1 & \text{if } b_{2i-1} = 1 \\ -1 & \text{if } b_{2i-1} = 0 \end{cases} \qquad d_Q = \begin{cases} 1 & \text{if } b_{2i} = 1 \\ -1 & \text{if } b_{2i} = 0 \end{cases}$$

- Modulator



Bandwidth Efficiency of QPSK



- Symbol rate: $R_{S,QPSK} = 1/\tau$
- Bit rate: $R_{b,QPSK} = 2R_{S,QPSK} = 2/\tau$
- Required Channel Bandwidth: $B_{h\_90\%} = 2R_{S,QPSK} = R_{b,QPSK}$

  $B_{h\_95\%} = 4R_{S,QPSK} = 2R_{b,QPSK}$
- Bandwidth Efficiency:

$$\boxed{\begin{array}{ll} \gamma_{QPSK} = 1 & \text{with 90\% in-band power} \\ \gamma_{QPSK} = 0.5 & \text{with 95\% in-band power} \end{array}}$$

QPSK achieves higher bandwidth efficiency than BPSK!

Summary II: Digital Bandpass Modulation

	Bandwidth Efficiency (90% in-band power)
Binary ASK	0.5
Binary FSK	$0.5 \cdot \dfrac{1}{1 + \Delta f / R_b}$
Binary PSK	0.5
QPSK	1