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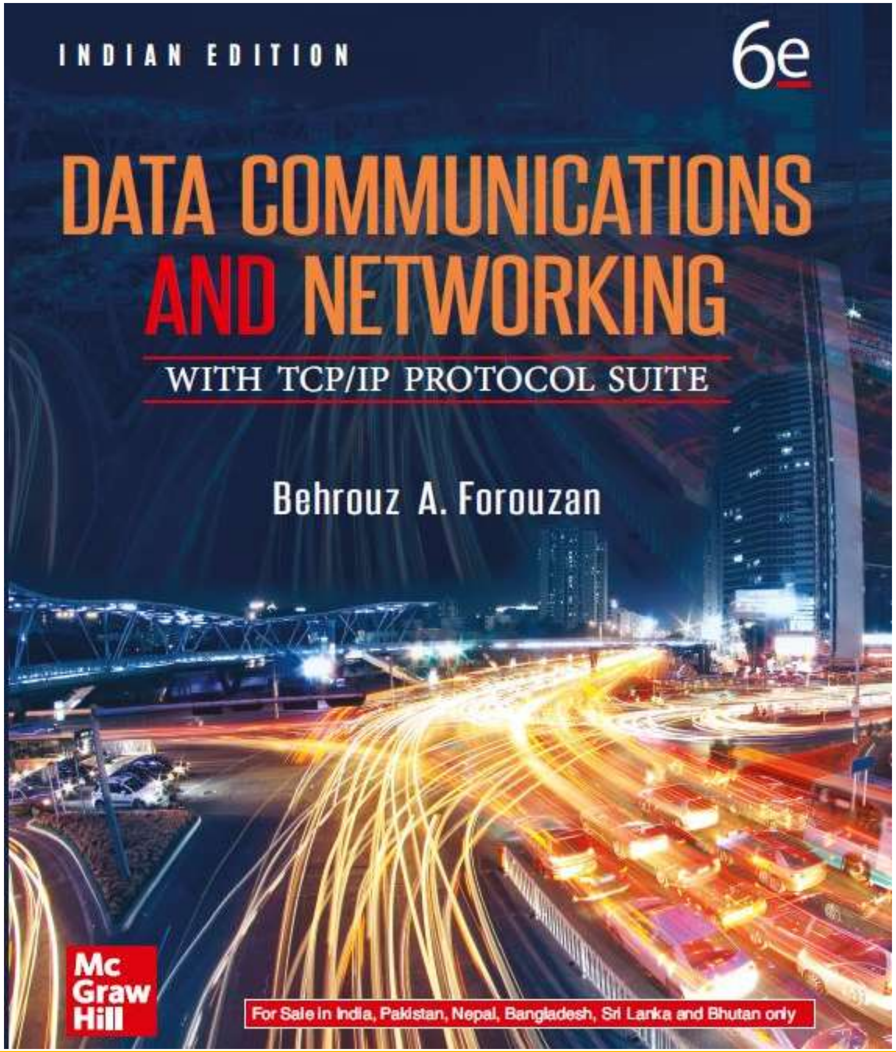
Chapter 02

Physical Layer

Data Communications and Networking, With TCP/IP protocol suite
Sixth Edition
Behrouz A. Forouzan



Chapter 2: Outline

2.1 SIGNALS

2.2 SIGNAL IMPAIRMENT

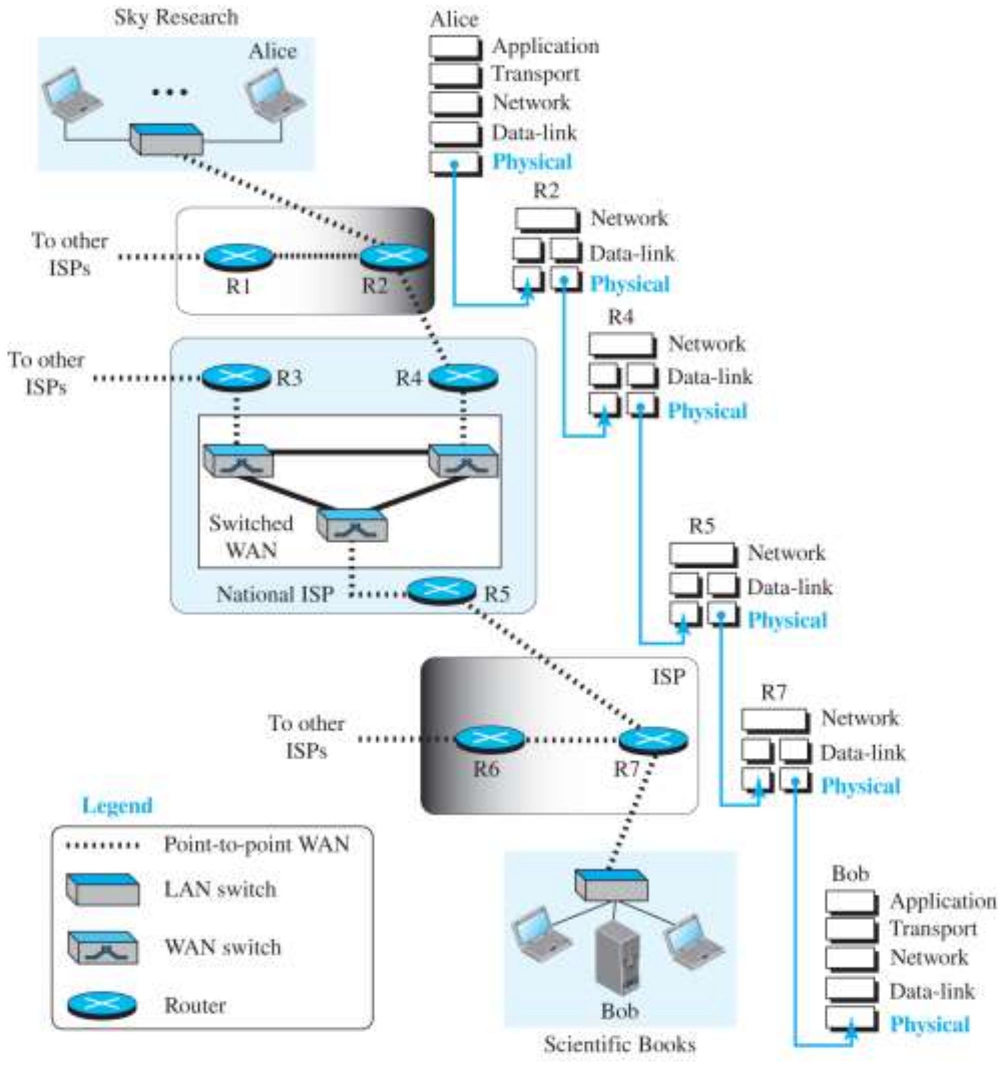
2.3 DIGITAL TRANSMISSION

2.4 ANALOG TRANSMISSION

2.5 MULTIPLEXING

2.6 TRANSMISSION MEDIA

Figure 2.1 Communication at the physical layer



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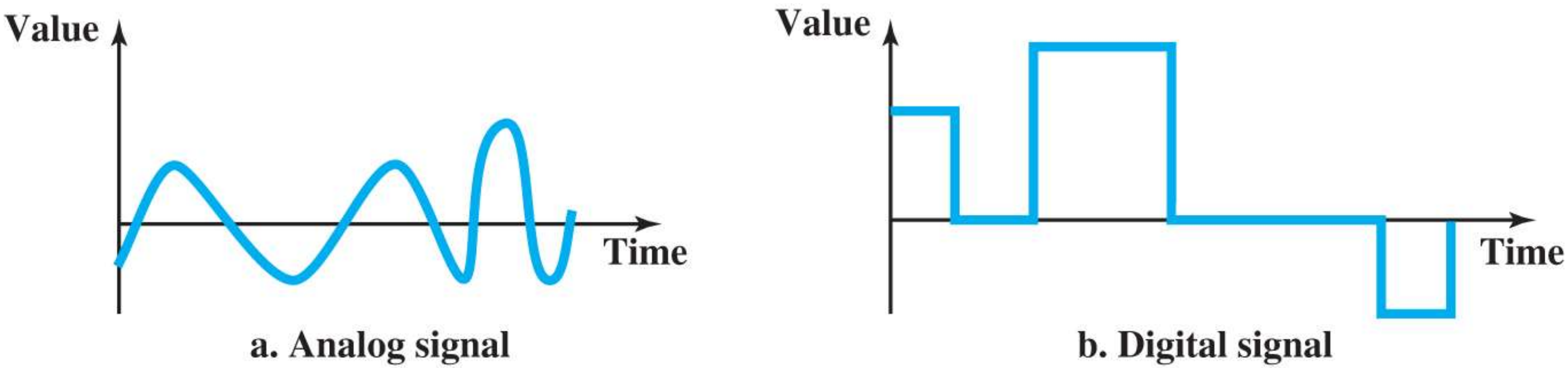
2-1 SIGNALS

What is exchanged between Alice and Bob is data, but what goes through the network at the physical layer is signals.

Figure 2.2 Comparison of analog and digital signals



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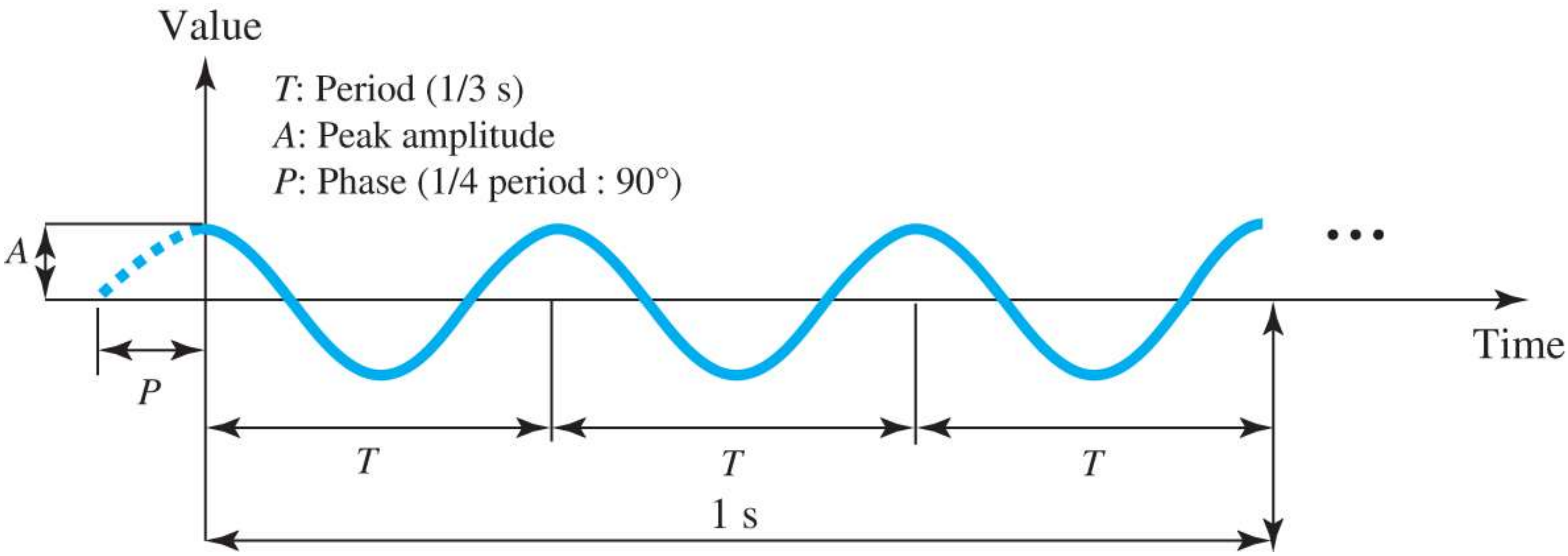
2.1.1 Analog Signal

An analog signal can take one of the two forms: periodic or aperiodic. In data communication, we normally use periodic signals. A simple periodic signal, a sine wave, cannot be decomposed into simpler signals.

Figure 2.3 A sine wave



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Peak Amplitude

The peak amplitude of a signal is the absolute value of its highest intensity.

Period and Frequency

The period (T) refers to the amount of time, in seconds, that a signal needs to complete one cycle. The frequency (f), measured in Hertz (Hz), refers to the number of periods in one second. Note that period and frequency are just one characteristic defined in two ways. Period and frequency are inverse of each other, in other words ($f = 1/T$).

Example 2.1

The voltage of a battery is constant. However, this can be considered as periodic with frequency of 0 and period of infinity.

Example 2.2

The electrical voltage in hour house in US is periodic with peak value of 120 to 120 volts. Its frequency is 60 Hz.

Phase

The term phase describes the position of the waveform relative to time 0. If we think of the wave as something that can be shifted backward or forward along the time axis, phase describes the amount of that shift.

Wavelength

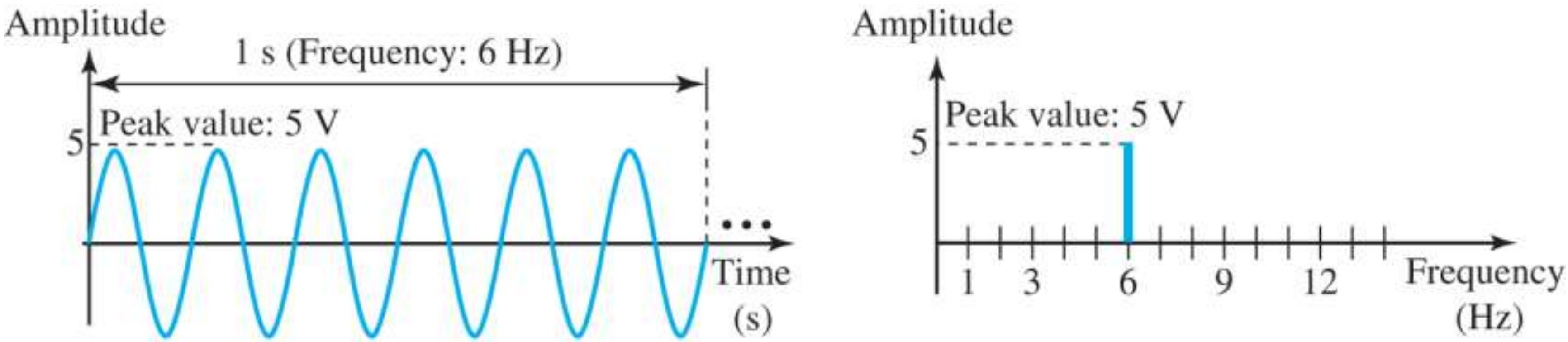
The wavelength is the distance a simple signal can travel in one period. Wavelength binds the period or the frequency of a simple sine wave to the propagation speed in the medium. If we represent wavelength by l, propagation speed by c, and frequency by f, and period by T, we get

$$\lambda = c/f = c \cdot T$$

Time and Frequency Domain

A sine waves is comprehensively defined by its amplitude, frequency, and phase. This can be done in both time and frequency domain.

Figure 2.4 The time-domain and frequency-domain plots of a sine wave



a. Time domain

b. Frequency domain

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Composite Signal

- *So far, we have focused on simple sine waves. A composite signal is made of many simple sine waves.*
- *The range of frequencies contained in a composite signal is its bandwidth. The bandwidth of a signal is the difference between the lowest and highest frequencies in the signal.*

Bandwidth *1*

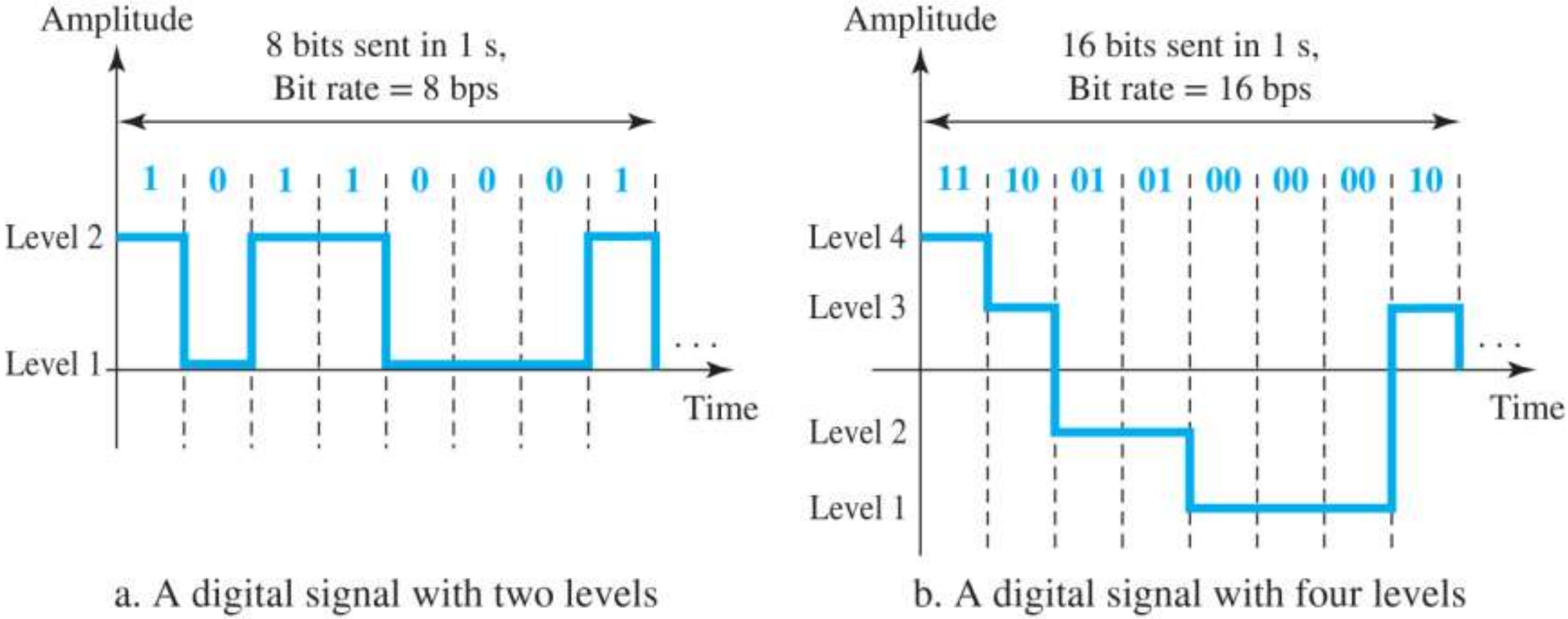
The range of frequencies contained in a composite signal is its bandwidth. The bandwidth of a signal is the difference between the lowest and highest frequencies in the signal.

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

2.1.2 Digital Signal

Information can also be represented by a digital signal. For example, a value 1 can be encoded as a positive voltage and a value 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. Figure 2.5 shows two signals, one with two levels and the other with four.

Figure 2.5 Two digital signals, one with two and one with four bit-levels



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Bit Rate

Most digital signal are nonperiodic, and thus period and frequency are not appropriate characteristics. Another term-bit rate (instead of frequency) is used. The bit rate is the number of bits sent in 1 second.

Example 2.3

Assume we have downloaded text documentation at the rate of 100 pages per minute. A page is an average of 24 lines with 80 characters per line. If we assume that one character requires 8 bits, the bit rate is:

$$100 * 24 * 80 * 8 = 1{,}536{,}000 \text{ bps} = 1.536 \text{ Mbps}$$

Bit Length

We discuss the concept of a wavelength for an analog signal. We can define something similar for a digital signal: the bit length. The bit length is the distance one bit occupy on the transmission medium.

bit length = 1 / bit rate

Example 2.4

The length of the bit in Example 2.3 is

$$1 / 1{,}536{,}000 = 0.651 \text{ microseconds}$$

Transmission of Digital Signal

A digital signal is a composite analog signal with frequency between zero and infinity. We can have two types of transmission: baseband and broadband. The first means sending the digital signal without changing it to analog signal. The second means changing the digital signal to analog signal and send the analog signal.

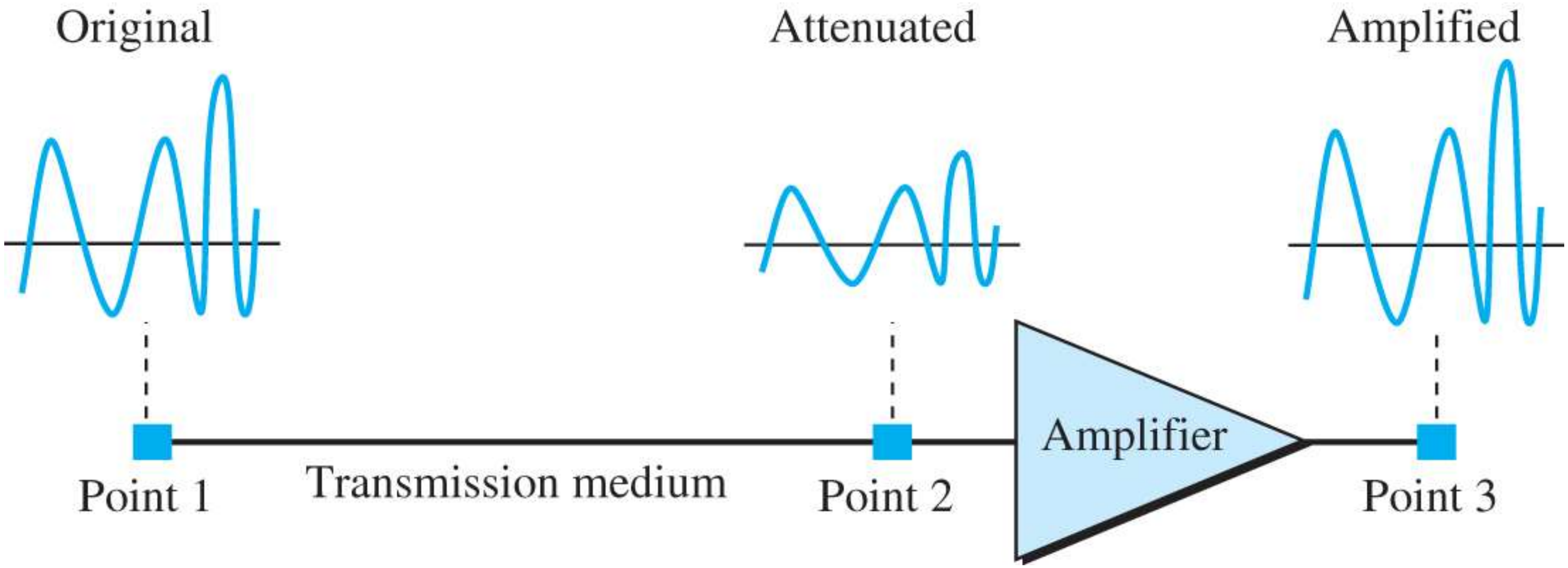
2-2 SIGNAL IMPAIRMENT

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.

2.2.1 Attenuation and Amplification

Attenuation means a loss of energy. To compensate for this loss we need amplification. When a signal, simple or composite, travels through a medium, it loses some of its energy in overcoming the resistance of the medium. To compensate for this loss, we need amplification. Figure 2.6 shows the effect of attenuation and amplification.

Figure 2.6 Attenuation and amplification



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Example 2.5

Suppose a signal travels through a transmission medium and its power is reduced to one half. This means that $P_2 = 0.5\ P_1$. In this case, the attenuation (loss of power) can be calculated as

$$\boxed{\mathbf{10\ \log_{10} P_2/P_1 = 10\ \log_{10}(0.5P_1)/P_1 = 10\ \log_{10} 0.5 = 10 \times (-0.3) = -3dB.}}$$

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

2.2.2 Distortion

Distortion means that the signal changes its form or shape. Distortion can occur in a composite signal made up of different frequencies.

Noise

Noise is another cause of impairment. Several type of noise may occur during the signal transmission.

Signal-to-Noise Ratio (SNR) is defined as

SNR = (average signal power) / (average noise power)

2.2.3 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)*

Two theoretical formulas were developed to calculate the data rate: one by Nyquist for a noiseless channel, another by Shannon for a noisy channel.

Noiseless Channel: Nyquist Bit Rate

For a noiseless channel, the Nyquist bit rate formula defines the theoretical maximum bit rate.

$$\text{Bit Rate} = 2 \cdot B \cdot \log_2 L$$

Example 2.6

We need to send 265 kbps over a noiseless (ideal) channel with a bandwidth of 20 kHz. How many signal levels do we need? We can use the Nyquist formula as shown:

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

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.

Noisy Channel: Shannon Capacity

For a noisy channel, we have

$$C = B \cdot \log_2(1 + SNR)$$

Example 2.7

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 shown below.

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

This means that the capacity of this channel is zero regardless of the bandwidth. In other words, the data is so corrupted in this channel that it is useless when received.

Example 2.8

We can calculate the theoretical highest bit rate of a regular telephone line. A telephone line normally has a bandwidth of 3000 Hz (300 to 3300 Hz) assigned for data communications. The signal-to-noise ratio is usually 3162. For this channel the capacity is calculated as shown below.

$$\boxed{\mathbf{C = B\ log_2(1 + SNR) = 3000\ log_2(1 + 3162) = 34{,}881\ bps}}$$

This means that the highest bit rate for a telephone line is 34.881 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.

Using Both Limits

In practice, we need to use both limits.

$$C = B \, . \, \log_2(1 + SNR)$$

Example 2.9

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.

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

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

$$\boxed{\mathbf{4\ Mbps = 2 \times 1\ MHz \times log_2 L \rightarrow log_2 L = 2 \rightarrow L = 4}}$$

2.2.4 Performance

Up to now, we have discussed the tools of transmitting data (signals) over a network and how the data behave. One important issue in networking is the performance of the network—how good is it?

Bandwidth 2

One characteristic that measure network performance is bandwidth.

Example 2.10

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 kbps, using a sophisticated modem to change the digital signal to analog. If the telephone company improves the quality of the line and increases the bandwidth to 8 kHz, we can send 112 kbps.

Example 2.11

For example, one can say that the bandwidth of a fast Ethernet network is 100 Mbps. This means we can send 100 Mbps through this network.

Throughput

The throughput is the measure of how fast we can actually send data through a network.

Latency (Delay)

The latency or delay defines how long it takes for an entire message to completely arrive at the destination from the time the first bit is sent out from the source. We say that normally have four types of delay: propagation delay, transmission delay, queuing delay, and processing delay. The latency or total delay is

Latency = propagation delay + transmission delay + queuing delay + processing delay

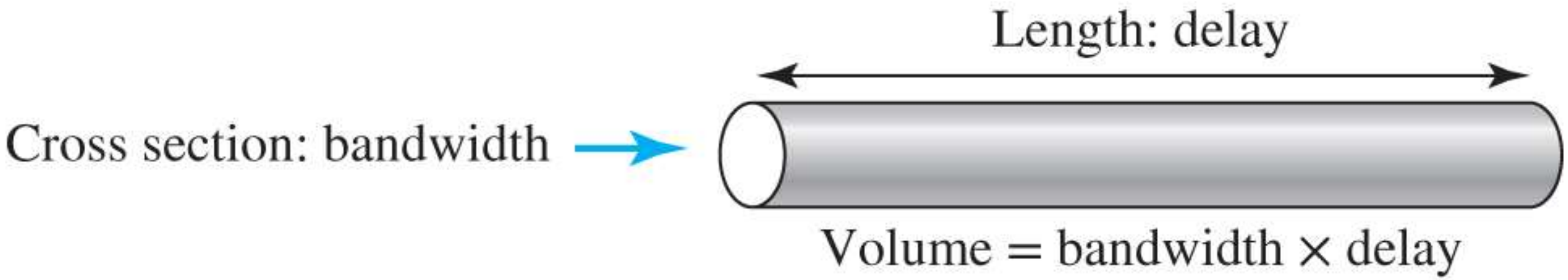
Bandwidth-Delay Product

Bandwidth and delay are two performance metric of a link. However, what is very important in data communications is the product of the two, the bandwidth-delay product.

Example 2.12

We can think about the link between two points as a pipe. We can say that the volume of the pipe defines the bandwidth-delay product

Figure 2.7 Bandwidth-delay product



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Jitter

Another performance issue that is related to delay is jitter. We can roughly say that jitter is a problem if different packets of data encounter different delays and the application using the data at the receiver site is time-sensitive (audio and video data, for example). If the delay for the first packet is 20 ms, for the second is 45 ms, and for the third is 40 ms, then the real-time application that uses the packets endures jitter.

2-3 DIGITAL TRANSMISSION

A computer network is designed to send information from one point to another. This information needs to be converted to either a digital signal or an analog signal for transmission. In this section, we discuss the first choice, conversion to digital signals; in the next section, we discuss the second choice, conversion to analog signals.

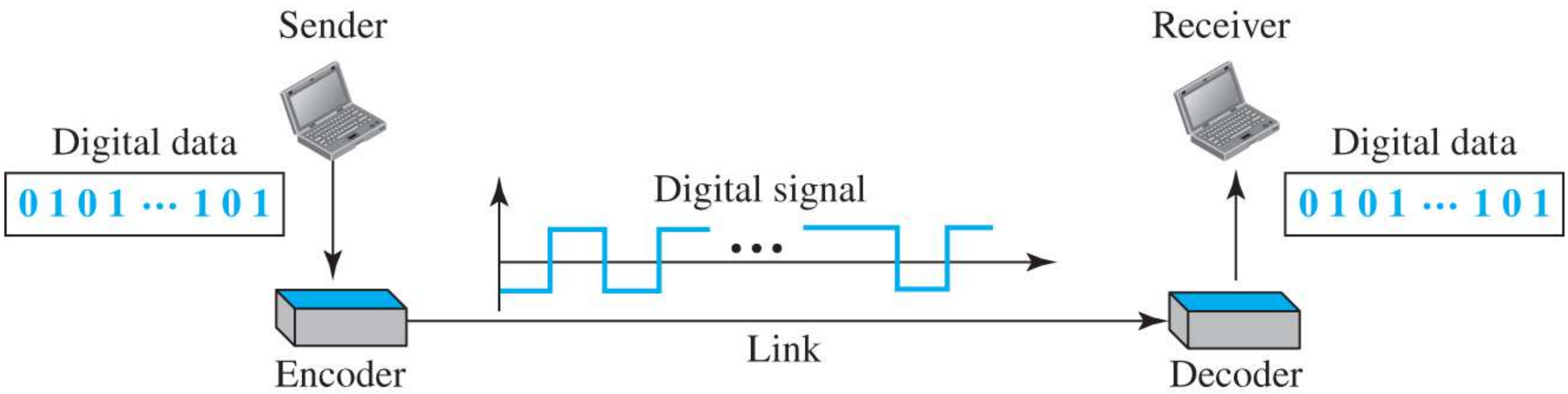
2.3.1 Digital-to-Digital Conversion

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.

Line Coding

Line coding is the process of converting digital data to digital signals. We assume that data, in the form of text, numbers, graphical images, audio, or video, are stored in computer memory as sequences of bits.

Figure 2.8 Line coding and decoding



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Block Coding

We need redundancy to ensure synchronization and to provide inherent error detecting. Block coding can give us this redundancy and improve the performance of line coding. In general, block coding changes a block of m bits into a block of n bits, where n is larger than m. Block coding is referred to as an mB/nB encoding technique.

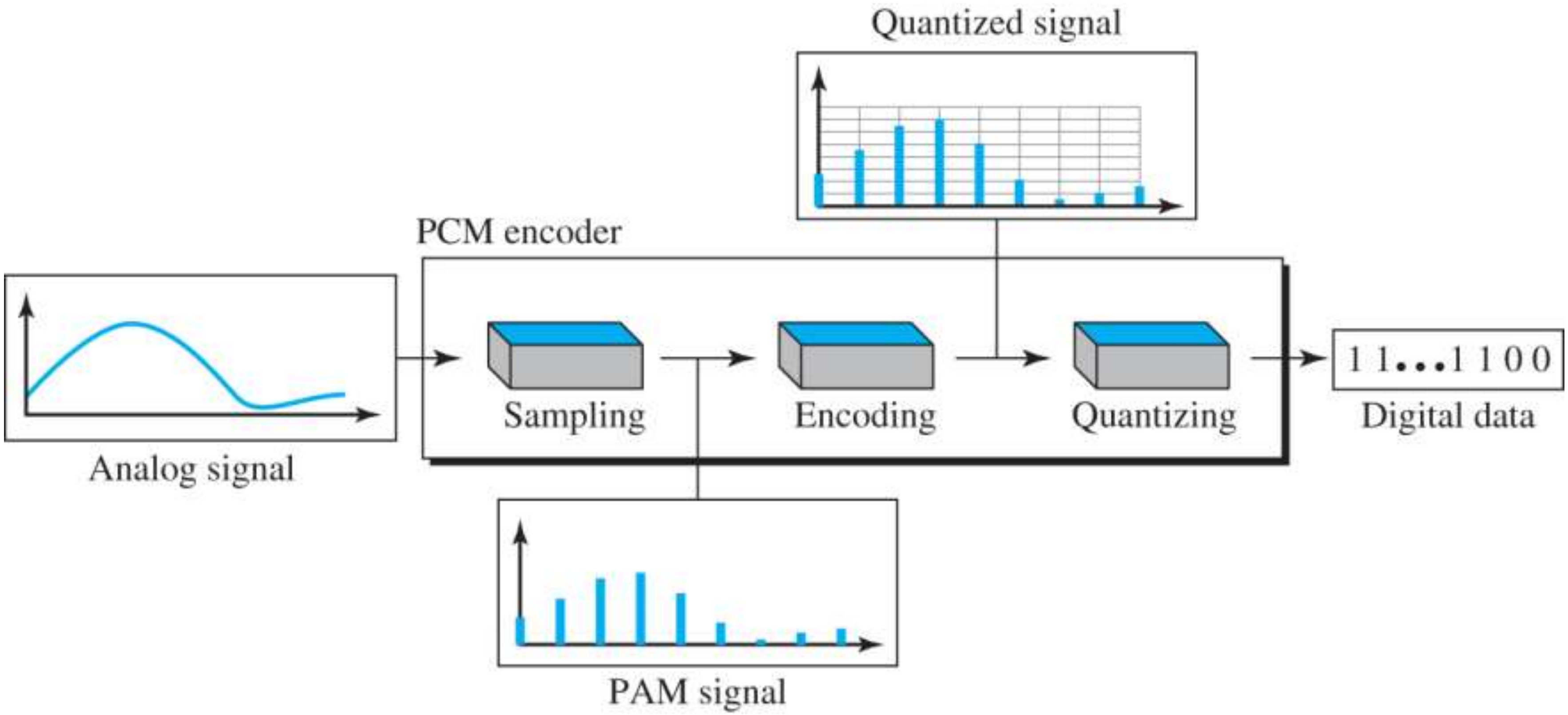
2.3.2 Analog-to-Digital Conversion

Sometimes we have an analog signal such as one created by a microphone or camera. The tendency today is to change an analog signal to digital data because the digital signal is less susceptible to noise. In this section we describe two techniques, pulse code modulation and delta modulation.

Pulse-Code Modulation (PCM)

The most common technique to change to change an analog signal to a digital signal is called pulse code modulation (PCM) , as shown in Figure 2.9.

Figure 2.9 Components of PCM encoder



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Example 2.13

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

Solution

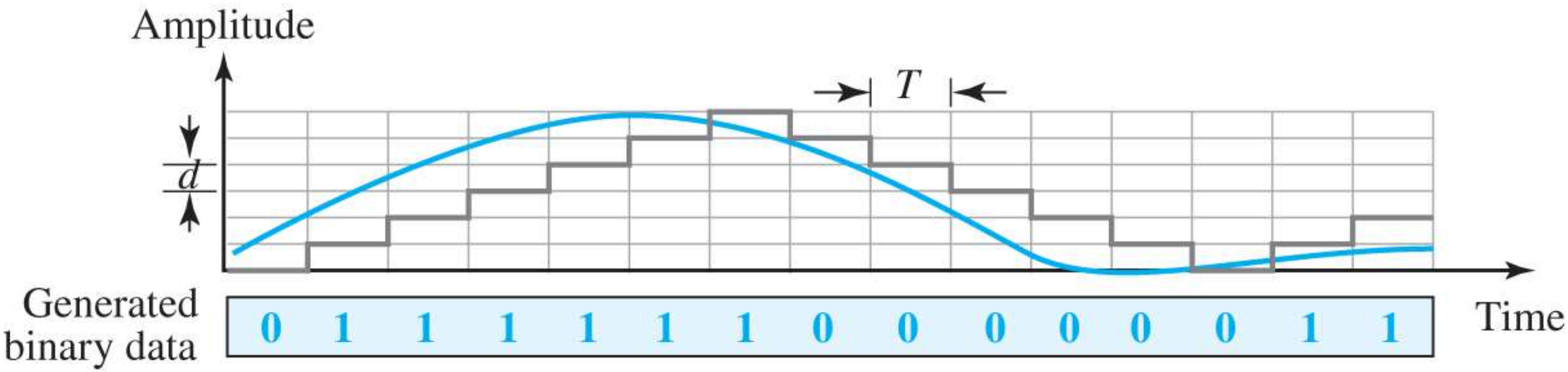
The human voice normally contains frequencies from 0 to 4000 Hz. So the sampling rate and bit rate are calculated as follows.

$$\boxed{\textbf{Sampling rate} = \mathbf{4000 \times 2 = 8000\ samples/s} \rightarrow \textbf{Bit rate} = \mathbf{8000 \times 8 = 64{,}000\ bps = 64\ kbps}}$$

Delta Modulation (DM)

PCM is a very complex technique. Other techniques have been developed to reduce the complexity of PCM. The simplest is delta modulation. PCM finds the value of the signal amplitude for each sample; DM finds the change from the previous sample. Figure 2.10 shows the process.

Figure 2.10 The process of delta modulation



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2-4 ANALOG TRANSMISSION

While digital transmission is desirable, it needs a low-pass channel; analog transmission is the only choice if we have a bandpass channel. Converting digital data to a bandpass analog signal is traditionally called digital-to-analog conversion. Converting a low-pass analog signal to a bandpass analog signal is traditionally called analog-to-analog conversion.

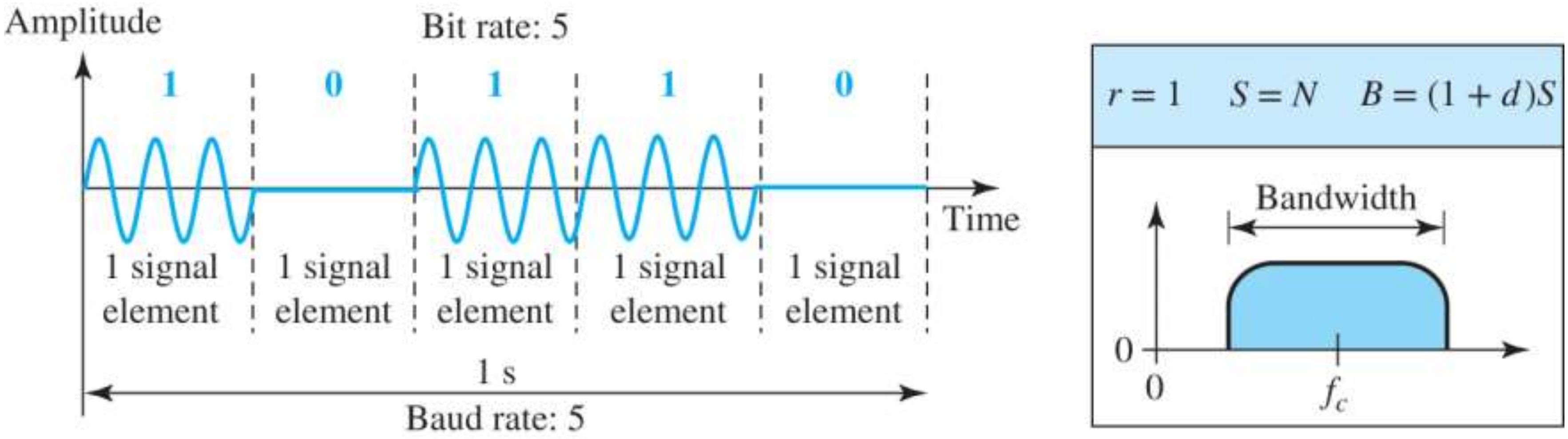
2.4.1 Digital-to-Analog Conversion

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

Amplitude Shift Keying (ASK)

In amplitude shift keying, the amplitude of the carrier signal is varied to create signal elements.

Figure 2.11 Binary amplitude shift keying



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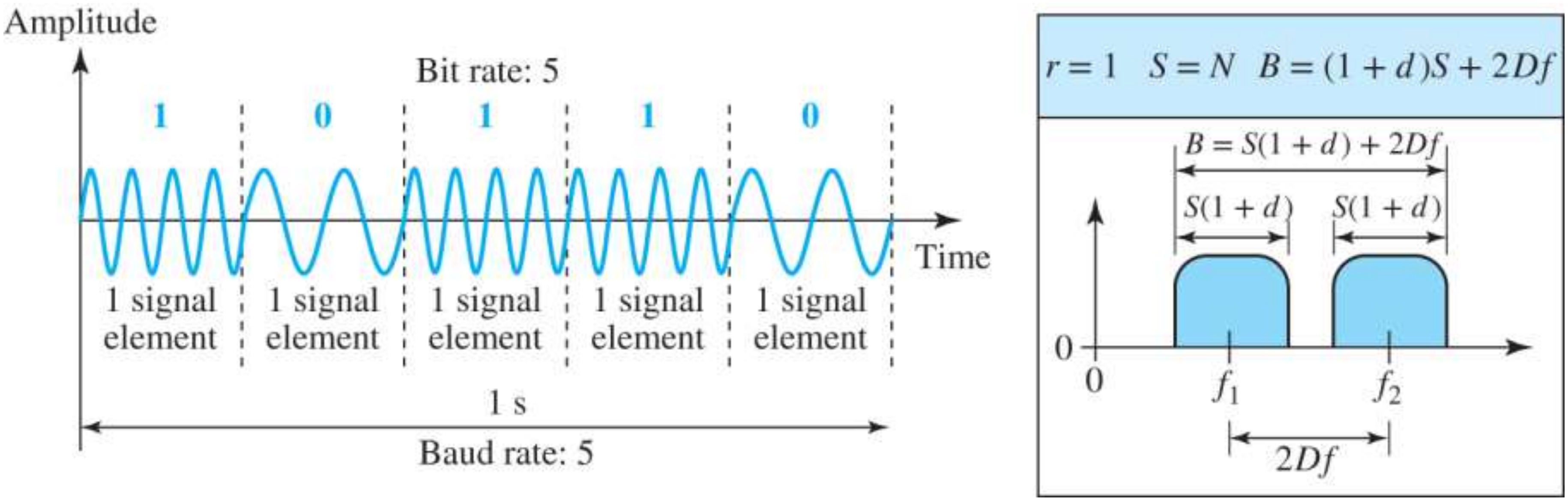
Frequency Shift Keying

In frequency shift keying, the frequency of the carrier signal is varied to represent data.

Figure 2.12 Binary frequency shift keying



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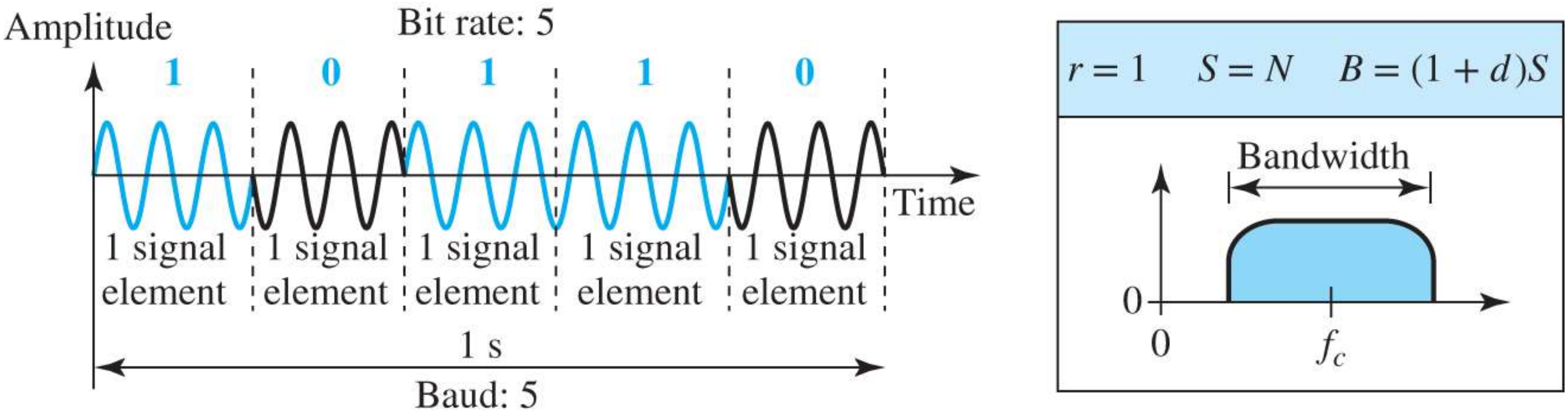
Phase Shift Keying

In phase shift keying, the phase of the carrier signal is varied to represent data.

Figure 2.13 Binary phase shift keying



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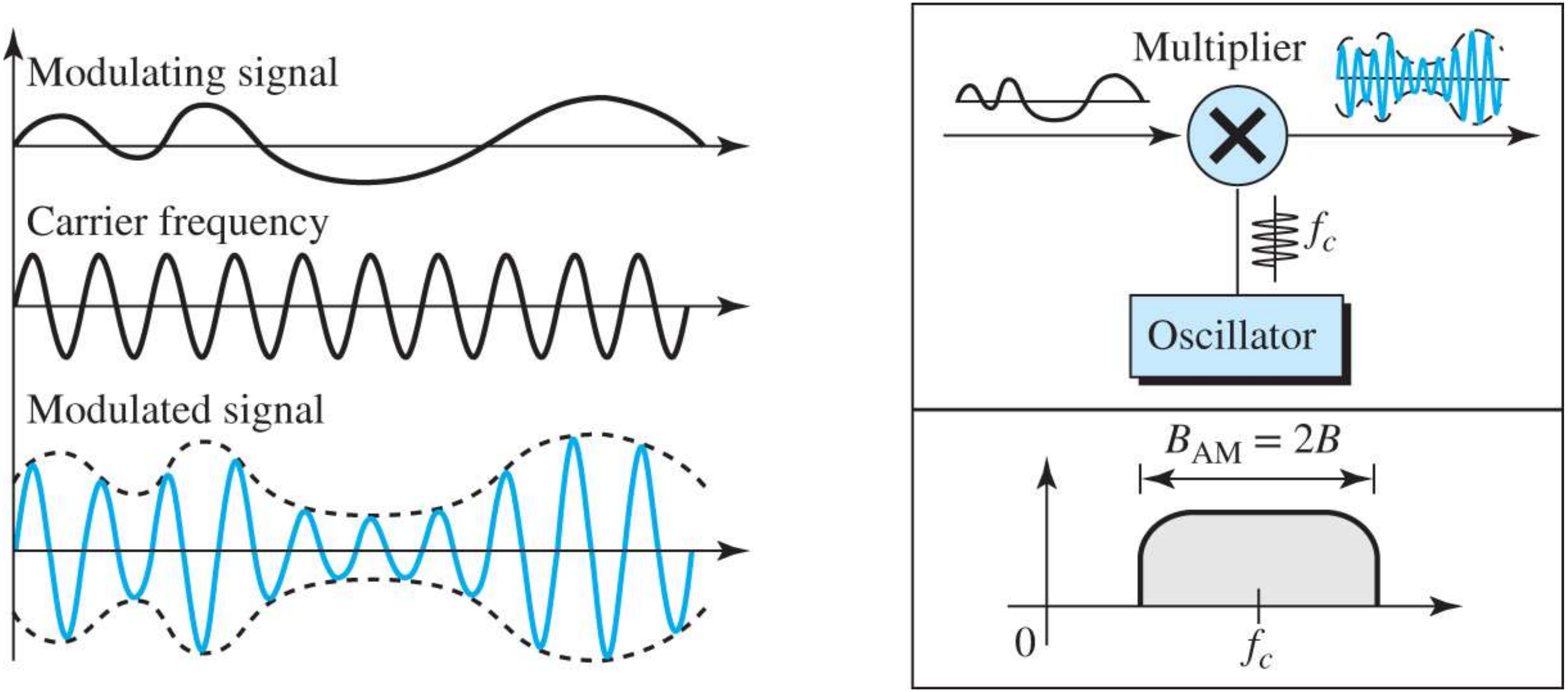
2.4.2 Analog-to-Analog Conversion

Analog-to-analog conversion, or analog modulation, 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.

Amplitude Modulation (AM)

In amplitude modulation, the amplitude of the carrier signal changes to follow the changes in modulating signal.

Figure 2.14 Amplitude modulation



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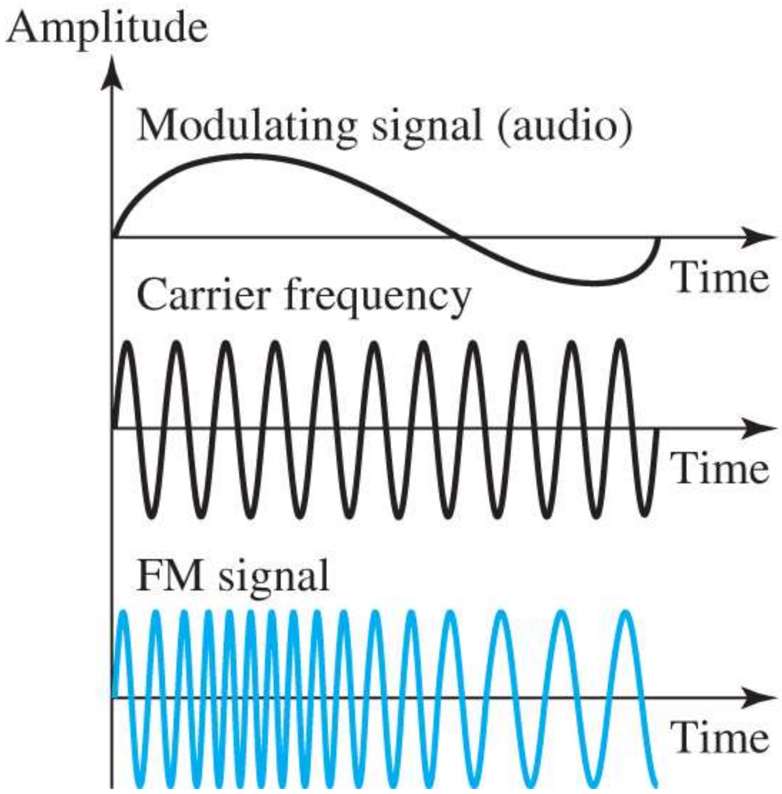
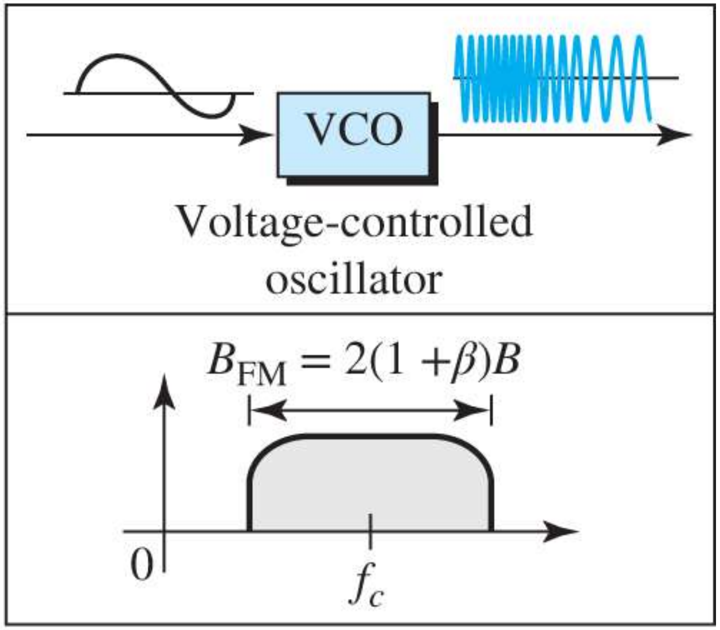
Frequency Modulation (FM)

In frequency modulation, the frequency of carrier signal changes to follow the changes in the modulating signal.

Figure 2.15 Frequency modulation





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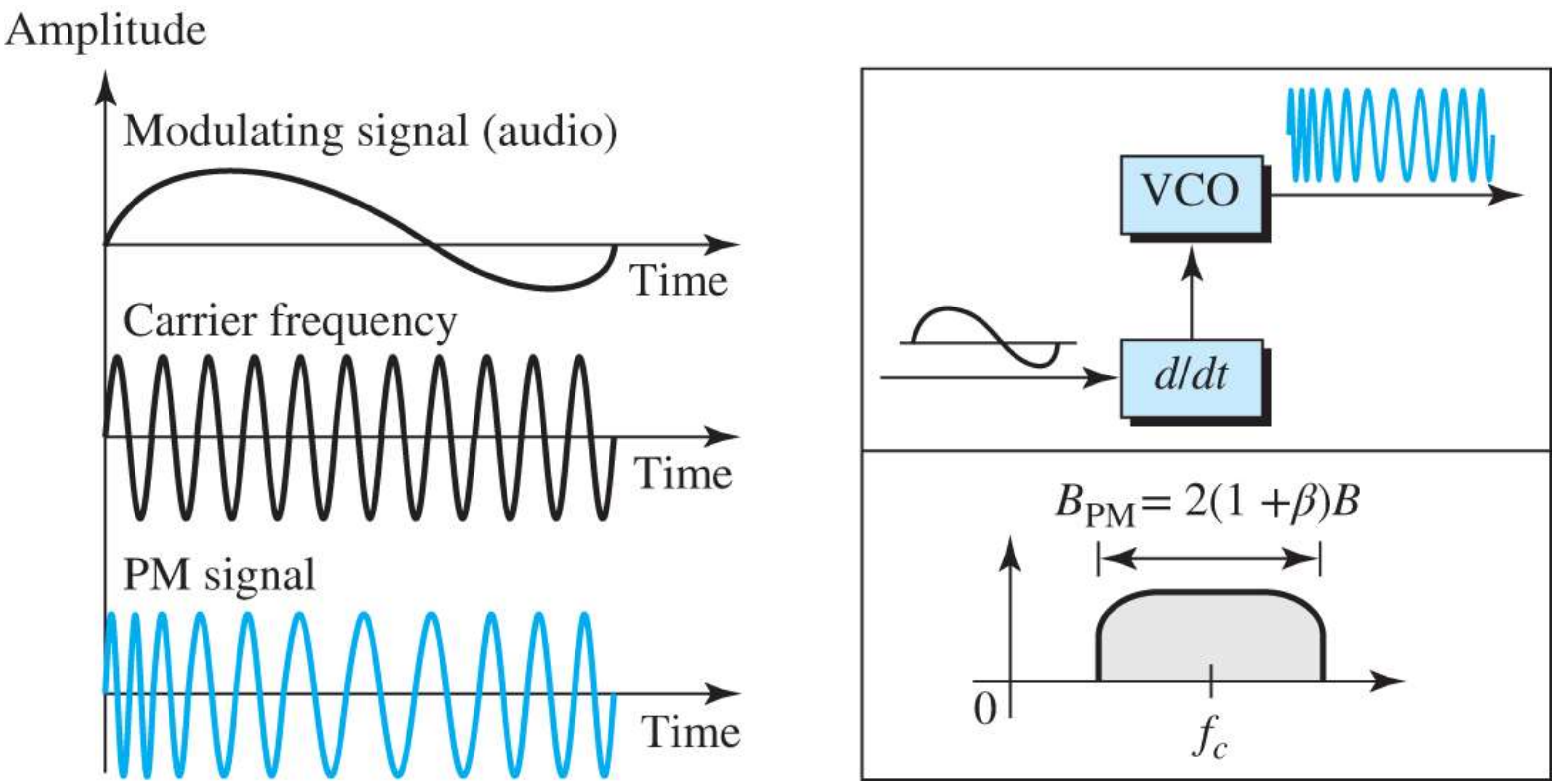
Phase Modulation (PM)

In phase modulation, the phase of carrier signal changes to follow the changes in the modulating signal.

Figure 2.16 Phase modulation



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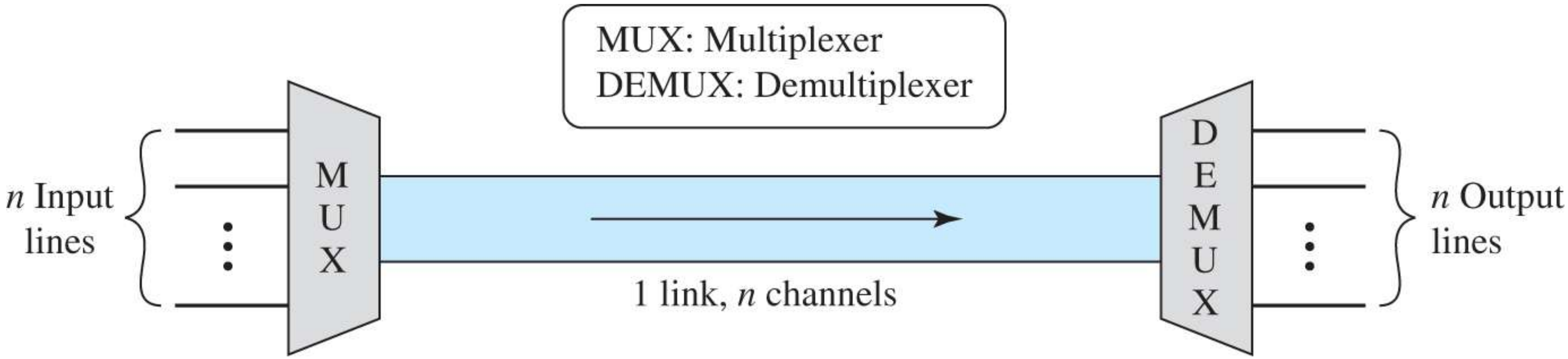
2-5 MULTIPLEXING

In real life, we have links with limited bandwidths. Sometimes we need to combine several low-bandwidth channels to make use of one channel with a larger bandwidth. Sometimes we need to expand the bandwidth of a channel to achieve goals such as privacy and anti-jamming.

Figure 2.17 Dividing a link into channels



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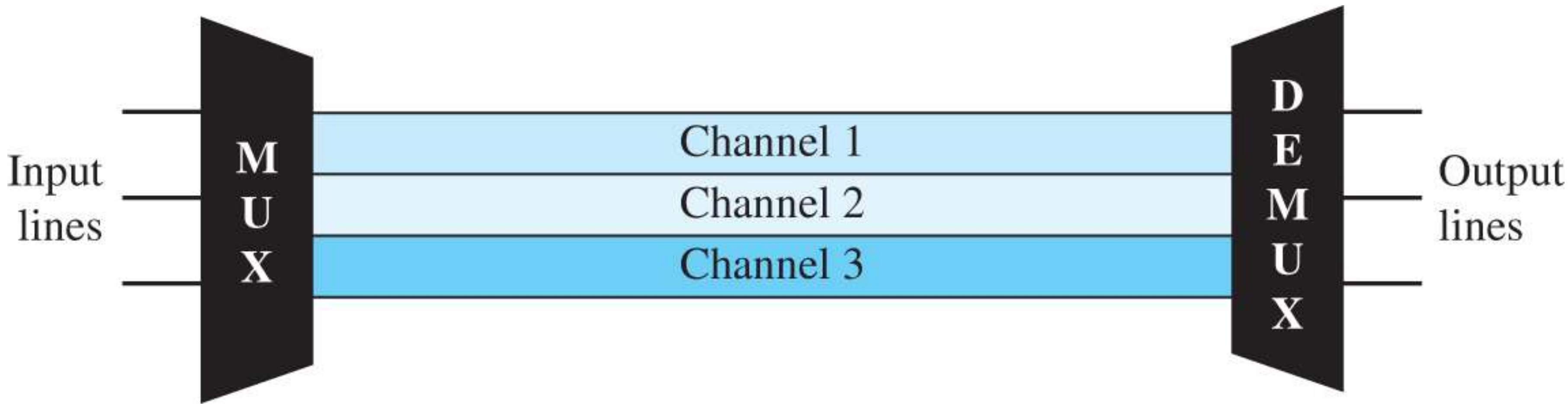
2.5.1 Frequency-Division Multiplexing

Frequency-division multiplexing is an analog technique that can be applied when the bandwidth of a link is greater than the combined bandwidth of the signals to be transmitted together.

Figure 2.18 Frequency-division multiplexing



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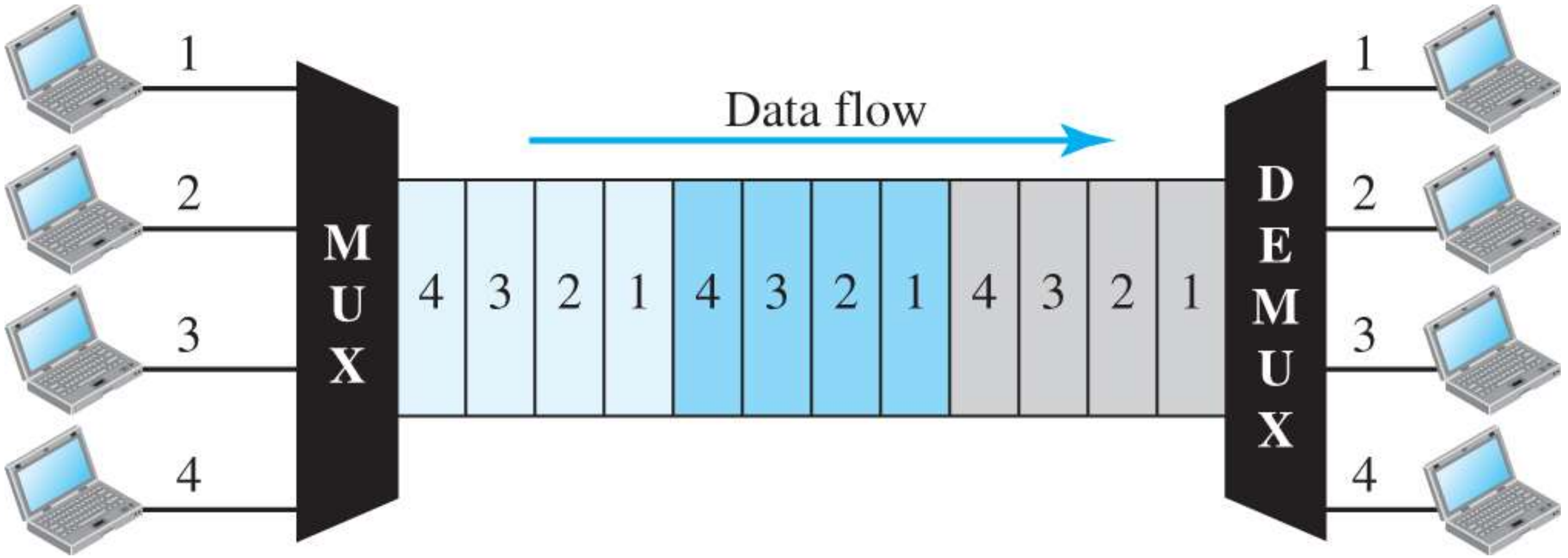
2.5.2 Time-Division Multiplexing

Time-division multiplexing (TDM) is a digital technique that allows several connections to share the high bandwidth of a link.

Figure 2.19 Time division multiplexing (TDM)



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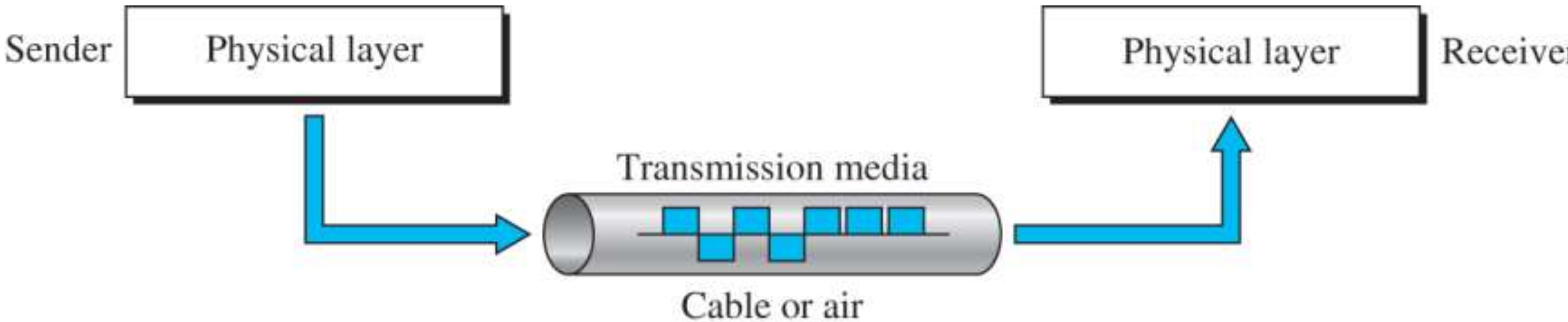
2-6 TRANSMISSION MEDIA

We discussed many issues related to the physical layer in this chapter. In this section, we discuss transmission media. Transmission media are located below the physical layer and are directly controlled by the physical layer.

Figure 2.20 Transmission media and physical layer



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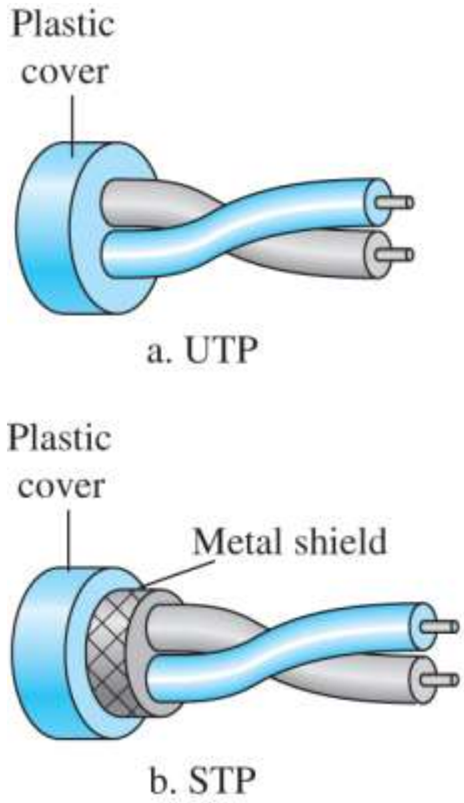
2.6.1 Guided Media

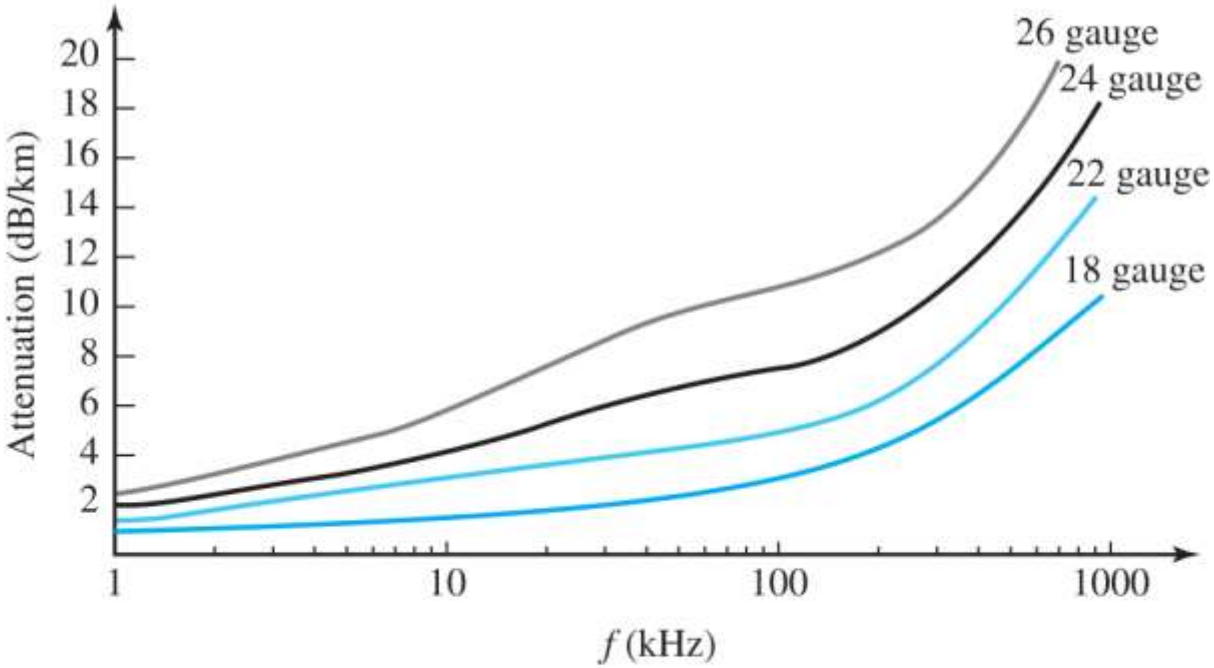
Guided media, which are those that provide a conduit from one device to another, include twisted-pair cable, coaxial cable, and fiber-optic cable.

Twisted-Pair Cable

A twisted-pair cable consists of two conductors, each with its own plastic insulation, twisted together as shown in Figure 2.21.

Figure 2.21 Twisted-pair cable





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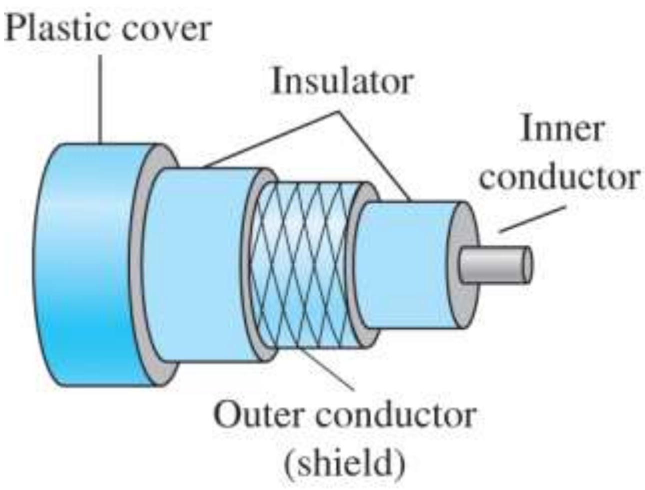
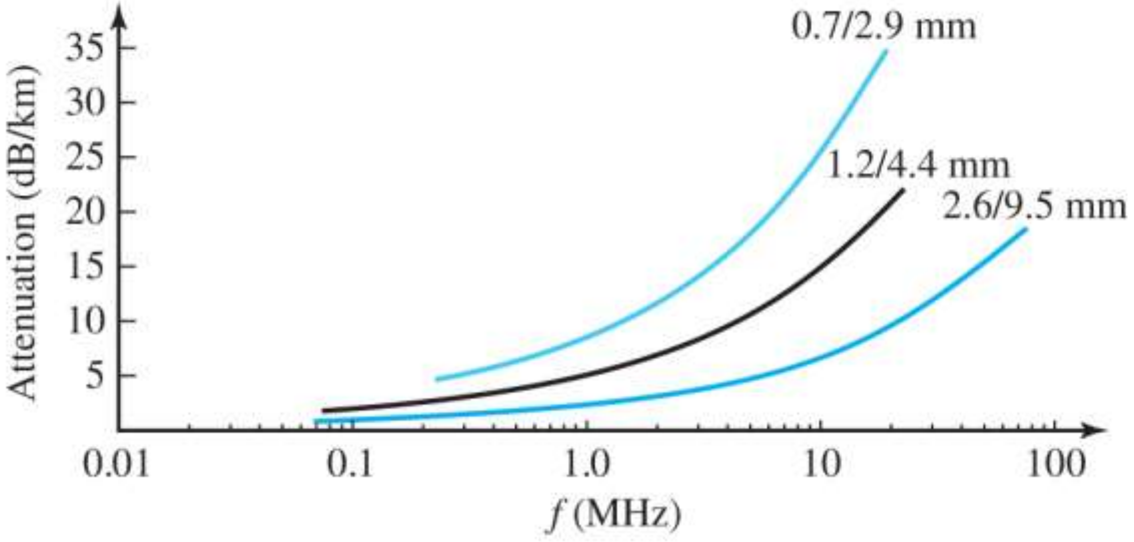
Coaxial Cable

Coaxial cable carries signals of higher frequency ranges more than those in twisted-pair cable. Coaxial cable has a central core enclosed in an insulating sheath as shown in Figure 2.22.

Figure 2.22 Coaxial cable





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Fiber-Optic Cable

A fiber-optic cable is made of glass or plastic and transmits signal in the form of light. If a light traveling in a substance enters another substance, the ray changes direction as shown in Figure 2.23. Figure 2.24 shows how a beam of light travels through an optical fiber.

Figure 2.23 Bending of light ray

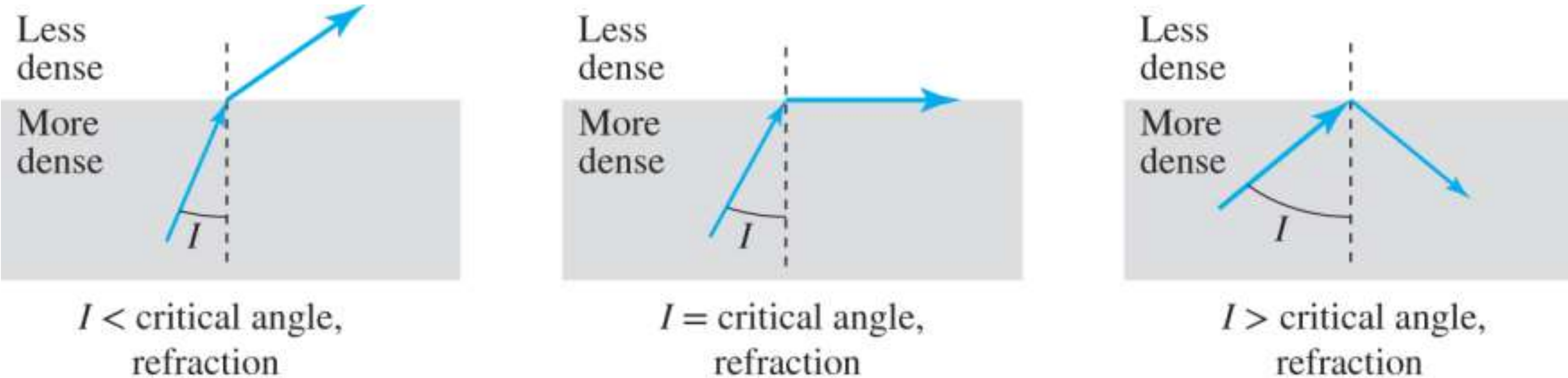

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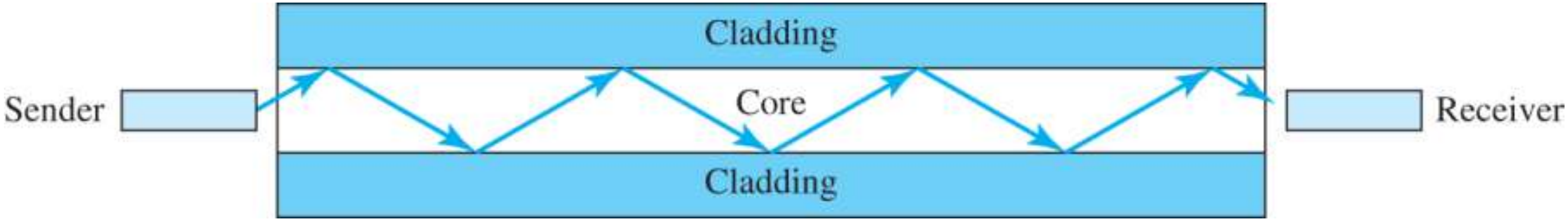
Figure 2.24 Optical fiber



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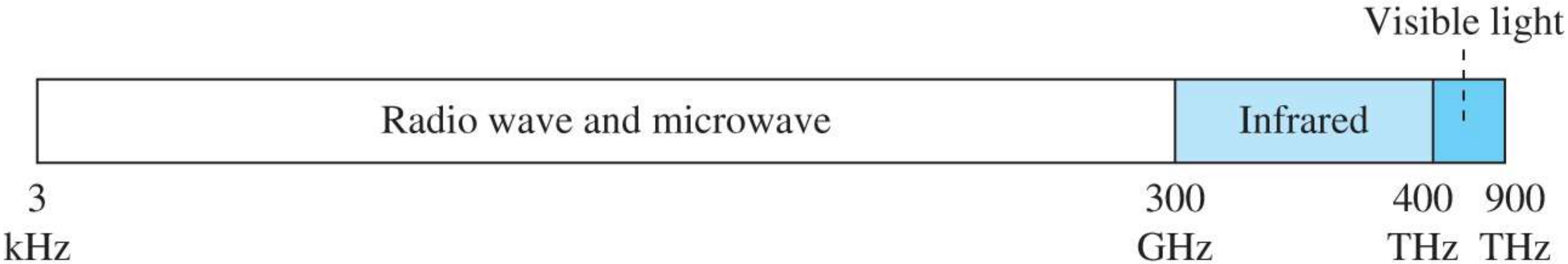
2.6.2 Unguided Media: Wireless

Unguided media transport electromagnetic waves without using a physical conductor. This type of communication is often referred to as wireless communication. Signals are normally broadcast through free space and thus are available to anyone who has a device capable of receiving them. Figure 2.25 shows part of the electromagnetic spectrum from 3KHz to 800 THz used for wireless communication.

Figure 2.25 Electromagnetic spectrum for wireless communication



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Radio Waves

Although there is no clear-cut demarcation between radio waves and microwaves, electromagnetic waves ranging in frequencies between 3 kHz and 1 GHz are normally called radio waves; waves ranging in frequencies between 1 and 300 GHz are called microwaves. However, the behavior of the waves, rather than the frequencies, is a better criterion for classification. Radio waves, for the most part, are omnidirectional.

Microwaves

Electromagnetic waves having frequencies between 1 and 300 GHz are called microwaves. Microwaves are unidirectional. When an antenna transmits microwaves, they can be narrowly focused. This means that the sending and receiving antennas need to be aligned. The unidirectional property has an obvious advantage. A pair of antennas can be aligned without interfering with another pair of aligned antennas.

Infrared

Infrared waves, with frequencies from 300 GHz to 400 THz (wavelengths from 1 mm to 770 nm), can be used for short-range communication. Infrared waves, having high frequencies, cannot penetrate walls. This advantageous characteristic prevents interference between one system and another; a short-range communication system in one room cannot be affected by another system in the next room.

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