Chapter 5

Analog Transmission

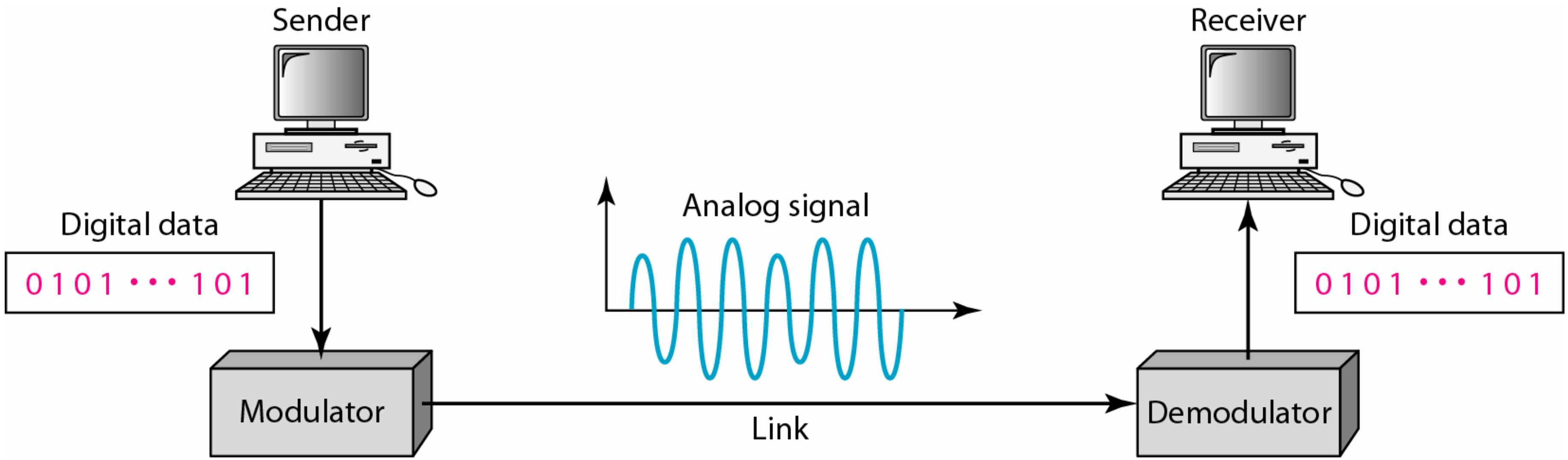
5-1 DIGITAL-TO-ANALOG CONVERSION

Digital-to-analog ***conversion is the process of changing one of the characteristics of an analog signal based on the information in digital data.***

Topics discussed in this section:

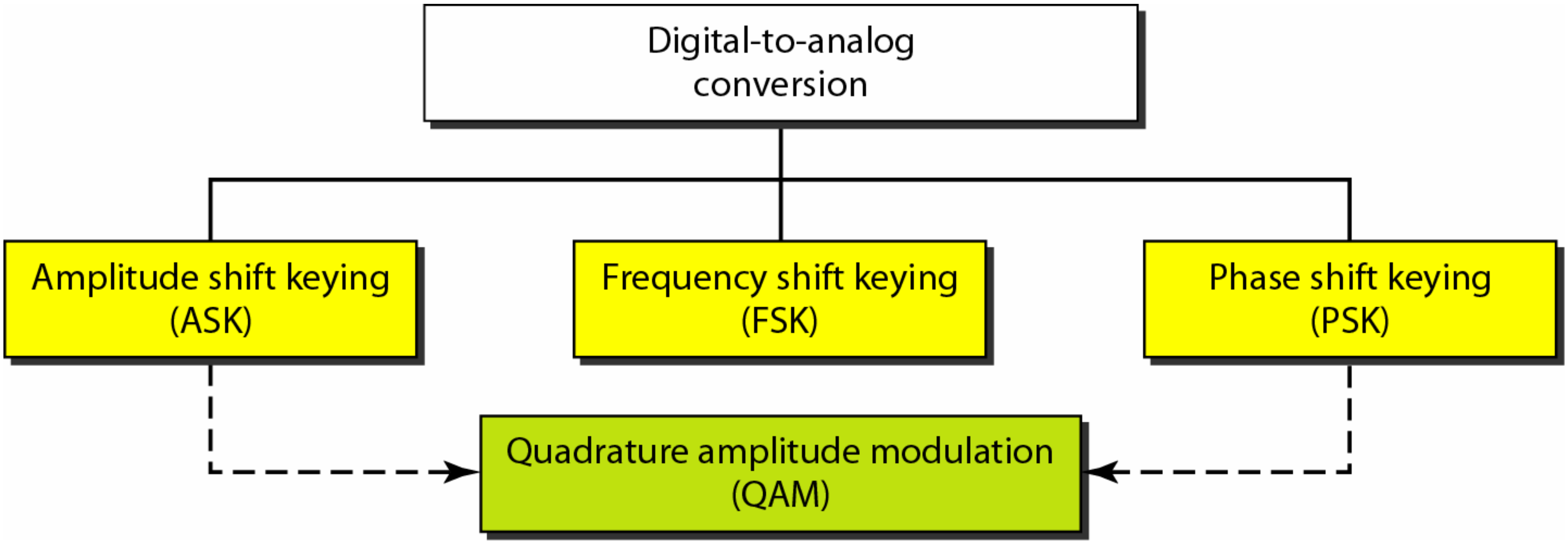
Aspects of Digital-to-Analog Conversion
Amplitude Shift Keying
Frequency Shift Keying
Phase Shift Keying
Quadrature Amplitude Modulation

Figure 5.1 *Digital-to-analog conversion*



- <u>Digital-to-analog modulation (or shift keying):</u> changing one of the characteristics of the analog signal based on the information of the digital signal (carrying digital information onto analog signals)
- <u>Remember</u>: changing any of the characteristics of the simple signal (amplitude, frequency, or phase) would change the nature of the signal to become a composite signal
- The digital information can be carried as predefined changes to one or more of the characteristics (e.g. no-change = 0 and some-change = 1)

Figure 5.2 *Types of digital-to-analog conversion*



Aspects of Digital-to-Analog Conversion

- Data Element vs. Signal Element
- Data Rate vs. Signal Rate
  - $S = N/r$
  - $r = \log_2 L$, where L is the number of signal elements
- Bandwidth:
  - The required bandwidth for analog transmission of digital data is proportional to the signal rate
- Carrier Signal:
  - The digital data changes the carrier signal by modifying one of its characteristics
  - This is called modulation (or Shift Keying)
  - The receiver is tuned to the carrier signal’s frequency

Note

Bit rate is the number of bits per second. Baud rate is the number of signal elements per second.

In the analog transmission of digital data, the baud rate is less than or equal to the bit rate.

Example 5.1

An analog signal carries 4 bits per signal element. If 1000 signal elements are sent per second, find the bit rate.

Solution

In this case, r = 4, S = 1000, and N is unknown. We can find the value of N from

$$S = N \times \frac{1}{r} \qquad \text{or} \qquad N = S \times r = 1000 \times 4 = 4000 \text{ bps}$$

Example 5.2

An analog signal has a bit rate of 8000 bps and a baud rate of 1000 baud. How many data elements are carried by each signal element? How many signal elements do we need?

Solution

In this example, S = 1000, N = 8000, and r and L are unknown. We find first the value of r and then the value of L.

$$S = N \times \frac{1}{r} \quad \Rightarrow \quad r = \frac{N}{S} = \frac{8000}{1000} = 8 \text{ bits/baud}$$

$$r = \log_2 L \quad \Rightarrow \quad L = 2^r = 2^8 = 256$$

Amplitude Shift Keying (ASK)

- ASK: varying the peak amplitude of the carrier signal to represent binary 1 or 0
- Other signal characteristics remain constant as the amplitude changes
- During each bit duration, the peak amplitude remains constant
- Transmission medium noise is usually additive (i.e.; affects the amplitude), therefore, ASK is very susceptible to noise interference
- Binary ASK (BASK) or On/Off Keying (OOK) modulation technique:
  - One of the binary bits is represented by no voltage
  - Advantage: requires less transmission energy compared to two-level techniques
- BASK spectrum is most significantly between $[f_c - S/2, f_c + S/2]$, where f_c is frequency of the carrier signal and S is the baud rate
- The ASK bandwidth is $B_{BASK} = (1+d)\,S$, where d is a factor related to the modulation process, of which the value is between 0 and 1
- The min. bandwidth required to transmit an ASK is equal to the baud rate
- The baud rate is the same as the bit rate ➔ $N = S$

Figure 5.3 *Binary amplitude shift keying*

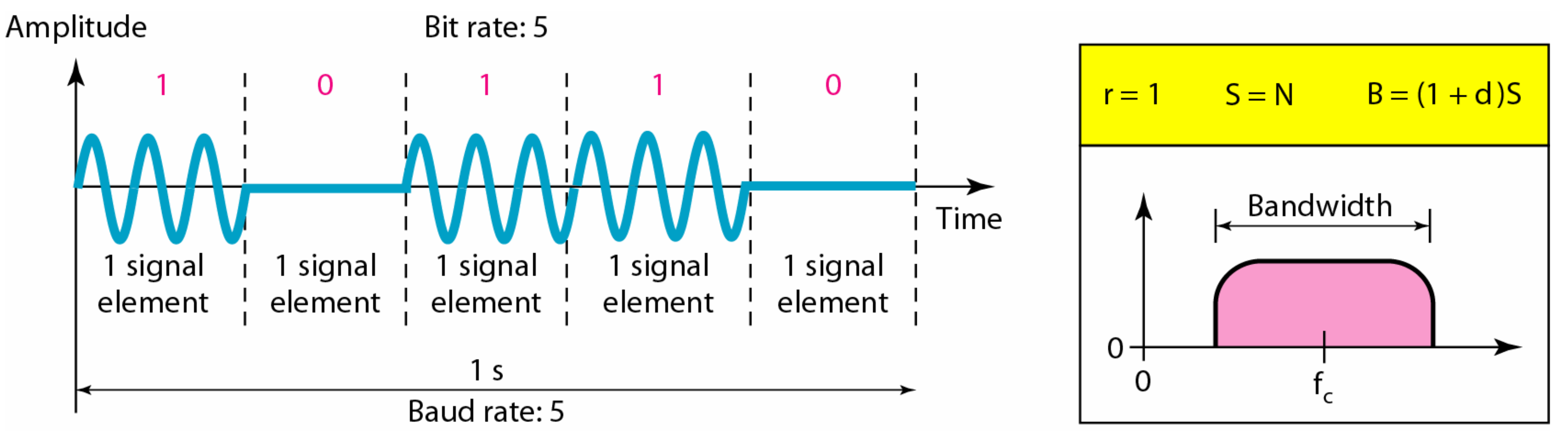
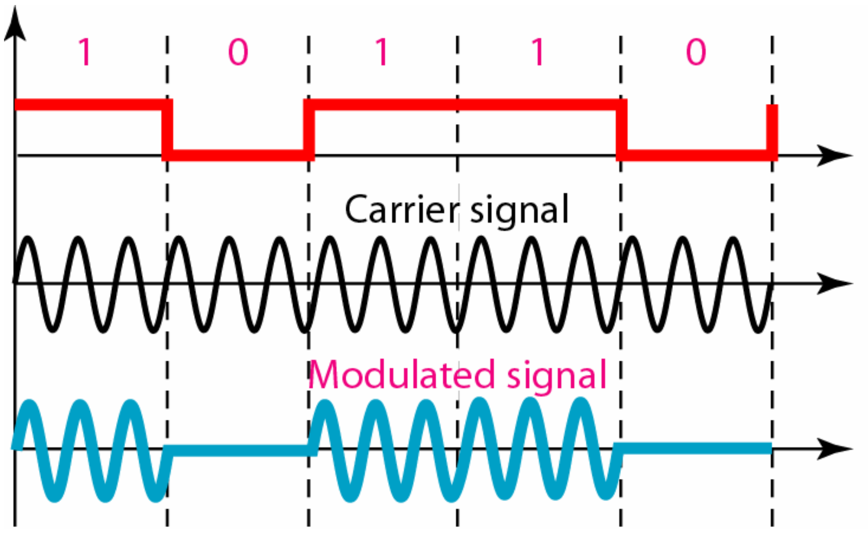
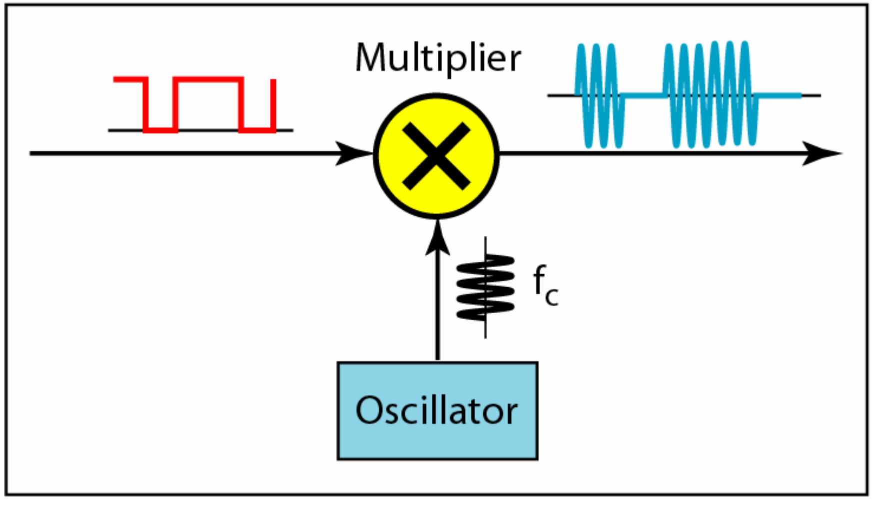


Figure 5.4 *Implementation of binary ASK*





Example 5.3

We have an available bandwidth of 100 kHz which spans from 200 to 300 kHz. What are the carrier frequency and the bit rate if we modulated our data by using ASK with d = 1?

Solution

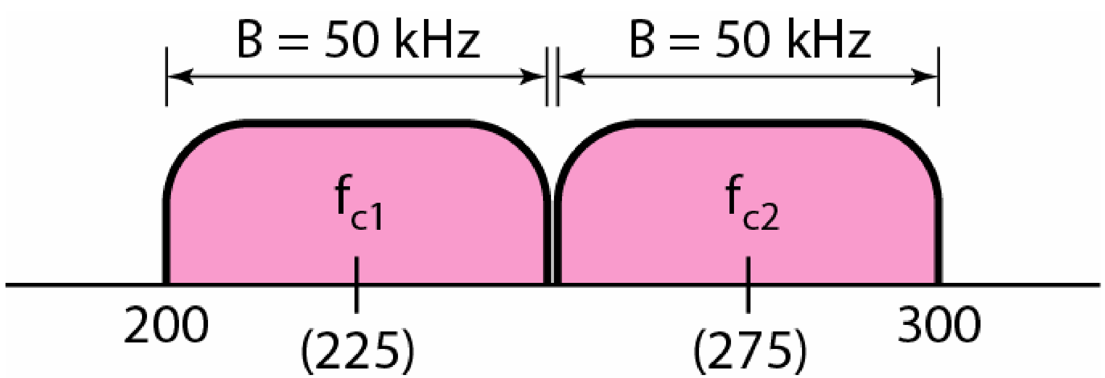
The middle of the bandwidth is located at 250 kHz. This means that our carrier frequency can be at f_c = 250 kHz. We can use the formula for bandwidth to find the bit rate (with d = 1 and r = 1).

$$B = (1 + d) \times S = 2 \times N \times \frac{1}{r} = 2 \times N = 100 \text{ kHz} \quad \Rightarrow \quad N = 50 \text{ kbps}$$

Example 5.4

In data communications, we normally use full-duplex links with communication in both directions. We need to divide the bandwidth into two with two carrier frequencies, as shown in Figure 5.5. The figure shows the positions of two carrier frequencies and the bandwidths. The available bandwidth for each direction is now 50 kHz, which leaves us with a data rate of 25 kbps in each direction.

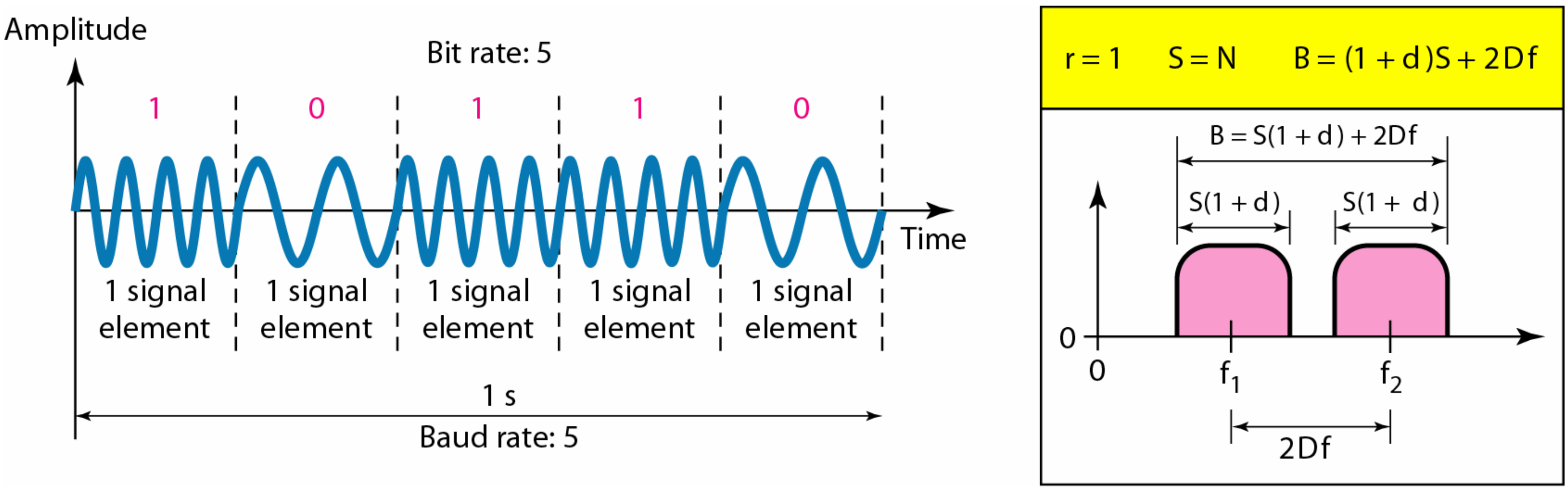
Figure 5.5 ***Bandwidth of full-duplex ASK used in Example 5.4***



Frequency Shift Keying (FSK)

- FSK: varying the frequency of the carrier signal to represent binary 1 or 0
- Other signal characteristics remain constant as the frequency changes
- During each bit duration, the frequency remains constant
- FSK is mostly immune to the transmission medium additive noise interference since FSK only cares about Frequency changes
- The Binary FSK (BFSK) can be thought of as two ASK signals, each with its own carrier frequency f_1 and f_2
- f_1 and f_2 are $2\triangle f$ apart
- The BFSK required bandwidth is $B_{BFSK} = (1+d)\,S + 2\triangle f$
- What is the minimum value of $2\triangle f$?
- The baud rate is the same as the bit rate ➔ N = S

Figure 5.6 *Binary frequency shift keying*



Example 5.5

We have an available bandwidth of 100 kHz which spans from 200 to 300 kHz. What should be the carrier frequency and the bit rate if we modulated our data by using FSK with d = 1?

Solution

This problem is similar to Example 5.3, but we are modulating by using FSK. The midpoint of the band is at 250 kHz. We choose 2Δf to be 50 kHz; this means

$$B = (1 + d) \times S + 2\Delta f = 100 \quad \Rightarrow \quad 2S = 50 \text{ kHz} \quad S = 25 \text{ kbaud} \quad N = 25 \text{ kbps}$$

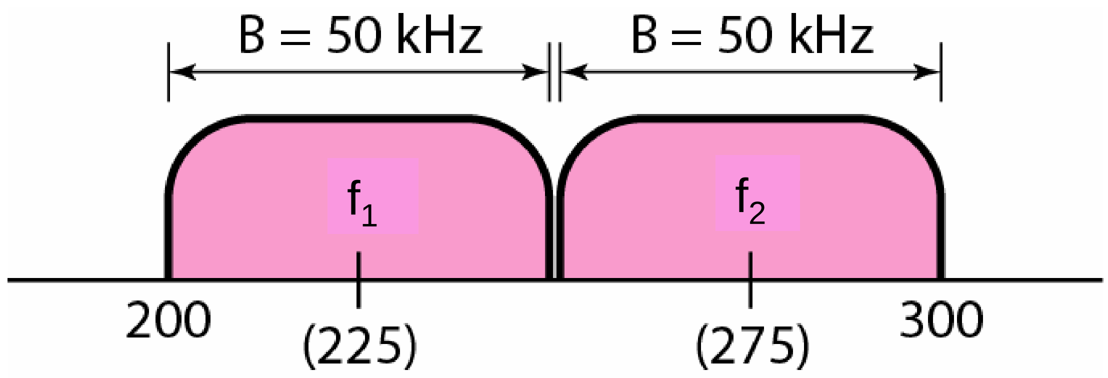
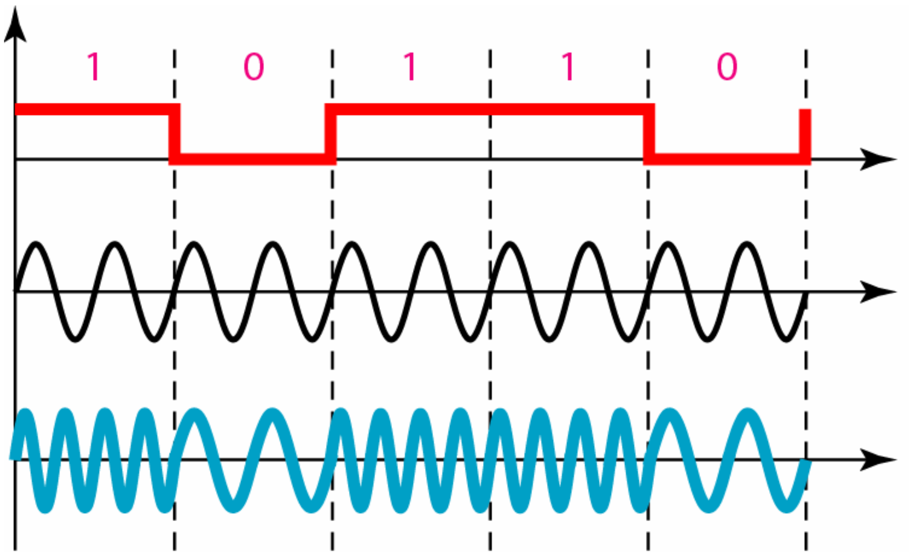
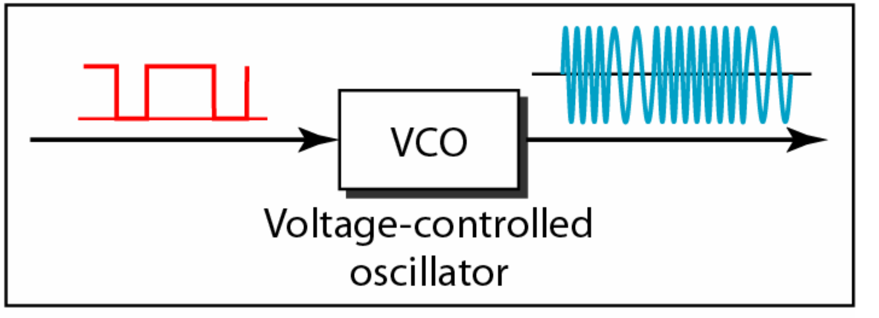


Figure 5.7 *Implementation of BFSK*





Multi-Level FSK (MFSK)

- More than two frequencies can be used to represent more than one bit each
  - For example: four different frequencies can be used to send 2 bits at a time
- However, each adjacent pair of frequencies must be $2\triangle f$ apart
- The MFSK required bandwidth is

$$B_{MFSK} = (1+d)\ S + (L-1)\ 2\triangle f$$

- When d=0, the minimum Bandwidth $B_{MFSK} = L \times S$

Example 5.6

We need to send data 3 bits at a time at a bit rate of 3 Mbps. The ~~carrier~~ center frequency is 10 MHz. Calculate the number of levels (different frequencies), the baud rate, and the minimum bandwidth.

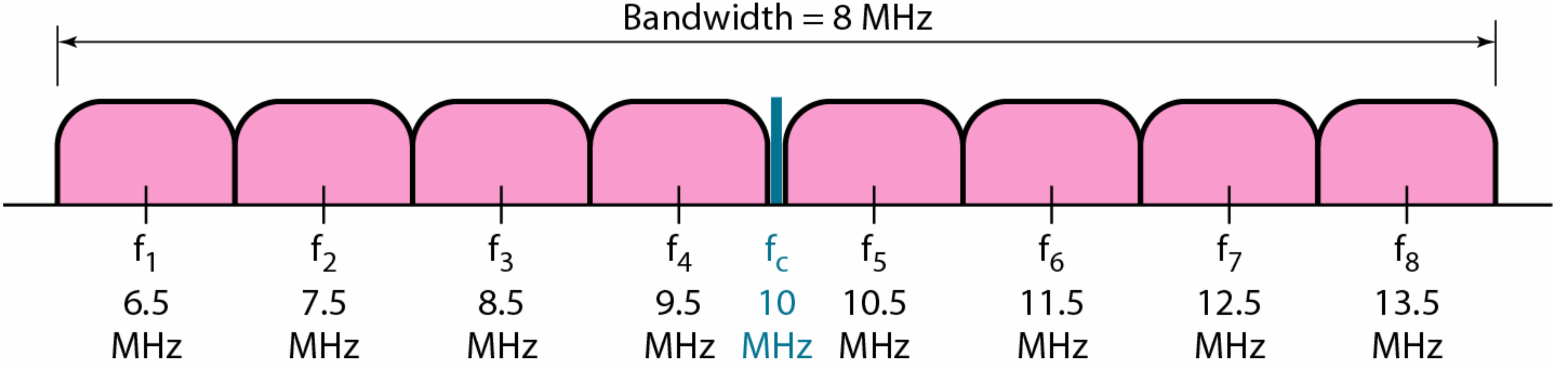
Solution

We have $L = 2^3 = 8$. The baud rate is $S = 3$ MHz/3 = 1 Mbaud ➔ the carrier frequencies must be 1 MHz apart ($2\Delta f = 1$ MHz).

The bandwidth is $B = 8 \times 1$MHz = 8 MHz

Figure 5.8 shows the allocation of frequencies and bandwidth.

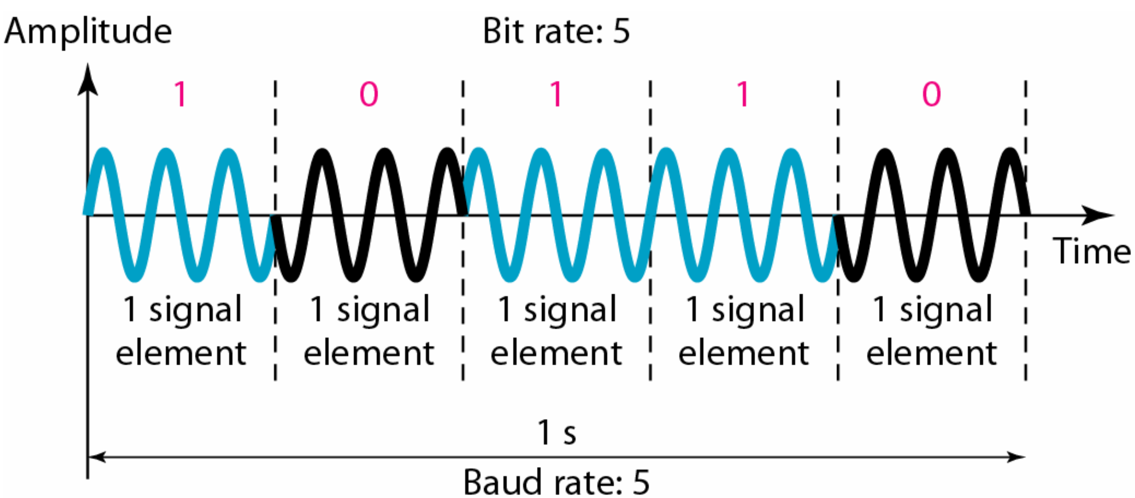
Figure 5.8 *Bandwidth of MFSK used in Example 5.6*



Phase Shift Keying (PSK)

- PSK: varying the phase of carrier signal to represent binary 1 or 0
- Other signal characteristics remain constant as the phase changes
- During each bit duration, the phase remains constant
- PSK is mostly immune to the transmission medium additive noise interference since PSK only cares about phase changes
- PSK spectrum and bandwidth requirements are similar to ASK
- PSK is better than both ASK and FSK. Why?
- 2-PSK or Binary PSK (BPSK): uses 2 different phases (usually 0 and 180) each representing 1 bit of data ➔ N = S
- 4-PSK or Quad PSK (QPSK): uses 4 different phases (e.g.; 45, -45, 135, and -135) each representing 2 bits of data ➔ N = 2 S
- PSK is represented by a Constellation (or Phase-State) diagram
- PSK is limited by the ability of the receiver to distinguish small phase difference, therefore, limiting the potential bit rate

Figure 5.9 *Binary phase shift keying*



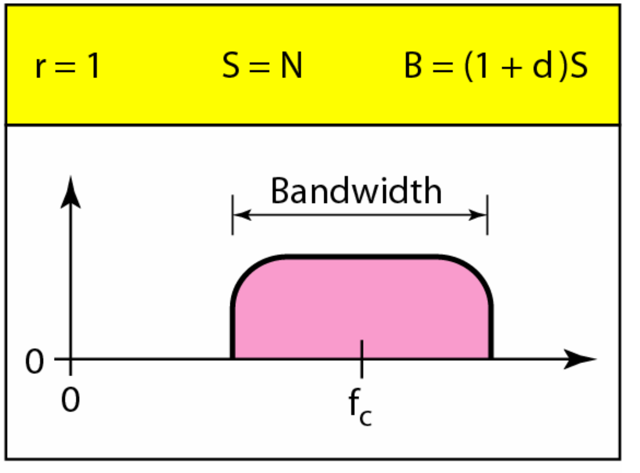


Figure 5.10 *Implementation of BPSK*

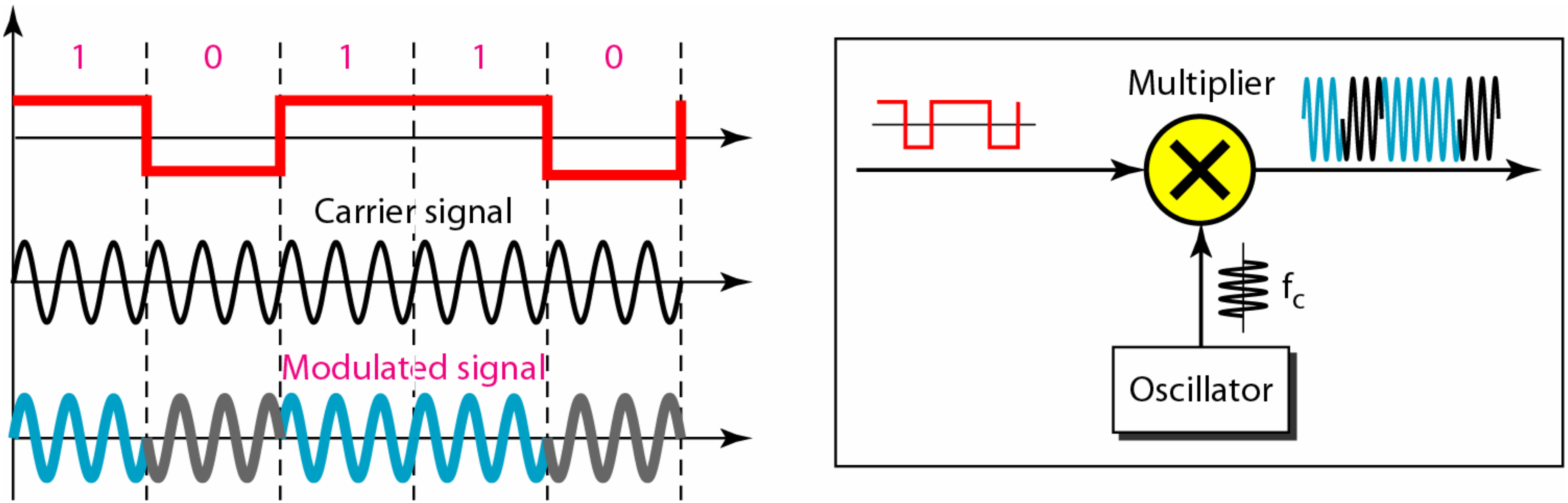
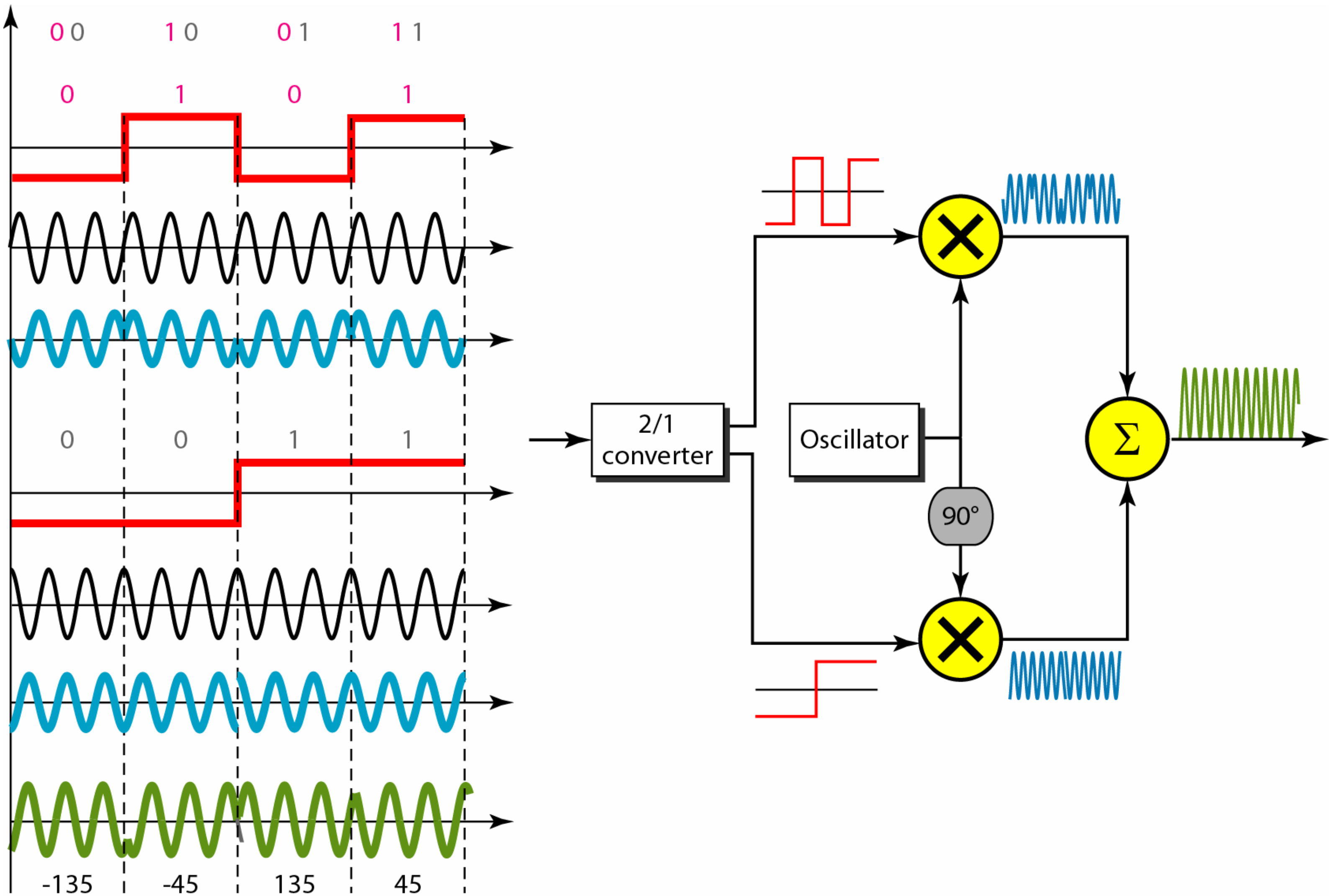


Figure 5.11 *QPSK and its implementation*



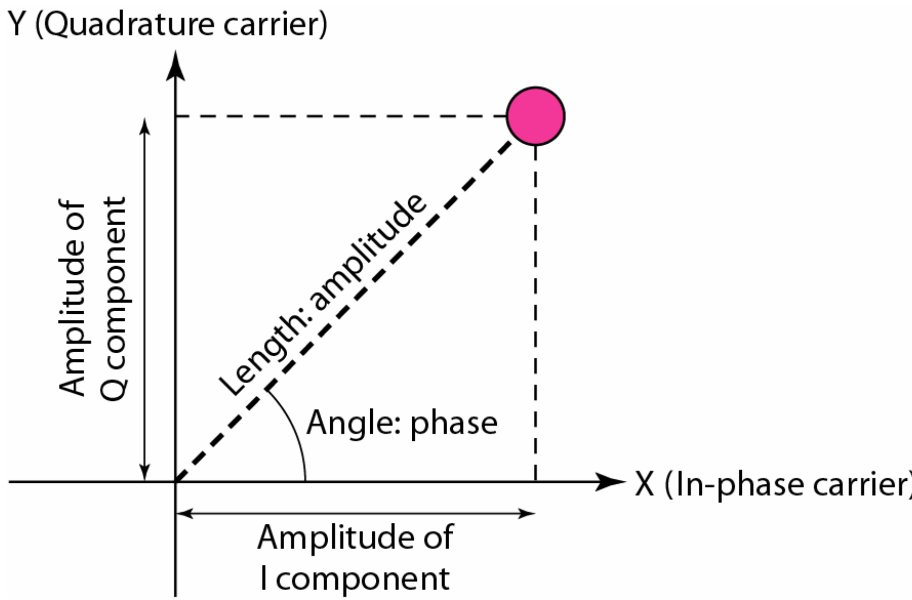
Example 5.7

Find the bandwidth for a signal transmitting at 12 Mbps for QPSK. The value of d = 0.

Solution

For QPSK, 2 bits is carried by one signal element. This means that r = 2. So the signal rate (baud rate) is S = N × (1/r) = 6 Mbaud. With a value of d = 0, we have B = S = 6 MHz.

Figure 5.12 *Concept of a constellation diagram*



- Used to define the amplitude and phase of a signal element when using two carriers or when dealing with multi-level shift keying
- A signal element is represented by a dot in the diagram, of which:
  - The projection on the X axis defines the peak amplitude of the in-phase component
  - The projection on the Y axis defines the peak amplitude of the quadrature component
  - The length of the line connecting the point to the origin is the peak amplitude of the signal element
  - The angle the line makes with the X axis is the phase of the signal element

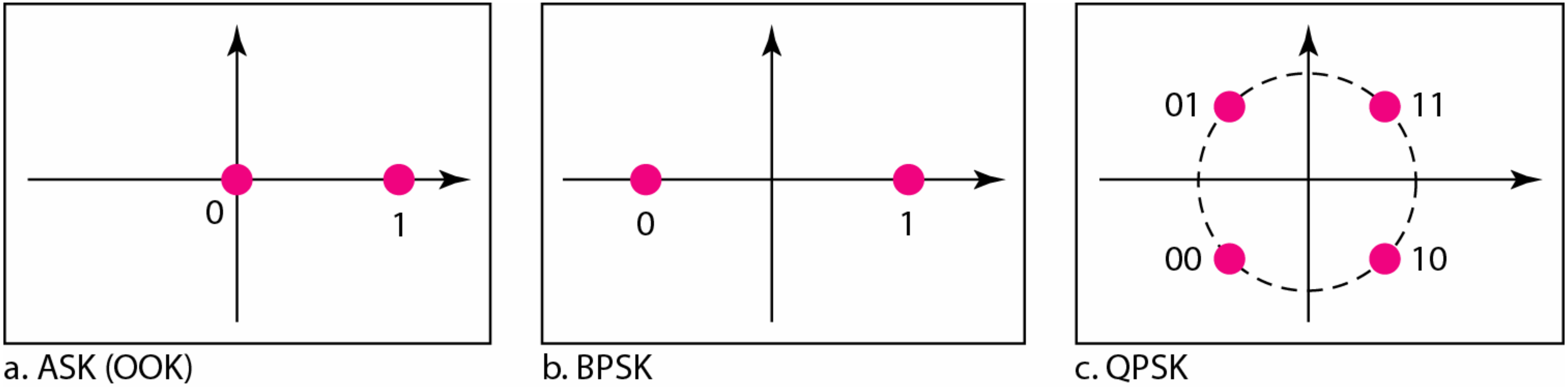
Example 5.8

Show the constellation diagrams for an ASK (OOK), BPSK, and QPSK signals.

Solution

Figure 5.13 shows the three constellation diagrams.

Figure 5.13 *Three constellation diagrams*



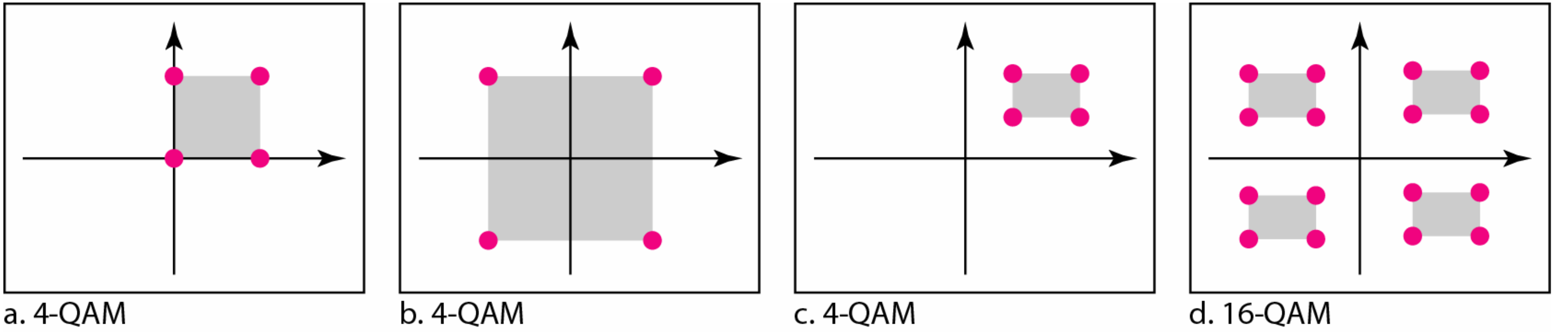
Quadrature Amplitude Modulation (QAM)

- QAM: varying both the peak amplitude and the phase of the carrier signal to represent binary combination
- During each bit duration, the phase and amplitude remain constant
- Theoretically, any number of measurable changes in phase and amplitude can be combined to give several variations in the signal
- The number of phase shifts is always greater than the amplitude shifts. Why?
- The greater the ratio of phase to amplitude shifts, the better the noise immunity
- QAM spectrum and bandwidth requirements are similar to ASK and PSK

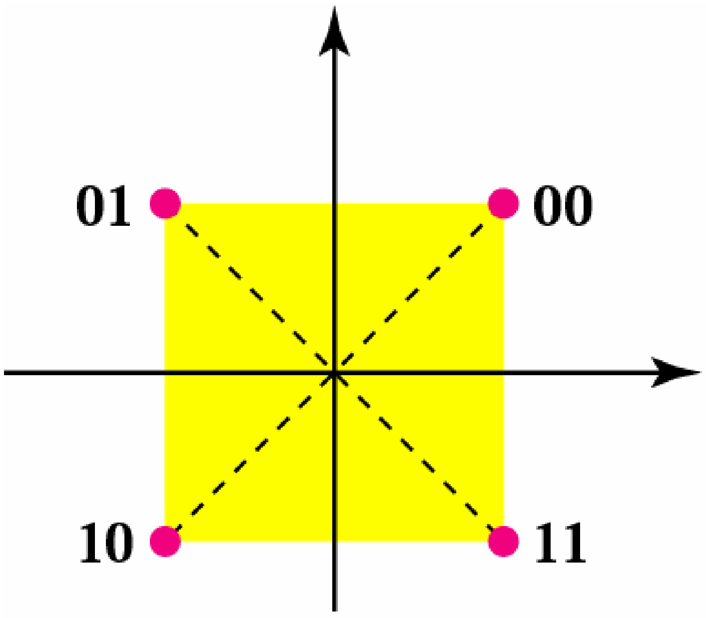
Note

Quadrature amplitude modulation is a combination of ASK and PSK.

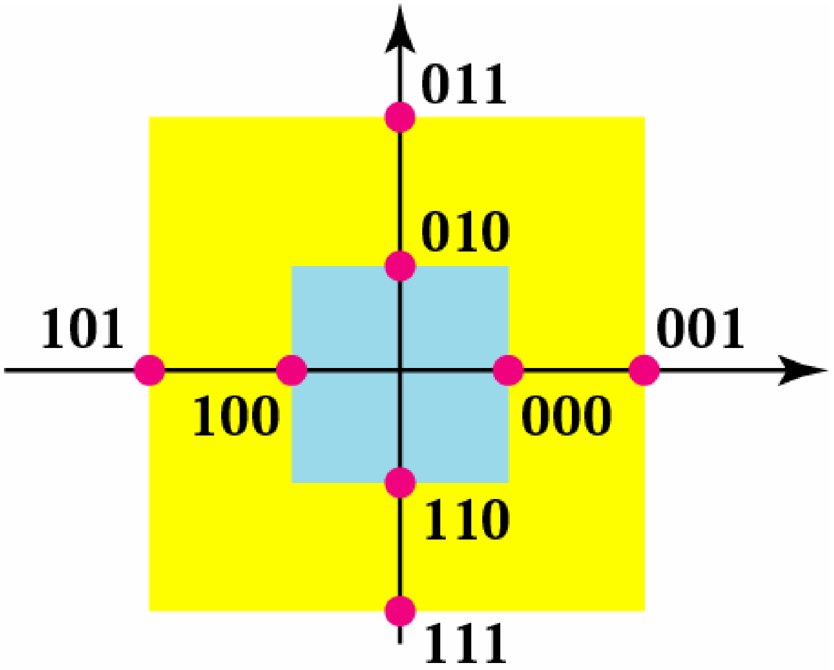
Figure 5.14 *Constellation diagrams for some QAMs*



Examples of 4-QAM and 8-QAM constellations



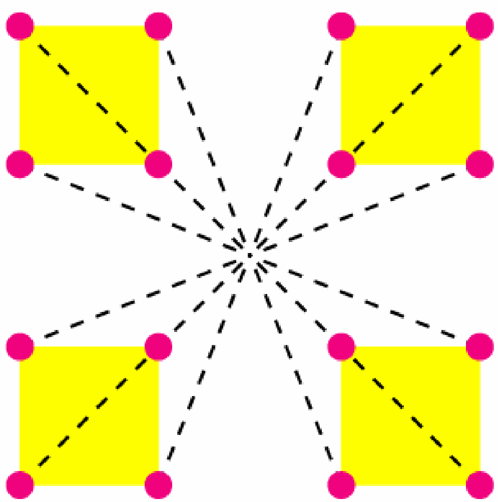
4-QAM
1 amplitude, 4 phases



8-QAM
2 amplitudes, 4 phases

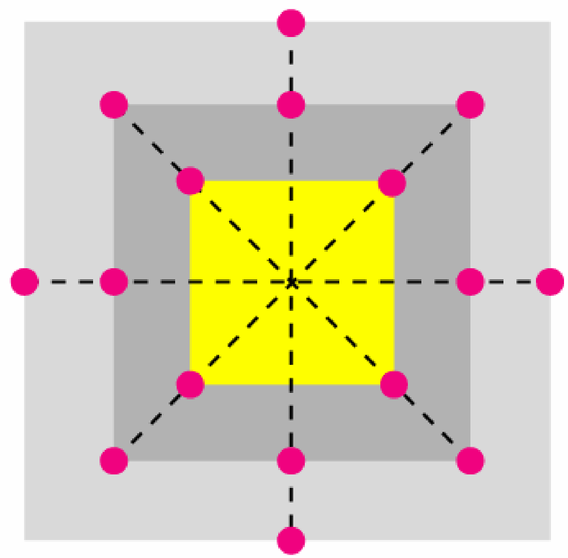
Examples of 16-QAM constellations

3 amplitudes, 12 phases



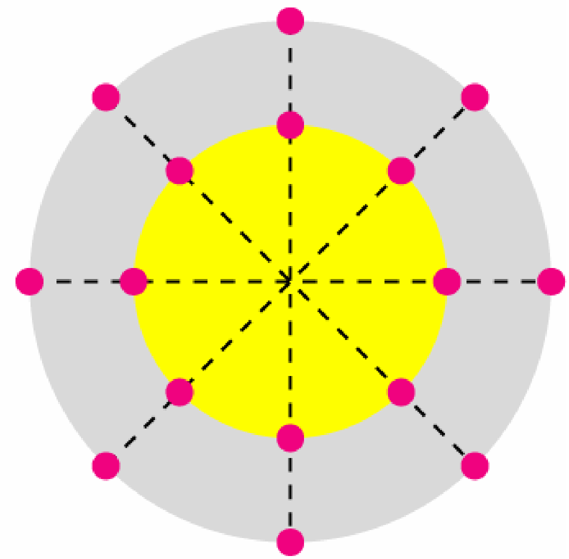
16-QAM

4 amplitudes, 8 phases



16-QAM

2 amplitudes, 8 phases



16-QAM

Example

A constellation diagram consists of eight equally spaced points on a circle. If the bit rate is 4800 bps, what is the baud rate?

Solution

The constellation indicates 8-PSK with the points 45 degrees apart. Since $2^3 = 8$, 3 bits are transmitted with each signal unit. Therefore, the baud rate is

$$4800 / 3 = 1600 \text{ baud}$$

Example

Compute the bit rate for a 1000-baud 16-QAM signal.

Solution

A 16-QAM signal has 4 bits per signal unit since

$$\log_2 16 = 4.$$

Thus,

$$(1000)(4) = 4000 \text{ bps}$$

Example

Compute the baud rate for a 72,000-bps 64-QAM signal.

Solution

A 64-QAM signal has 6 bits per signal unit since

$$\log_2 64 = 6.$$

Thus,

$$72000 / 6 = 12{,}000 \text{ baud}$$

Bit and baud rate comparison

Modulation	Units	Bits/Baud	Baud rate	Bit Rate
ASK, FSK, 2-PSK	Bit	1	N	N
4-PSK, 4-QAM	Dibit	2	N	2N
8-PSK, 8-QAM	Tribit	3	N	3N
16-QAM	Quadbit	4	N	4N
32-QAM	Pentabit	5	N	5N
64-QAM	Hexabit	6	N	6N
128-QAM	Septabit	7	N	7N
256-QAM	Octabit	8	N	8N

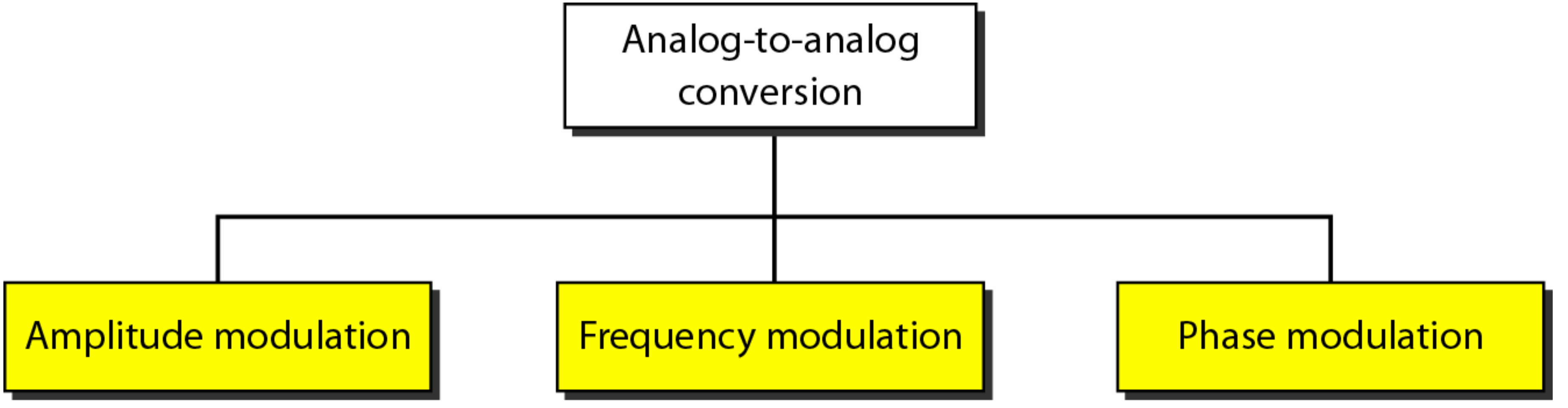
5-2 ANALOG-TO-ANALOG CONVERSION

Analog-to-analog conversion is the representation of analog information by an analog signal. One may ask why we need to modulate an analog signal; it is already analog. Modulation is needed if the medium is bandpass in nature or if only a bandpass channel is available to us.

Topics discussed in this section:

Amplitude Modulation
Frequency Modulation
Phase Modulation

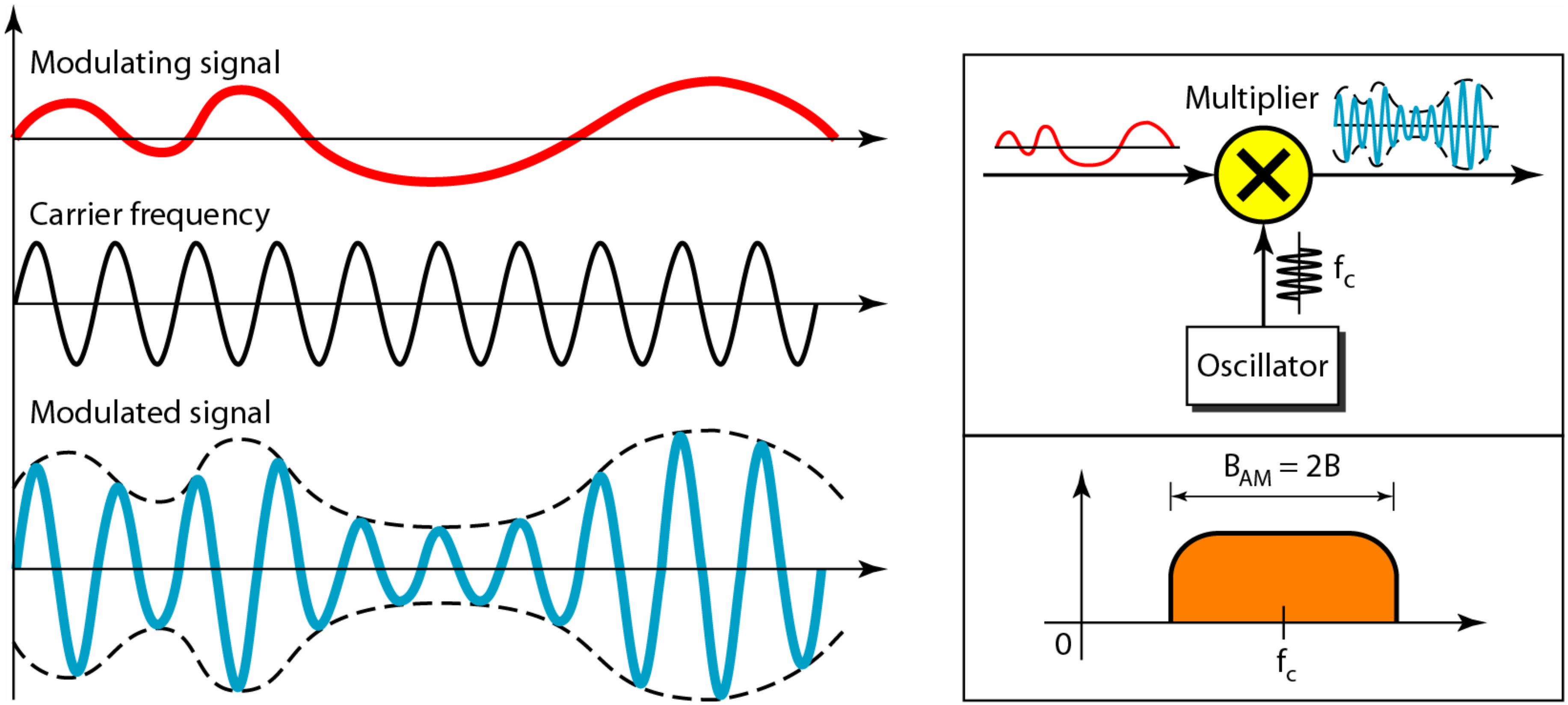
Figure 5.15 *Types of analog-to-analog modulation*



Amplitude Modulation (AM)

- The amplitude of the carrier (or modulated) signal changes with the amplitude changes of the modulating signal
- The frequency and phase of the modulated signal remain constant
- The modulating signal becomes the envelope (i.e.; the outer shape) of the modulated signal
- The bandwidth of the AM signal is equal to twice the bandwidth of the modulating signal
- The bandwidth of an audio signal (voice and music) is 5 kHz
- AM radio stations are assigned 10 kHz band per channel
- Every other band is used as a guard band to prevent interference among adjacent channels

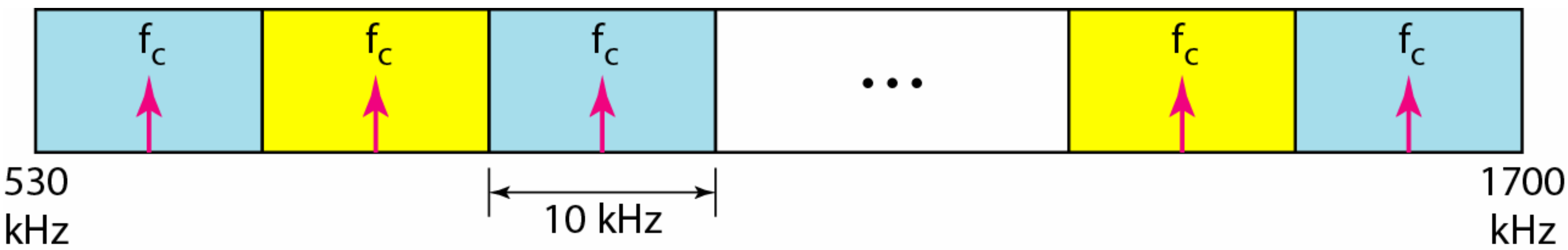
Figure 5.16 *Amplitude modulation*



Note

The total bandwidth required for AM can be determined from the bandwidth of the audio signal: $B_{AM} = 2B$.

Figure 5.17 *AM band allocation*



Frequency Modulation (FM)

- The frequency of the carrier (or modulated) signal changes with the amplitude changes of the modulating signal
- The peak amplitude and phase of the modulated signal remain constant
- The bandwidth of the FM signal is usually about 10 times the bandwidth of the modulating signal
- The bandwidth of a stereo audio signal (voice and music) is about 15 kHz
- FM radio stations are assigned 200 kHz band per channel
- Every other band is used as a guard band to prevent interference among adjacent channels

Note

The total bandwidth required for FM can be determined from the bandwidth of the audio signal: $B_{FM} = 2(1 + \beta)B$.

Figure 5.18 *Frequency modulation*

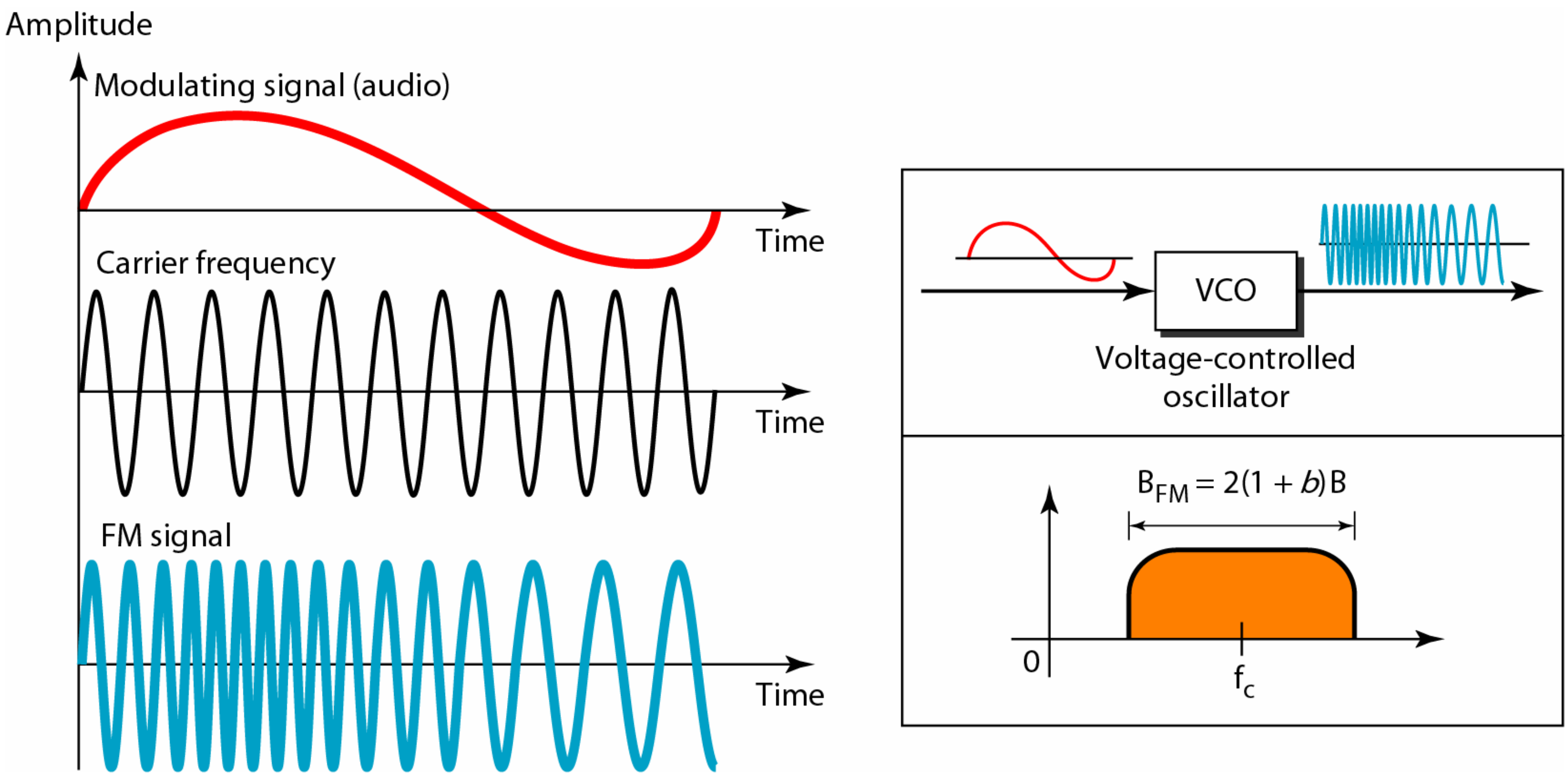
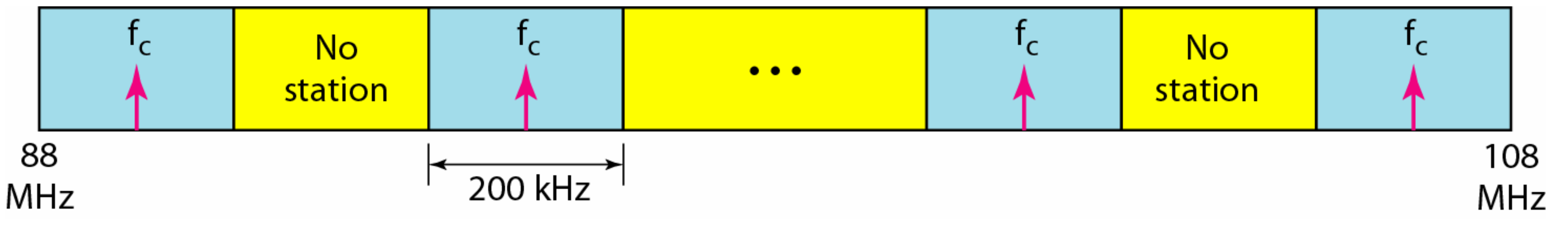


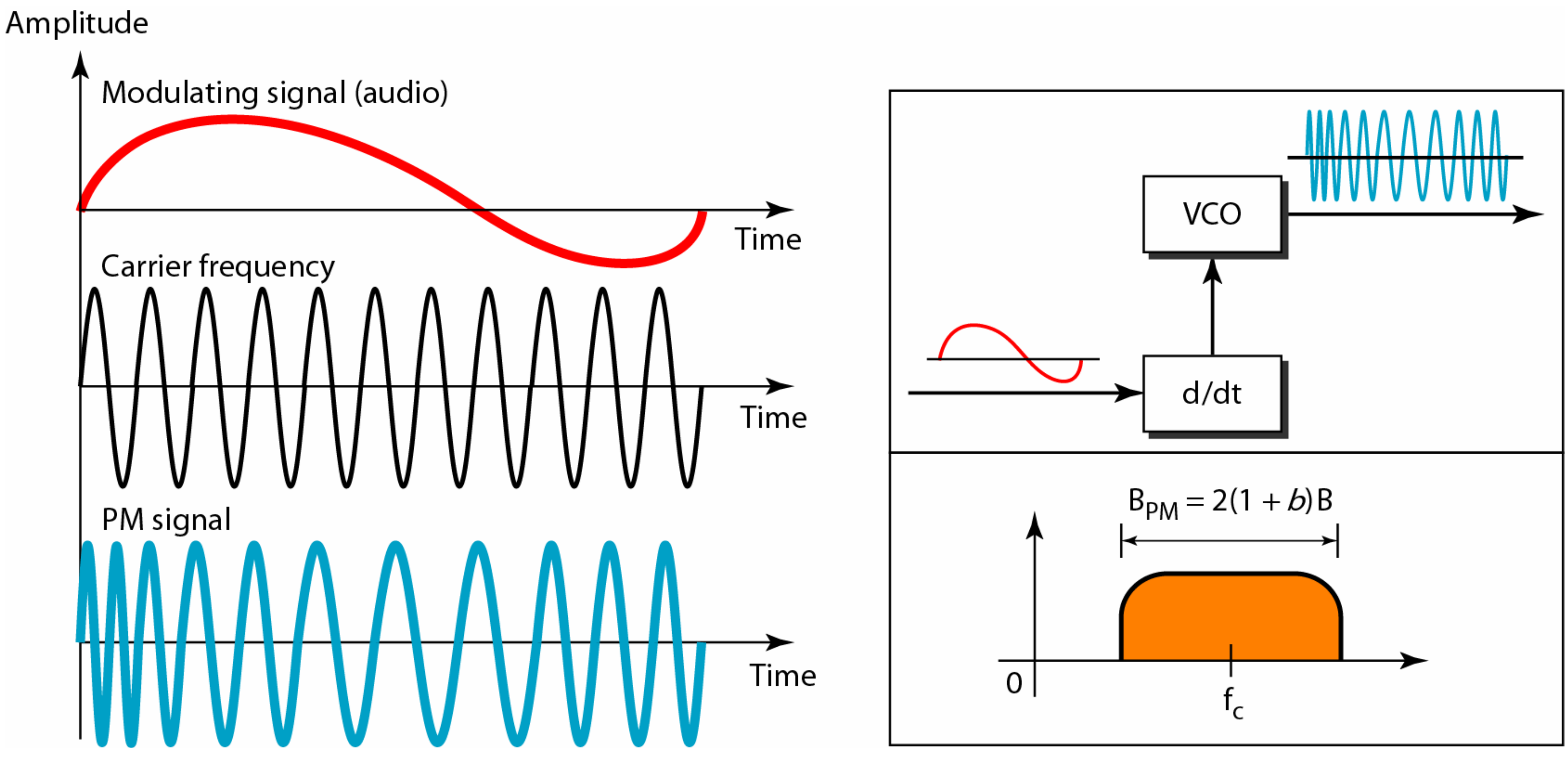
Figure 5.19 *FM band allocation*



Phase Modulation (PM)

- The phase of the carrier (or modulated) signal changes with the amplitude changes of the modulating signal
- The peak amplitude and frequency of the modulated signal remain constant
- PM is the same as FM except that in FM, the instantaneous change in the carrier frequency is proportional to the amplitude of the modulating signal, while in PM it is proportional to the rate of change of the amplitude
- The bandwidth of the PM signal is usually abut 6 times the bandwidth of the modulating signal

Figure 5.20 *Phase modulation*



Note

The total bandwidth required for PM can be determined from the bandwidth and maximum amplitude of the modulating signal:

$$B_{PM} = 2(1 + \beta)B.$$