Wireless Networks & Systems

Spring 2025

Week # 09


Ramadan Mubarak

Course Learning Outcomes (CLOs):

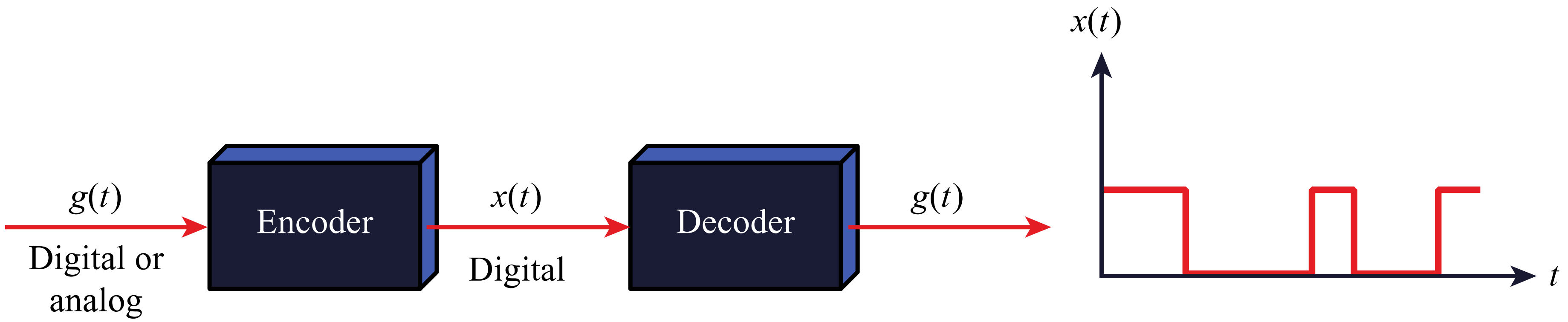
CLO # 01	Demonstrate an in-depth understanding of wireless network system's architecture, protocols, and Services.	**Cog. 3**
CLO # 02	Explore advanced technologies and features in wireless networks related to coverage, capacity, interference management, and mobility.	**Cog. 3**
CLO # 03	Examine the evolution of Wi-Fi networks, highlighting architectural differences across its various standards.	**Cog. 4**
CLO # 04	Analyze key cellular concepts used in cellular networks and the architectural advancements in 5G and beyond.	**Cog. 4**

Wireless Communication Technology:

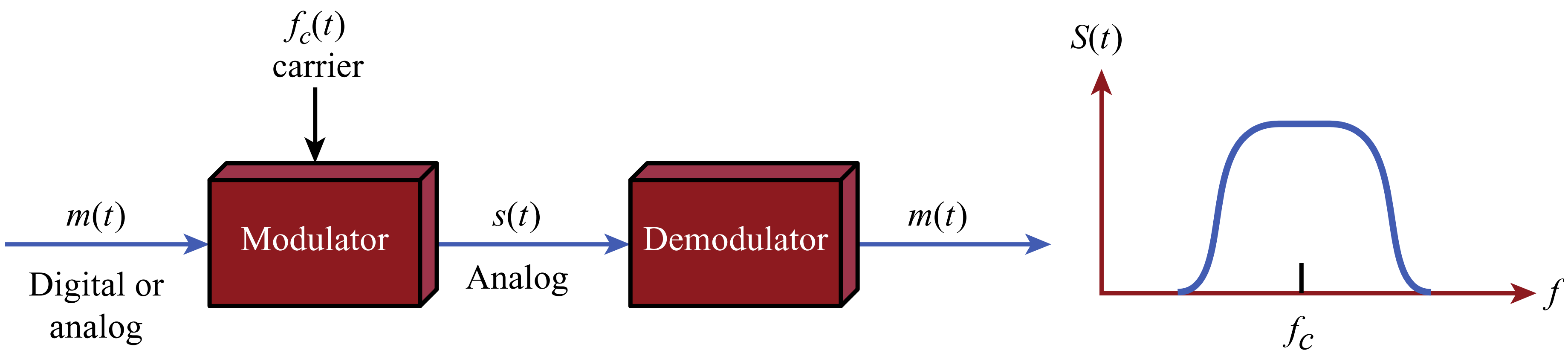
<u>CLO 02 :</u>

- Chapter 05 – Overview of Wireless Communications
- Chapter 06 – The wireless channel
- Chapter 07 – Signal Encoding Techniques
- Chapter 08 – Orthogonal Frequency division multiplexing
- Chapter 09 – Spread Spectrum
- Chapter 10 – Coding and Error Control

Signal Encoding Techniques:

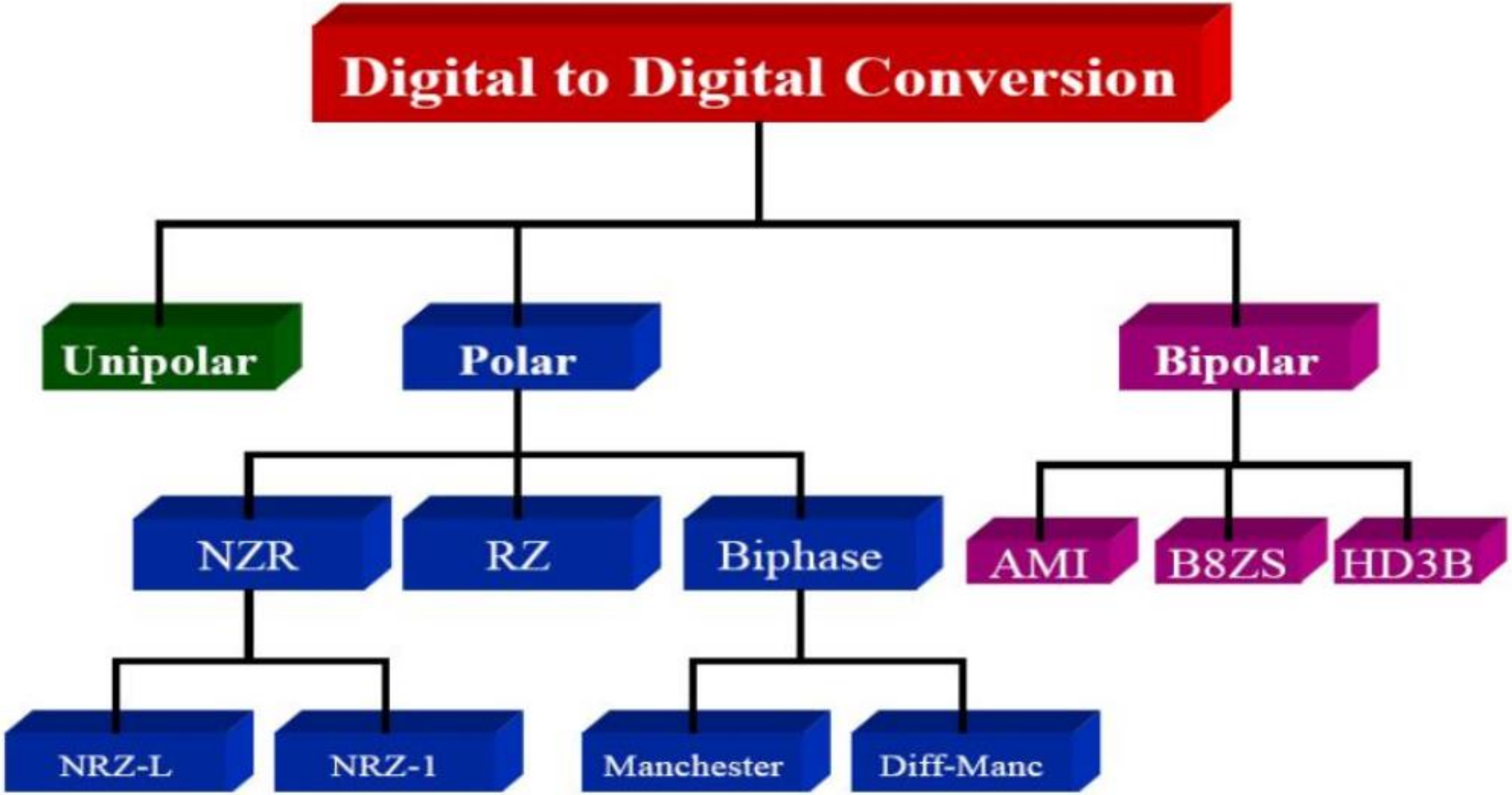


(a) Encoding onto a digital signal



(b) Modulation onto an analog signal

Encoding into Digital Signal:



Modulation onto Analog Signal:

Baseband Modulation:

Low-frequency modulation is called the baseband modulation. Examples are Encoding schemes like unipolar and polar formats.

Passband Modulation:

In this approach, user binary data are multiplied by a high-frequency carrier at the transmitter side. It is a high-frequency modulation.

Modulation onto Analog Signal:

Types of Passband Modulation:

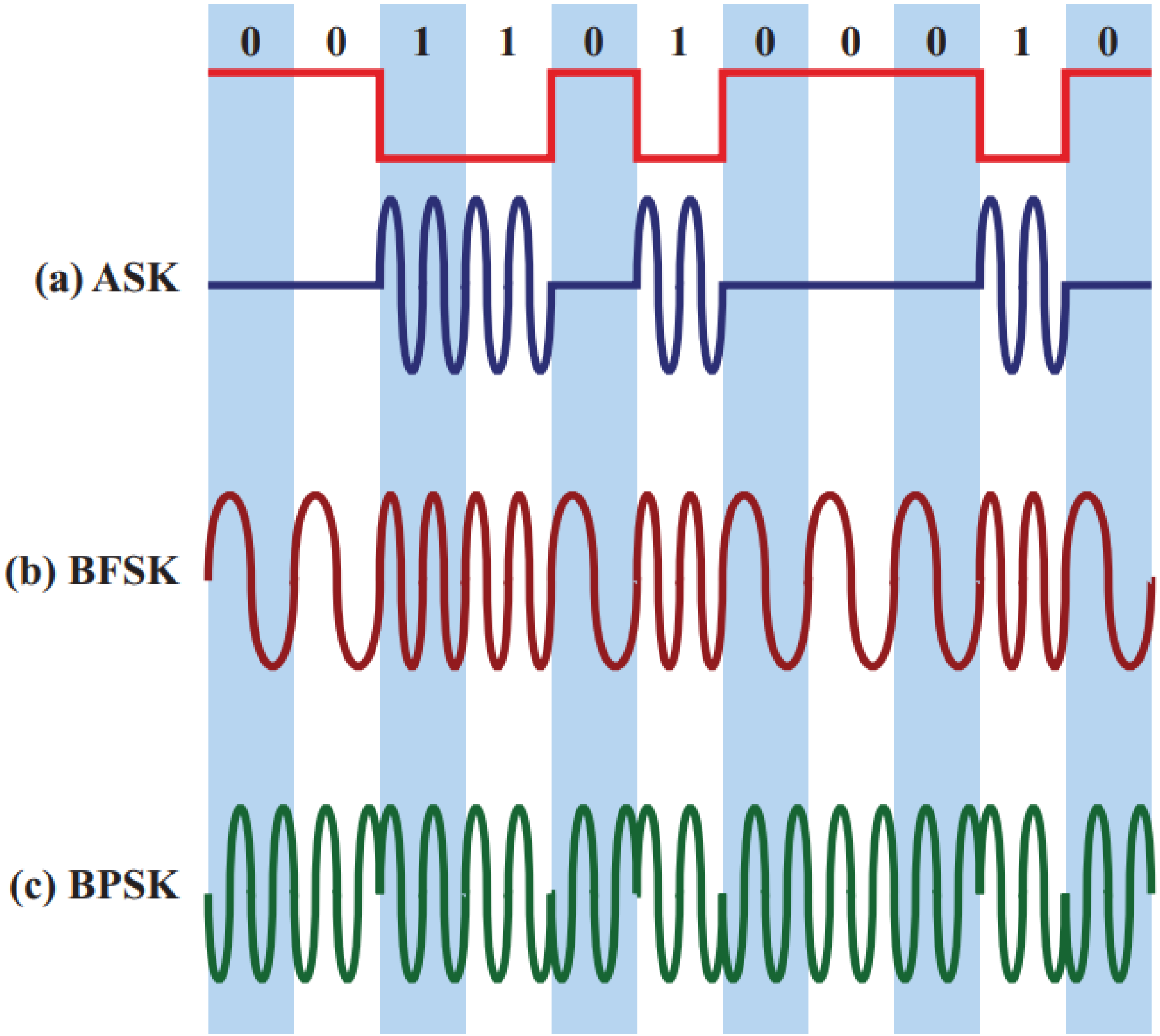
Binary Passband modulation

In the binary modulation technique, bit 0 or 1 can be transmitted for every symbol (time interval). The various binary modulation approaches are Amplitude shift keying (ASK), Phase shift keying (PSK), and Frequency Shift keying (FSK).

M-ary Passband modulation

In the M-ary modulation technique, more than one bit can be transmitted for every symbol. Example QPSK (Quadrature Phase Shift Keying), where two binary digits transmit at a time.

Modulation onto Analog Signal:

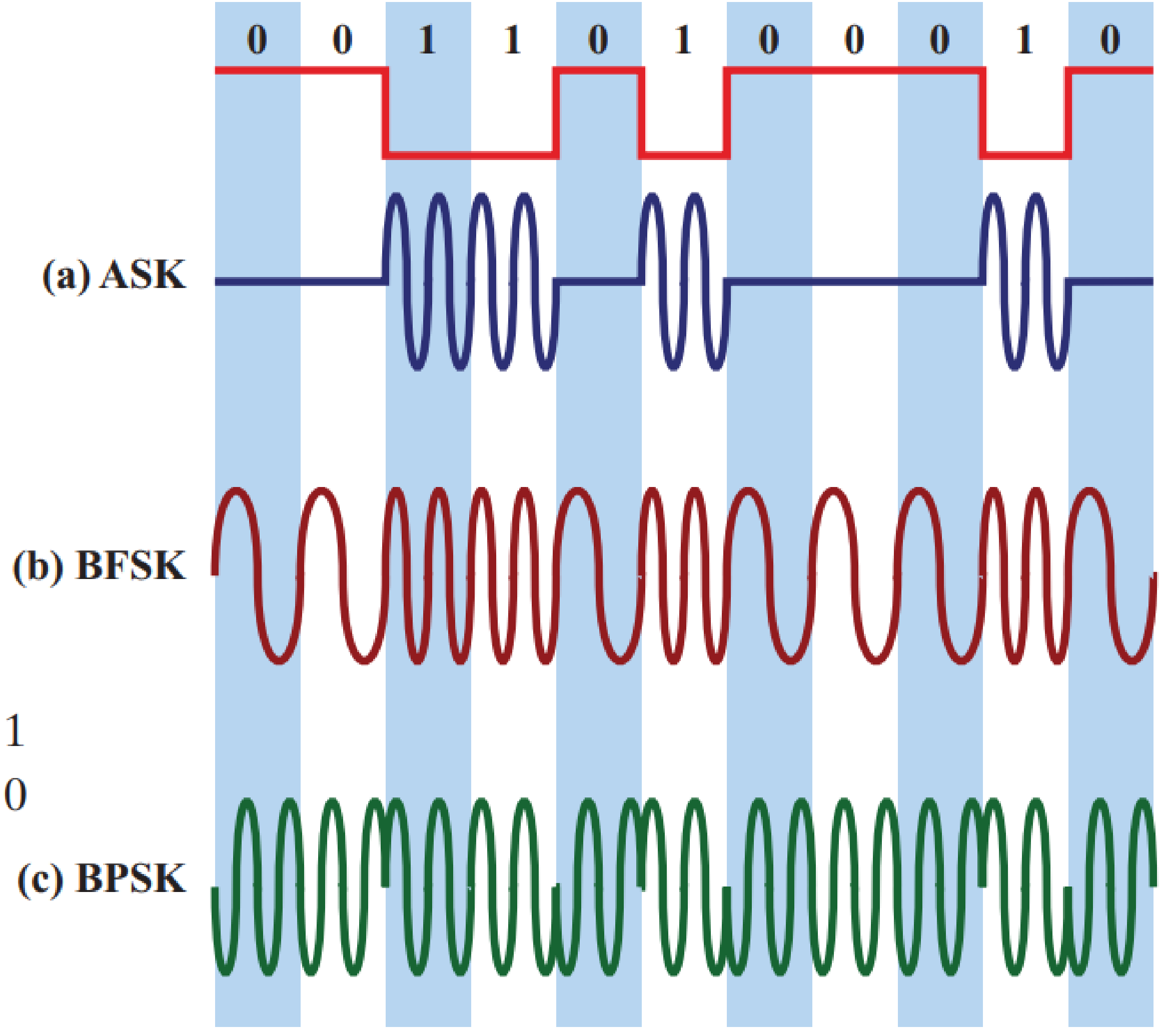


Modulation onto Analog Signal:

ASK
$$s(t) = \begin{cases} A\cos(2\pi f_c t) & \text{binary 1} \\ 0 & \text{binary 0} \end{cases}$$

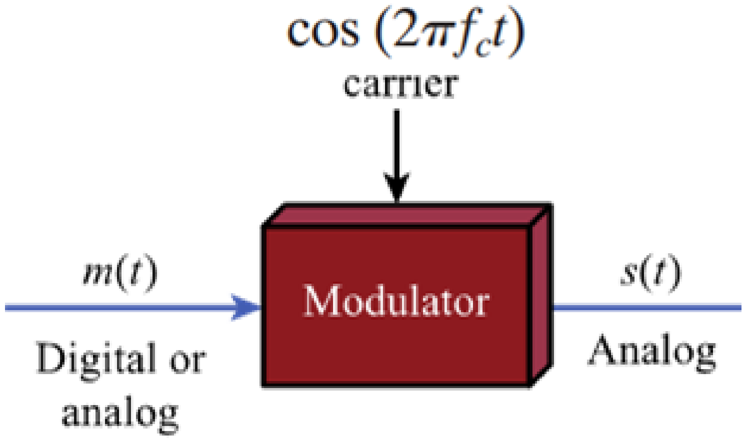
BFSK
$$s(t) = \begin{cases} A\cos(2\pi f_1 t) & \text{binary 1} \\ A\cos(2\pi f_2 t) & \text{binary 0} \end{cases}$$

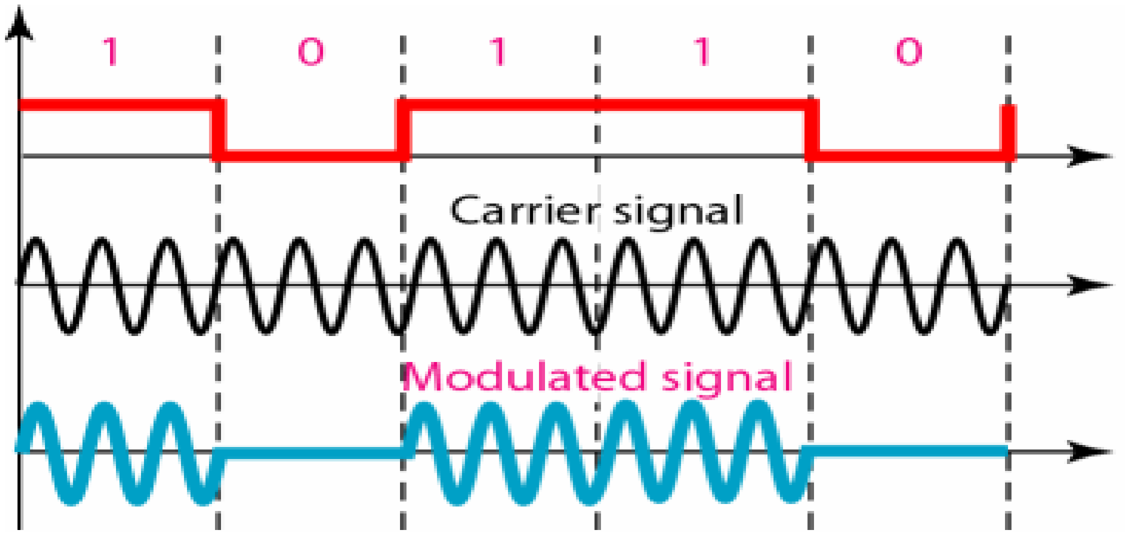
BPSK
$$s(t) = \begin{cases} A\cos(2\pi f_c t) \\ A\cos(2\pi f_c t + \pi) \end{cases} = \begin{cases} A\cos(2\pi f_c t) & \text{binary 1} \\ -A\cos(2\pi f_c t) & \text{binary 0} \end{cases}$$



Modulation onto Analog Signal:

ASK Modulation





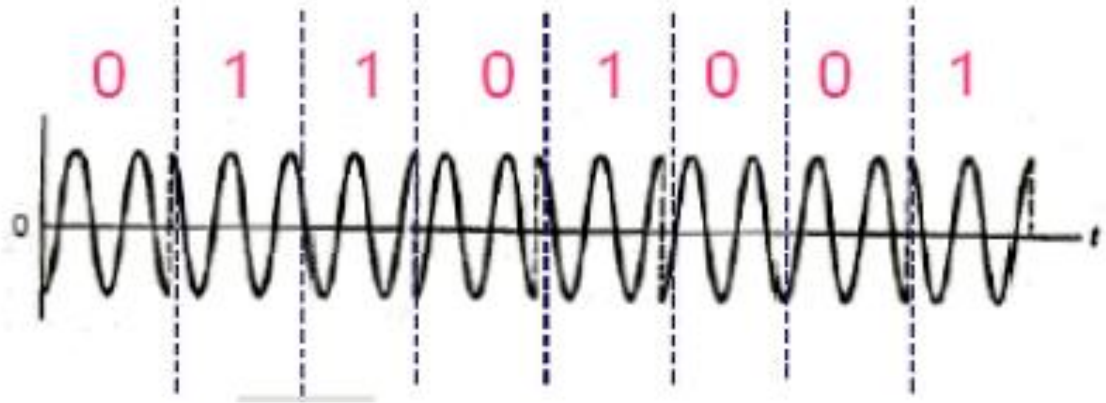
Unipolar Format:
0 represents 0V
1 represents A V

$$\textbf{ASK} \qquad s(t) = \begin{cases} A\cos(2\pi f_c t) & \text{binary } 1 \\ 0 & \text{binary } 0 \end{cases}$$

Modulation onto Analog Signal:

Phase Shift Keying (PSK)

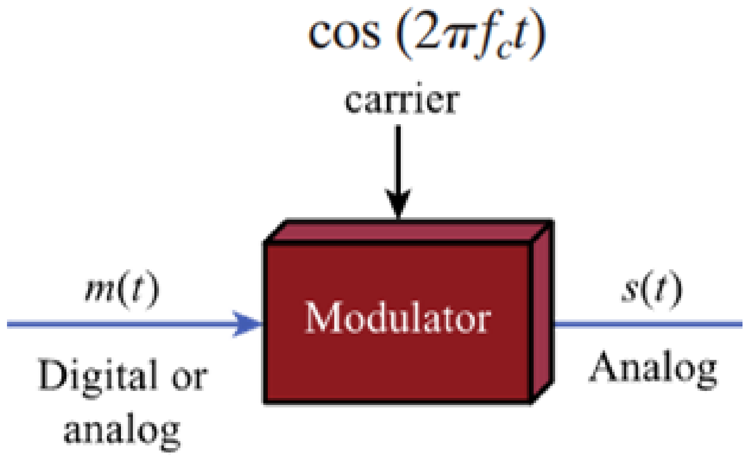
In PSK, binary digit 1 is represented by some phase angle (for example, 0 ◦), and binary digit 0 represents another phase angle (for example 180 ◦).

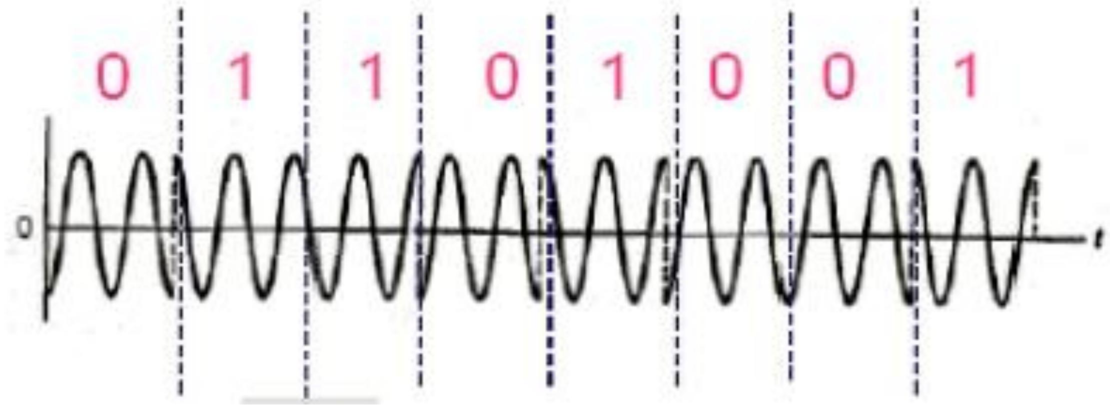


$$\textbf{BPSK} \quad s(t) = \begin{cases} A\cos(2\pi f_c t) \\ A\cos(2\pi f_c t + \pi) \end{cases} = \begin{cases} A\cos(2\pi f_c t) & \text{binary } 1 \\ -A\cos(2\pi f_c t) & \text{binary } 0 \end{cases}$$

Modulation onto Analog Signal:

PSK Modulation/Generation

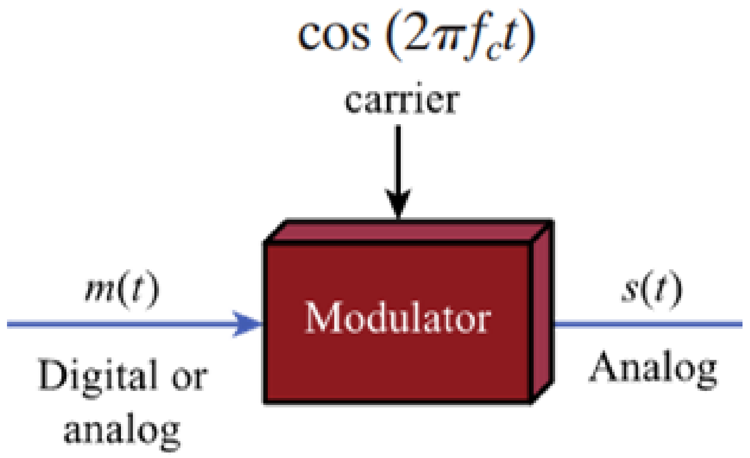




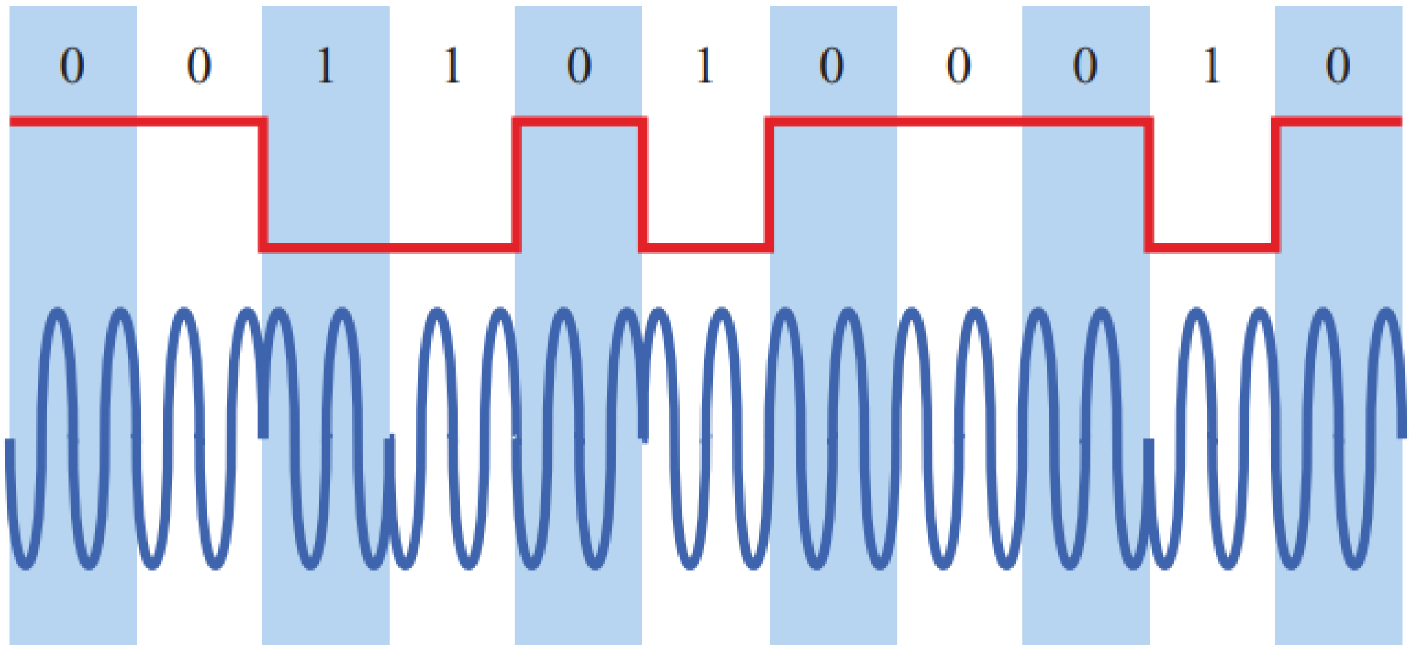
Polar Format:
0 represents - A
1 represents + A

Modulation onto Analog Signal:

PSK Modulation/Generation



Differential Phase-Shift Keying (DPSK)

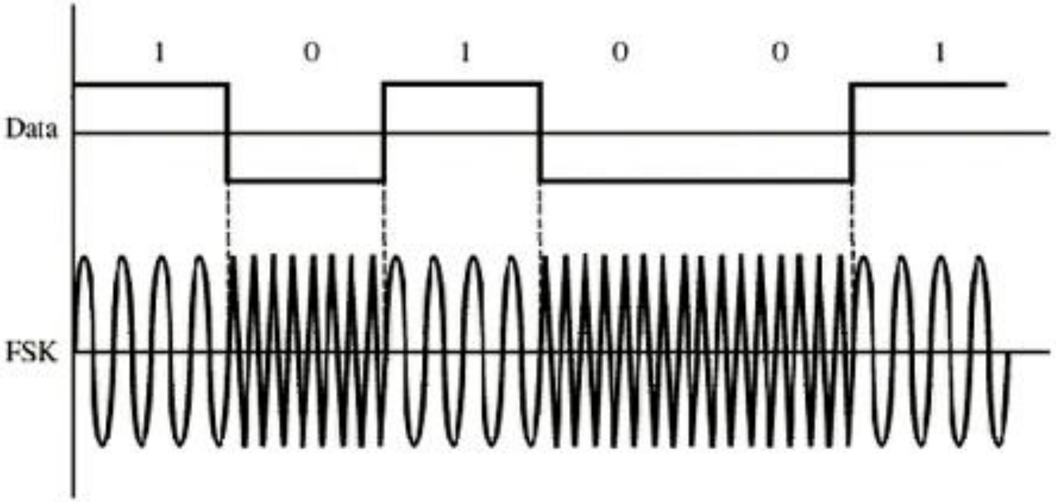


Unipolar Format:
0 represents   0
1 represents + A

Modulation onto Analog Signal:

Frequency Shift Keying (FSK)

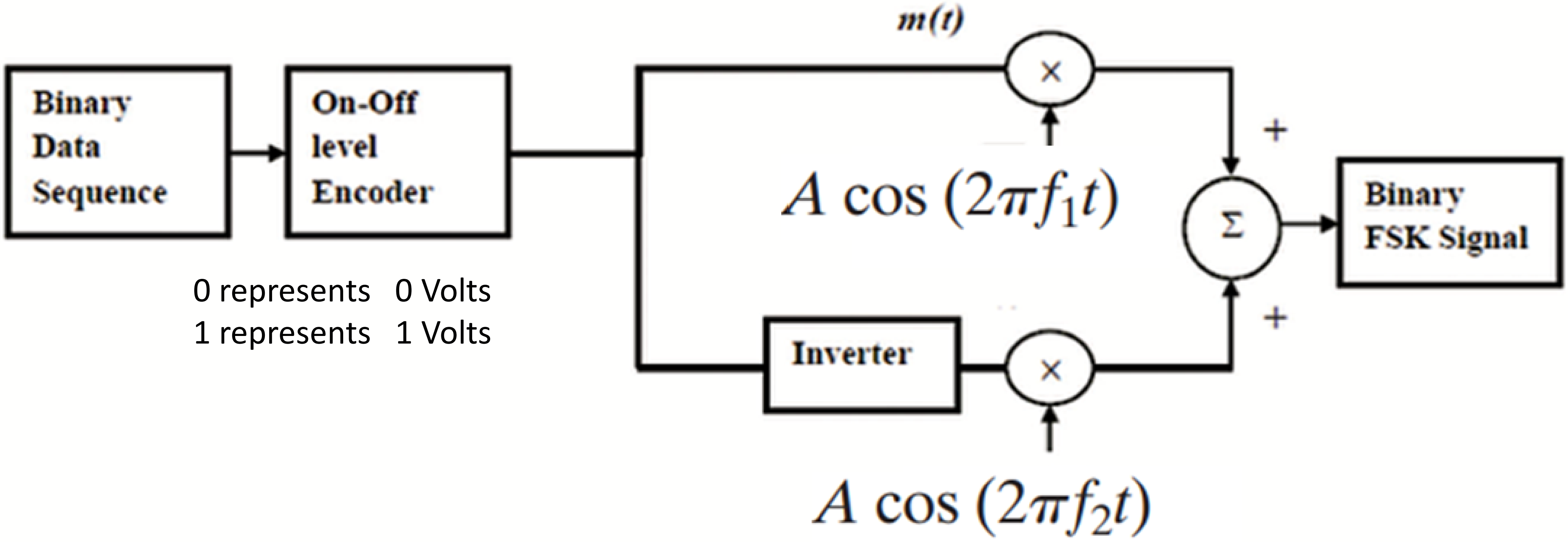
In FSK, binary digit 1 is represented by frequency $f_{1,}$ and binary digit 0 represented by another frequency f_2



BFSK $$s(t) = \begin{cases} A \cos(2\pi f_1 t) & \text{binary } 1 \\ A \cos(2\pi f_2 t) & \text{binary } 0 \end{cases}$$

Modulation onto Analog Signal:

FSK Modulation/Generation



0 represents 0 Volts
1 represents 1 Volts

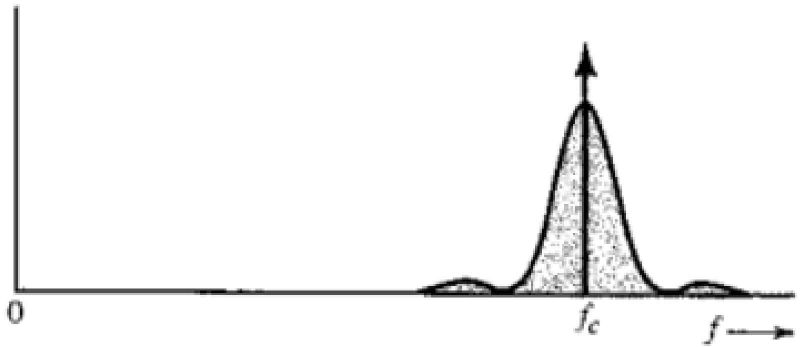
Modulation onto Analog Signal:

- The performance of a modulation scheme is often measured in terms of its power efficiency and bandwidth efficiency.

- The Power Efficiency is the ability of a modulation technique to have the reliability (acceptable BER) of the digital message at low power levels.
- The bandwidth efficiency is the ability of a modulation technique to consume less bandwidth of the communication channel.

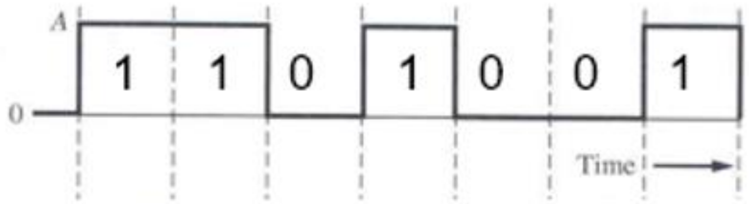
Modulation onto Analog Signal:

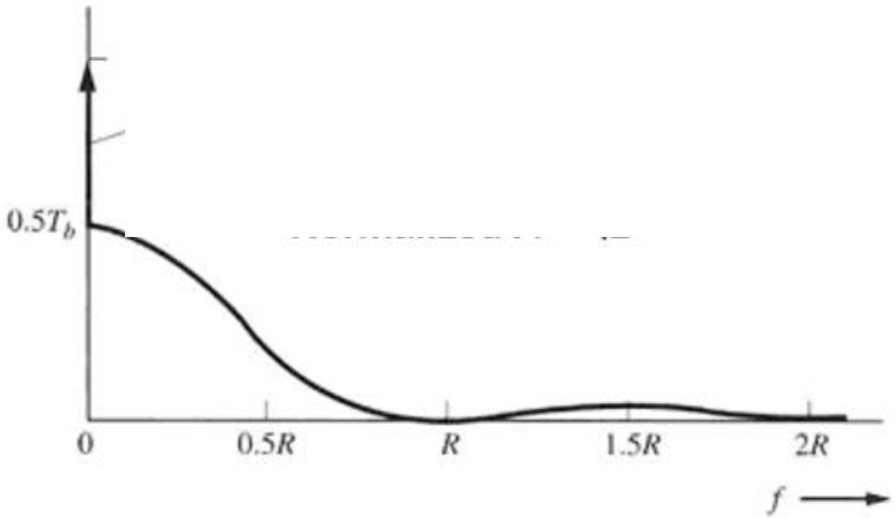
PSD of the ASK signal



BW= Twice the BW of Baseband signaling

Unipolar NRZ

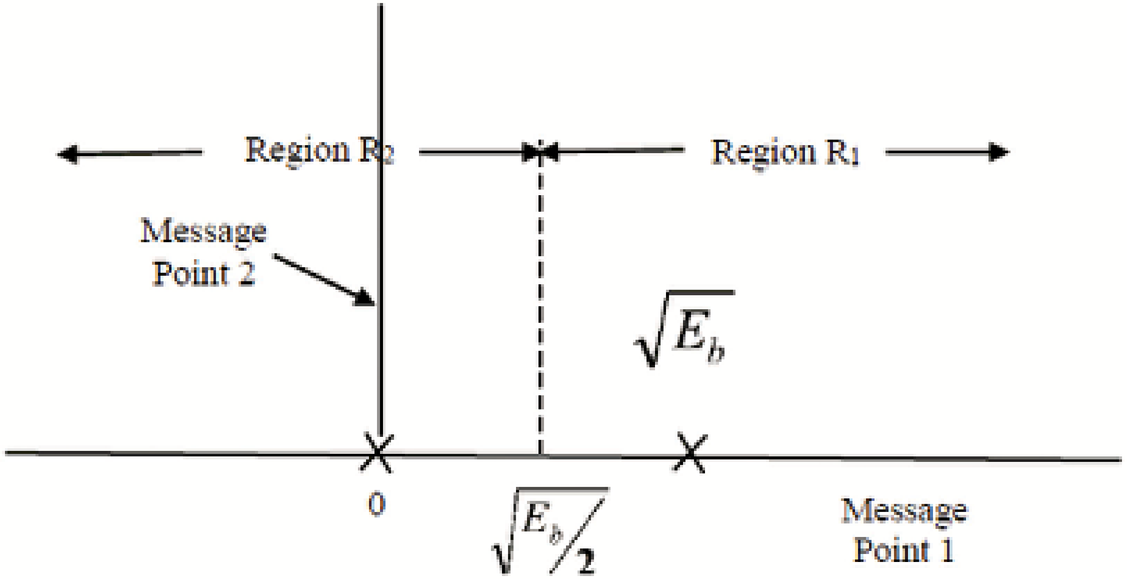




PSD of the ASK signal is the same as that of an on-off signal shifted to $\pm\omega_c$

Modulation onto Analog Signal:

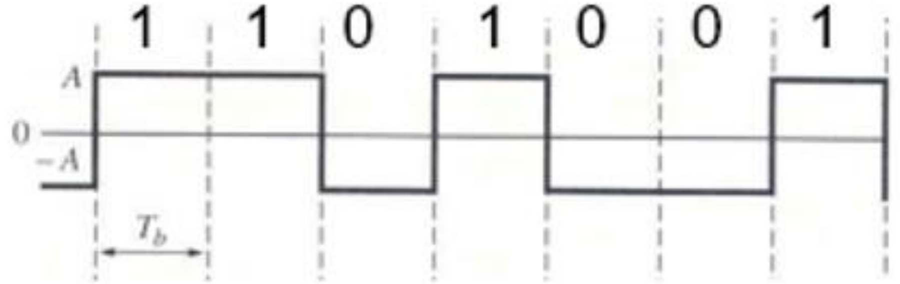
Bit Detection at Receiver - ASK



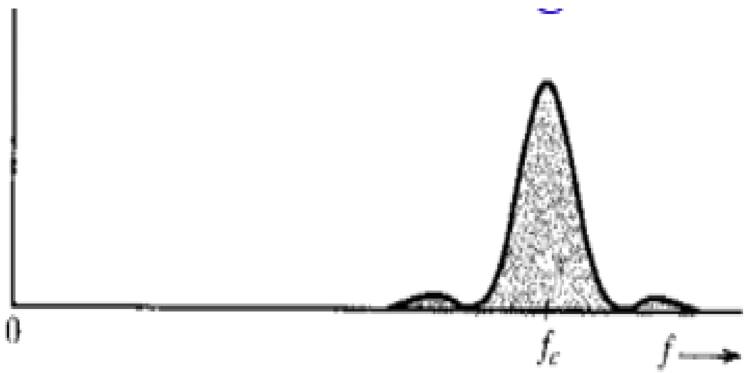
Error probability of the modulation technique depends on the distance between two signal points, called "Euclidean distance".

Modulation onto Analog Signal:

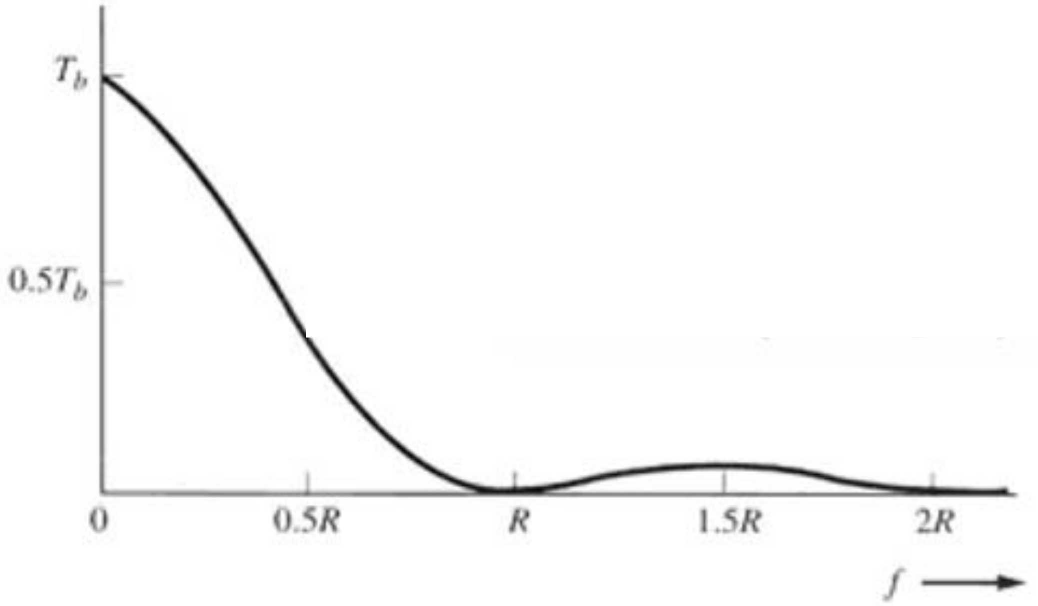
Polar NRZ



PSD of the PSK signal



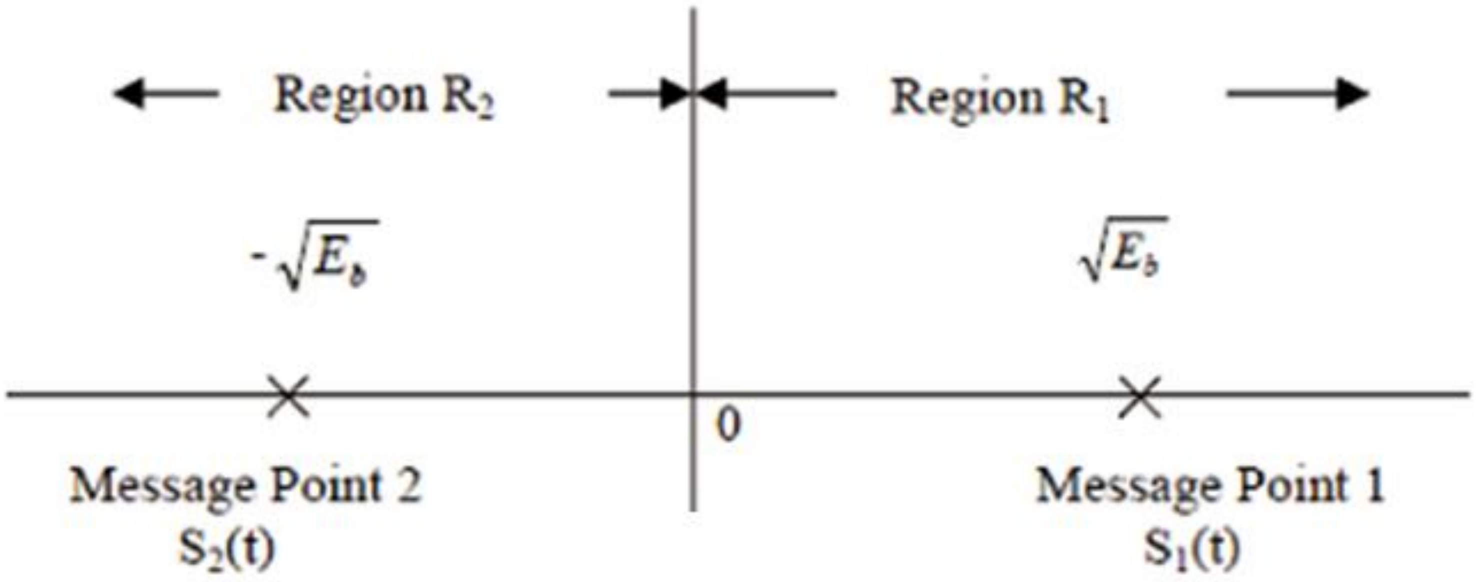
BW= Twice the BW of Baseband signaling



PSD of the PSK signal is the same as that of a Polar signal shifted to $\pm\omega_c$

Modulation onto Analog Signal:

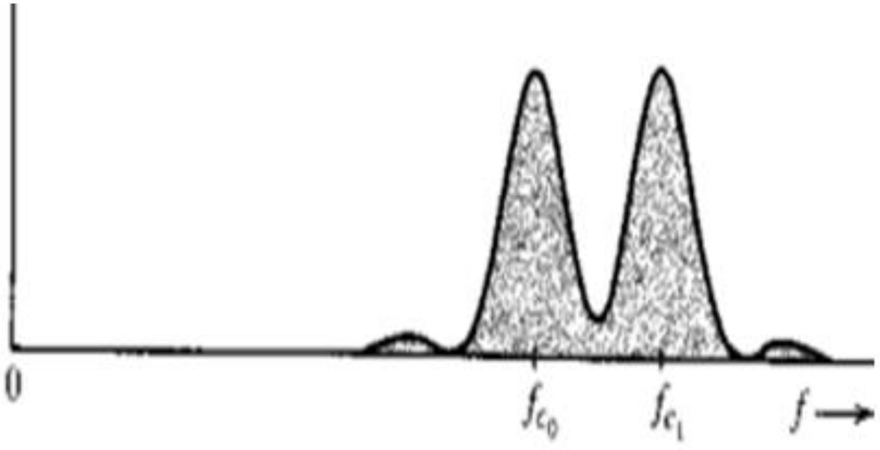
Bit Detection at Receiver - PSK



Error probability of the modulation technique depends on the distance between two signal points. The Euclidean distance between the two points $S_1(t)$ and $S_2(t)$ is $2\sqrt{E_b}$.

Modulation onto Analog Signal:

PSD of the FSK signal



BW= BW= Twice the BW of Baseband signaling <u>Plus</u> f_{c1}-f_{co} (difference b/w carrier frequencies)

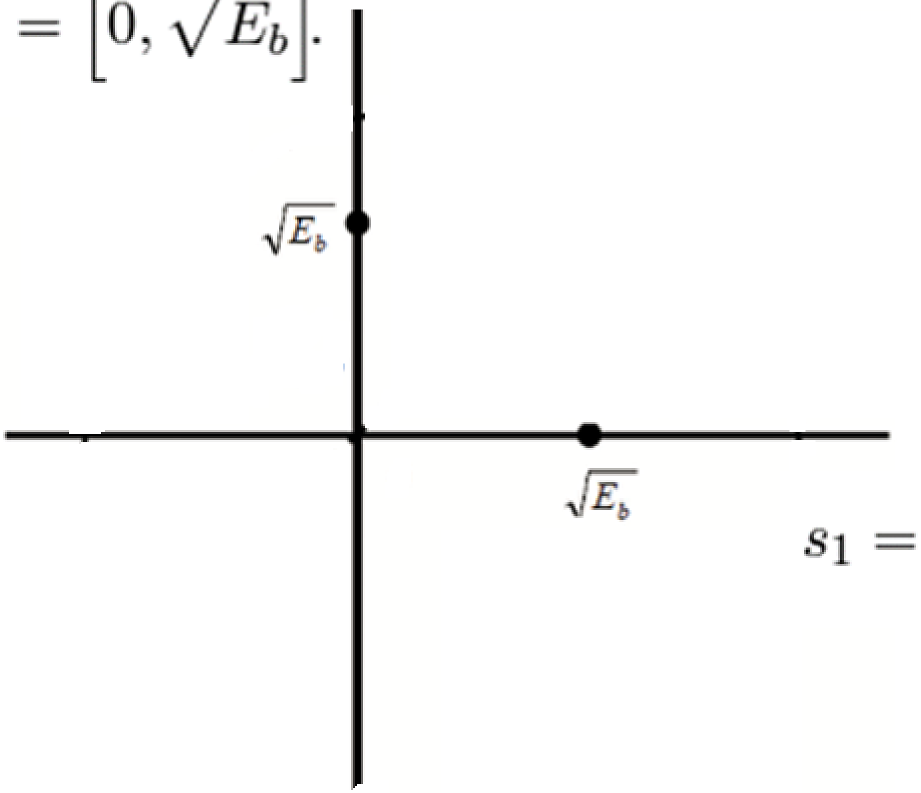
FSK signal may be viewed as a sum of two interleaved ASK signals.

Modulation onto Analog Signal:

Bit Detection at Receiver - FSK

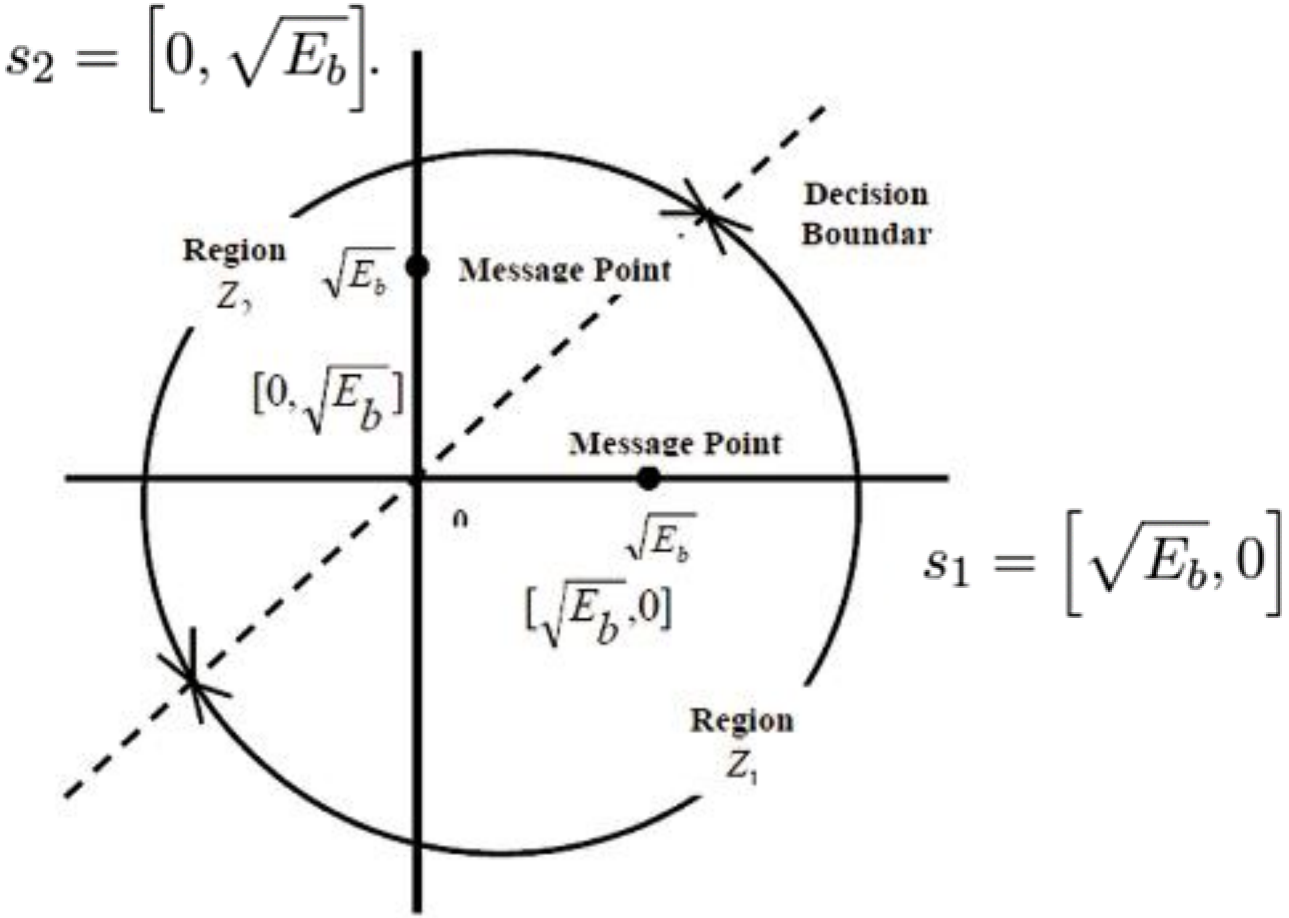
Assuming both carriers are orthogonal.

$$s_2 = \left[0, \sqrt{E_b}\right].$$



$$s_1 = \left[\sqrt{E_b}, 0\right]$$

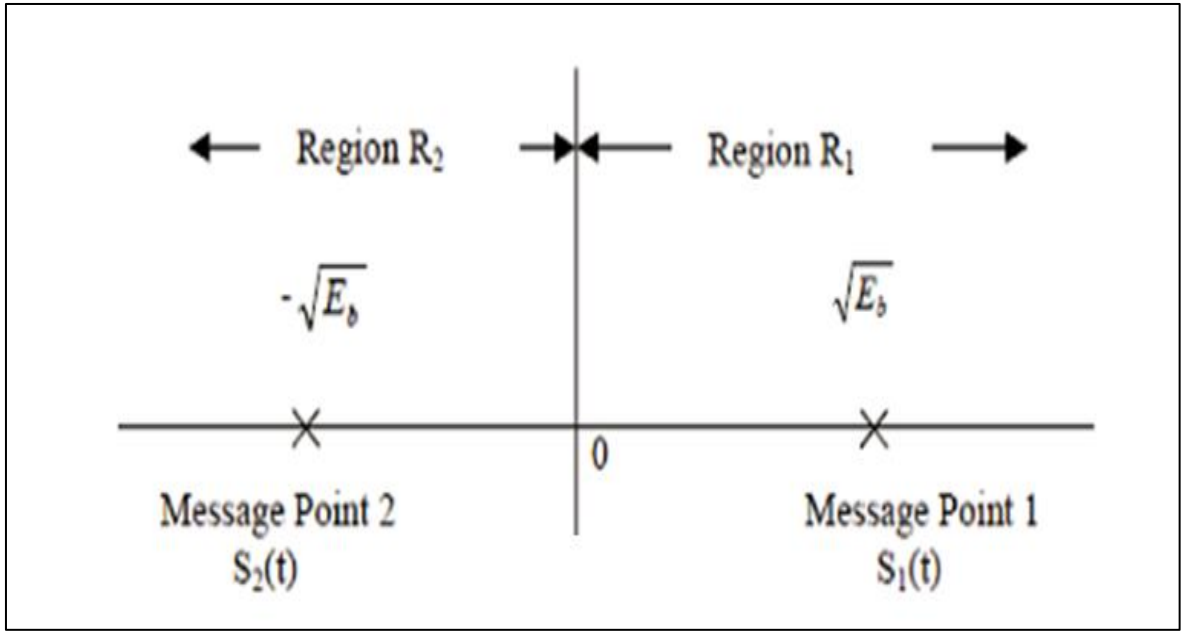
Modulation onto Analog Signal:



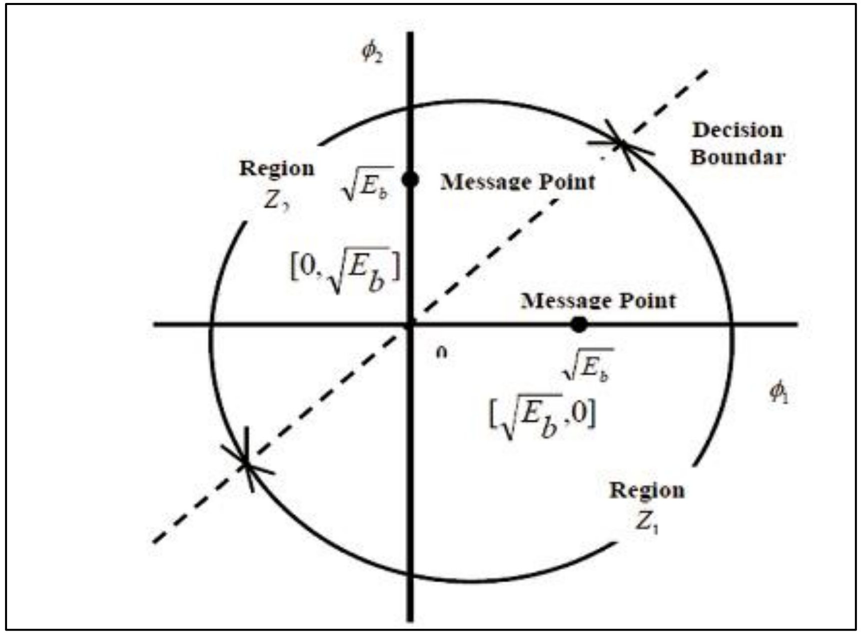
Error probability of the modulation technique depends on the distance between two signal points. The distance between the two points $S_1(t)$ and $S_2(t)$ is $\sqrt{2E_b}$ called the Euclidean distance.

Modulation onto Analog Signal:

PSK: signaling distance $2\sqrt{E_b}$

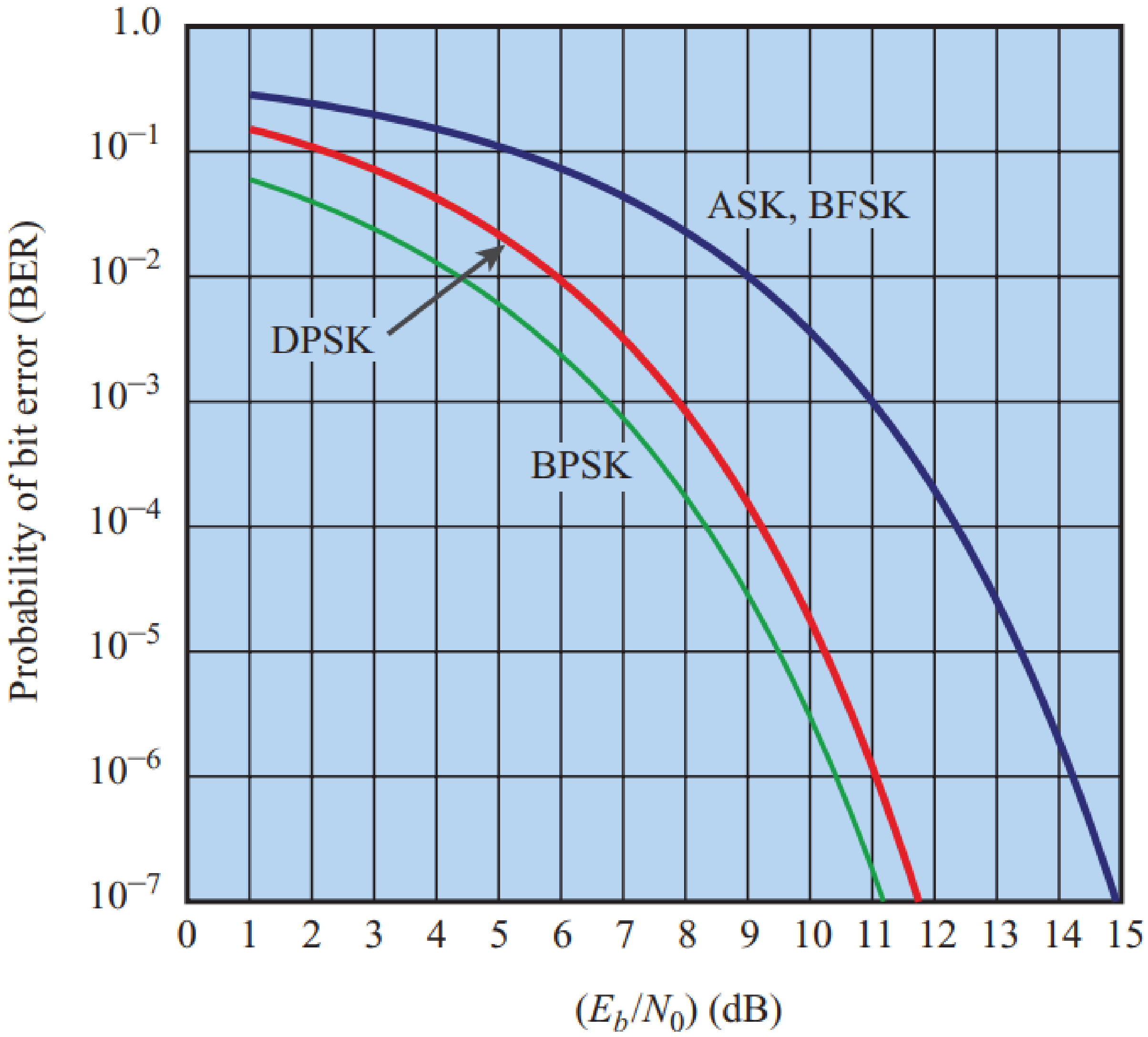


FSK: signaling distance $\sqrt{2E_b}$



With Large distance between two signaling points on the signal space diagram mean a low probability of error detection. Therefore to attain the same level of bit error rate (BER) or probability of Error, FSK needs twice the Bit energy as compared to PSK.

Modulation onto Analog Signal:

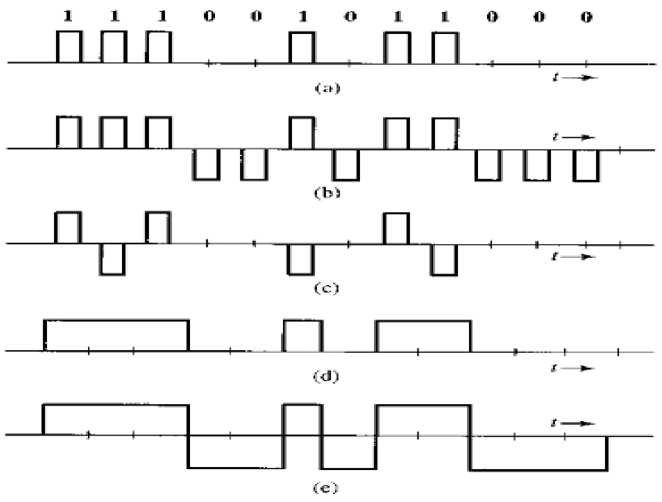


End of session # 01

Modulation onto Analog Signal:

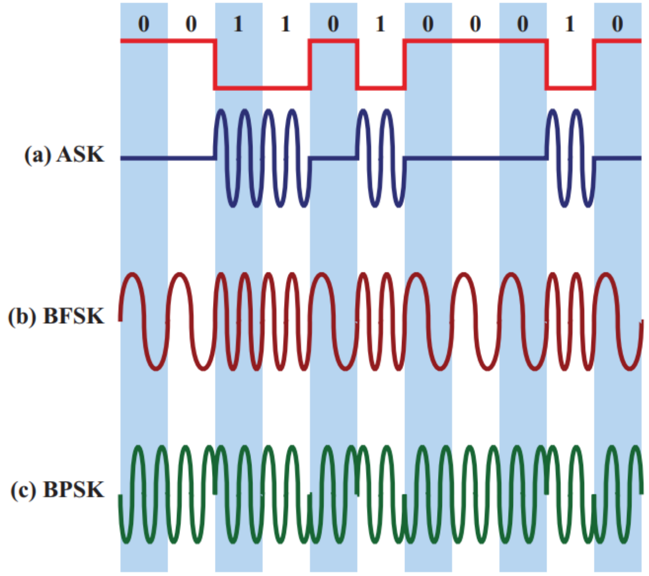
Baseband Modulation:

Low-frequency modulation is called the baseband modulation. Examples are Encoding schemes like unipolar and polar formats.



Passband Modulation:

In this approach, user binary data are multiplied by a high-frequency carrier at the transmitter side. It is a high-frequency modulation.



Modulation onto Analog Signal:

Types of Passband Modulation:

Binary Passband modulation

In the binary modulation technique, bit 0 or 1 can be transmitted for every symbol (time interval). The various binary modulation approaches are Amplitude shift keying (ASK), Phase shift keying (PSK), and Frequency Shift keying (FSK).

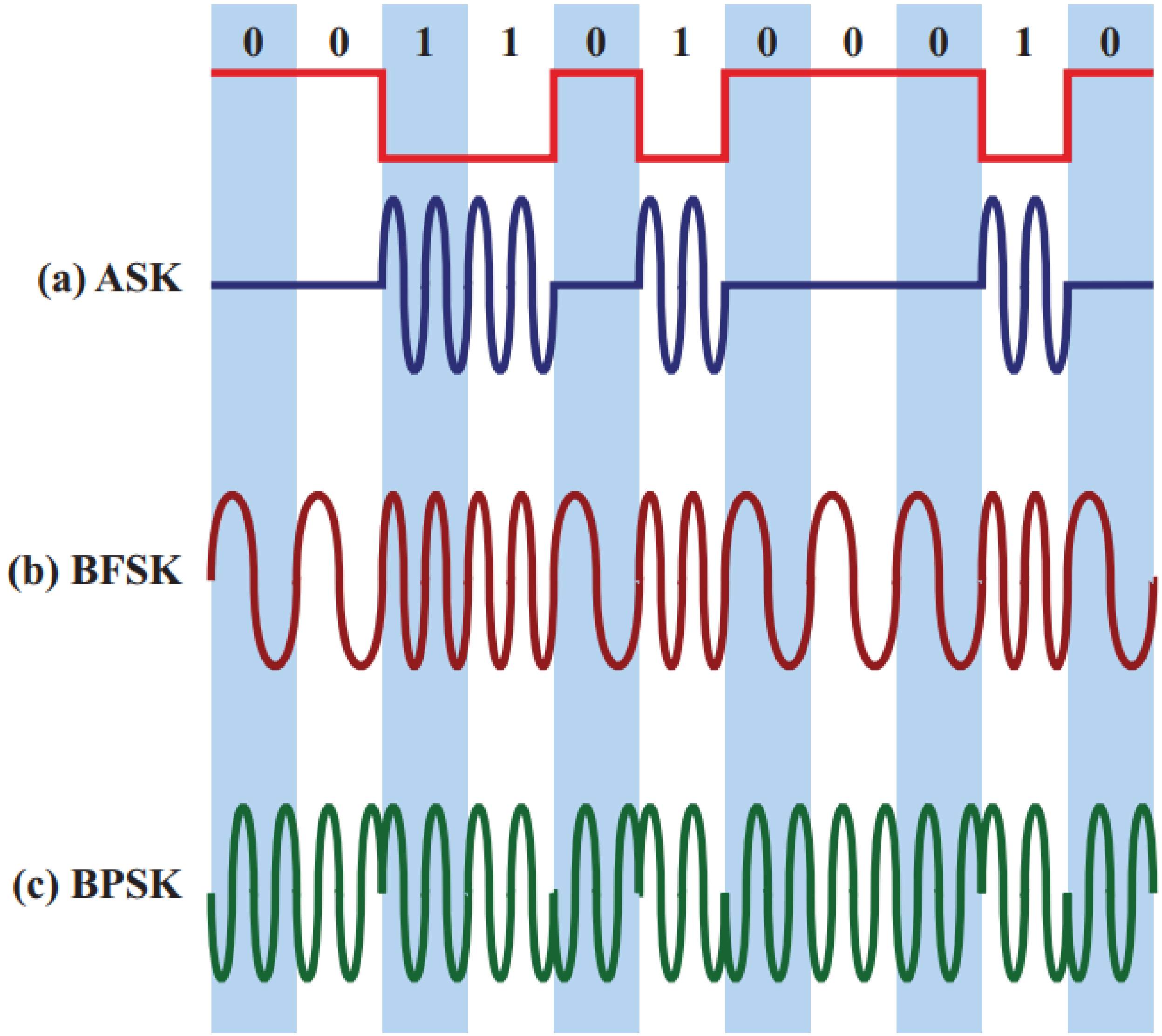
M-ary Passband modulation

In the M-ary modulation technique, more than one bit can be transmitted for every symbol. Example QPSK (Quadrature Phase Shift Keying), where two binary digits transmit at a time.

Modulation onto Analog Signal:

Binary Passband modulation

Or Binary broadband modulation



Modulation onto Analog Signal:

Example 7.3 What is the bandwidth efficiency for FSK, ASK, PSK, and QPSK for a bit error rate of 10^{-7} on a channel with an SNR of 12 dB?

Using Equation (6.9), we have

$$\left(\frac{E_b}{N_0}\right)_{\mathrm{dB}} = \left(\frac{S/R}{N/B_T}\right)_{\mathrm{dB}} = \left(\frac{S}{N}\right)_{\mathrm{dB}} - \left(\frac{R}{B_T}\right)_{\mathrm{dB}} = 12\,\mathrm{dB} - \left(\frac{R}{B_T}\right)_{\mathrm{dB}}$$

For FSK and ASK, from Figure 7.9,

$$\left(\frac{E_b}{N_0}\right)_{\mathrm{dB}} = 14.8\,\mathrm{dB}$$

$$\left(\frac{R}{B_T}\right)_{\mathrm{dB}} = -2.8\,\mathrm{dB}$$

$$\frac{R}{B_T} = 0.53$$

For PSK, from Figure 7.9

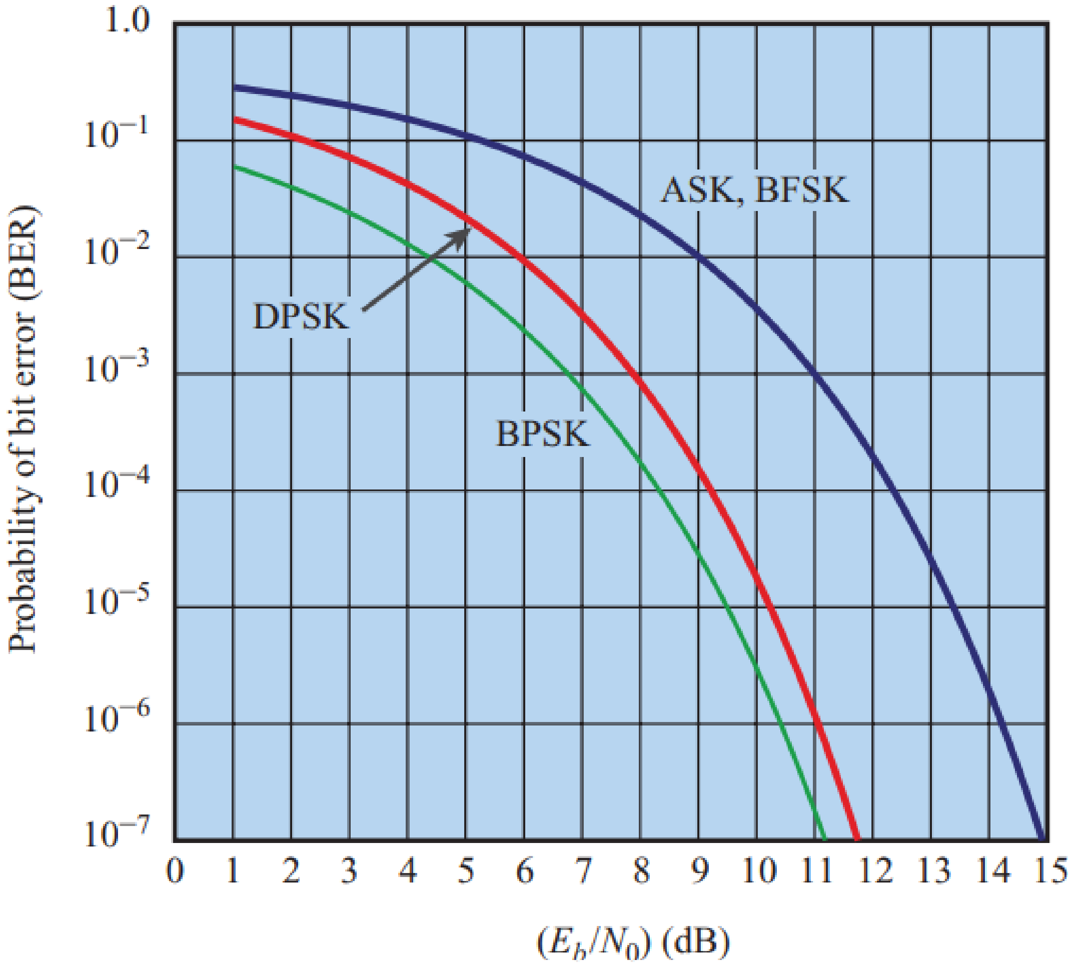
$$\left(\frac{E_b}{N_0}\right)_{\mathrm{dB}} = 11.2\,\mathrm{dB}$$

$$\left(\frac{R}{B_T}\right)_{\mathrm{dB}} = 0.8\,\mathrm{dB}$$

$$\frac{R}{B_T} = 1.2$$

R: bit rate

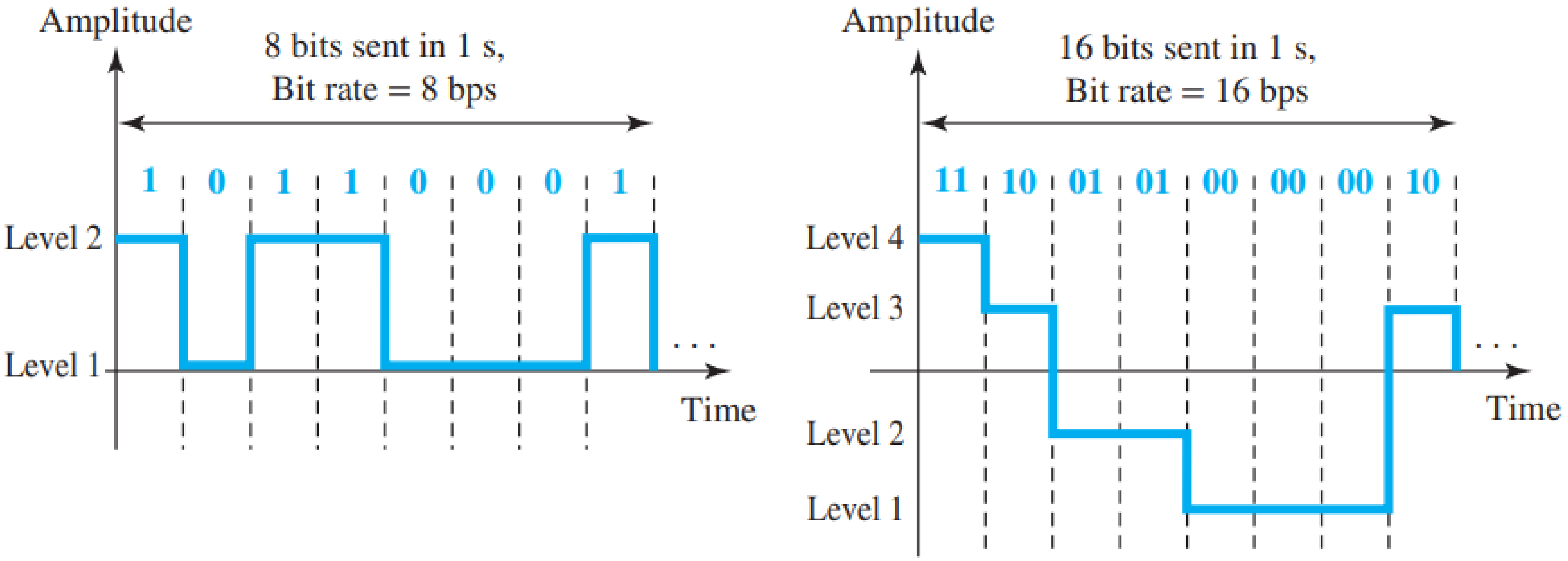
B: bandwidth



Modulation onto Analog Signal:

M-ary Passband modulation

In the M-ary modulation technique, more than one bit can be transmitted for every symbol.



a. A digital signal with two levels

b. A digital signal with four levels

Modulation onto Analog Signal:

M-ary Passband modulation

$$D = \frac{R}{L} = \frac{R}{\log_2 M}$$

$$\text{Symbol Rate} = \frac{\text{Bit Rate}}{\text{Bits per Symbol}}$$

D = modulation rate, baud (symbols/second)

R = data rate, bps R = 1/Tb.

M = number of different signal elements $= 2^L$

L = number of bits per signal element

Shannon Capacity

$$C = B \times \log_2 (1 + \mathrm{SNR})$$

Nyquist Bit Rate

$$\mathrm{BitRate} = 2 \times B \times \log_2 L$$

Bandwidth saving:

If the Bandwidth value without M-ary is B then with M-ary the new bandwidth would be $B/\log_2 M$

Modulation onto Analog Signal:

M-ary Passband modulation

We have a channel with a 1-MHz bandwidth. The SNR for this channel is 63. What are the appropriate bit rate and signal level?

Solution

First, we use the Shannon formula to find the upper limit.

$$C = B \log_2 (1 + \text{SNR}) = 10^6 \log_2 (1 + 63) = 10^6 \log_2 64 = 6 \text{ Mbps}$$

The Shannon formula gives us 6 Mbps, the upper limit. For better performance we choose something lower, 4 Mbps, for example. Then we use the Nyquist formula to find the number of signal levels.

$$4 \text{ Mbps} = 2 \times 1 \text{ MHz} \times \log_2 L \quad \rightarrow \quad \log_2 L = 2 \quad \rightarrow \quad L = 4$$

The Shannon capacity gives us the upper limit;
the Nyquist formula tells us how many signal levels we need

Modulation onto Analog Signal:

M-ary Passband modulation

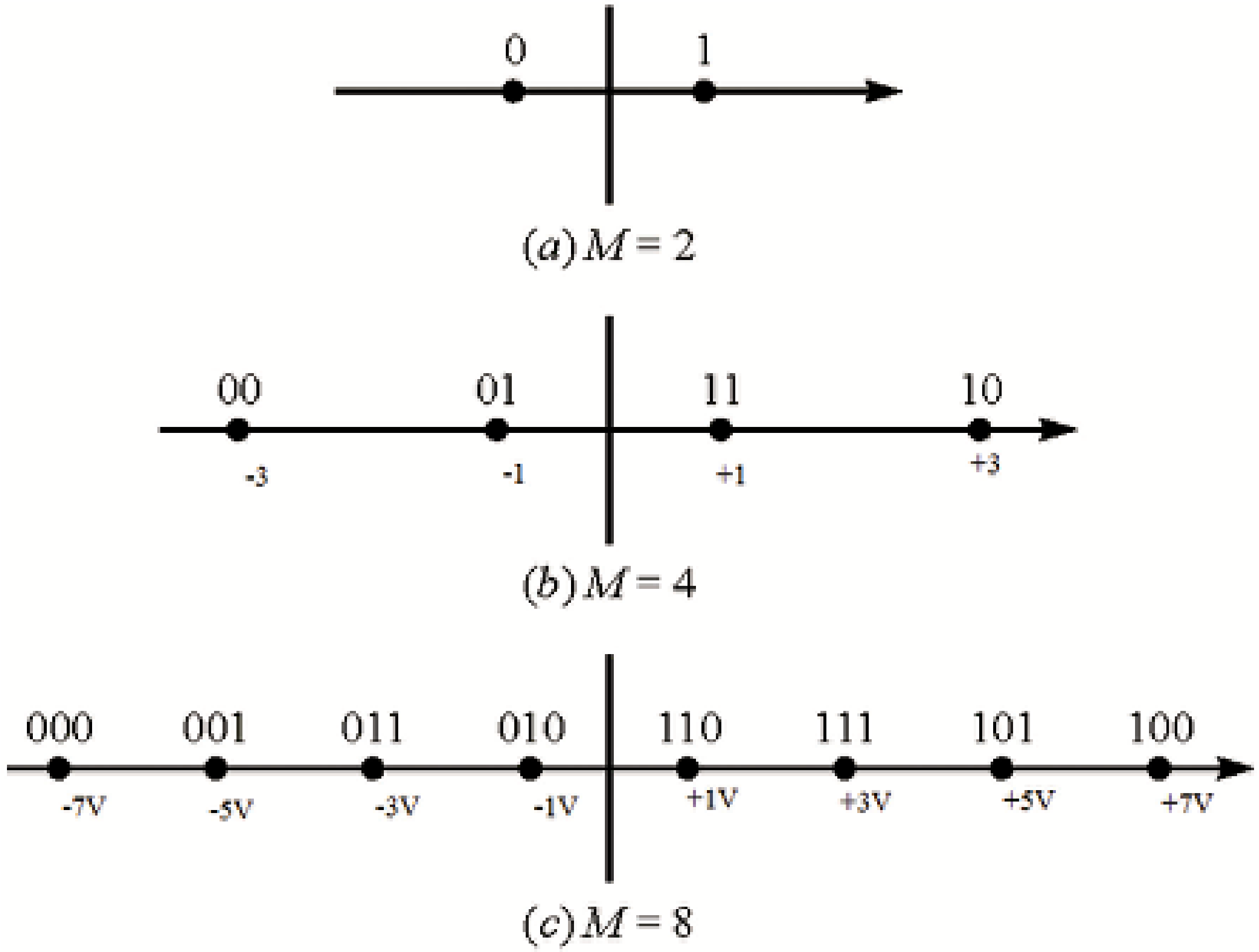
A communication system transmits data using a modulation scheme where each symbol represents 4 bits. If the symbol rate (baud rate) is 2,000 symbols per second, calculate the bit rate of the system.

$$\text{Bit Rate} = \text{Symbol Rate} \times \text{Bits per Symbol}$$

$$\text{Bit Rate} = 2000\,\text{symbols/second} \times 4\,\text{bits/symbol} = 8,000\,\text{bits/second}$$

Modulation onto Analog Signal:

M-ary ASK

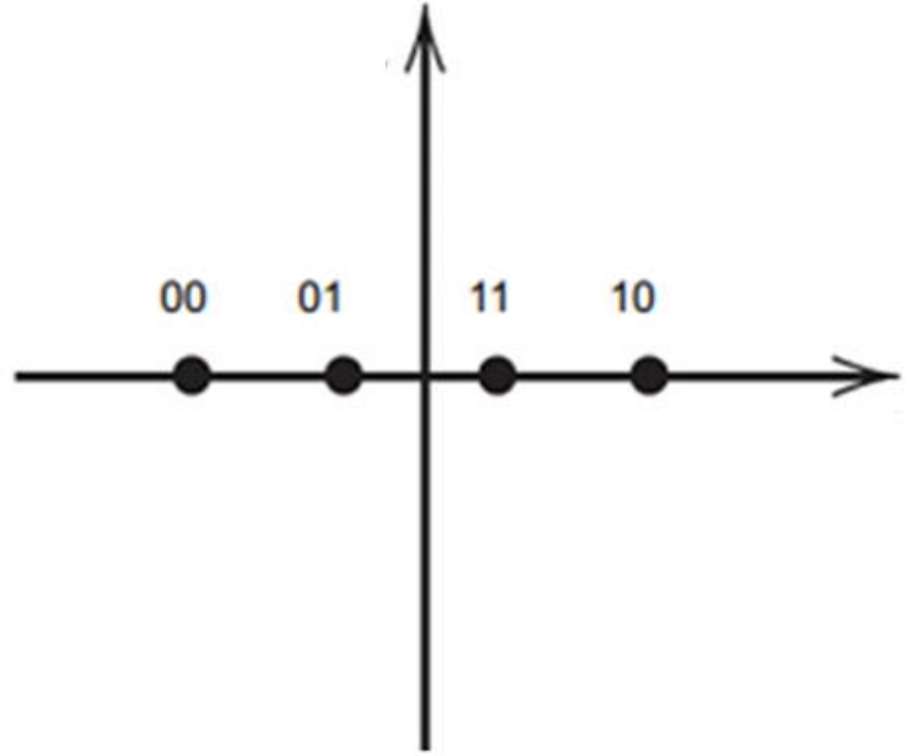


Modulation onto Analog Signal:

M-ary ASK

AM signal uses M different amplitudes, its bandwidth remains the same as that of the binary ASK while its power is increased proportionally with M^2.

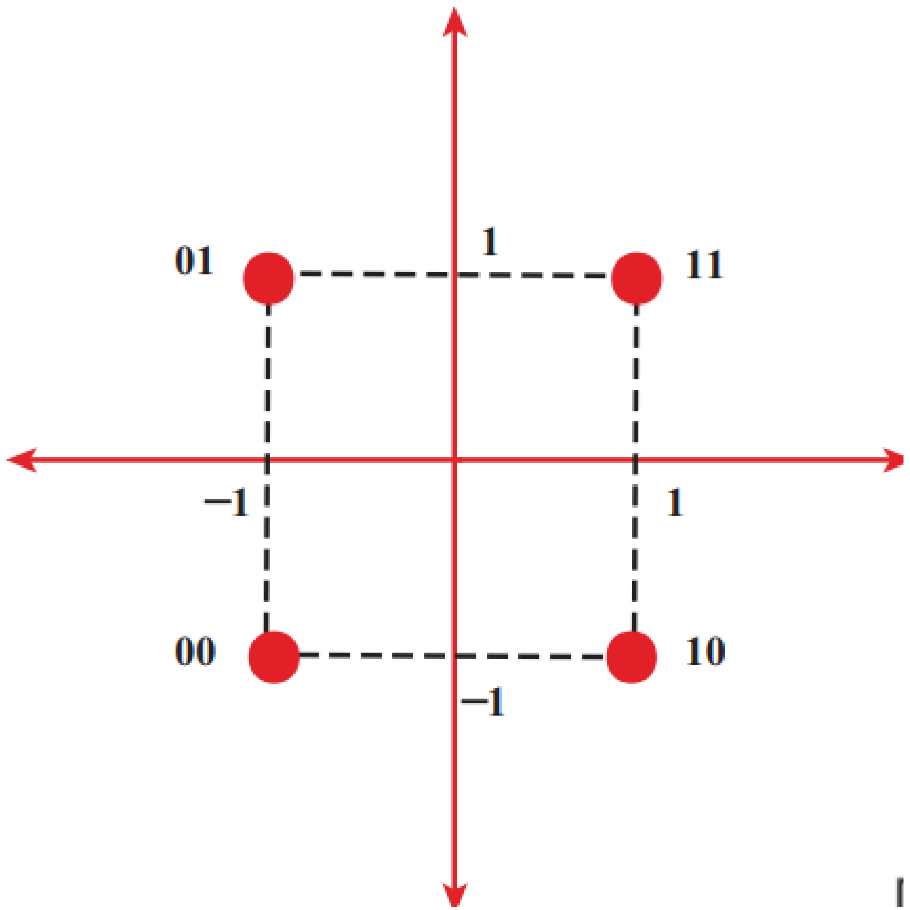
$$\varphi(t) = 0,\ A\cos\omega_c t,\ 2A\cos\omega_c t,\ \ldots,\ (M-1)A\cos\omega_c t$$



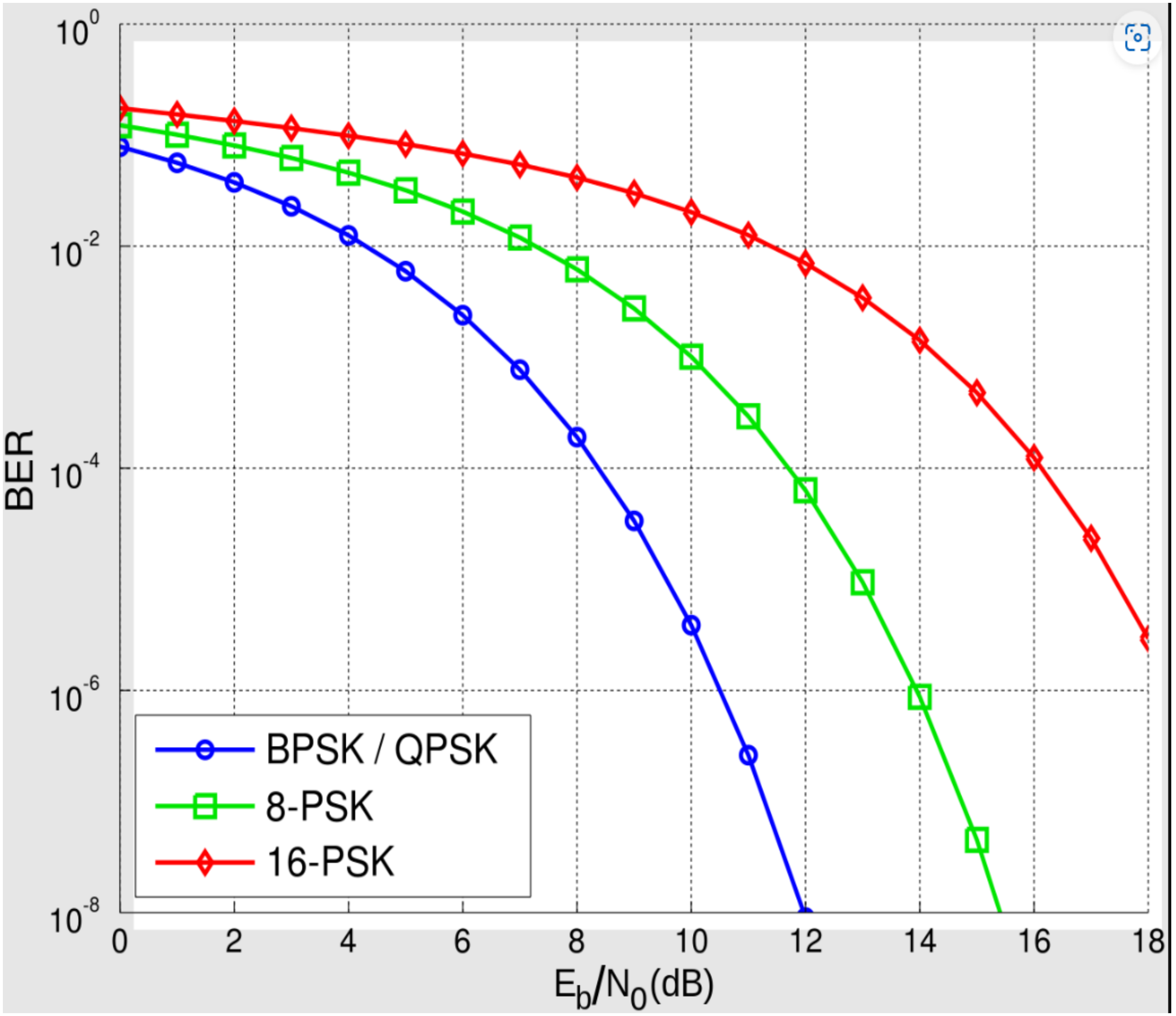
Modulation onto Analog Signal:

M-ARY PSK

QPSK $$s(t) = \begin{cases} A\cos\left(2\pi f_c t + \dfrac{\pi}{4}\right) & 11 \\ A\cos\left(2\pi f_c t + \dfrac{3\pi}{4}\right) & 01 \\ A\cos\left(2\pi f_c t - \dfrac{3\pi}{4}\right) & 00 \\ A\cos\left(2\pi f_c t - \dfrac{\pi}{4}\right) & 10 \end{cases}$$



Modulation onto Analog Signal:



Modulation onto Analog Signal:

Example 7.3 What is the bandwidth efficiency for FSK, ASK, PSK, and QPSK for a bit error rate of 10^{-7} on a channel with an SNR of 12 dB?

Using Equation (6.9), we have

$$\left(\frac{E_b}{N_0}\right)_{dB} = \left(\frac{S/R}{N/B_T}\right)_{dB} = \left(\frac{S}{N}\right)_{dB} - \left(\frac{R}{B_T}\right)_{dB} = 12\,\text{dB} - \left(\frac{R}{B_T}\right)_{dB}$$

For FSK and ASK, from Figure 7.9,

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For PSK, from Figure 7.9

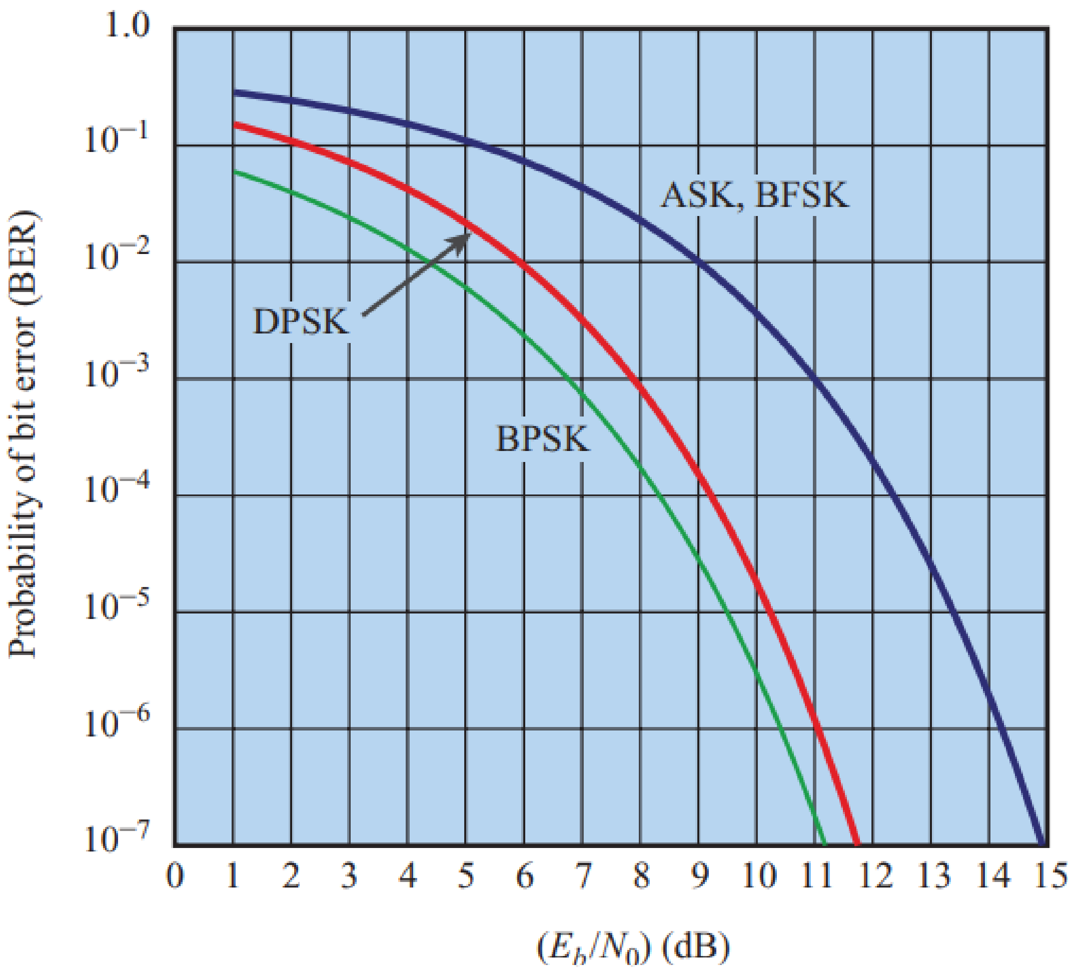
$$\left(\frac{E_b}{N_0}\right)_{dB} = 11.2\,\text{dB}$$

$$\left(\frac{R}{B_T}\right)_{dB} = 0.8\,\text{dB}$$

$$\frac{R}{B_T} = 1.2$$

The result for QPSK must take into account that the baud rate $D = R/2$. Thus,

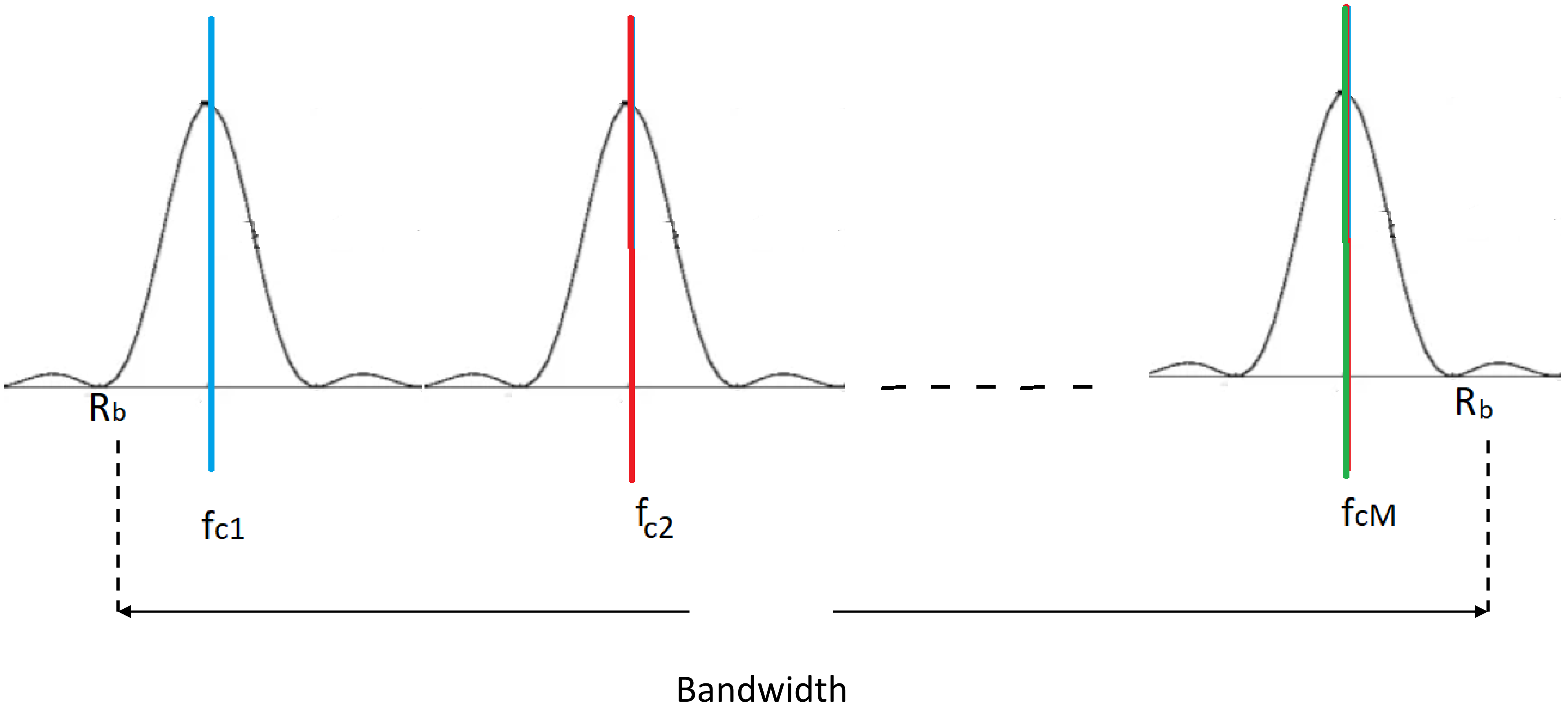
$$\frac{R}{B_T} = 2.4$$



Modulation onto Analog Signal:

M-ary FSK

Here every symbol will use a unique carrier frequency



Modulation onto Analog Signal:

M-ary FSK

- In M-ary FSK, the selection of different carrier frequencies determines the performance and the bandwidth of the FSK modulation.
- If the difference between the carrier Frequencies ($\mathbf{f_d}$) is chosen too large, then the M-ary FSK will use too much bandwidth.
- On the other hand, if $\mathbf{f_d}$ is chosen too small then different FSK symbols will show virtually no difference and the receiver will be unable to distinguish the different symbols reliably.
- Thus large $\mathbf{f_d}$ leads to bandwidth waste, whereas small $\mathbf{f_d}$ leads to detection error due to transmission noise and interference.

Modulation onto Analog Signal:

Example 7.2 Figure 7.4 shows an example of MFSK with $M = 4$. An input bit stream of 20 bits is encoded 2 bits at a time, with each of the four possible 2-bit combinations transmitted as a different frequency. The display in the figure shows the frequency transmitted (y-axis) as a function of time (x-axis). Each column represents a time unit T_s in which a single 2-bit signal element is transmitted. The shaded rectangle in the column indicates the frequency transmitted during that time unit.

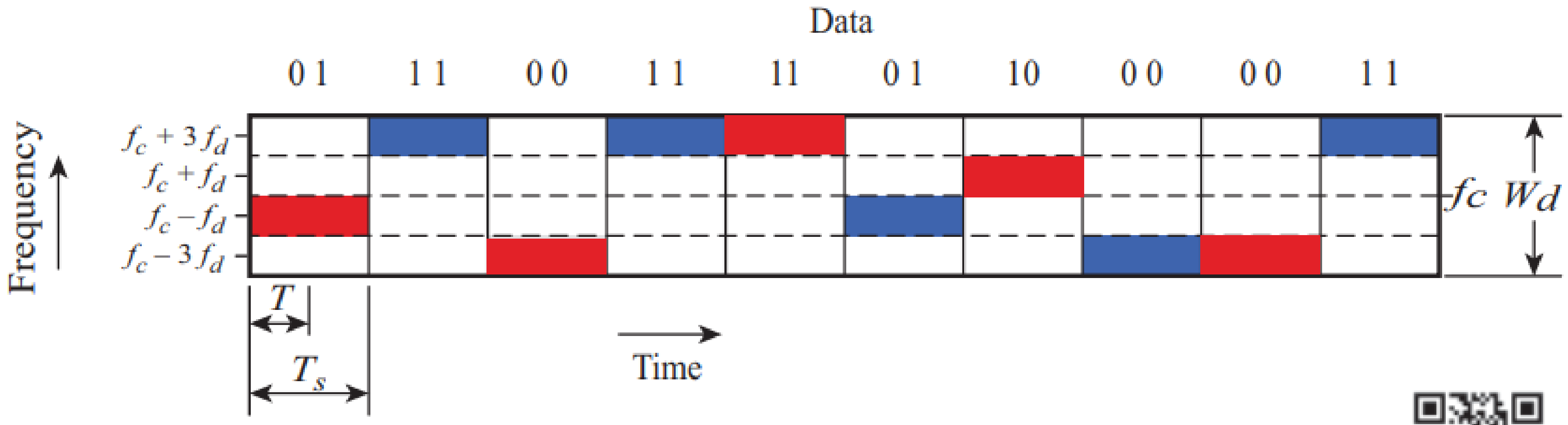
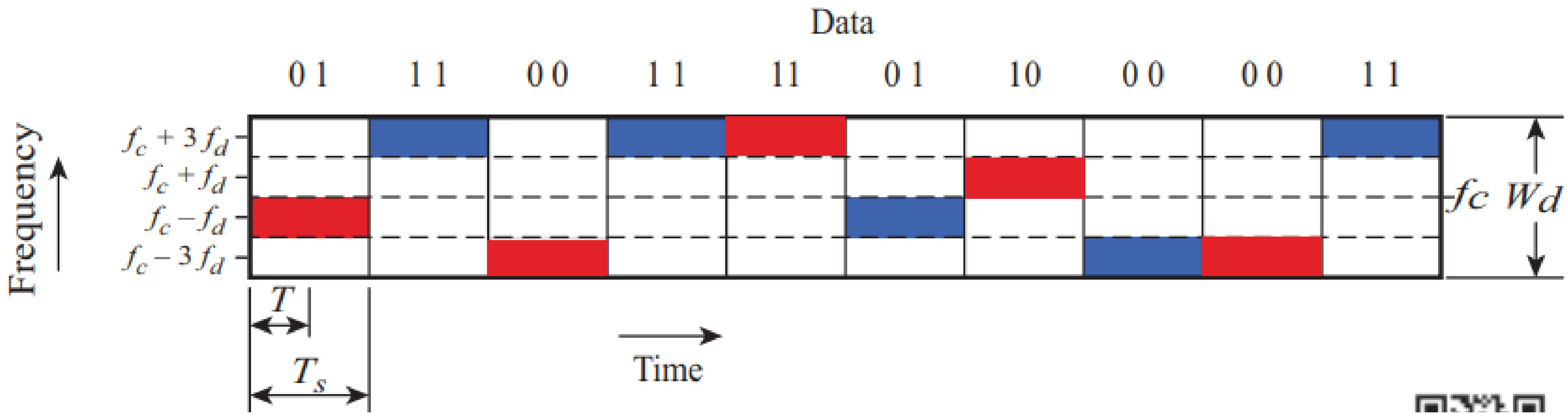


Figure 7.4 MFSK Frequency Use ($M = 4$)

Modulation onto Analog Signal:



- Each output signal element is held for a period of T_s = LT seconds, where T is the bit period (data rate = 1/T) and Ts is called Baud rate (symbols/sec)

- The minimum frequency separation required is $2f_d = 1/T_s$
- The total bandwidth required is approximately $W_d = 2Mf_d$

Modulation onto Analog Signal:

$$\textbf{MFSK} \qquad s_i(t) = A\cos 2\pi f_i t, \qquad 1 \le i \le M$$

where

$$f_i = f_c + (2i - 1 - M)f_d$$

f_c = the carrier frequency

f_d = the difference frequency

M = number of different signal elements $= 2^L$

L = number of bits per signal element

Modulation onto Analog Signal:

$$f_i = f_c + (2i - 1 - M)f_d$$

Example 7.1 With $f_c = 250$ kHz, $f_d = 25$ kHz, and $M = 8$ ($L = 3$ bits), we have the following frequency assignments for each of the eight possible 3-bit data combinations:

$f_1 = 75$ kHz 000	$f_2 = 125$ kHz 001	$f_3 = 175$ kHz 010	$f_4 = 225$ kHz 011
$f_5 = 275$ kHz 100	$f_6 = 325$ kHz 101	$f_7 = 375$ kHz 110	$f_8 = 425$ kHz 111

This scheme can support a data rate of $1/T = 2Lf_d = 150$ kbps.

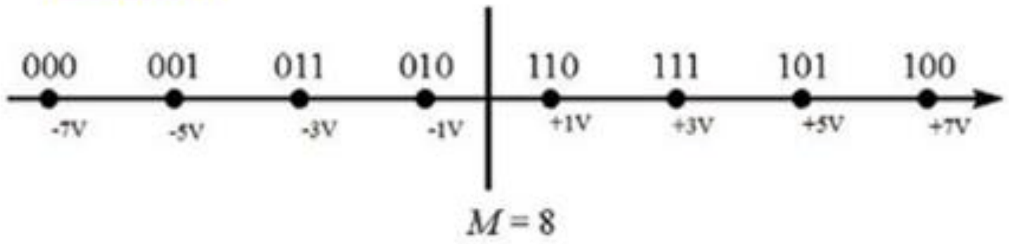
Modulation onto Analog Signal:

- M-ary signaling allows great flexibility in trading signal power and transmission bandwidth. The choice of the appropriate technique depends on system needs & constraints.
- In the case of **M- ary ASK** , the transmitted power increases with M^2 while the bandwidth remains constant.
- In **M-ary FSK**, the transmitted power is practically independent of M (Number of Symbols, $M = 2^n$) but the transmission bandwidth increases with M.
- Therefore, it will be appropriate to use M- ary ASK signaling if the bandwidth is at a premium (bandwidth constraint design; telephone lines) and to use M-ary FSK when power is at a premium (power constraint design; space communication).

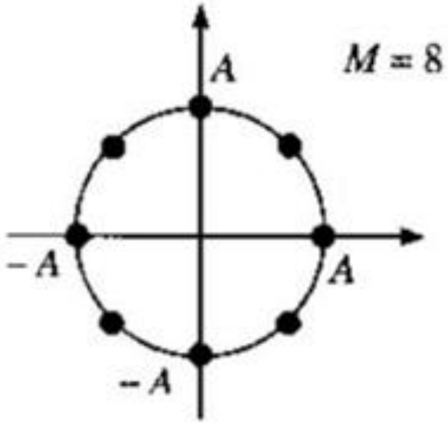
Modulation onto Analog Signal:

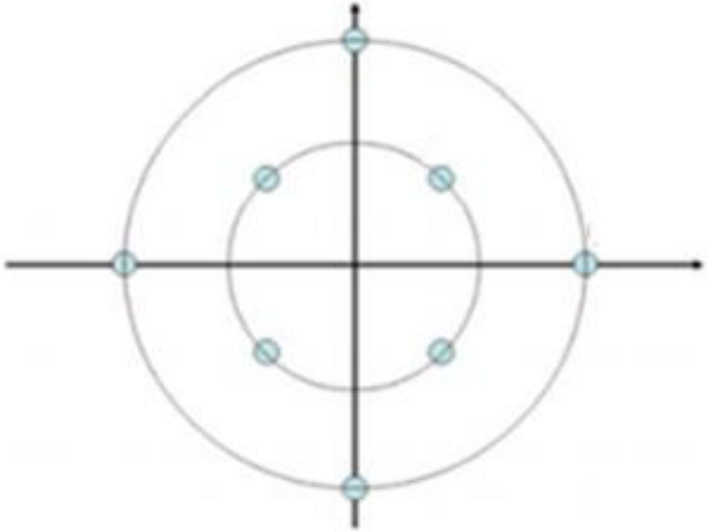
Quadrature Amplitude Modulation

M-ASK



M-PSK





QAM; M= 8

Modulation onto Analog Signal:

Quadrature Amplitude Modulation:

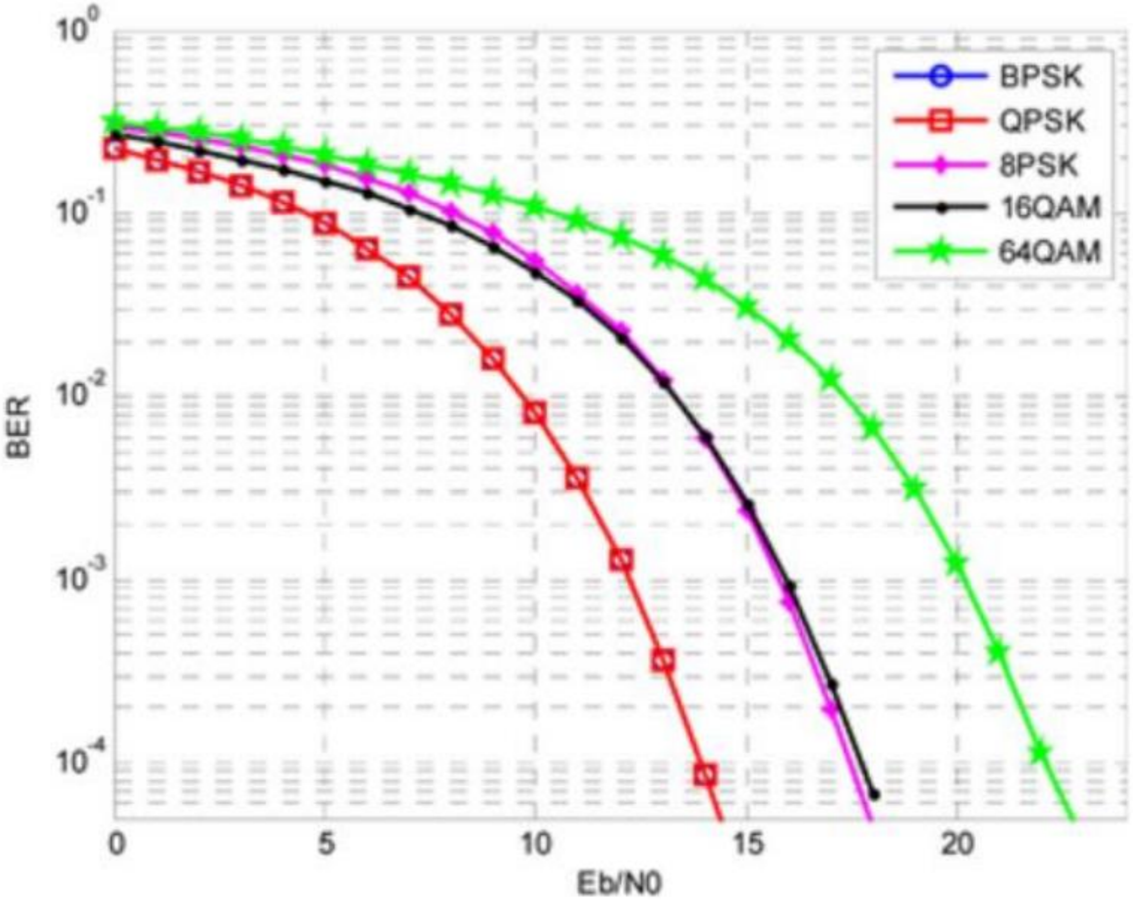
- Quadrature Amplitude Modulation (QAM) is a modulation scheme that combines both amplitude modulation (AM) and phase modulation (PM) to transmit data.

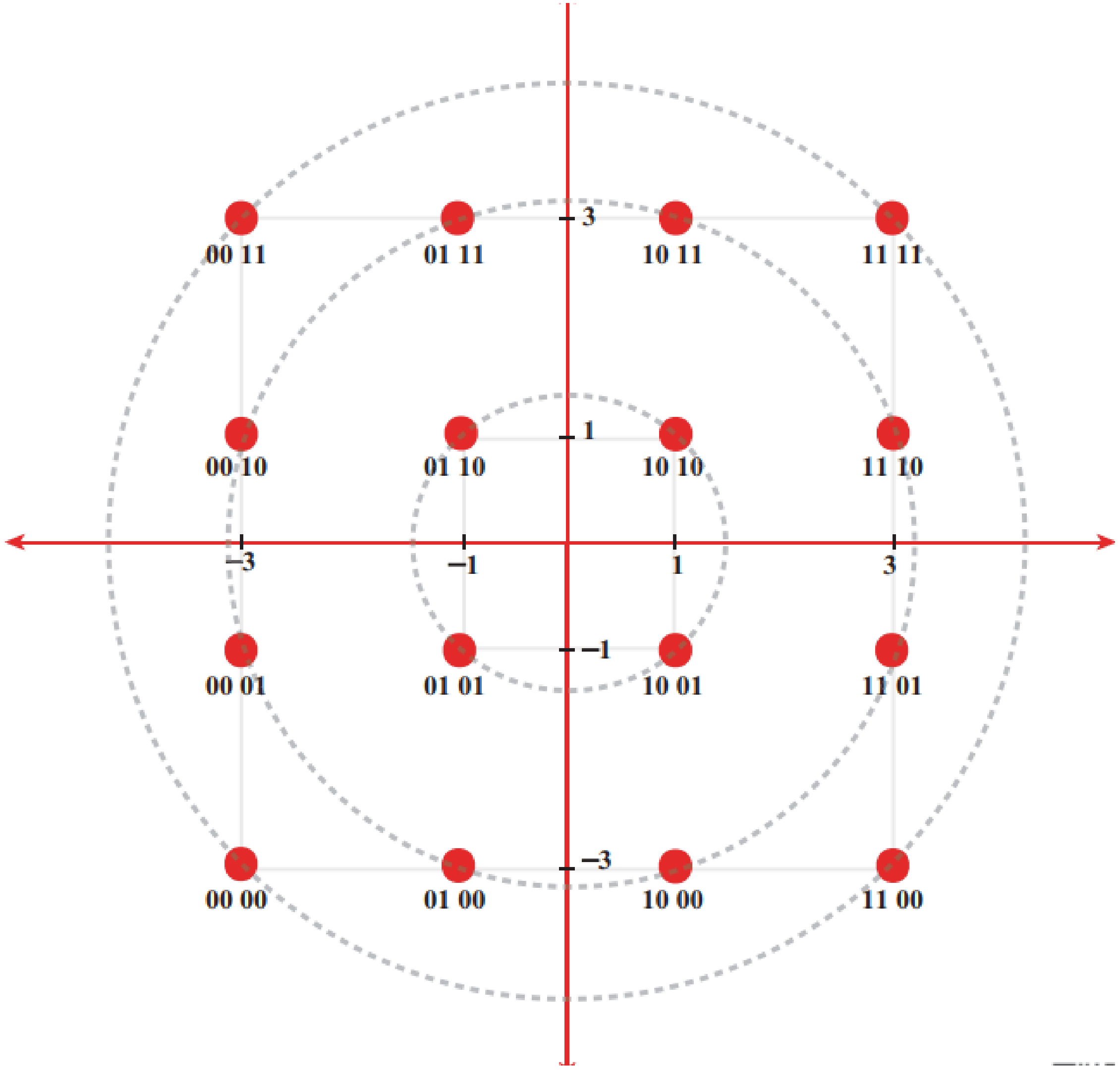
- QAM works by varying both the amplitude and the phase of the carrier signal. Each QAM symbol has a unique combination of amplitude and phase combination.

- QAM is often represented using a constellation diagram, where each point in the diagram represents a unique combination of amplitude and phase. The more points in the constellation, the higher the order of the QAM, which means more bits per symbol can be transmitted.

Modulation onto Analog Signal:

Quadrature Amplitude Modulation

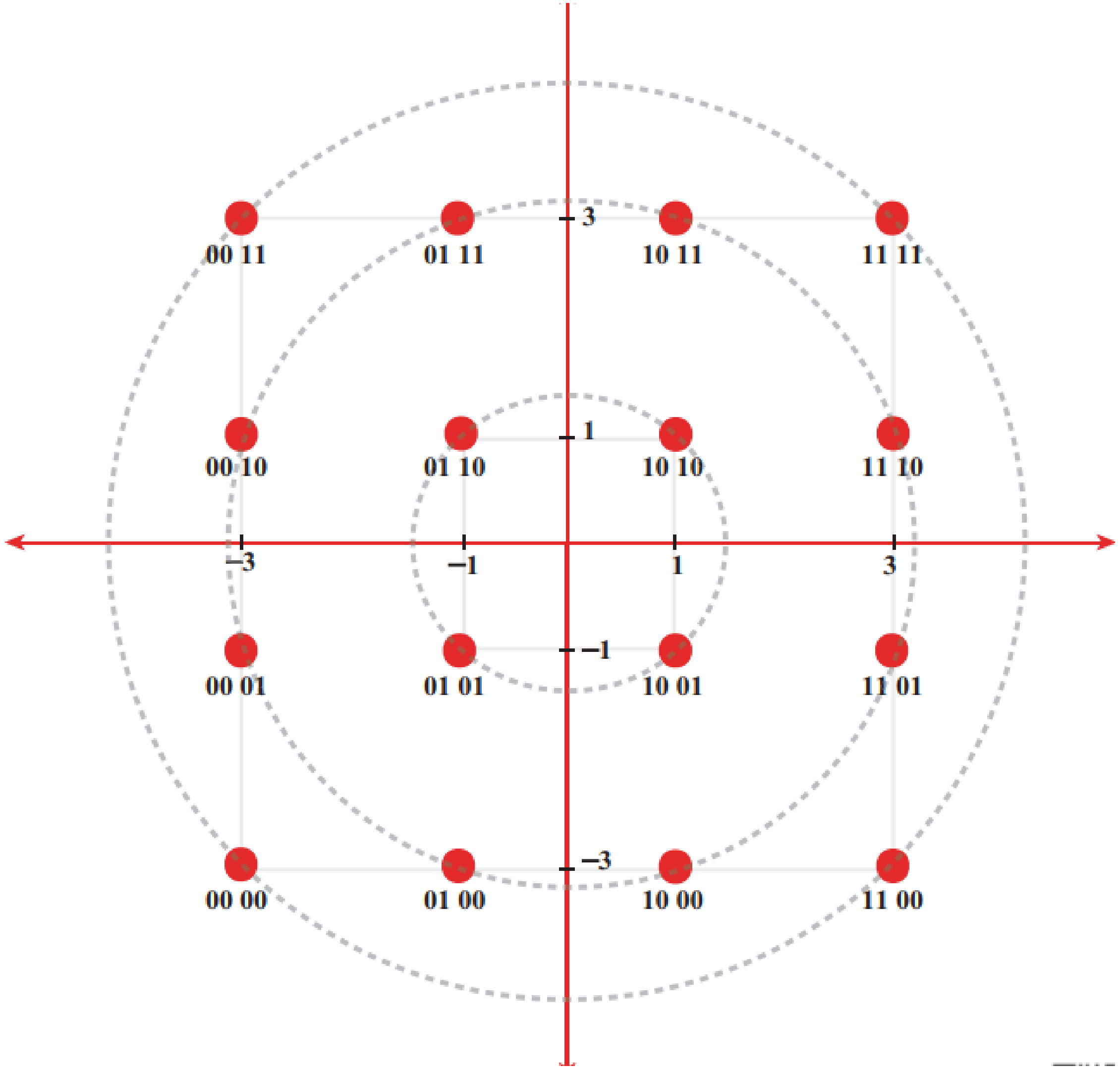




Modulation onto Analog Signal:

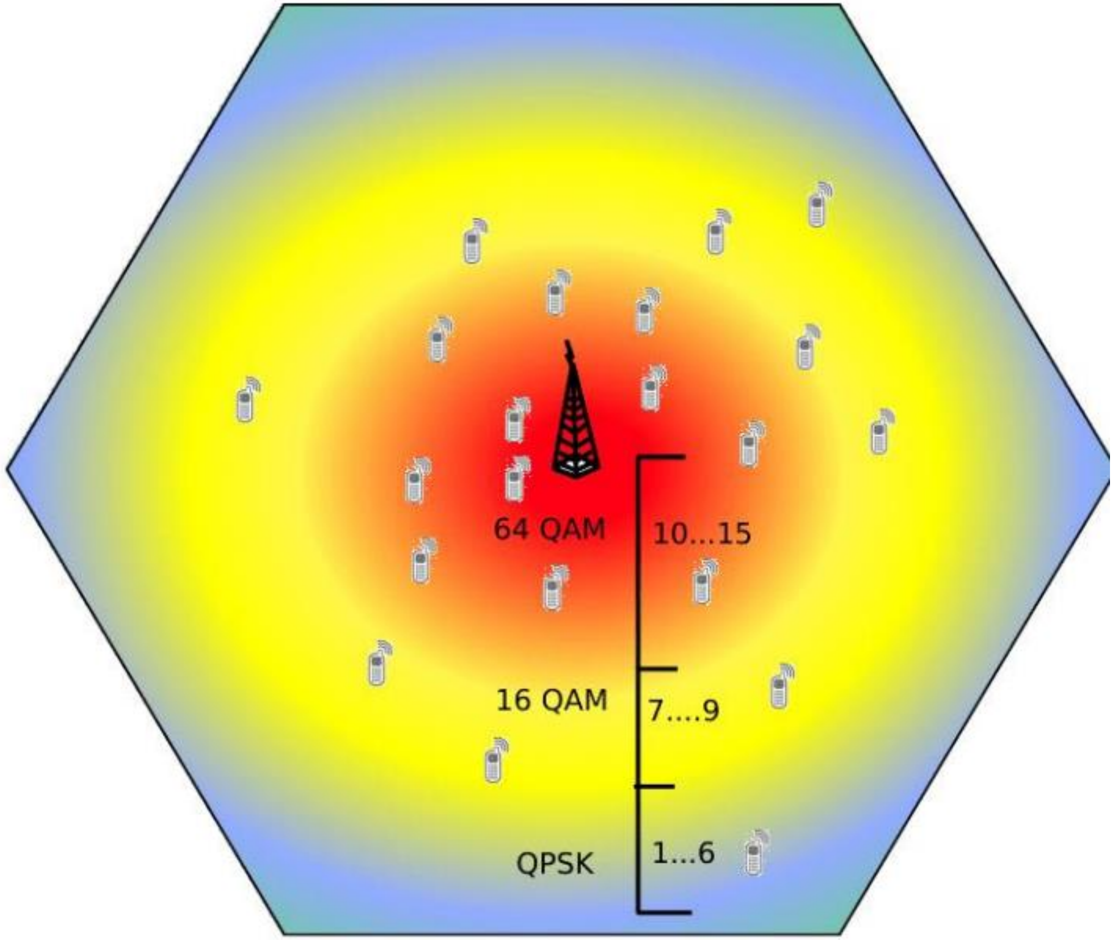
Quadrature Amplitude Modulation:

- QAM allows for high data rates over a given bandwidth by packing multiple bits into each symbol that leads to high bandwidth efficiency
- But higher-order QAM (like 64-QAM or 256-QAM) are very more sensitive to noise, because the symbols are closer together in the constellation diagram, making it easier for noise to cause errors.
- That’s means high order QAM need high SNR to meet desired BER performance. Therefore, Higher-order QAM requires more power to maintain signal integrity.



Modulation onto Analog Signal:

Adaptive Modulation



Thanks!