



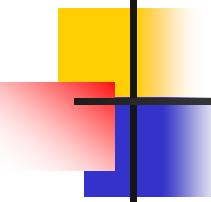
Data Communications and Networking

Fourth Edition

Forouzan

Chapter 3

Data and Signals



Note

To be transmitted, data must be transformed to electromagnetic signals.

3-1 ANALOG AND DIGITAL

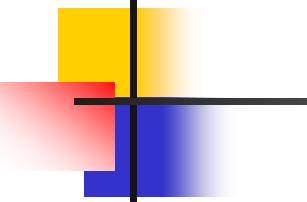
*Data can be **analog** or **digital**. The term **analog data** refers to information that is continuous; **digital data** refers to information that has discrete states. Analog data take on continuous values. Digital data take on discrete values.*

Topics discussed in this section:

Analog and Digital Data

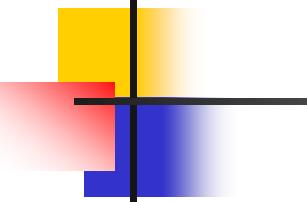
Analog and Digital Signals

Periodic and Nonperiodic Signals



Note

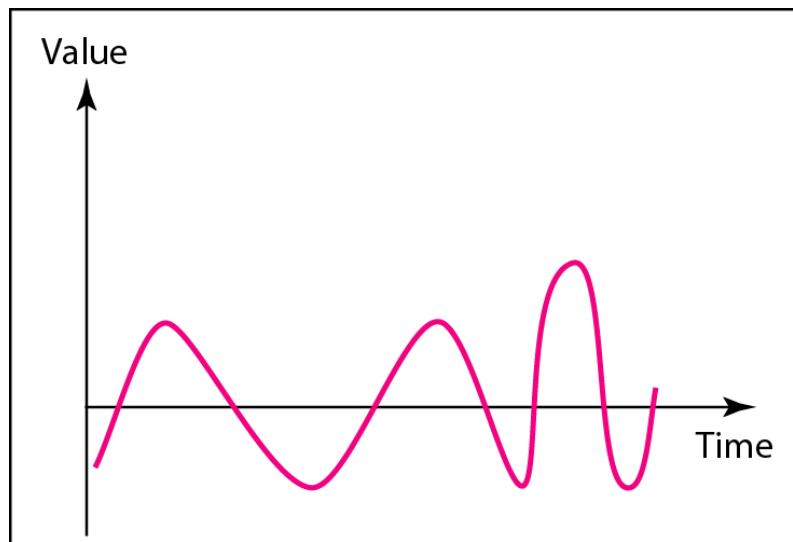
Data can be analog or digital.
Analog data are continuous and take continuous values.
Digital data have discrete states and take discrete values.



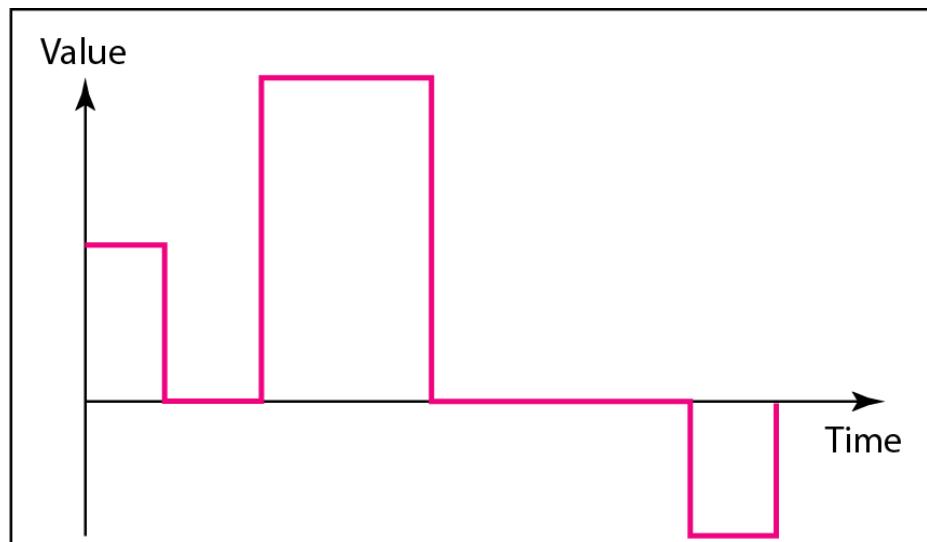
Note

Signals can be analog or digital.
Analog signals can have an infinite number of values in a range; digital signals can have only a limited number of values.

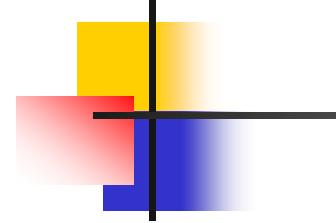
Figure 3.1 Comparison of analog and digital signals



a. Analog signal



b. Digital signal



Note

In data communications, we commonly use periodic analog signals and nonperiodic digital signals.

3-2 PERIODIC ANALOG SIGNALS

*Periodic analog signals can be classified as **simple** or **composite**. A simple periodic analog signal, a **sine wave**, cannot be decomposed into simpler signals. A composite periodic analog signal is composed of multiple sine waves.*

Topics discussed in this section:

Sine Wave

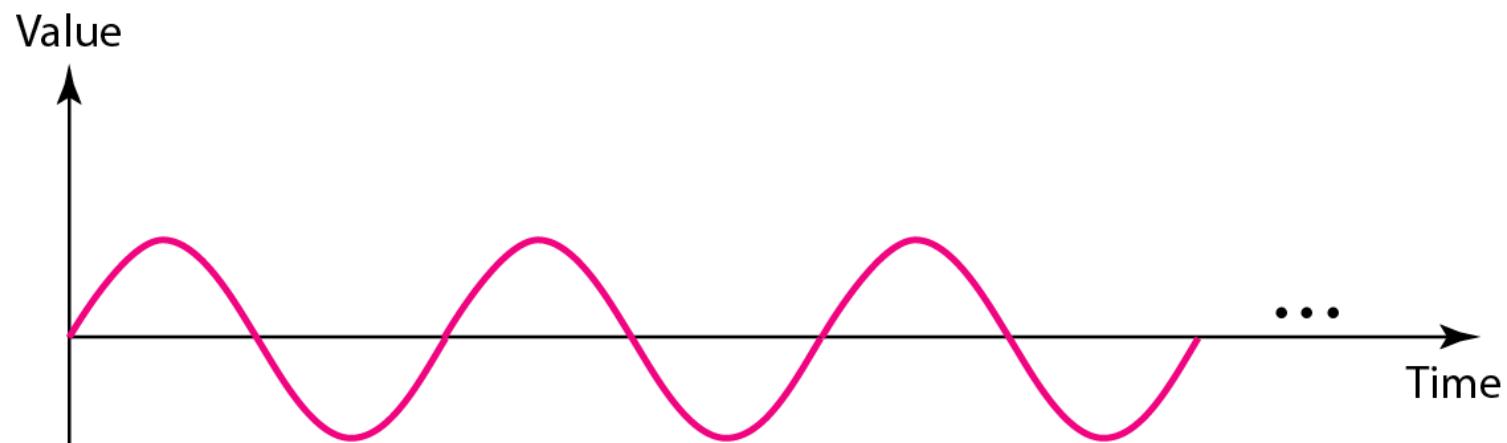
Wavelength

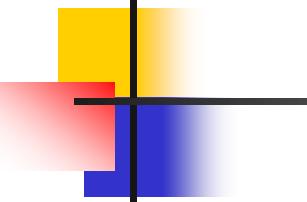
Time and Frequency Domain

Composite Signals

Bandwidth

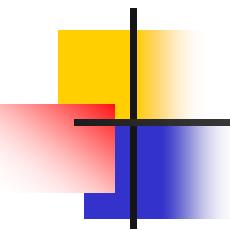
Figure 3.2 *A sine wave*





Note

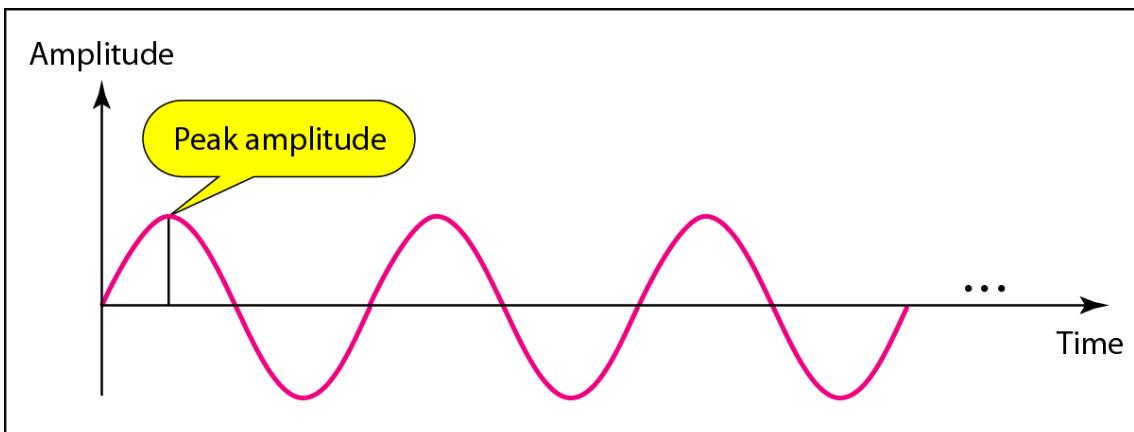
We discuss a mathematical approach to sine waves in Appendix C.



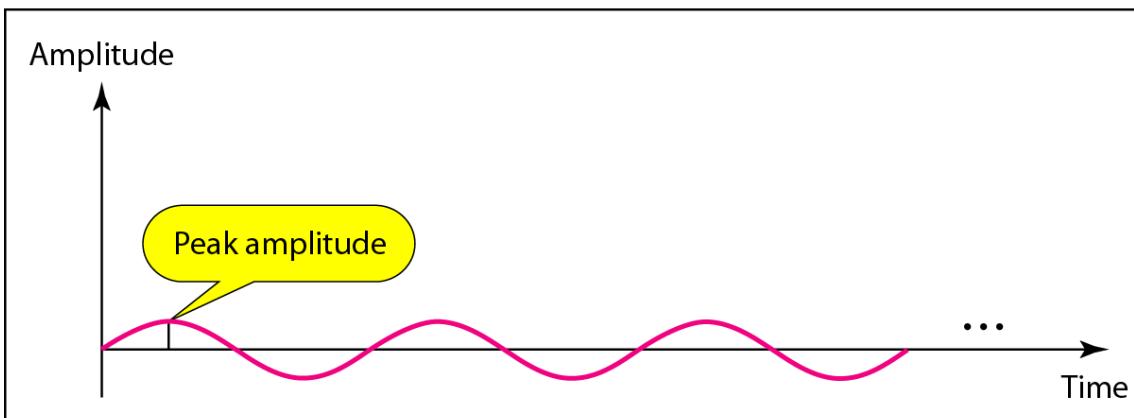
Example 3.1

*The power in your house can be represented by a sine wave with a peak amplitude of 155 to 170 V. However, it is common knowledge that the voltage of the power in U.S. homes is 110 to 120 V. This discrepancy is due to the fact that these are **root mean square** (rms) values. The signal is squared and then the average amplitude is calculated. The peak value is equal to $2^{1/2} \times \text{rms}$ value.*

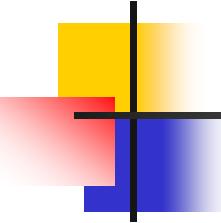
Figure 3.3 *Two signals with the same phase and frequency, but different amplitudes*



a. A signal with high peak amplitude

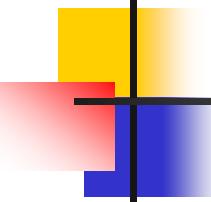


b. A signal with low peak amplitude



Example 3.2

The voltage of a battery is a constant; this constant value can be considered a sine wave, as we will see later. For example, the peak value of an AA battery is normally 1.5 V.

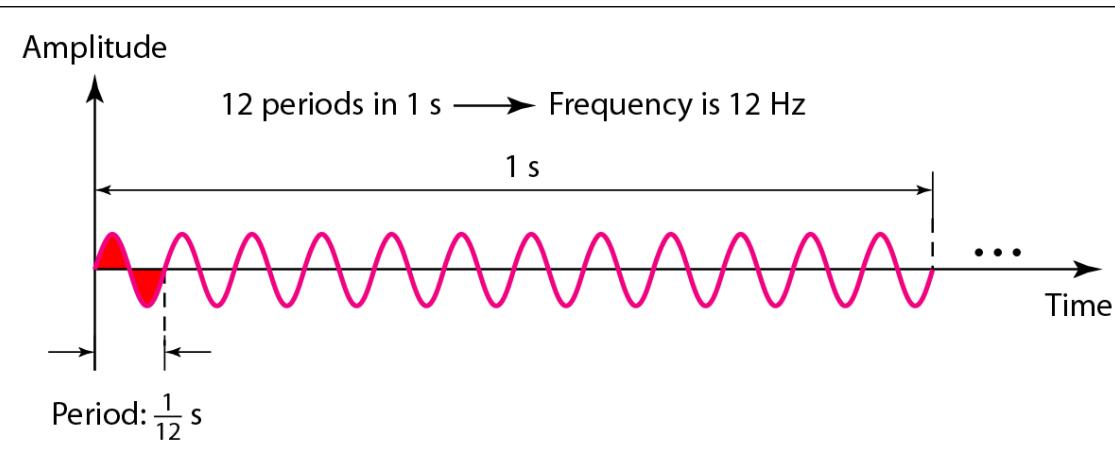


Note

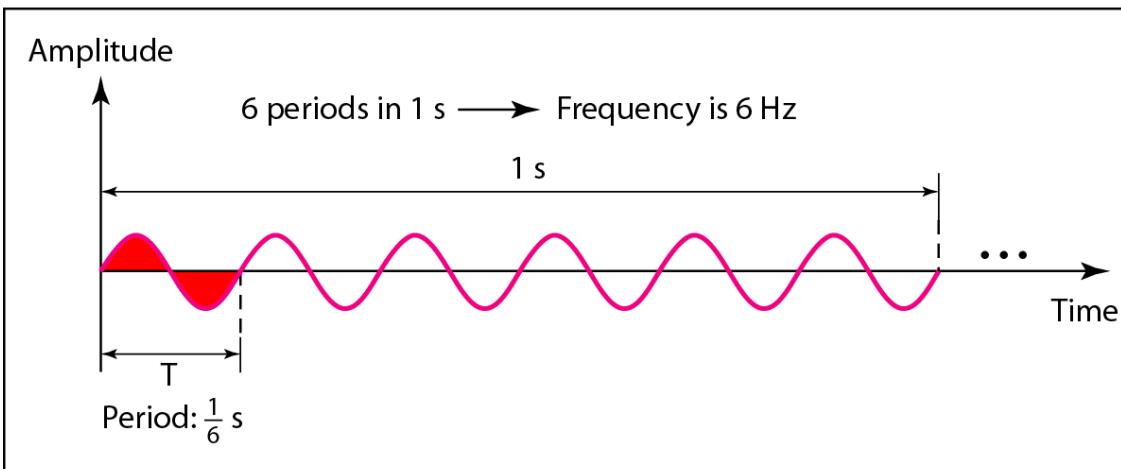
Frequency and period are the inverse of each other.

$$f = \frac{1}{T} \quad \text{and} \quad T = \frac{1}{f}$$

Figure 3.4 Two signals with the same amplitude and phase, but different frequencies



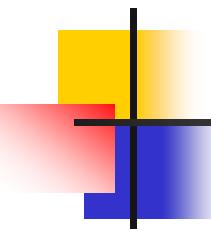
a. A signal with a frequency of 12 Hz



b. A signal with a frequency of 6 Hz

Table 3.1 *Units of period and frequency*

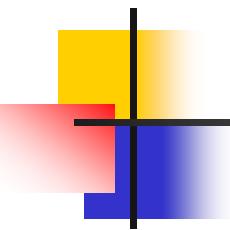
<i>Unit</i>	<i>Equivalent</i>	<i>Unit</i>	<i>Equivalent</i>
Seconds (s)	1 s	Hertz (Hz)	1 Hz
Milliseconds (ms)	10^{-3} s	Kilohertz (kHz)	10^3 Hz
Microseconds (μ s)	10^{-6} s	Megahertz (MHz)	10^6 Hz
Nanoseconds (ns)	10^{-9} s	Gigahertz (GHz)	10^9 Hz
Picoseconds (ps)	10^{-12} s	Terahertz (THz)	10^{12} Hz



Example 3.3

The power we use at home has a frequency of 60 Hz. The period of this sine wave can be determined as follows:

$$T = \frac{1}{f} = \frac{1}{60} = 0.0166 \text{ s} = 0.0166 \times 10^3 \text{ ms} = 16.6 \text{ ms}$$



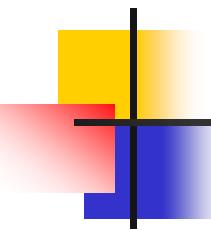
Example 3.4

Express a period of 100 ms in microseconds.

Solution

From Table 3.1 we find the equivalents of 1 ms (1 ms is 10^{-3} s) and 1 s (1 s is 10^6 μ s). We make the following substitutions::

$$100 \text{ ms} = 100 \times 10^{-3} \text{ s} = 100 \times 10^{-3} \times 10^6 \mu\text{s} = 10^2 \times 10^{-3} \times 10^6 \mu\text{s} = 10^5 \mu\text{s}$$



Example 3.5

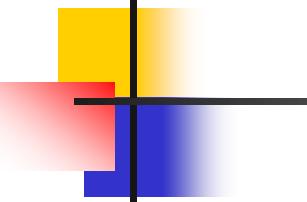
The period of a signal is 100 ms. What is its frequency in kilohertz?

Solution

First we change 100 ms to seconds, and then we calculate the frequency from the period ($1 \text{ Hz} = 10^{-3} \text{ kHz}$).

$$100 \text{ ms} = 100 \times 10^{-3} \text{ s} = 10^{-1} \text{ s}$$

$$f = \frac{1}{T} = \frac{1}{10^{-1}} \text{ Hz} = 10 \text{ Hz} = 10 \times 10^{-3} \text{ kHz} = 10^{-2} \text{ kHz}$$

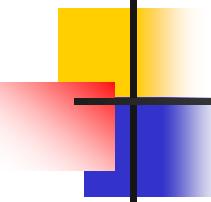


Note

Frequency is the rate of change with respect to time.

Change in a short span of time means high frequency.

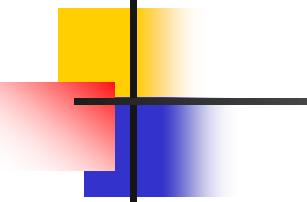
Change over a long span of time means low frequency.



Note

If a signal does not change at all, its frequency is zero.

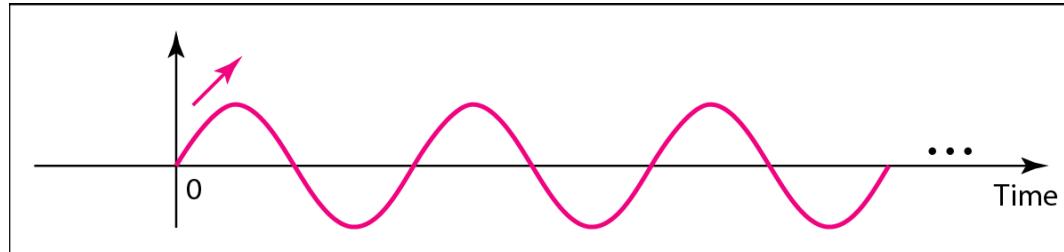
If a signal changes instantaneously, its frequency is infinite.



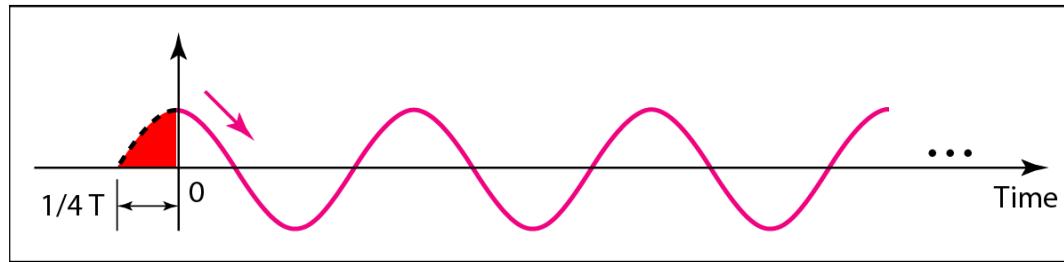
Note

Phase describes the position of the waveform relative to time 0.

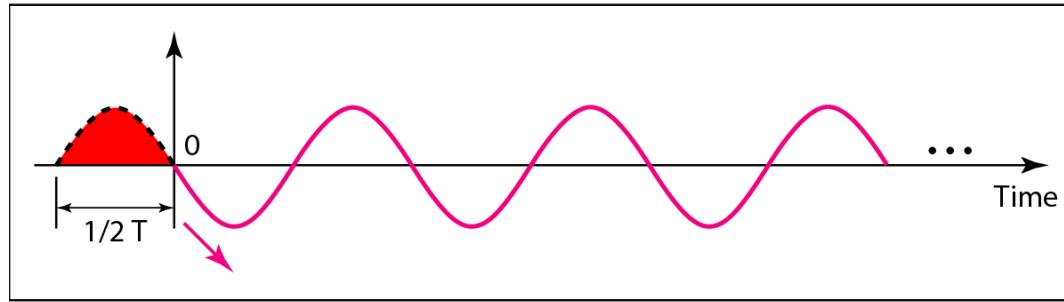
Figure 3.5 *Three sine waves with the same amplitude and frequency, but different phases*



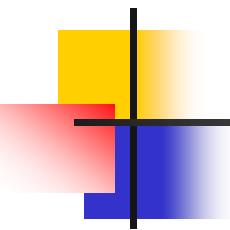
a. 0 degrees



b. 90 degrees



c. 180 degrees



Example 3.6

A sine wave is offset 1/6 cycle with respect to time 0. What is its phase in degrees and radians?

Solution

We know that 1 complete cycle is 360° . Therefore, 1/6 cycle is

$$\frac{1}{6} \times 360 = 60^\circ = 60 \times \frac{2\pi}{360} \text{ rad} = \frac{\pi}{3} \text{ rad} = 1.046 \text{ rad}$$

Figure 3.6 *Wavelength and period*

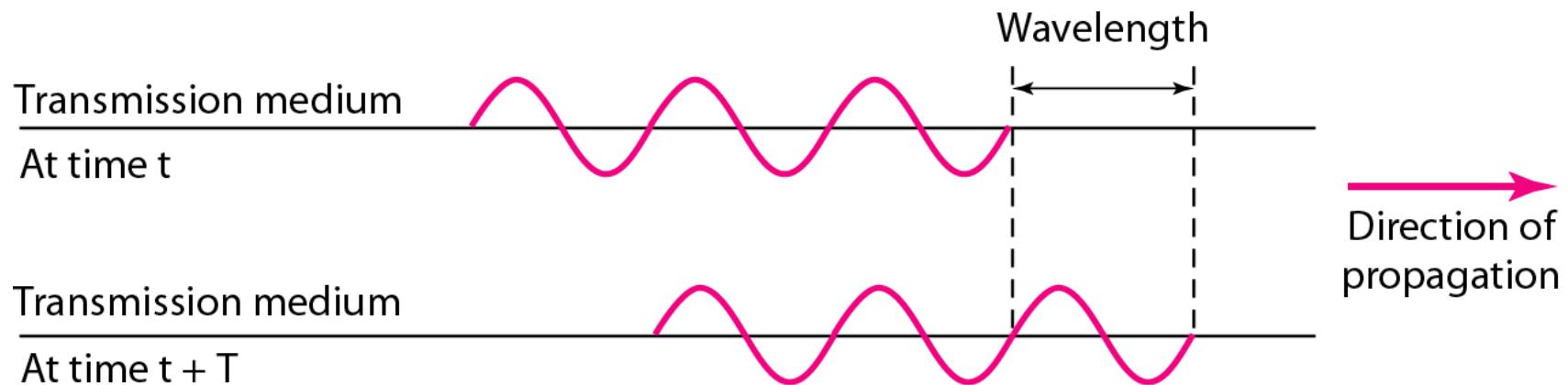
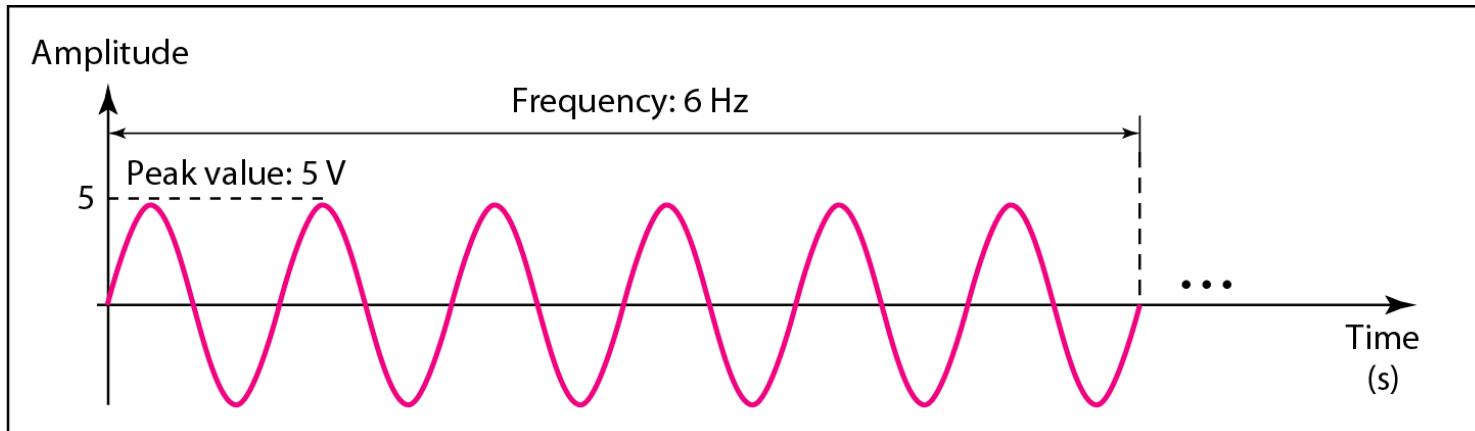
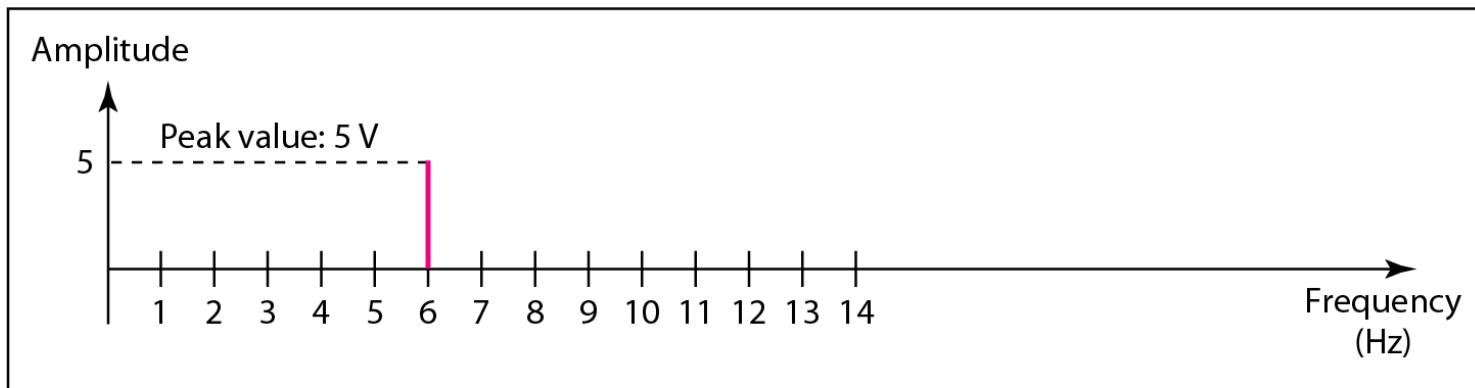


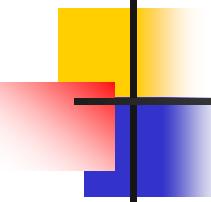
Figure 3.7 The time-domain and frequency-domain plots of a sine wave



a. A sine wave in the time domain (peak value: 5 V, frequency: 6 Hz)

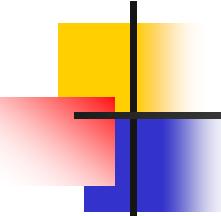


b. The same sine wave in the frequency domain (peak value: 5 V, frequency: 6 Hz)



Note

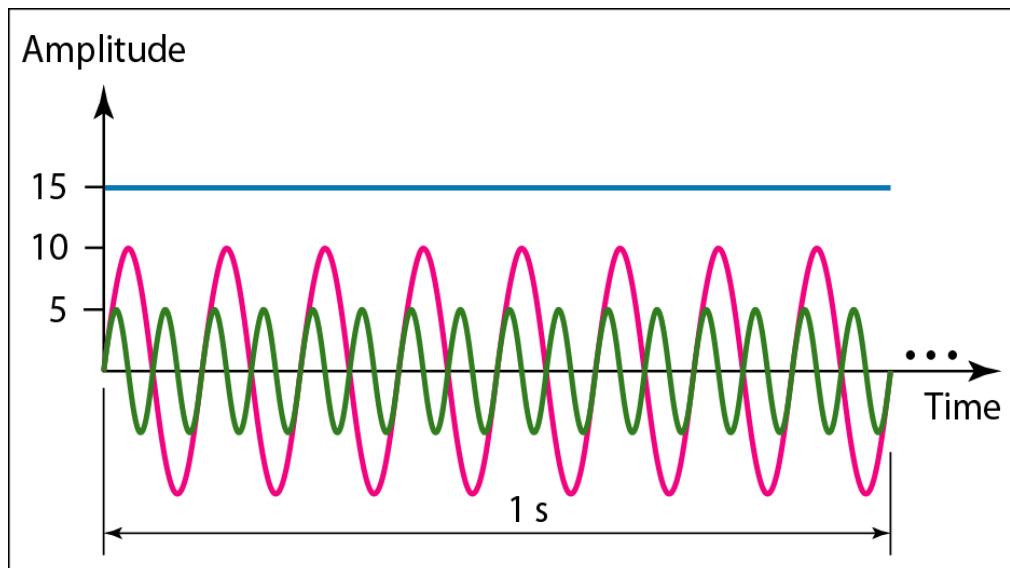
A complete sine wave in the time domain can be represented by one single spike in the frequency domain.



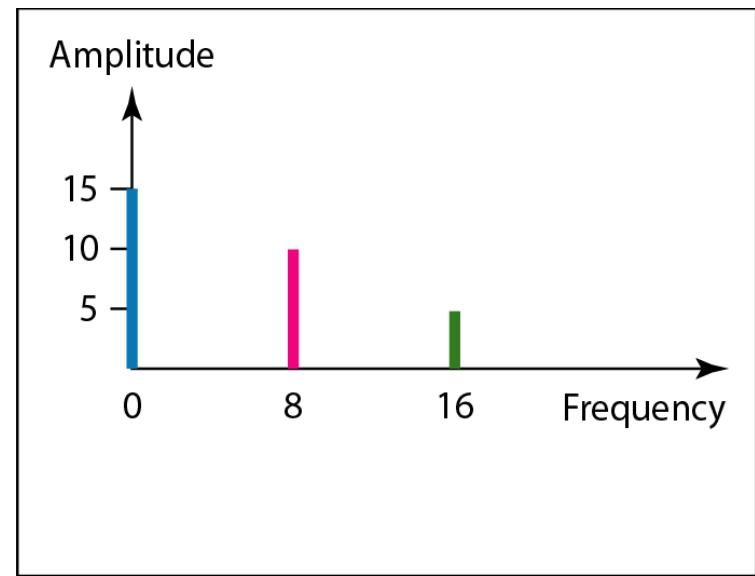
Example 3.7

The frequency domain is more compact and useful when we are dealing with more than one sine wave. For example, Figure 3.8 shows three sine waves, each with different amplitude and frequency. All can be represented by three spikes in the frequency domain.

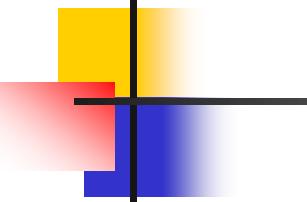
Figure 3.8 *The time domain and frequency domain of three sine waves*



a. Time-domain representation of three sine waves with frequencies 0, 8, and 16

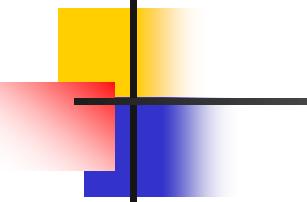


b. Frequency-domain representation of the same three signals



Note

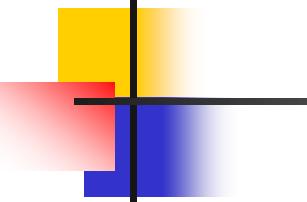
A single-frequency sine wave is not useful in data communications; we need to send a composite signal, a signal made of many simple sine waves.



Note

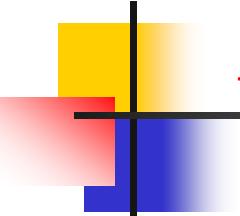
According to Fourier analysis, any composite signal is a combination of simple sine waves with different frequencies, amplitudes, and phases.

Fourier analysis is discussed in Appendix C.



Note

If the composite signal is periodic, the decomposition gives a series of signals with discrete frequencies; if the composite signal is nonperiodic, the decomposition gives a combination of sine waves with continuous frequencies.



Example 3.8

Figure 3.9 shows a periodic composite signal with frequency f . This type of signal is not typical of those found in data communications. We can consider it to be three alarm systems, each with a different frequency. The analysis of this signal can give us a good understanding of how to decompose signals.

Figure 3.9 A composite periodic signal

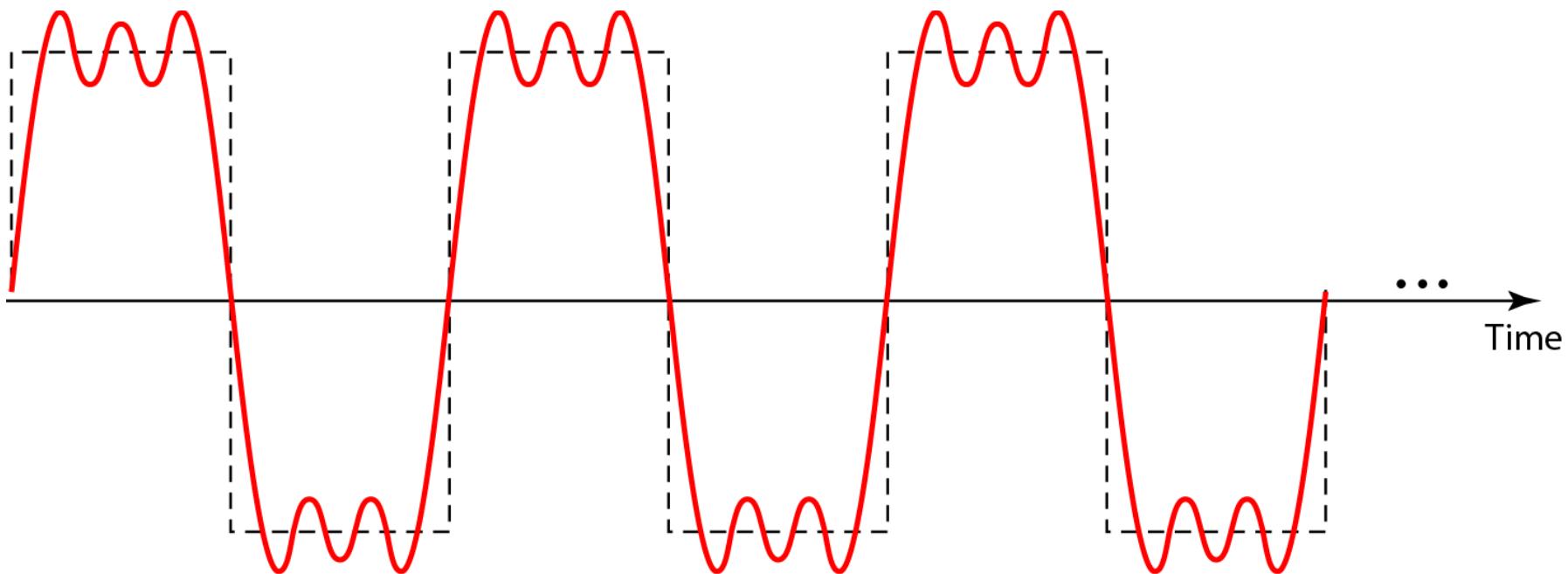
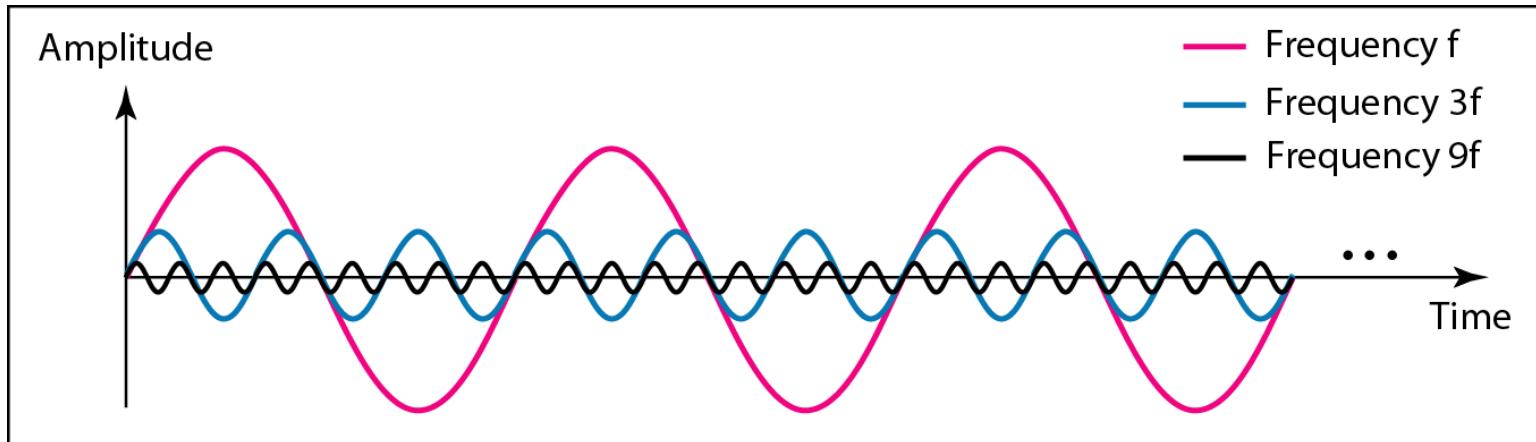
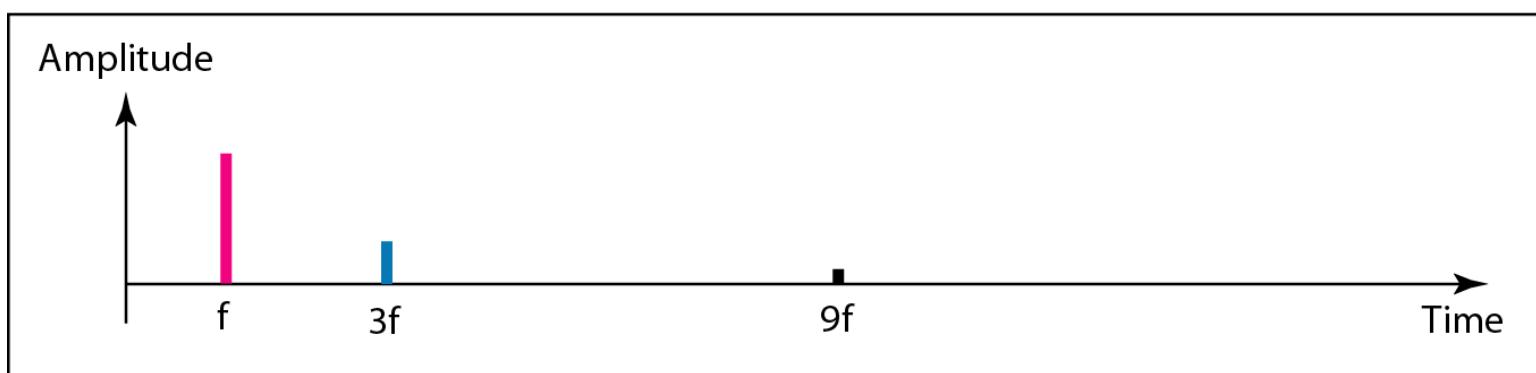


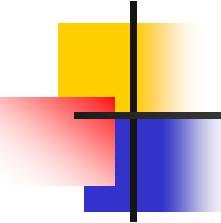
Figure 3.10 Decomposition of a composite periodic signal in the time and frequency domains



a. Time-domain decomposition of a composite signal



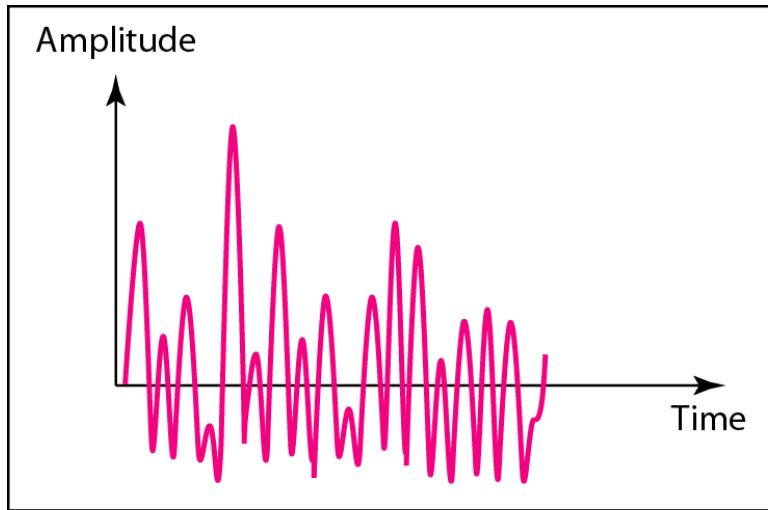
b. Frequency-domain decomposition of the composite signal



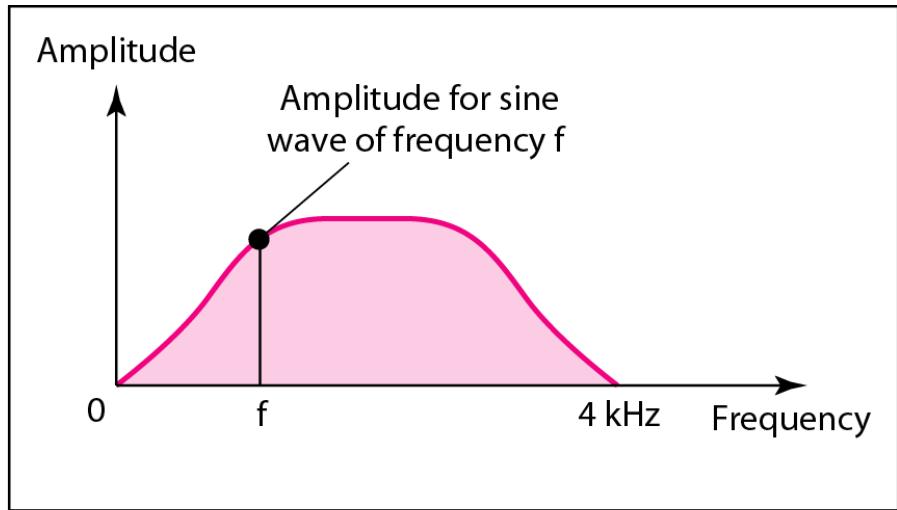
Example 3.9

Figure 3.11 shows a nonperiodic composite signal. It can be the signal created by a microphone or a telephone set when a word or two is pronounced. In this case, the composite signal cannot be periodic, because that implies that we are repeating the same word or words with exactly the same tone.

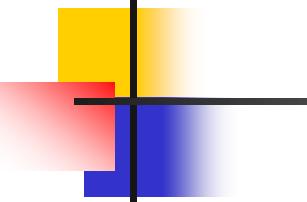
Figure 3.11 *The time and frequency domains of a nonperiodic signal*



a. Time domain



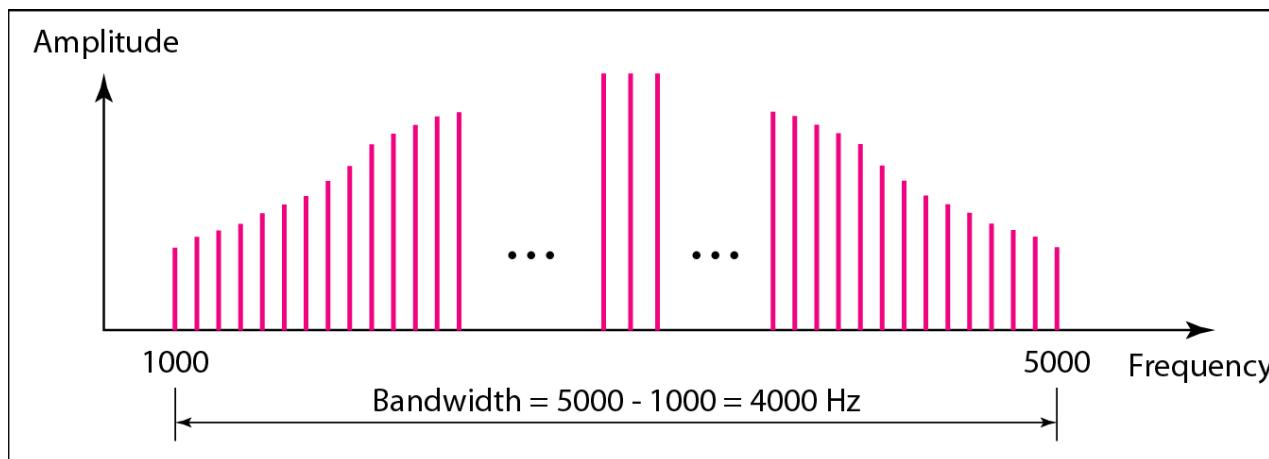
b. Frequency domain



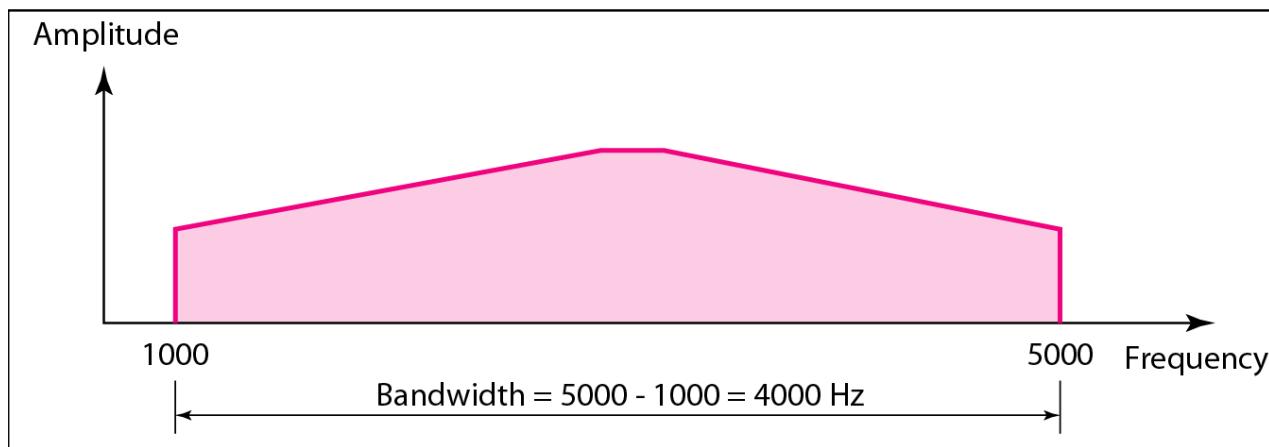
Note

The bandwidth of a composite signal is the difference between the highest and the lowest frequencies contained in that signal.

Figure 3.12 *The bandwidth of periodic and nonperiodic composite signals*



a. Bandwidth of a periodic signal



b. Bandwidth of a nonperiodic signal

Example 3.10

If a periodic signal is decomposed into five sine waves with frequencies of 100, 300, 500, 700, and 900 Hz, what is its bandwidth? Draw the spectrum, assuming all components have a maximum amplitude of 10 V.

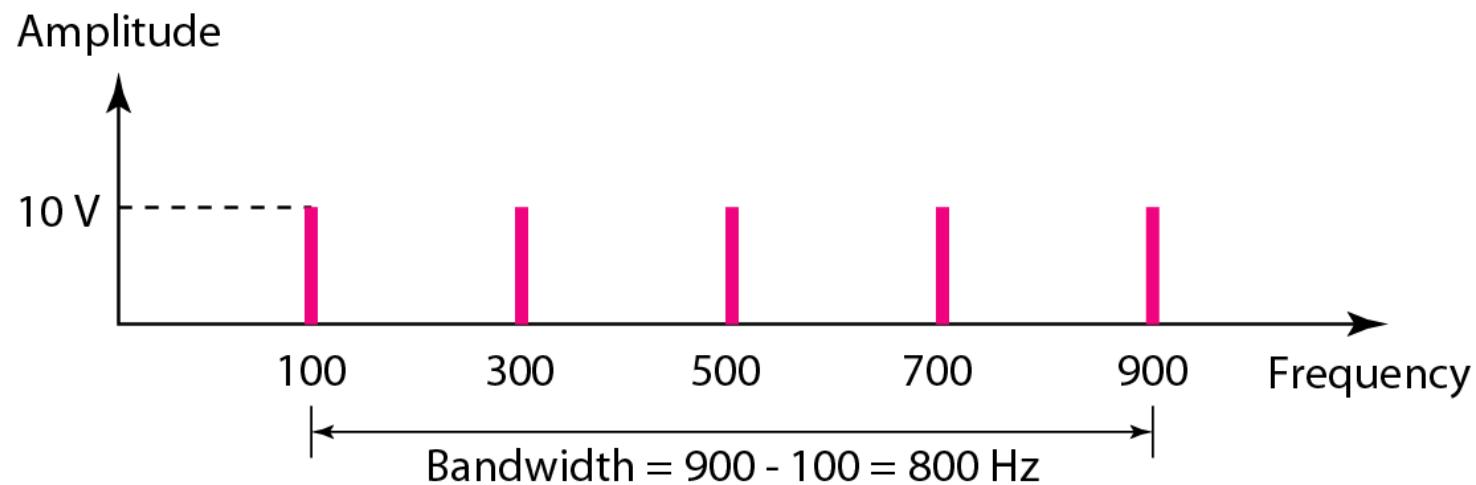
Solution

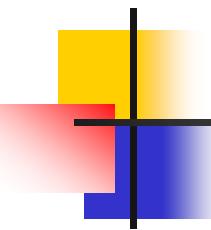
Let f_h be the highest frequency, f_l the lowest frequency, and B the bandwidth. Then

$$B = f_h - f_l = 900 - 100 = 800 \text{ Hz}$$

The spectrum has only five spikes, at 100, 300, 500, 700, and 900 Hz (see Figure 3.13).

Figure 3.13 *The bandwidth for Example 3.10*





Example 3.11

A periodic signal has a bandwidth of 20 Hz. The highest frequency is 60 Hz. What is the lowest frequency? Draw the spectrum if the signal contains all frequencies of the same amplitude.

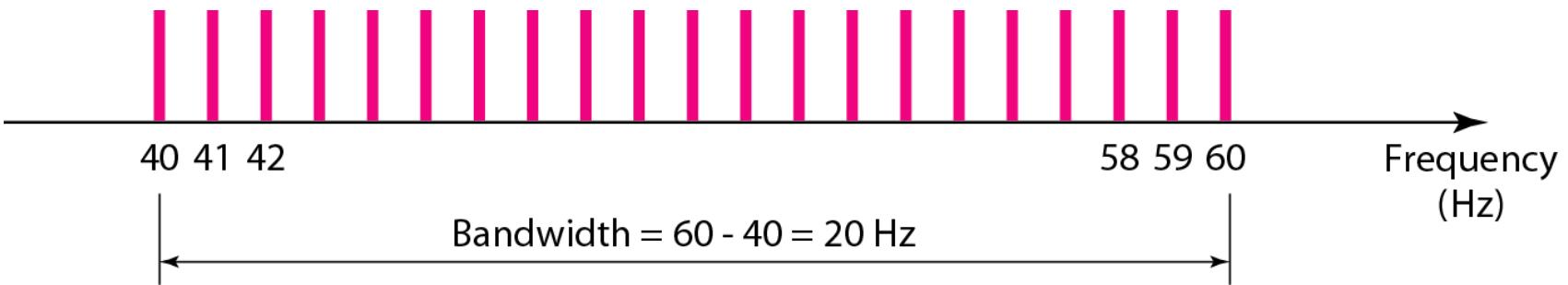
Solution

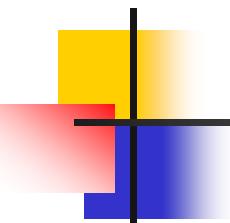
Let f_h be the highest frequency, f_l the lowest frequency, and B the bandwidth. Then

$$B = f_h - f_l \Rightarrow 20 = 60 - f_l \Rightarrow f_l = 60 - 20 = 40 \text{ Hz}$$

The spectrum contains all integer frequencies. We show this by a series of spikes (see Figure 3.14).

Figure 3.14 *The bandwidth for Example 3.11*





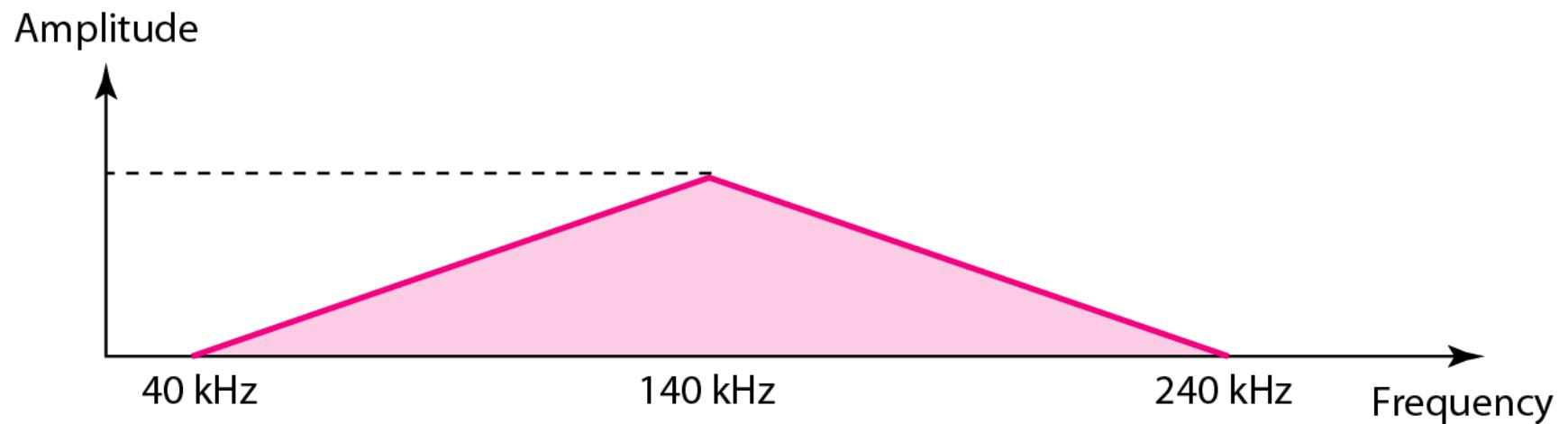
Example 3.12

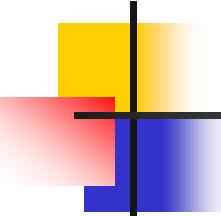
A nonperiodic composite signal has a bandwidth of 200 kHz, with a middle frequency of 140 kHz and peak amplitude of 20 V. The two extreme frequencies have an amplitude of 0. Draw the frequency domain of the signal.

Solution

The lowest frequency must be at 40 kHz and the highest at 240 kHz. Figure 3.15 shows the frequency domain and the bandwidth.

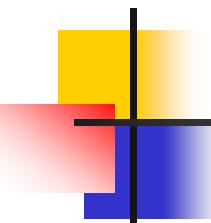
Figure 3.15 *The bandwidth for Example 3.12*





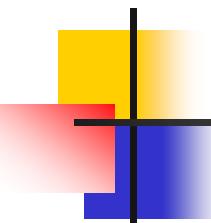
Example 3.13

An example of a nonperiodic composite signal is the signal propagated by an AM radio station. In the United States, each AM radio station is assigned a 10-kHz bandwidth. The total bandwidth dedicated to AM radio ranges from 530 to 1700 kHz. We will show the rationale behind this 10-kHz bandwidth in Chapter 5.



Example 3.14

Another example of a nonperiodic composite signal is the signal propagated by an FM radio station. In the United States, each FM radio station is assigned a 200-kHz bandwidth. The total bandwidth dedicated to FM radio ranges from 88 to 108 MHz. We will show the rationale behind this 200-kHz bandwidth in Chapter 5.



Example 3.15

Another example of a nonperiodic composite signal is the signal received by an old-fashioned analog black-and-white TV. A TV screen is made up of pixels. If we assume a resolution of 525×700 , we have 367,500 pixels per screen. If we scan the screen 30 times per second, this is $367,500 \times 30 = 11,025,000$ pixels per second. The worst-case scenario is alternating black and white pixels. We can send 2 pixels per cycle. Therefore, we need $11,025,000 / 2 = 5,512,500$ cycles per second, or Hz. The bandwidth needed is 5.5125 MHz.

3-3 DIGITAL SIGNALS

*In addition to being represented by an analog signal, information can also be represented by a **digital signal**. For example, a 1 can be encoded as a positive voltage and a 0 as zero voltage. A digital signal can have more than two levels. In this case, we can send more than 1 bit for each level.*

Topics discussed in this section:

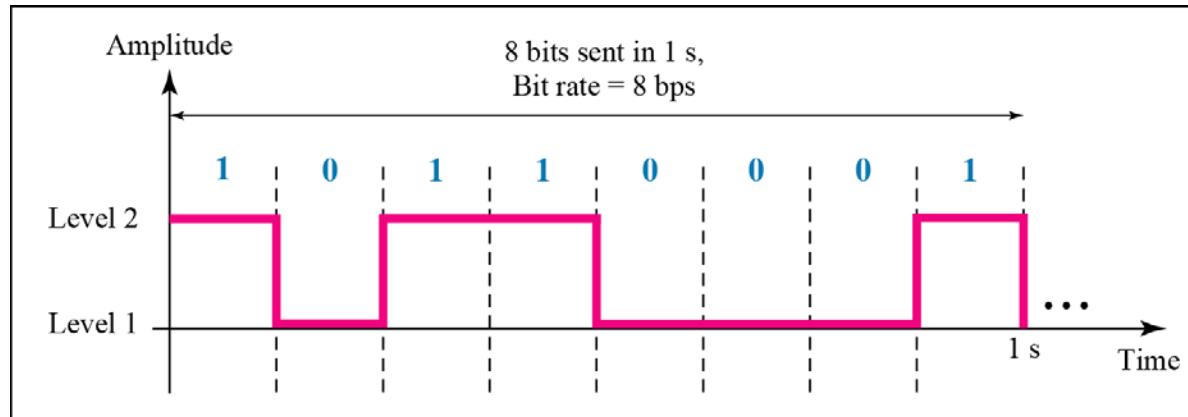
Bit Rate

Bit Length

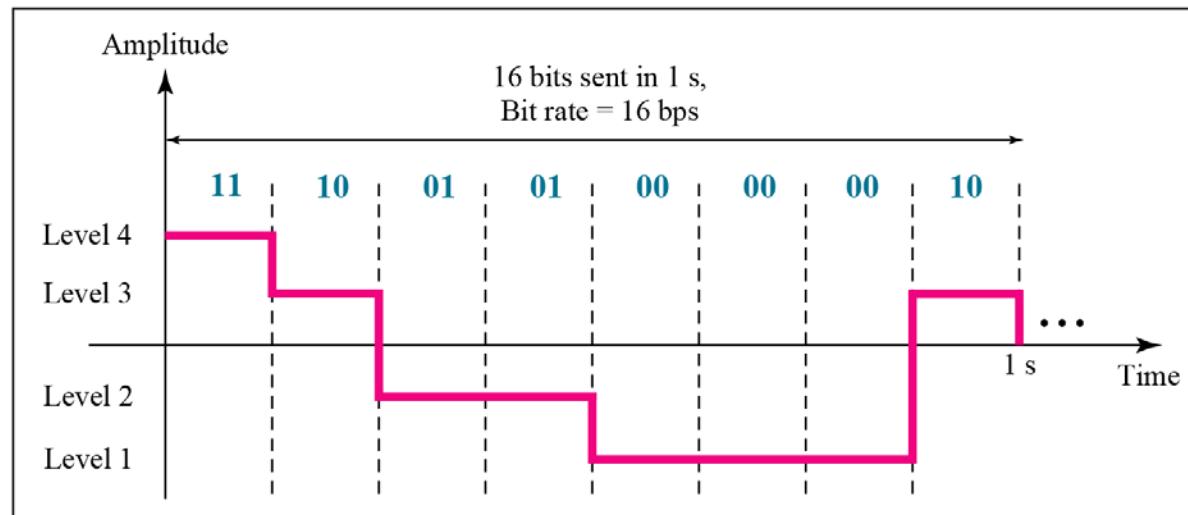
Digital Signal as a Composite Analog Signal

Application Layer

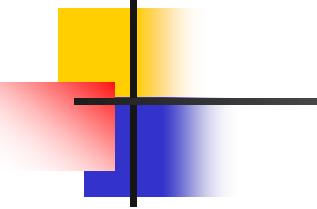
Figure 3.16 Two digital signals: one with two signal levels and the other with four signal levels



a. A digital signal with two levels

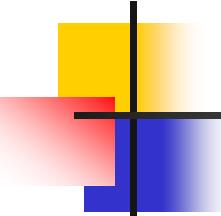


b. A digital signal with four levels



Note

Appendix C reviews information about exponential and logarithmic functions.

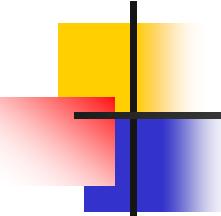


Example 3.16

A digital signal has eight levels. How many bits are needed per level? We calculate the number of bits from the formula

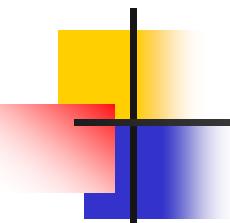
$$\text{Number of bits per level} = \log_2 8 = 3$$

Each signal level is represented by 3 bits.



Example 3.17

A digital signal has nine levels. How many bits are needed per level? We calculate the number of bits by using the formula. Each signal level is represented by 3.17 bits. However, this answer is not realistic. The number of bits sent per level needs to be an integer as well as a power of 2. For this example, 4 bits can represent one level.



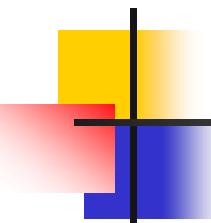
Example 3.18

Assume we need to download text documents at the rate of 100 pages per minute. What is the required bit rate of the channel?

Solution

A page is an average of 24 lines with 80 characters in each line. If we assume that one character requires 8 bits, the bit rate is

$$100 \times 24 \times 80 \times 8 = 1,636,000 \text{ bps} = 1.636 \text{ Mbps}$$



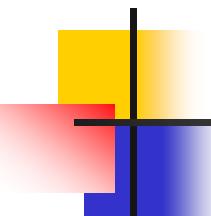
Example 3.19

A digitized voice channel, as we will see in Chapter 4, is made by digitizing a 4-kHz bandwidth analog voice signal. We need to sample the signal at twice the highest frequency (two samples per hertz). We assume that each sample requires 8 bits. What is the required bit rate?

Solution

The bit rate can be calculated as

$$2 \times 4000 \times 8 = 64,000 \text{ bps} = 64 \text{ kbps}$$



Example 3.20

What is the bit rate for high-definition TV (HDTV)?

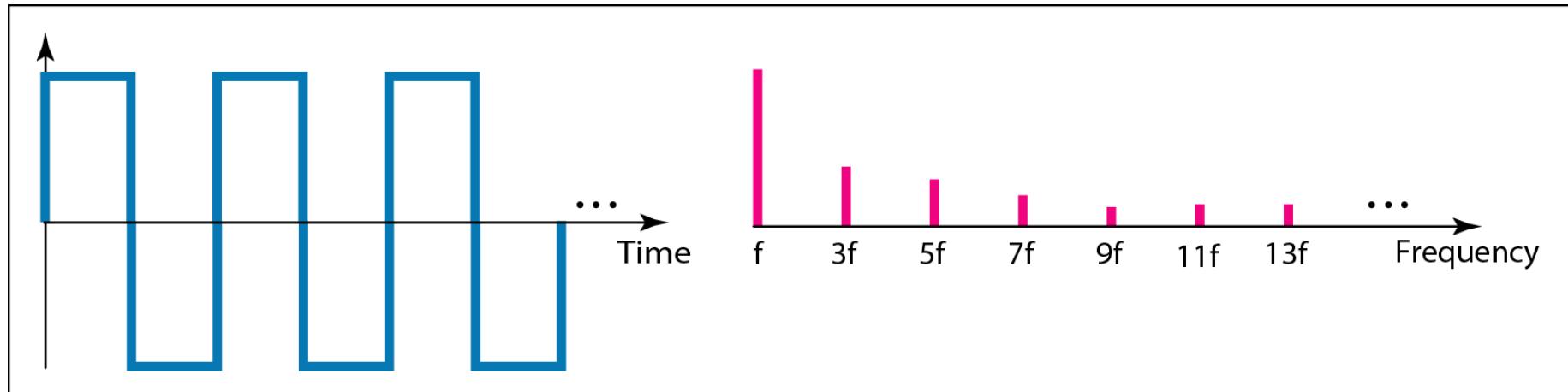
Solution

HDTV uses digital signals to broadcast high quality video signals. The HDTV screen is normally a ratio of 16 : 9. There are 1920 by 1080 pixels per screen, and the screen is renewed 30 times per second. Twenty-four bits represents one color pixel.

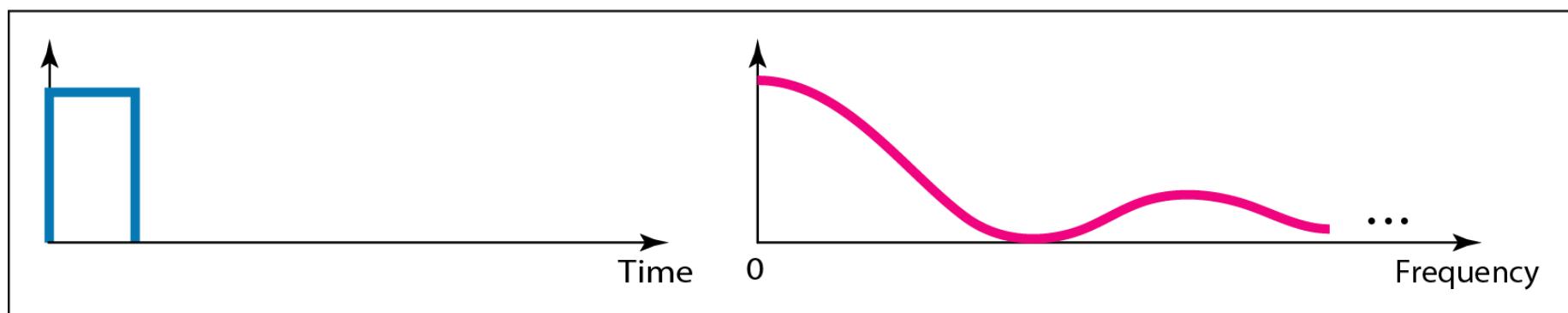
$$1920 \times 1080 \times 30 \times 24 = 1,492,992,000 \text{ or } 1.5 \text{ Gbps}$$

The TV stations reduce this rate to 20 to 40 Mbps through compression.

Figure 3.17 *The time and frequency domains of periodic and nonperiodic digital signals*

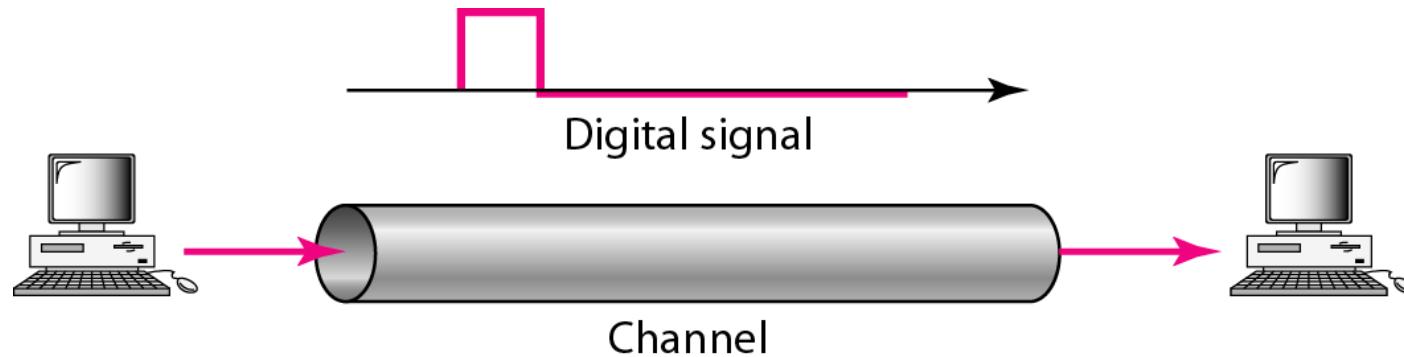


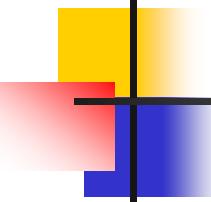
a. Time and frequency domains of periodic digital signal



b. Time and frequency domains of nonperiodic digital signal

Figure 3.18 *Baseband transmission*





Note

A digital signal is a composite analog signal with an infinite bandwidth.

Figure 3.19 *Bandwidths of two low-pass channels*

Amplitude



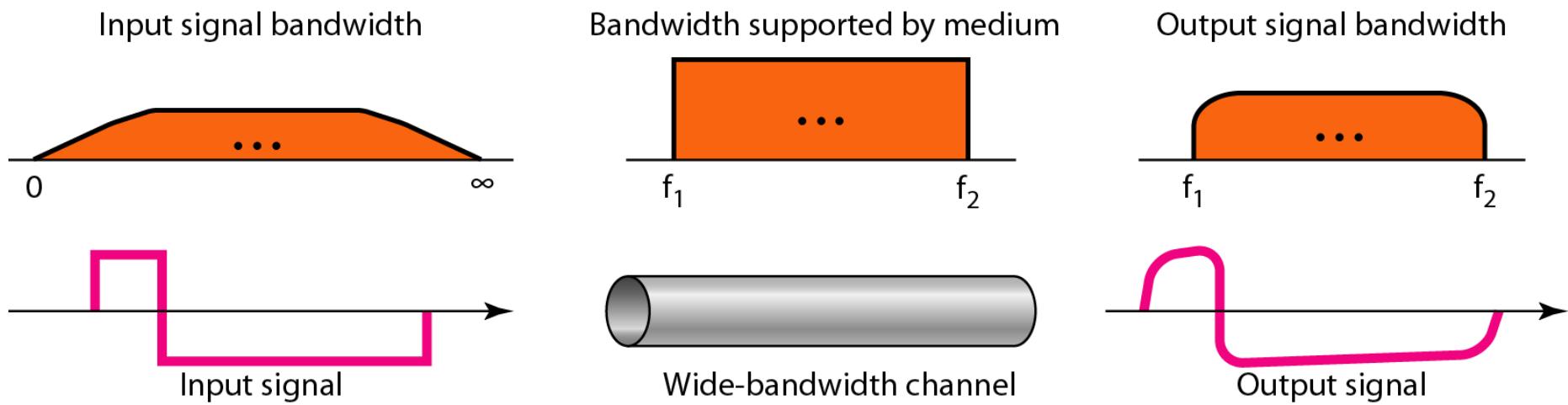
a. Low-pass channel, wide bandwidth

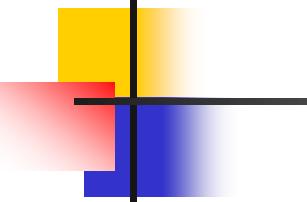
Amplitude



b. Low-pass channel, narrow bandwidth

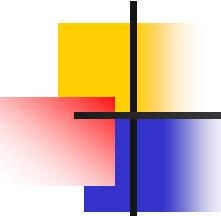
Figure 3.20 *Baseband transmission using a dedicated medium*





Note

Baseband transmission of a digital signal that preserves the shape of the digital signal is possible only if we have a low-pass channel with an infinite or very wide bandwidth.



Example 3.21

An example of a dedicated channel where the entire bandwidth of the medium is used as one single channel is a LAN. Almost every wired LAN today uses a dedicated channel for two stations communicating with each other. In a bus topology LAN with multipoint connections, only two stations can communicate with each other at each moment in time (timesharing); the other stations need to refrain from sending data. In a star topology LAN, the entire channel between each station and the hub is used for communication between these two entities. We study LANs in Chapter 14.

Figure 3.21 *Rough approximation of a digital signal using the first harmonic for worst case*

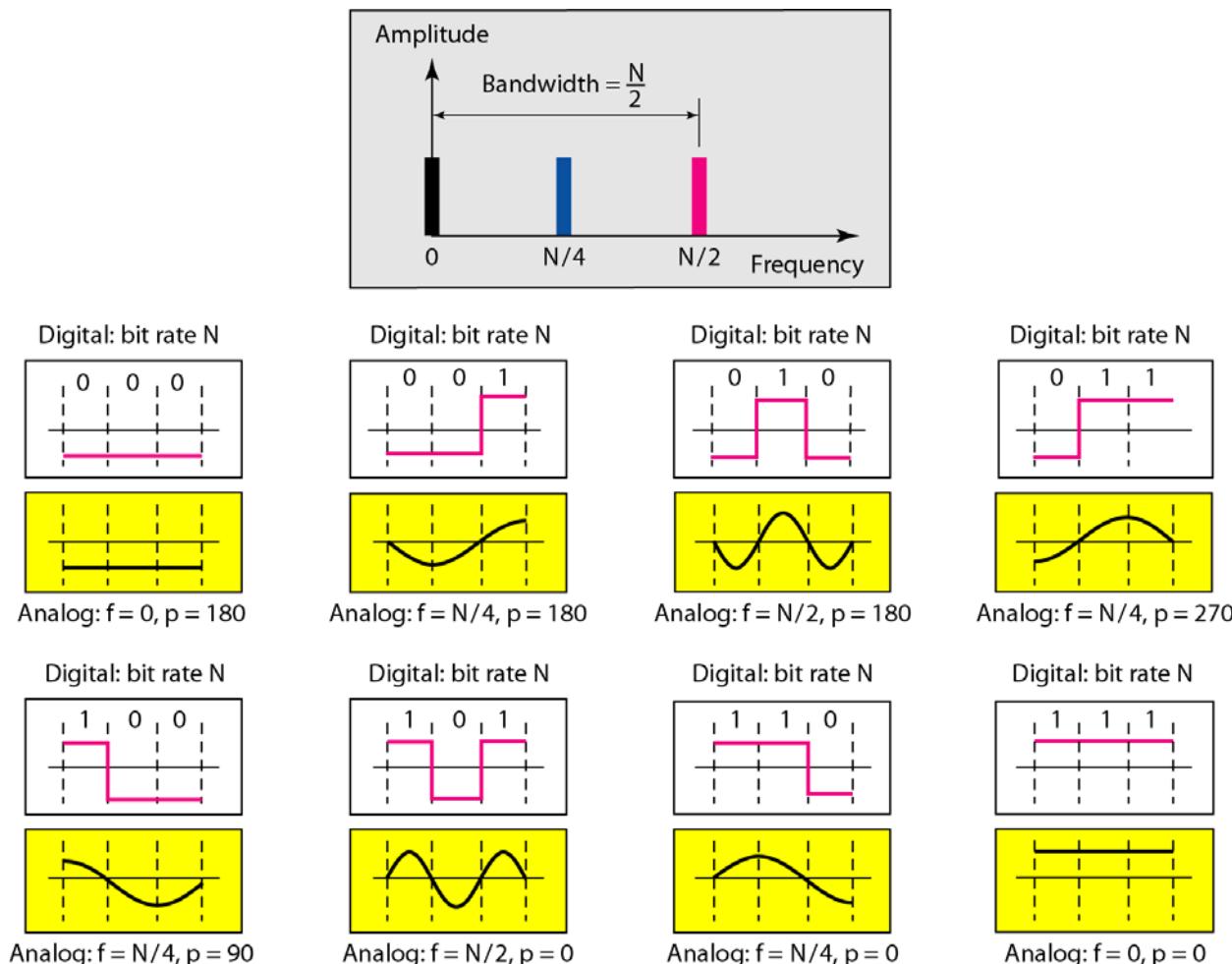
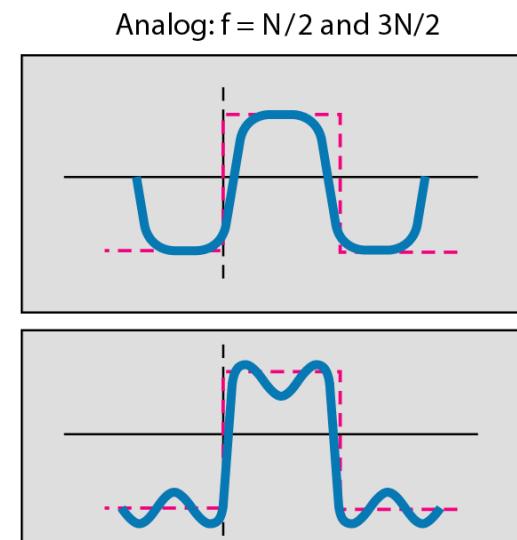
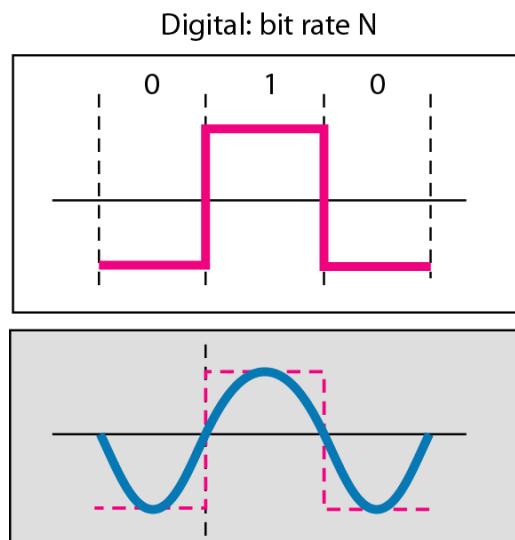
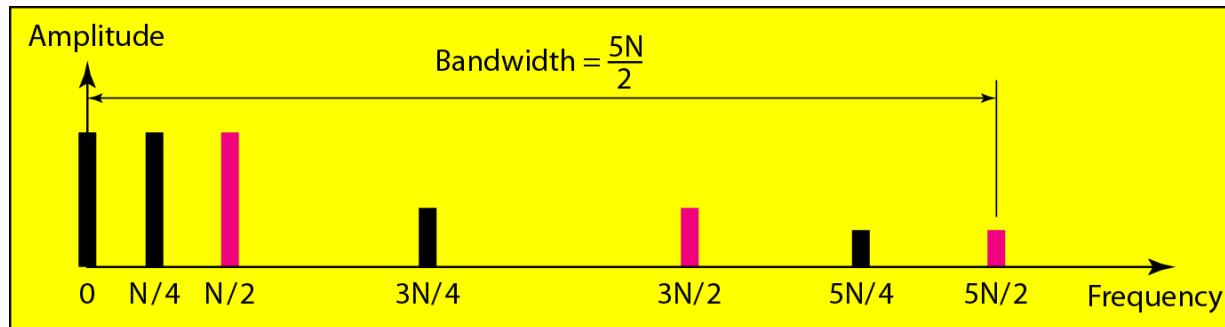
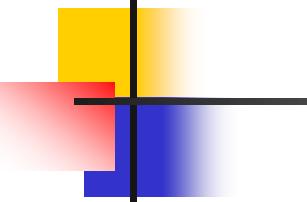


Figure 3.22 Simulating a digital signal with first three harmonics



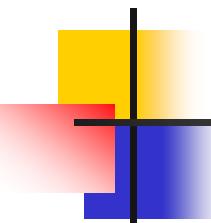


Note

In baseband transmission, the required bandwidth is proportional to the bit rate; if we need to send bits faster, we need more bandwidth.

Table 3.2 *Bandwidth requirements*

<i>Bit Rate</i>	<i>Harmonic 1</i>	<i>Harmonics 1, 3</i>	<i>Harmonics 1, 3, 5</i>
$n = 1 \text{ kbps}$	$B = 500 \text{ Hz}$	$B = 1.5 \text{ kHz}$	$B = 2.5 \text{ kHz}$
$n = 10 \text{ kbps}$	$B = 5 \text{ kHz}$	$B = 15 \text{ kHz}$	$B = 25 \text{ kHz}$
$n = 100 \text{ kbps}$	$B = 50 \text{ kHz}$	$B = 150 \text{ kHz}$	$B = 250 \text{ kHz}$



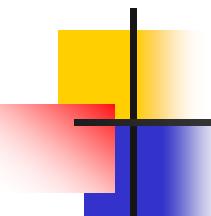
Example 3.22

What is the required bandwidth of a low-pass channel if we need to send 1 Mbps by using baseband transmission?

Solution

The answer depends on the accuracy desired.

- a. The minimum bandwidth, is $B = \text{bit rate} / 2$, or 500 kHz.*
- b. A better solution is to use the first and the third harmonics with $B = 3 \times 500 \text{ kHz} = 1.5 \text{ MHz}$.*
- c. Still a better solution is to use the first, third, and fifth harmonics with $B = 5 \times 500 \text{ kHz} = 2.5 \text{ MHz}$.*



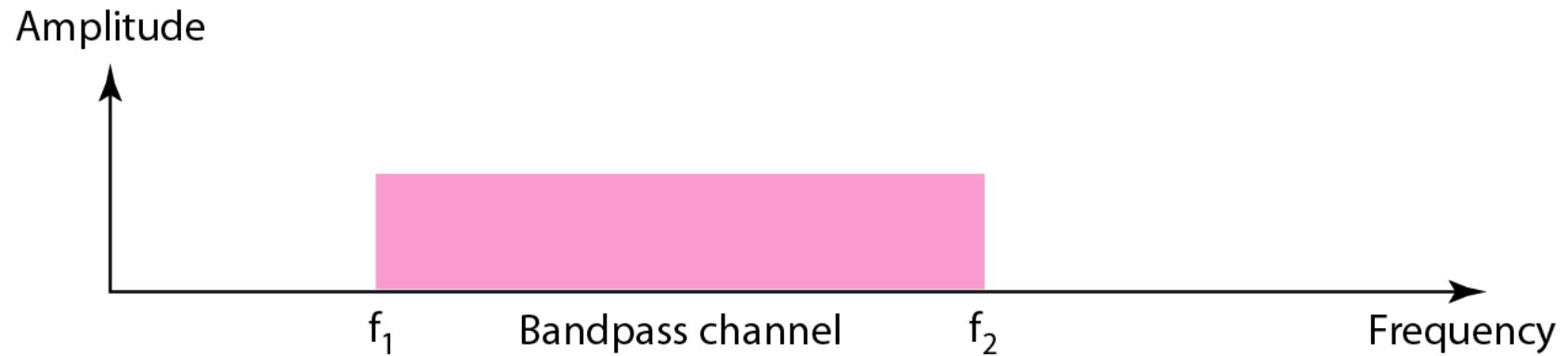
Example 3.22

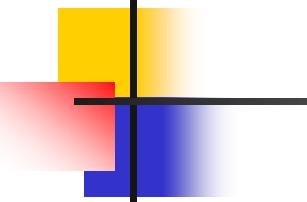
*We have a low-pass channel with bandwidth 100 kHz.
What is the maximum bit rate of this
channel?*

Solution

The maximum bit rate can be achieved if we use the first harmonic. The bit rate is 2 times the available bandwidth, or 200 kbps.

Figure 3.23 *Bandwidth of a bandpass channel*

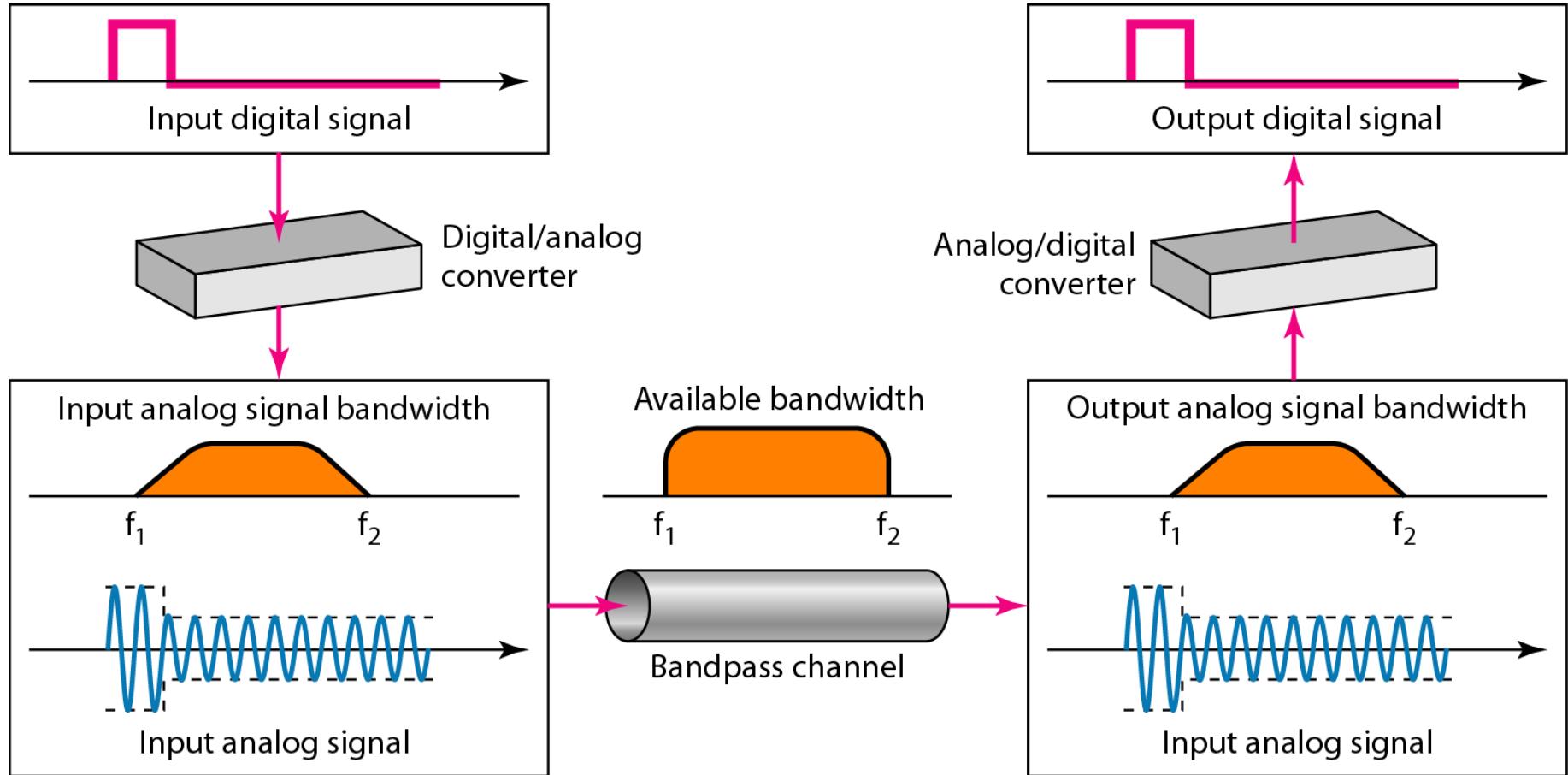


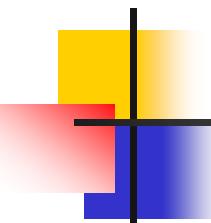


Note

If the available channel is a bandpass channel, we cannot send the digital signal directly to the channel; we need to convert the digital signal to an analog signal before transmission.

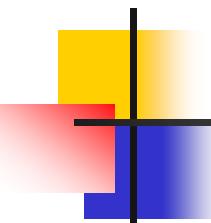
Figure 3.24 Modulation of a digital signal for transmission on a bandpass channel





Example 3.24

*An example of broadband transmission using modulation is the sending of computer data through a telephone subscriber line, the line connecting a resident to the central telephone office. These lines are designed to carry voice with a limited bandwidth. The channel is considered a bandpass channel. We convert the digital signal from the computer to an analog signal, and send the analog signal. We can install two converters to change the digital signal to analog and vice versa at the receiving end. The converter, in this case, is called a **modem** which we discuss in detail in Chapter 5.*



Example 3.25

A second example is the digital cellular telephone. For better reception, digital cellular phones convert the analog voice signal to a digital signal (see Chapter 16). Although the bandwidth allocated to a company providing digital cellular phone service is very wide, we still cannot send the digital signal without conversion. The reason is that we only have a bandpass channel available between caller and callee. We need to convert the digitized voice to a composite analog signal before sending.

3-4 TRANSMISSION IMPAIRMENT

*Signals travel through transmission media, which are not perfect. The imperfection causes signal impairment. This means that the signal at the beginning of the medium is not the same as the signal at the end of the medium. What is sent is not what is received. Three causes of impairment are **attenuation**, **distortion**, and **noise**.*

Topics discussed in this section:

Attenuation

Distortion

Noise

Figure 3.25 *Causes of impairment*

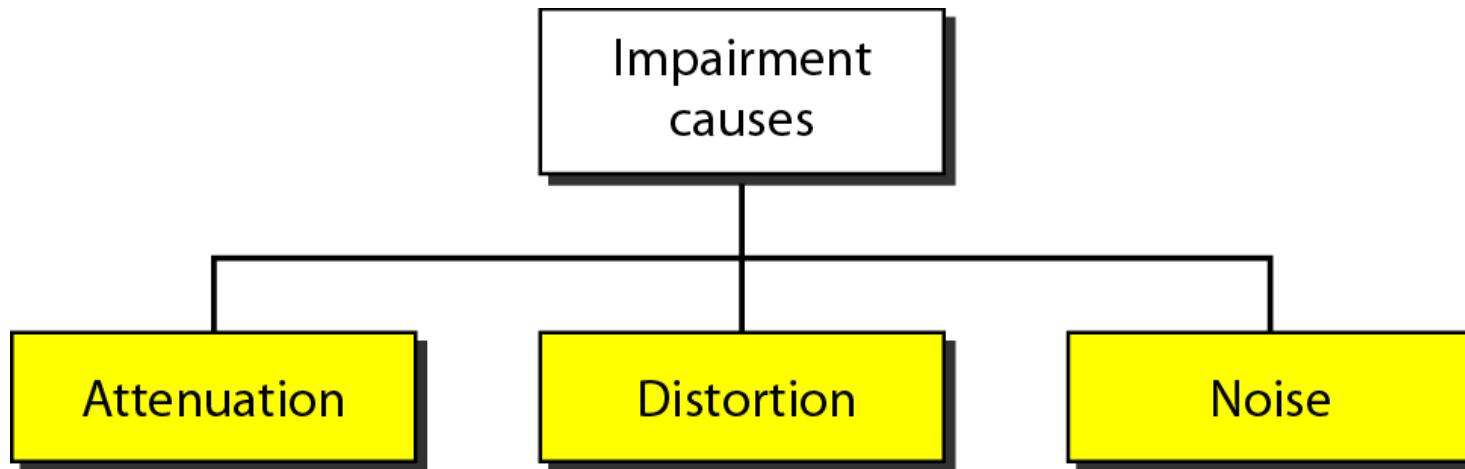
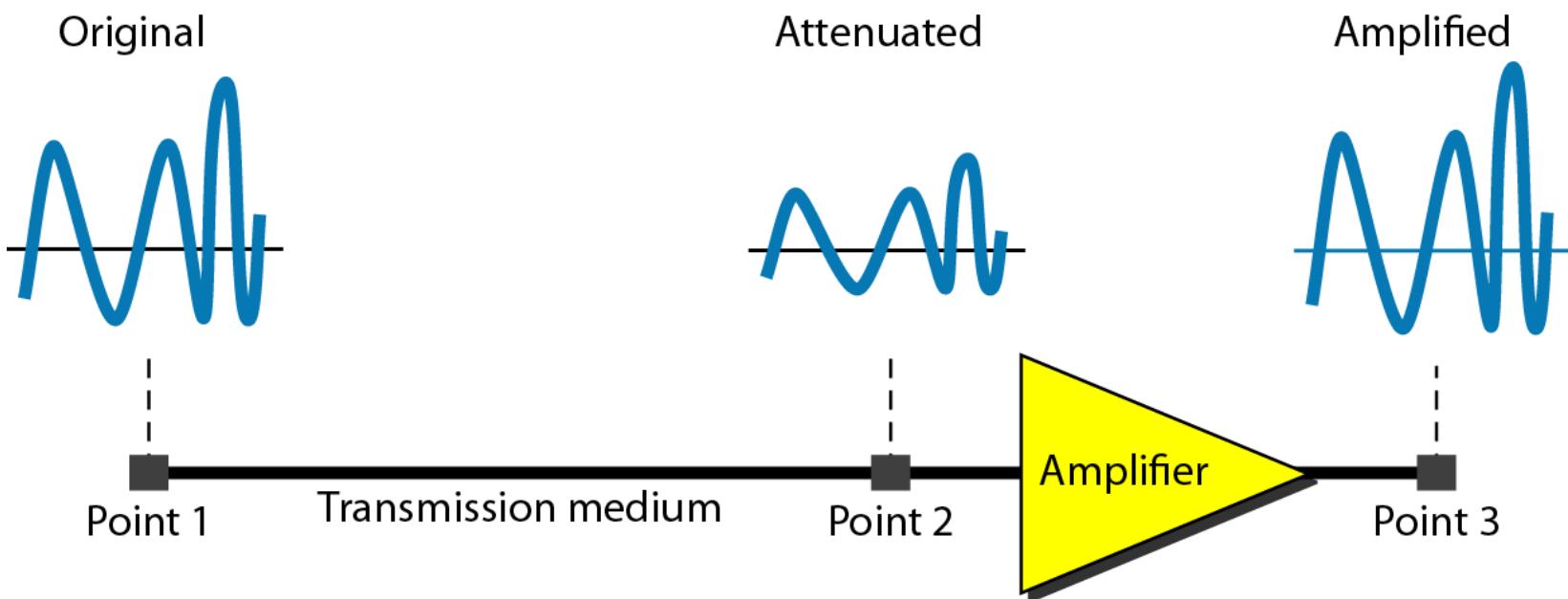
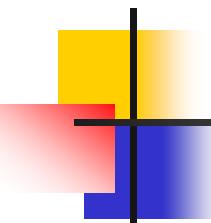


Figure 3.26 Attenuation



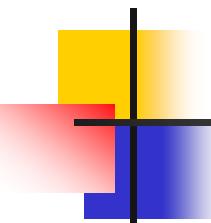


Example 3.26

Suppose a signal travels through a transmission medium and its power is reduced to one-half. This means that P_2 is $(1/2)P_1$. In this case, the attenuation (loss of power) can be calculated as

$$10 \log_{10} \frac{P_2}{P_1} = 10 \log_{10} \frac{0.5 P_1}{P_1} = 10 \log_{10} 0.5 = 10(-0.3) = -3 \text{ dB}$$

A loss of 3 dB (-3 dB) is equivalent to losing one-half the power.

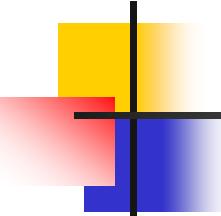


Example 3.27

A signal travels through an amplifier, and its power is increased 10 times. This means that $P_2 = 10P_1$. In this case, the amplification (gain of power) can be calculated as

$$10 \log_{10} \frac{P_2}{P_1} = 10 \log_{10} \frac{10P_1}{P_1}$$

$$= 10 \log_{10} 10 = 10(1) = 10 \text{ dB}$$

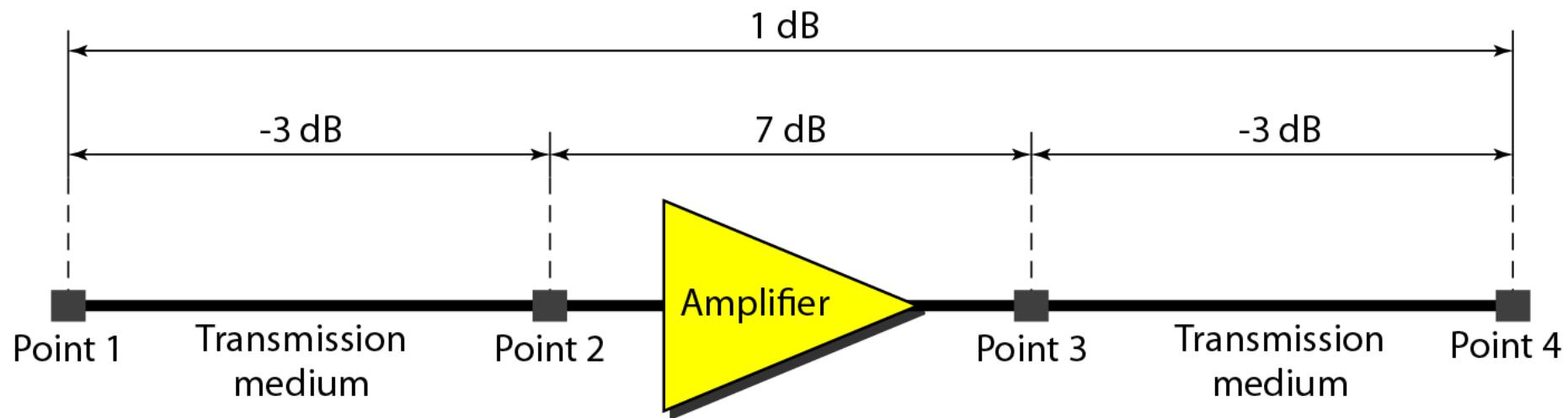


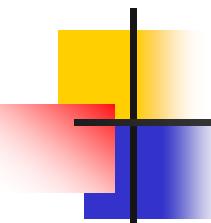
Example 3.28

One reason that engineers use the decibel to measure the changes in the strength of a signal is that decibel numbers can be added (or subtracted) when we are measuring several points (cascading) instead of just two. In Figure 3.27 a signal travels from point 1 to point 4. In this case, the decibel value can be calculated as

$$\text{dB} = -3 + 7 - 3 = +1$$

Figure 3.27 Decibels for Example 3.28





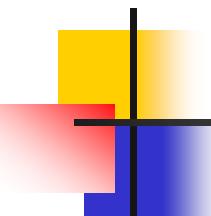
Example 3.29

Sometimes the decibel is used to measure signal power in milliwatts. In this case, it is referred to as dB_m and is calculated as $dB_m = 10 \log_{10} P_m$, where P_m is the power in milliwatts. Calculate the power of a signal with $dB_m = -30$.

Solution

We can calculate the power in the signal as

$$\begin{aligned} dB_m &= 10 \log_{10} P_m = -30 \\ \log_{10} P_m &= -3 \quad P_m = 10^{-3} \text{ mW} \end{aligned}$$



Example 3.30

The loss in a cable is usually defined in decibels per kilometer (dB/km). If the signal at the beginning of a cable with -0.3 dB/km has a power of 2 mW , what is the power of the signal at 5 km ?

Solution

The loss in the cable in decibels is $5 \times (-0.3) = -1.5 \text{ dB}$.

We can calculate the power as

$$\text{dB} = 10 \log_{10} \frac{P_2}{P_1} = -1.5$$

$$\frac{P_2}{P_1} = 10^{-0.15} = 0.71$$

$$P_2 = 0.71P_1 = 0.7 \times 2 = 1.4 \text{ mW}$$

Figure 3.28 *Distortion*

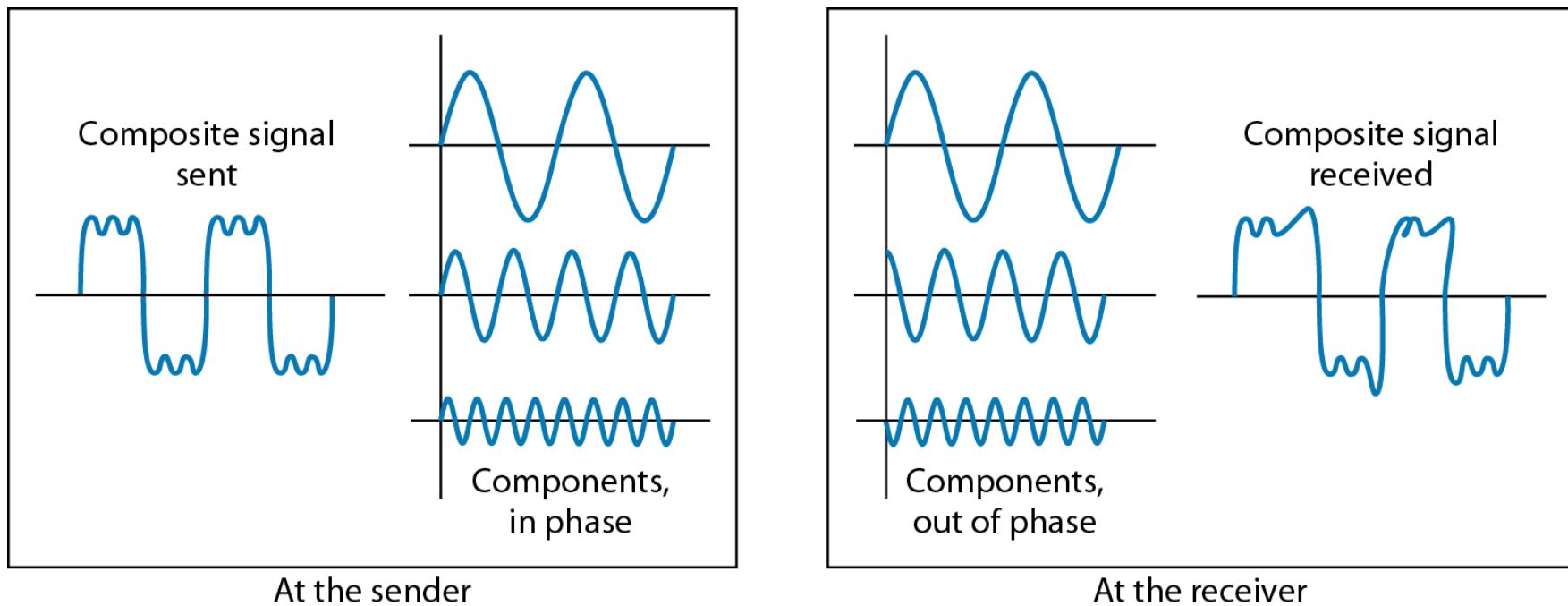
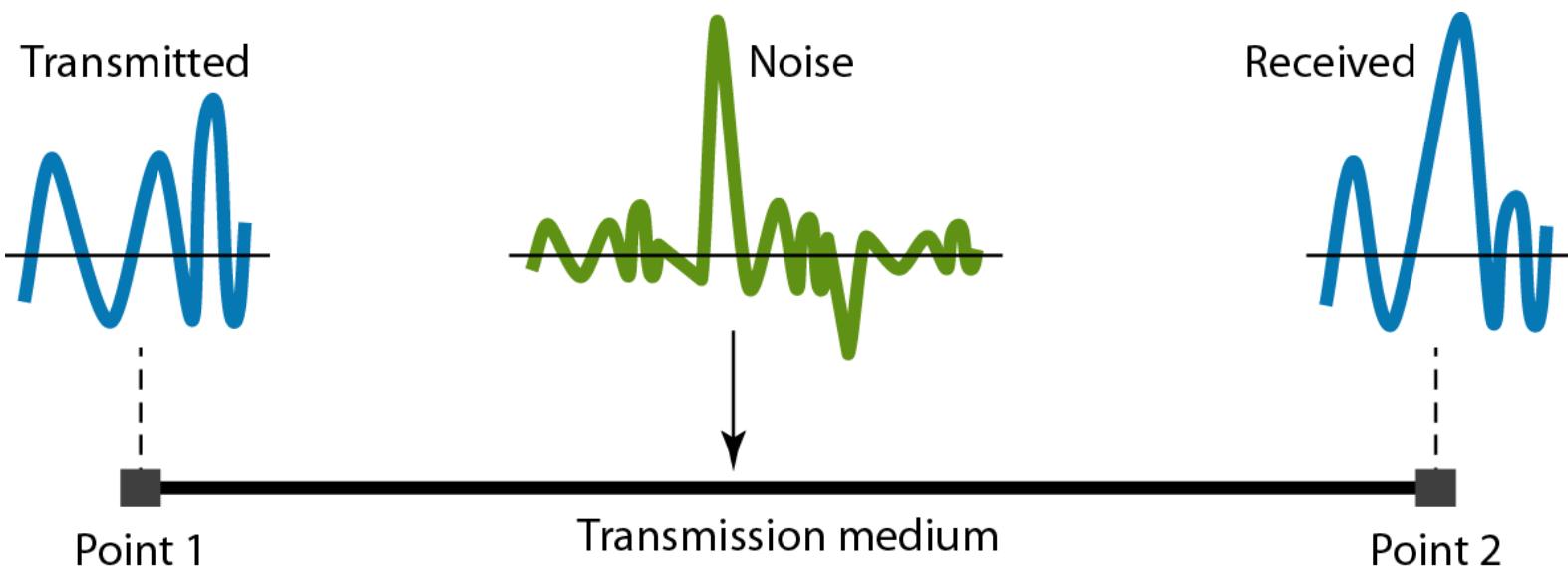
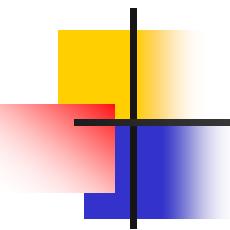


Figure 3.29 *Noise*





Example 3.31

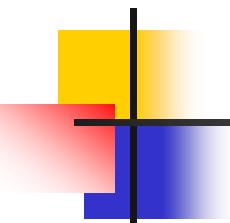
The power of a signal is 10 mW and the power of the noise is 1 μW; what are the values of SNR and SNR_{dB}?

Solution

The values of SNR and SNR_{dB} can be calculated as follows:

$$\text{SNR} = \frac{10,000 \mu\text{W}}{1 \text{ mW}} = 10,000$$

$$\text{SNR}_{\text{dB}} = 10 \log_{10} 10,000 = 10 \log_{10} 10^4 = 40$$



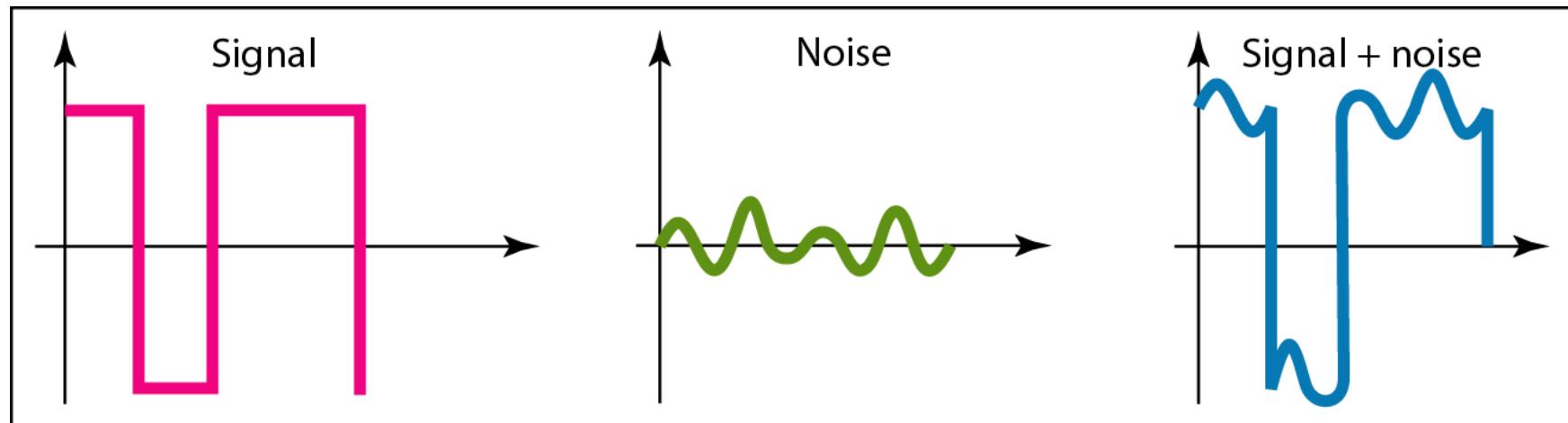
Example 3.32

The values of SNR and SNR_{dB} for a noiseless channel are

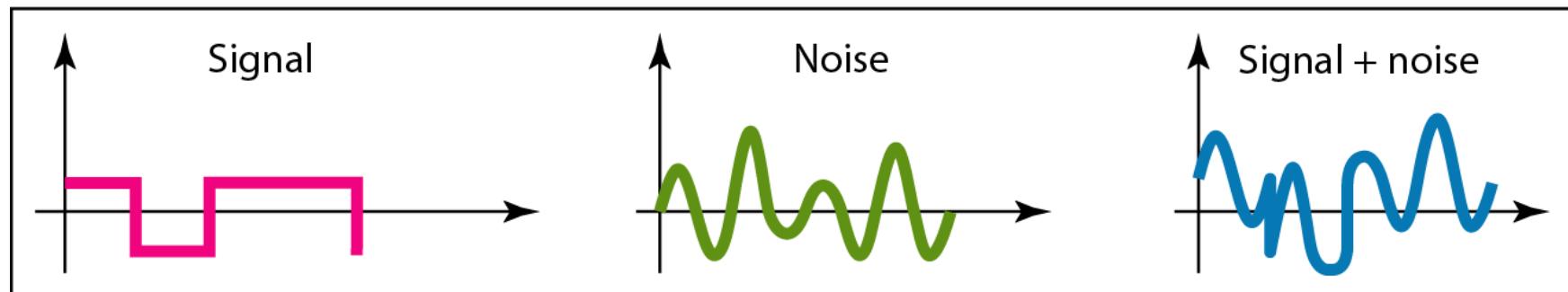
$$\text{SNR} = \frac{\text{signal power}}{0} = \infty$$
$$\text{SNR}_{\text{dB}} = 10 \log_{10} \infty = \infty$$

We can never achieve this ratio in real life; it is an ideal.

Figure 3.30 *Two cases of SNR: a high SNR and a low SNR*



a. Large SNR



b. Small SNR

3-5 DATA RATE LIMITS

A very important consideration in data communications is how fast we can send data, in bits per second, over a channel. Data rate depends on three factors:

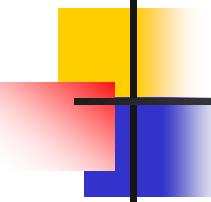
- 1. The bandwidth available**
- 2. The level of the signals we use**
- 3. The quality of the channel (the level of noise)**

Topics discussed in this section:

Noiseless Channel: Nyquist Bit Rate

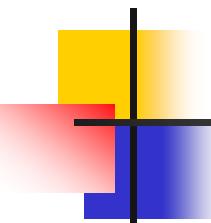
Noisy Channel: Shannon Capacity

Using Both Limits



Note

Increasing the levels of a signal may reduce the reliability of the system.

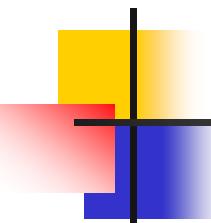


Example 3.33

Does the Nyquist theorem bit rate agree with the intuitive bit rate described in baseband transmission?

Solution

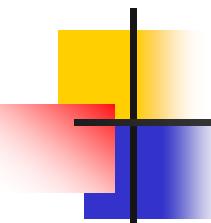
They match when we have only two levels. We said, in baseband transmission, the bit rate is 2 times the bandwidth if we use only the first harmonic in the worst case. However, the Nyquist formula is more general than what we derived intuitively; it can be applied to baseband transmission and modulation. Also, it can be applied when we have two or more levels of signals.



Example 3.34

Consider a noiseless channel with a bandwidth of 3000 Hz transmitting a signal with two signal levels. The maximum bit rate can be calculated as

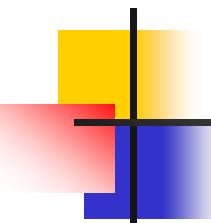
$$\text{BitRate} = 2 \times 3000 \times \log_2 2 = 6000 \text{ bps}$$



Example 3.35

Consider the same noiseless channel transmitting a signal with four signal levels (for each level, we send 2 bits). The maximum bit rate can be calculated as

$$\text{BitRate} = 2 \times 3000 \times \log_2 4 = 12,000 \text{ bps}$$



Example 3.36

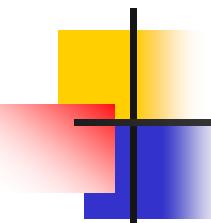
We need to send 265 kbps over a noiseless channel with a bandwidth of 20 kHz. How many signal levels do we need?

Solution

We can use the Nyquist formula as shown:

$$265,000 = 2 \times 20,000 \times \log_2 L$$
$$\log_2 L = 6.625 \quad L = 2^{6.625} = 98.7 \text{ levels}$$

Since this result is not a power of 2, we need to either increase the number of levels or reduce the bit rate. If we have 128 levels, the bit rate is 280 kbps. If we have 64 levels, the bit rate is 240 kbps.

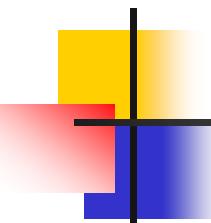


Example 3.37

Consider an extremely noisy channel in which the value of the signal-to-noise ratio is almost zero. In other words, the noise is so strong that the signal is faint. For this channel the capacity C is calculated as

$$C = B \log_2 (1 + \text{SNR}) = B \log_2 (1 + 0) = B \log_2 1 = B \times 0 = 0$$

This means that the capacity of this channel is zero regardless of the bandwidth. In other words, we cannot receive any data through this channel.



Example 3.38

We can calculate the theoretical highest bit rate of a regular telephone line. A telephone line normally has a bandwidth of 3000. The signal-to-noise ratio is usually 3162. For this channel the capacity is calculated as

$$\begin{aligned}C &= B \log_2 (1 + \text{SNR}) = 3000 \log_2 (1 + 3162) = 3000 \log_2 3163 \\&= 3000 \times 11.62 = 34,860 \text{ bps}\end{aligned}$$

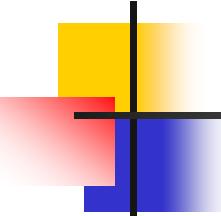
This means that the highest bit rate for a telephone line is 34.860 kbps. If we want to send data faster than this, we can either increase the bandwidth of the line or improve the signal-to-noise ratio.

Example 3.39

The signal-to-noise ratio is often given in decibels. Assume that $SNR_{dB} = 36$ and the channel bandwidth is 2 MHz. The theoretical channel capacity can be calculated as

$$SNR_{dB} = 10 \log_{10} SNR \rightarrow SNR = 10^{SNR_{dB}/10} \rightarrow SNR = 10^{3.6} = 3981$$

$$C = B \log_2 (1+ SNR) = 2 \times 10^6 \times \log_2 3982 = 24 \text{ Mbps}$$



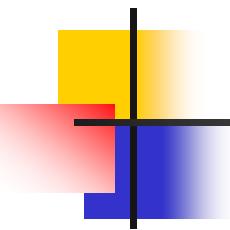
Example 3.40

For practical purposes, when the SNR is very high, we can assume that $\text{SNR} + 1$ is almost the same as SNR . In these cases, the theoretical channel capacity can be simplified to

$$C = B \times \frac{\text{SNR}_{\text{dB}}}{3}$$

For example, we can calculate the theoretical capacity of the previous example as

$$C = 2 \text{ MHz} \times \frac{36}{3} = 24 \text{ Mbps}$$



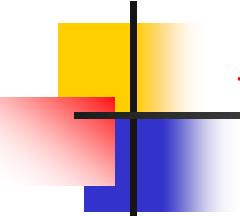
Example 3.41

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.

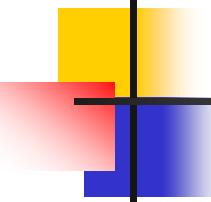
$$C = B \log_2 (1 + \text{SNR}) = 10^6 \log_2 (1 + 63) = 10^6 \log_2 64 = 6 \text{ Mbps}$$



Example 3.41 (continued)

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.

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



Note

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

3-6 PERFORMANCE

*One important issue in networking is the **performance** of the network—how good is it? We discuss quality of service, an overall measurement of network performance, in greater detail in Chapter 24. In this section, we introduce terms that we need for future chapters.*

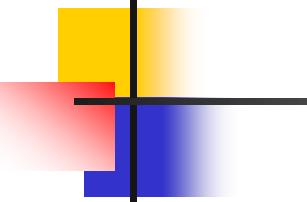
Topics discussed in this section:

Bandwidth

Throughput

Latency (Delay)

Bandwidth-Delay Product

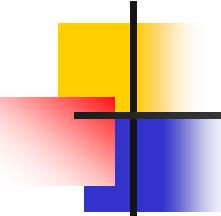


Note

In networking, we use the term bandwidth in two contexts.

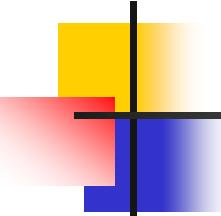
- ❑ The first, bandwidth in hertz, refers to the range of frequencies in a composite signal or the range of frequencies that a channel can pass.

- ❑ The second, bandwidth in bits per second, refers to the speed of bit transmission in a channel or link.



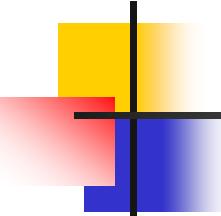
Example 3.42

The bandwidth of a subscriber line is 4 kHz for voice or data. The bandwidth of this line for data transmission can be up to 56,000 bps using a sophisticated modem to change the digital signal to analog.



Example 3.43

If the telephone company improves the quality of the line and increases the bandwidth to 8 kHz, we can send 112,000 bps by using the same technology as mentioned in Example 3.42.



Example 3.44

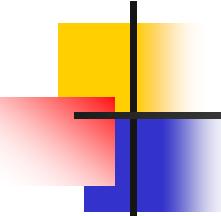
A network with bandwidth of 10 Mbps can pass only an average of 12,000 frames per minute with each frame carrying an average of 10,000 bits. What is the throughput of this network?

Solution

We can calculate the throughput as

$$\text{Throughput} = \frac{12,000 \times 10,000}{60} = 2 \text{ Mbps}$$

The throughput is almost one-fifth of the bandwidth in this case.



Example 3.45

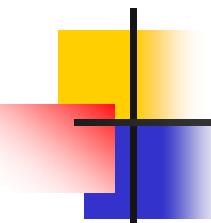
What is the propagation time if the distance between the two points is 12,000 km? Assume the propagation speed to be 2.4×10^8 m/s in cable.

Solution

We can calculate the propagation time as

$$\text{Propagation time} = \frac{12,000 \times 1000}{2.4 \times 10^8} = 50 \text{ ms}$$

The example shows that a bit can go over the Atlantic Ocean in only 50 ms if there is a direct cable between the source and the destination.



Example 3.46

What are the propagation time and the transmission time for a 2.5-kbyte message (an e-mail) if the bandwidth of the network is 1 Gbps? Assume that the distance between the sender and the receiver is 12,000 km and that light travels at 2.4×10^8 m/s.

Solution

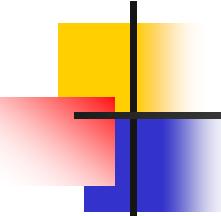
We can calculate the propagation and transmission time as shown on the next slide:

Example 3.46 (continued)

$$\text{Propagation time} = \frac{12,000 \times 1000}{2.4 \times 10^8} = 50 \text{ ms}$$

$$\text{Transmission time} = \frac{2500 \times 8}{10^9} = 0.020 \text{ ms}$$

Note that in this case, because the message is short and the bandwidth is high, the dominant factor is the propagation time, not the transmission time. The transmission time can be ignored.

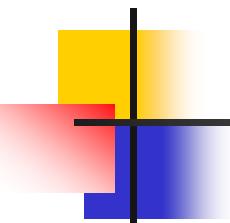


Example 3.47

What are the propagation time and the transmission time for a 5-Mbyte message (an image) if the bandwidth of the network is 1 Mbps? Assume that the distance between the sender and the receiver is 12,000 km and that light travels at 2.4×10^8 m/s.

Solution

We can calculate the propagation and transmission times as shown on the next slide.



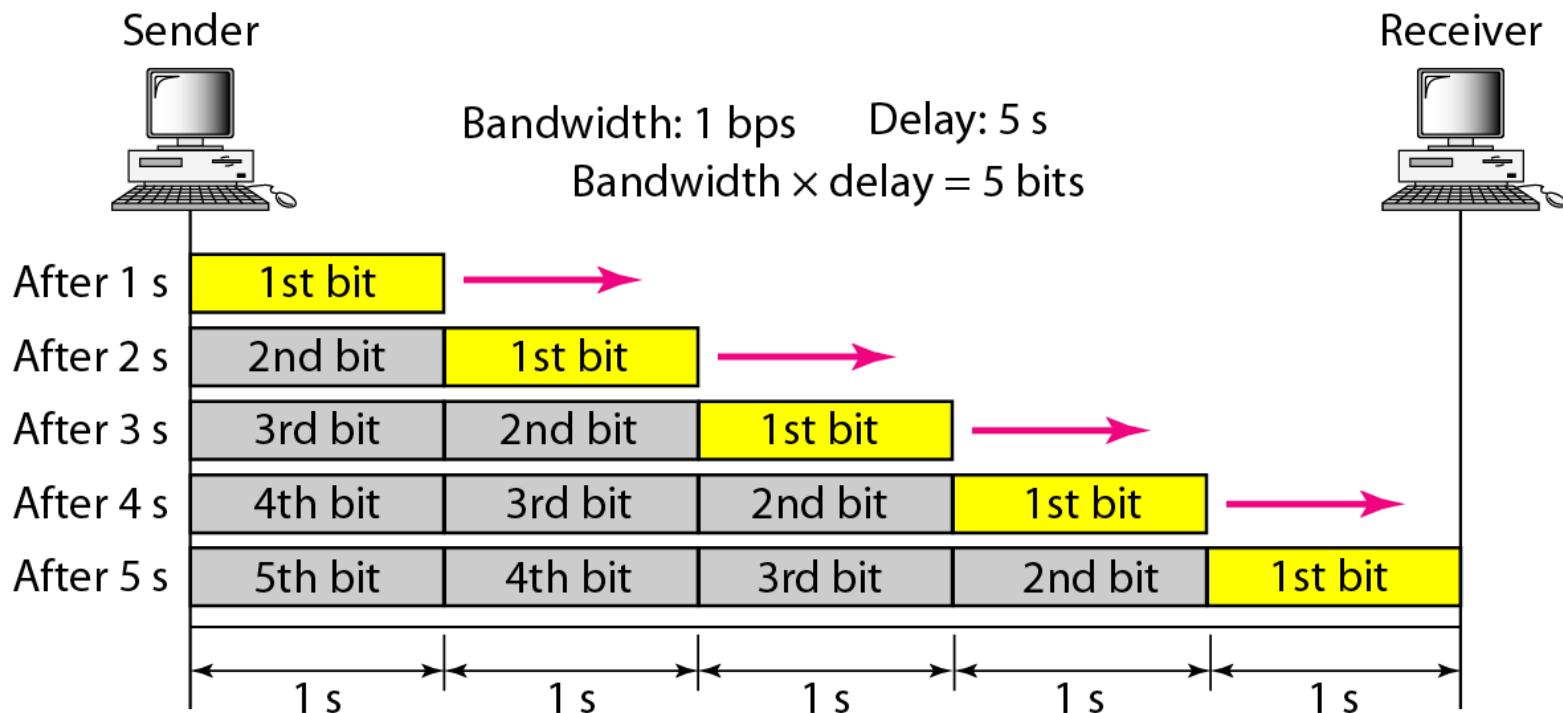
Example 3.47 (continued)

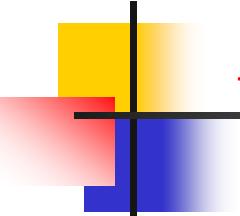
$$\text{Propagation time} = \frac{12,000 \times 1000}{2.4 \times 10^8} = 50 \text{ ms}$$

$$\text{Transmission time} = \frac{5,000,000 \times 8}{10^6} = 40 \text{ s}$$

Note that in this case, because the message is very long and the bandwidth is not very high, the dominant factor is the transmission time, not the propagation time. The propagation time can be ignored.

Figure 3.31 Filling the link with bits for case 1

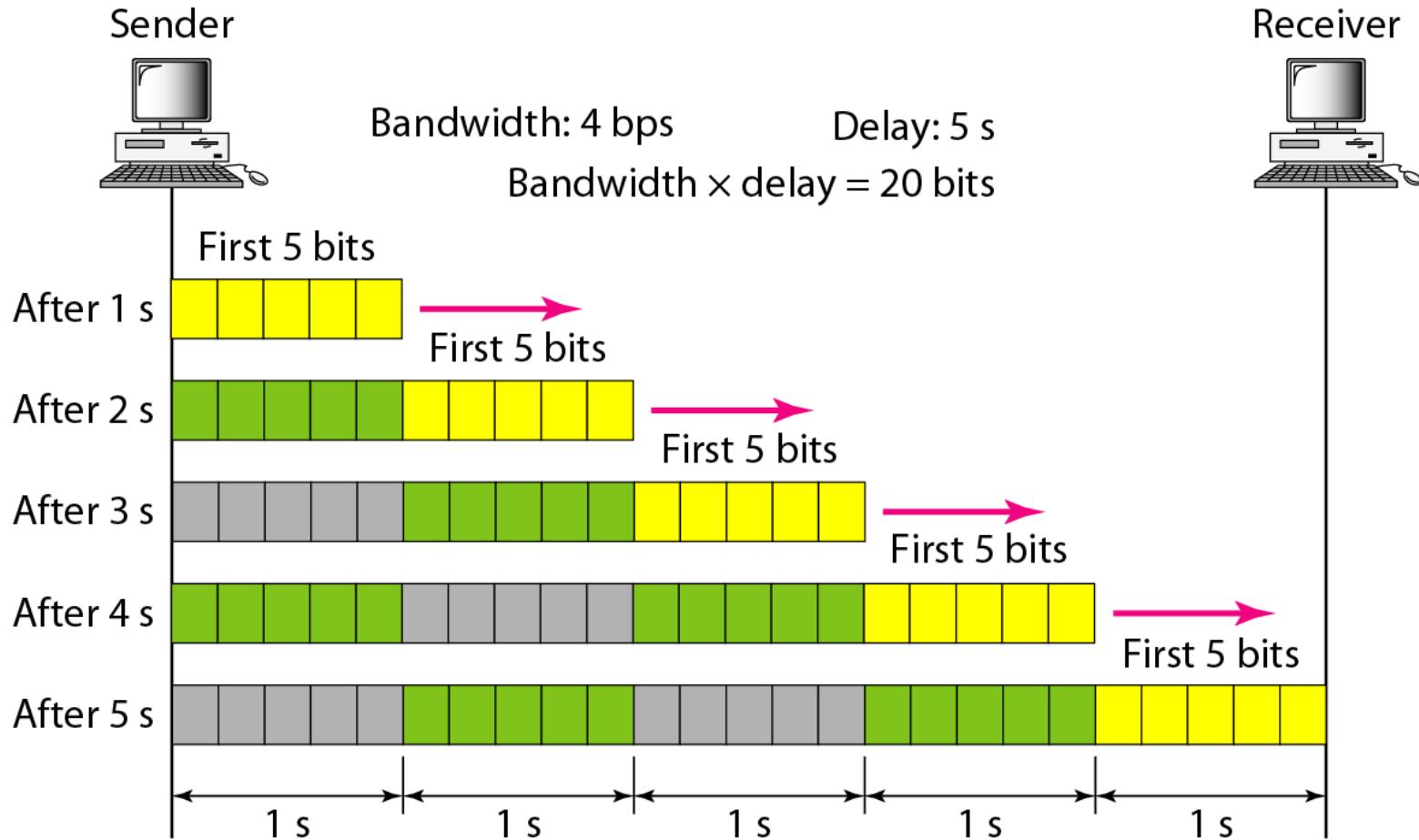


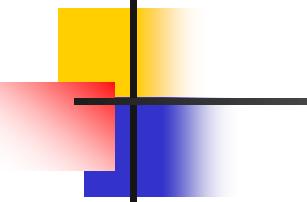


Example 3.48

We can think about the link between two points as a pipe. The cross section of the pipe represents the bandwidth, and the length of the pipe represents the delay. We can say the volume of the pipe defines the bandwidth-delay product, as shown in Figure 3.33.

Figure 3.32 Filling the link with bits in case 2

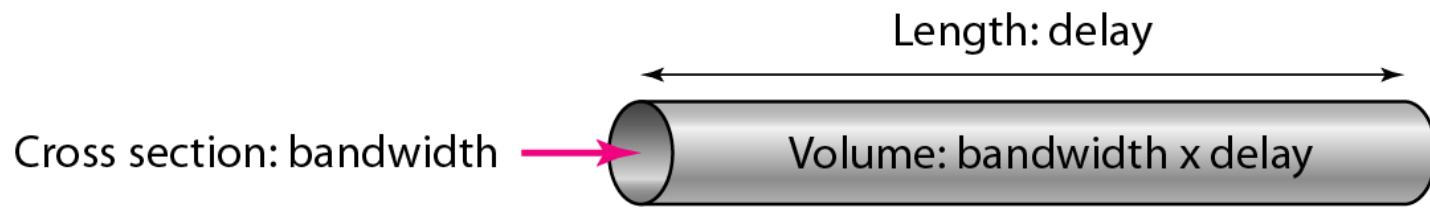




Note

The bandwidth-delay product defines the number of bits that can fill the link.

Figure 3.33 *Concept of bandwidth-delay product*





Data Communications and Networking

Fourth Edition

Forouzan

Chapter 4

Digital Transmission

4-1 DIGITAL-TO-DIGITAL CONVERSION

*In this section, we see how we can represent digital data by using digital signals. The conversion involves three techniques: **line coding**, **block coding**, and **scrambling**. Line coding is always needed; block coding and scrambling may or may not be needed.*

Topics discussed in this section:

Line Coding

Line Coding Schemes

Block Coding

Scrambling

Figure 4.1 *Line coding and decoding*

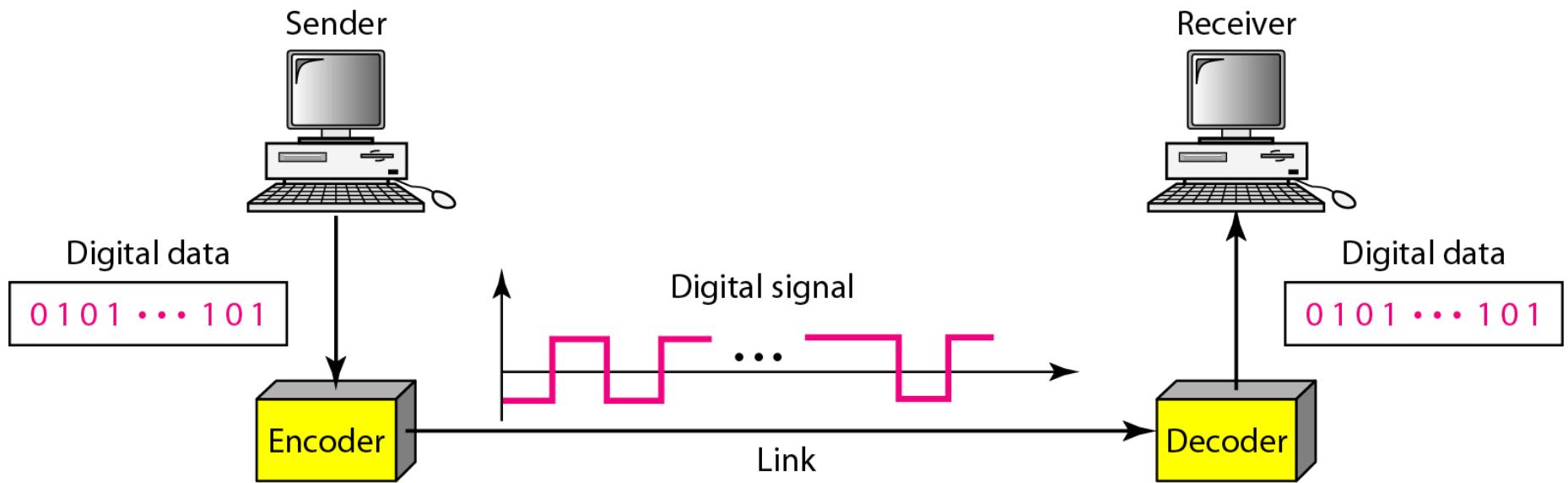
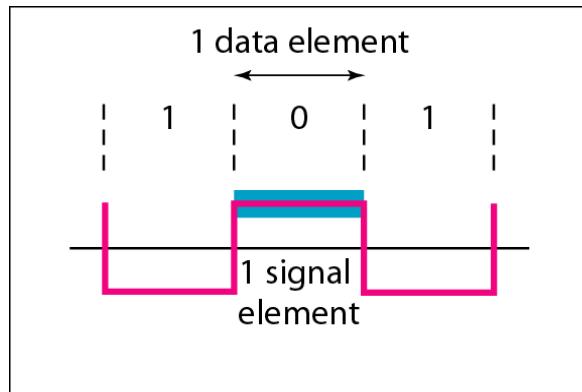
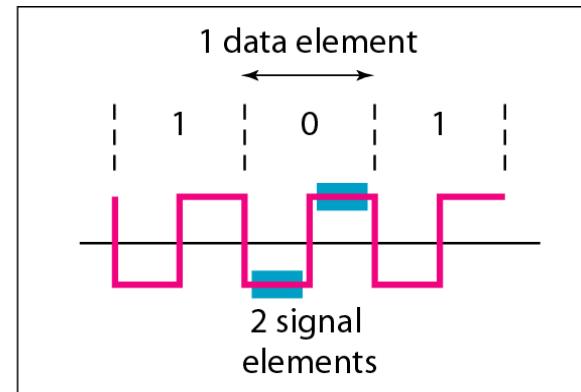


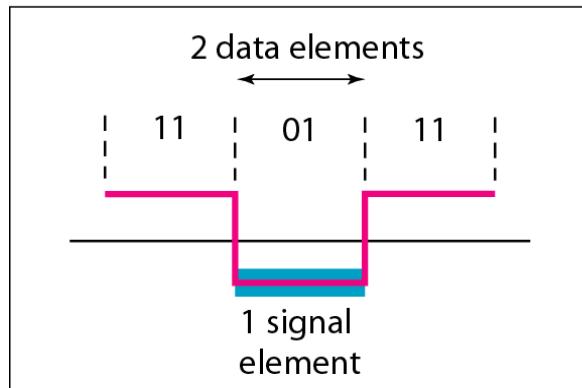
Figure 4.2 Signal element versus data element



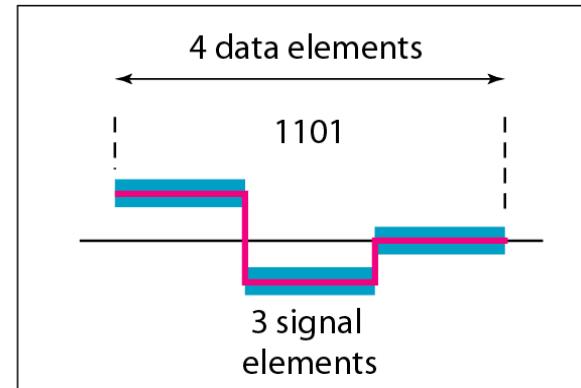
a. One data element per one signal element ($r = 1$)



b. One data element per two signal elements ($r = \frac{1}{2}$)



c. Two data elements per one signal element ($r = 2$)



d. Four data elements per three signal elements ($r = \frac{4}{3}$)

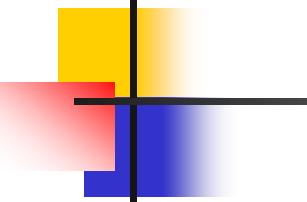
Example 4.1

A signal is carrying data in which one data element is encoded as one signal element ($r = 1$). If the bit rate is 100 kbps, what is the average value of the baud rate if c is between 0 and 1?

Solution

We assume that the average value of c is $1/2$. The baud rate is then

$$S = c \times N \times \frac{1}{r} = \frac{1}{2} \times 100,000 \times \frac{1}{1} = 50,000 = 50 \text{ kbaud}$$



Note

Although the actual bandwidth of a digital signal is infinite, the effective bandwidth is finite.

Example 4.2

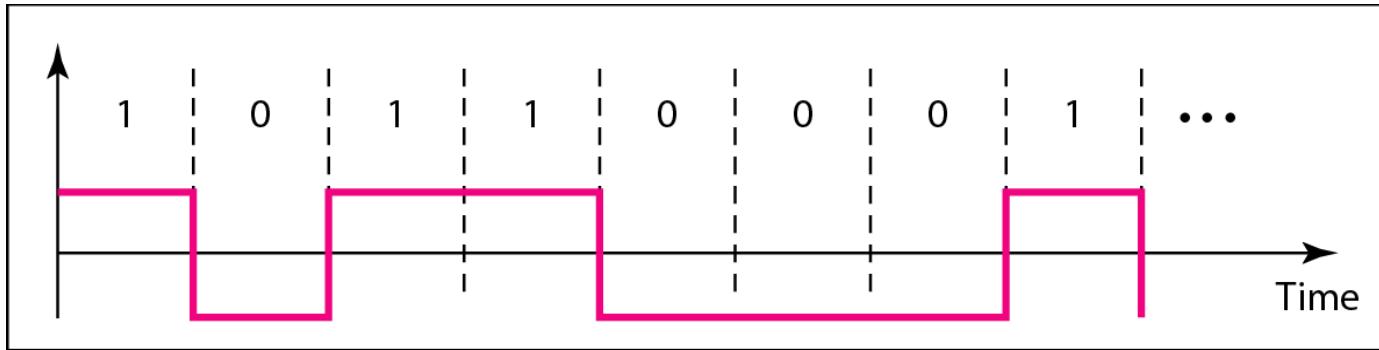
The maximum data rate of a channel (see Chapter 3) is $N_{max} = 2 \times B \times \log_2 L$ (defined by the Nyquist formula). Does this agree with the previous formula for N_{max} ?

Solution

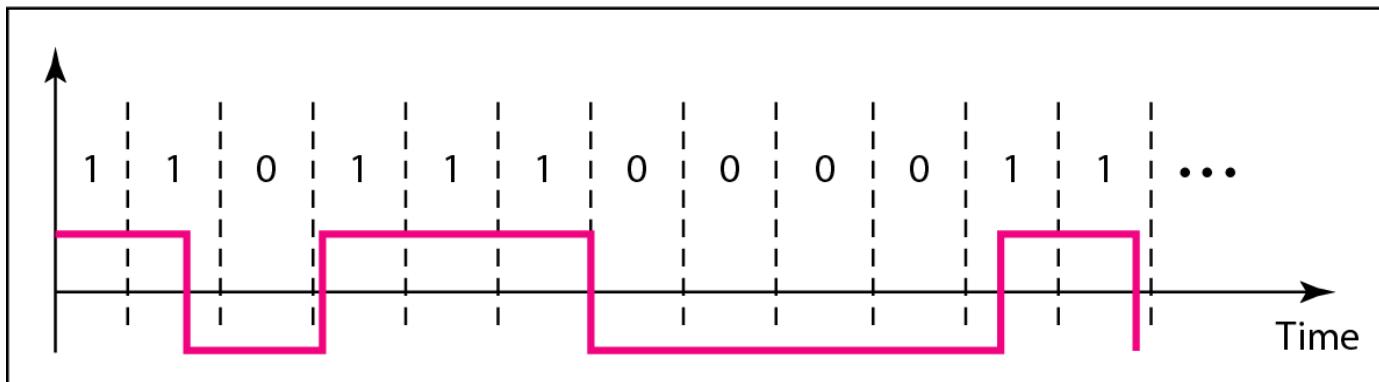
A signal with L levels actually can carry $\log_2 L$ bits per level. If each level corresponds to one signal element and we assume the average case ($c = 1/2$), then we have

$$N_{max} = \frac{1}{c} \times B \times r = 2 \times B \times \log_2 L$$

Figure 4.3 *Effect of lack of synchronization*



a. Sent



b. Received

Example 4.3

In a digital transmission, the receiver clock is 0.1 percent faster than the sender clock. How many extra bits per second does the receiver receive if the data rate is 1 kbps? How many if the data rate is 1 Mbps?

Solution

At 1 kbps, the receiver receives 1001 bps instead of 1000 bps.

1000 bits sent

1001 bits received

1 extra bps

At 1 Mbps, the receiver receives 1,001,000 bps instead of 1,000,000 bps.

1,000,000 bits sent

1,001,000 bits received

1000 extra bps

Figure 4.4 *Line coding schemes*

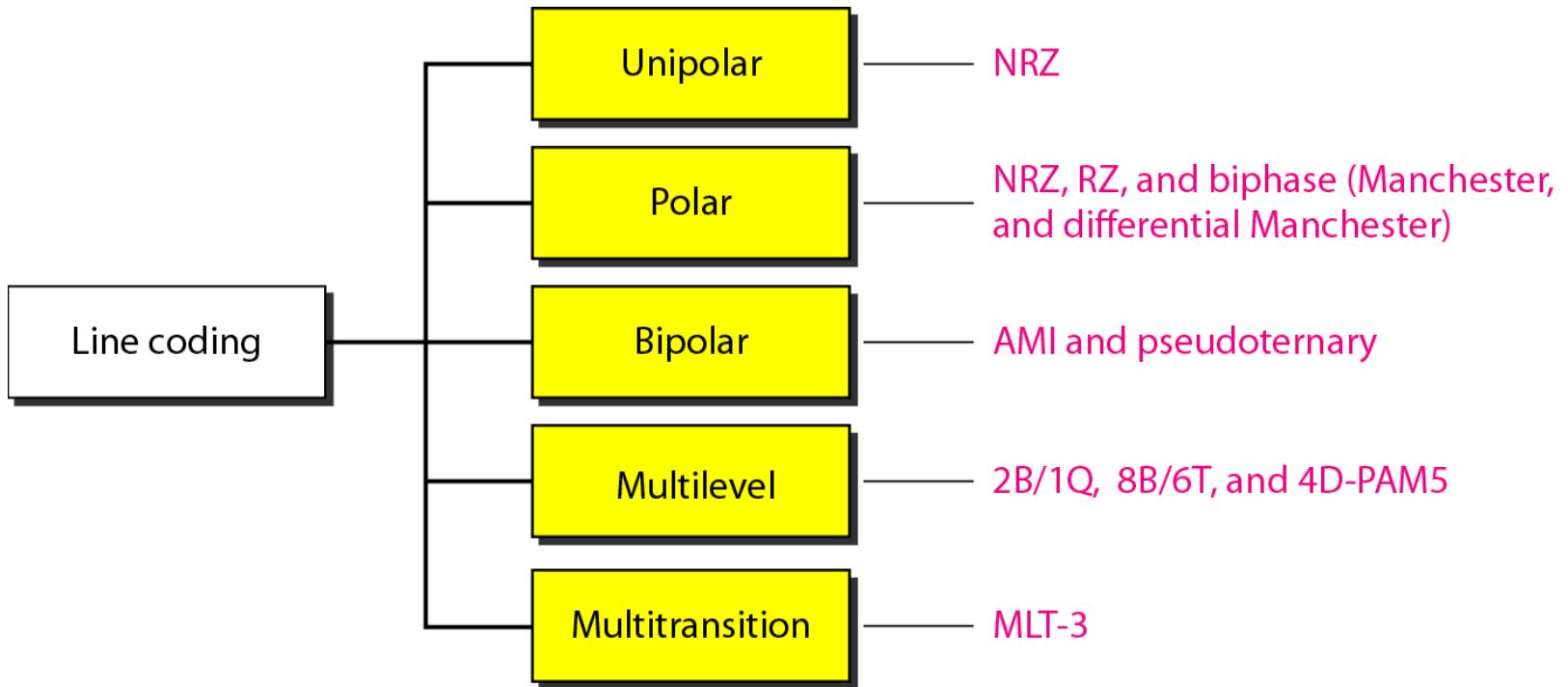
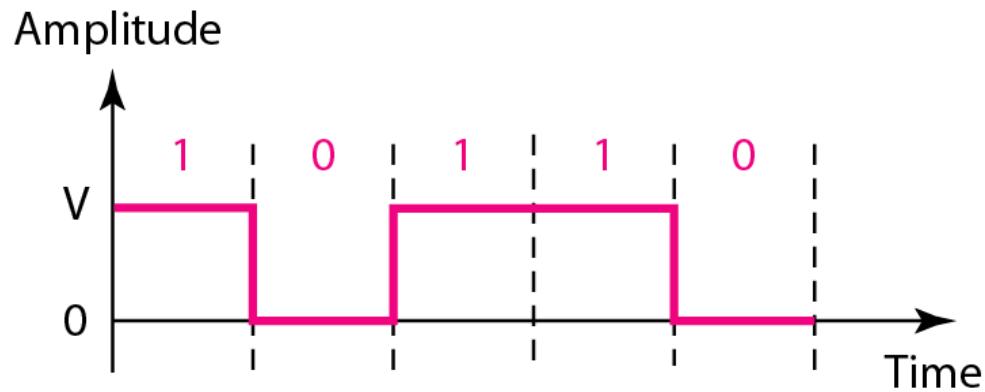


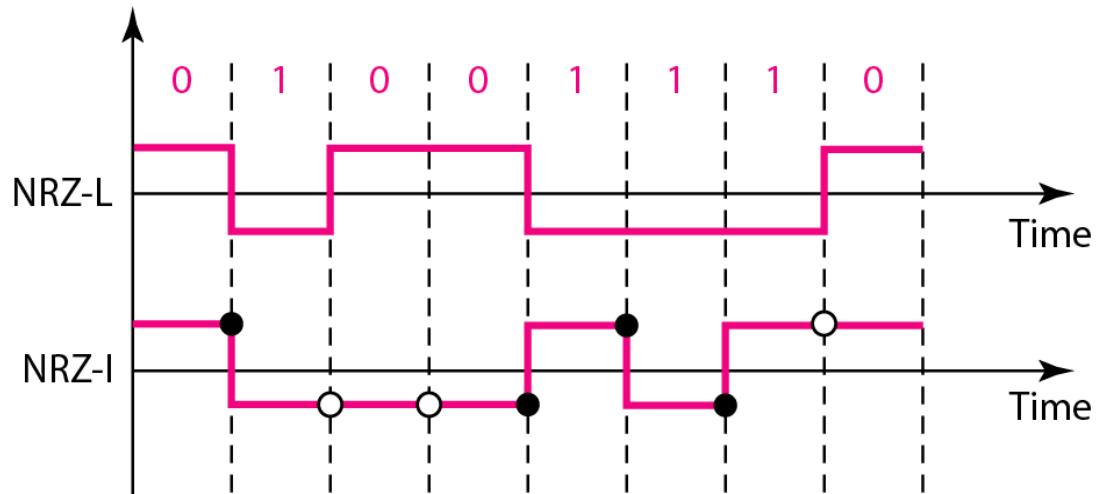
Figure 4.5 Unipolar NRZ scheme



$$\frac{1}{2}V^2 + \frac{1}{2}(0)^2 = \frac{1}{2}V^2$$

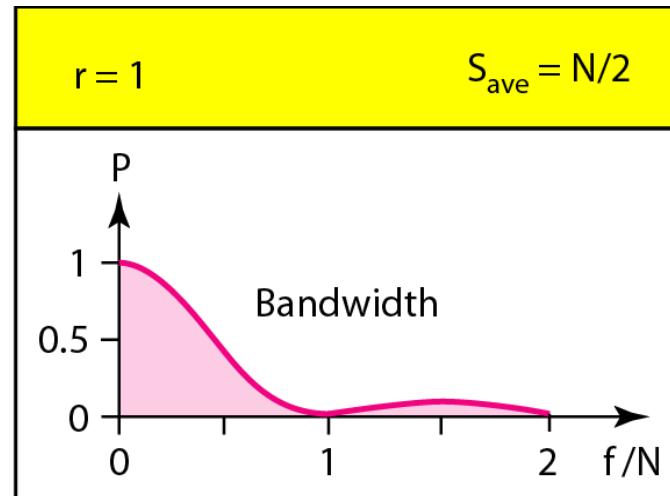
Normalized power

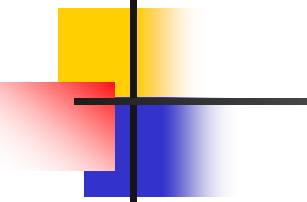
Figure 4.6 Polar NRZ-L and NRZ-I schemes



○ No inversion: Next bit is 0

● Inversion: Next bit is 1

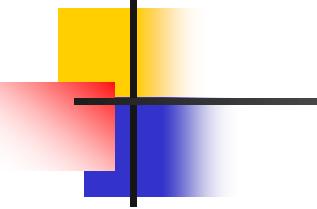




Note

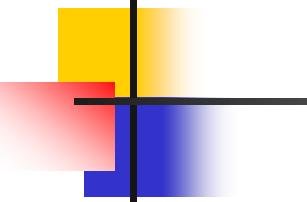
In NRZ-L the level of the voltage determines the value of the bit.

In NRZ-I the inversion or the lack of inversion determines the value of the bit.



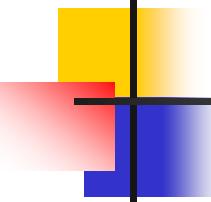
Note

NRZ-L and NRZ-I both have an average signal rate of $N/2$ Bd.



Note

NRZ-L and NRZ-I both have a DC component problem.



Example 4.4

A system is using NRZ-I to transfer 10-Mbps data. What are the average signal rate and minimum bandwidth?

Solution

The average signal rate is $S = N/2 = 500$ kbaud. The minimum bandwidth for this average baud rate is $B_{min} = S = 500$ kHz.

Figure 4.7 *Polar RZ scheme*

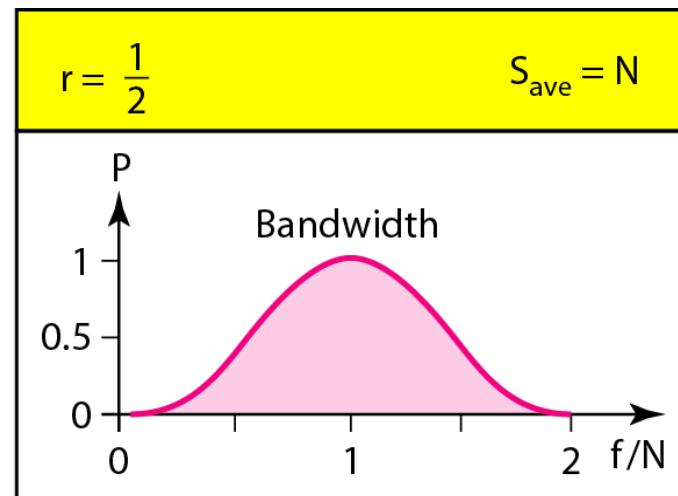
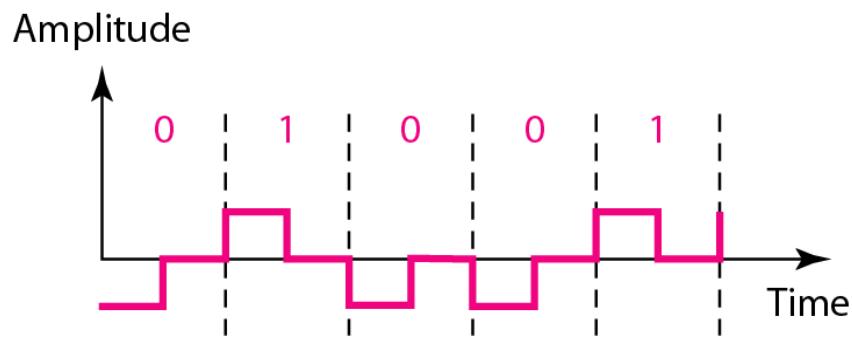
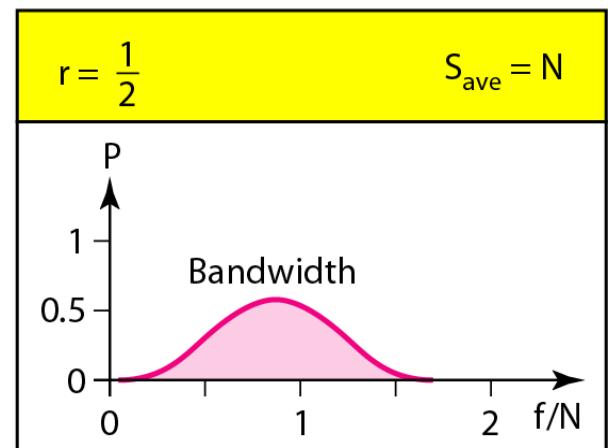
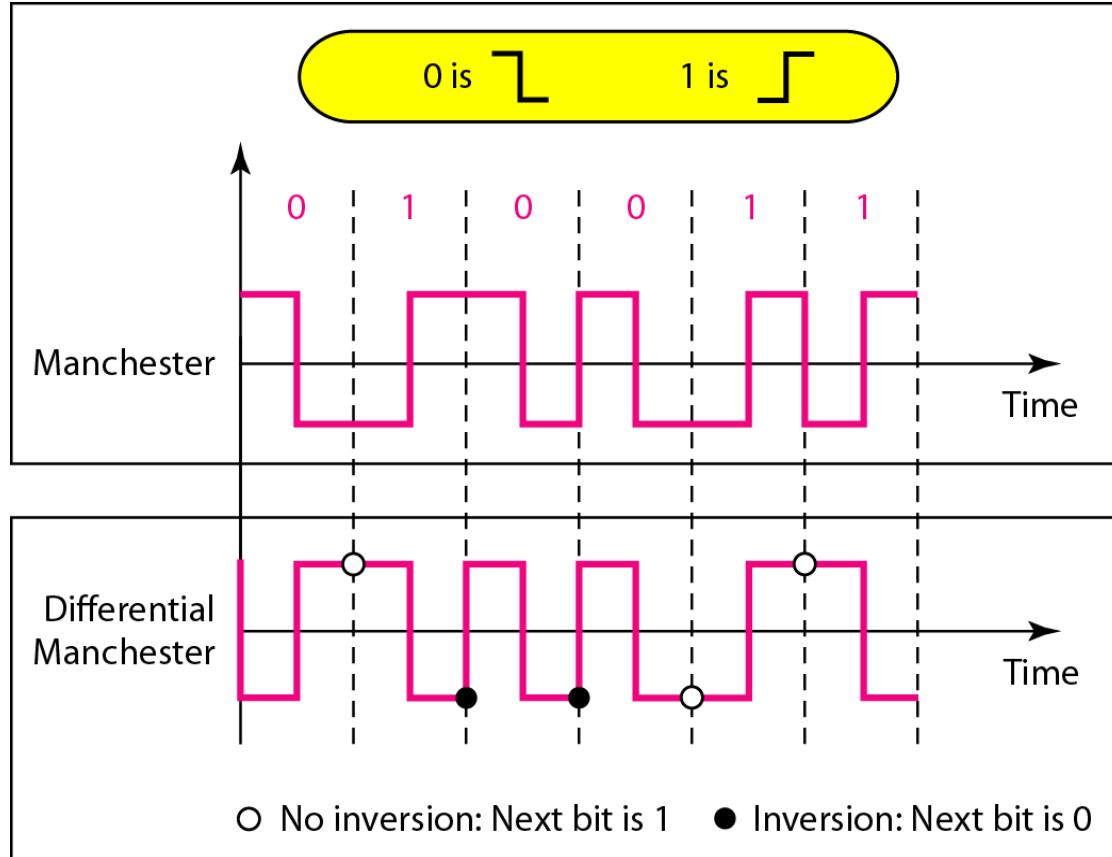
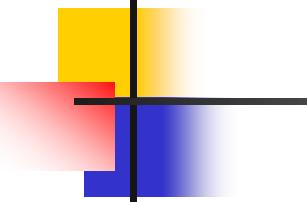


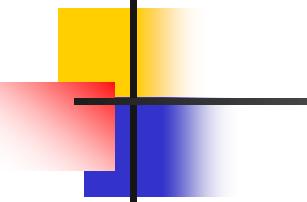
Figure 4.8 Polar biphasic: Manchester and differential Manchester schemes





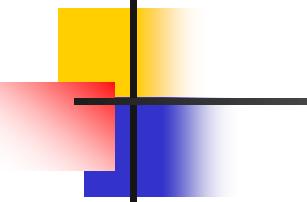
Note

In Manchester and differential Manchester encoding, the transition at the middle of the bit is used for synchronization.



Note

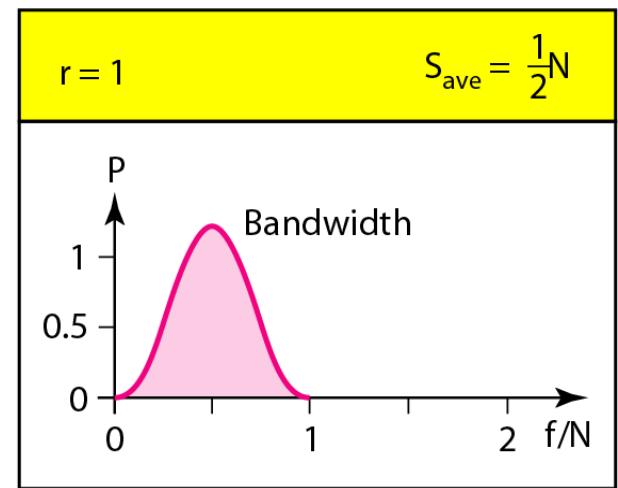
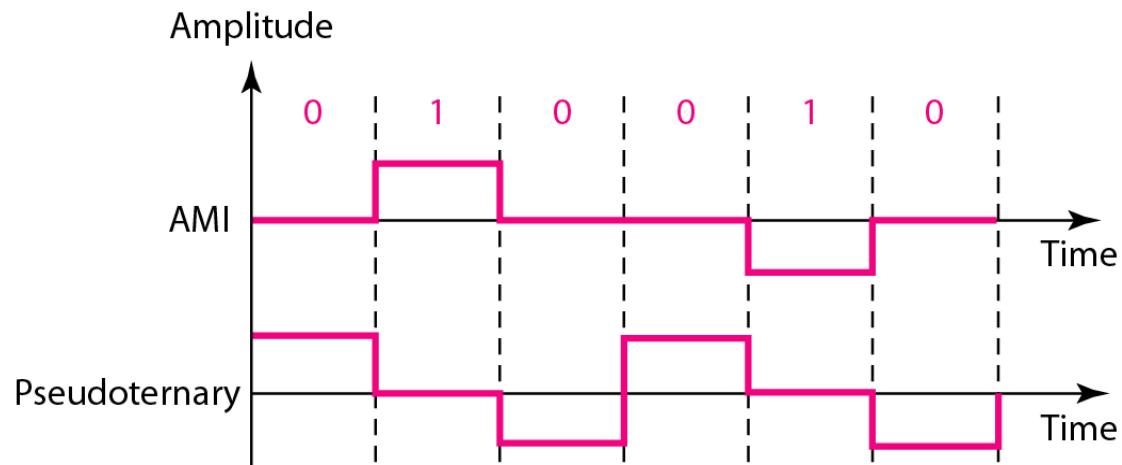
The minimum bandwidth of Manchester and differential Manchester is 2 times that of NRZ.

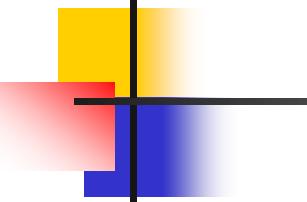


Note

**In bipolar encoding, we use three levels:
positive, zero, and negative.**

Figure 4.9 Bipolar schemes: AMI and pseudoternary





Note

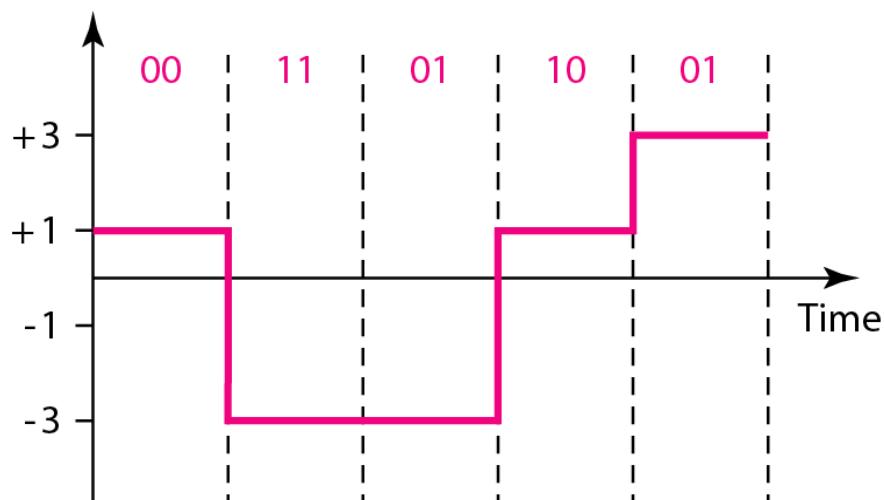
In $mBnL$ schemes, a pattern of m data elements is encoded as a pattern of n signal elements in which $2^m \leq L^n$.

Figure 4.10 Multilevel: 2B1Q scheme

Previous level:
positive Previous level:
negative

Next bits	Next level	Next level
00	+1	-1
01	+3	-3
10	-1	+1
11	-3	+3

Transition table



Assuming positive original level

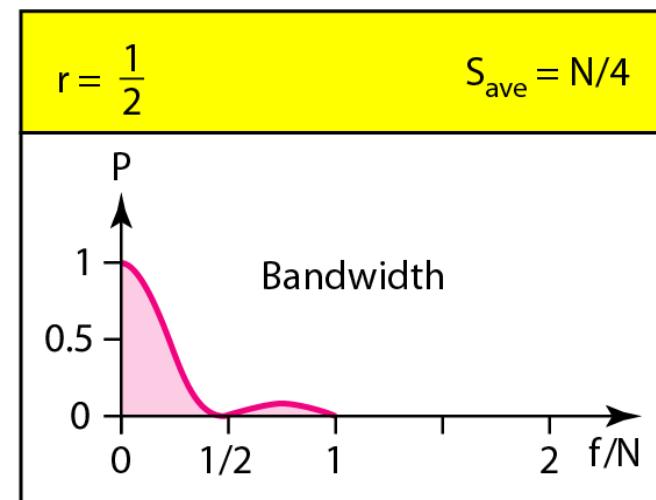


Figure 4.11 Multilevel: 8B6T scheme

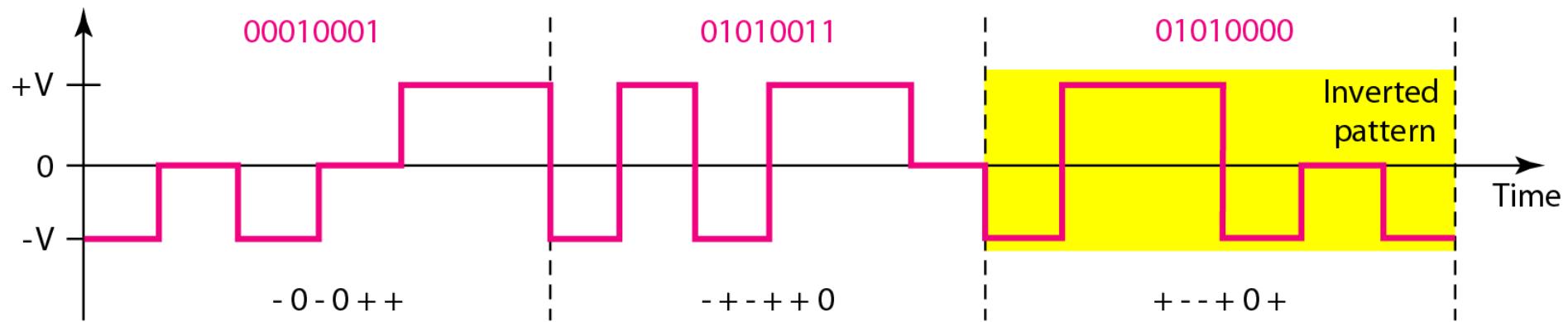


Figure 4.12 Multilevel: 4D-PAM5 scheme

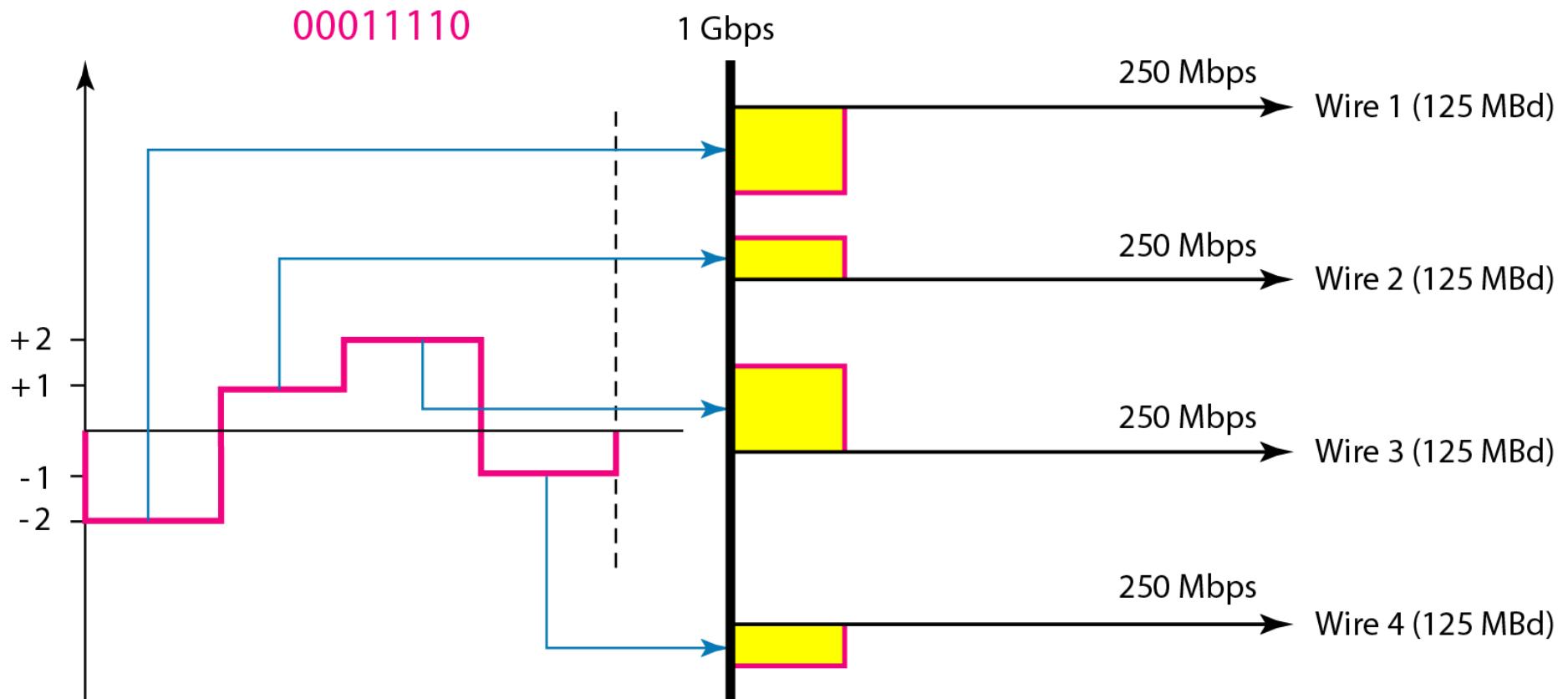
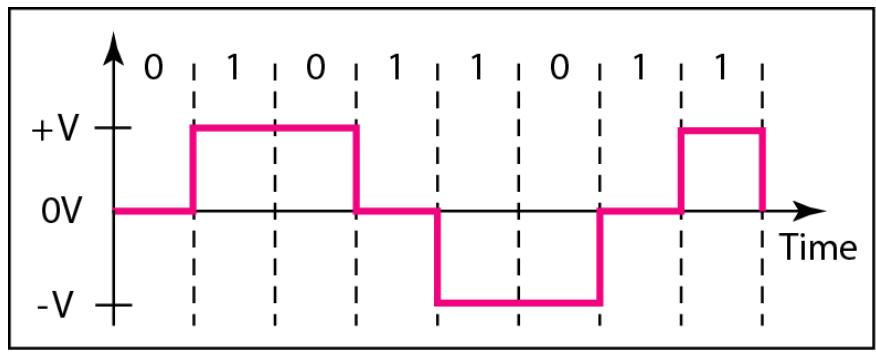
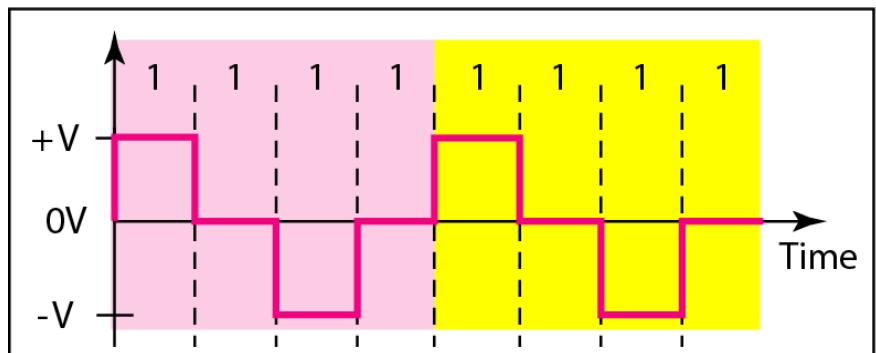


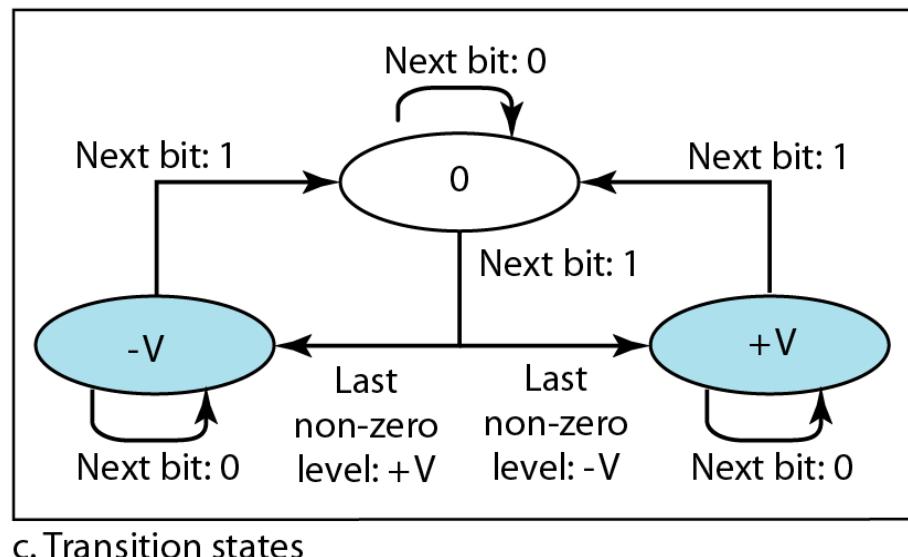
Figure 4.13 Multitransition: MLT-3 scheme



a. Typical case



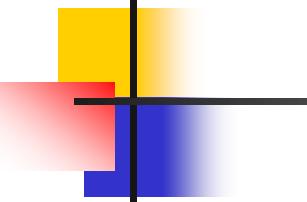
b. Worse case



c. Transition states

Table 4.1 *Summary of line coding schemes*

Category	Scheme	Bandwidth (average)	Characteristics
Unipolar	NRZ	$B = N/2$	Costly, no self-synchronization if long 0s or 1s, DC
Unipolar	NRZ-L	$B = N/2$	No self-synchronization if long 0s or 1s, DC
	NRZ-I	$B = N/2$	No self-synchronization for long 0s, DC
	Biphase	$B = N$	Self-synchronization, no DC, high bandwidth
Bipolar	AMI	$B = N/2$	No self-synchronization for long 0s, DC
Multilevel	2B1Q	$B = N/4$	No self-synchronization for long same double bits
	8B6T	$B = 3N/4$	Self-synchronization, no DC
	4D-PAM5	$B = N/8$	Self-synchronization, no DC
Multiline	MLT-3	$B = N/3$	No self-synchronization for long 0s



Note

**Block coding is normally referred to as
 mB/nB coding;
it replaces each m -bit group with an
 n -bit group.**

Figure 4.14 *Block coding concept*

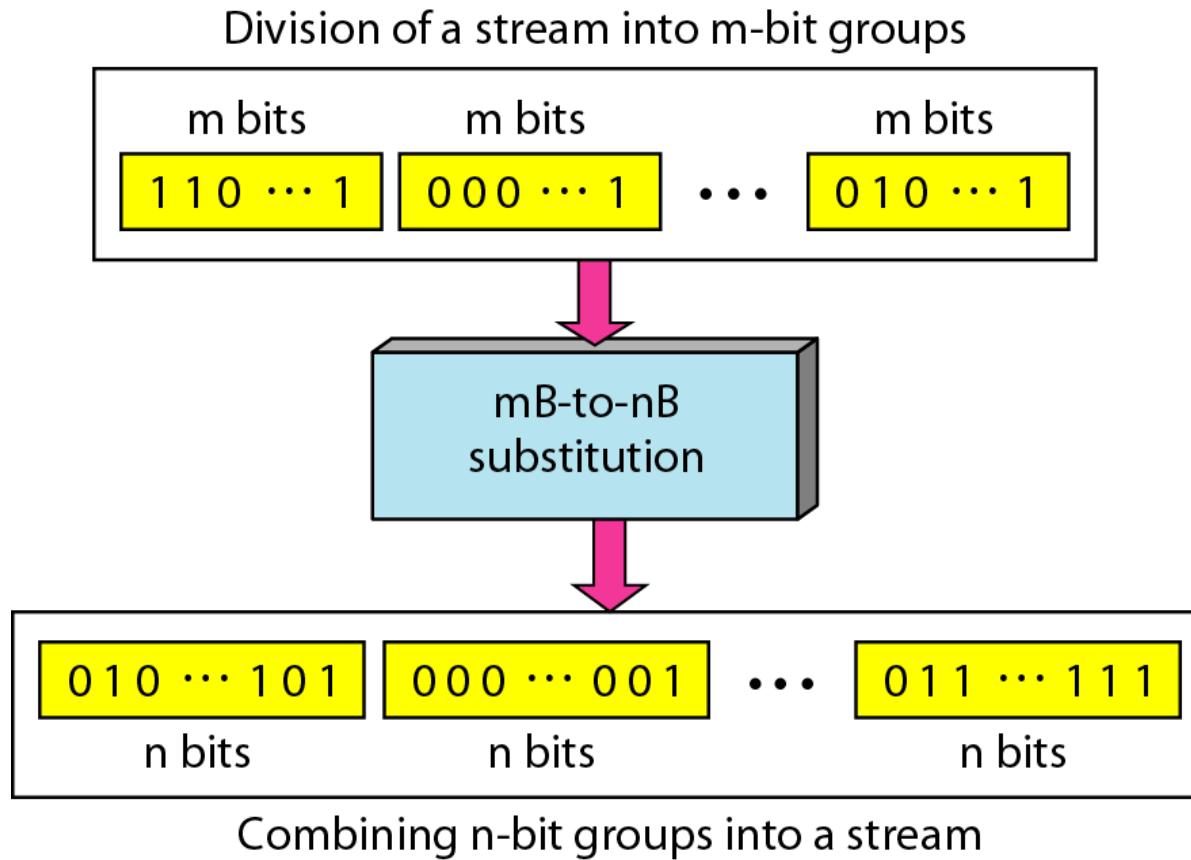


Figure 4.15 *Using block coding 4B/5B with NRZ-I line coding scheme*

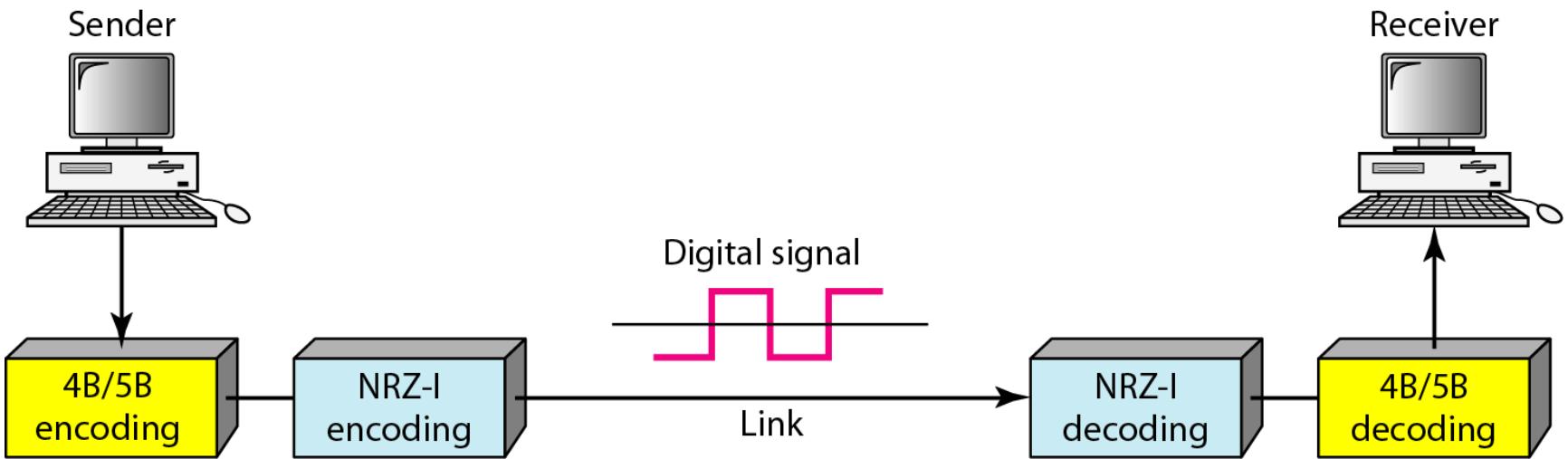
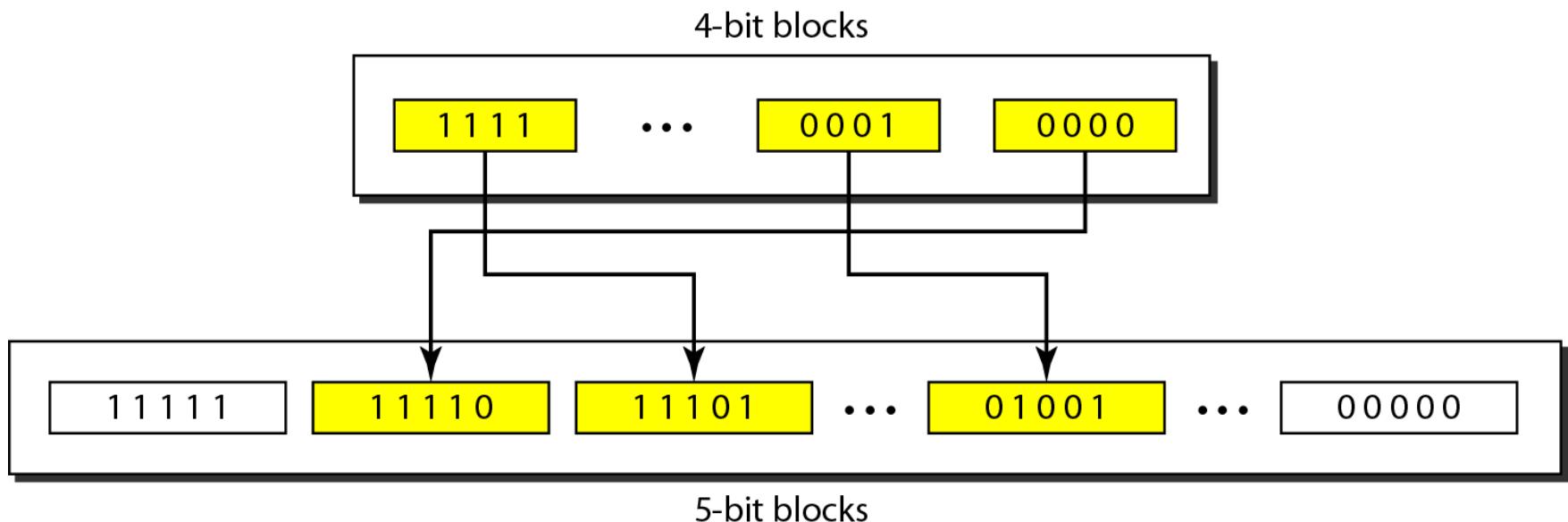


Table 4.2 4B/5B mapping codes

<i>Data Sequence</i>	<i>Encoded Sequence</i>	<i>Control Sequence</i>	<i>Encoded Sequence</i>
0000	11110	Q (Quiet)	00000
0001	01001	I (Idle)	11111
0010	10100	H (Halt)	00100
0011	10101	J (Start delimiter)	11000
0100	01010	K (Start delimiter)	10001
0101	01011	T (End delimiter)	01101
0110	01110	S (Set)	11001
0111	01111	R (Reset)	00111
1000	10010		
1001	10011		
1010	10110		
1011	10111		
1100	11010		
1101	11011		
1110	11100		
1111	11101		

Figure 4.16 Substitution in 4B/5B block coding



Example 4.5

We need to send data at a 1-Mbps rate. What is the minimum required bandwidth, using a combination of 4B/5B and NRZ-I or Manchester coding?

Solution

First 4B/5B block coding increases the bit rate to 1.25 Mbps. The minimum bandwidth using NRZ-I is $N/2$ or 625 kHz. The Manchester scheme needs a minimum bandwidth of 1 MHz. The first choice needs a lower bandwidth, but has a DC component problem; the second choice needs a higher bandwidth, but does not have a DC component problem.

Figure 4.17 *8B/10B block encoding*

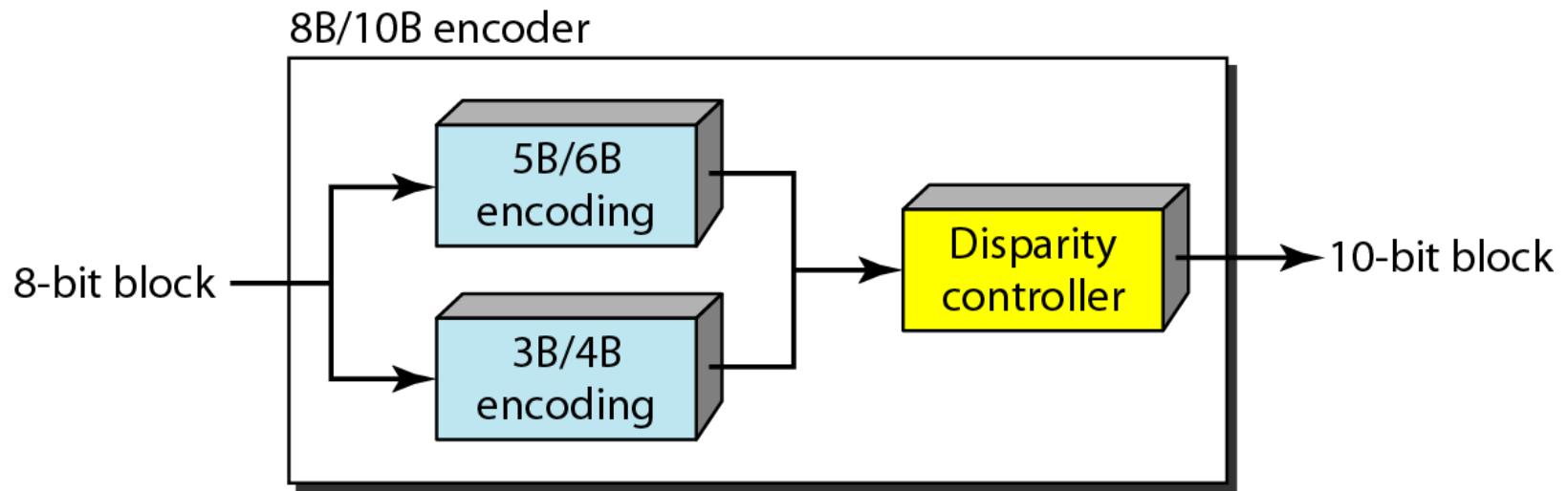


Figure 4.18 *AMI used with scrambling*

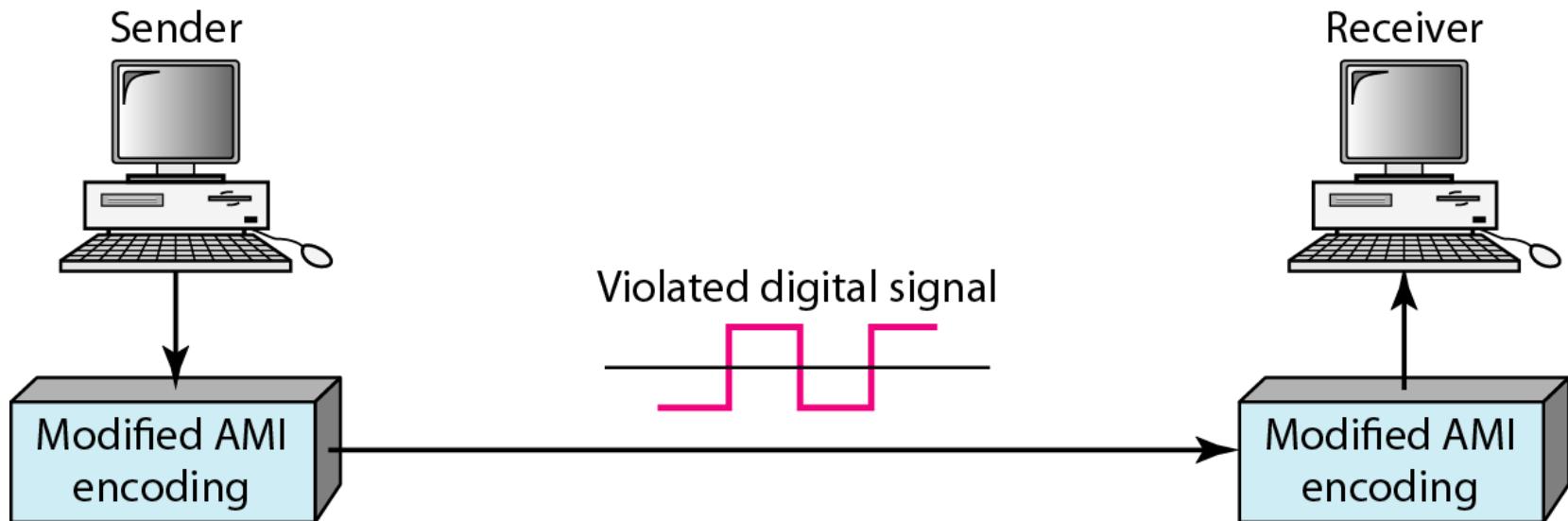
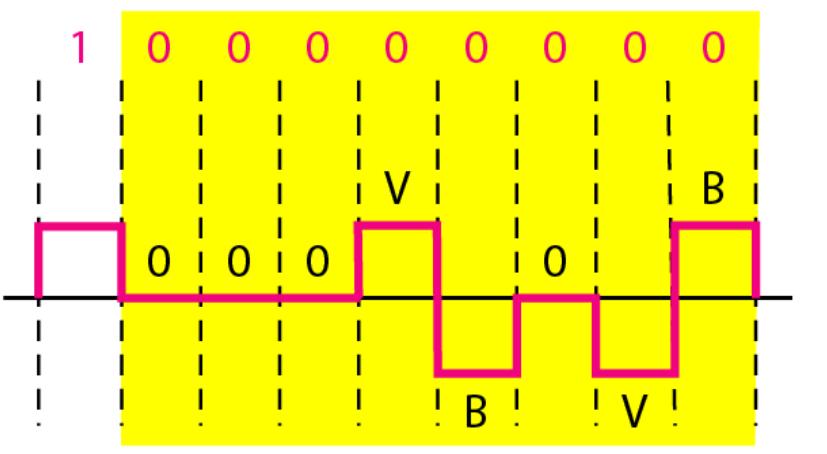
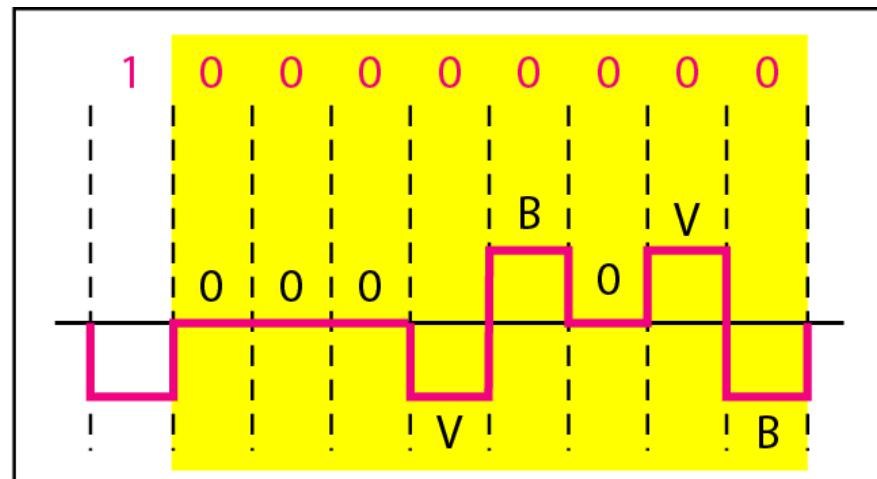


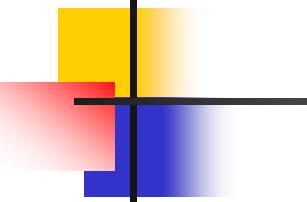
Figure 4.19 Two cases of B8ZS scrambling technique



a. Previous level is positive.



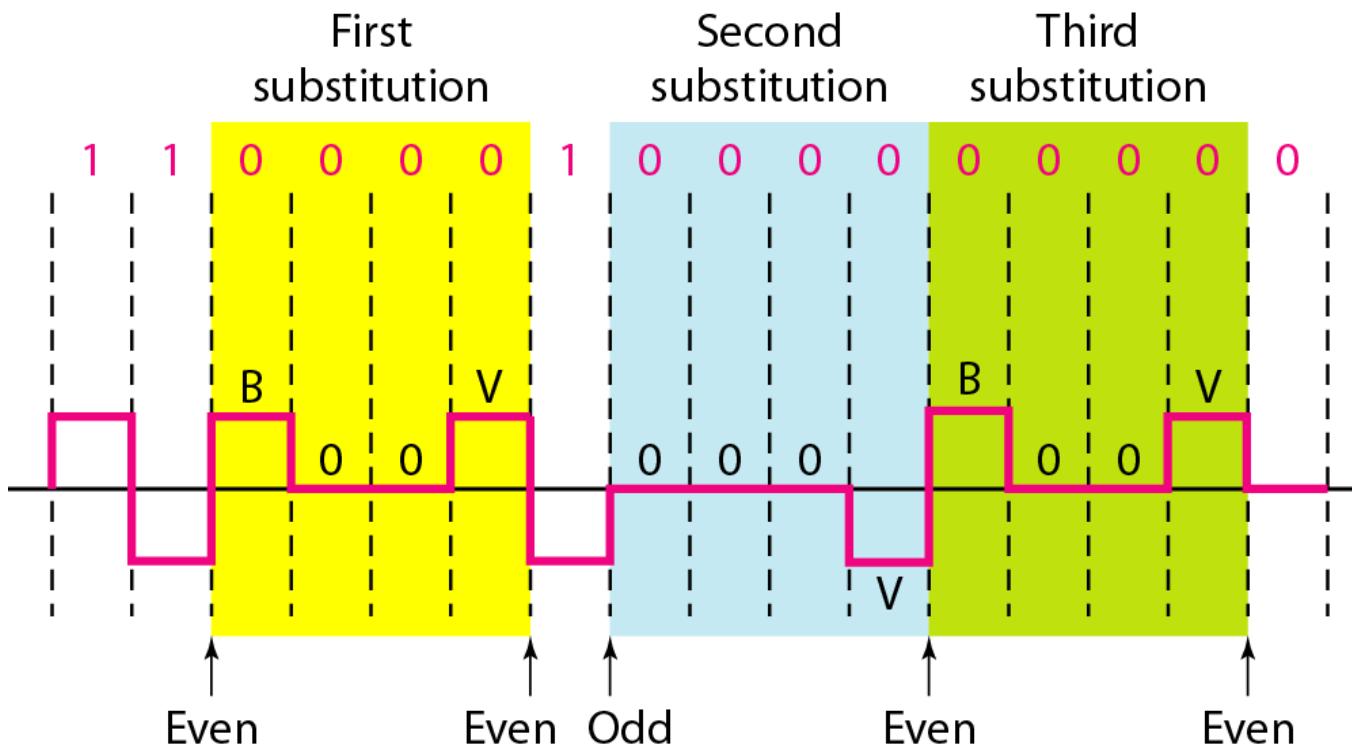
b. Previous level is negative.

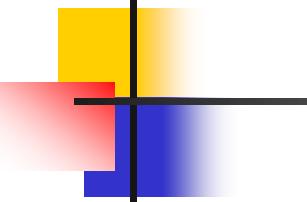


Note

B8ZS substitutes eight consecutive zeros with 000VB0VB.

Figure 4.20 *Different situations in HDB3 scrambling technique*





Note

HDB3 substitutes four consecutive zeros with 000V or B00V depending on the number of nonzero pulses after the last substitution.

4-2 ANALOG-TO-DIGITAL CONVERSION

We have seen in Chapter 3 that a digital signal is superior to an analog signal. The tendency today is to change an analog signal to digital data. In this section we describe two techniques, **pulse code modulation** and **delta modulation**.

Topics discussed in this section:

Pulse Code Modulation (PCM)

Delta Modulation (DM)

Figure 4.21 Components of PCM encoder

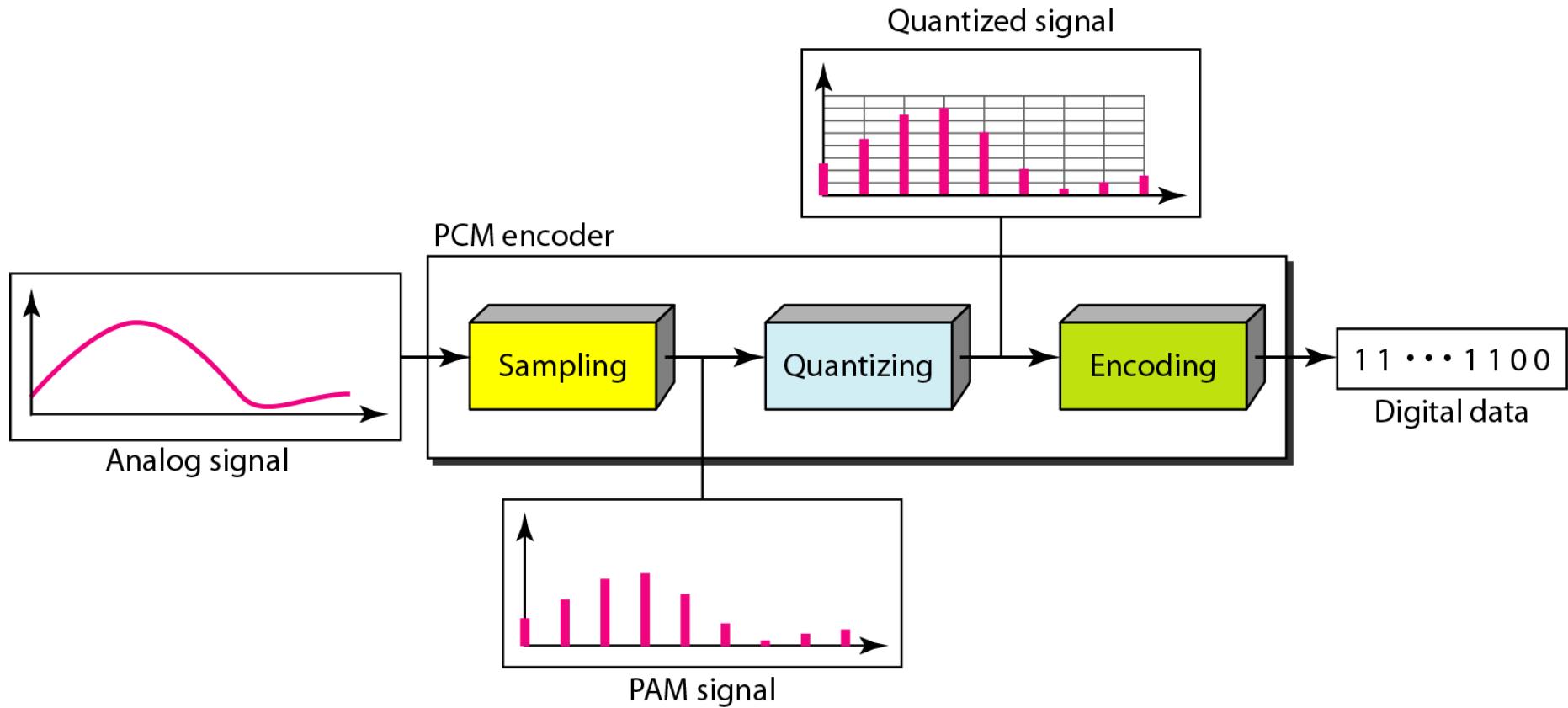
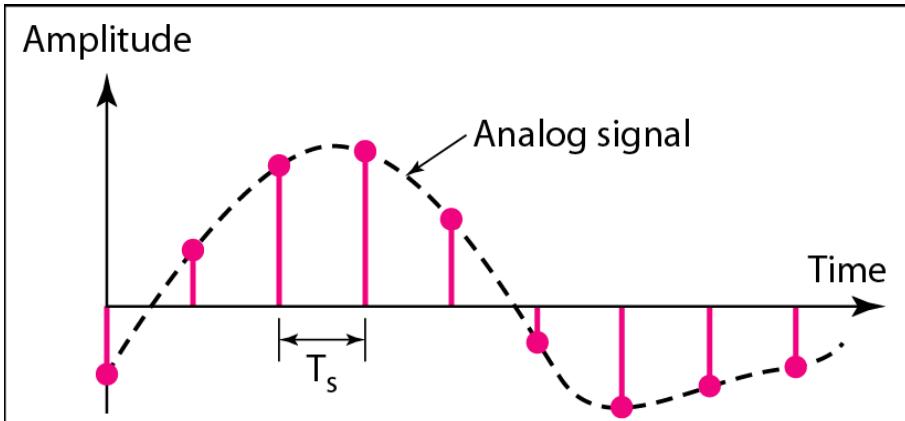
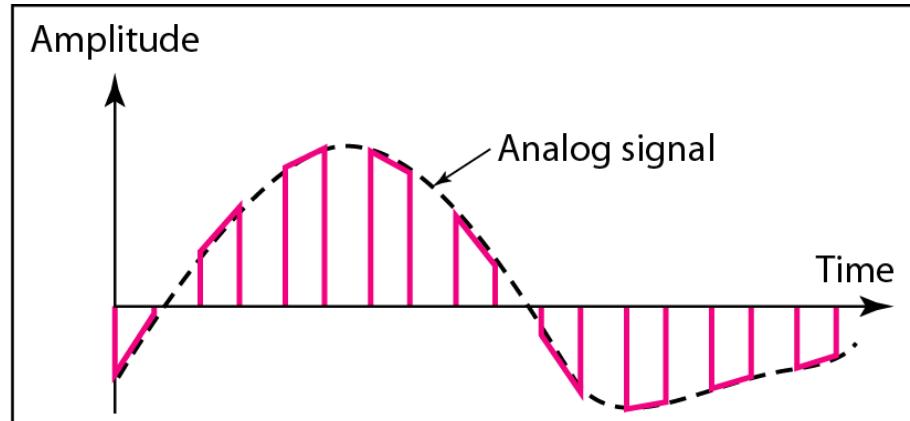


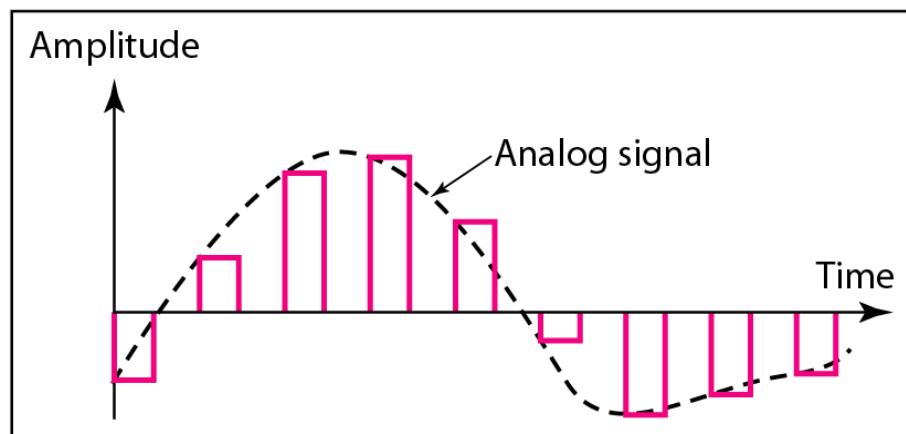
Figure 4.22 Three different sampling methods for PCM



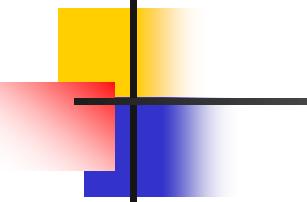
a. Ideal sampling



b. Natural sampling



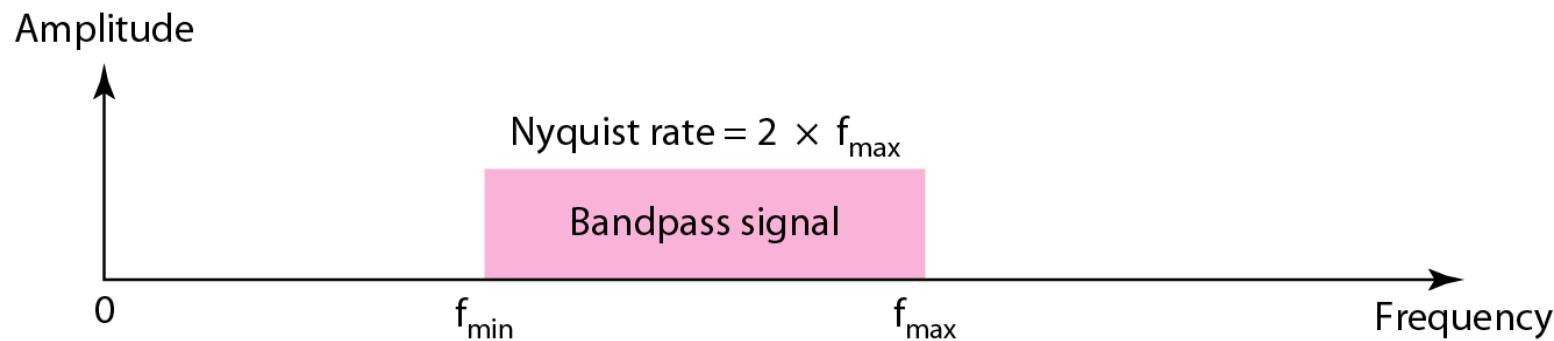
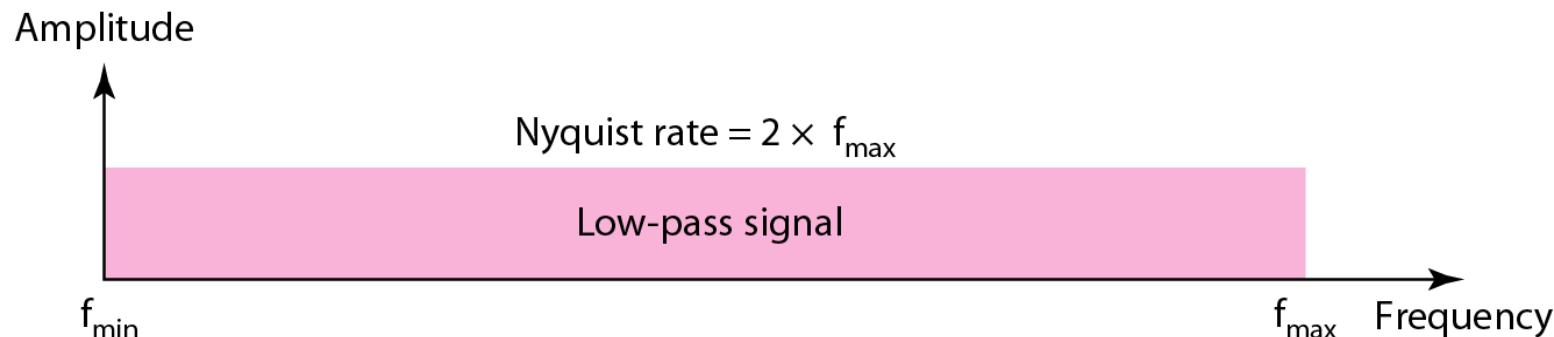
c. Flat-top sampling



Note

According to the Nyquist theorem, the sampling rate must be at least 2 times the highest frequency contained in the signal.

Figure 4.23 Nyquist sampling rate for low-pass and bandpass signals

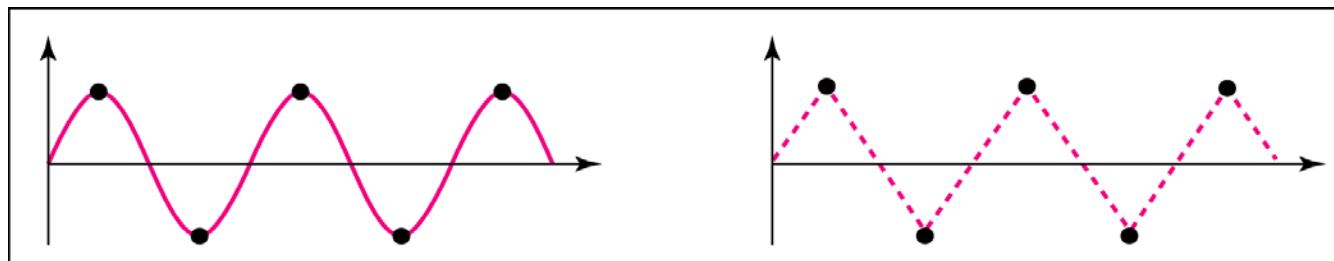


Example 4.6

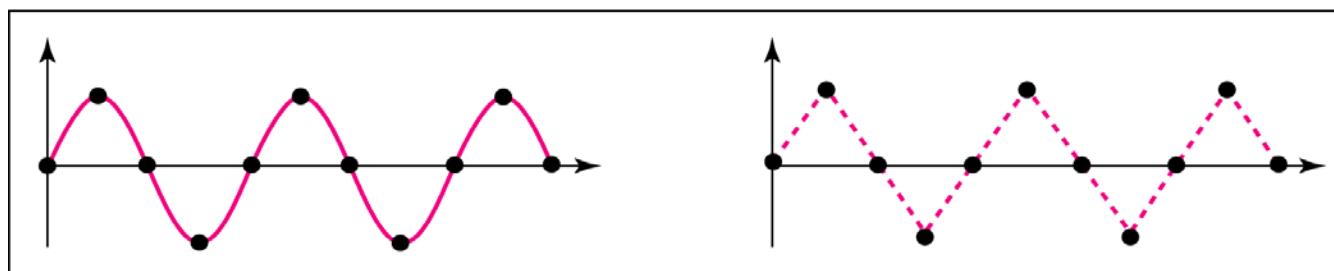
For an intuitive example of the Nyquist theorem, let us sample a simple sine wave at three sampling rates: $f_s = 4f$ (2 times the Nyquist rate), $f_s = 2f$ (Nyquist rate), and $f_s = f$ (one-half the Nyquist rate). Figure 4.24 shows the sampling and the subsequent recovery of the signal.

It can be seen that sampling at the Nyquist rate can create a good approximation of the original sine wave (part a). Oversampling in part b can also create the same approximation, but it is redundant and unnecessary. Sampling below the Nyquist rate (part c) does not produce a signal that looks like the original sine wave.

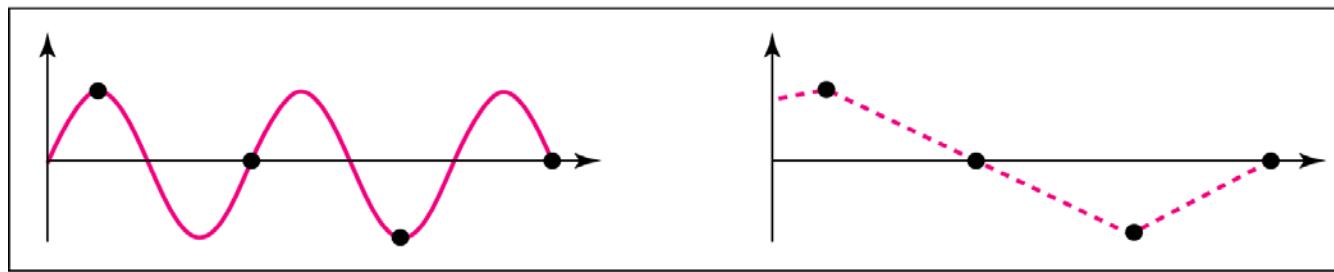
Figure 4.24 Recovery of a sampled sine wave for different sampling rates



a. Nyquist rate sampling: $f_s = 2 f$



b. Oversampling: $f_s = 4 f$

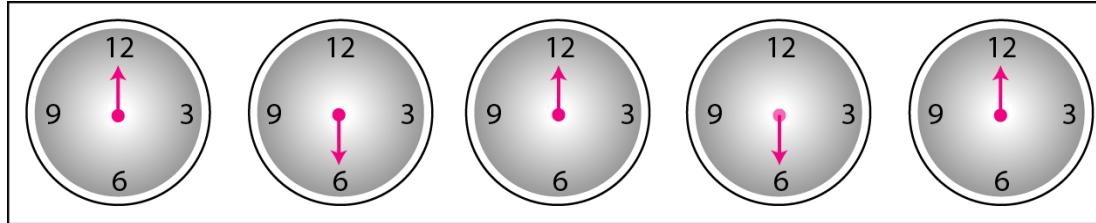
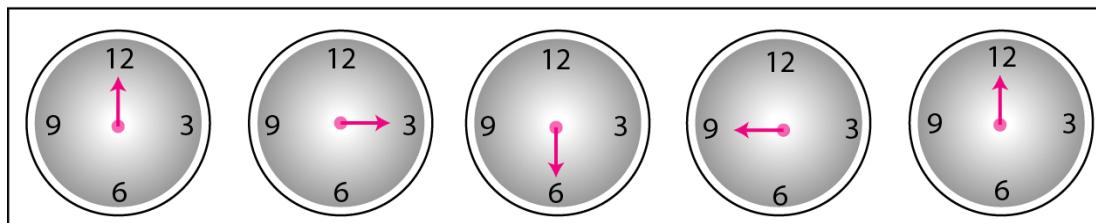
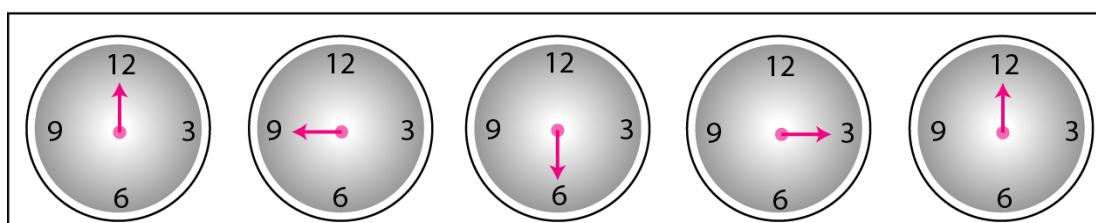


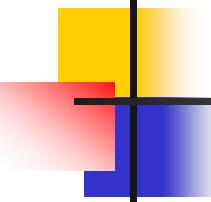
c. Undersampling: $f_s = f$

Example 4.7

Consider the revolution of a hand of a clock. The second hand of a clock has a period of 60 s. According to the Nyquist theorem, we need to sample the hand every 30 s ($T_s = T$ or $f_s = 2f$). In Figure 4.25a, the sample points, in order, are 12, 6, 12, 6, 12, and 6. The receiver of the samples cannot tell if the clock is moving forward or backward. In part b, we sample at double the Nyquist rate (every 15 s). The sample points are 12, 3, 6, 9, and 12. The clock is moving forward. In part c, we sample below the Nyquist rate ($T_s = T$ or $f_s = f$). The sample points are 12, 9, 6, 3, and 12. Although the clock is moving forward, the receiver thinks that the clock is moving backward.

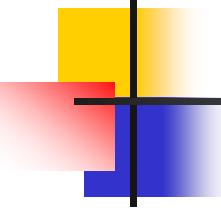
Figure 4.25 Sampling of a clock with only one hand

- a. Sampling at Nyquist rate: $T_s = T \frac{1}{2}$
- 
- Samples can mean that the clock is moving either forward or backward.
(12-6-12-6-12)
- b. Oversampling (above Nyquist rate): $T_s = T \frac{1}{4}$
- 
- Samples show clock is moving forward.
(12-3-6-9-12)
- c. Undersampling (below Nyquist rate): $T_s = T \frac{3}{4}$
- 
- Samples show clock is moving backward.
(12-9-6-3-12)



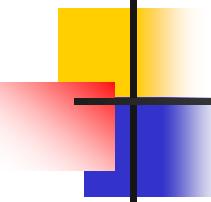
Example 4.8

An example related to Example 4.7 is the seemingly backward rotation of the wheels of a forward-moving car in a movie. This can be explained by under-sampling. A movie is filmed at 24 frames per second. If a wheel is rotating more than 12 times per second, the under-sampling creates the impression of a backward rotation.



Example 4.9

Telephone companies digitize voice by assuming a maximum frequency of 4000 Hz. The sampling rate therefore is 8000 samples per second.

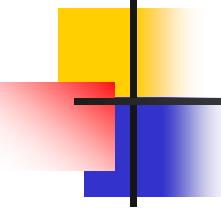


Example 4.10

A complex low-pass signal has a bandwidth of 200 kHz. What is the minimum sampling rate for this signal?

Solution

The bandwidth of a low-pass signal is between 0 and f , where f is the maximum frequency in the signal. Therefore, we can sample this signal at 2 times the highest frequency (200 kHz). The sampling rate is therefore 400,000 samples per second.



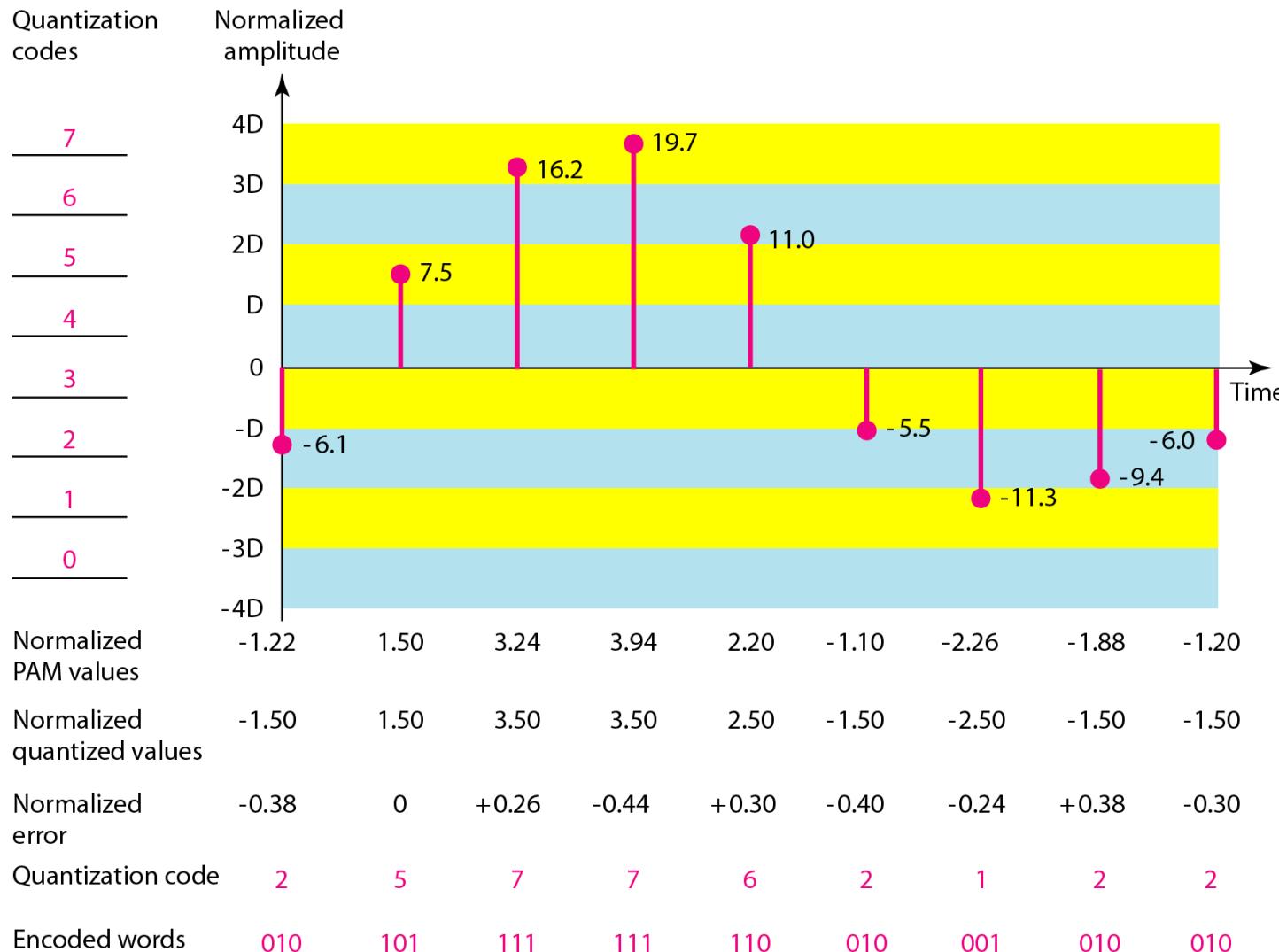
Example 4.11

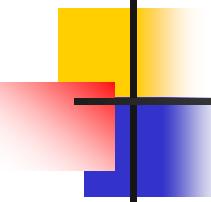
A complex bandpass signal has a bandwidth of 200 kHz. What is the minimum sampling rate for this signal?

Solution

We cannot find the minimum sampling rate in this case because we do not know where the bandwidth starts or ends. We do not know the maximum frequency in the signal.

Figure 4.26 Quantization and encoding of a sampled signal





Example 4.12

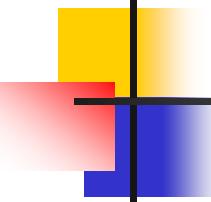
What is the SNR_{dB} in the example of Figure 4.26?

Solution

We can use the formula to find the quantization. We have eight levels and 3 bits per sample, so

$$SNR_{dB} = 6.02(3) + 1.76 = 19.82 \text{ dB}$$

Increasing the number of levels increases the SNR.



Example 4.13

A telephone subscriber line must have an SNR_{dB} above 40. What is the minimum number of bits per sample?

Solution

We can calculate the number of bits as

$$SNR_{dB} = 6.02n_b + 1.76 = 40 \rightarrow n = 6.35$$

Telephone companies usually assign 7 or 8 bits per sample.

Example 4.14

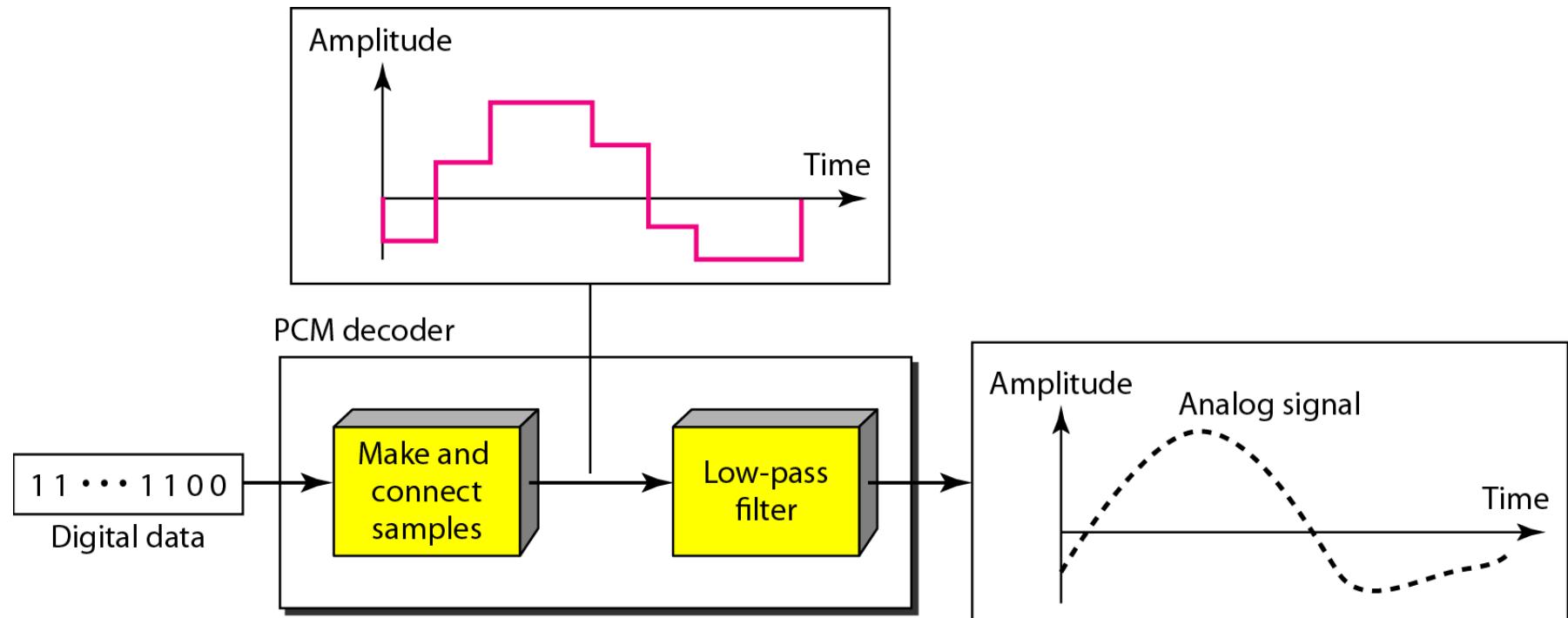
We want to digitize the human voice. What is the bit rate, assuming 8 bits per sample?

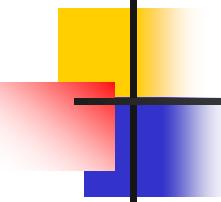
Solution

The human voice normally contains frequencies from 0 to 4000 Hz. So the sampling rate and bit rate are calculated as follows:

$$\begin{aligned}\text{Sampling rate} &= 4000 \times 2 = 8000 \text{ samples/s} \\ \text{Bit rate} &= 8000 \times 8 = 64,000 \text{ bps} = 64 \text{ kbps}\end{aligned}$$

Figure 4.27 Components of a PCM decoder





Example 4.15

We have a low-pass analog signal of 4 kHz. If we send the analog signal, we need a channel with a minimum bandwidth of 4 kHz. If we digitize the signal and send 8 bits per sample, we need a channel with a minimum bandwidth of $8 \times 4 \text{ kHz} = 32 \text{ kHz}$.

Figure 4.28 *The process of delta modulation*

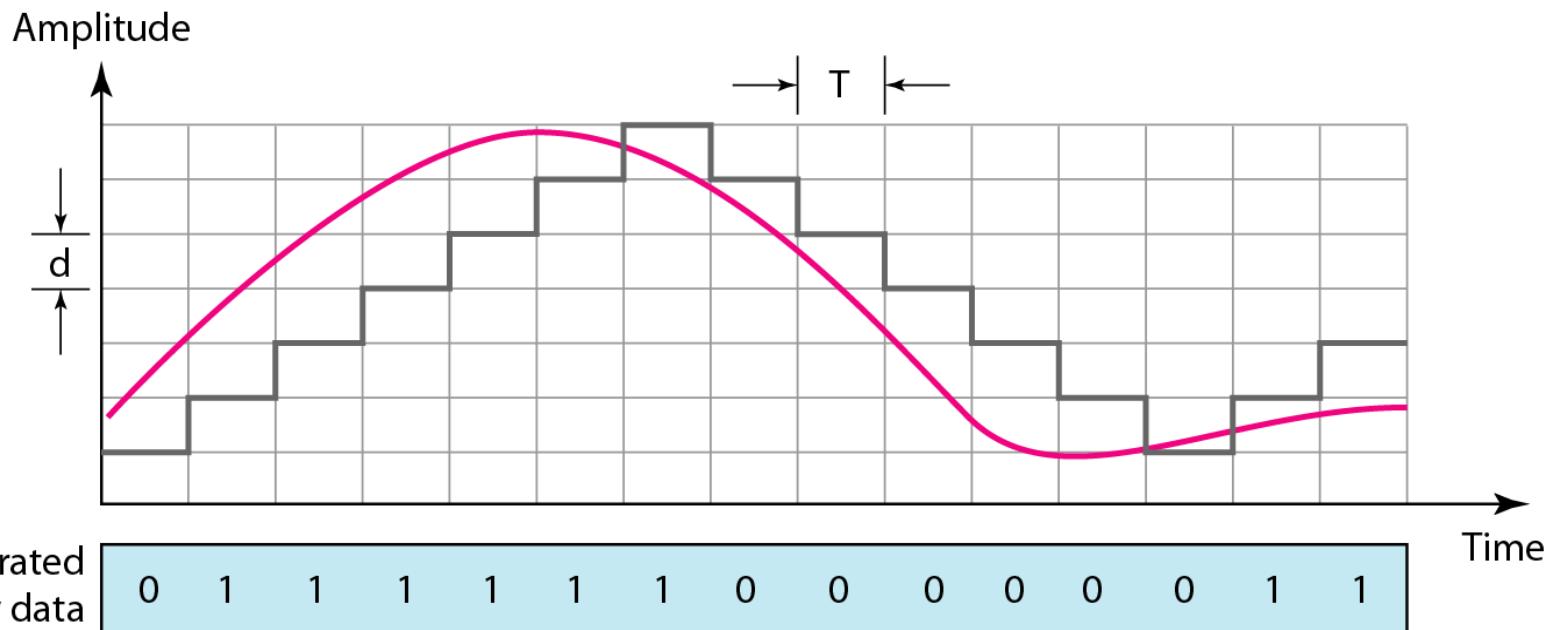


Figure 4.29 *Delta modulation components*

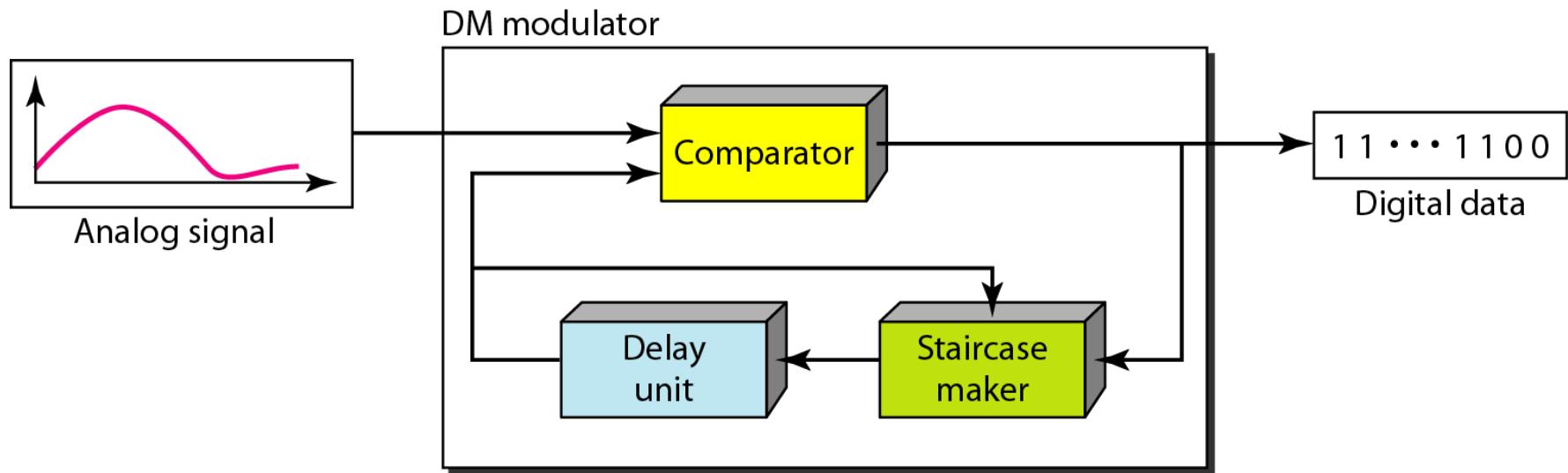
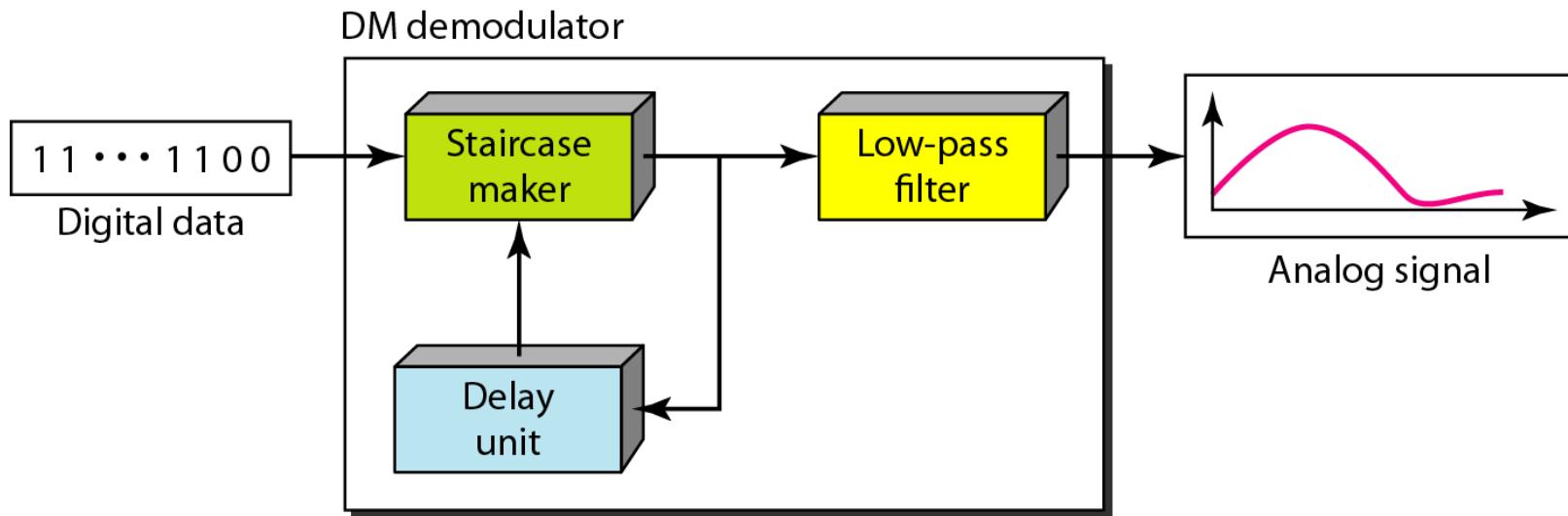


Figure 4.30 *Delta demodulation components*



4-3 TRANSMISSION MODES

The transmission of binary data across a link can be accomplished in either parallel or serial mode. In parallel mode, multiple bits are sent with each clock tick. In serial mode, 1 bit is sent with each clock tick. While there is only one way to send parallel data, there are three subclasses of serial transmission: asynchronous, synchronous, and isochronous.

Topics discussed in this section:

Parallel Transmission

Serial Transmission

Figure 4.31 *Data transmission and modes*

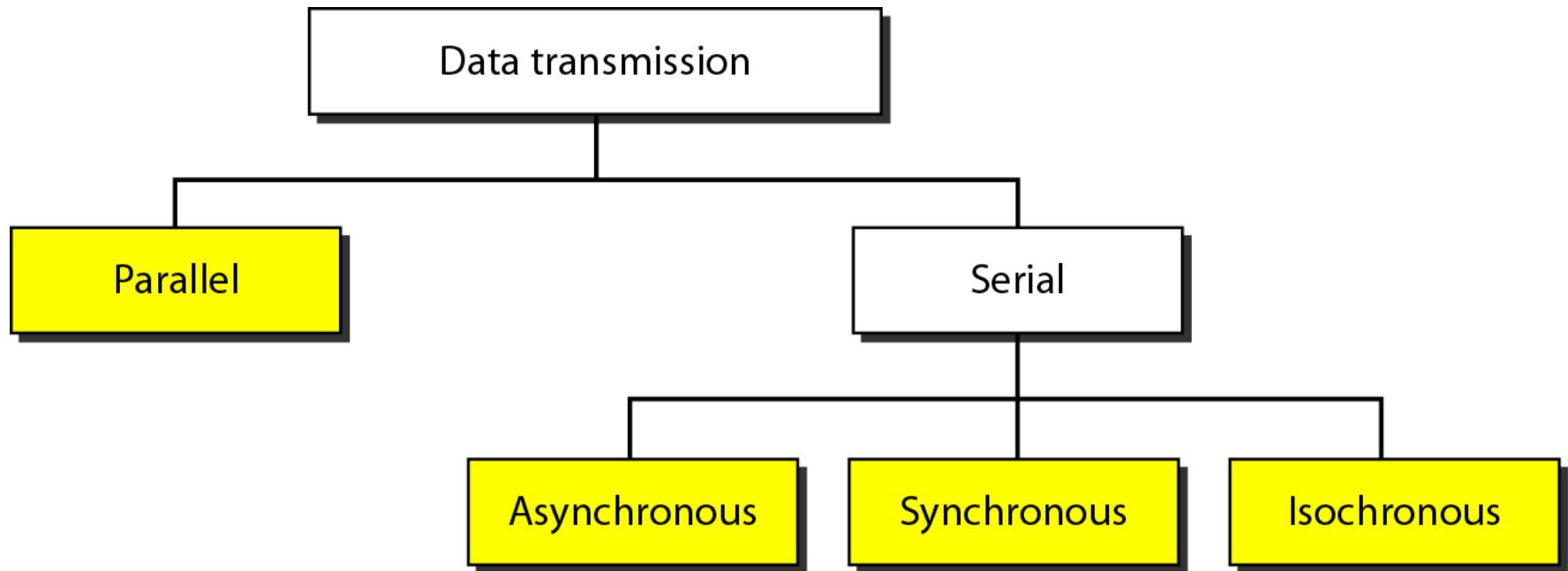


Figure 4.32 *Parallel transmission*

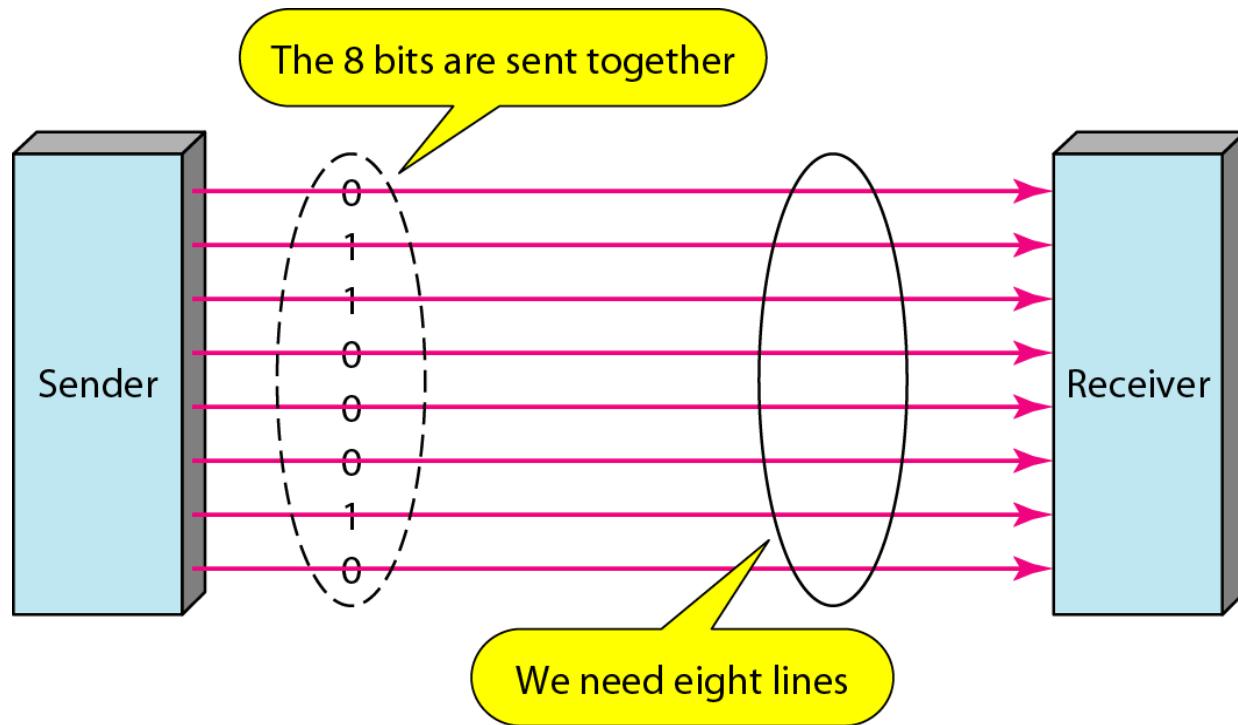
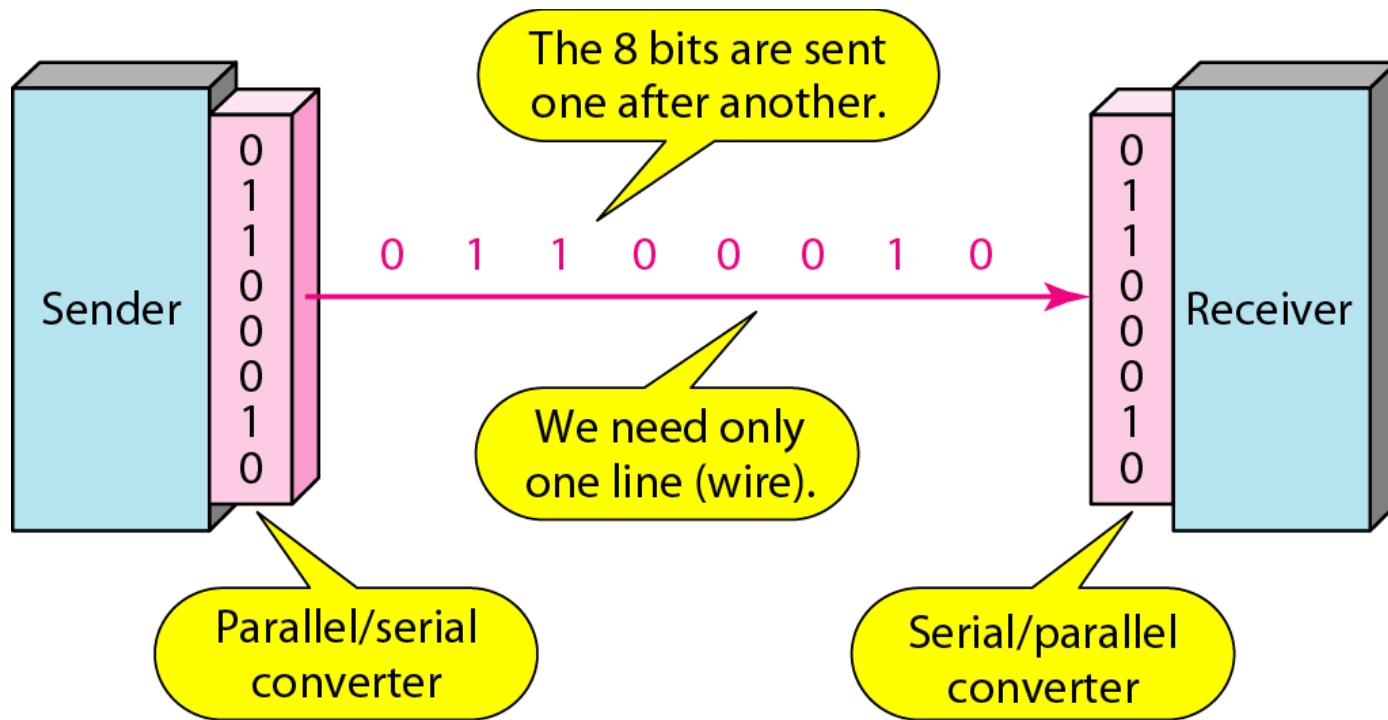
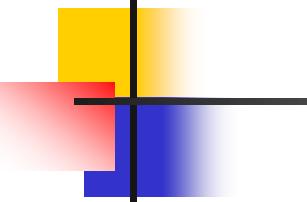


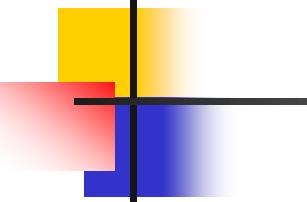
Figure 4.33 *Serial transmission*





Note

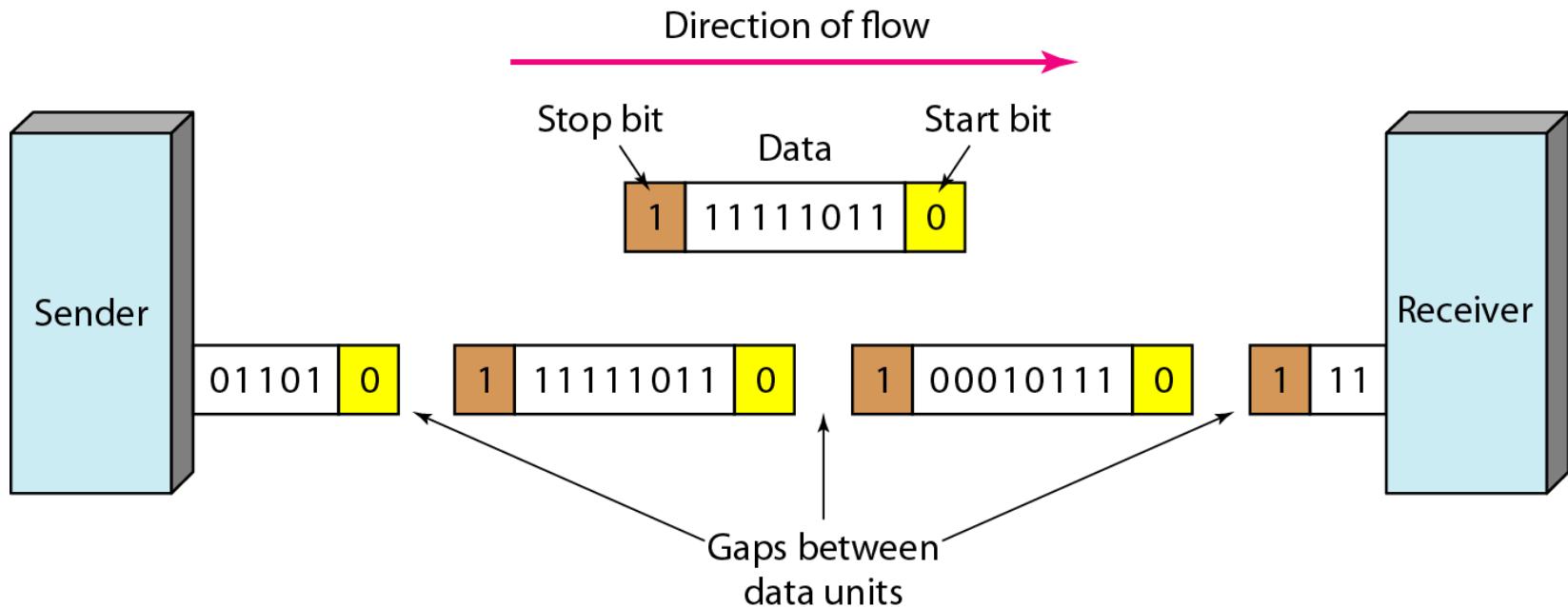
In asynchronous transmission, we send 1 start bit (0) at the beginning and 1 or more stop bits (1s) at the end of each byte. There may be a gap between each byte.

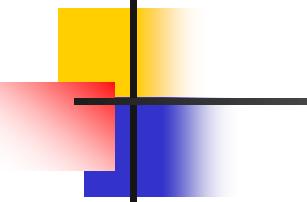


Note

**Asynchronous here means
“asynchronous at the byte level,”
but the bits are still synchronized;
their durations are the same.**

Figure 4.34 Asynchronous transmission

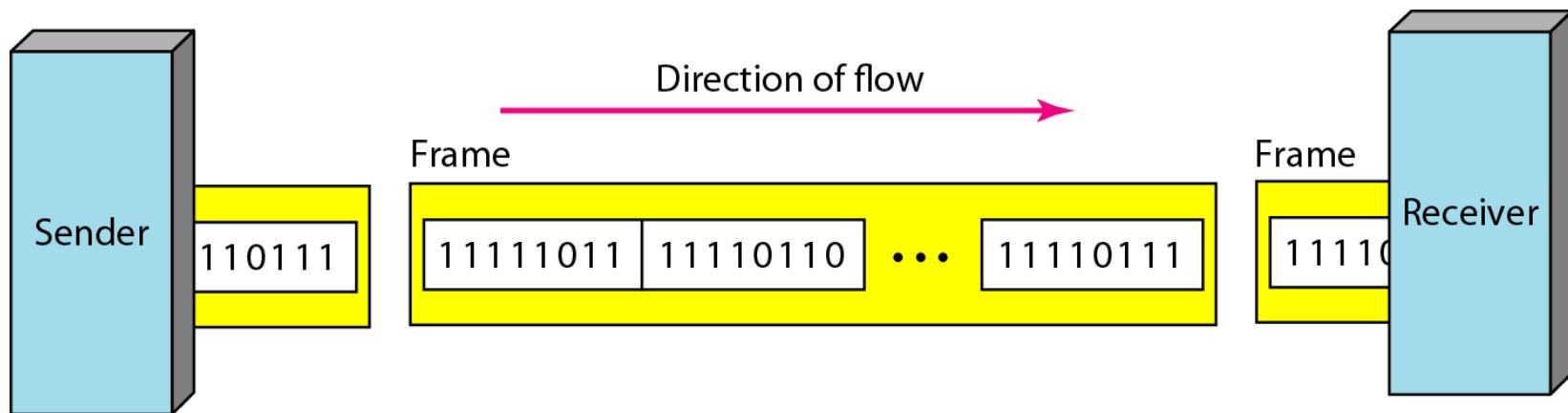




Note

In synchronous transmission, we send bits one after another without start or stop bits or gaps. It is the responsibility of the receiver to group the bits.

Figure 4.35 *Synchronous transmission*





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

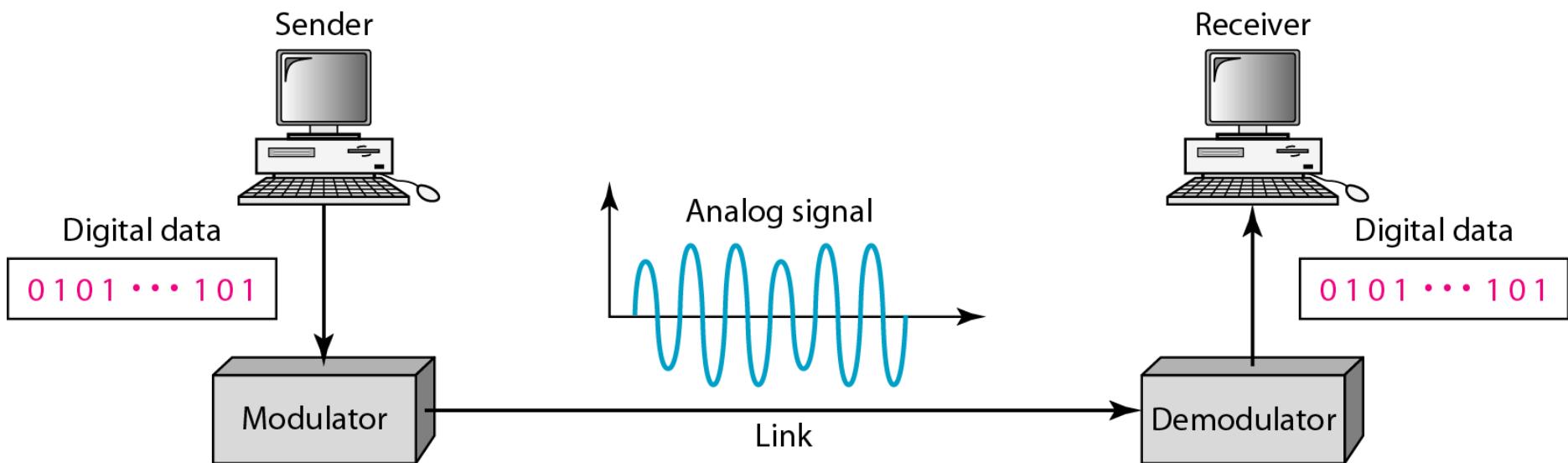
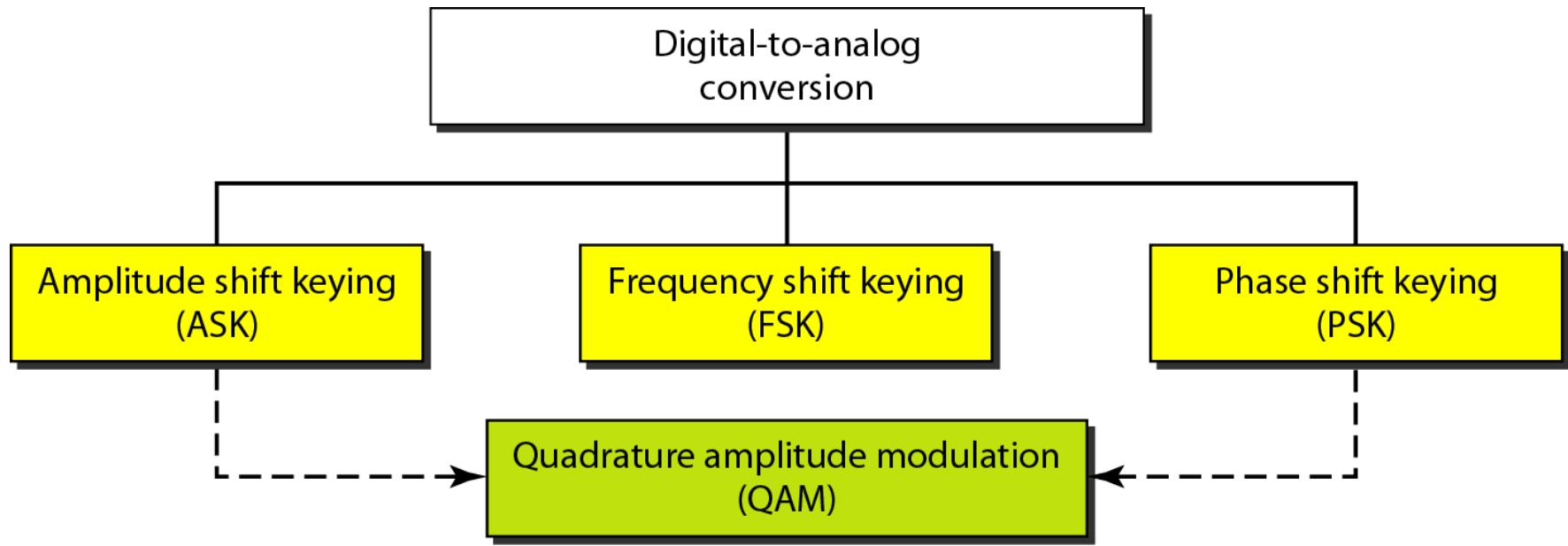
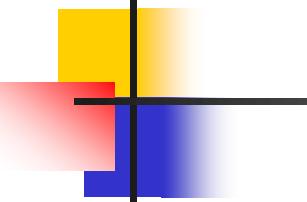


Figure 5.2 *Types of digital-to-analog conversion*



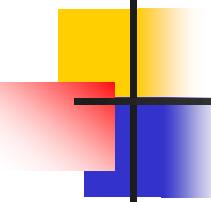


Note

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

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

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 .

$$S = N \times \frac{1}{r} \quad \rightarrow \quad r = \frac{N}{S} = \frac{8000}{1000} = 8 \text{ bits/baud}$$
$$r = \log_2 L \quad \rightarrow \quad L = 2^r = 2^8 = 256$$

Figure 5.3 *Binary amplitude shift keying*

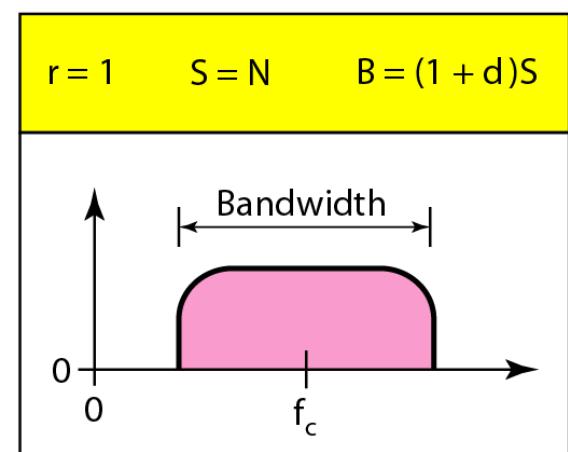
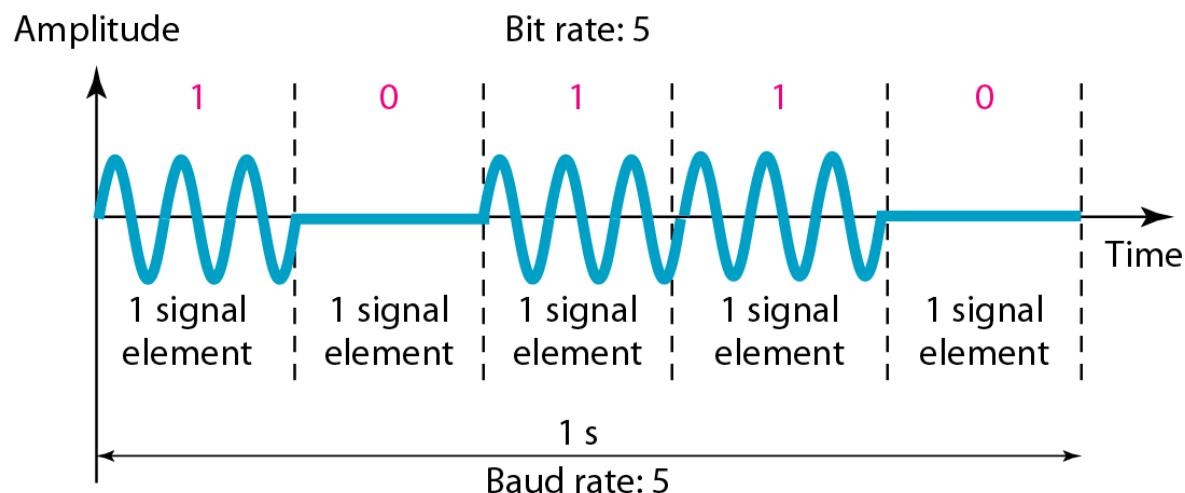
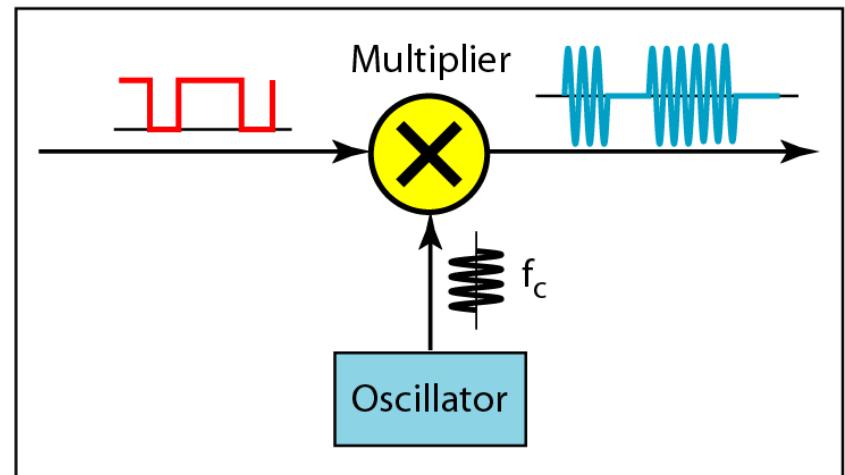
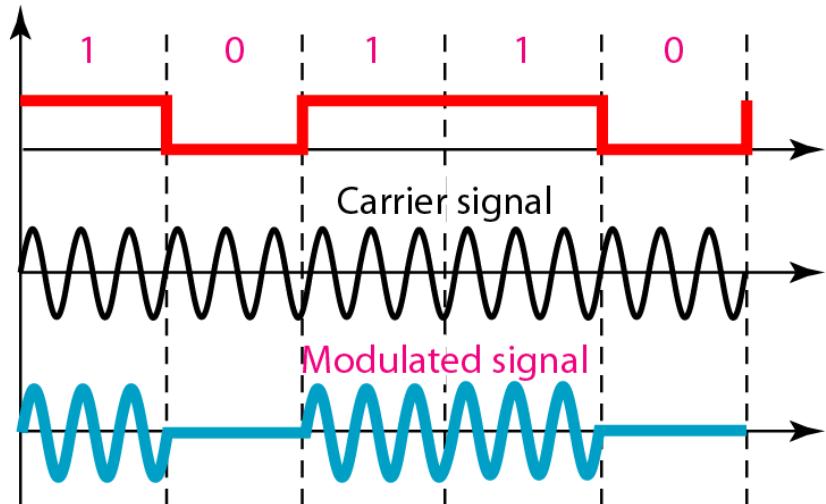


Figure 5.4 Implementation of binary ASK



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

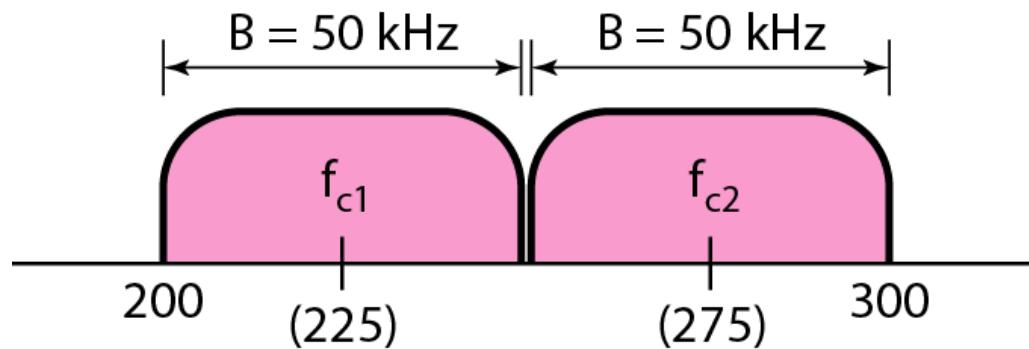
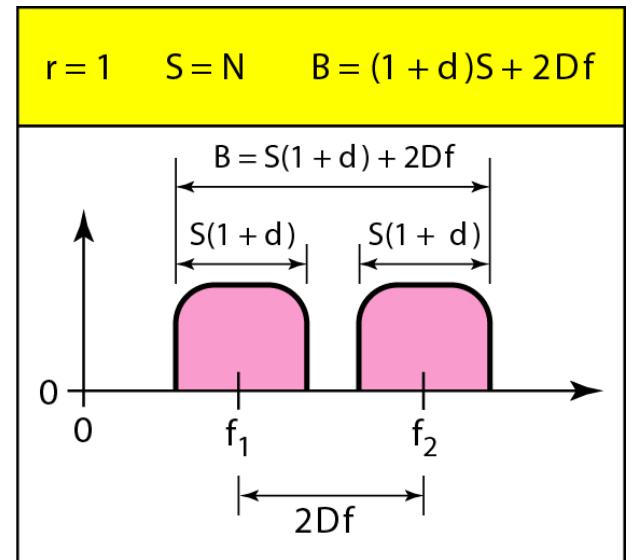
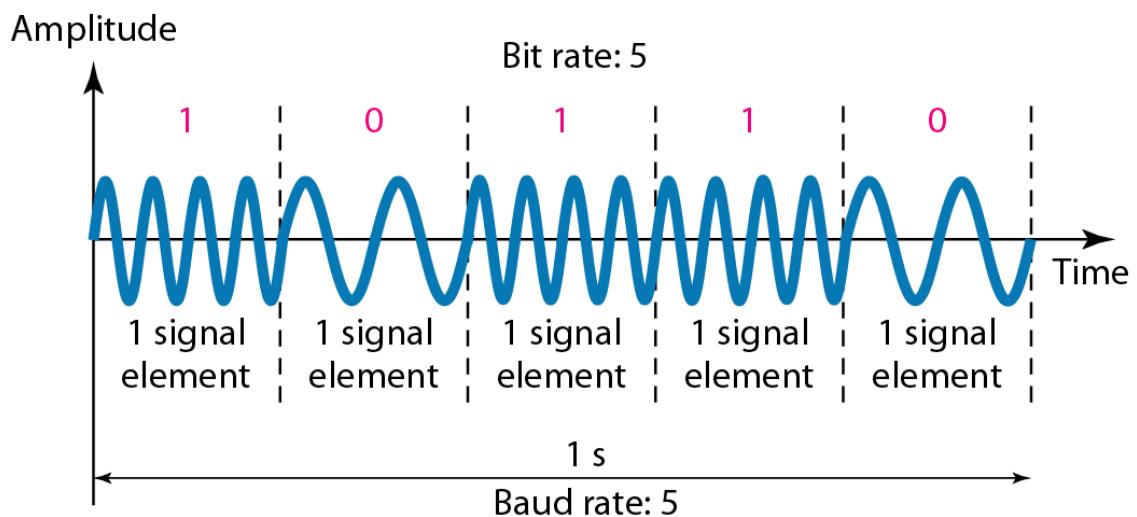


Figure 5.6 *Binary frequency shift keying*



Example 5.5

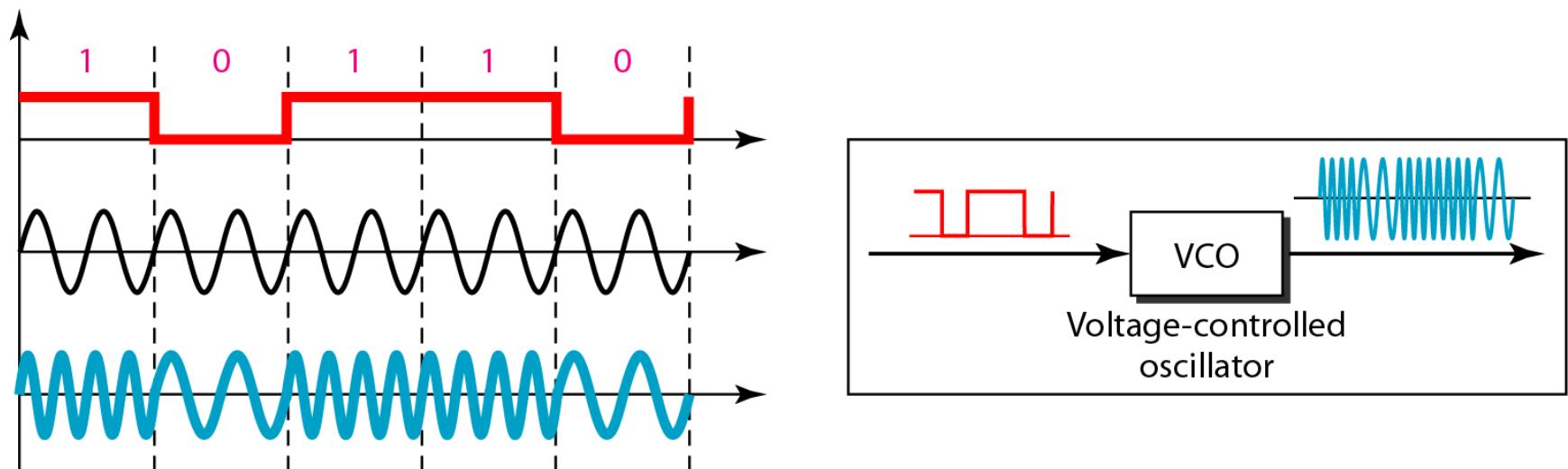
We have an available bandwidth of 100 kHz which spans from 200 to 300 kHz. What should be the carrier frequency and the bit rate if we modulated our data by using FSK with $d = 1$?

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 $2\Delta f$ to be 50 kHz; this means

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

Figure 5.7 Bandwidth of MFSK used in Example 5.6



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 $S = 3 \text{ MHz}/3 = 1000 \text{ Mbaud}$. This means that the carrier frequencies must be 1 MHz apart ($2\Delta f = 1 \text{ MHz}$). The bandwidth is $B = 8 \times 1000 = 8000$. Figure 5.8 shows the allocation of frequencies and bandwidth.

Figure 5.8 Bandwidth of MFSK used in Example 5.6

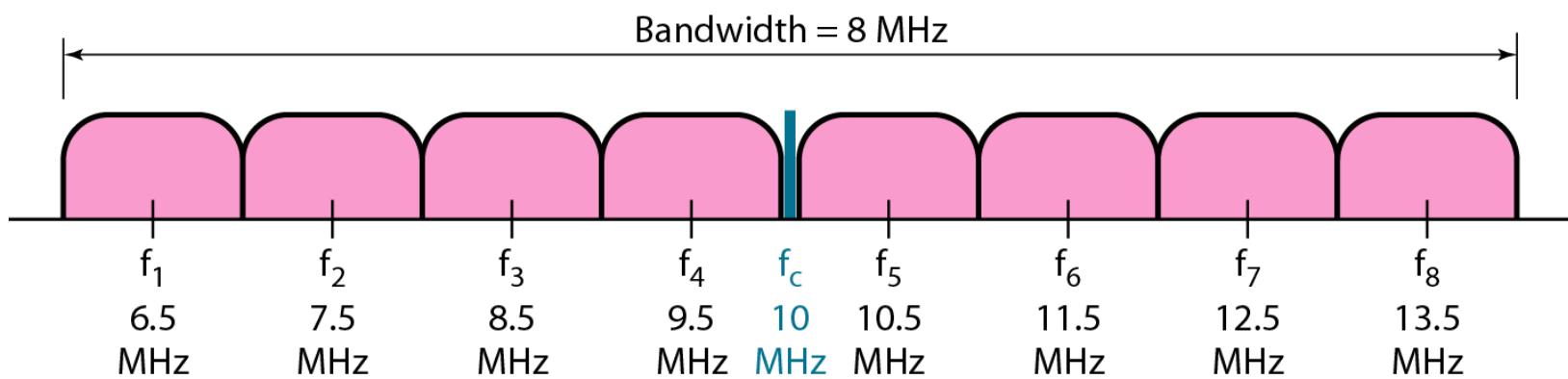


Figure 5.9 *Binary phase shift keying*

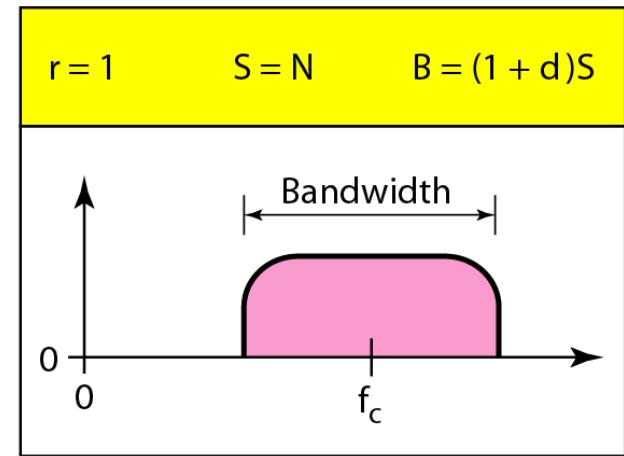
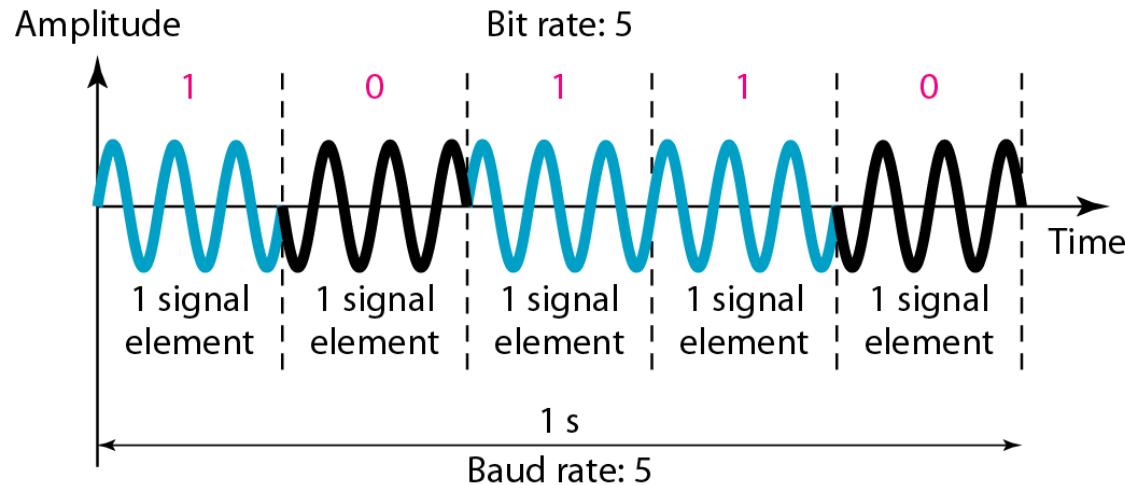


Figure 5.10 *Implementation of BASK*

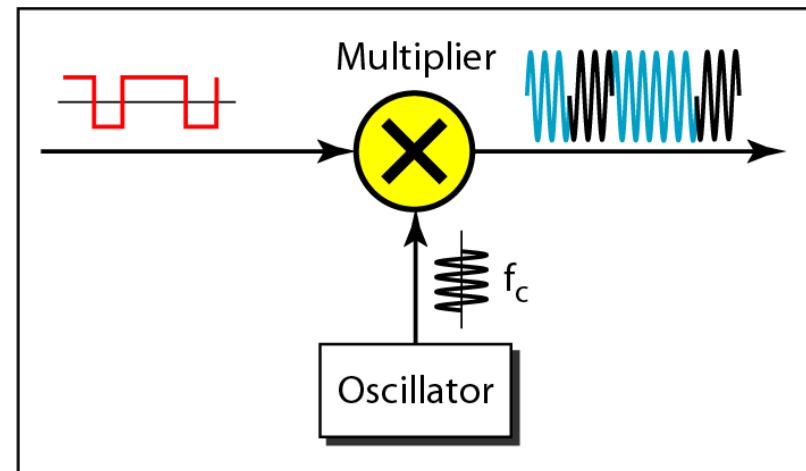
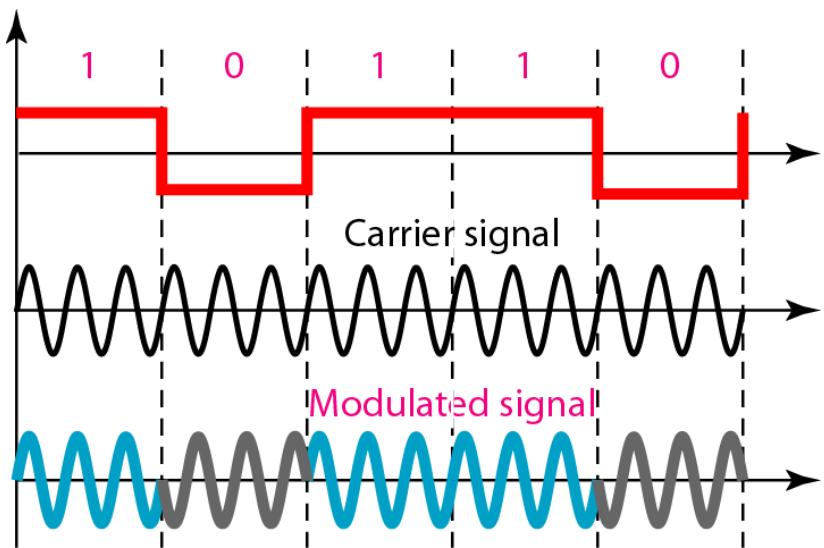
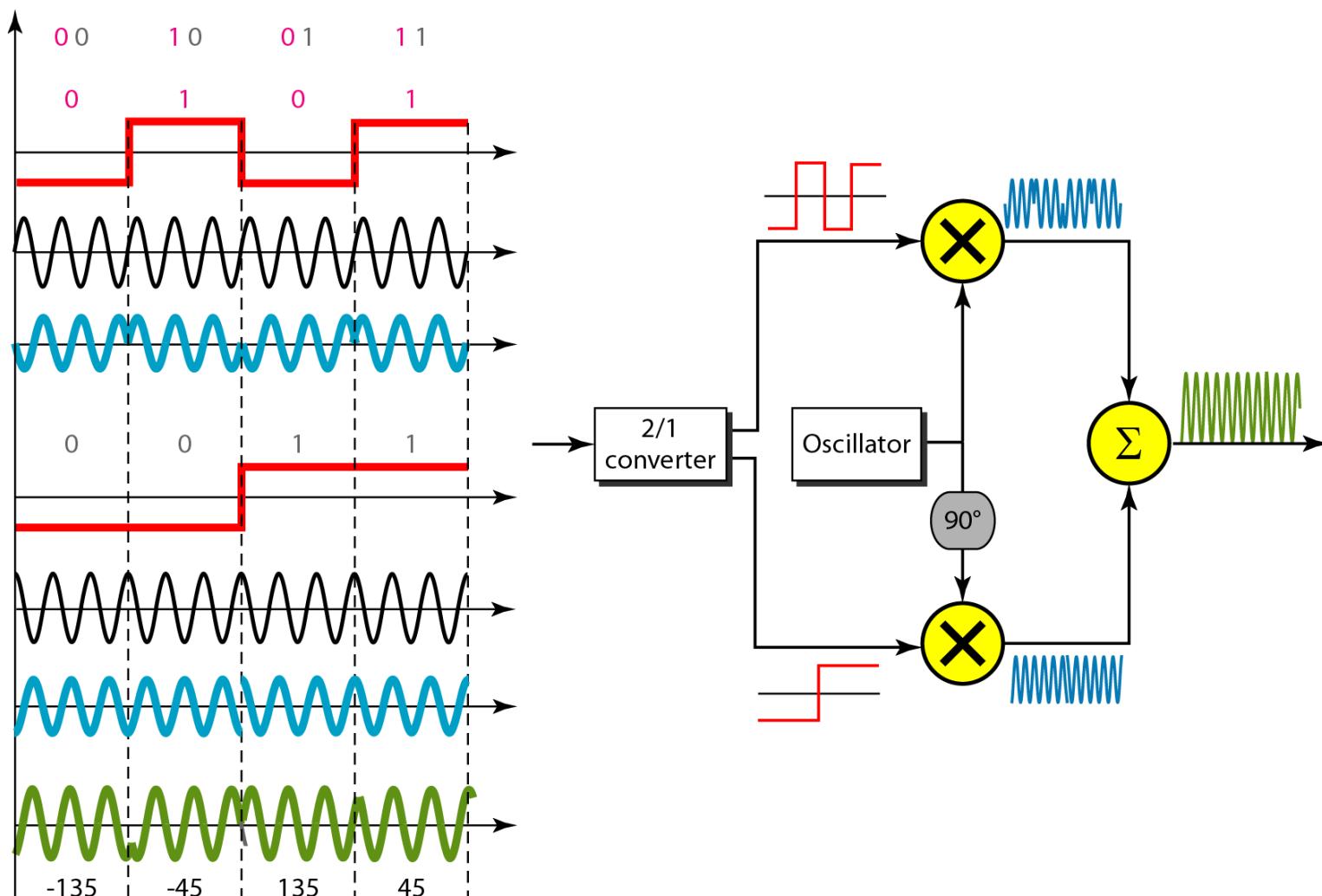
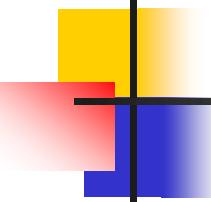


Figure 5.11 QPSK and its implementation





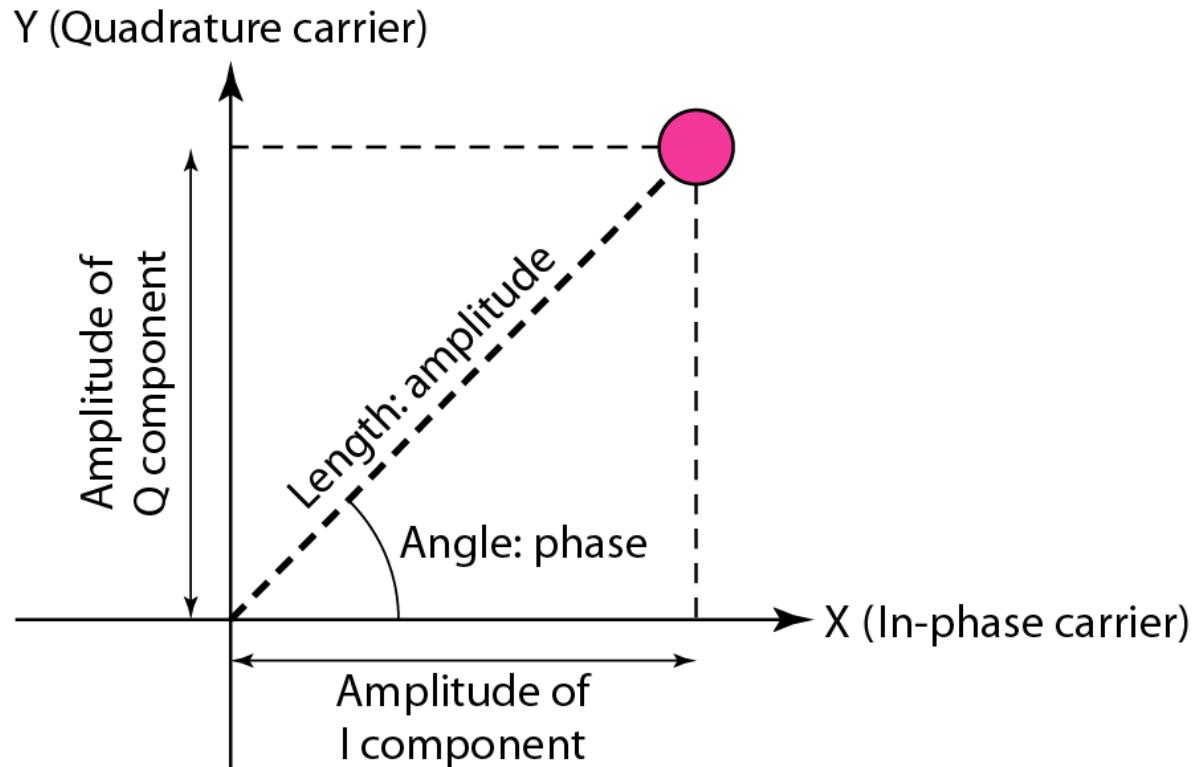
Example 5.7

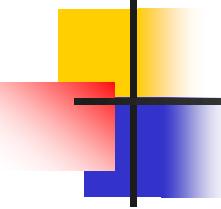
Find the bandwidth for a signal transmitting at 12 Mbps for QPSK. The value of $d = 0$.

Solution

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

Figure 5.12 *Concept of a constellation diagram*





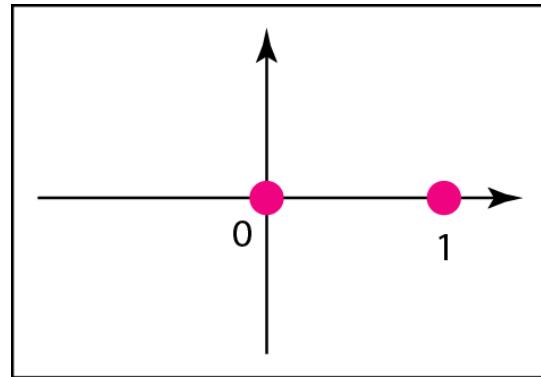
Example 5.8

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

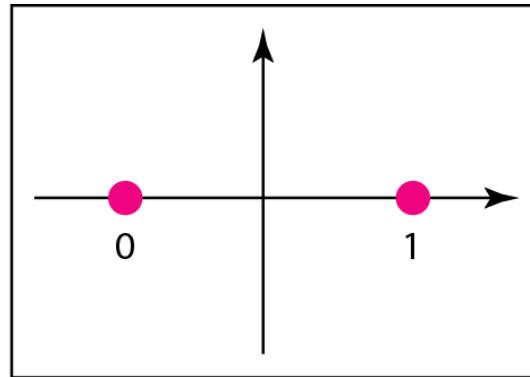
Solution

Figure 5.13 shows the three constellation diagrams.

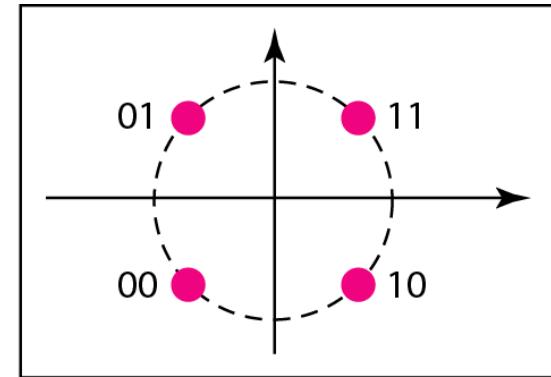
Figure 5.13 *Three constellation diagrams*



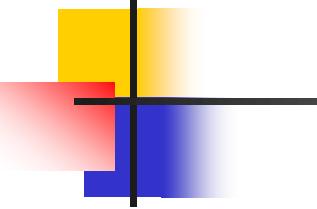
a. ASK (OOK)



b. BPSK



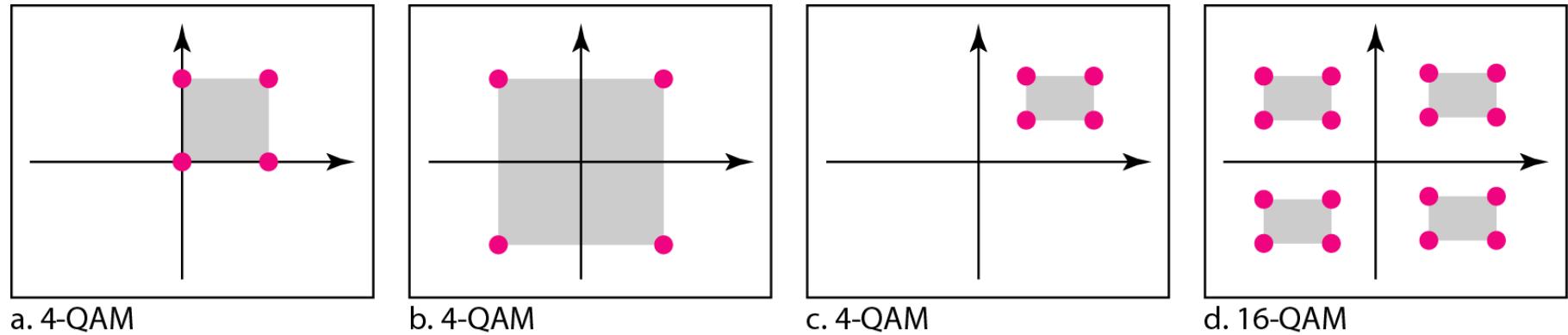
c. QPSK



Note

Quadrature amplitude modulation is a combination of ASK and PSK.

Figure 5.14 Constellation diagrams for some QAMs



5-2 ANALOG AND DIGITAL

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*

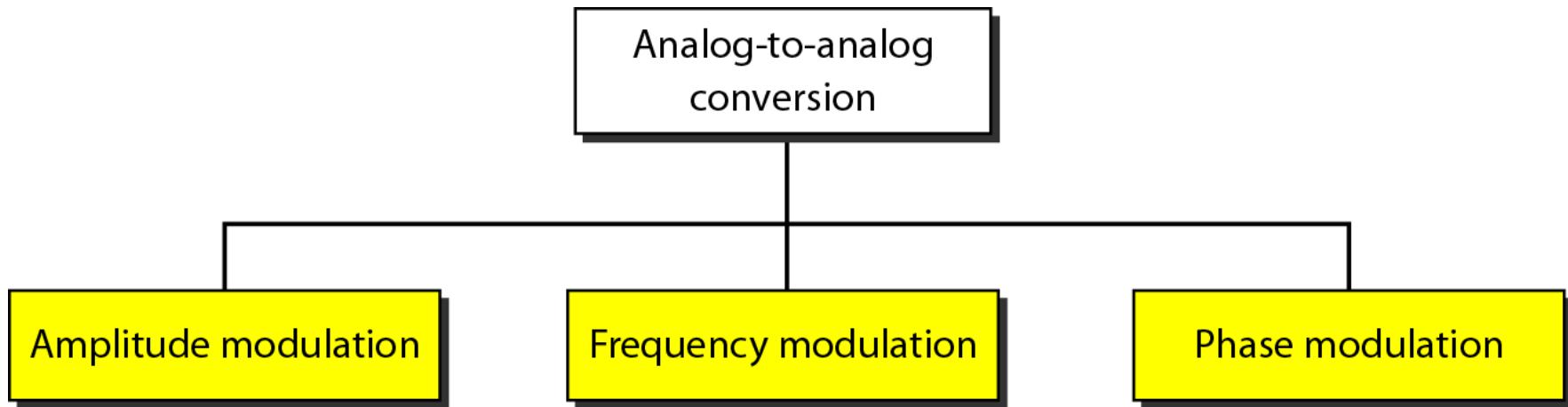
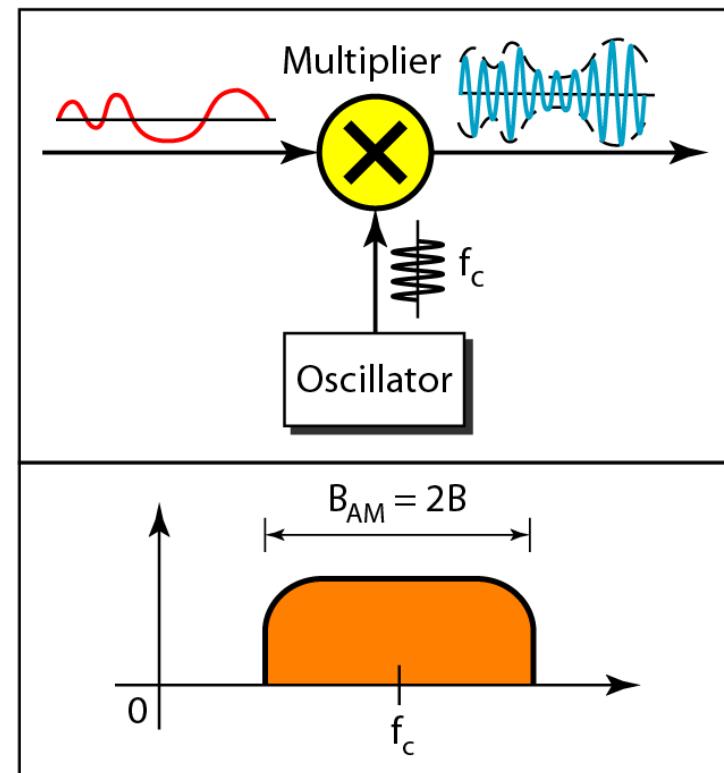
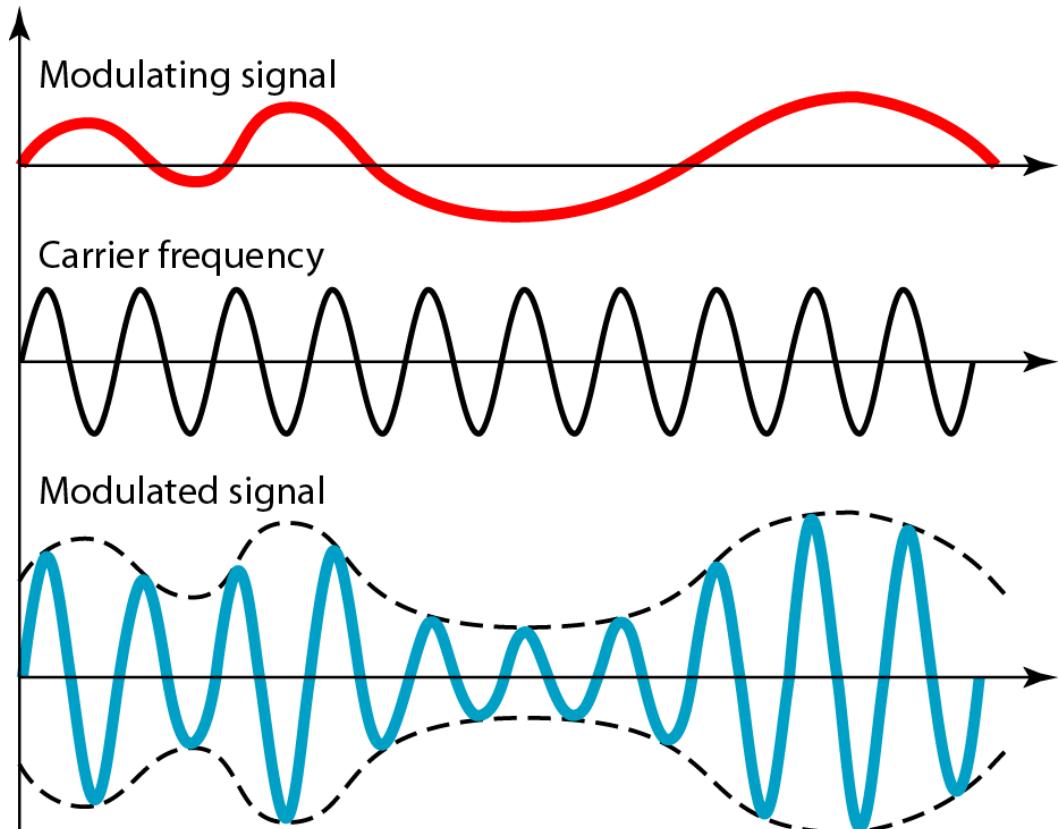
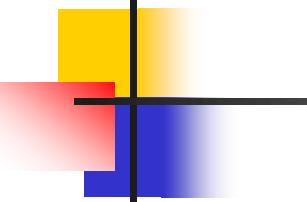


Figure 5.16 Amplitude modulation

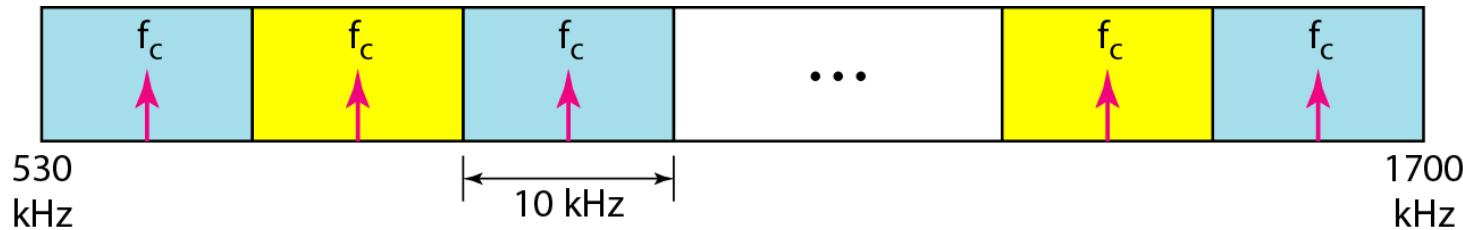


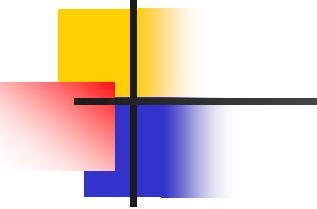


Note

**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





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

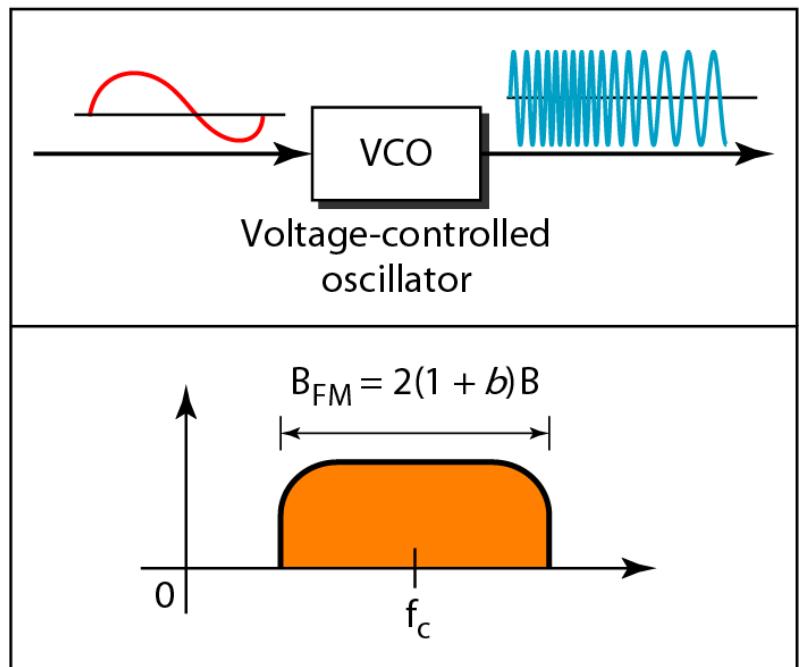
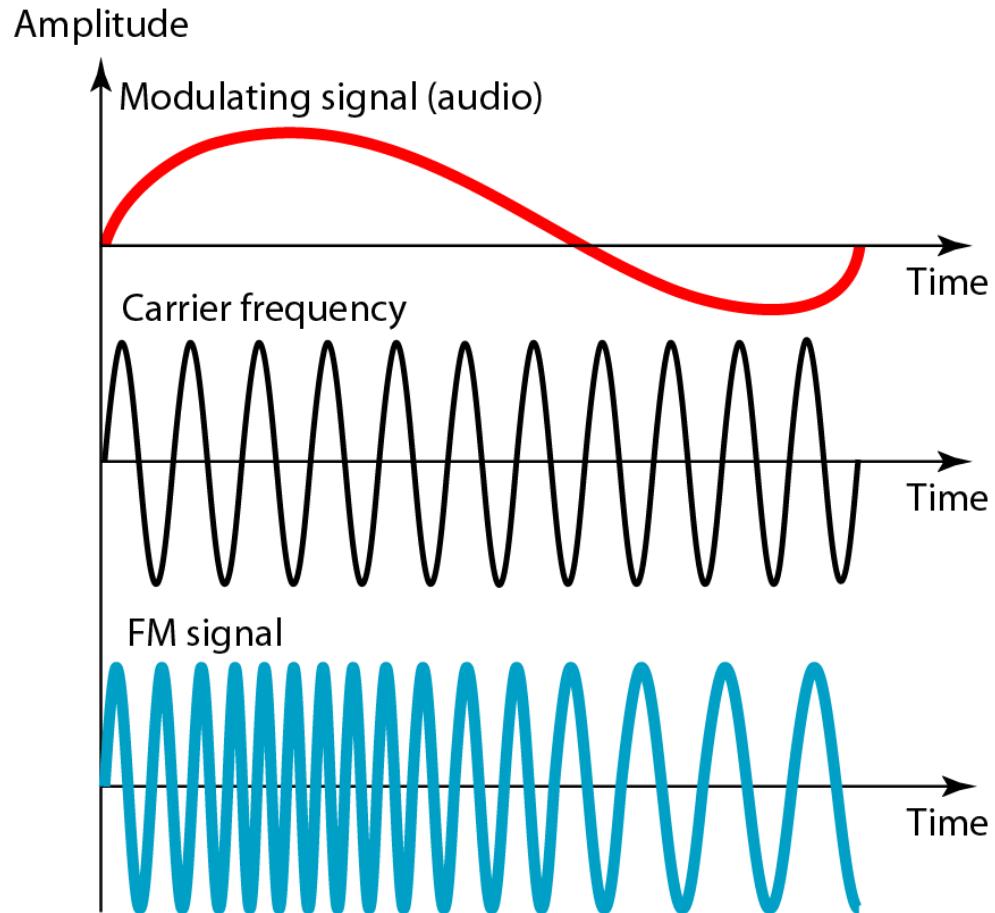


Figure 5.19 FM band allocation

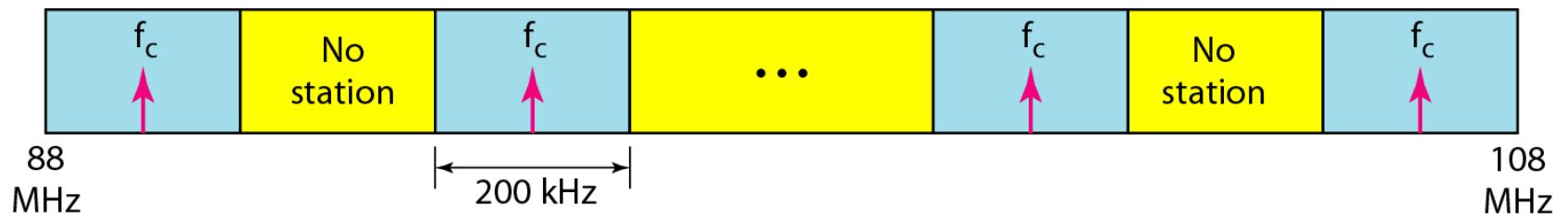
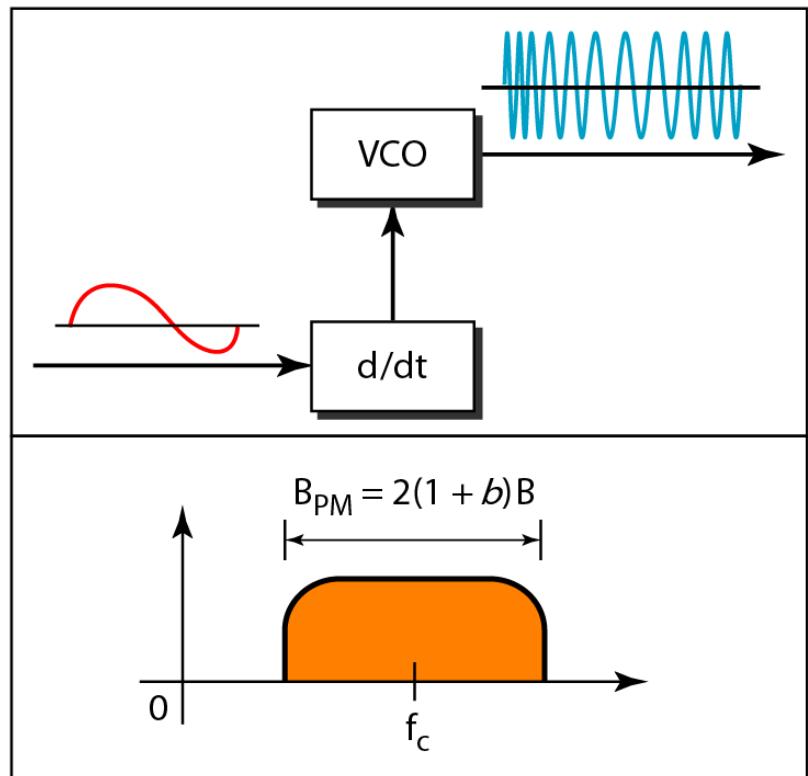
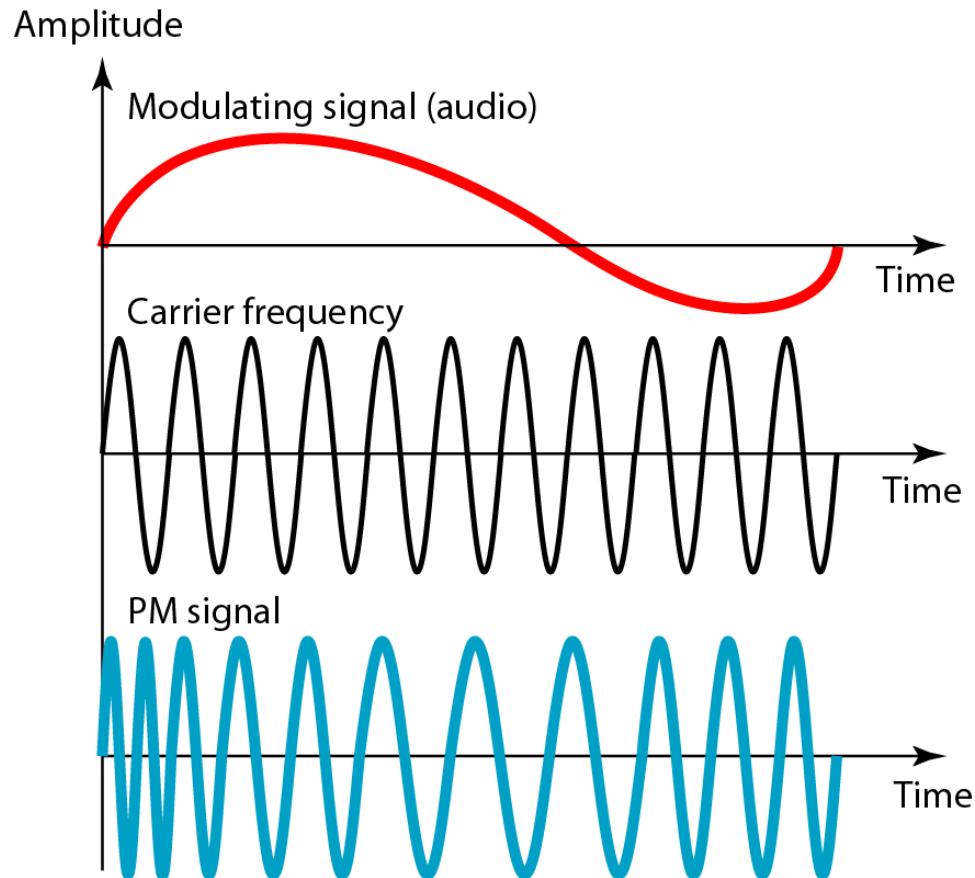
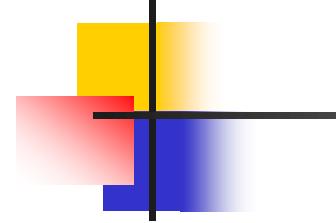


Figure 5.20 Phase modulation





Note

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

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



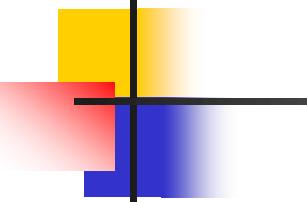
Data Communications and Networking

Fourth Edition

Forouzan

Chapter 6

Bandwidth Utilization: Multiplexing and Spreading



Note

Bandwidth utilization is the wise use of available bandwidth to achieve specific goals.

Efficiency can be achieved by multiplexing; privacy and anti-jamming can be achieved by spreading.

6-1 MULTIPLEXING

Whenever the bandwidth of a medium linking two devices is greater than the bandwidth needs of the devices, the link can be shared. Multiplexing is the set of techniques that allows the simultaneous transmission of multiple signals across a single data link. As data and telecommunications use increases, so does traffic.

Topics discussed in this section:

Frequency-Division Multiplexing

Wavelength-Division Multiplexing

Synchronous Time-Division Multiplexing

Statistical Time-Division Multiplexing

Figure 6.1 *Dividing a link into channels*

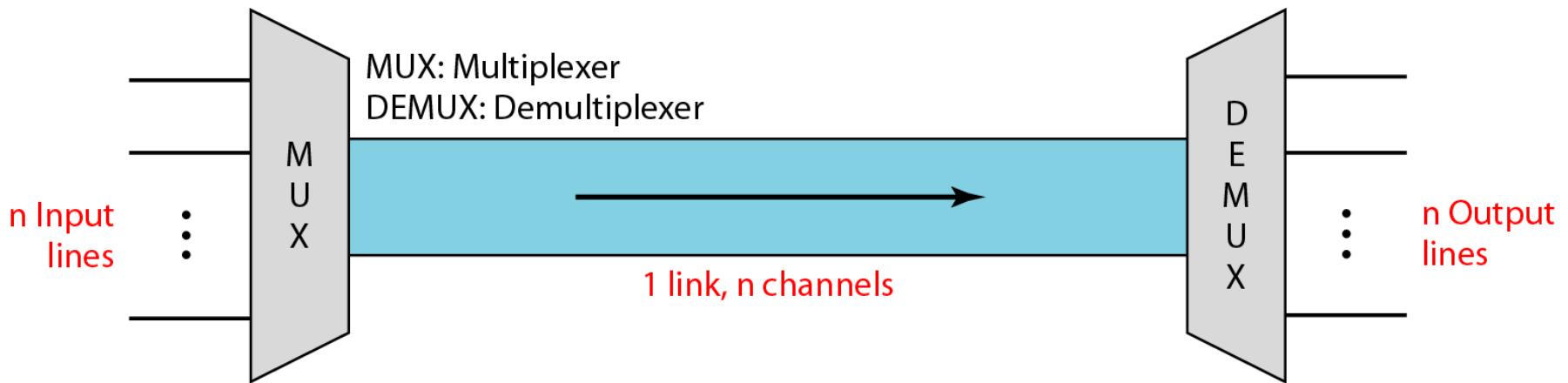


Figure 6.2 *Categories of multiplexing*

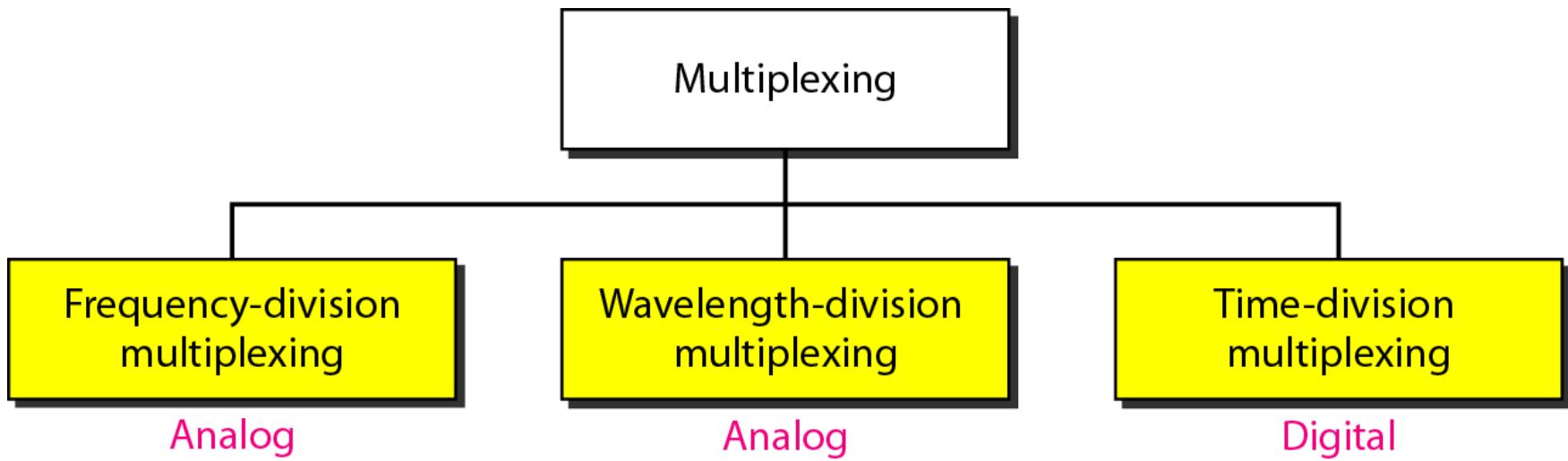
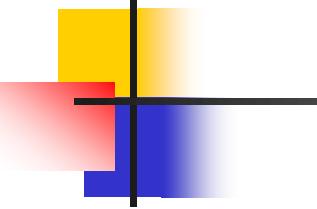


Figure 6.3 Frequency-division multiplexing





Note

**FDM is an analog multiplexing technique
that combines analog signals.**

Figure 6.4 FDM process

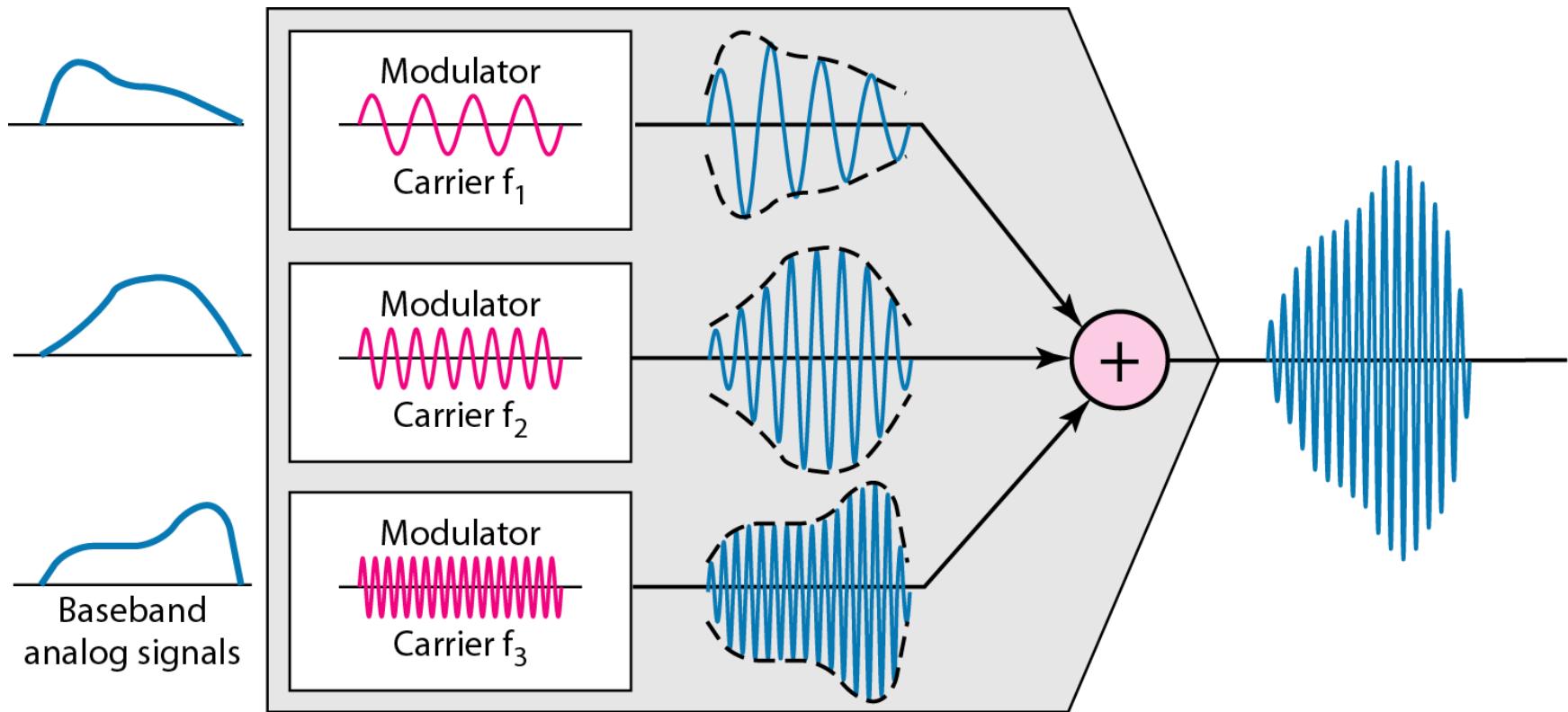
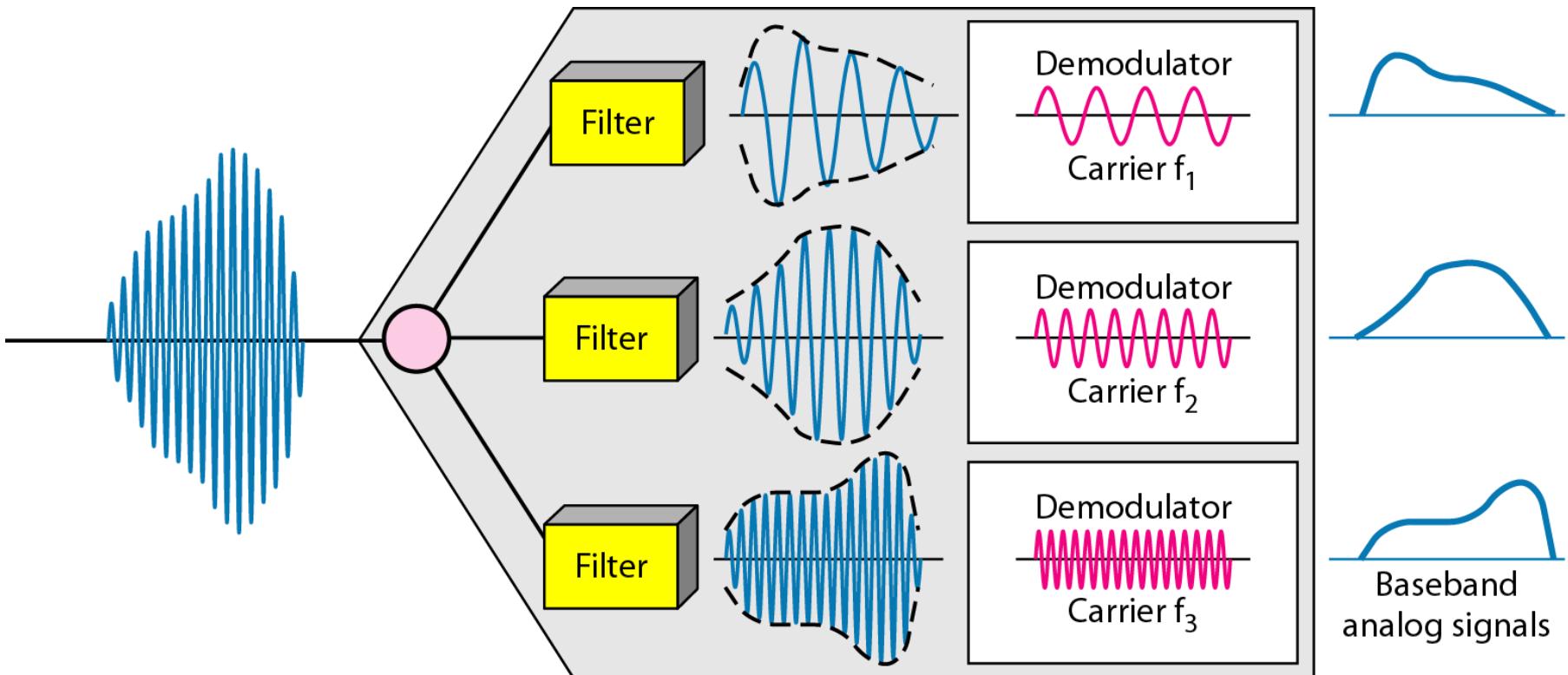


Figure 6.5 FDM demultiplexing example



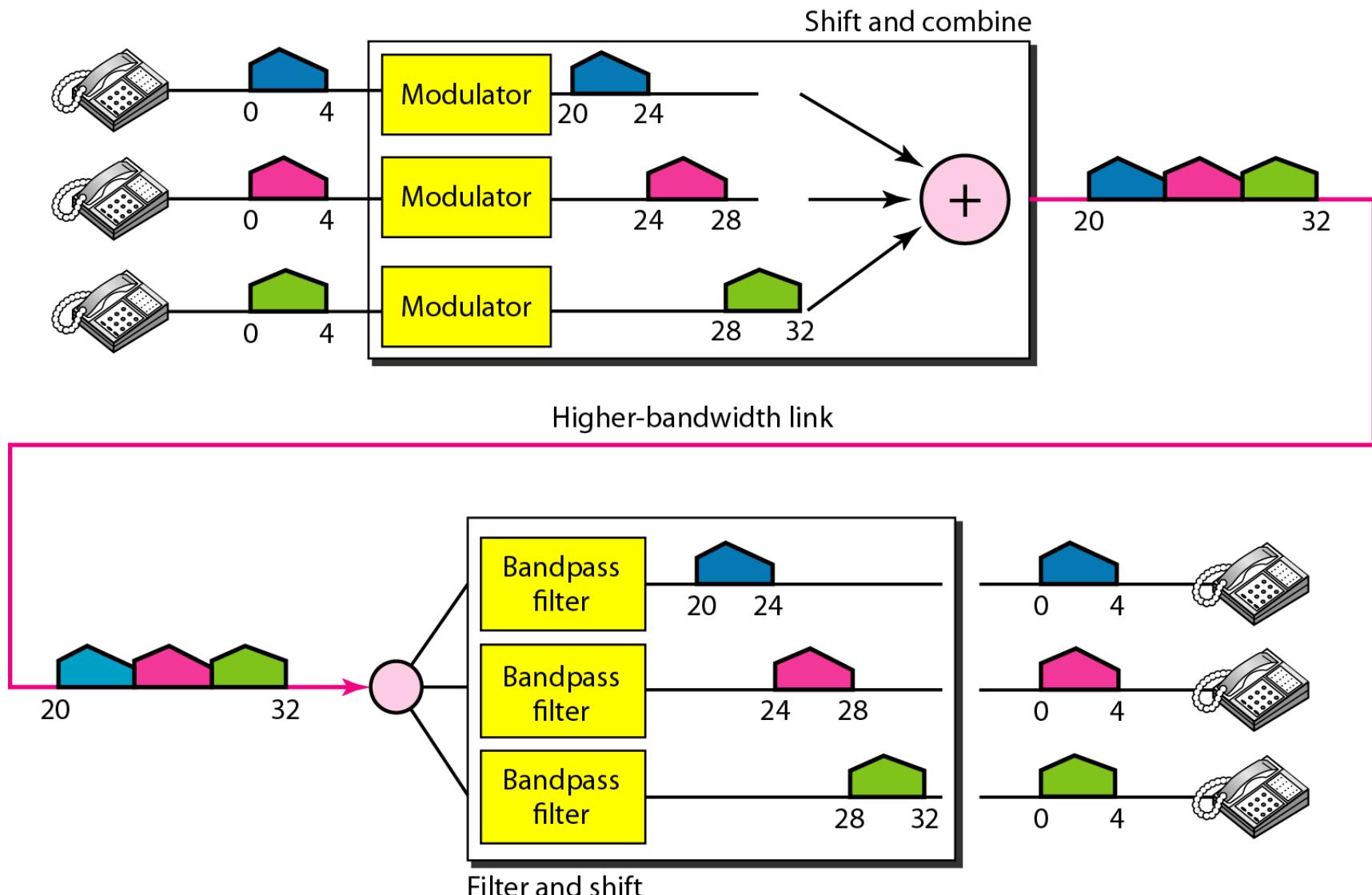
Example 6.1

Assume that a voice channel occupies a bandwidth of 4 kHz. We need to combine three voice channels into a link with a bandwidth of 12 kHz, from 20 to 32 kHz. Show the configuration, using the frequency domain. Assume there are no guard bands.

Solution

We shift (modulate) each of the three voice channels to a different bandwidth, as shown in Figure 6.6. We use the 20- to 24-kHz bandwidth for the first channel, the 24- to 28-kHz bandwidth for the second channel, and the 28- to 32-kHz bandwidth for the third one. Then we combine them as shown in Figure 6.6.

Figure 6.6 Example 6.1



Example 6.2

Five channels, each with a 100-kHz bandwidth, are to be multiplexed together. What is the minimum bandwidth of the link if there is a need for a guard band of 10 kHz between the channels to prevent interference?

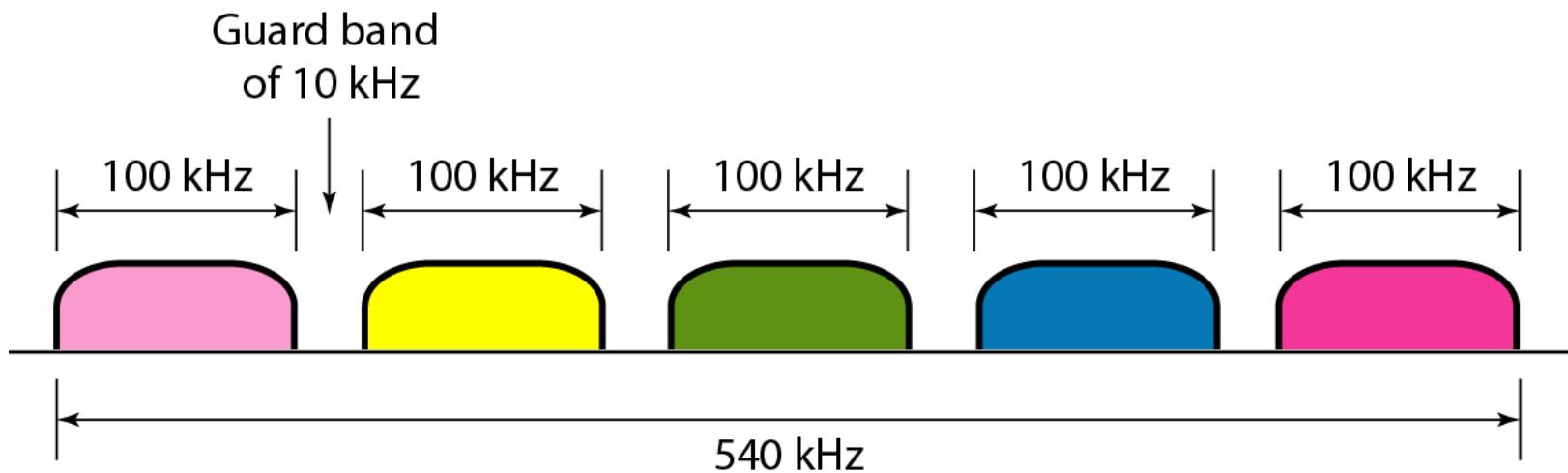
Solution

For five channels, we need at least four guard bands. This means that the required bandwidth is at least

$$5 \times 100 + 4 \times 10 = 540 \text{ kHz},$$

as shown in Figure 6.7.

Figure 6.7 Example 6.2



Example 6.3

Four data channels (digital), each transmitting at 1 Mbps, use a satellite channel of 1 MHz. Design an appropriate configuration, using FDM.

Solution

The satellite channel is analog. We divide it into four channels, each channel having a 250-kHz bandwidth. Each digital channel of 1 Mbps is modulated such that each 4 bits is modulated to 1 Hz. One solution is 16-QAM modulation. Figure 6.8 shows one possible configuration.

Figure 6.8 Example 6.3

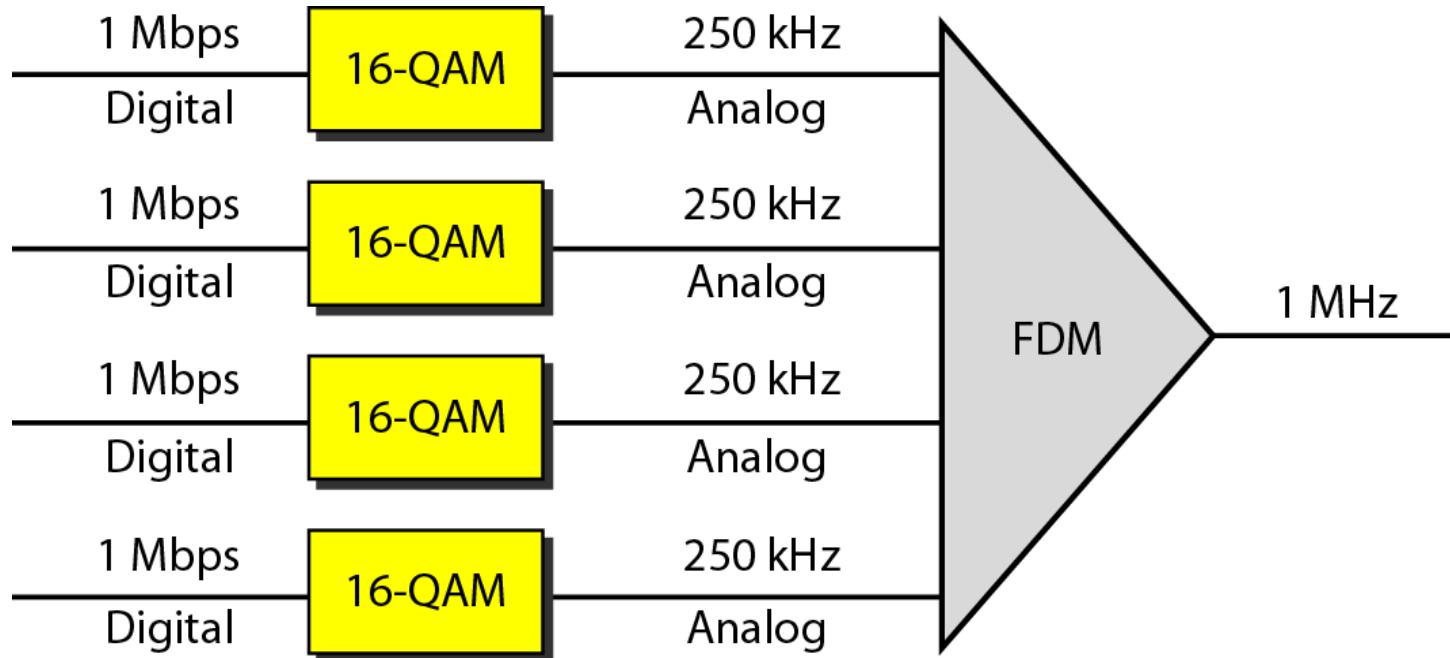
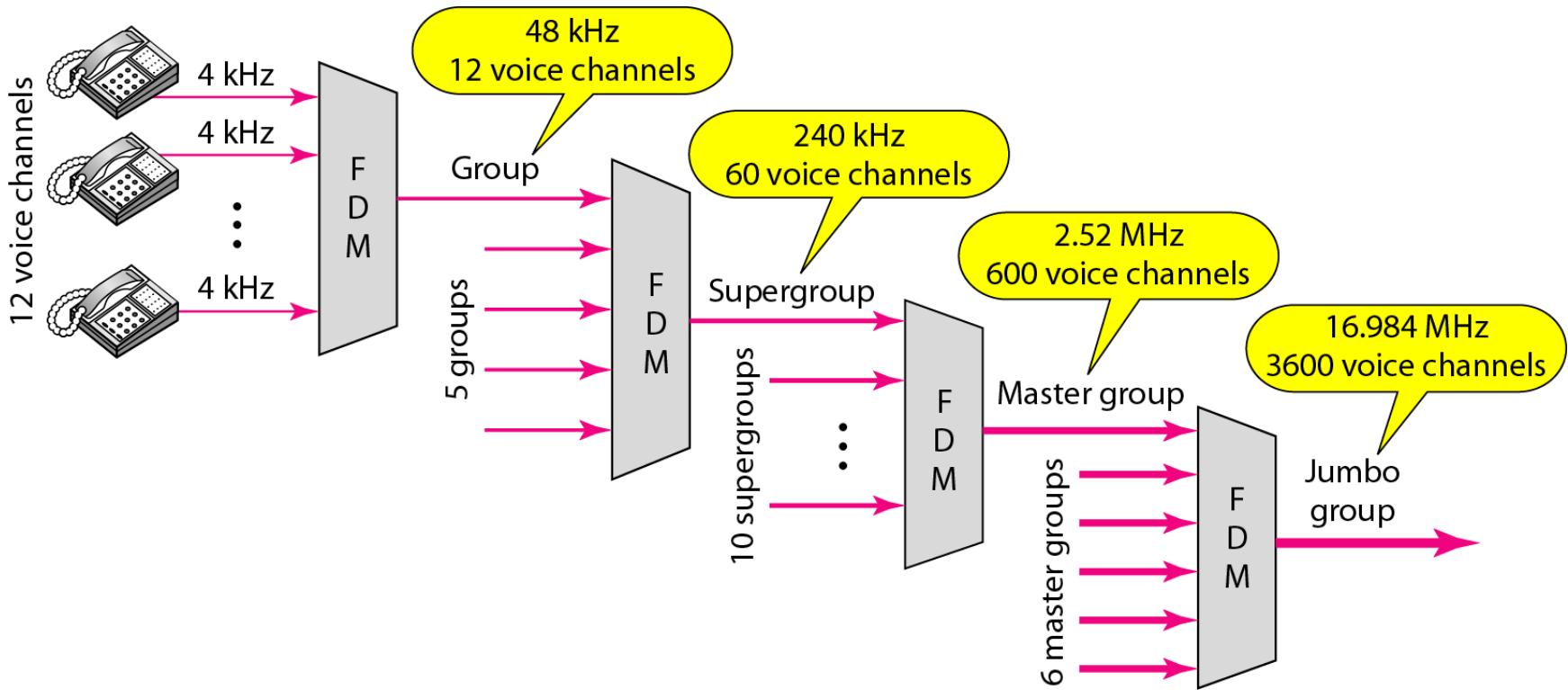
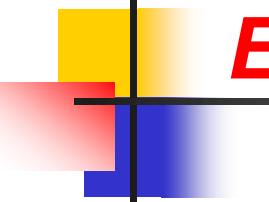


Figure 6.9 Analog hierarchy





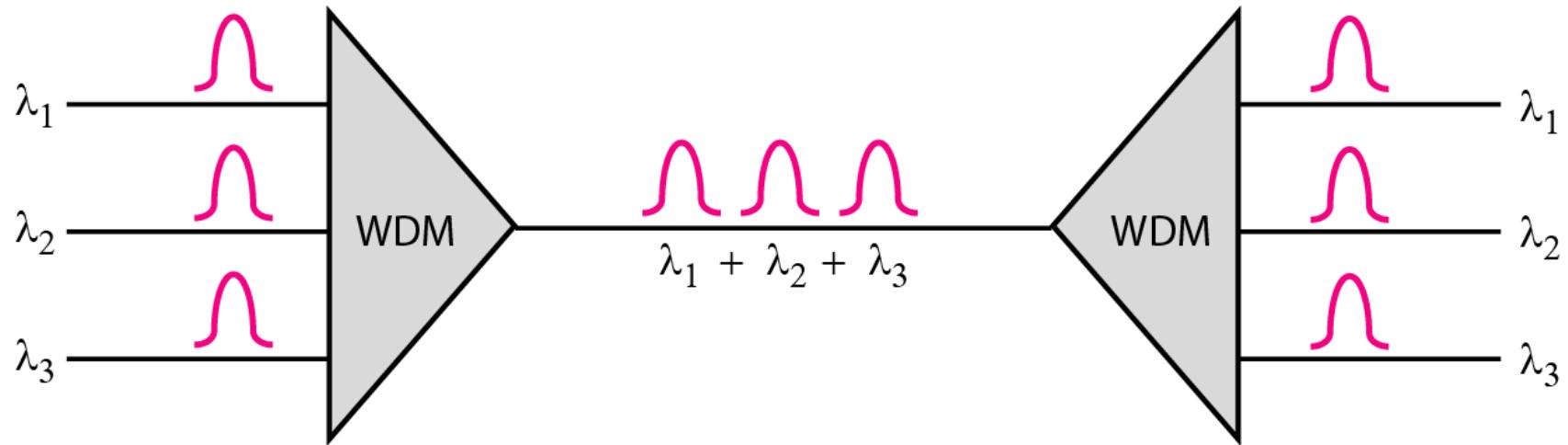
Example 6.4

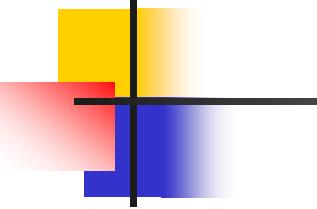
The Advanced Mobile Phone System (AMPS) uses two bands. The first band of 824 to 849 MHz is used for sending, and 869 to 894 MHz is used for receiving. Each user has a bandwidth of 30 kHz in each direction. How many people can use their cellular phones simultaneously?

Solution

Each band is 25 MHz. If we divide 25 MHz by 30 kHz, we get 833.33. In reality, the band is divided into 832 channels. Of these, 42 channels are used for control, which means only 790 channels are available for cellular phone users.

Figure 6.10 *Wavelength-division multiplexing*





Note

WDM is an analog multiplexing technique to combine optical signals.

Figure 6.11 *Prisms in wavelength-division multiplexing and demultiplexing*

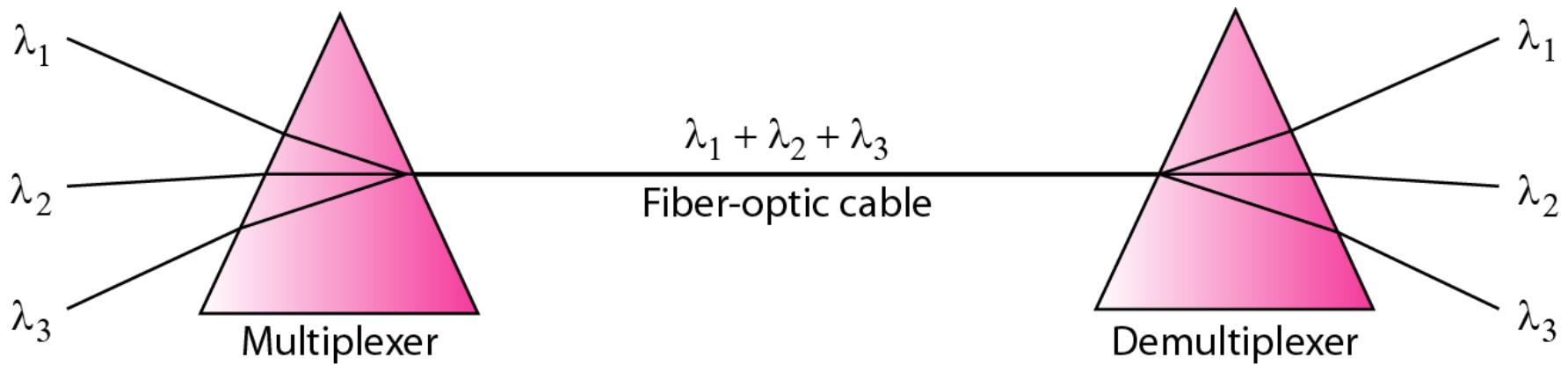
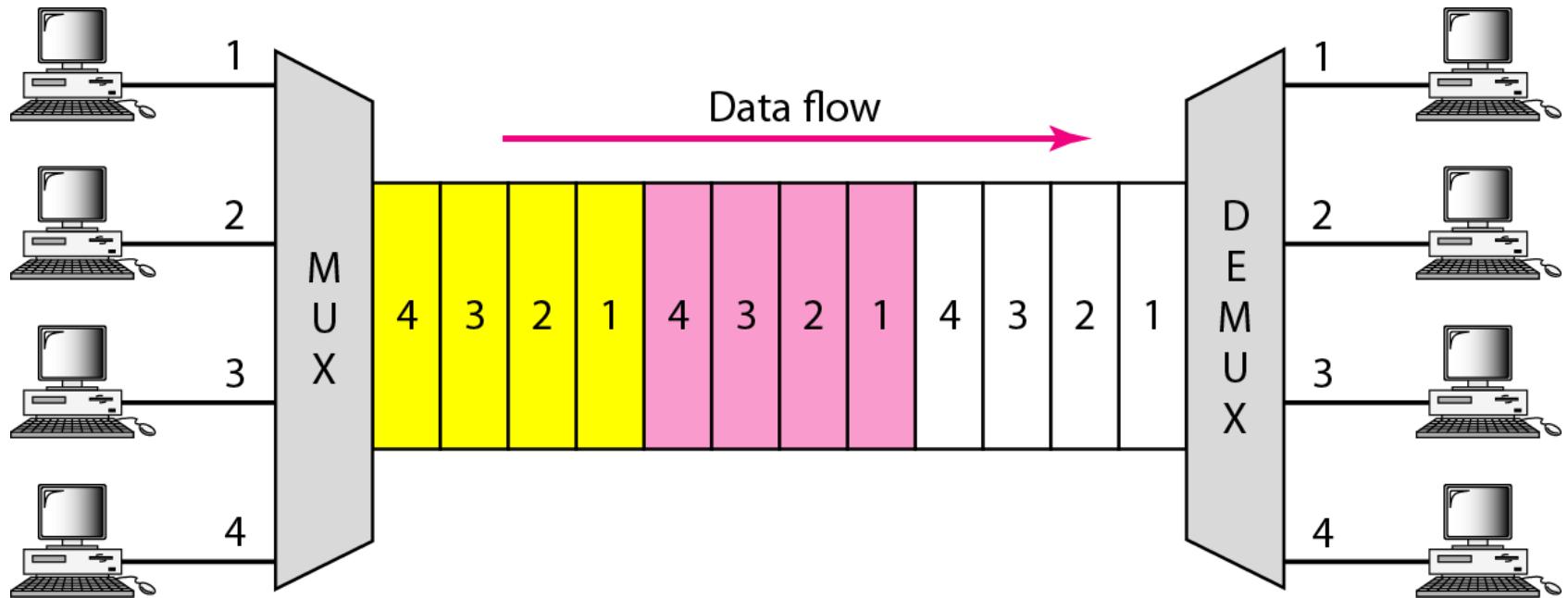
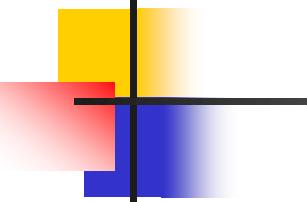


Figure 6.12 TDM

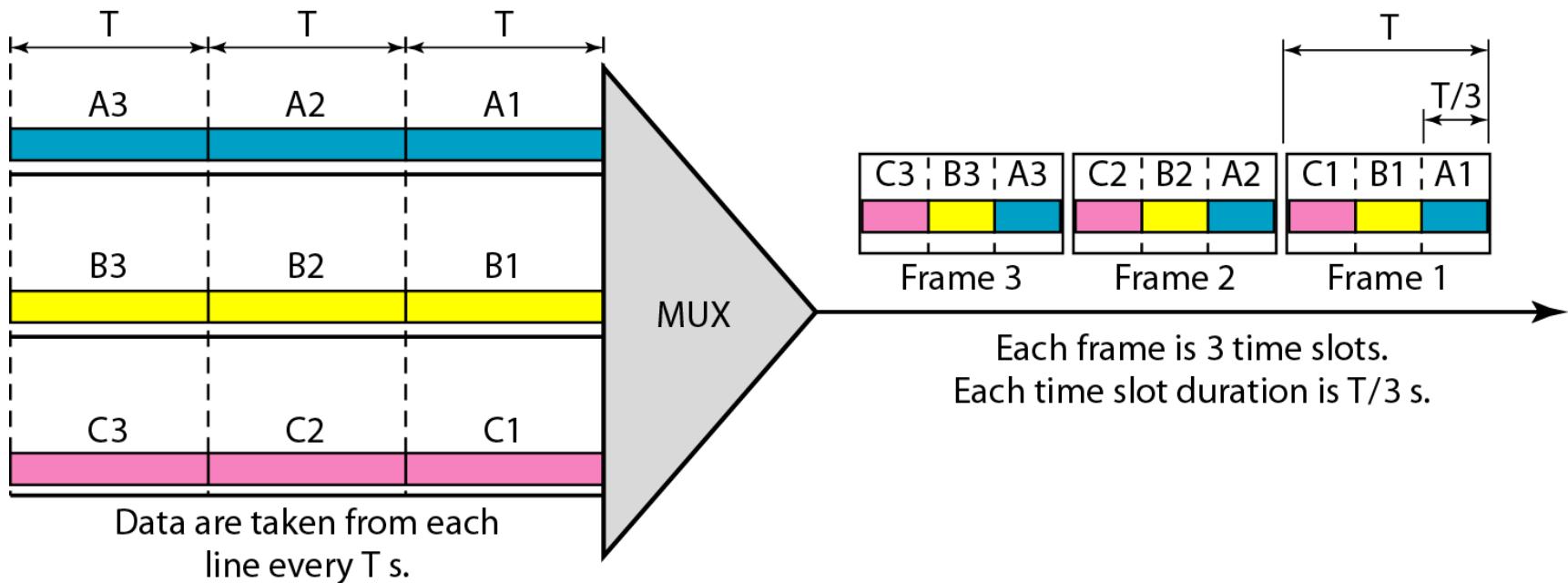


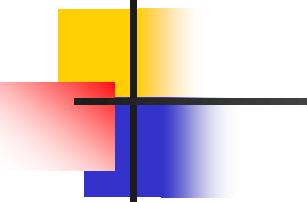


Note

**TDM is a digital multiplexing technique
for combining several low-rate
channels into one high-rate one.**

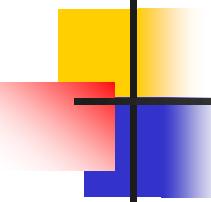
Figure 6.13 Synchronous time-division multiplexing





Note

In synchronous TDM, the data rate of the link is n times faster, and the unit duration is n times shorter.



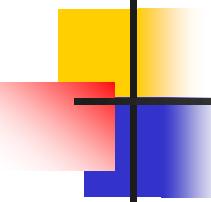
Example 6.5

In Figure 6.13, the data rate for each input connection is 3 kbps. If 1 bit at a time is multiplexed (a unit is 1 bit), what is the duration of (a) each input slot, (b) each output slot, and (c) each frame?

Solution

We can answer the questions as follows:

- a. *The data rate of each input connection is 1 kbps. This means that the bit duration is 1/1000 s or 1 ms. The duration of the input time slot is 1 ms (same as bit duration).*



Example 6.5 (continued)

- b.** *The duration of each output time slot is one-third of the input time slot. This means that the duration of the output time slot is $1/3$ ms.*
- c.** *Each frame carries three output time slots. So the duration of a frame is $3 \times 1/3$ ms, or 1 ms. The duration of a frame is the same as the duration of an input unit.*

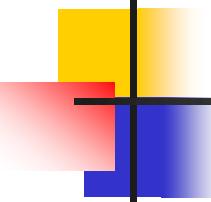
Example 6.6

Figure 6.14 shows synchronous TDM with a data stream for each input and one data stream for the output. The unit of data is 1 bit. Find (a) the input bit duration, (b) the output bit duration, (c) the output bit rate, and (d) the output frame rate.

Solution

We can answer the questions as follows:

- a. *The input bit duration is the inverse of the bit rate:
 $1/1 \text{ Mbps} = 1 \mu\text{s}$.*
- b. *The output bit duration is one-fourth of the input bit duration, or $\frac{1}{4} \mu\text{s}$.*

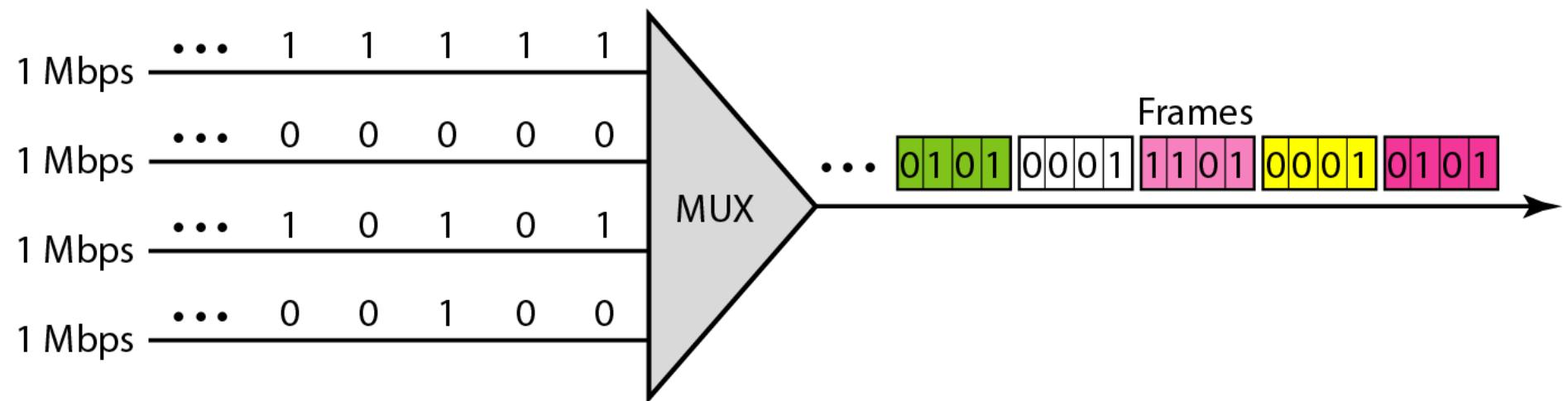


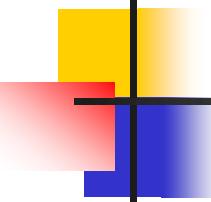
Example 6.6 (continued)

- c. *The output bit rate is the inverse of the output bit duration or $1/(4\mu s)$ or 4 Mbps. This can also be deduced from the fact that the output rate is 4 times as fast as any input rate; so the output rate = $4 \times 1 \text{ Mbps} = 4 \text{ Mbps}$.*

- d. *The frame rate is always the same as any input rate. So the frame rate is 1,000,000 frames per second. Because we are sending 4 bits in each frame, we can verify the result of the previous question by multiplying the frame rate by the number of bits per frame.*

Figure 6.14 Example 6.6





Example 6.7

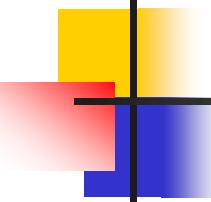
Four 1-kbps connections are multiplexed together. A unit is 1 bit. Find (a) the duration of 1 bit before multiplexing, (b) the transmission rate of the link, (c) the duration of a time slot, and (d) the duration of a frame.

Solution

We can answer the questions as follows:

- a. The duration of 1 bit before multiplexing is $1 / 1 \text{ kbps}$, or $0.001 \text{ s} (1 \text{ ms})$.*

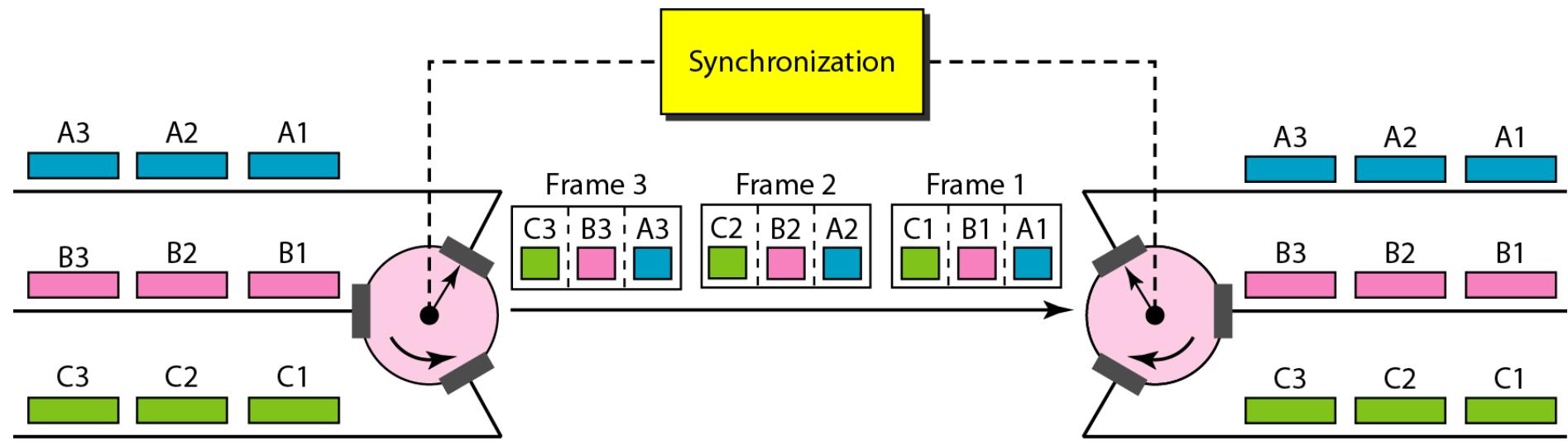
- b. The rate of the link is 4 times the rate of a connection, or 4 kbps .*



Example 6.7 (continued)

- c. The duration of each time slot is one-fourth of the duration of each bit before multiplexing, or $1/4$ ms or $250 \mu\text{s}$. Note that we can also calculate this from the data rate of the link, 4 kbps. The bit duration is the inverse of the data rate, or $1/4$ kbps or $250 \mu\text{s}$.
- d. The duration of a frame is always the same as the duration of a unit before multiplexing, or 1 ms. We can also calculate this in another way. Each frame in this case has four time slots. So the duration of a frame is 4 times $250 \mu\text{s}$, or 1 ms.

Figure 6.15 *Interleaving*



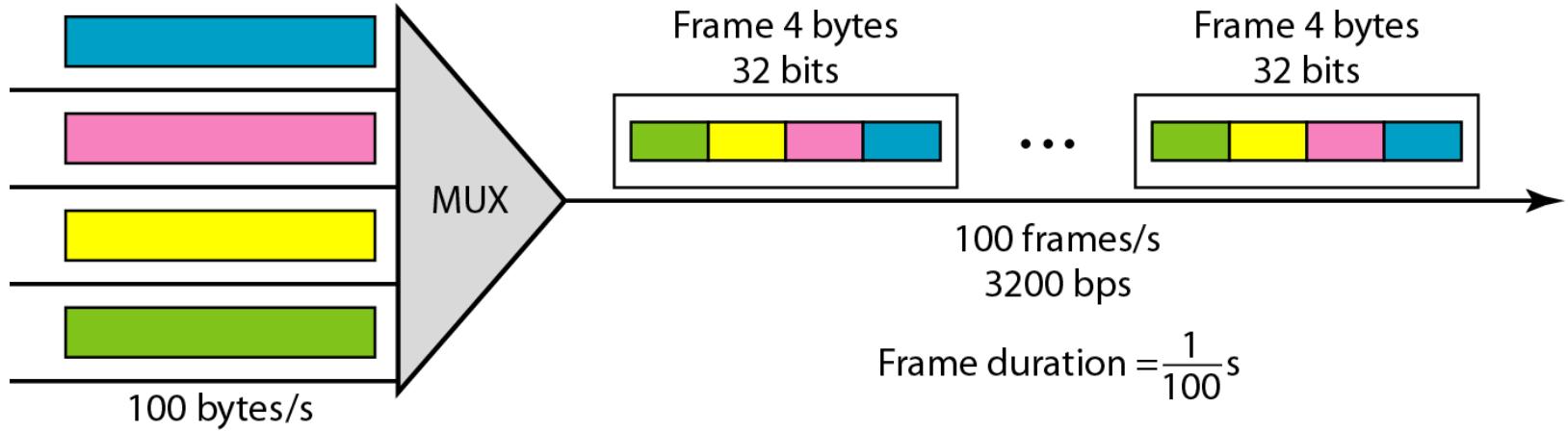
Example 6.8

Four channels are multiplexed using TDM. If each channel sends 100 bytes /s and we multiplex 1 byte per channel, show the frame traveling on the link, the size of the frame, the duration of a frame, the frame rate, and the bit rate for the link.

Solution

The multiplexer is shown in Figure 6.16. Each frame carries 1 byte from each channel; the size of each frame, therefore, is 4 bytes, or 32 bits. Because each channel is sending 100 bytes/s and a frame carries 1 byte from each channel, the frame rate must be 100 frames per second. The bit rate is 100×32 , or 3200 bps.

Figure 6.16 Example 6.8



Example 6.9

A multiplexer combines four 100-kbps channels using a time slot of 2 bits. Show the output with four arbitrary inputs. What is the frame rate? What is the frame duration? What is the bit rate? What is the bit duration?

Solution

Figure 6.17 shows the output for four arbitrary inputs. The link carries 50,000 frames per second. The frame duration is therefore $1/50,000$ s or 20 μ s. The frame rate is 50,000 frames per second, and each frame carries 8 bits; the bit rate is $50,000 \times 8 = 400,000$ bits or 400 kbps. The bit duration is $1/400,000$ s, or 2.5 μ s.

Figure 6.17 Example 6.9

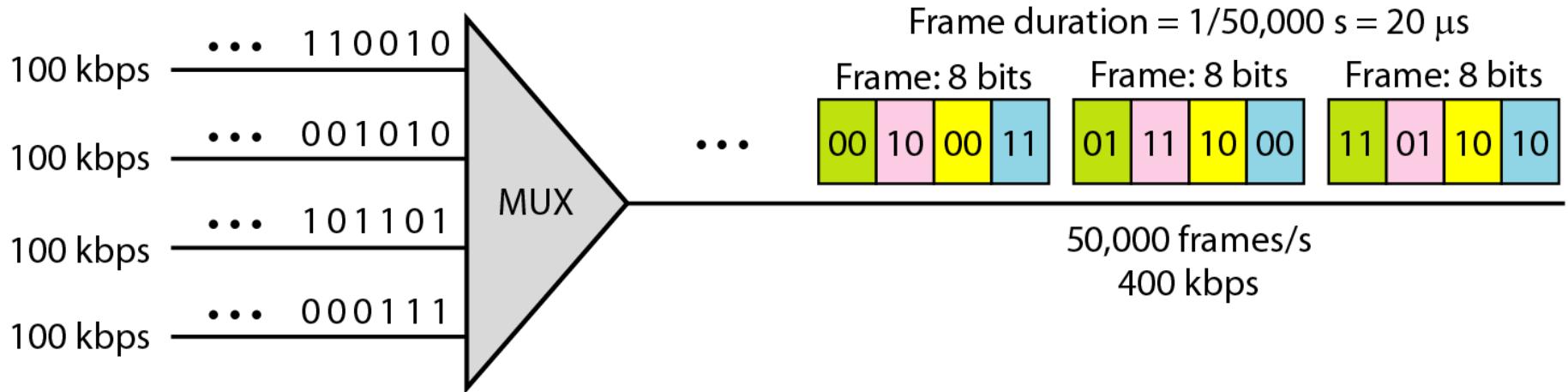


Figure 6.18 *Empty slots*

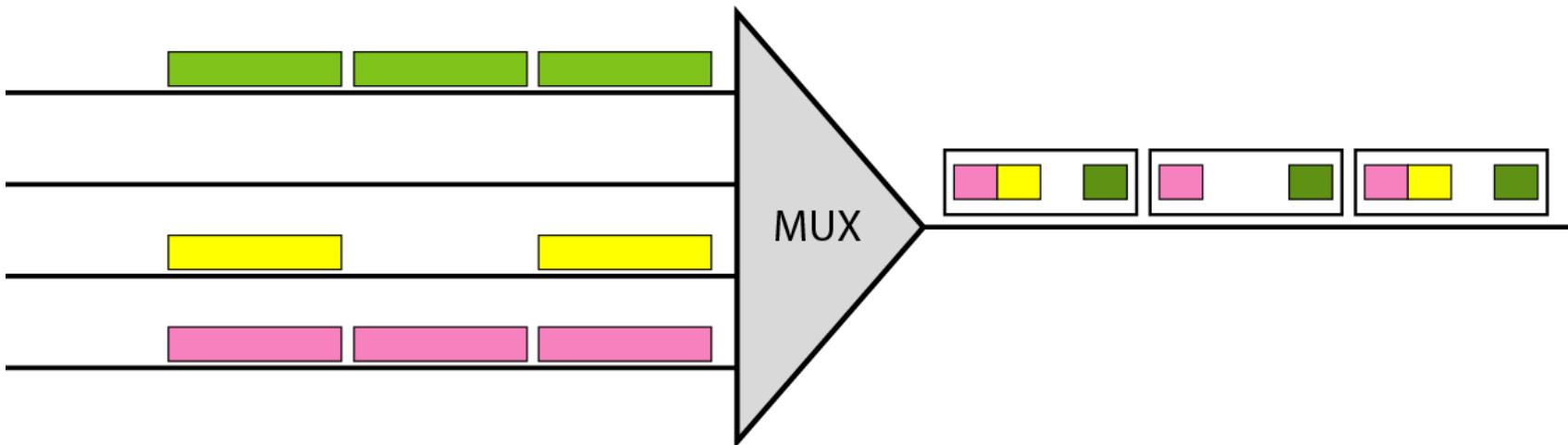


Figure 6.19 *Multilevel multiplexing*

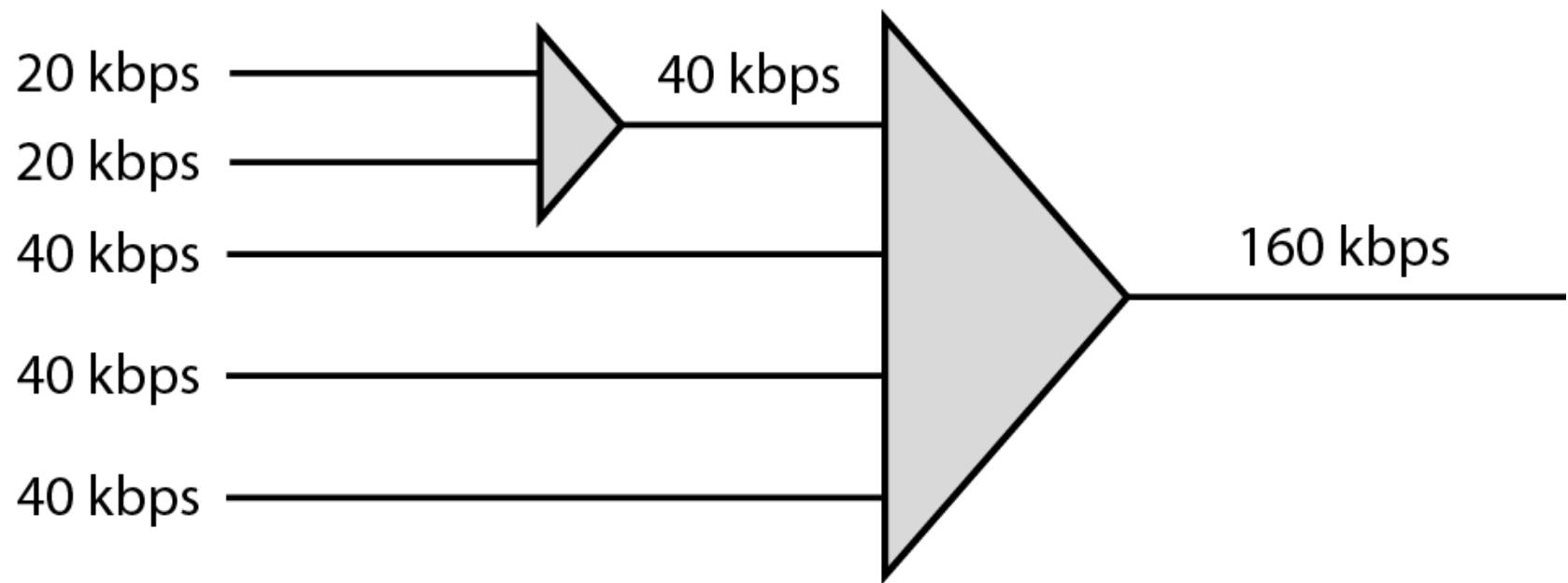


Figure 6.20 *Multiple-slot multiplexing*

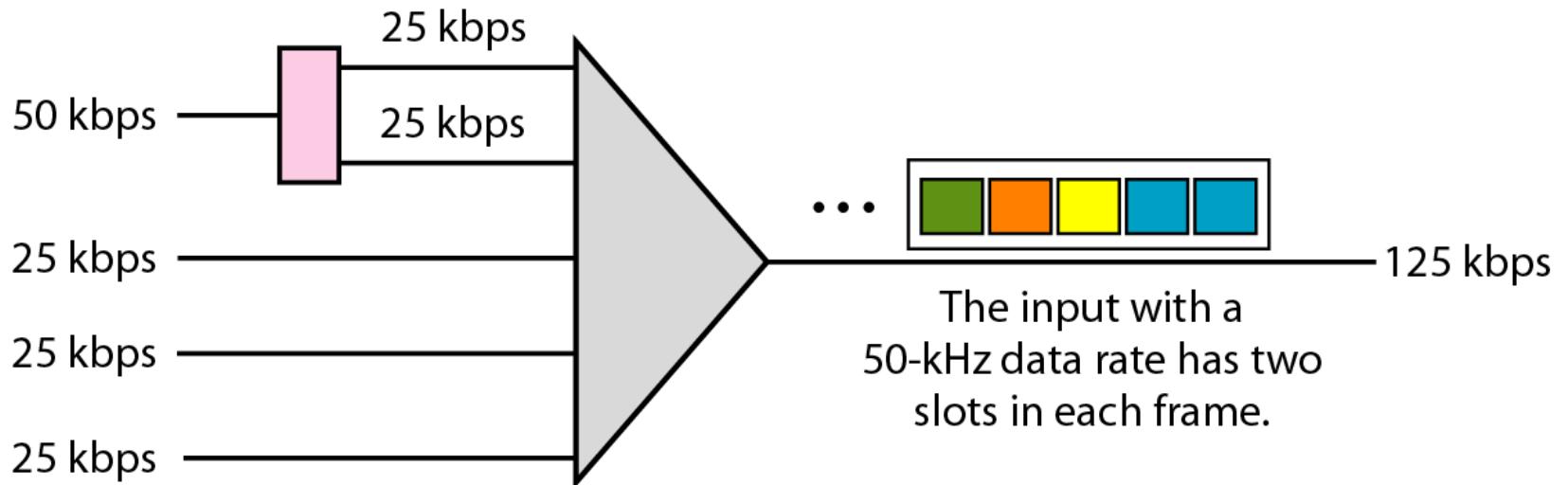


Figure 6.21 *Pulse stuffing*

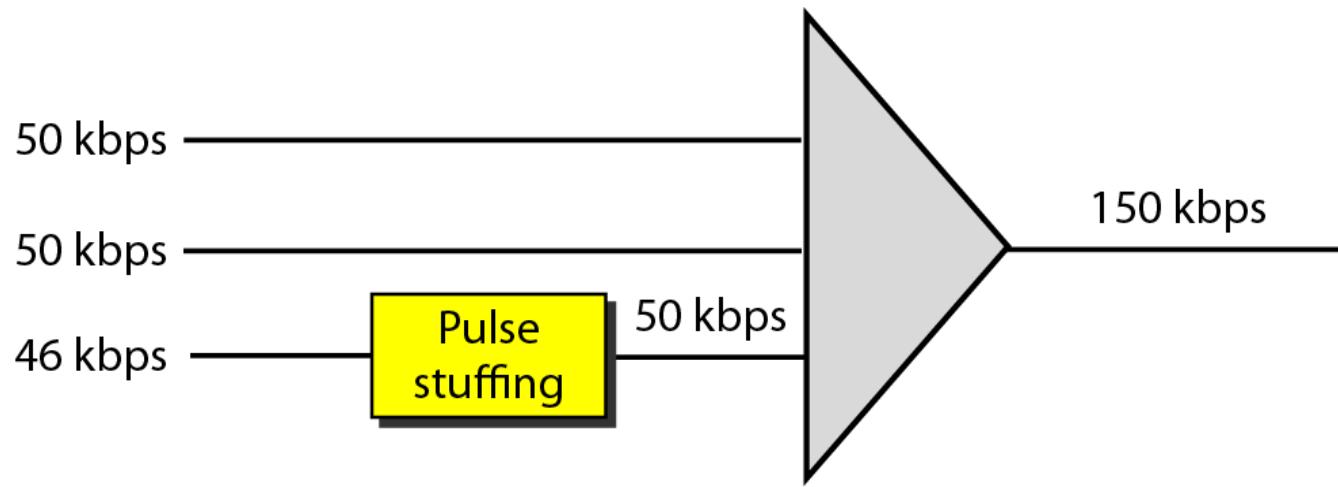
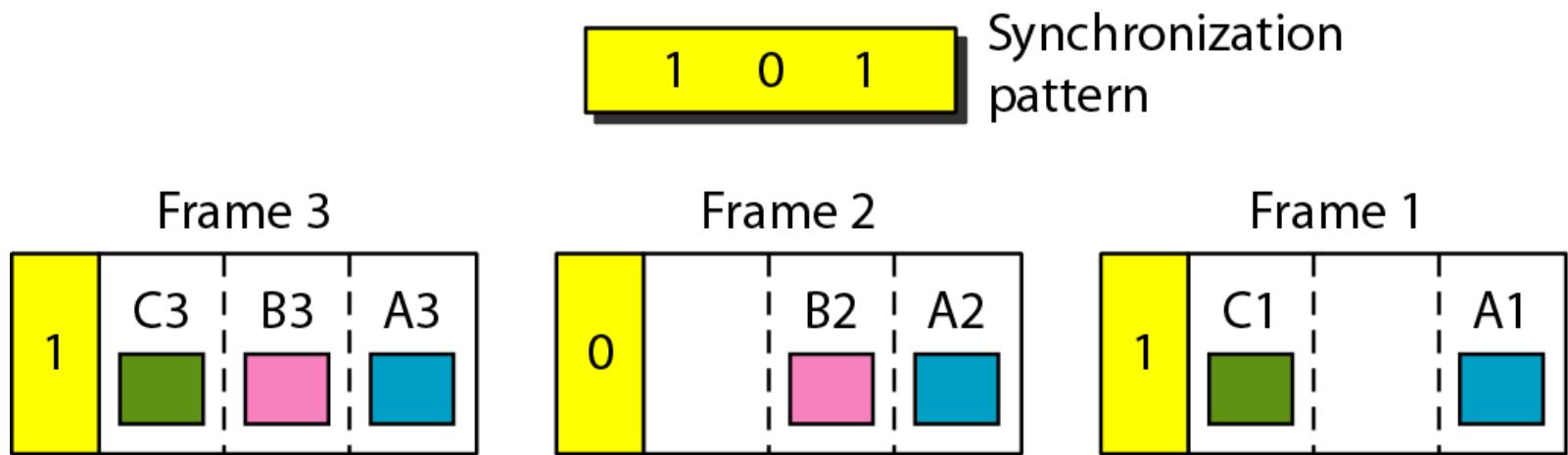
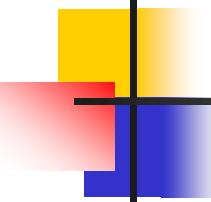


Figure 6.22 *Framing bits*





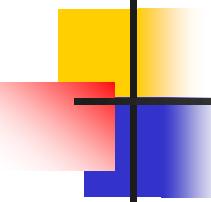
Example 6.10

We have four sources, each creating 250 characters per second. If the interleaved unit is a character and 1 synchronizing bit is added to each frame, find (a) the data rate of each source, (b) the duration of each character in each source, (c) the frame rate, (d) the duration of each frame, (e) the number of bits in each frame, and (f) the data rate of the link.

Solution

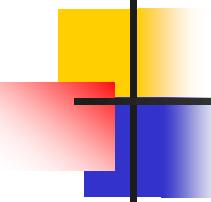
We can answer the questions as follows:

- a. The data rate of each source is $250 \times 8 = 2000 \text{ bps} = 2 \text{ kbps}$.



Example 6.10 (continued)

- b.** *Each source sends 250 characters per second; therefore, the duration of a character is 1/250 s, or 4 ms.*
- c.** *Each frame has one character from each source, which means the link needs to send 250 frames per second to keep the transmission rate of each source.*
- d.** *The duration of each frame is 1/250 s, or 4 ms. Note that the duration of each frame is the same as the duration of each character coming from each source.*
- e.** *Each frame carries 4 characters and 1 extra synchronizing bit. This means that each frame is $4 \times 8 + 1 = 33$ bits.*



Example 6.11

Two channels, one with a bit rate of 100 kbps and another with a bit rate of 200 kbps, are to be multiplexed. How this can be achieved? What is the frame rate? What is the frame duration? What is the bit rate of the link?

Solution

We can allocate one slot to the first channel and two slots to the second channel. Each frame carries 3 bits. The frame rate is 100,000 frames per second because it carries 1 bit from the first channel. The bit rate is 100,000 frames/s × 3 bits per frame, or 300 kbps.

Figure 6.23 *Digital hierarchy*

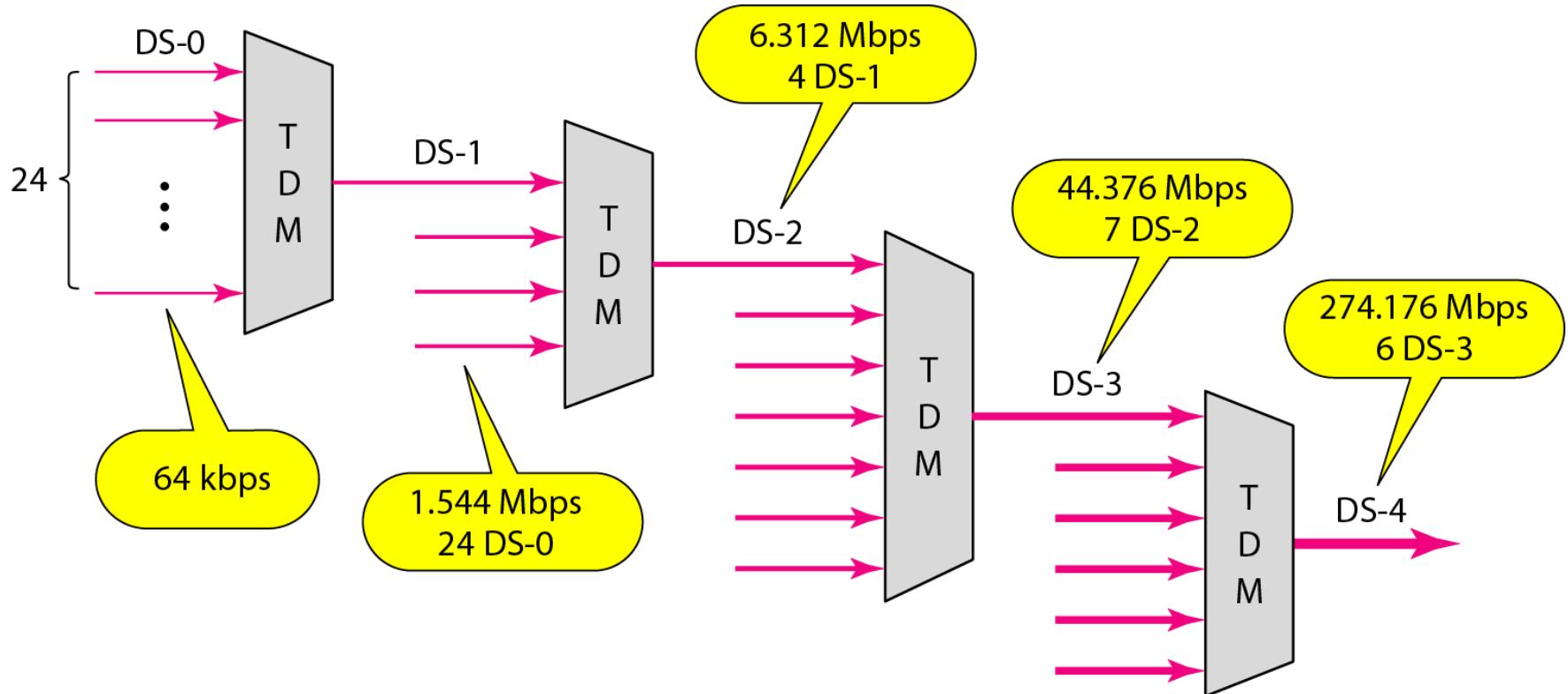


Table 6.1 DS and T line rates

<i>Service</i>	<i>Line</i>	<i>Rate (Mbps)</i>	<i>Voice Channels</i>
DS-1	T-1	1.544	24
DS-2	T-2	6.312	96
DS-3	T-3	44.736	672
DS-4	T-4	274.176	4032

Figure 6.24 T-1 line for multiplexing telephone lines

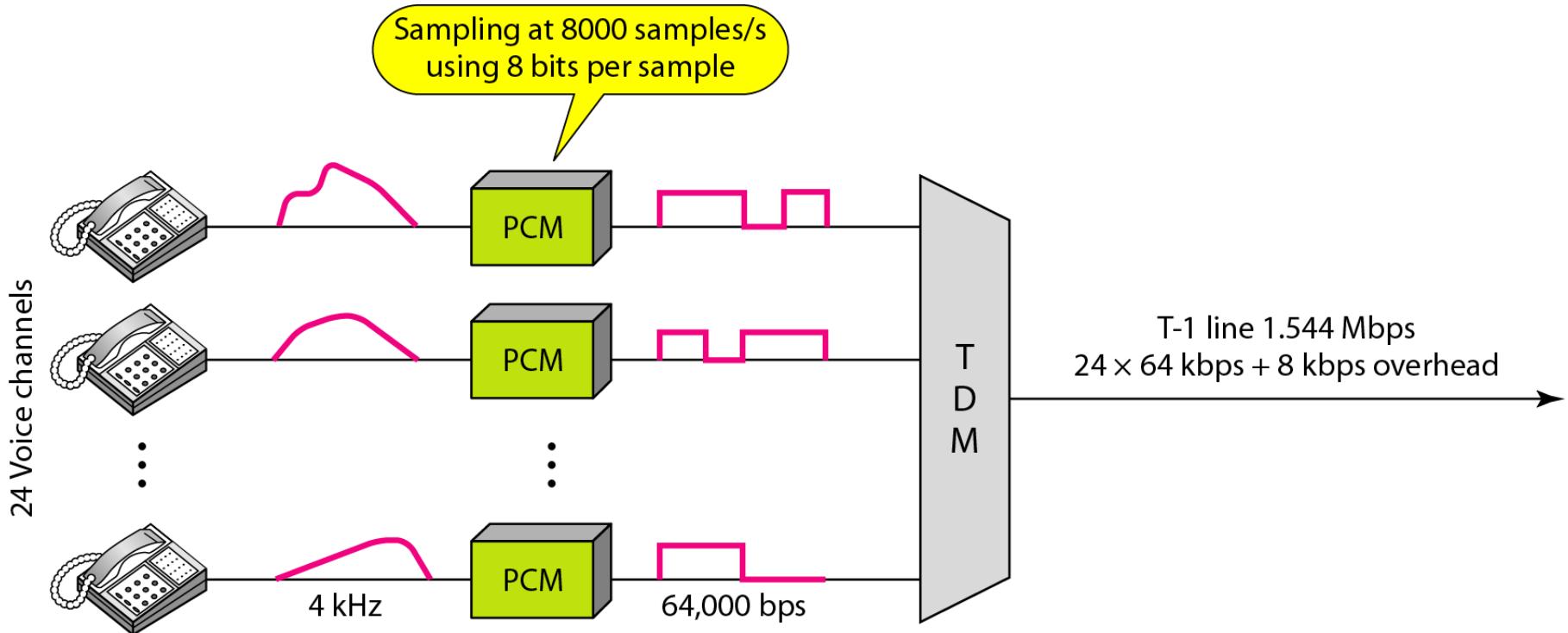


Figure 6.25 T-1 frame structure

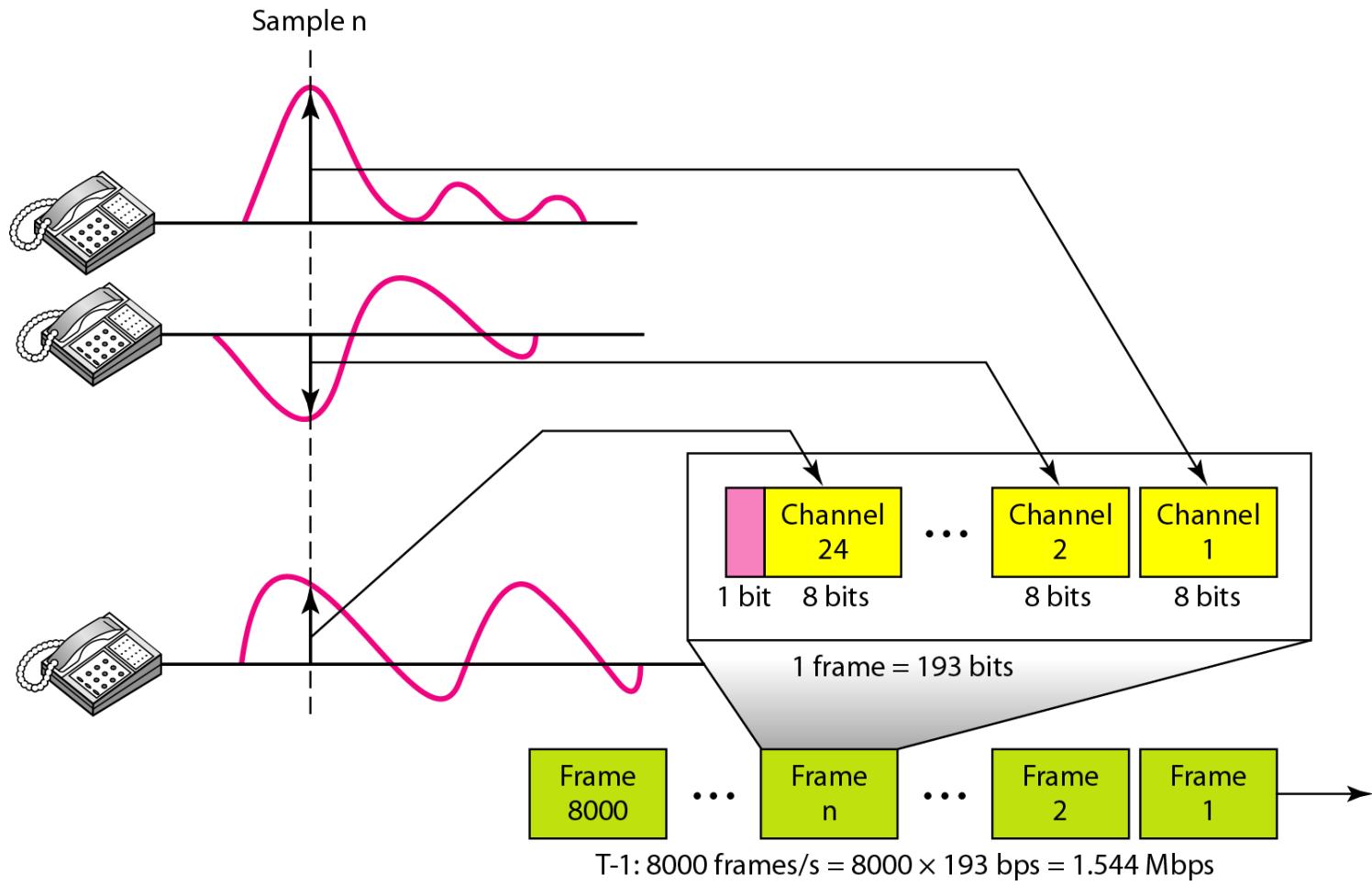
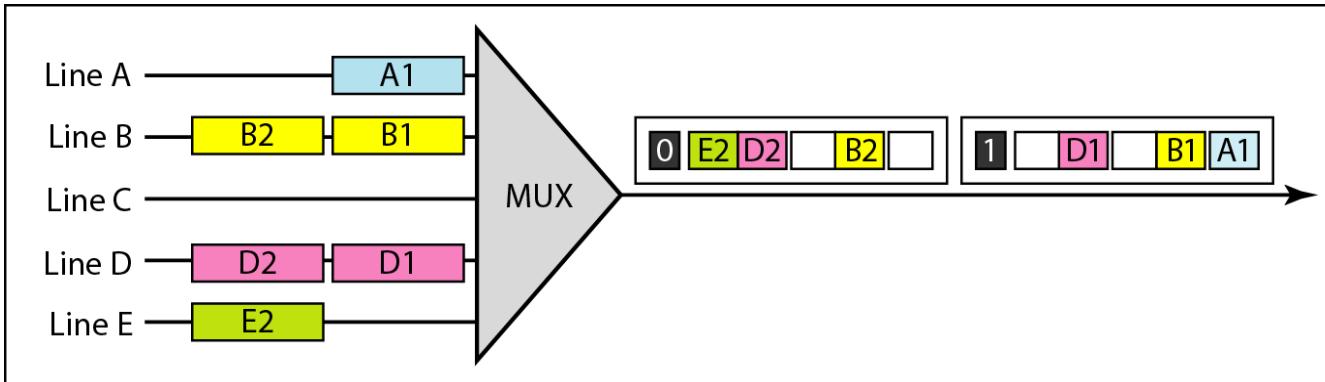


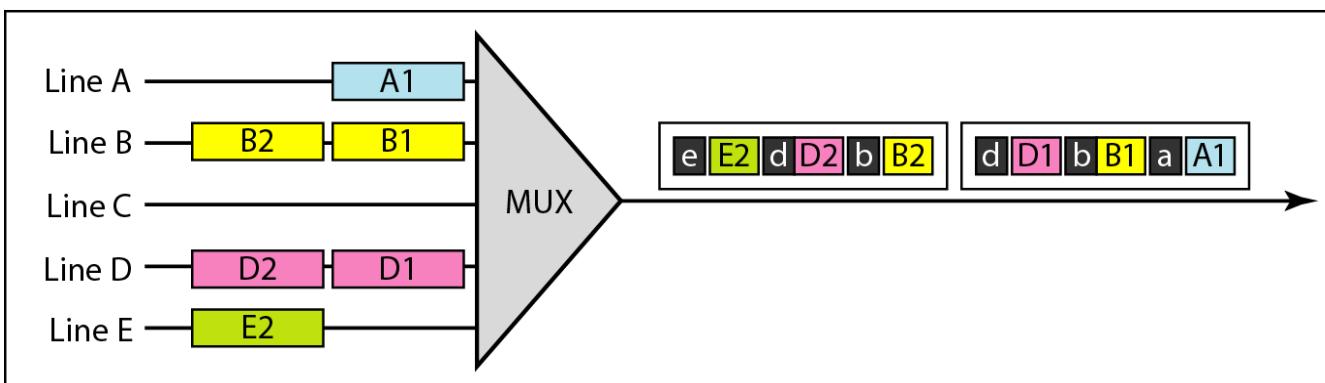
Table 6.2 *E line rates*

<i>Line</i>	<i>Rate (Mbps)</i>	<i>Voice Channels</i>
E-1	2.048	30
E-2	8.448	120
E-3	34.368	480
E-4	139.264	1920

Figure 6.26 TDM slot comparison



a. Synchronous TDM



b. Statistical TDM

6-1 SPREAD SPECTRUM

In spread spectrum (SS), we combine signals from different sources to fit into a larger bandwidth, but our goals are to prevent eavesdropping and jamming. To achieve these goals, spread spectrum techniques add redundancy.

Topics discussed in this section:

Frequency Hopping Spread Spectrum (FHSS)

Direct Sequence Spread Spectrum Synchronous (DSSS)

Figure 6.27 *Spread spectrum*

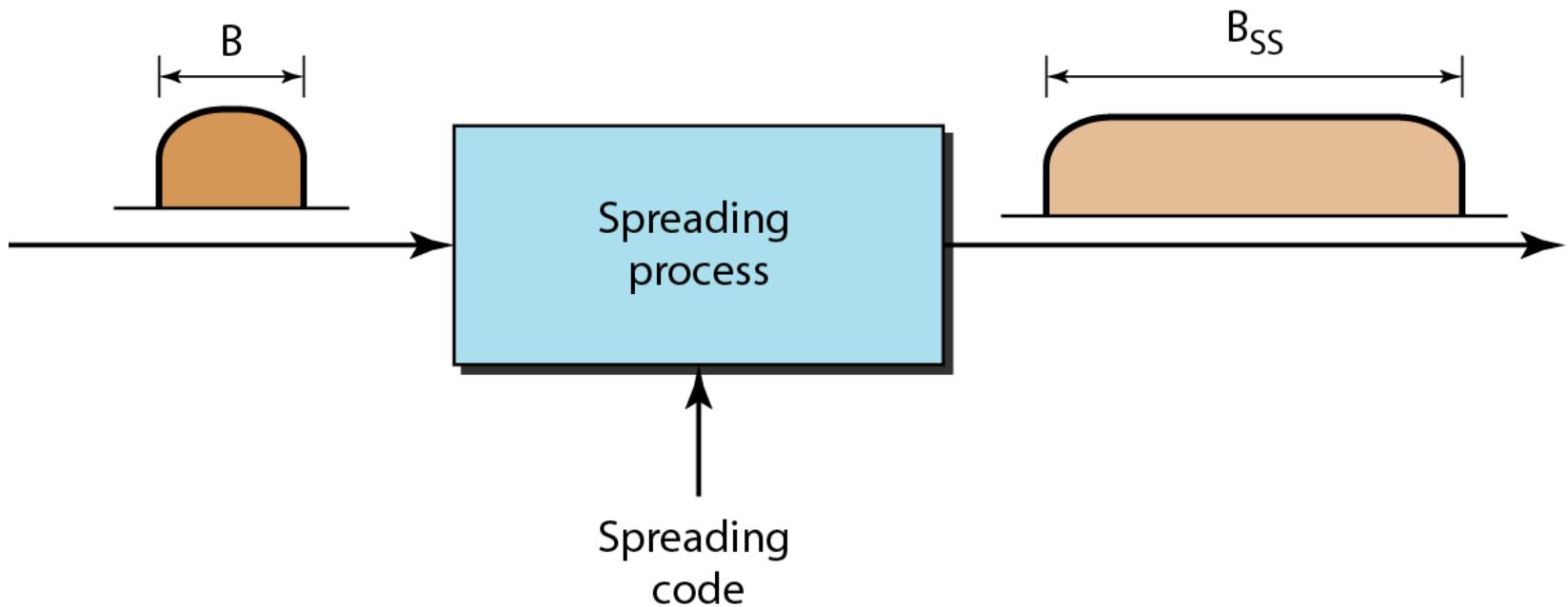


Figure 6.28 Frequency hopping spread spectrum (FHSS)

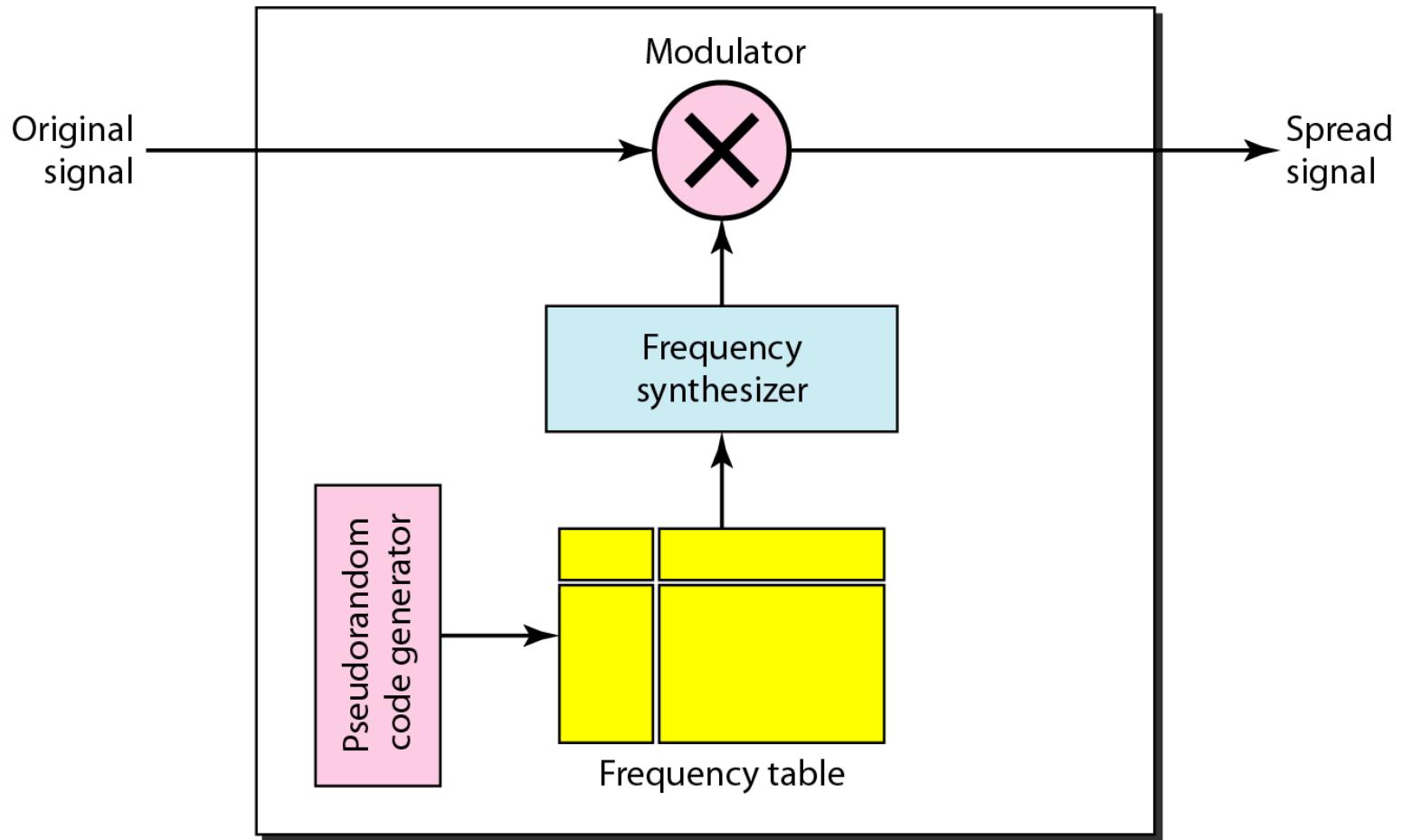


Figure 6.29 Frequency selection in FHSS

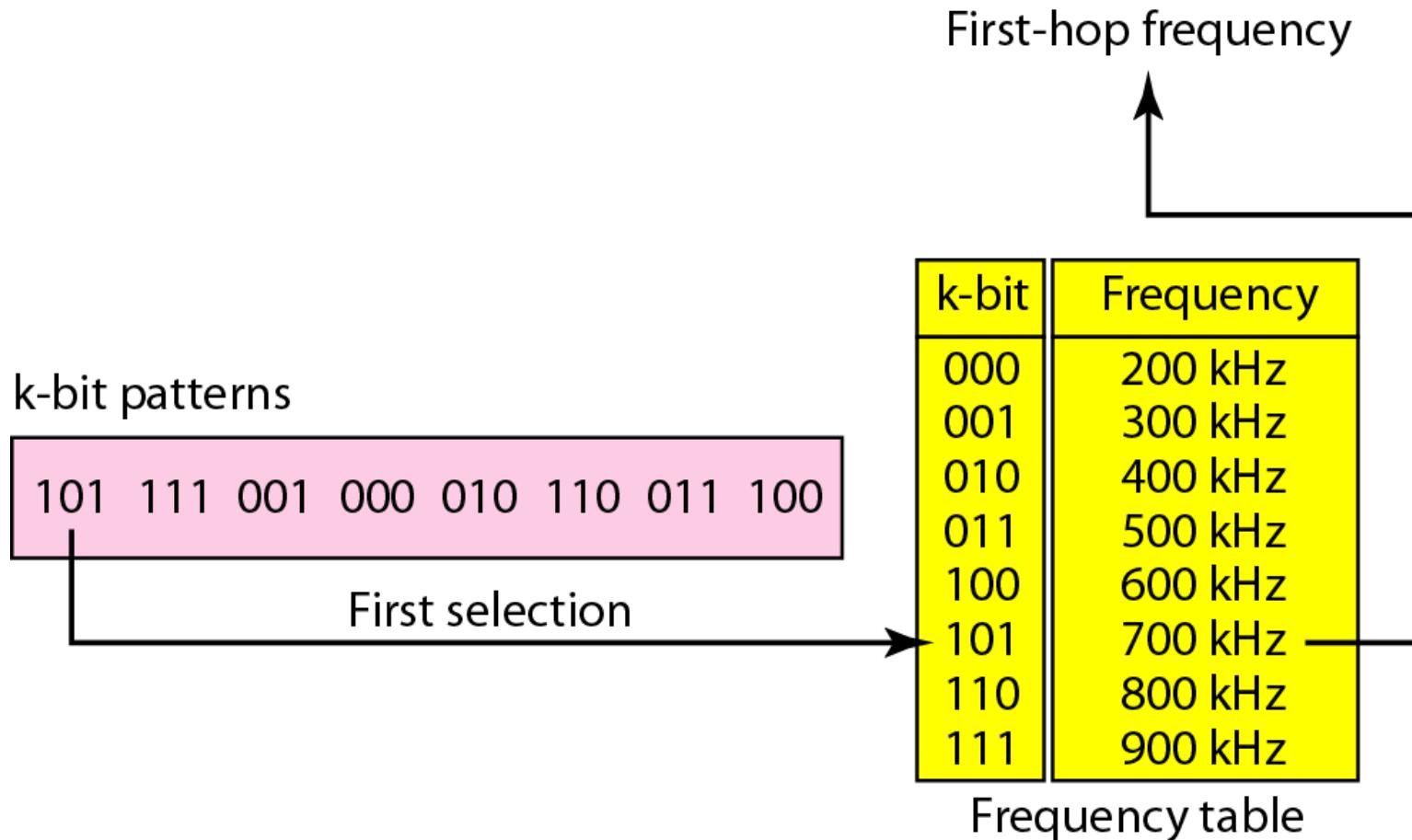


Figure 6.30 FHSS cycles

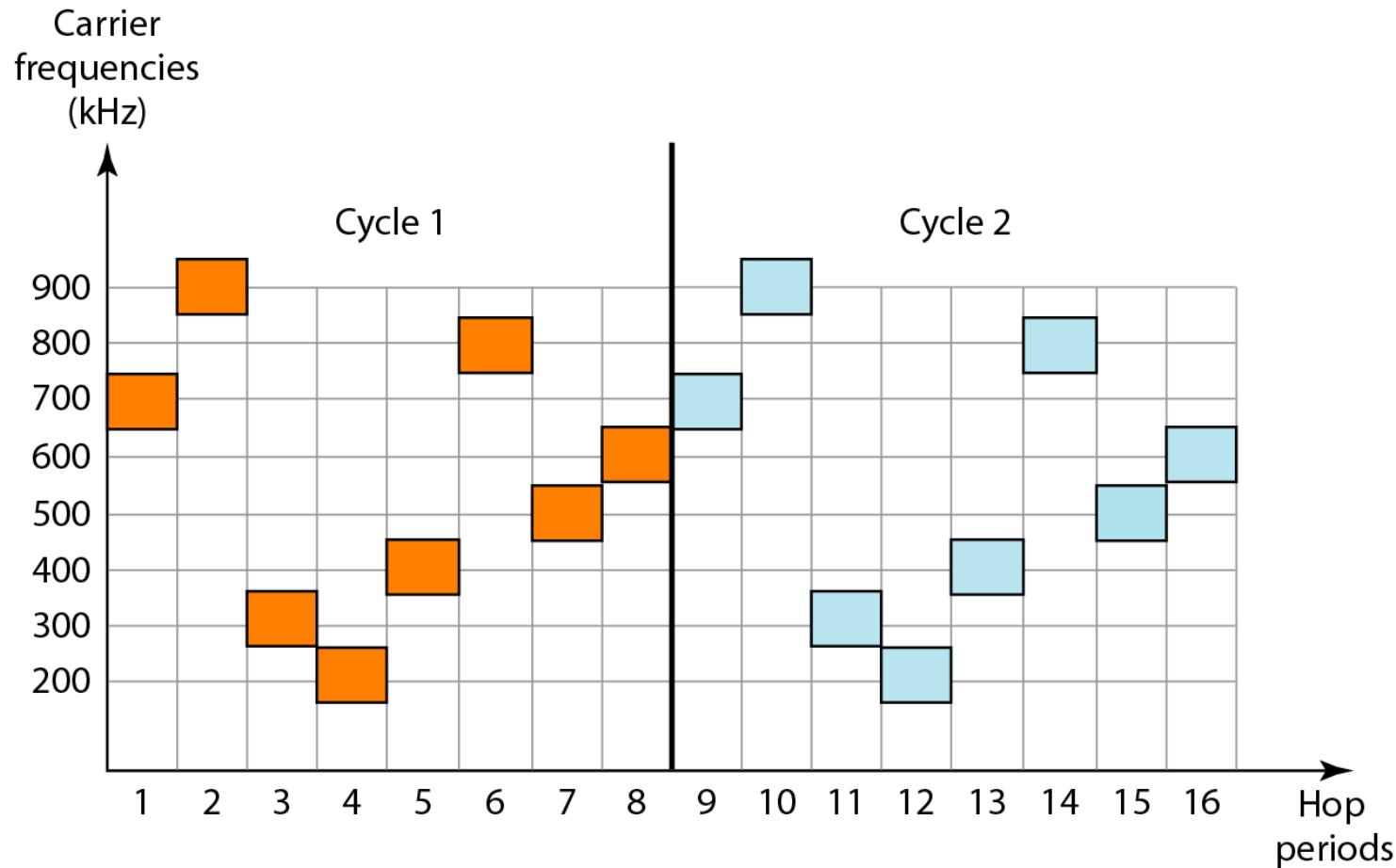
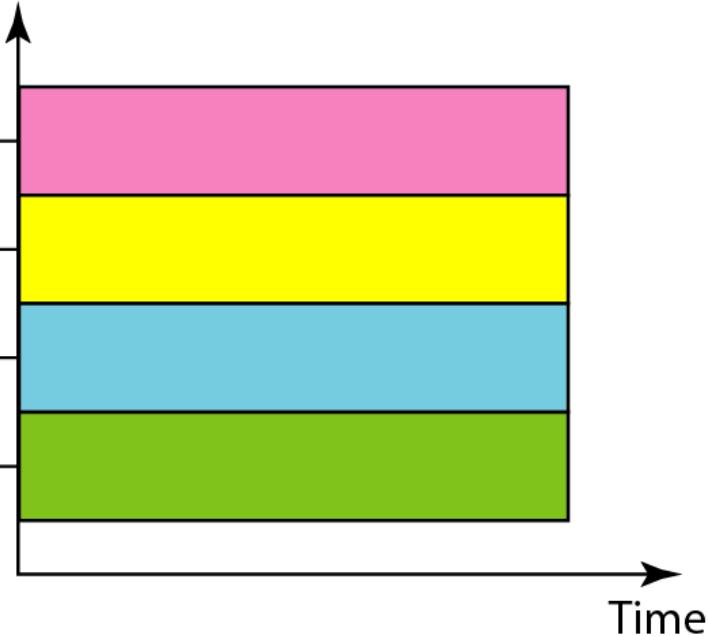


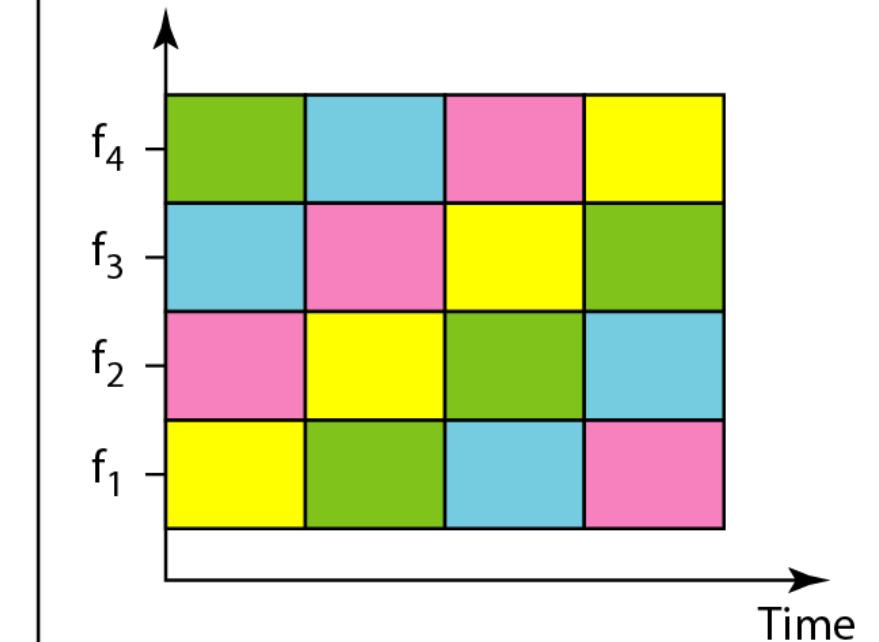
Figure 6.31 *Bandwidth sharing*

Frequency



a. FDM

Frequency



b. FHSS

Figure 6.32 DSSS

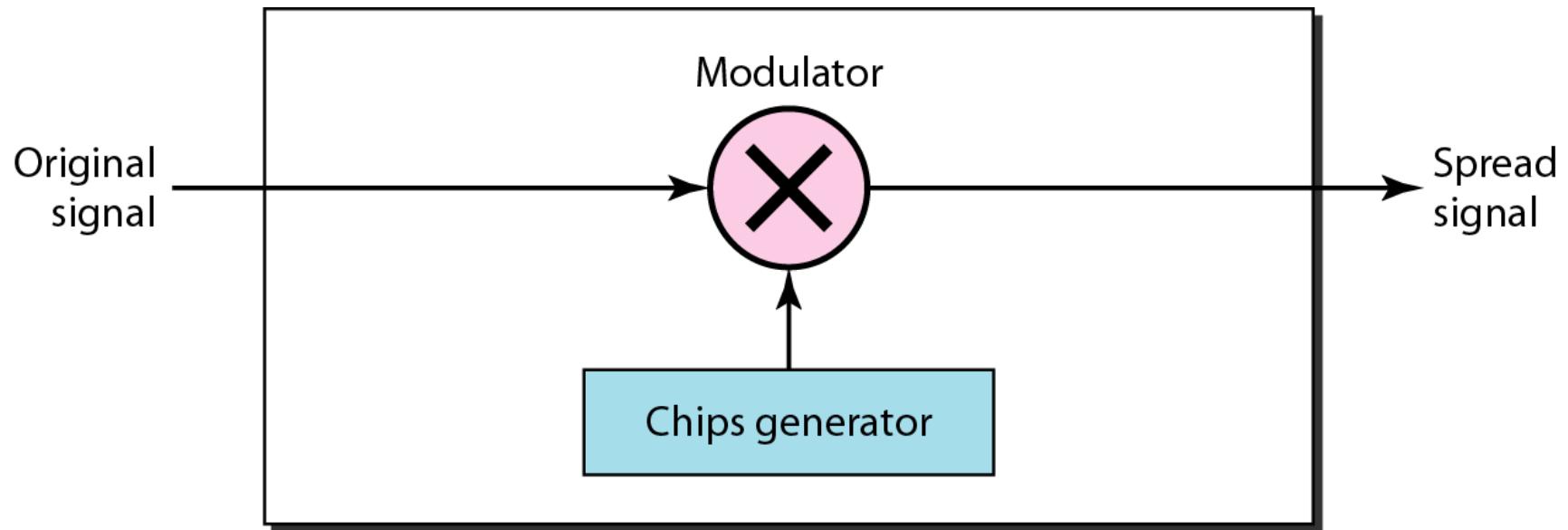
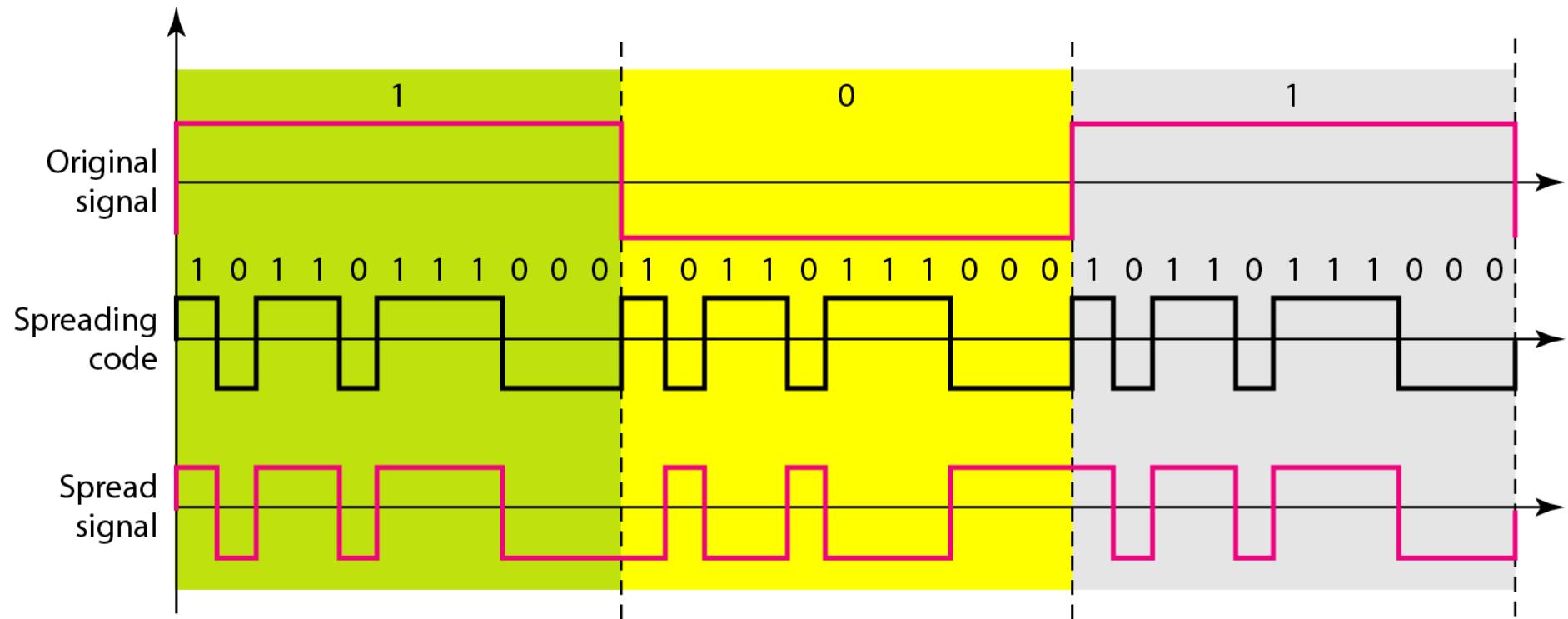


Figure 6.33 DSSS example





Chapter 7

Transmission Media

Figure 7.1 *Transmission medium and physical layer*

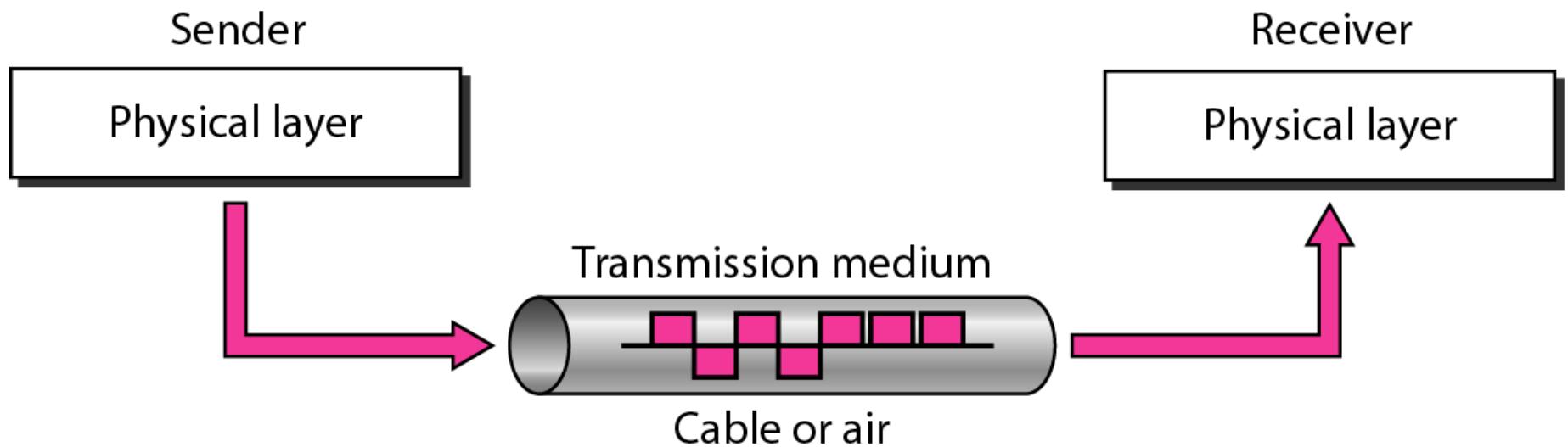
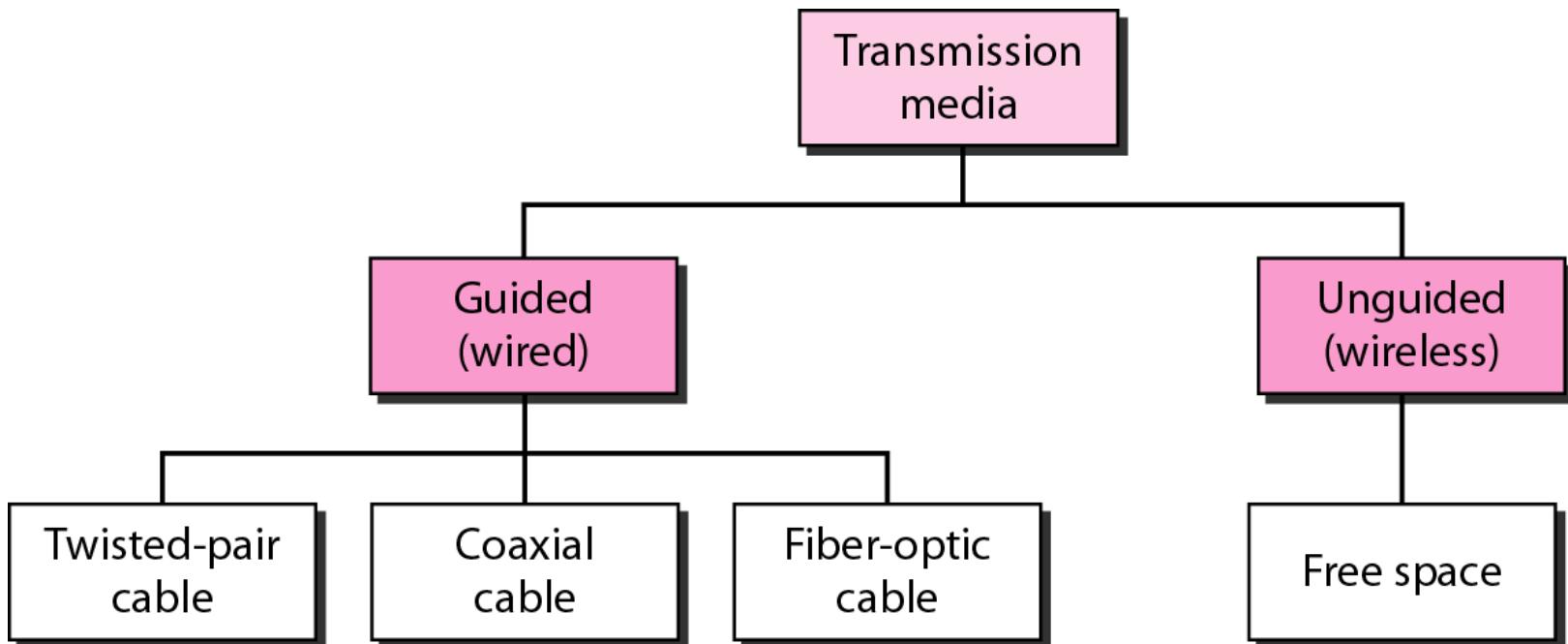


Figure 7.2 *Classes of transmission media*



7-1 GUIDED MEDIA

Guided media, which are those that provide a conduit from one device to another, include twisted-pair cable, coaxial cable, and fiber-optic cable.

Topics discussed in this section:

Twisted-Pair Cable

Coaxial Cable

Fiber-Optic Cable

Figure 7.3 *Twisted-pair cable*

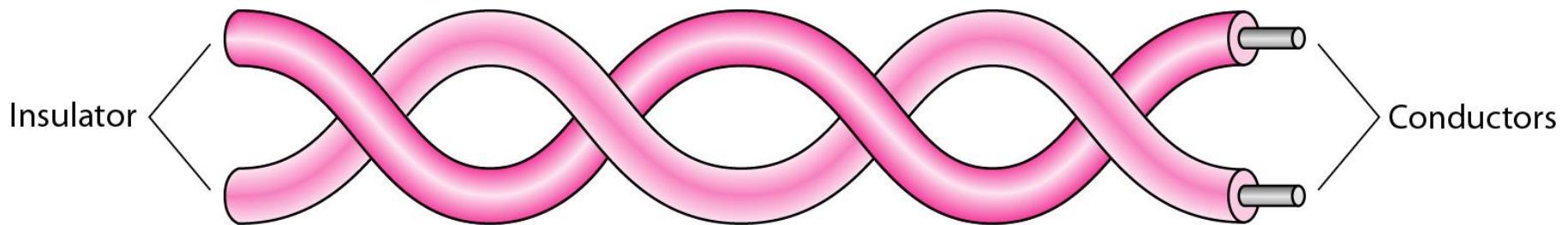
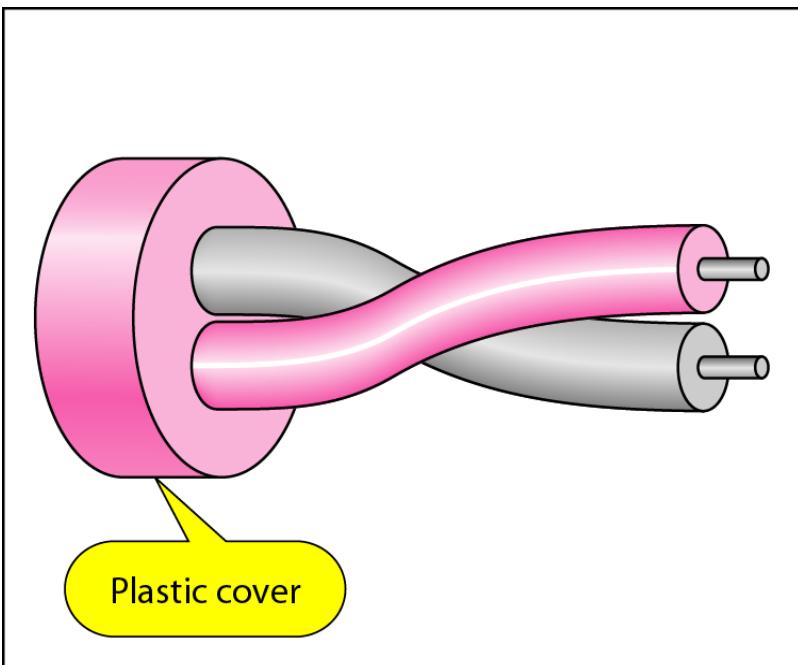
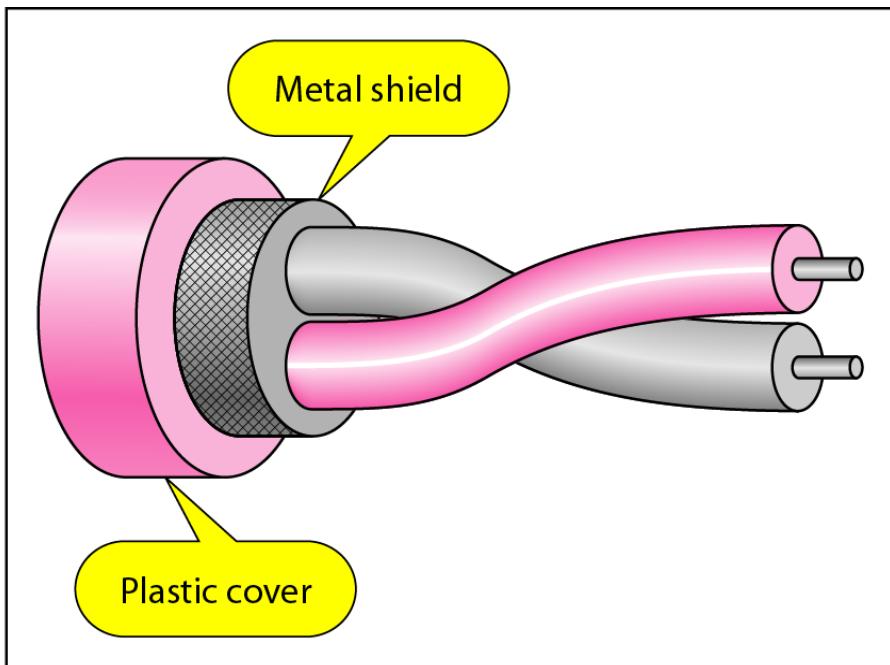


Figure 7.4 *UTP and STP cables*



a. UTP



b. STP

Table 7.1 *Categories of unshielded twisted-pair cables*

Category	Specification	Data Rate (Mbps)	Use
1	Unshielded twisted-pair used in telephone	< 0.1	Telephone
2	Unshielded twisted-pair originally used in T-lines	2	T-1 lines
3	Improved CAT 2 used in LANs	10	LANs
4	Improved CAT 3 used in Token Ring networks	20	LANs
5	Cable wire is normally 24 AWG with a jacket and outside sheath	100	LANs
5E	An extension to category 5 that includes extra features to minimize the crosstalk and electromagnetic interference	125	LANs
6	A new category with matched components coming from the same manufacturer. The cable must be tested at a 200-Mbps data rate.	200	LANs
7	Sometimes called SSTP (shielded screen twisted-pair). Each pair is individually wrapped in a helical metallic foil followed by a metallic foil shield in addition to the outside sheath. The shield decreases the effect of crosstalk and increases the data rate.	600	LANs

Figure 7.5 UTP connector

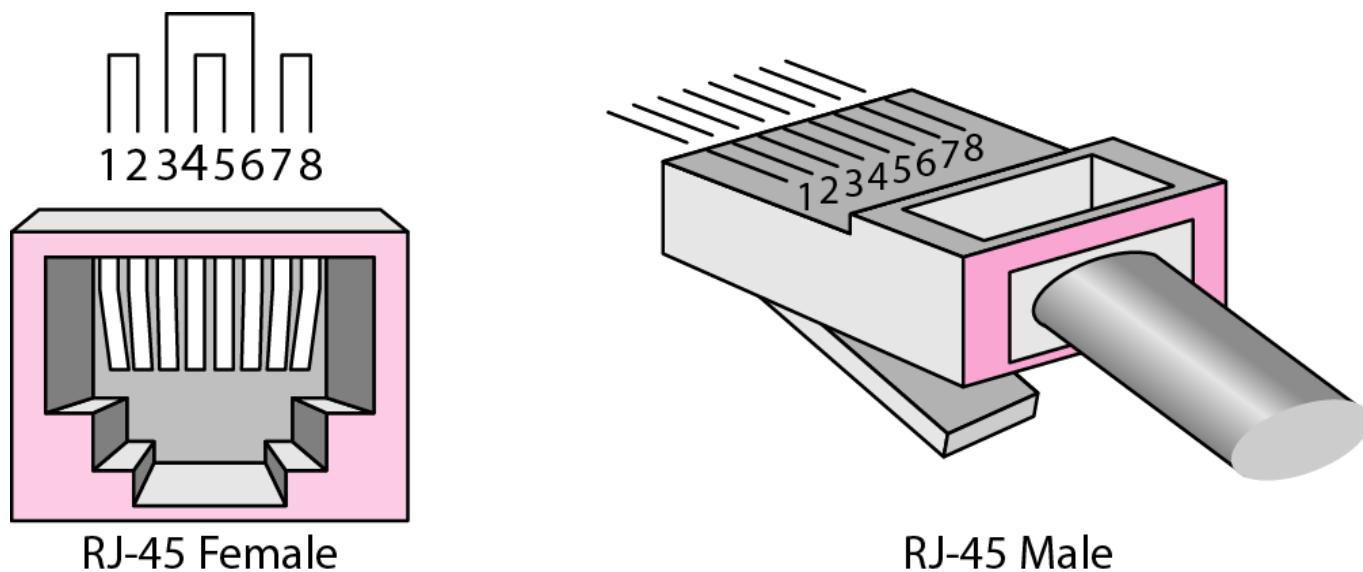


Figure 7.6 UTP performance

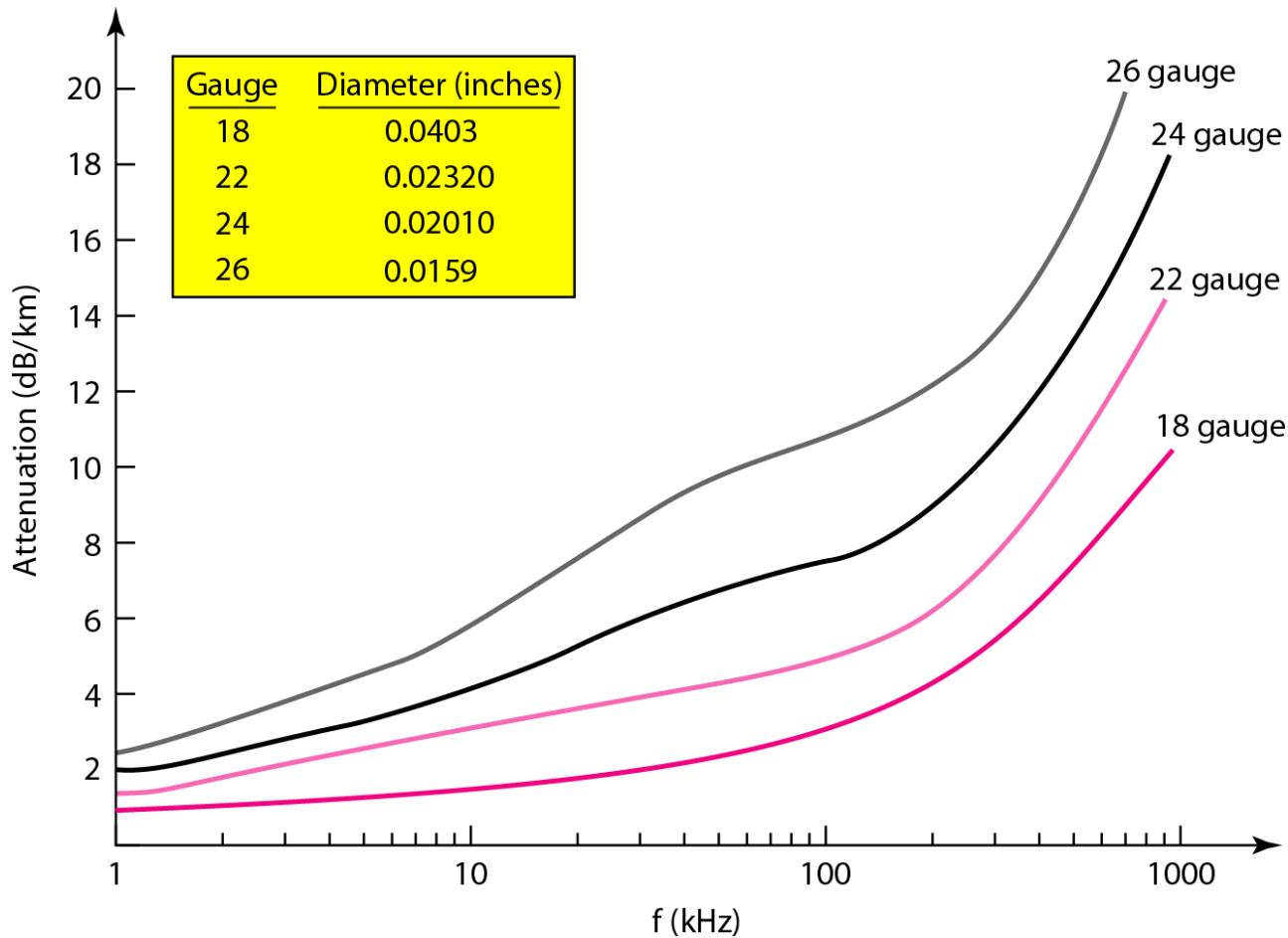


Figure 7.7 *Coaxial cable*

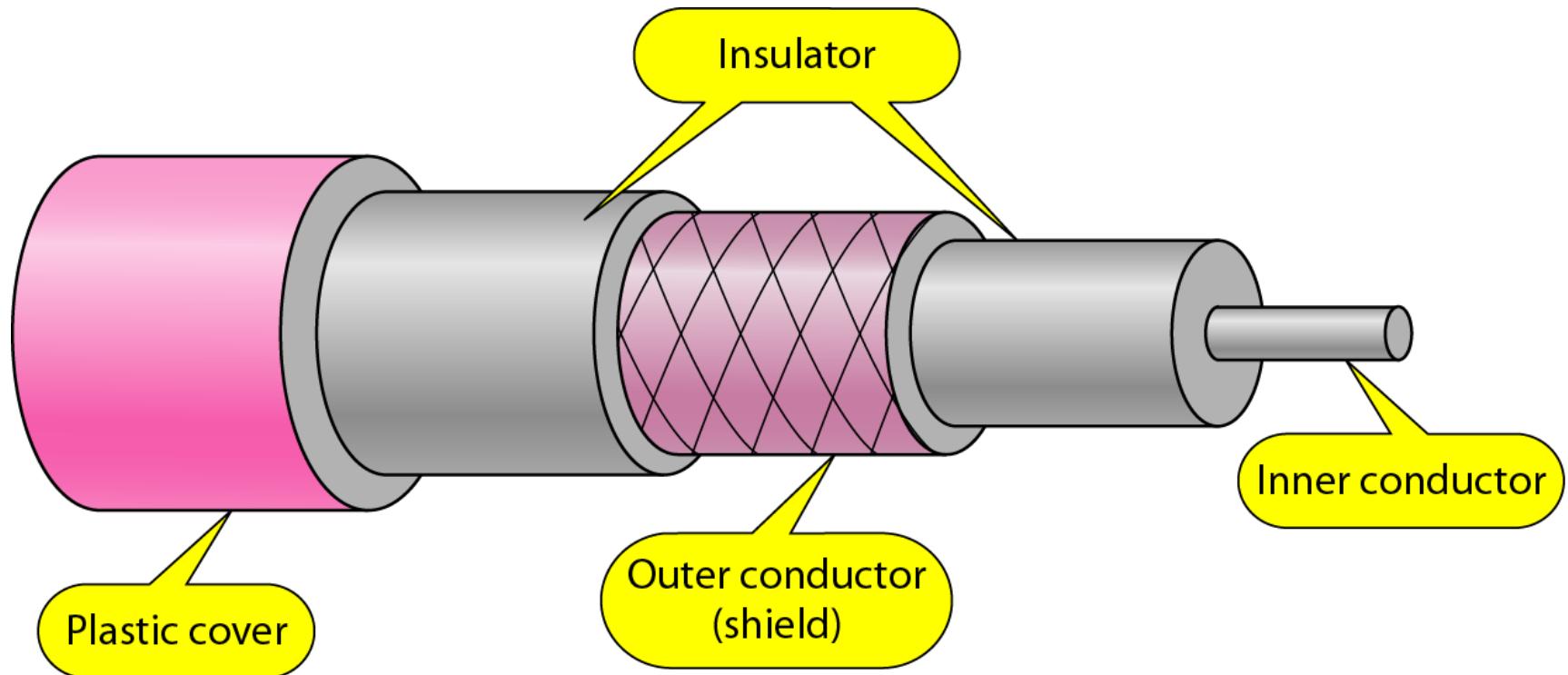


Table 7.2 *Categories of coaxial cables*

<i>Category</i>	<i>Impedance</i>	<i>Use</i>
RG-59	75Ω	Cable TV
RG-58	50Ω	Thin Ethernet
RG-11	50Ω	Thick Ethernet

Figure 7.8 *BNC connectors*

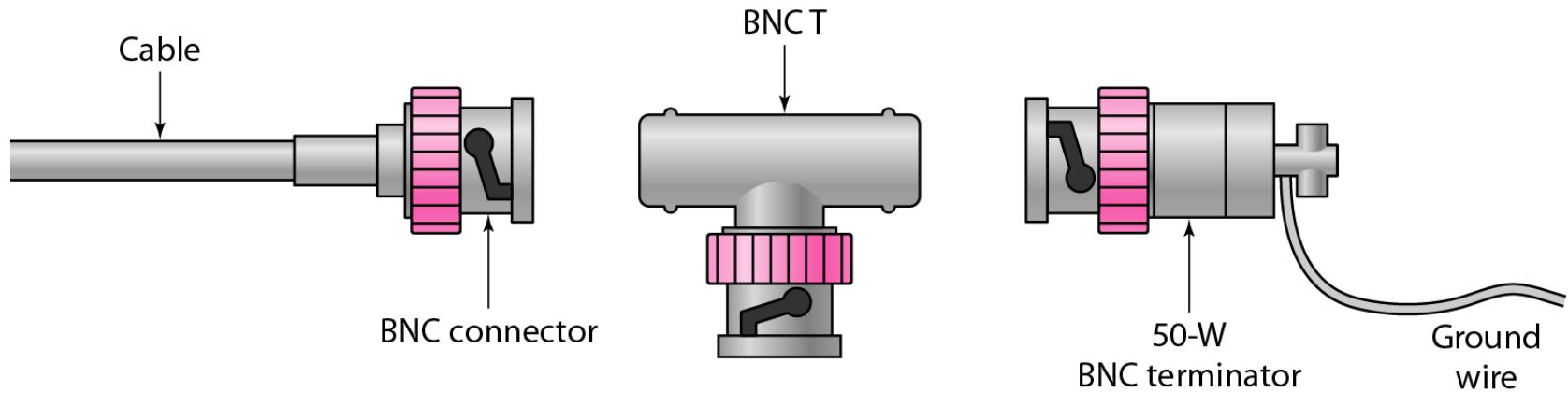


Figure 7.9 *Coaxial cable performance*

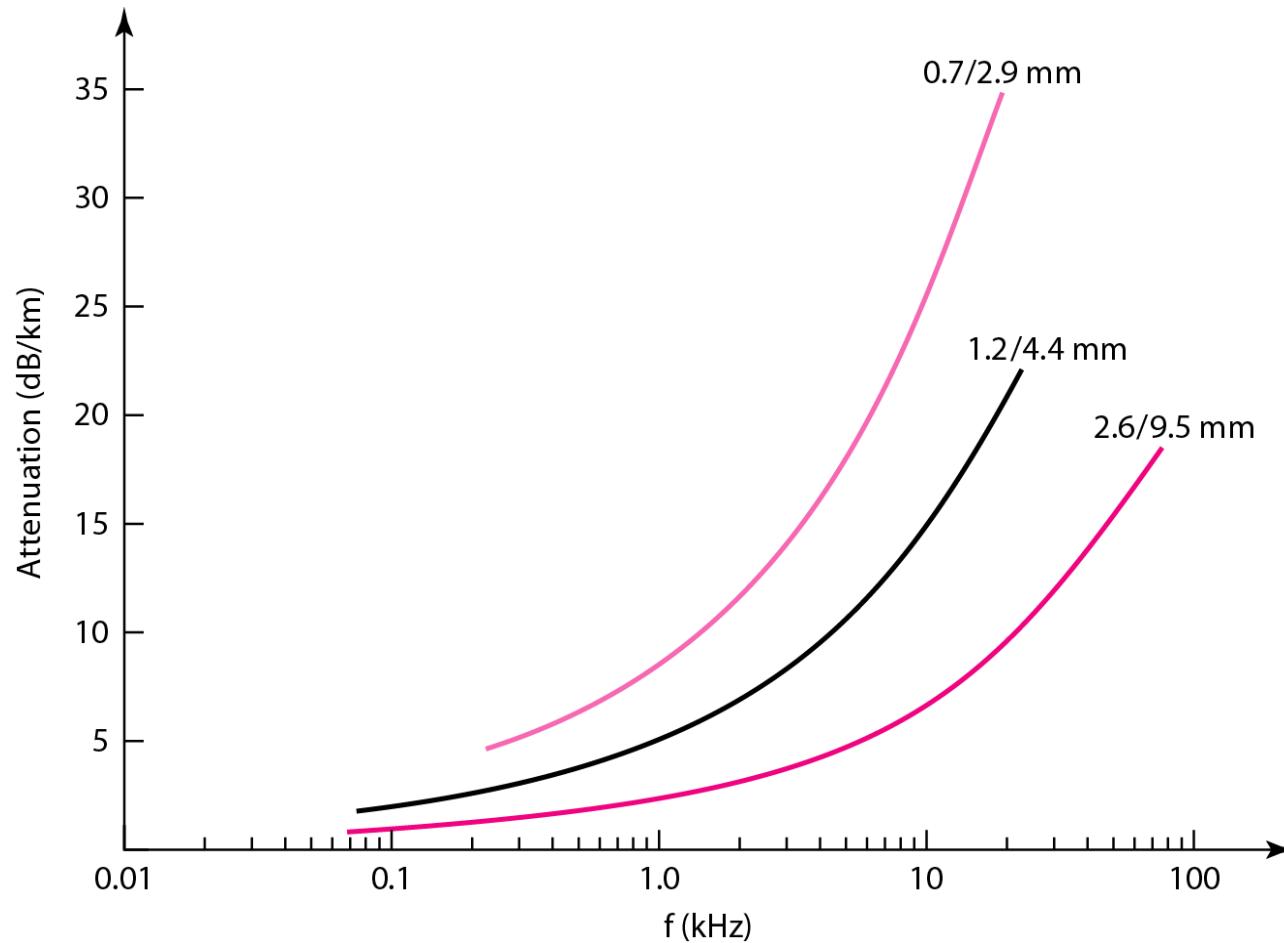


Figure 7.10 *Bending of light ray*

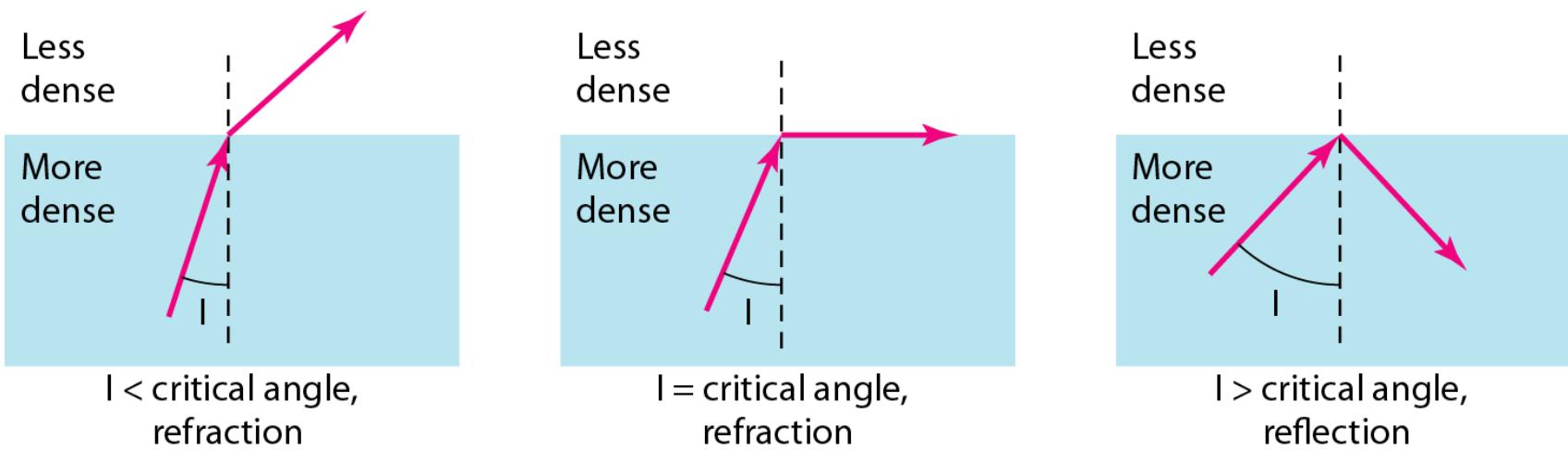


Figure 7.11 *Optical fiber*

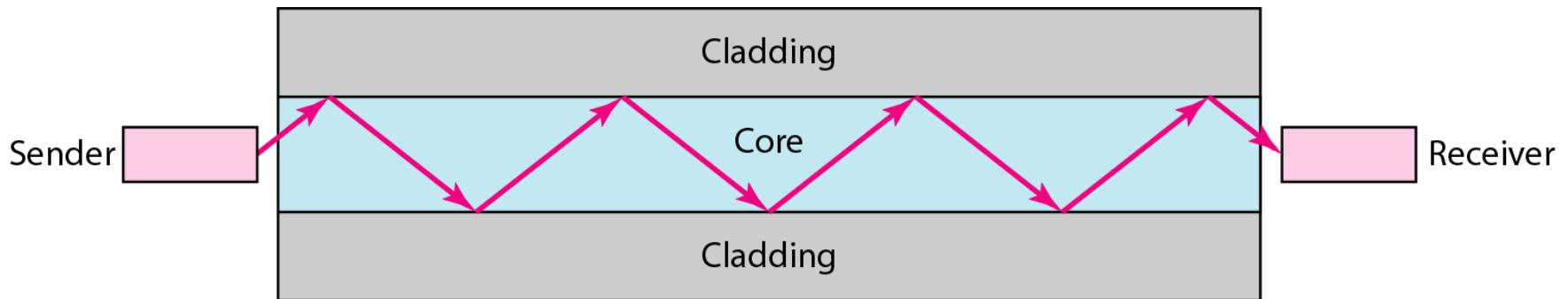


Figure 7.12 *Propagation modes*

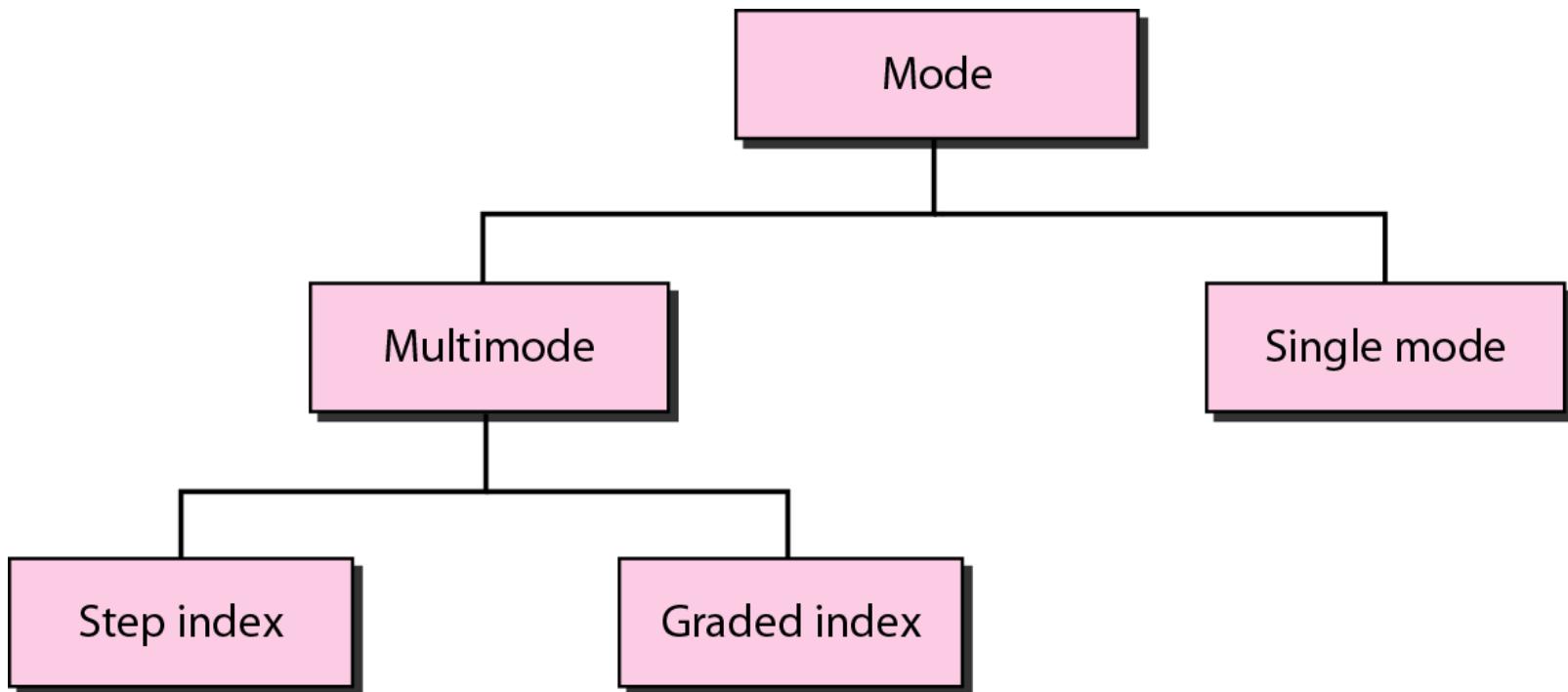
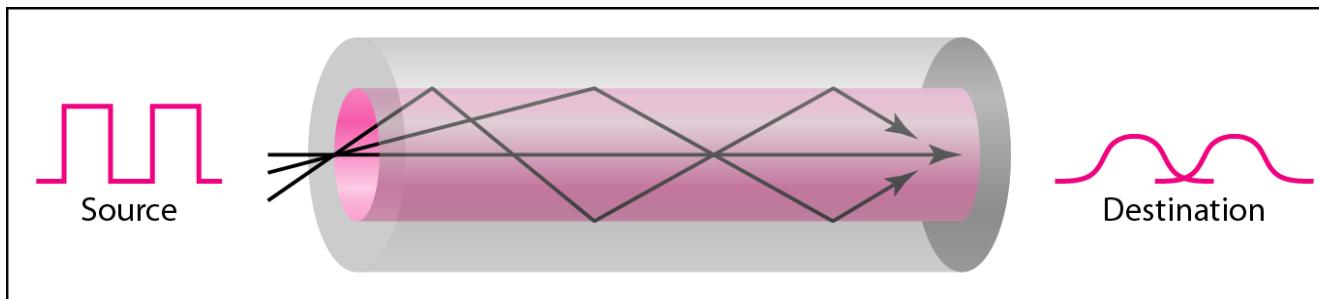
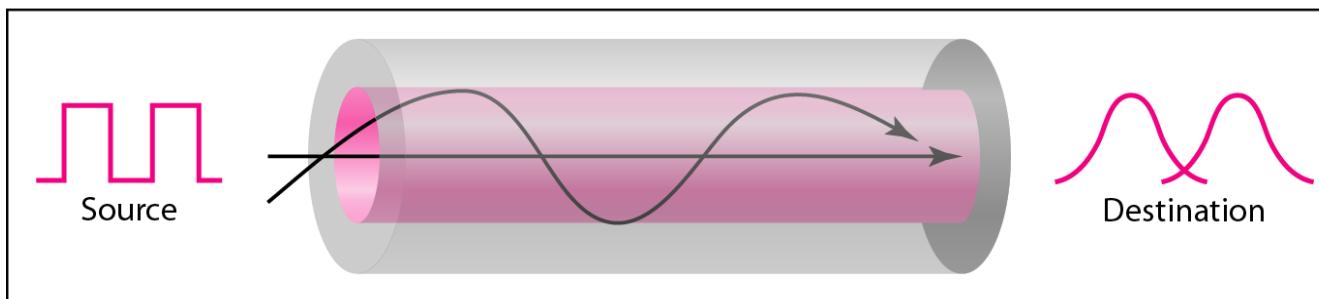


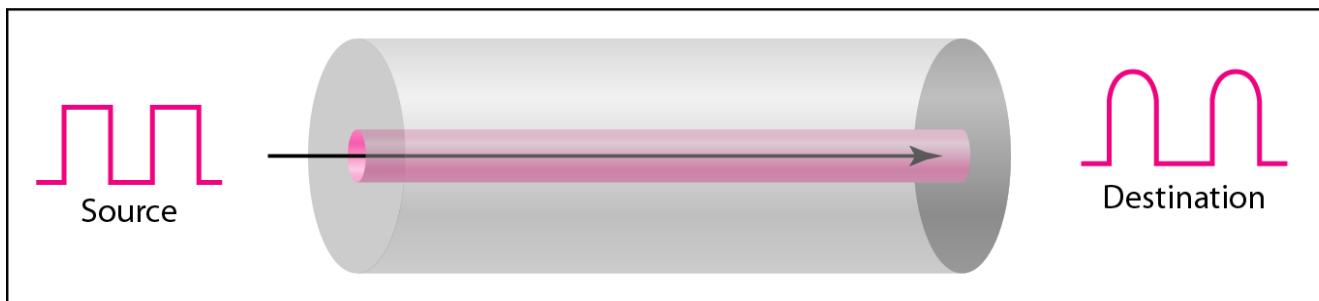
Figure 7.13 Modes



a. Multimode, step index



b. Multimode, graded index



c. Single mode

Table 7.3 *Fiber types*

Type	Core (μm)	Cladding (μm)	Mode
50/125	50.0	125	Multimode, graded index
62.5/125	62.5	125	Multimode, graded index
100/125	100.0	125	Multimode, graded index
7/125	7.0	125	Single mode

Figure 7.14 *Fiber construction*

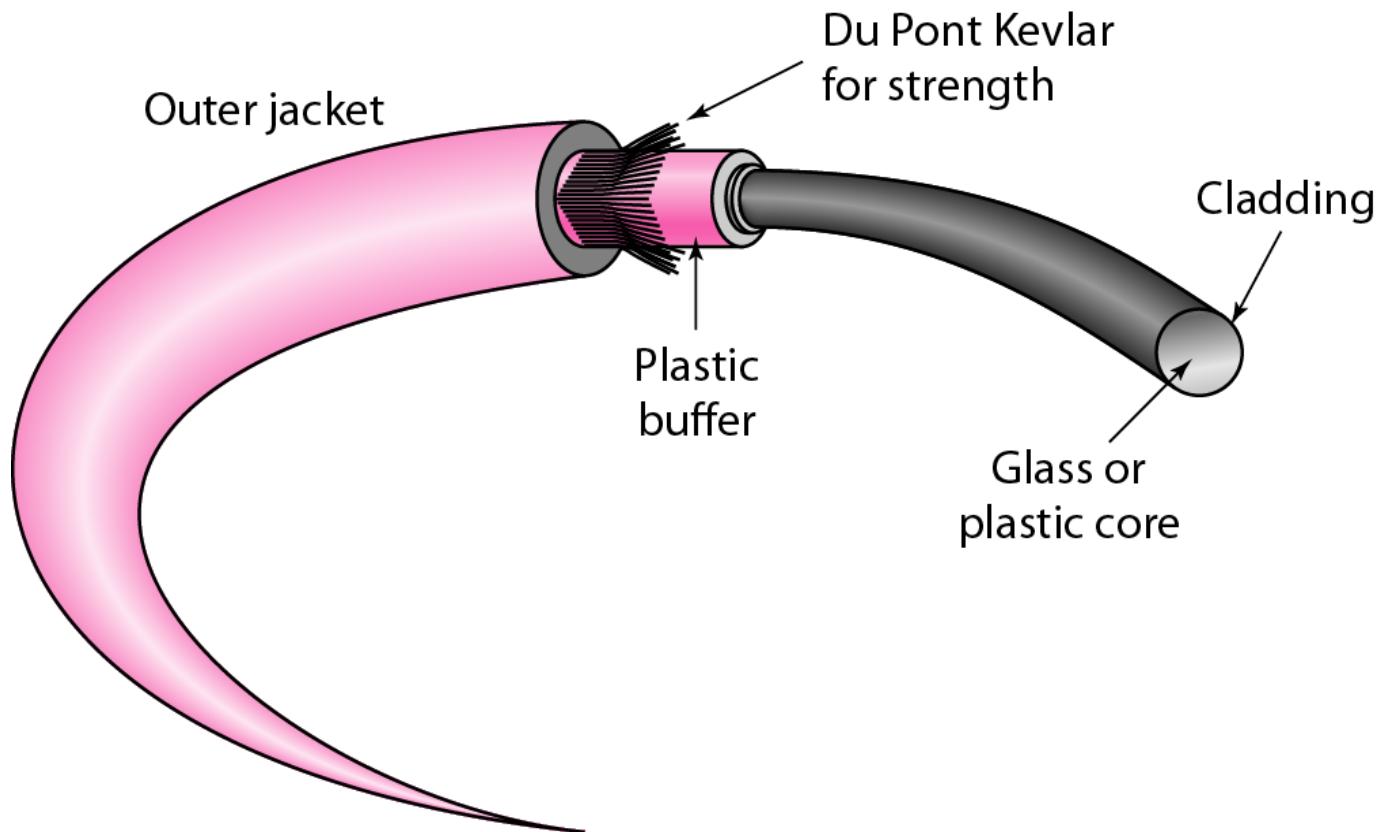
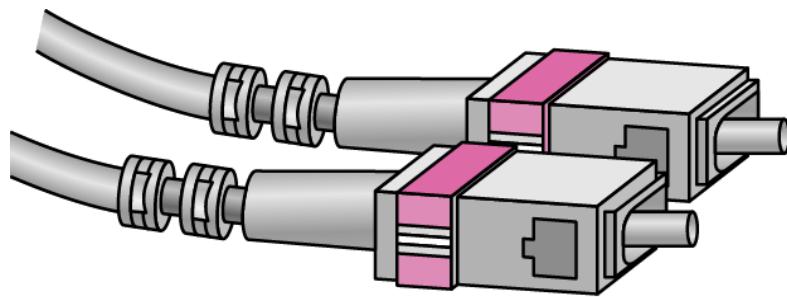
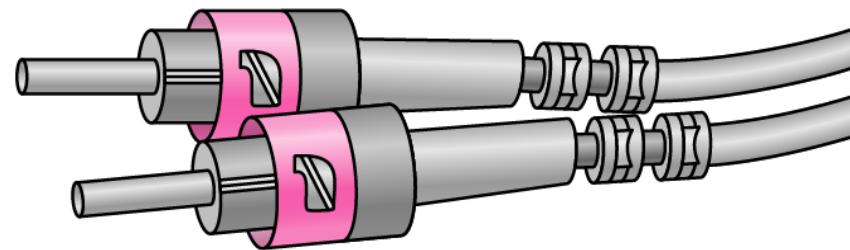


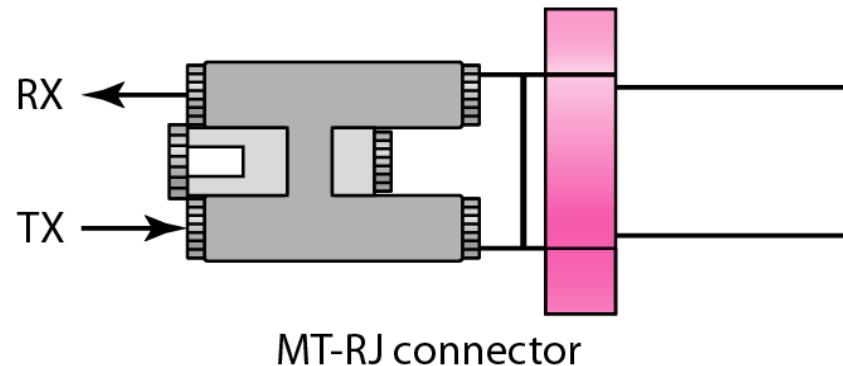
Figure 7.15 *Fiber-optic cable connectors*



SC connector

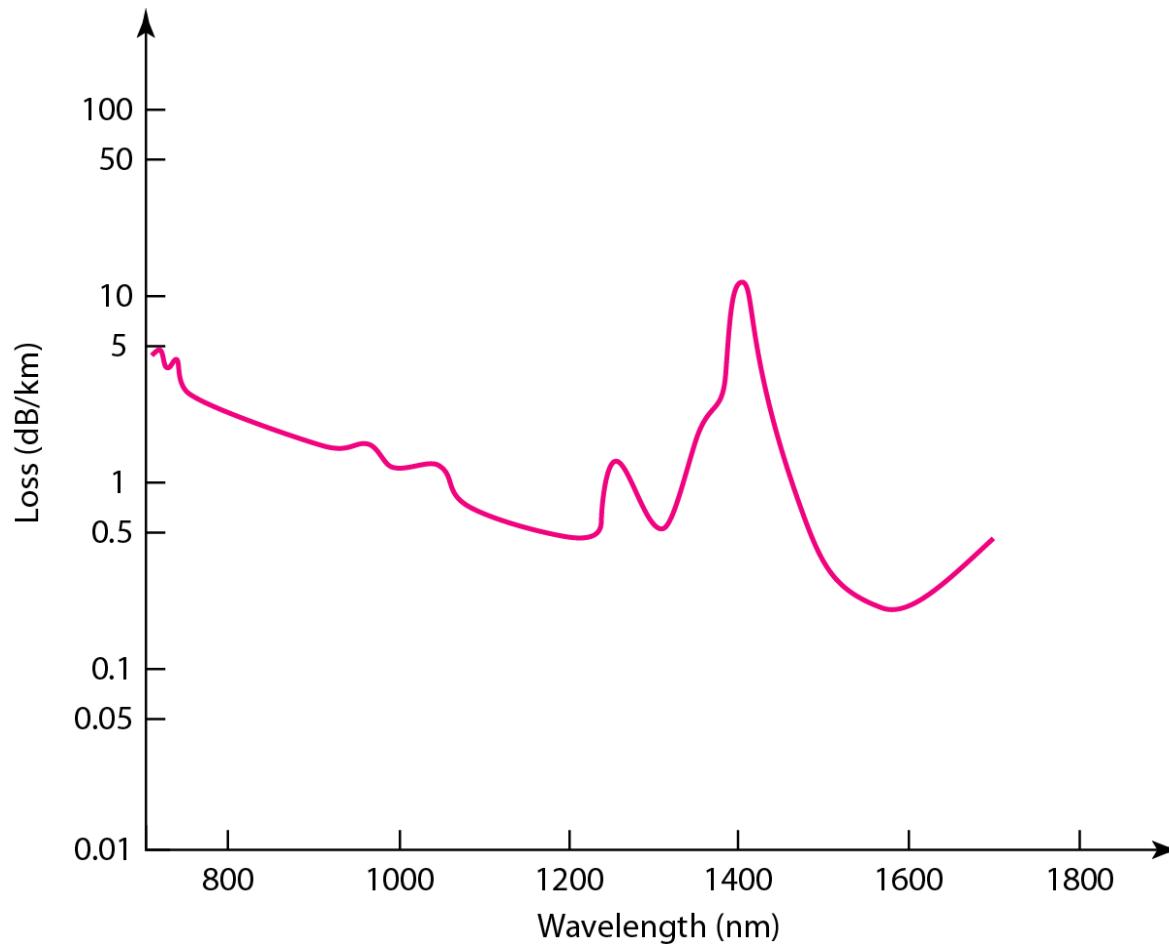


ST connector



MT-RJ connector

Figure 7.16 *Optical fiber performance*



7-2 UNGUIDED MEDIA: WIRELESS

Unguided media transport electromagnetic waves without using a physical conductor. This type of communication is often referred to as wireless communication.

Topics discussed in this section:

Radio Waves

Microwaves

Infrared

Figure 7.17 *Electromagnetic spectrum for wireless communication*

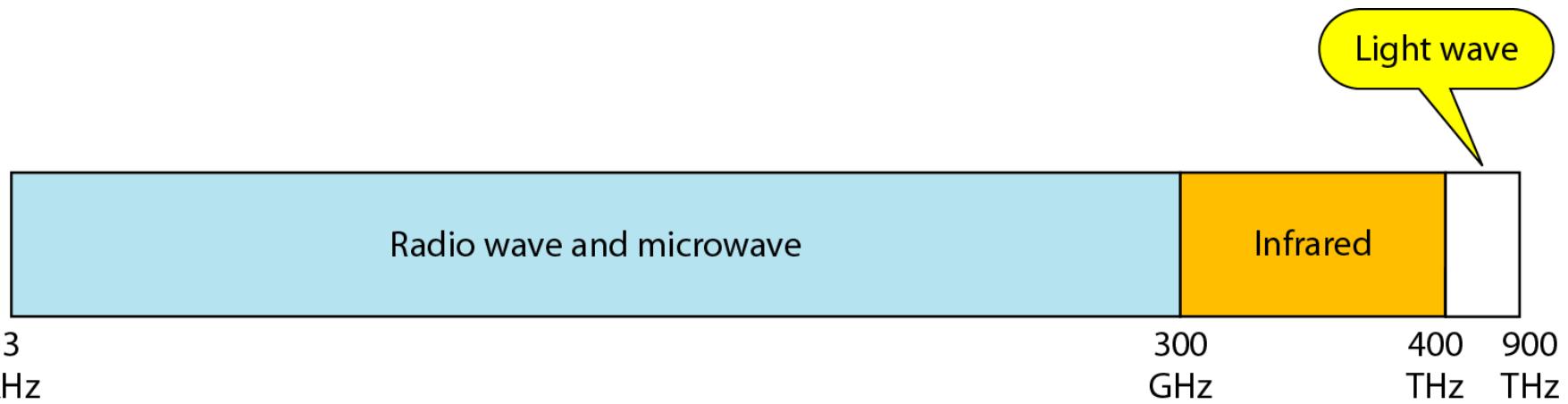


Figure 7.18 *Propagation methods*

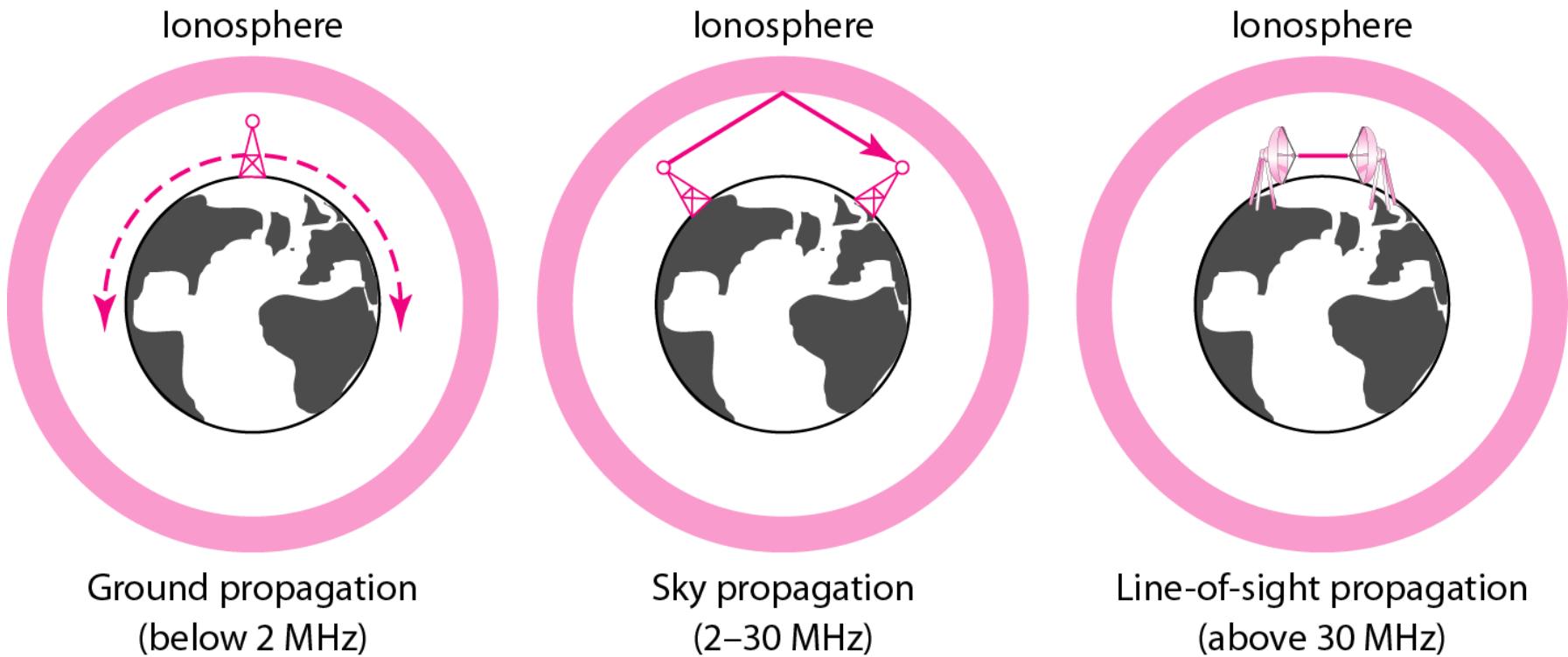


Table 7.4 *Bands*

<i>Band</i>	<i>Range</i>	<i>Propagation</i>	<i>Application</i>
VLF (very low frequency)	3–30 kHz	Ground	Long-range radio navigation
LF (low frequency)	30–300 kHz	Ground	Radio beacons and navigational locators
MF (middle frequency)	300 kHz–3 MHz	Sky	AM radio
HF (high frequency)	3–30 MHz	Sky	Citizens band (CB), ship/aircraft communication
VHF (very high frequency)	30–300 MHz	Sky and line-of-sight	VHF TV, FM radio
UHF (ultrahigh frequency)	300 MHz–3 GHz	Line-of-sight	UHF TV, cellular phones, paging, satellite
SHF (superhigh frequency)	3–30 GHz	Line-of-sight	Satellite communication
EHF (extremely high frequency)	30–300 GHz	Line-of-sight	Radar, satellite

Figure 7.19 *Wireless transmission waves*

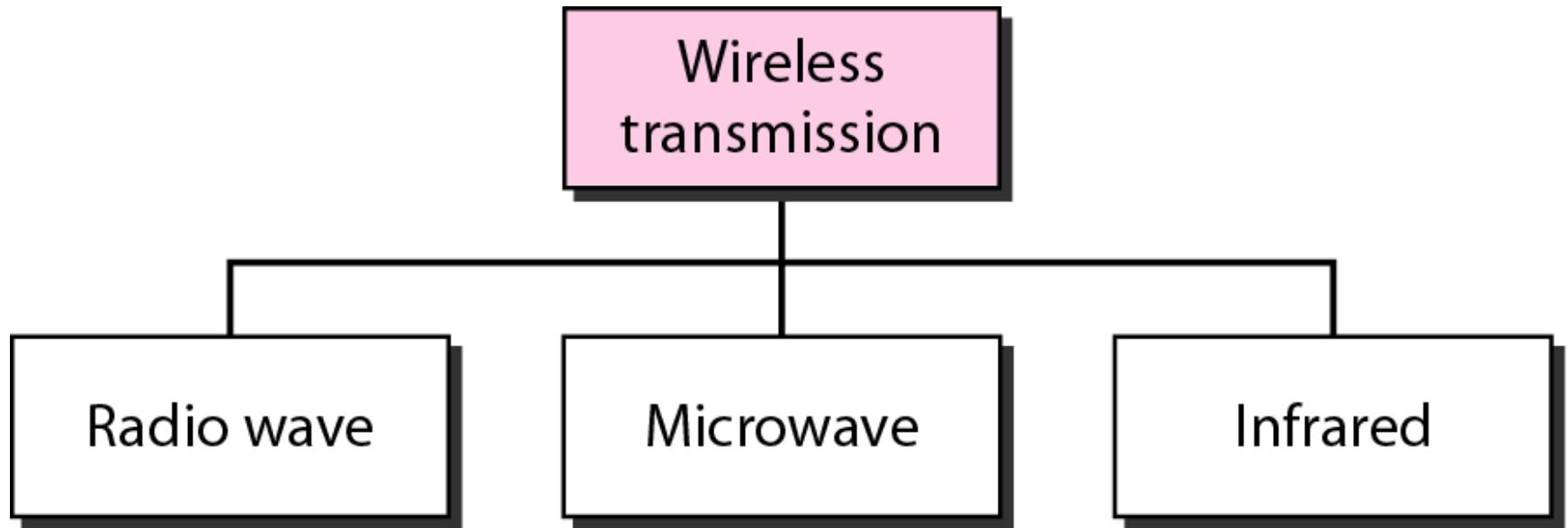
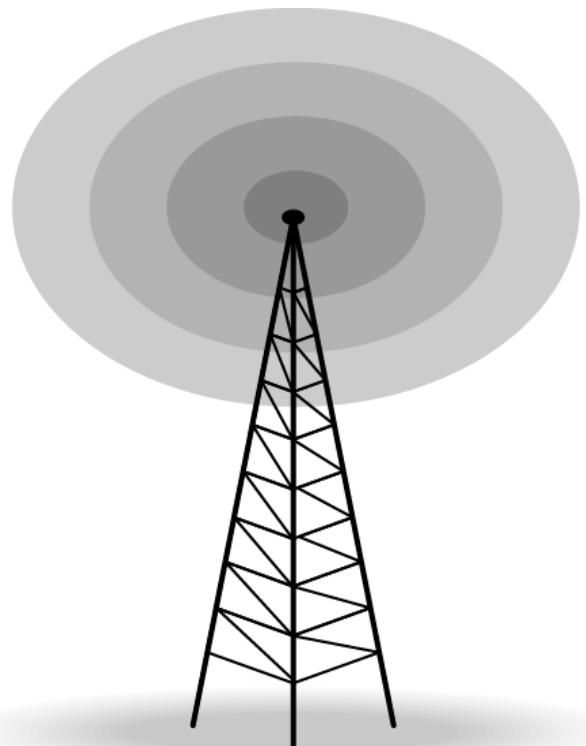
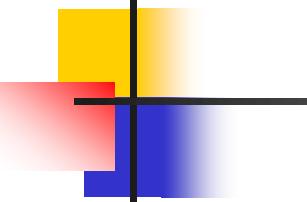


Figure 7.20 *Omnidirectional antenna*

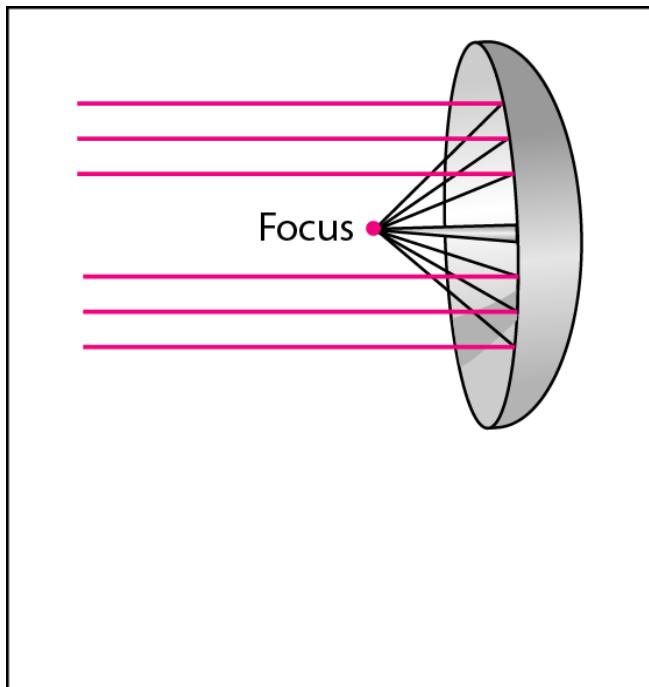




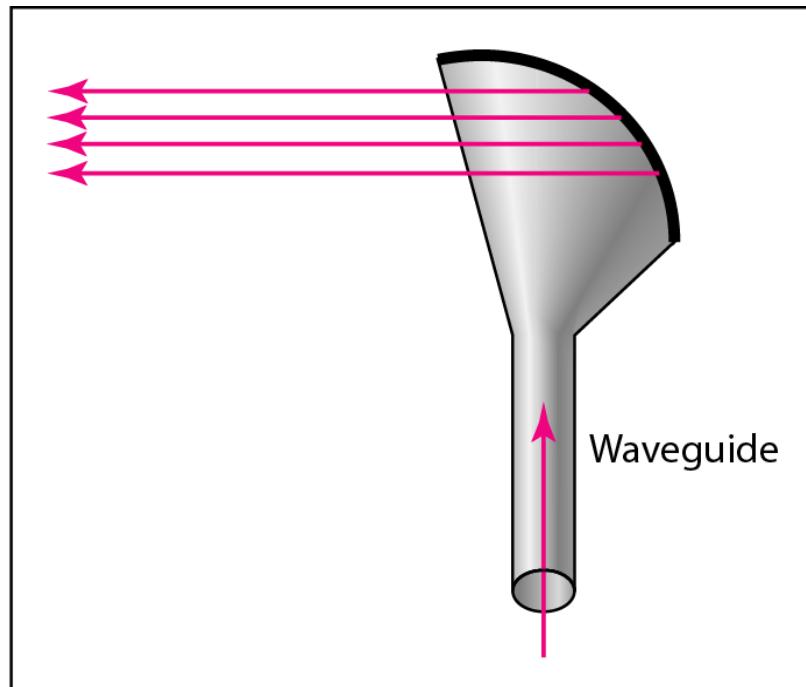
Note

Radio waves are used for multicast communications, such as radio and television, and paging systems.

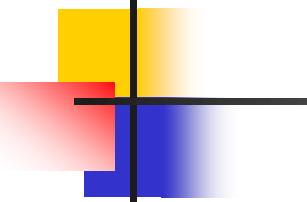
Figure 7.21 *Unidirectional antennas*



a. Dish antenna

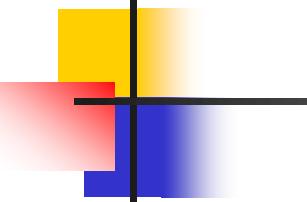


b. Horn antenna



Note

Microwaves are used for unicast communication such as cellular telephones, satellite networks, and wireless LANs.



Note

Infrared signals can be used for short-range communication in a closed area using line-of-sight propagation.



Data Communications and Networking

Fourth Edition

Forouzan

Chapter 9

Using Telephone and Cable Networks for Data Transmission

9-1 TELEPHONE NETWORK

Telephone networks use circuit switching. The telephone network had its beginnings in the late 1800s. The entire network, which is referred to as the plain old telephone system (POTS), was originally an analog system using analog signals to transmit voice.

Topics discussed in this section:

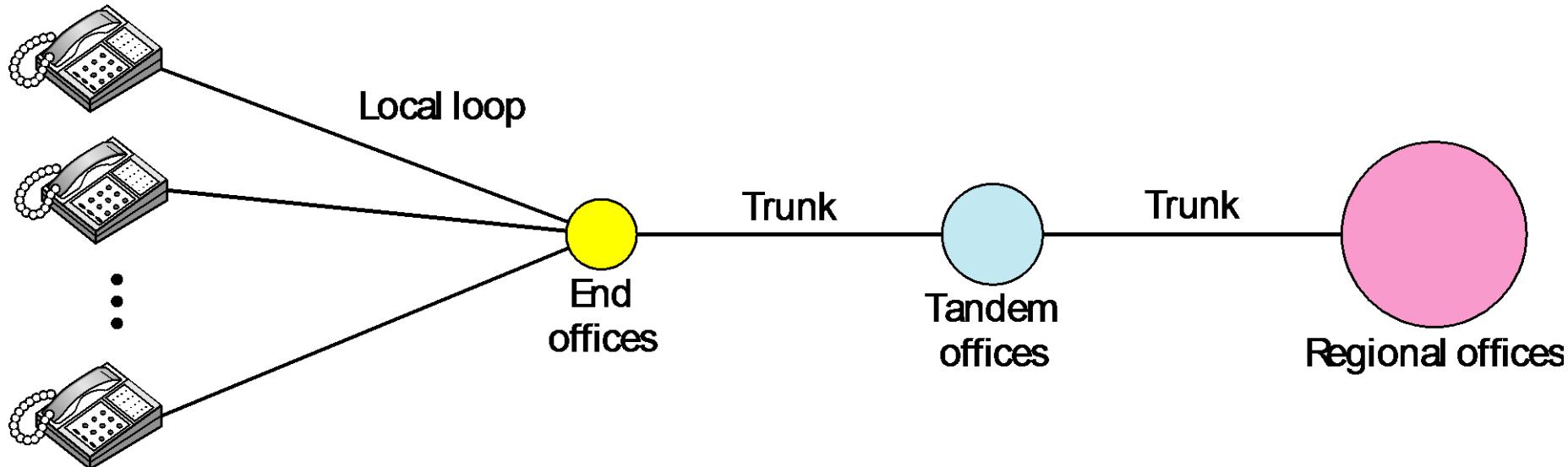
Major Components

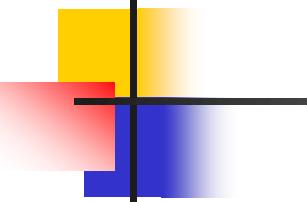
LATAs

Signaling

Services Provided by Telephone Networks

Figure 9.1 *A telephone system*





Note

Intra-LATA services are provided by local exchange carriers.

Since 1996, there are two types of LECs: incumbent local exchange carriers and competitive local exchange carriers.

Figure 9.2 *Switching offices in a LATA*

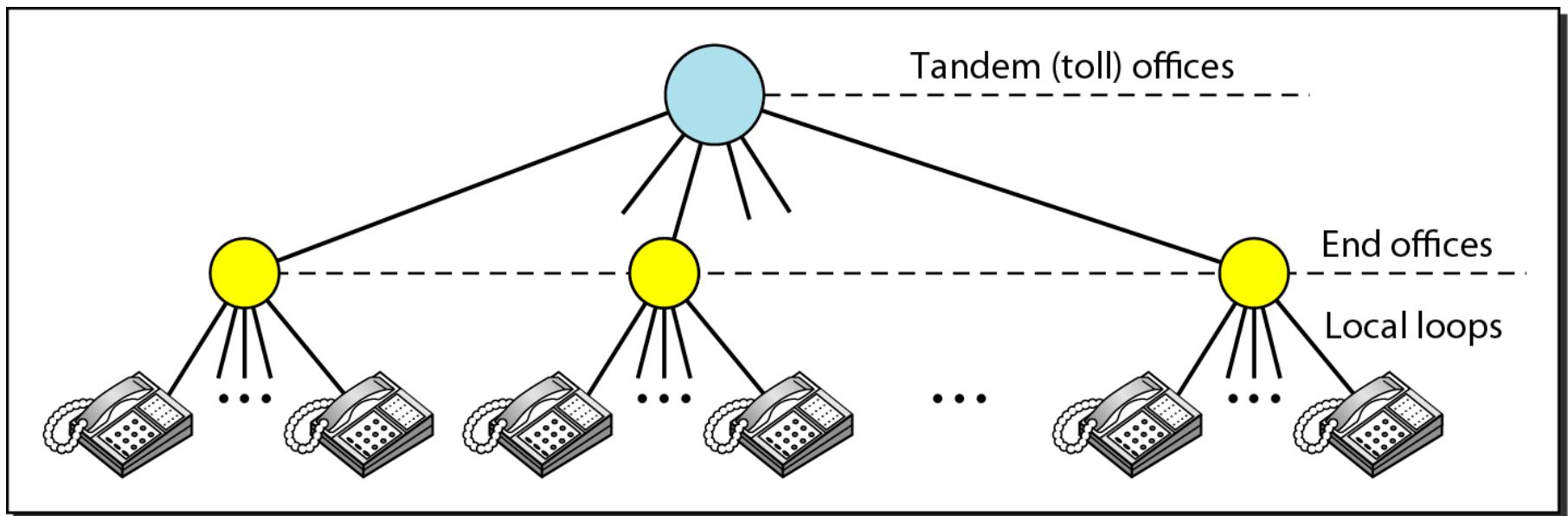
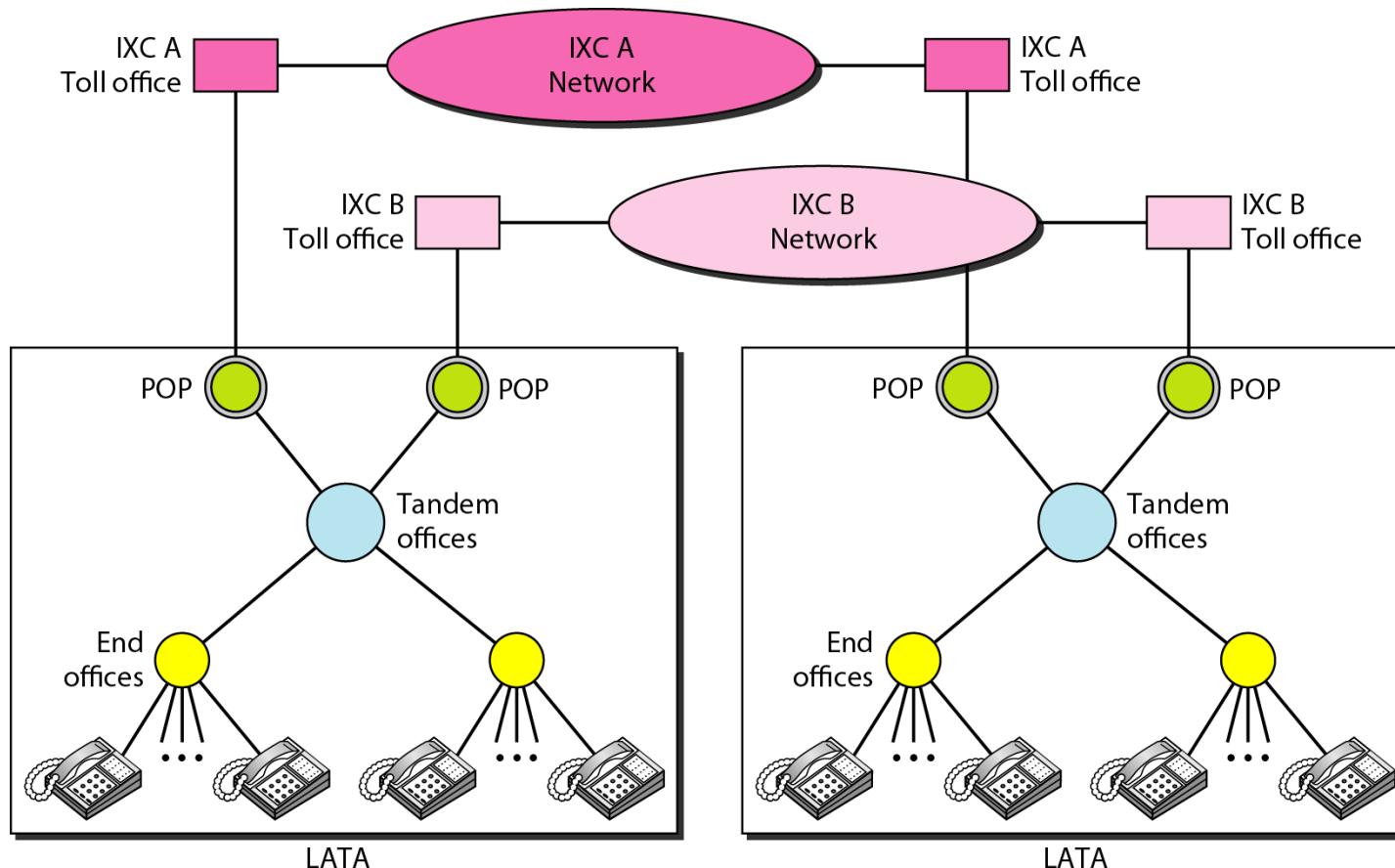
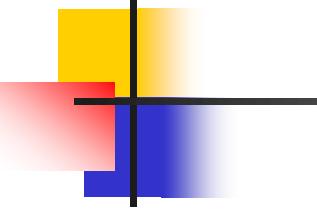


Figure 9.3 *Point of presences (POPs)*





Note

**The tasks of data transfer and signaling
are separated in modern telephone
networks: data transfer is done by one
network, signaling by another.**

Figure 9.4 *Data transfer and signaling networks*

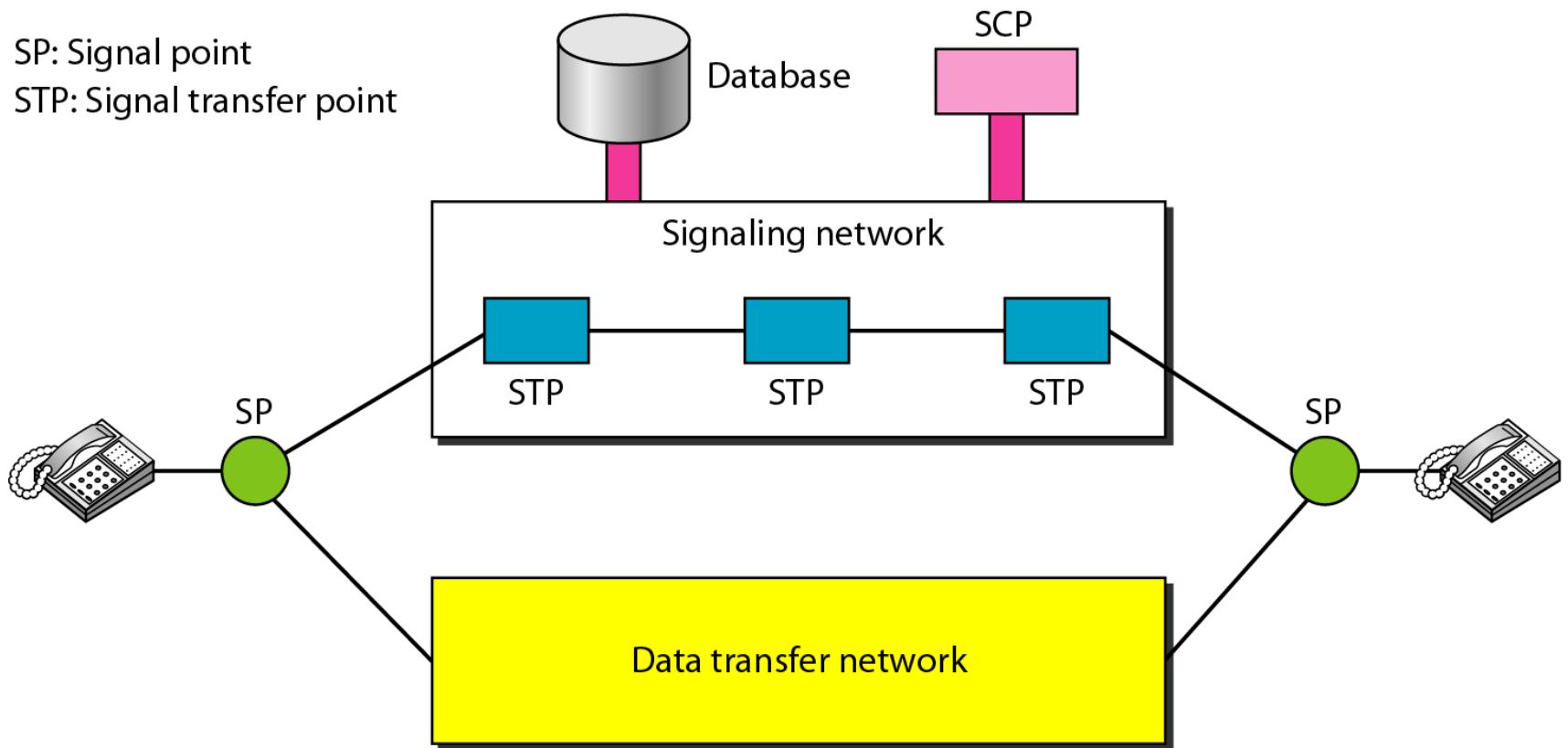
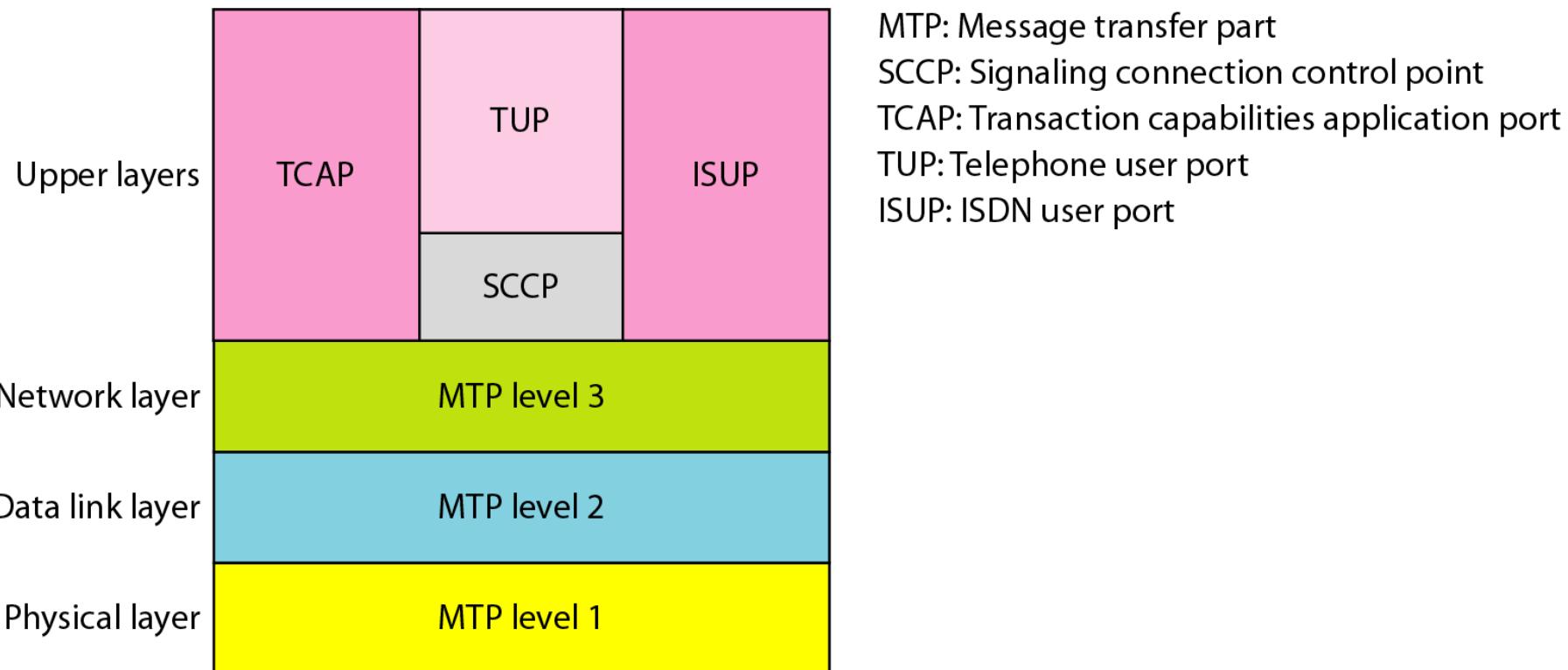


Figure 9.5 *Layers in SS7*



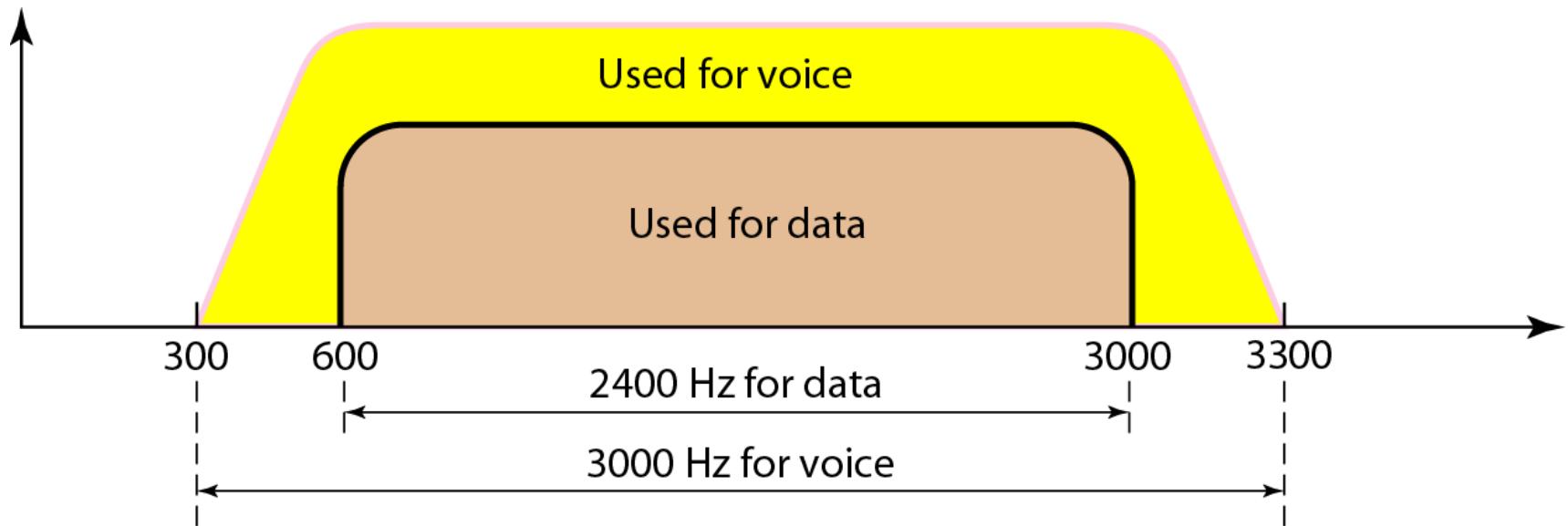
9-2 DIAL-UP MODEMS

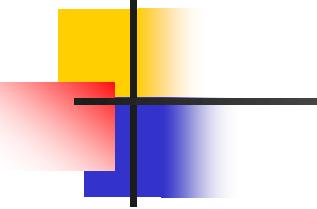
Traditional telephone lines can carry frequencies between 300 and 3300 Hz, giving them a bandwidth of 3000 Hz. All this range is used for transmitting voice, where a great deal of interference and distortion can be accepted without loss of intelligibility.

Topics discussed in this section:

Modem Standards

Figure 9.6 Telephone line bandwidth





Note

Modem
stands for modulator/demodulator.

Figure 9.7 Modulation/demodulation

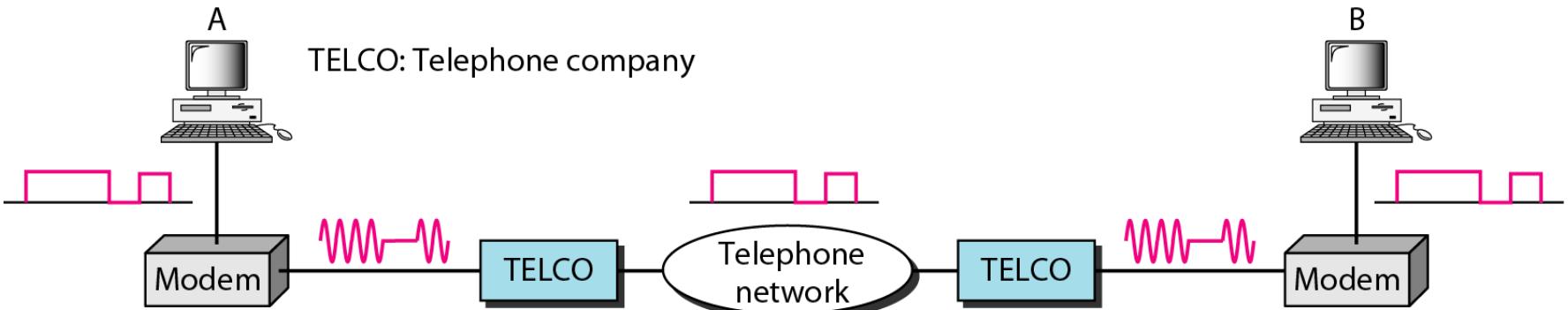
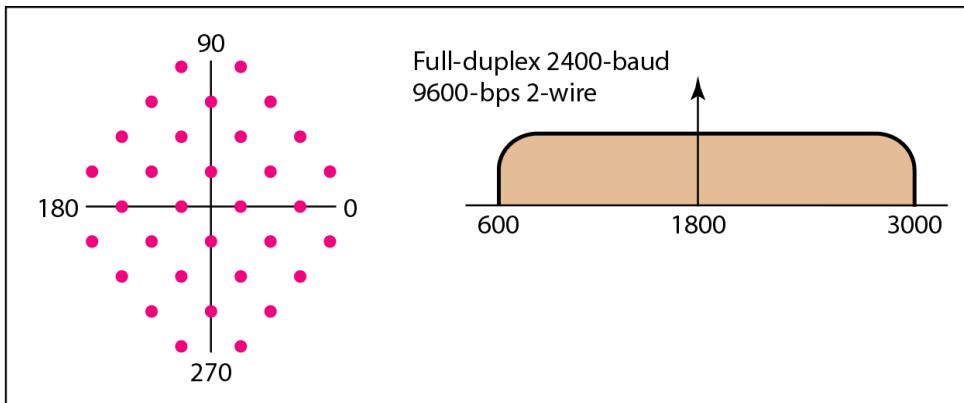
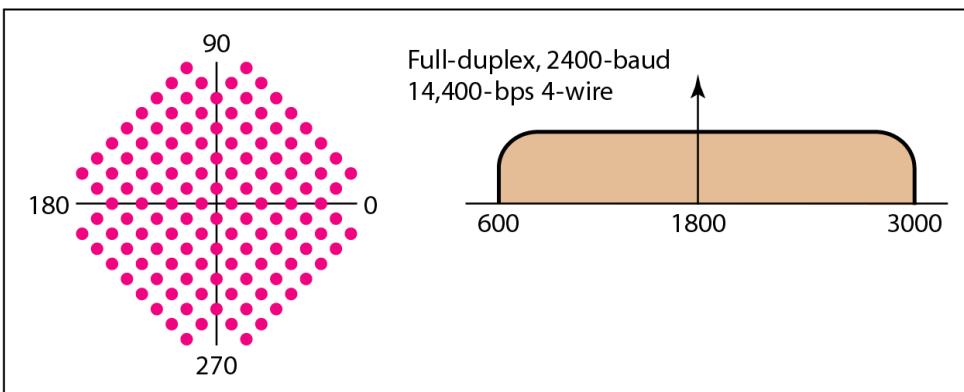


Figure 9.8 *The V.32 and V.32bis constellation and bandwidth*

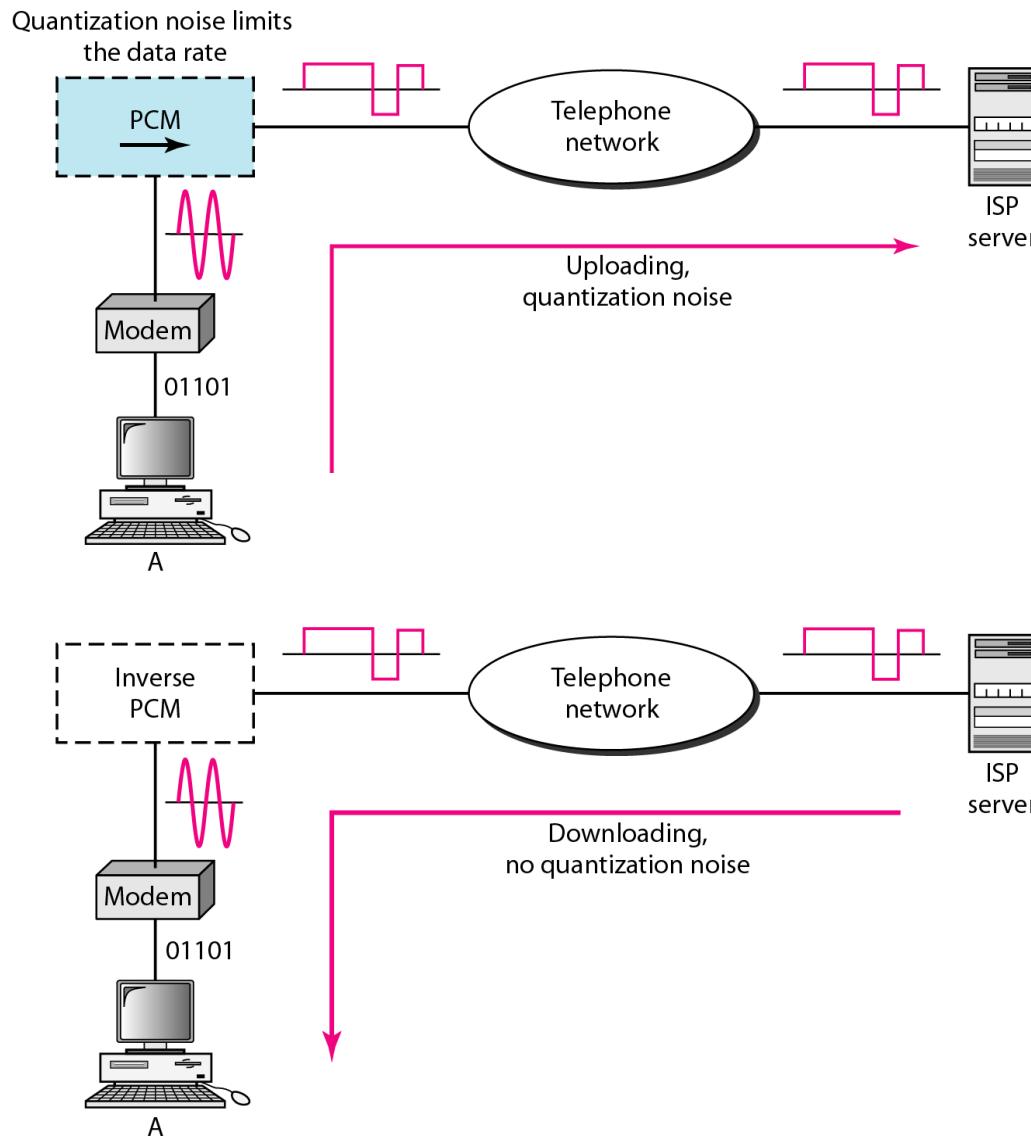


a. Constellation and bandwidth for V.32



b. Constellation and bandwidth for V.32bis

Figure 9.9 Uploading and downloading in 56K modems



9-3 DIGITAL SUBSCRIBER LINE

After traditional modems reached their peak data rate, telephone companies developed another technology, DSL, to provide higher-speed access to the Internet. Digital subscriber line (DSL) technology is one of the most promising for supporting high-speed digital communication over the existing local loops.

Topics discussed in this section:

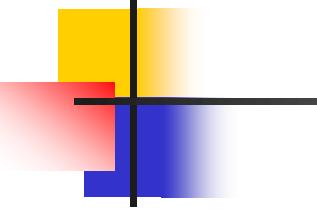
ADSL

ADSL Lite

HDSL

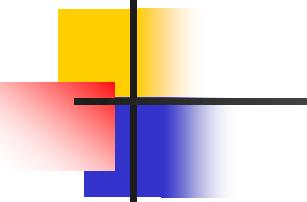
SDSL

VDSL



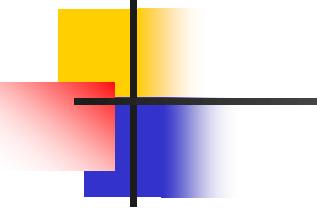
Note

ADSL is an asymmetric communication technology designed for residential users; it is not suitable for businesses.



Note

The existing local loops can handle bandwidths up to 1.1 MHz.



Note

**ADSL is an adaptive technology.
The system uses a data rate
based on the condition of
the local loop line.**

Figure 9.10 Discrete multitone technique

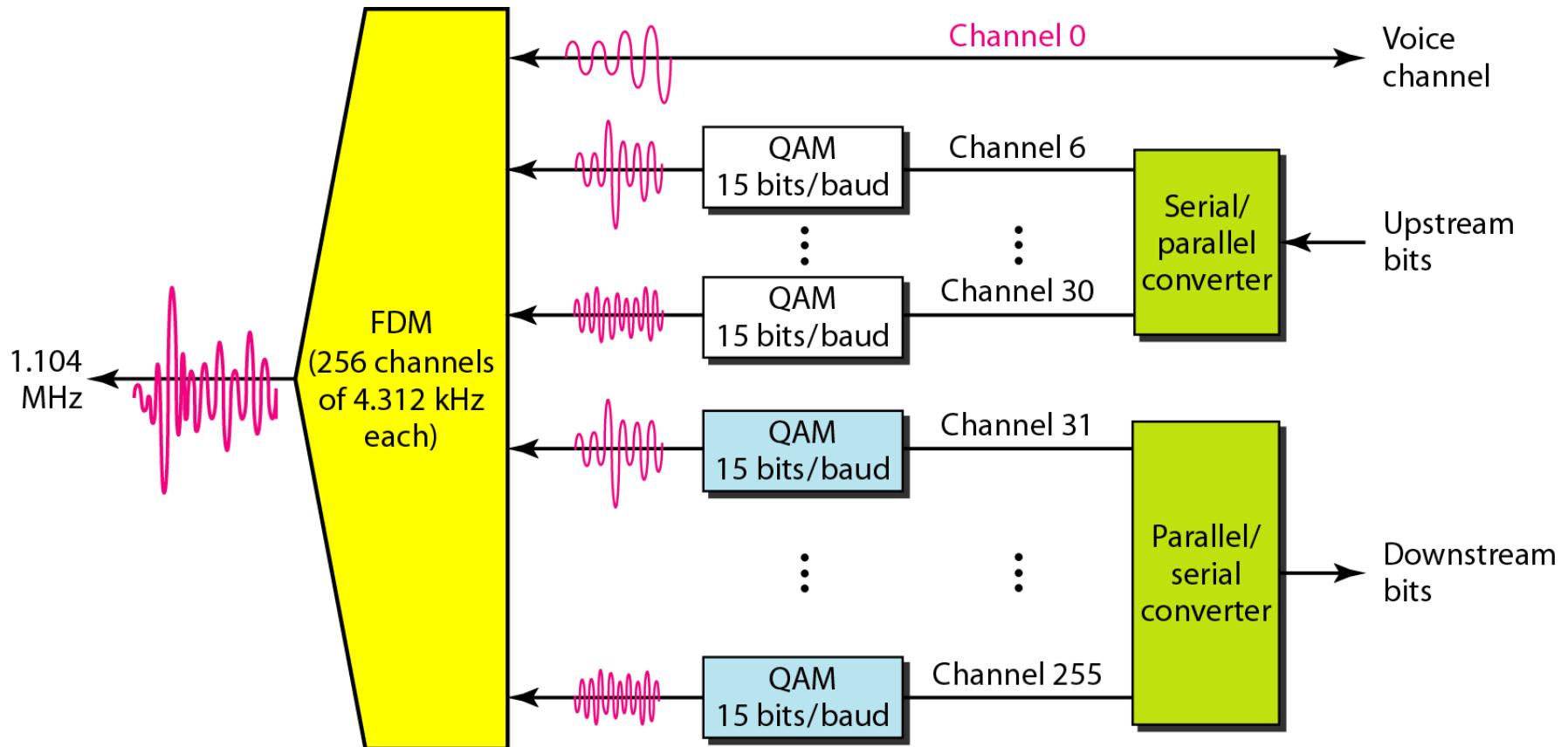


Figure 9.11 *Bandwidth division in ADSL*

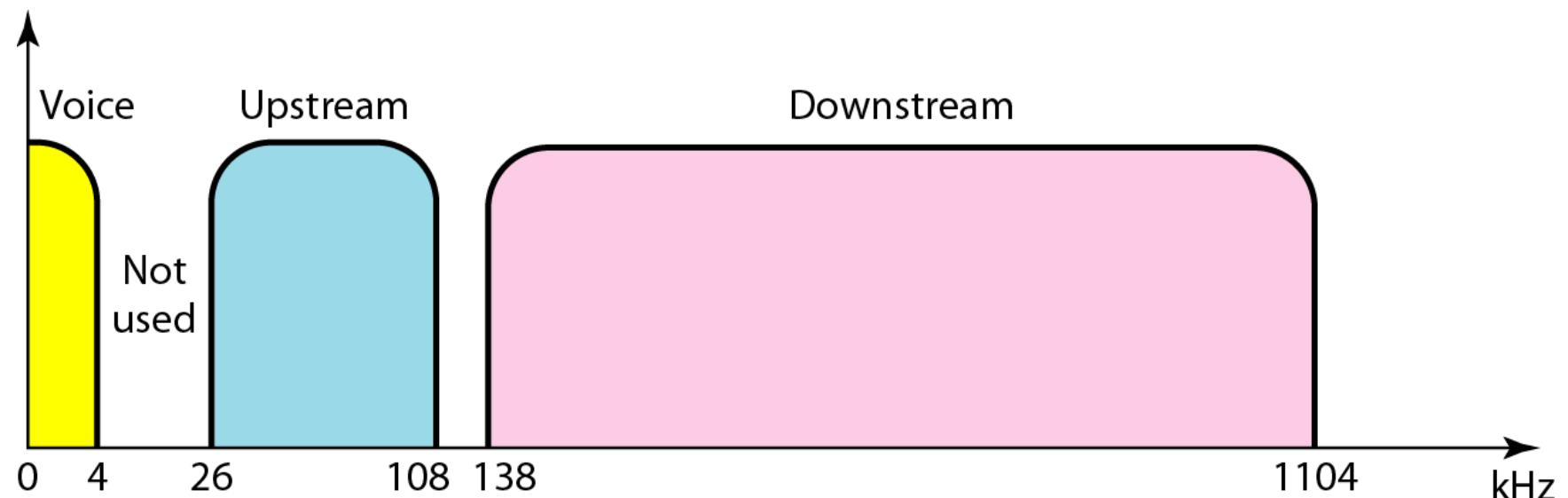


Figure 9.12 ADSL modem

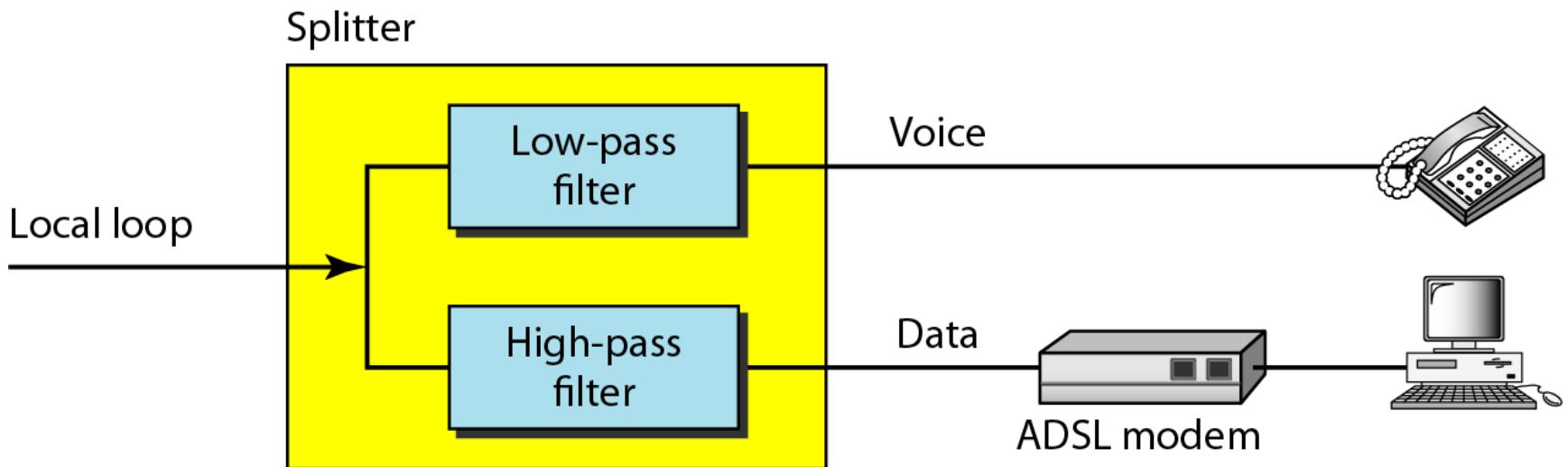


Figure 9.13 *DSLAM*

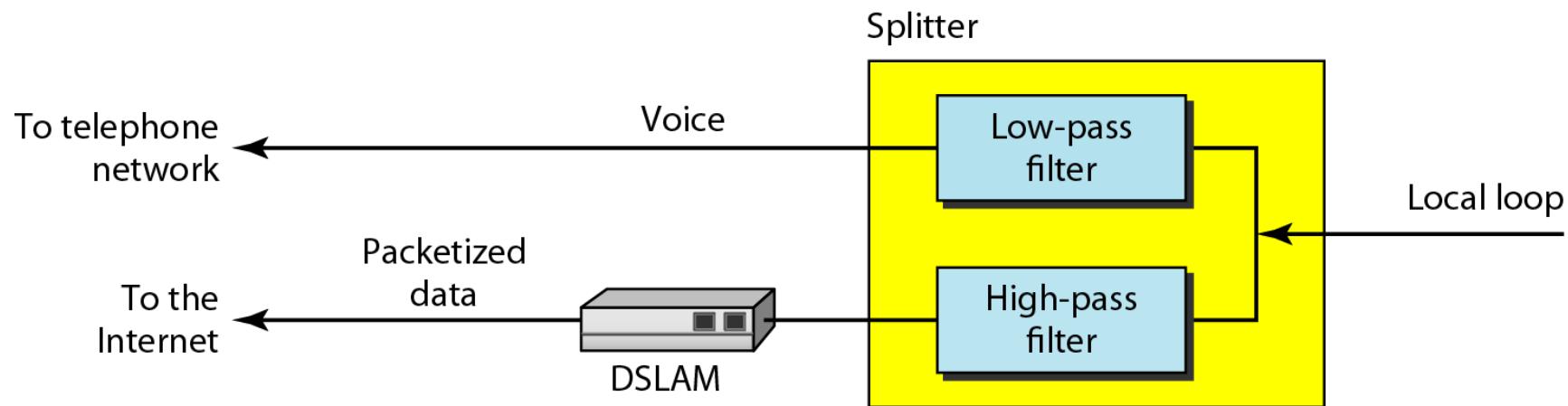


Table 9.2 *Summary of DSL technologies*

<i>Technology</i>	<i>Downstream Rate</i>	<i>Upstream Rate</i>	<i>Distance (ft)</i>	<i>Twisted Pairs</i>	<i>Line Code</i>
ADSL	1.5–6.1 Mbps	16–640 kbps	12,000	1	DMT
ADSL Lite	1.5 Mbps	500 kbps	18,000	1	DMT
HDSL	1.5–2.0 Mbps	1.5–2.0 Mbps	12,000	2	2B1Q
SDSL	768 kbps	768 kbps	12,000	1	2B1Q
VDSL	25–55 Mbps	3.2 Mbps	3000–10,000	1	DMT

9-4 CABLE TV NETWORKS

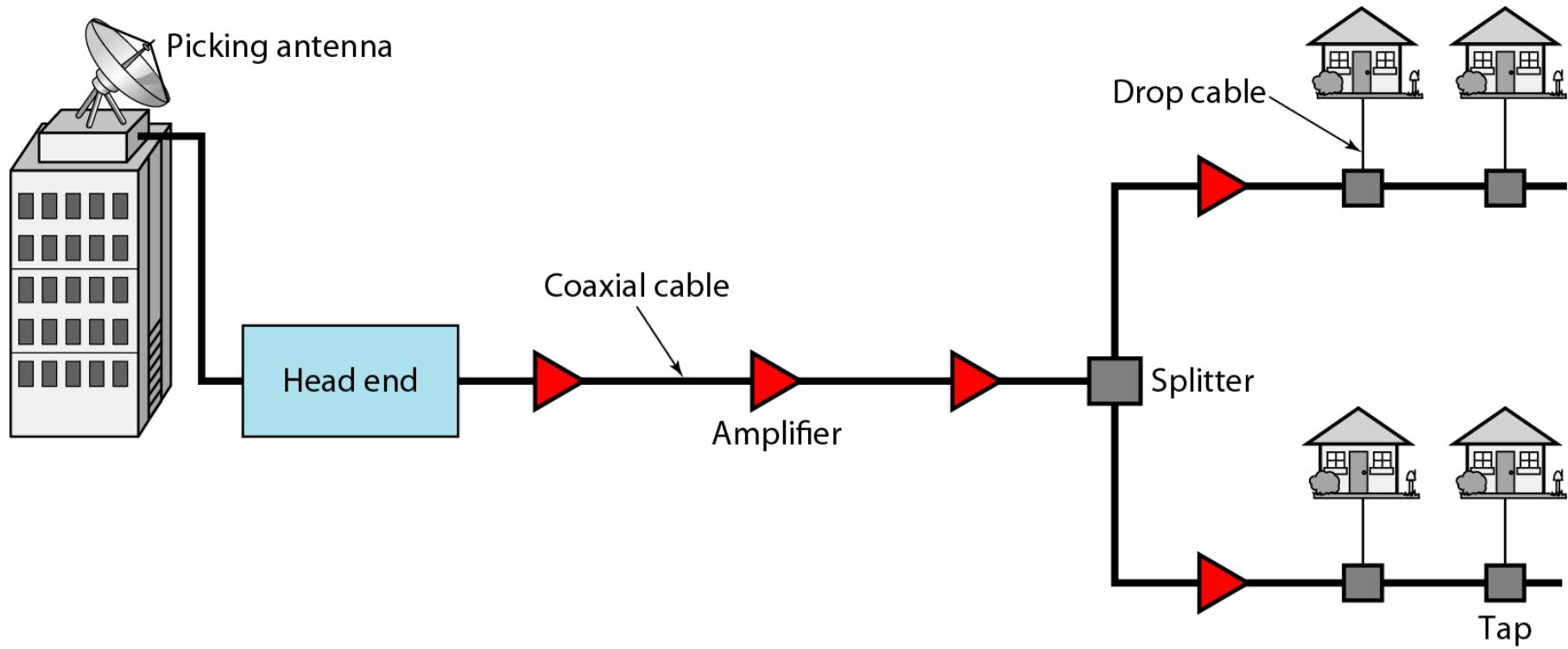
*The **cable TV network** started as a video service provider, but it has moved to the business of Internet access. In this section, we discuss cable TV networks *per se*; in Section 9.5 we discuss how this network can be used to provide high-speed access to the Internet.*

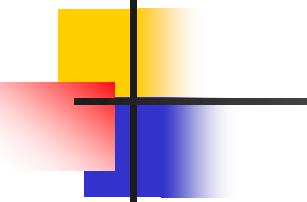
Topics discussed in this section:

Traditional Cable Networks

Hybrid Fiber-Coaxial (HFC) Network

Figure 9.14 Traditional cable TV network

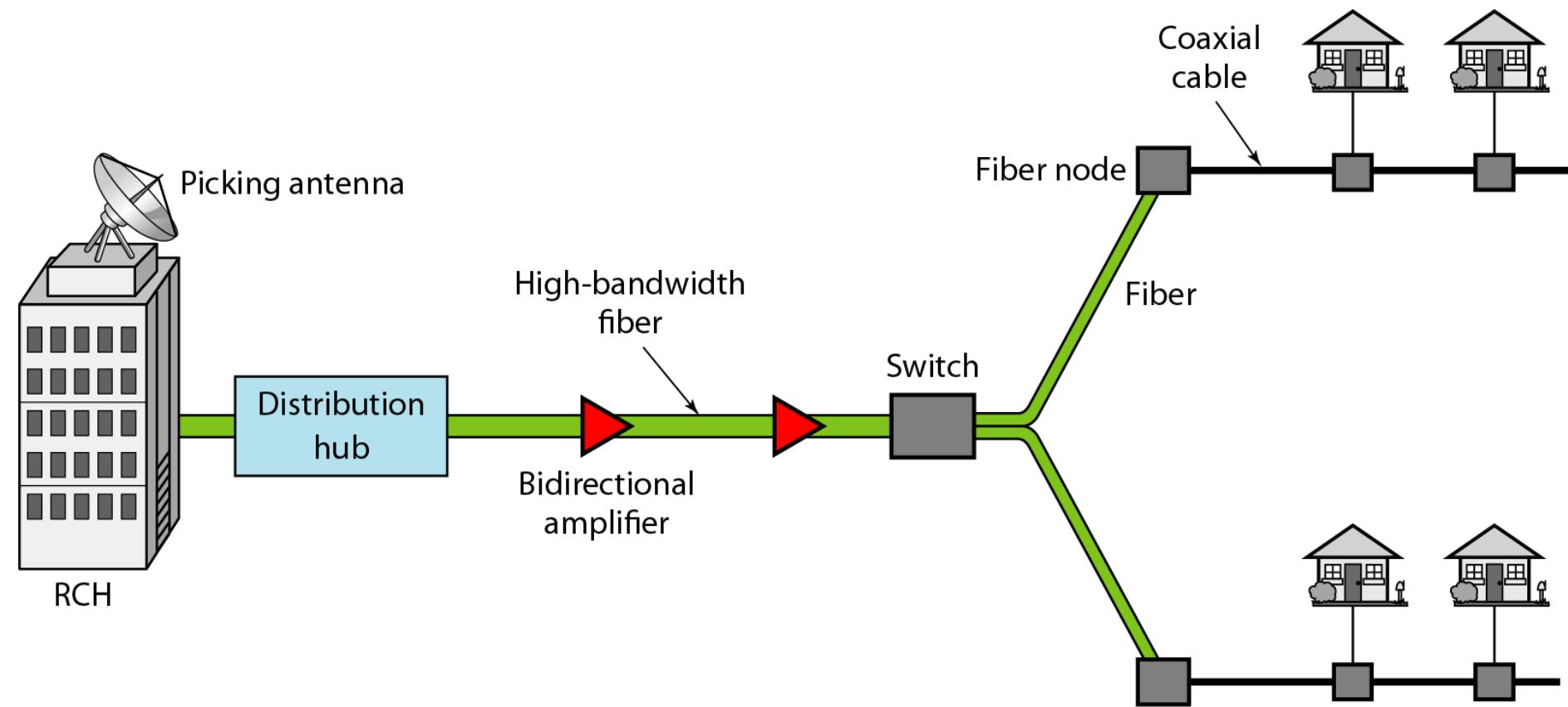


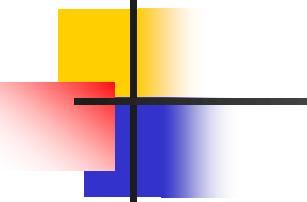


Note

Communication in the traditional cable TV network is unidirectional.

Figure 9.15 *Hybrid fiber-coaxial (HFC) network*





Note

Communication in an HFC cable TV network can be bidirectional.

9-5 CABLE TV FOR DATA TRANSFER

Cable companies are now competing with telephone companies for the residential customer who wants high-speed data transfer. In this section, we briefly discuss this technology.

Topics discussed in this section:

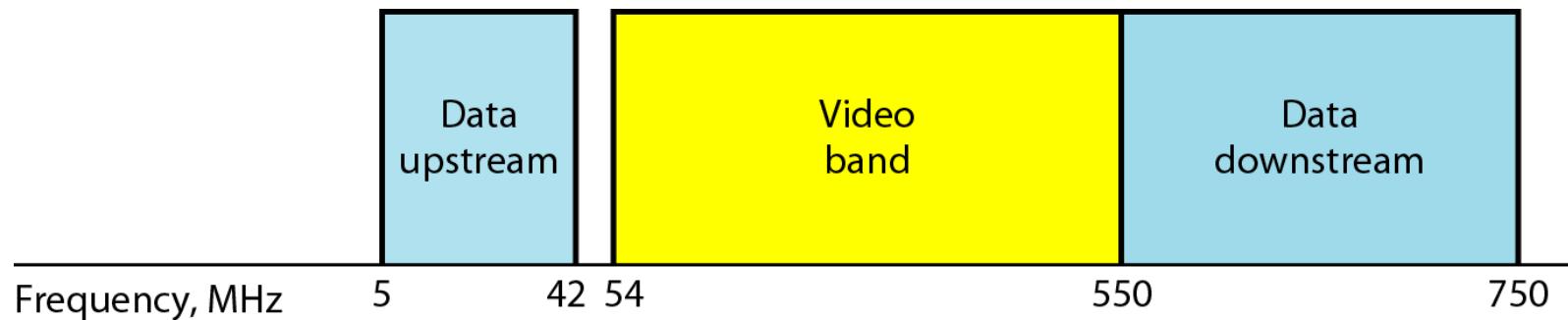
Bandwidth

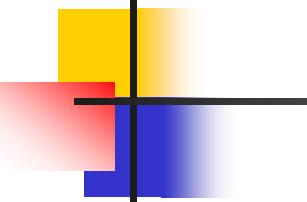
Sharing

CM and CMTS

Data Transmission Schemes: DOCSIS

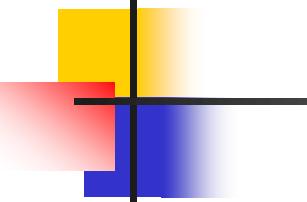
Figure 9.16 *Division of coaxial cable band by CATV*





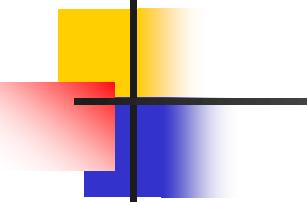
Note

Downstream data are modulated using the 64-QAM modulation technique.



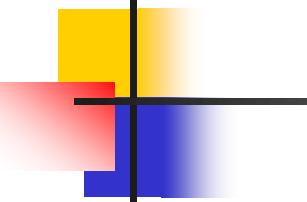
Note

**The theoretical downstream data rate
is 30 Mbps.**



Note

Upstream data are modulated using the QPSK modulation technique.



Note

**The theoretical upstream data rate
is 12 Mbps.**

Figure 9.17 *Cable modem (CM)*

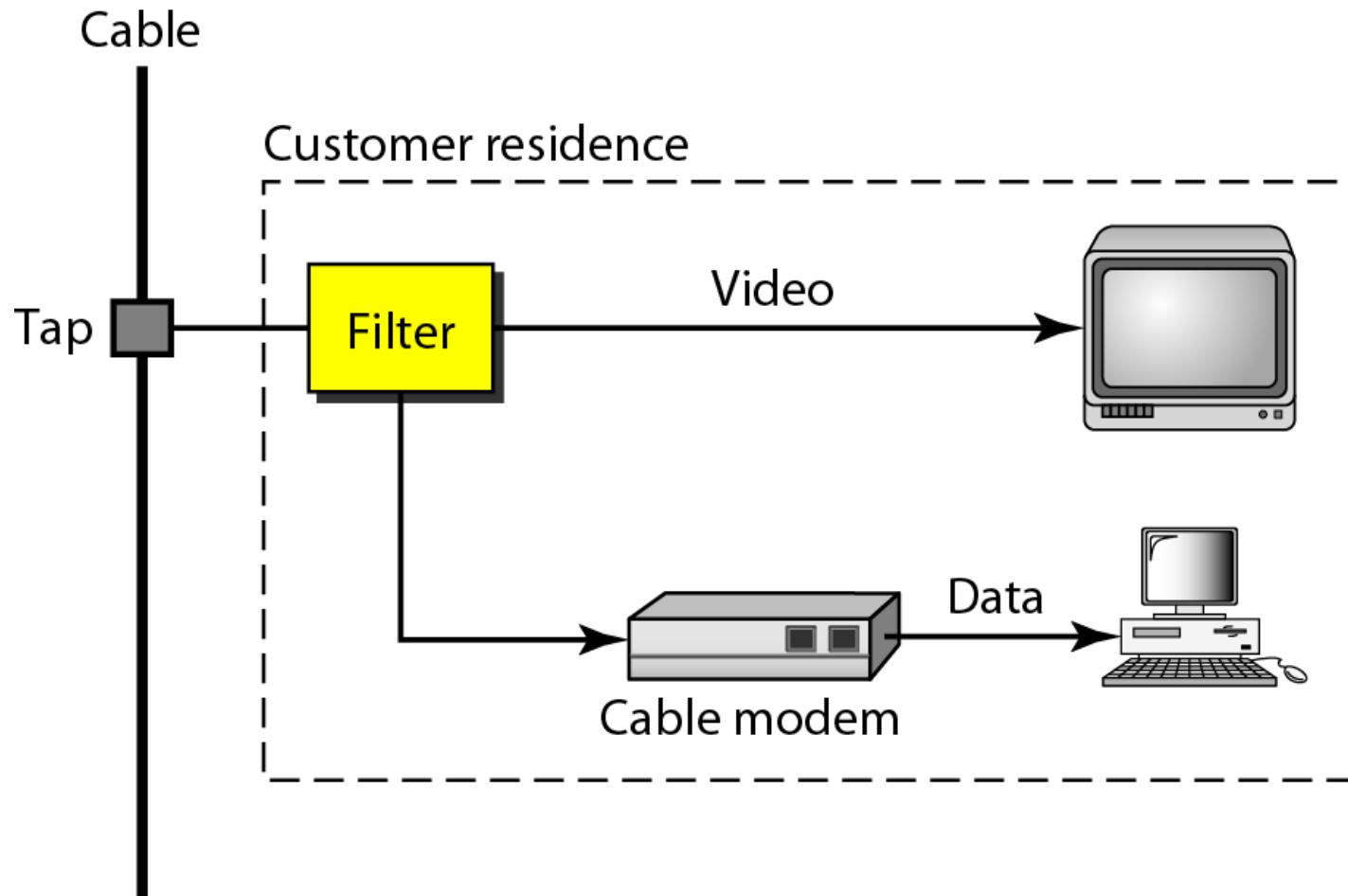


Figure 9.18 *Cable modem transmission system (CMTS)*

