Data Communications and Networking Fourth Edition

Forouzan

Chapter 5

Analog Transmission

Introduction

- For digital transmission low-pass channel is needed.
- Analog transmission is the only choice for band-pass channel.
- Converting digital data to a band-pass analog signal is traditionally known as digital-to-analog conversion.
- Converting a low-pass analog signal to a band-pass analog signal is traditionally called analog-to-analog transmission.

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.
- Digital data needs to be carried on an analog signal.
- A carrier signal (frequency f_c) performs the function of transporting the digital data in an analog waveform.
- The analog carrier signal is manipulated to uniquely identify the digital data being carried.

Digital to Analog Conversion (Conti…)

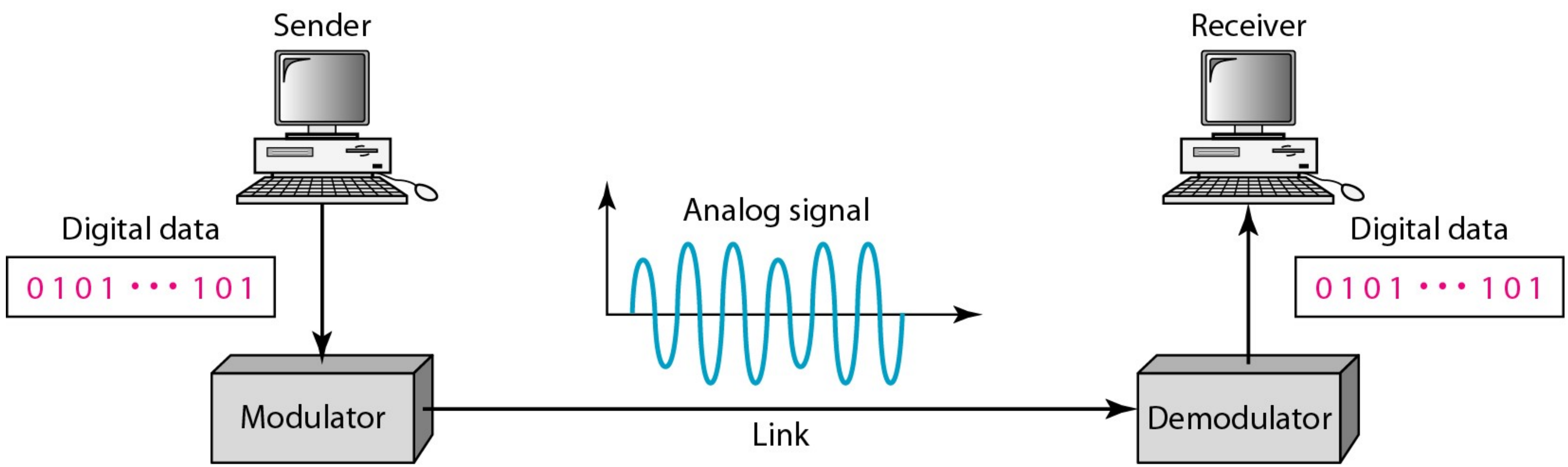

Figure 5.1 *Digital-to-analog conversion*

Digital to Analog Conversion (Conti…)

- A sine wave (analog signal) is defined by three characteristics: amplitude, frequency and phase.
- By changing any of these characteristics can create a different version of that wave.
- Digital to analog conversion mechanisms:
  - Amplitude Shift Keying (ASK)
  - Frequency Shift Keying (FSK)
  - Phase Shift Keying (PSK)
  - Quadrature Amplitude Modulation (QAM)

Digital to Analog Conversion (Conti…)

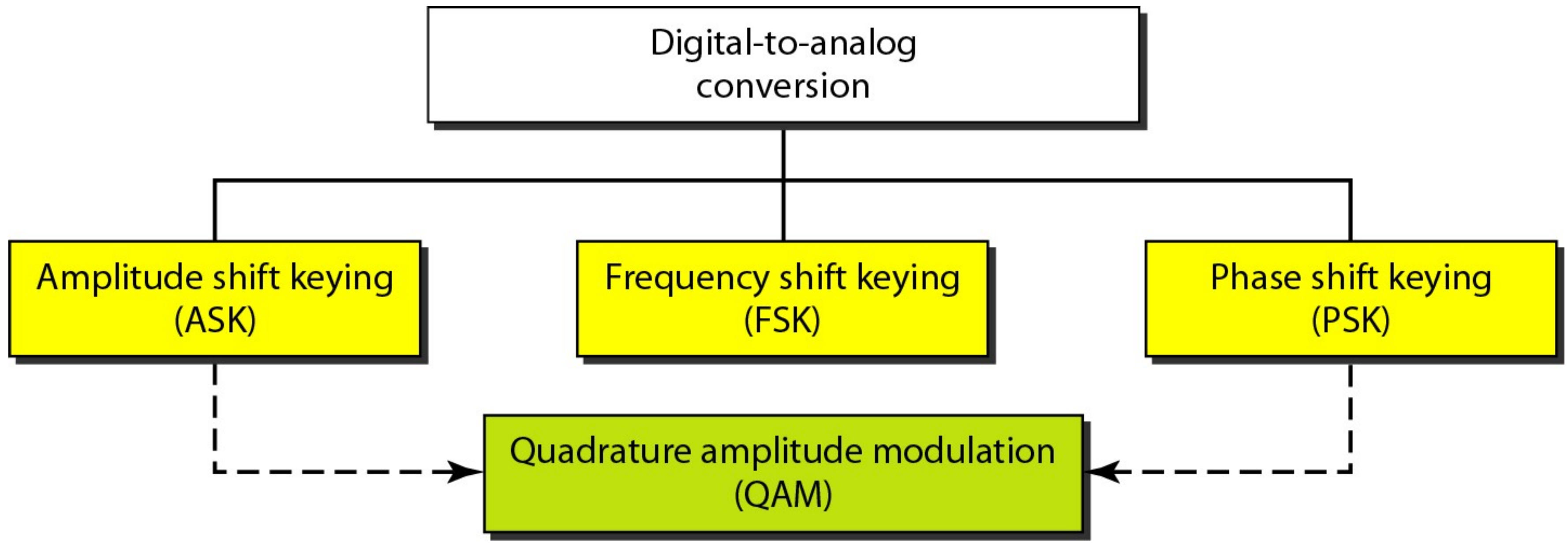

Figure 5.2 *Types of digital-to-analog conversion*

Aspects of Digital to Analog Conversion

- Data Element Versus Signal Element
- Data Rate Versus Signal Rate
- Bandwidth
- Carrier Signal
  - In analog transmission, the sender generate a high frequency signal acts as base for the message (information) signal, known as carrier signal or carrier frequency.

Aspects of Digital to Analog Conversion (Conti…)

- Carrier Signal (Conti…)
  - Digital data changes the carrier signal by modifying one or more of its characteristics (amplitude, frequency, or phase).
  - Such kind of modification is called as modulation (shift keying).
  - The receiver is tuned to the frequency of the carrier signal that it expects from the sender.

Aspects of Digital to Analog Conversion (Conti…)

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:

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

Aspects of Digital to Analog Conversion (Conti…)

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)

- In ASK, the amplitude of the carrier signal is varied to create signal elements, while both frequency and phase remain constant.
- ASK can have several levels (kinds) of signal elements, each with different amplitude.
- Normally it is implemented using only two levels, known as binary ASK (BASK) or On-Off-Keying (OOK).

ASK (Conti…)

- The peak amplitude of one signal level is 0 while other is same as amplitude of the carrier signal.
- The bandwidth B of ASK is proportional to the signal rate S:

$$B = (1+d)S$$

- “d” is due to modulation and filtering, lies between 0 and 1.

ASK (Conti…)

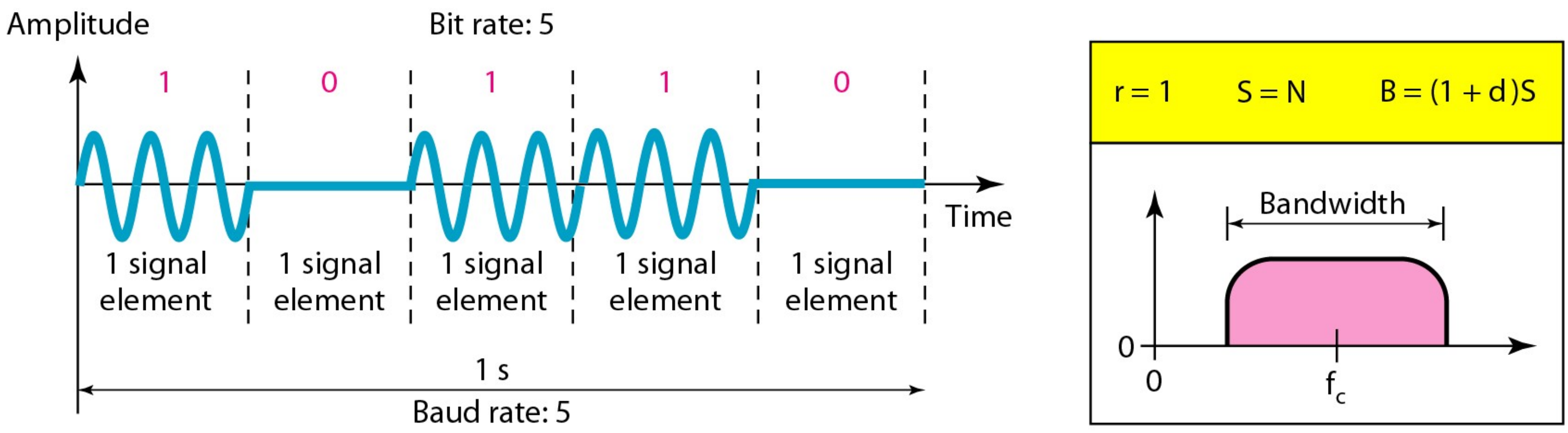

Figure 5.3 *Binary amplitude shift keying*

Implementation of ASK

- The line encoding will determine the values of the analog waveform to reflect the digital data being carried.
- If the digital data is presented as Unipolar NRZ digital signal with a high voltage of 1V and low voltage of 0V, the implementation can achieved by multiplying the NRZ digital signal by the carrier signal coming from an oscillator.
- When the amplitude of the NRZ signal is 1, the amplitude of the carrier signal is held while when it is 0, the amplitude of the carrier signal is 0.

Implementation of ASK (Conti…)

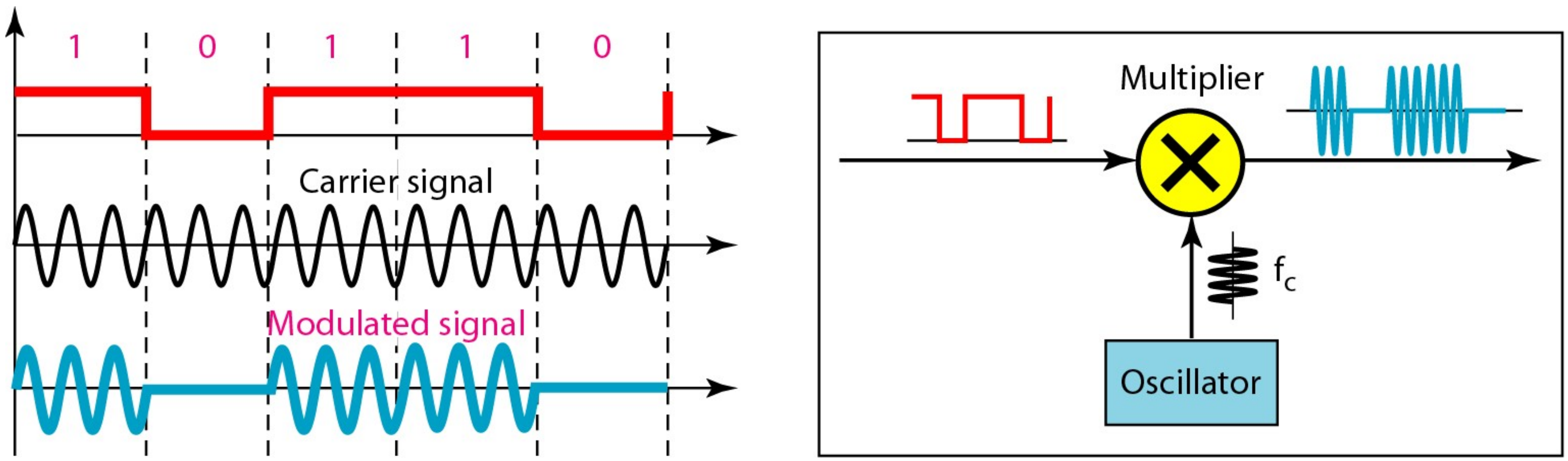

Figure 5.4 *Implementation of binary ASK*

ASK (Conti…)

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 fc = 250 kHz. We can use the formula for bandwidth to find the bit rate (with d = 1 and r = 1).

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

ASK (Conti…)

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.

ASK (Conti…)

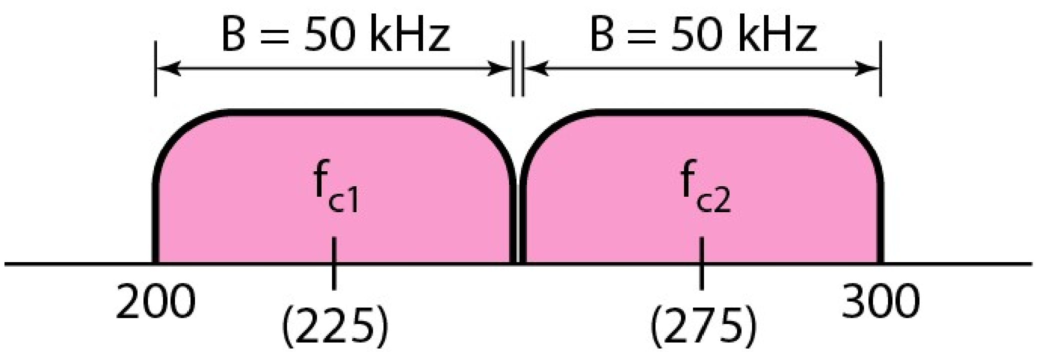

Figure 5.5 *Bandwidth of full-duplex ASK used in Example 5.4*

Frequency Shift Keying (FSK)

- In FSK, the frequency of the carrier signal is varied to represent the data.
- Both peak amplitude and phase remain constant for all signal elements.
- One way about binary FSK (BFSK) is to user two carrier frequencies.
- First carrier frequency is used if the data element is 0, while second is used if the data element is 1.

FSK (Conti…)

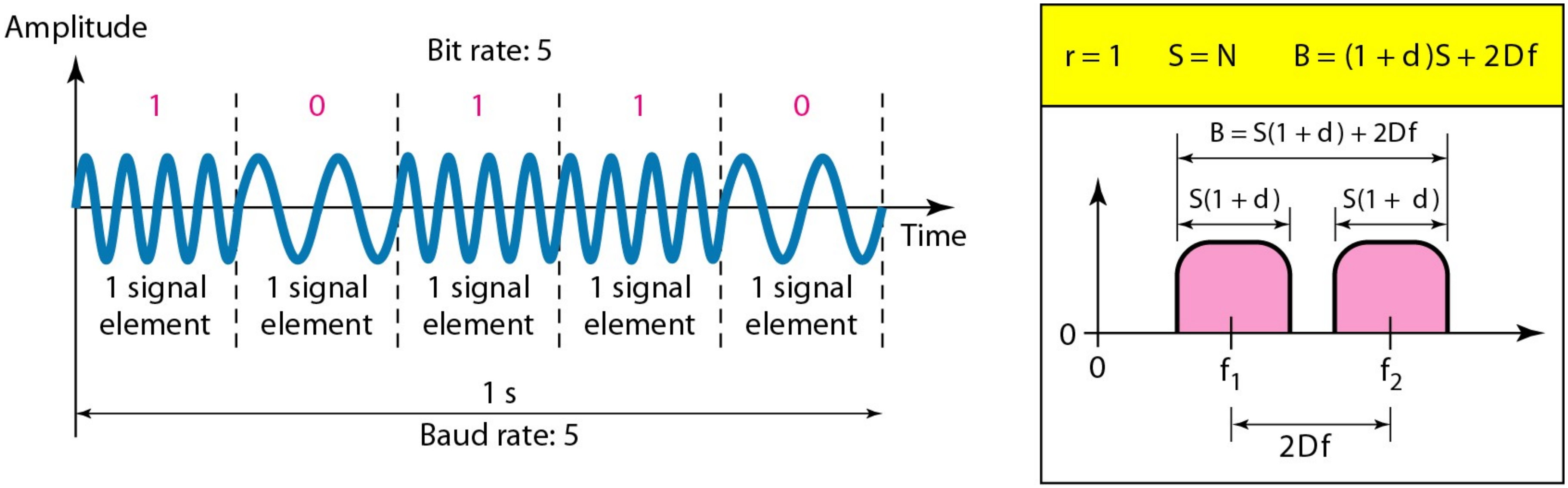

Figure 5.6 *Binary frequency shift keying*

Frequency Shift Keying (FSK)

- Figure 5.6 shows that the middle of one bandwidth is f_1 while the middle of other is f_2.
- Both f_1 and f_2 are $2\Delta f$ apart from the midpoint between the two bands.
- The difference between the two frequencies is $2\Delta f$.
- Bandwidth of FSK is:

$$B = (1+d) \times S + 2\Delta f$$

FSK (Conti…)

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:

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

FSK (Conti…)

- Two ways of implementation of BFSK: non-coherent and coherent.
- In non-coherent BFSK, there may be discontinuity in the phase when one signal element ends and the next begins.
- In coherent BFSK, the phase continues through the boundary of two signal elements.

FSK (Conti...)

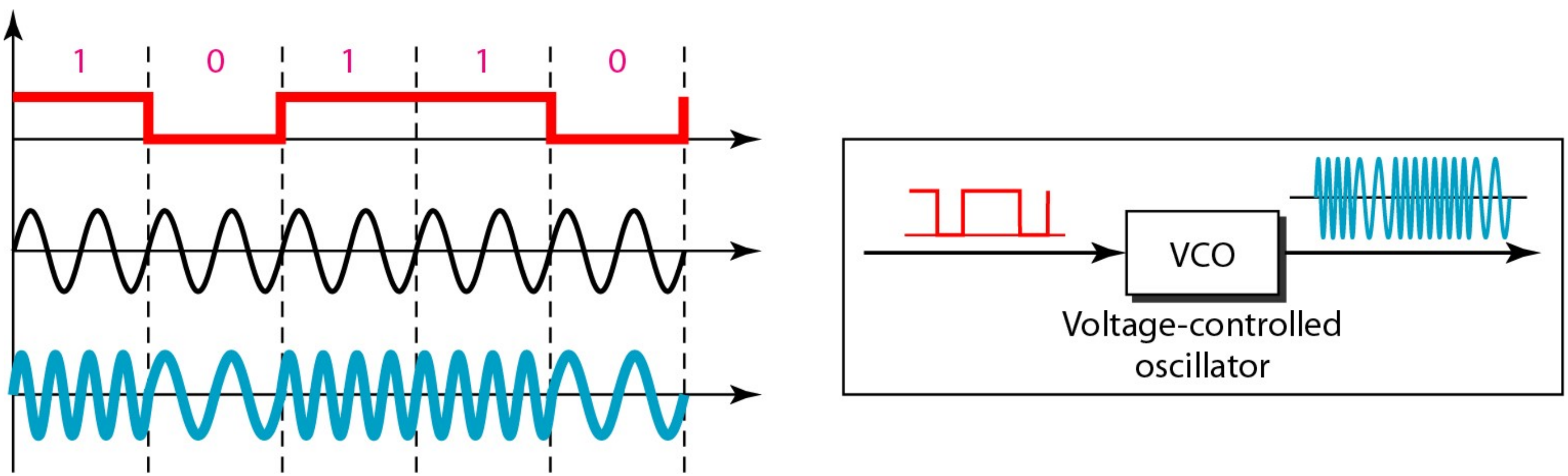

Figure 5.7 *Implementation of BFSK*

Multi-Level FSK

- Similarly to ASK, FSK can use multiple bits per signal element.
- For example four different frequencies f_1, f_2, f_3, f_4 and are used to send 2 bits at a time.
- Similarly to send 3 bits at a time, eight different frequencies can be used.
- The frequencies need to be $2\Delta f$ apart.
- Minimum value of $2\Delta f$ needs to be S.
- Bandwidth for Multi-Level FSK is:

$$B = (1+d) \times S + (L-1)/2\Delta f = L \times S$$

Multi-Level FSK (Conti…)

Example 5.6: We need to send data 3 bits at a time at a bit rate of 3 Mbps. The carrier frequency is 10 MHz. Calculate the number of levels (different frequencies), the baud rate, and the bandwidth.

Solution:

We can have $L = 2^3 = 8$. The baud rate is S = 3 Mbps/3 = 1 Mbaud. This means that the carrier frequencies must be 1 MHz apart ($2\Delta f$ = 1 MHz). The bandwidth is $B = 8 \times 1M = 8M$. Figure 5.8 shows the allocation of frequencies and bandwidth.

Multi-Level FSK (Conti…)

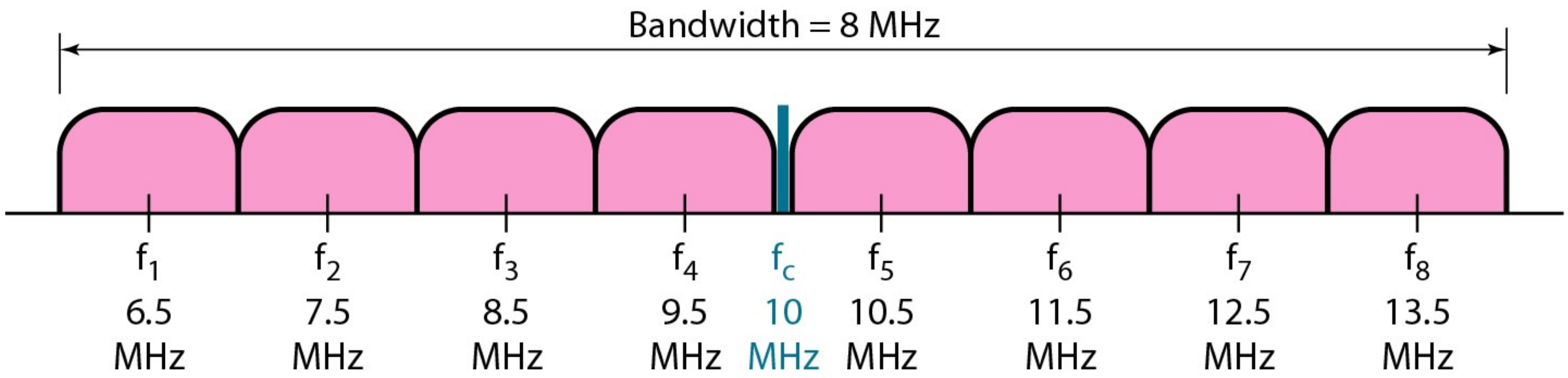

Figure 5.8 *Bandwidth of MFSK used in Example 5.6*

Phase Shift Keying (PSK)

- In PSK, the phase of the carrier signal is varied to represent the different signal elements carrying data.
- Both amplitude and frequency remain constant.
- PSK is more common than ASK and FSK.
- However, QAM is the dominant method of digital to analogy conversion.

PSK (Conti…)

- The simplest PSK is binary PSK (BPSK).
- BPSK has only two signal element: one with a phase 0^o and the other with a phase of 180^o.
- PSK is much more robust than ASK as it is not that vulnerable to noise.
- The bandwidth requirement, B is:

$$B = (1+d) \times S$$

PSK (Conti…)

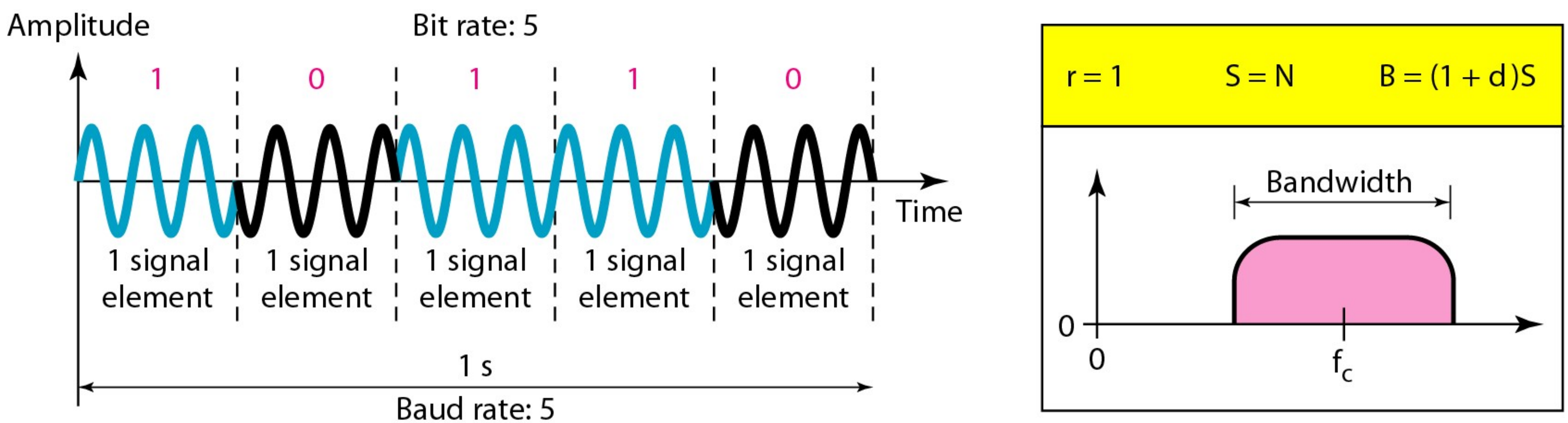

Figure 5.9 *Binary phase shift keying*

PSK (Conti…)

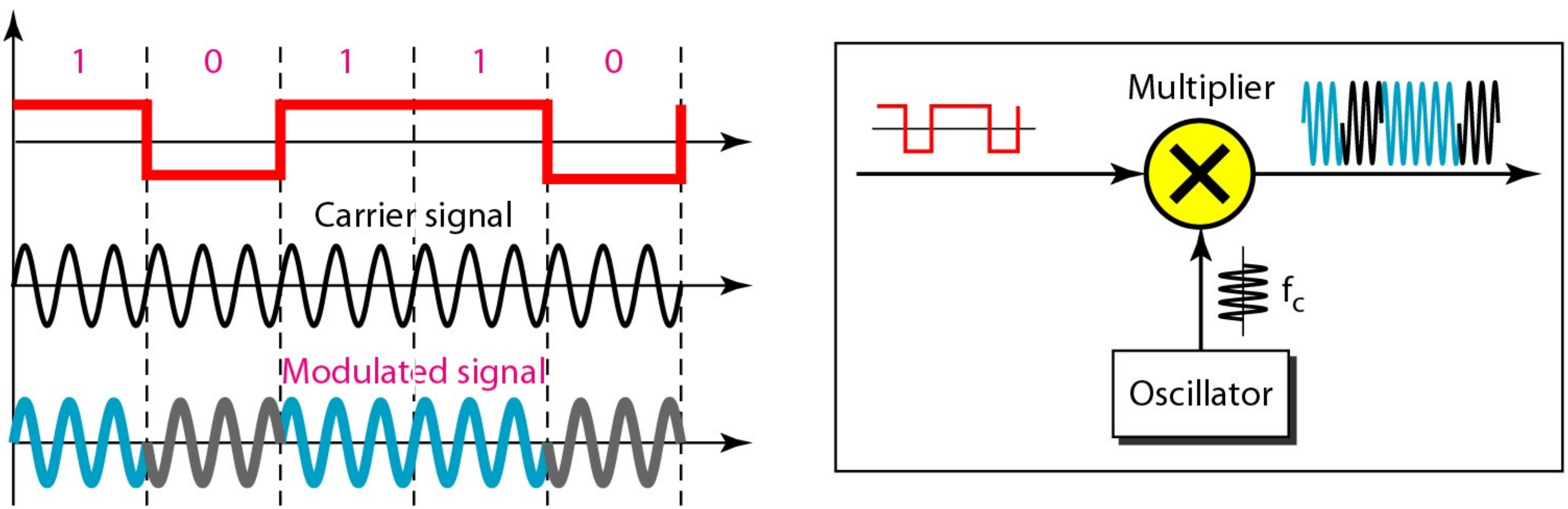

Figure 5.10 *Implementation of BASK*

Quadrature PSK (QPSK)

- Similarly to ASK and FSK, PSK can use multiple bits per signal element.
- Quadrature PSK (QPSK) is used to send 2 bits at a time in each signal element.
- QPSK used two separate BPSK modulation: one is in-phase and the other is out-of-phase.
- The incoming bits are first passed through a serial-to-parallel conversion that sends one bit to one modulator and next to another modulator.

QPSK (Conti…)

- If the duration of each bit in the incoming signal is *T* then the duration of each bit sent to the corresponding BPSK signal is *2T*.
- This means that the bit of each BPSK signal has one-half the frequency of the original signal.
- The two composite signals created by each multiplier have the same frequency but different phases.
- When they are added, the resultant signal has four possible phases: 45^o, -45^o, 135^o, and -135^o and L = 4.

QPSK (Conti…)

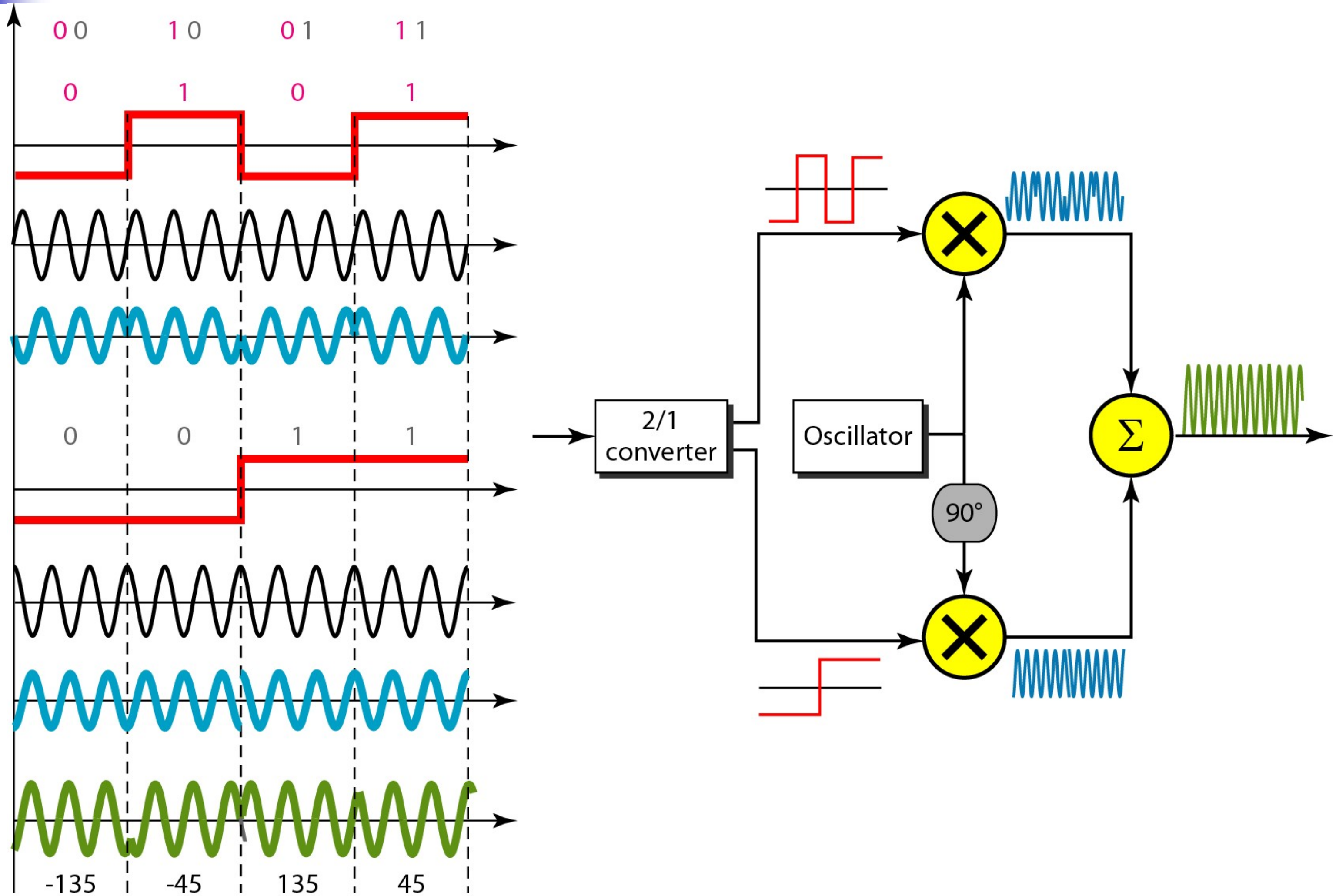

Figure 5.11 *QPSK and its implementation*

QPSK (Conti…)

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.

Constellation Diagram

- It helps in defining the amplitude and phase of a signal element particularly when two carrier signals (in-phase and out-of-phase) are used.
- It is useful when dealing with multi-level ASK, PSK or QAM.
- A signal element is represented by a dot and bit(s) it carry is/are written next to it.
- It has two axes: X-axis (horizontal) represents in-phase carrier, and Y-axis (vertical) represents out-of-phase carrier.

Constellation Diagram (Conti…)

- For each point on the diagram, four pieces of information can be deduced:
  - The projection of the point on X-axis defines the peak amplitude of in-phase component
  - The projection of the point on Y-axis defines the peak amplitude of out-of-phase component
  - The line that connects the point to the origin defines the peak amplitude of the signal
  - The angle of the line with X-axis defines the phase of the signal element

Constellation Diagram (Conti…)

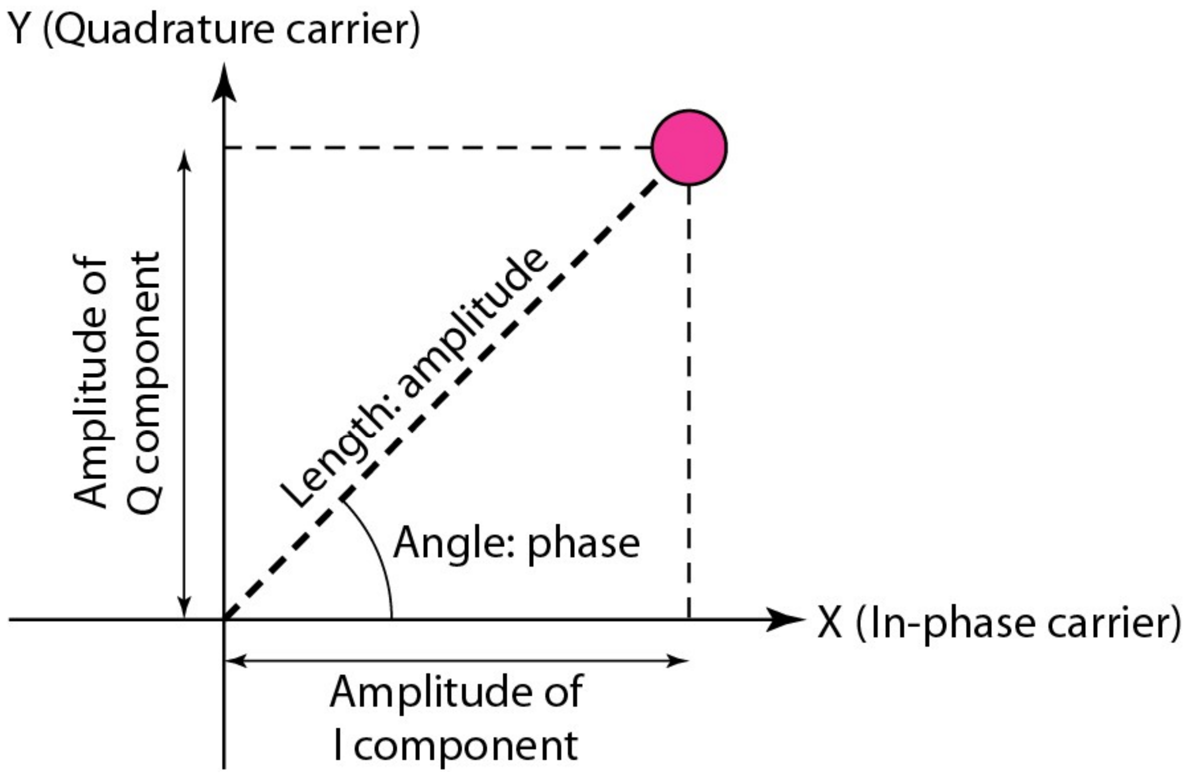

Figure 5.12 *Concept of a constellation diagram*

Constellation Diagram (Conti…)

Example 5.8: Show the constellation diagrams for an ASK (OOK), BPSK, and QPSK signals.

Solution:

Figure 5.13 shows the three constellation diagrams.

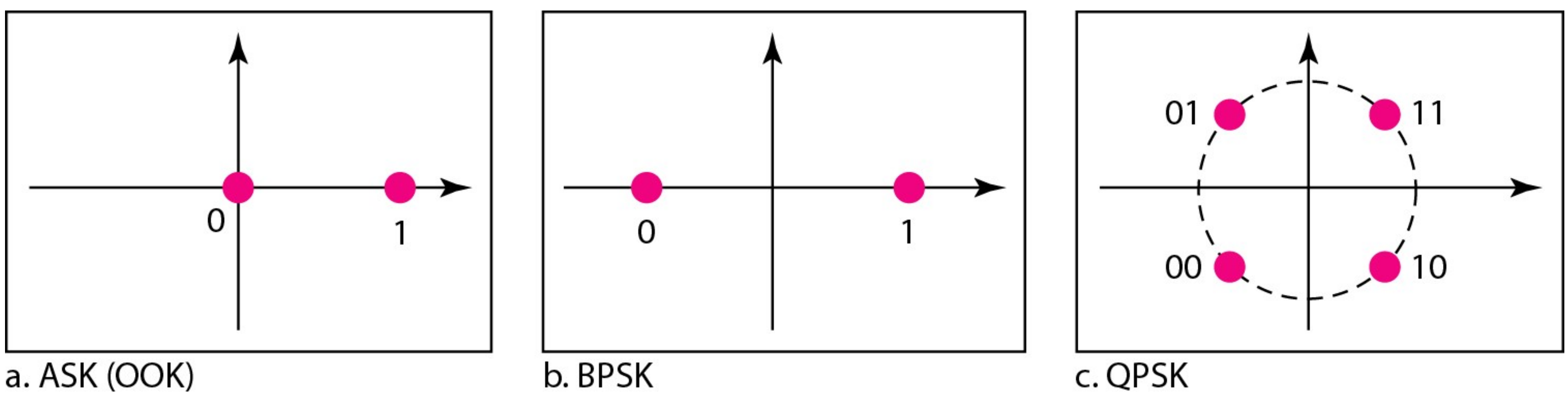

Figure 5.13 *Three constellation diagrams*

Constellation Diagram (Conti…)

- For ASK:
  - Only in-phase carrier is used, therefore, the two points should be on the X-axis
  - Binary 0 has an amplitude of 0V while binary 1 has an amplitude of 1V
  - The points are located at the origin and at 1 unit
- For BPSK:
  - Uses only an in-phase carrier creating two types of signal elements
  - One with amplitude 1V and phase 0^o (in-phase) and other amplitude of 1V and phase 180^o (out-of-phase)

Constellation Diagram (Conti…)

- For QPSK:
  - It uses two carrier; one in-phase while the other out-of-phase
  - Each point is made of two combined signal elements, both with an amplitude of 1V
  - One element is represented by in-phase carrier while the other is represented by out-of-phase carrier
  - All points have the same amplitude but phases are different (45^o, 135^o, -135^o, -45^o)

Quadrature Amplitude Modulation (QAM)

- The modulation schemes discussed so far alter only one of the three characteristics (amplitude, frequency, and phase) of a sine wave at a time.
- QAM is the combination of ASK and PSK
- The idea of using two carriers; one in-phase and other out-of-phase, with different amplitude levels for each carrier is the concept behind QAM.
- The possible variations of QAM are numerous. Figure 5.14 shows some these schemes.

QAM (Conti…)

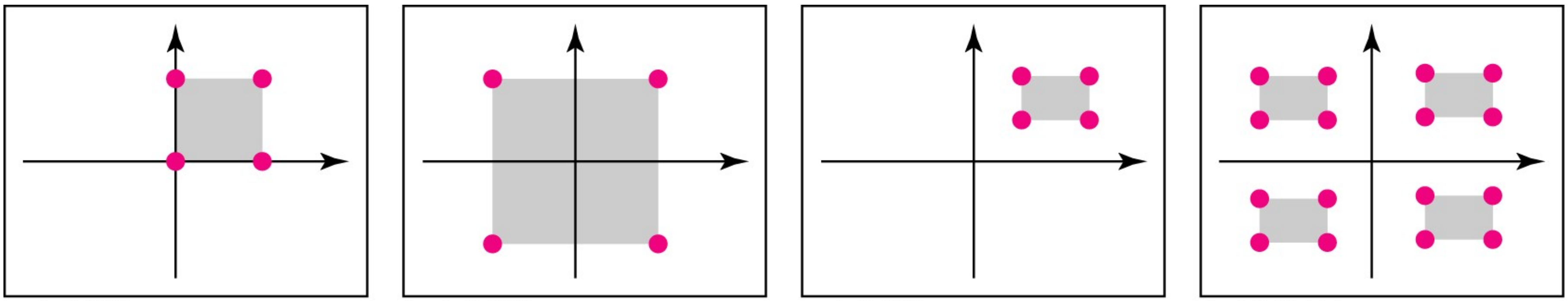

Figure 5.14 *Constellation diagrams for some QAMs*

QAM (Conti…)

- Figure 5.14a:
  - 4-QAM – Four different signal element types using unipolar NRZ signal to modulate each carrier, Same as ASK (OOK)
- Figure 5.14b:
  - 4-QAM – Uses polar NRZ, but exactly same as QPSK
- Figure 5.14c:
  - 4-QAM – Uses a signal with two positive levels to modulate each of the two carriers
- Figure 5.14d:
  - 16-QAM – a signal with eight level, four positive and four negative

Analog-to-Analog Conversion

- Analog-to-analog conversion is also known as analog modulation
- It the representation of the analog information (data, message) by an analog signal
- It is required if the medium is band-pass in nature or only band-pass channel is available
- For example, govt. assigns narrow bandwidth to each radio station, while the analog signal produced by each station is a low-pass signal

Analog-to-Analog Conversion (Conti…)

- To able to listen to different stations, the low-pass signals need to be shifted (modulated), each to a different range.

- Analog Modulation can be accomplished in three ways:

  - Amplitude Modulation (AM)

  - Frequency Modulation (FM)

  - Phase Modulation (PM)

Analog-to-Analog Conversion (Conti…)

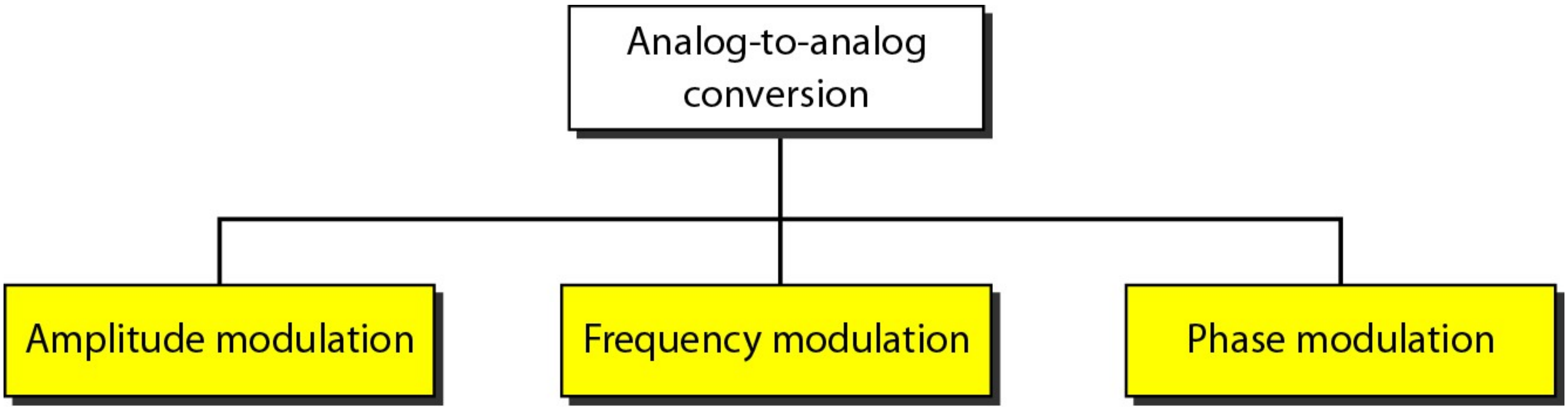

Figure 5.15 *Types of analog-to-analog modulation*

Amplitude Modulation (AM)

- In AM transmission, the carrier signal is modulated to that its amplitude varies with the changing amplitude of the modulating signal.
- The frequency and phase of the carrier signal remain the same.
- The modulating signal is the envelop of the carrier.
- The required bandwidth is 2B, where B is the bandwidth of the modulating signal.
- AM is normally implement by a simple multiplier.

AM (Conti…)

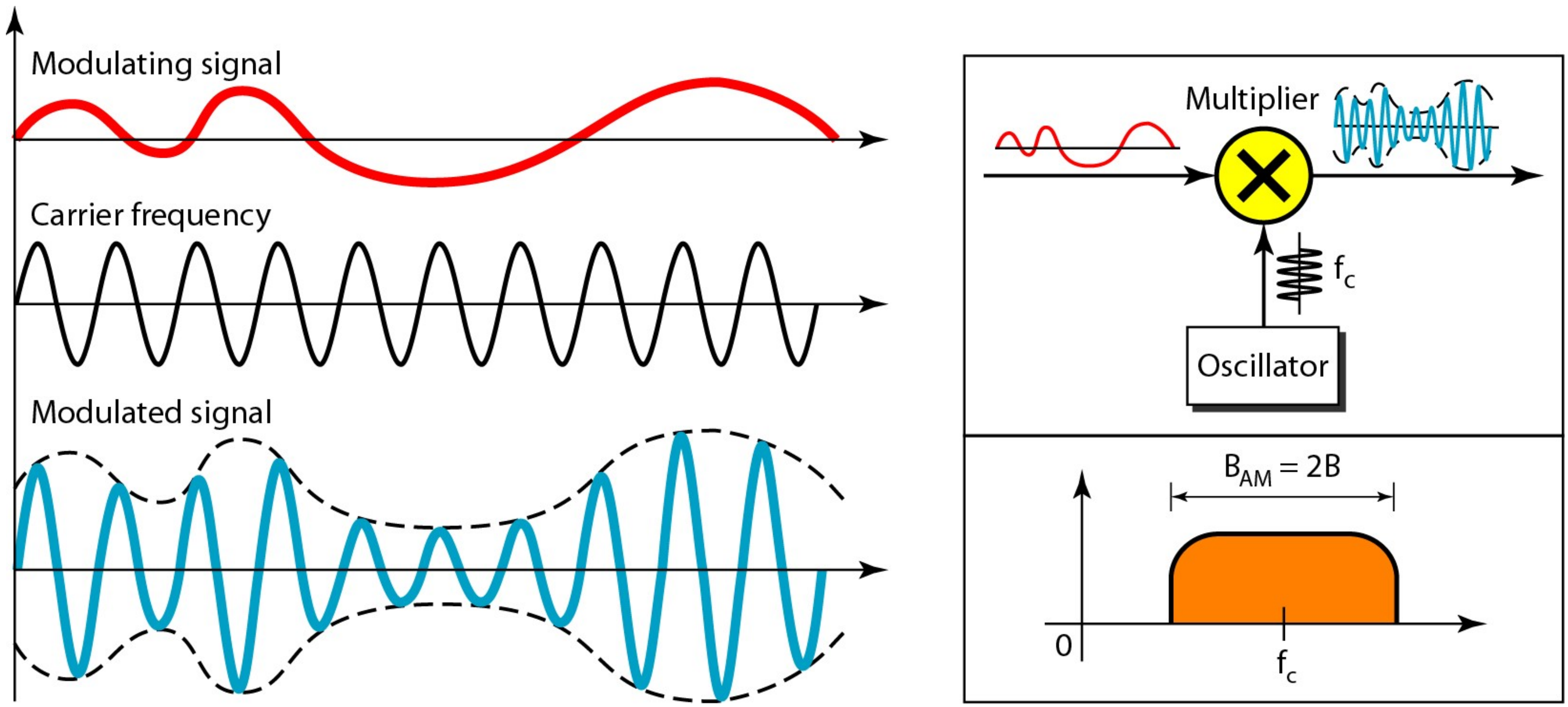

Figure 5.16 *Amplitude modulation*

AM (Conti…)

- The bandwidth of an audio signal (speed and music) is usually 5KHz.
- AM radio station requires bandwidth of 10KHz and Federal Communications Commission (FCC) allocate it for each AM station.
- AM stations are allowed to select carrier frequencies anywhere between 530KHz to 1700KHz (1.7 MHz).
- Stations must be separated by at least 10KHz to keep their bandwidths from overlapping.

AM (Conti…)

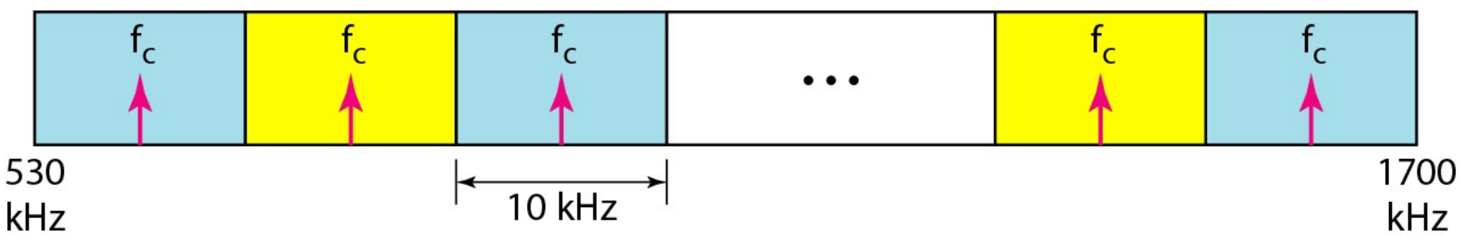

Figure 5.17 *AM band allocation*

Frequency Modulation (FM)

- In FM transmission, the frequency of the carrier signal is modulated to follow the changing amplitude of the modulating signal.
- The peak amplitude and phase of the carrier signal remains the same.
- The total bandwidth required for FM can be determined from the bandwidth of the audio signal: $B_{FM} = 2(1 + \beta)B$. Where β is usually 4.
- FM is normally implemented by using a voltage-controlled oscillator as with FSK.

FM (Conti…)

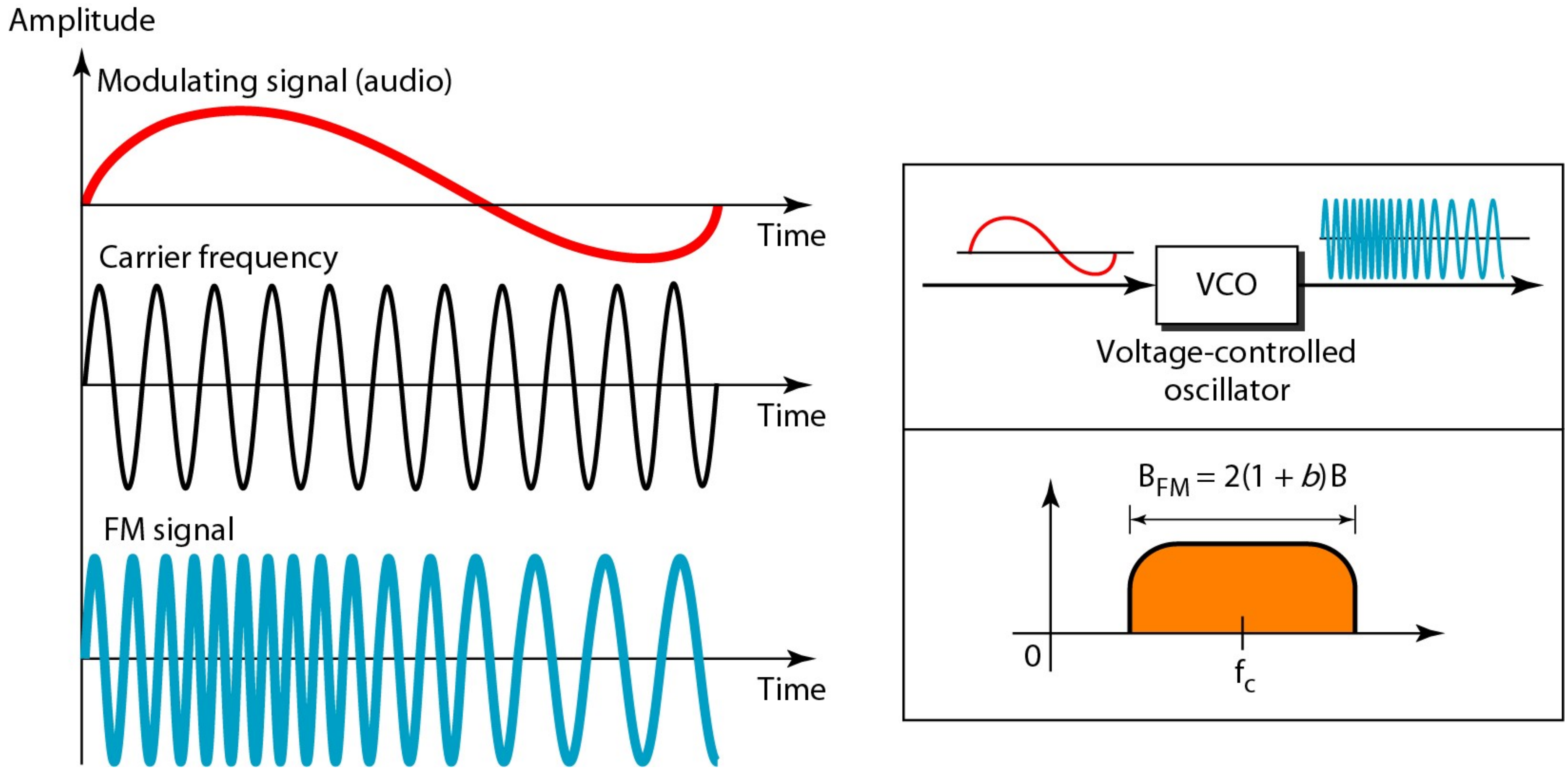

Figure 5.18 *Frequency modulation*

FM (Conti…)

- The bandwidth of an audio signal (speech and music) broadcast in stereo is almost 15KHz.
- The FCC allows 200KHz (0.2MHz) for each station, i.e. $\beta=4$ with some extra guard band.
- FM stations are allowed carrier frequencies anywhere between 88 and 108 MHz.
- Stations must be separated by at least 10KHz to keep their bandwidths from overlapping.

FM (Conti…)

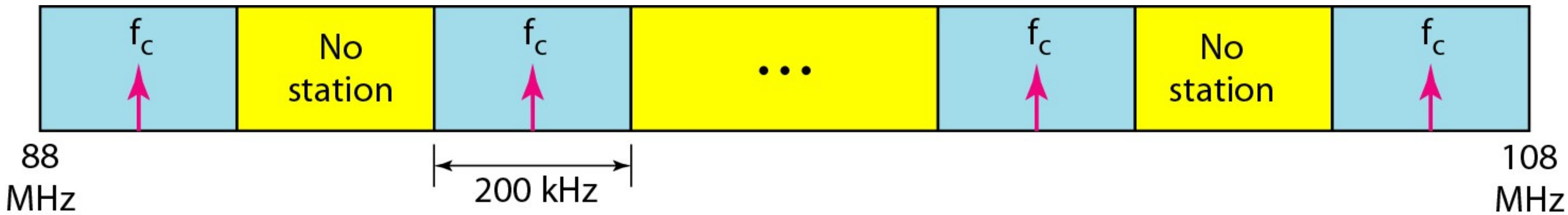

Figure 5.19 *FM band allocation*

Phase Modulation (PM)

- In PM transmission, the phase of the carrier signal is modulated to follow the changing amplitude of the modulating signal.
- The peak amplitude and frequency of the carrier frequency remains the same.
- It can be proved that mathematically PM is same as FM with only one difference.
- In FM, the instantaneous change in the carrier frequency is proportional to the amplitude of the of the modulating signal.

PM (Conti…)

- In PM the instantaneous change in the carrier frequency is proportional to the derivative of the amplitude of the modulating signal.
- PM is normally implemented by using a voltage controlled oscillator along with a derivative.
- The total bandwidth required for FM can be determined from the bandwidth of the audio signal: $B_{PM} = 2(1 + \beta)B$. Where β is 2 most often.

PM (Conti...)

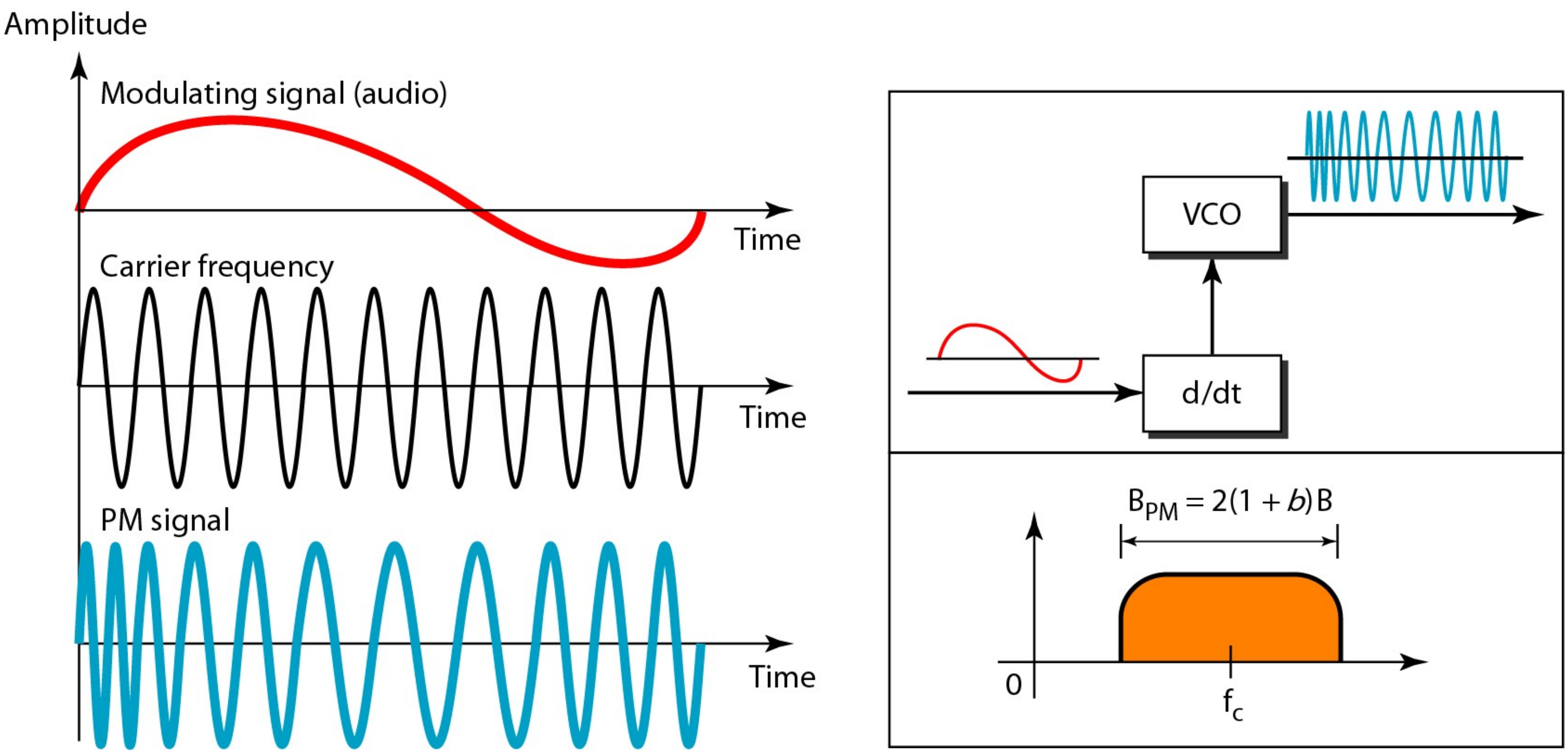

Figure 5.20 *Phase modulation*