Chapter 3

Introduction to Physical Layer

Analog and Digital Data

Data

- ***Analog:*** refers to information that is continuous
  e.g., analog clock

- ***Digital:*** refers to information that has discrete states
  e.g., digital clock

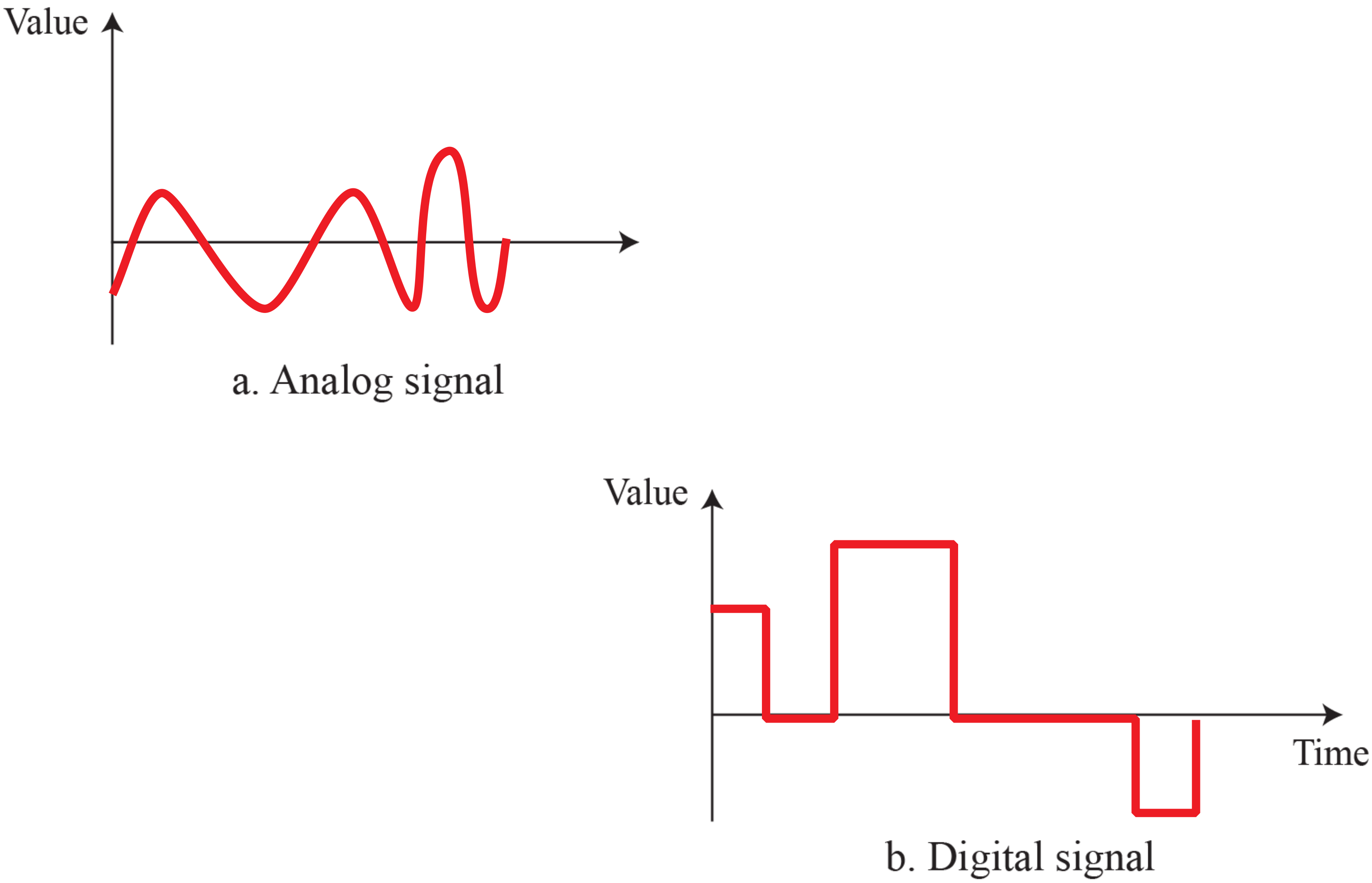
Analog and Digital Signals

Like the data they represent, signals can be either analog or digital.

- *An analog signal has infinitely many levels of intensity over a period of time*

- *A digital signal can have only a limited number of defined values.*

Figure 3.2: Comparison of analog and digital signals



Periodic and Nonperiodic

- *A periodic signal completes a pattern within a measurable time frame, called a period, and repeats that pattern over subsequent identical periods. The completion of one full pattern is called a cycle.*

- *A nonperiodic signal changes without exhibiting a pattern or cycle that repeats over time.*

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.*

Figure 3.3: ***A sine wave***

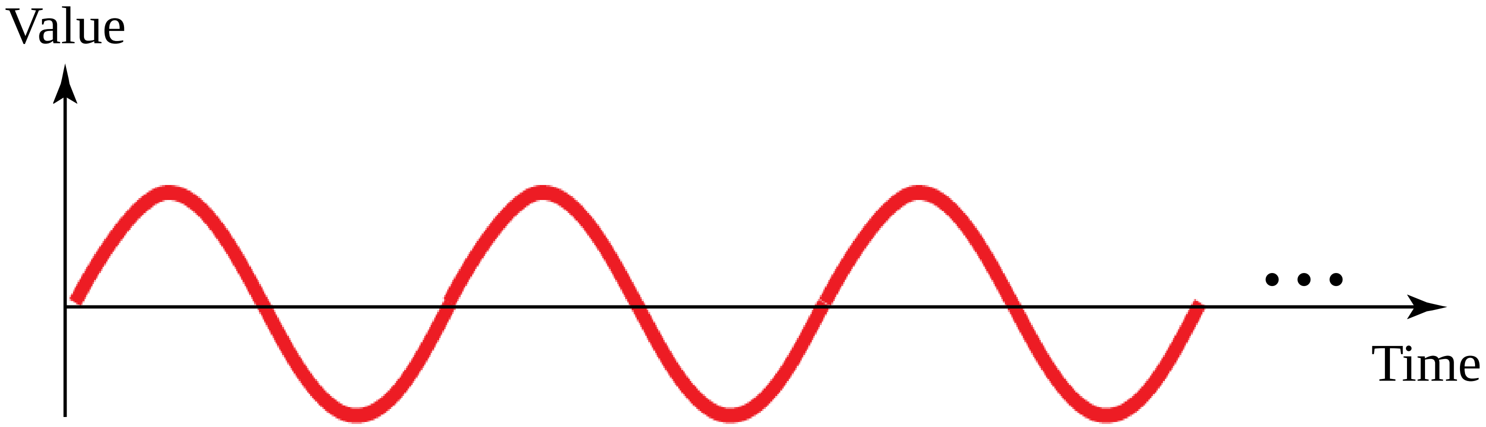
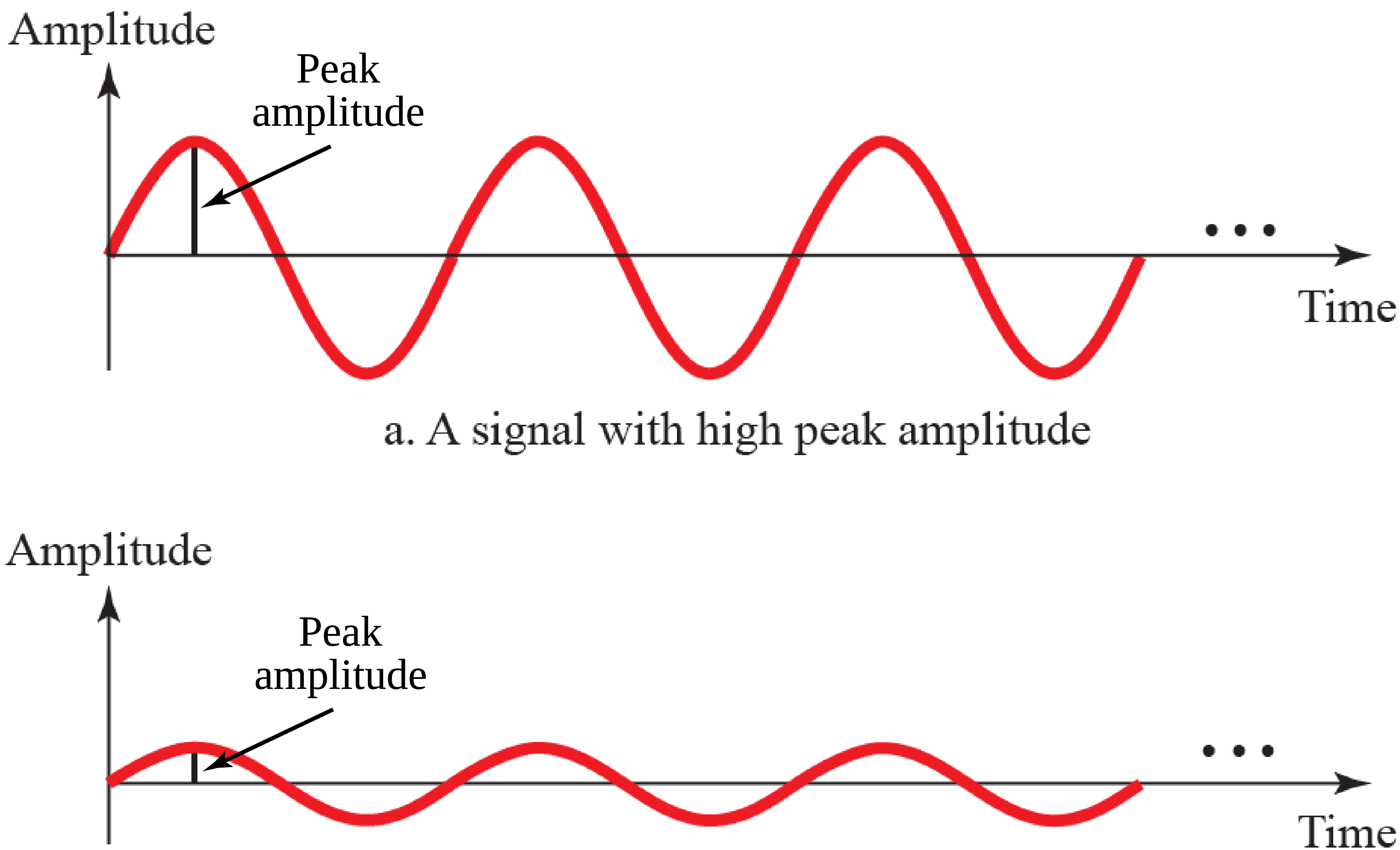


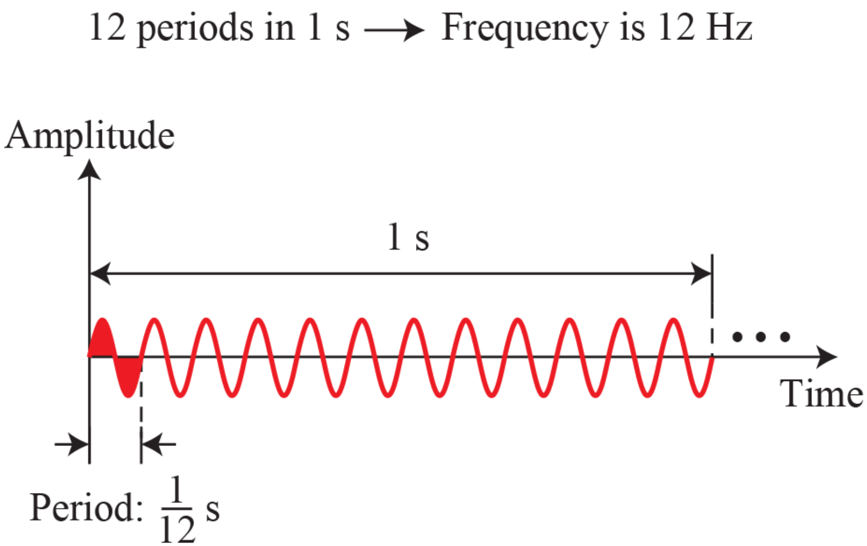
Figure 3.4: Two signals with two different amplitudes



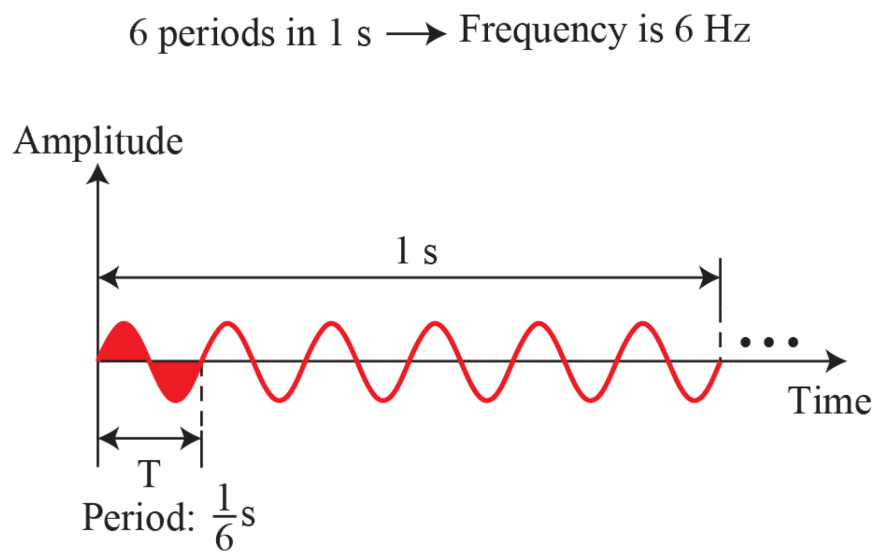
a. A signal with high peak amplitude

b. A signal with low peak amplitude

Figure 3.5: Two signals with the same phase and frequency, but different amplitudes



a. A signal with a frequency of 12 Hz



b. A signal with a frequency of 6 Hz

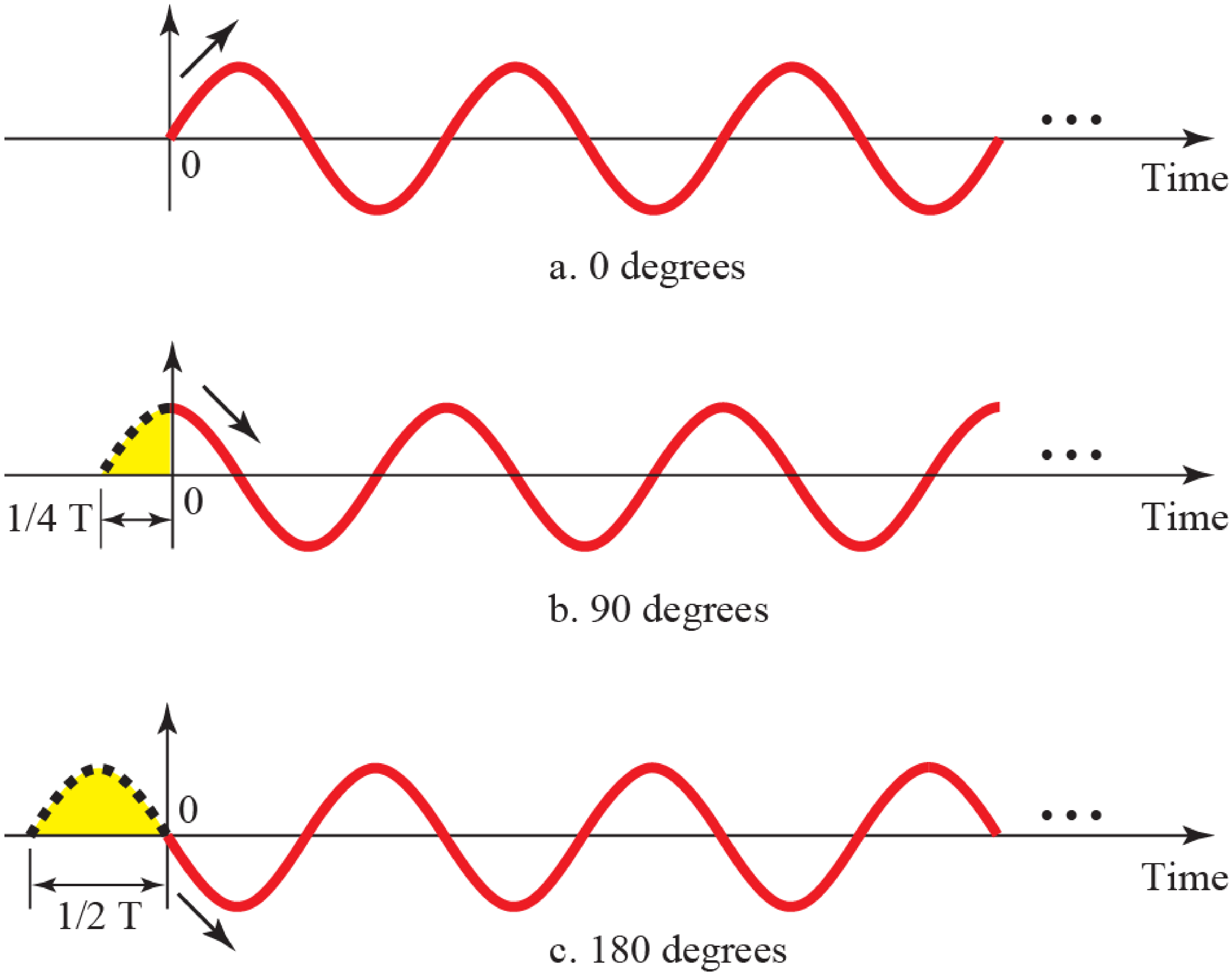
Table 3.1: Units of period and frequency

Period		*Frequency*	
Unit	*Equivalent*	*Unit*	*Equivalent*
Seconds (s)	1 s	Hertz (Hz)	1 Hz
Milliseconds (ms)	10^{-3} s	Kilohertz (kHz)	10^{3} Hz
Microseconds (μs)	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

Phase

The term phase, or phase shift, describes the position of the waveform relative to time 0.

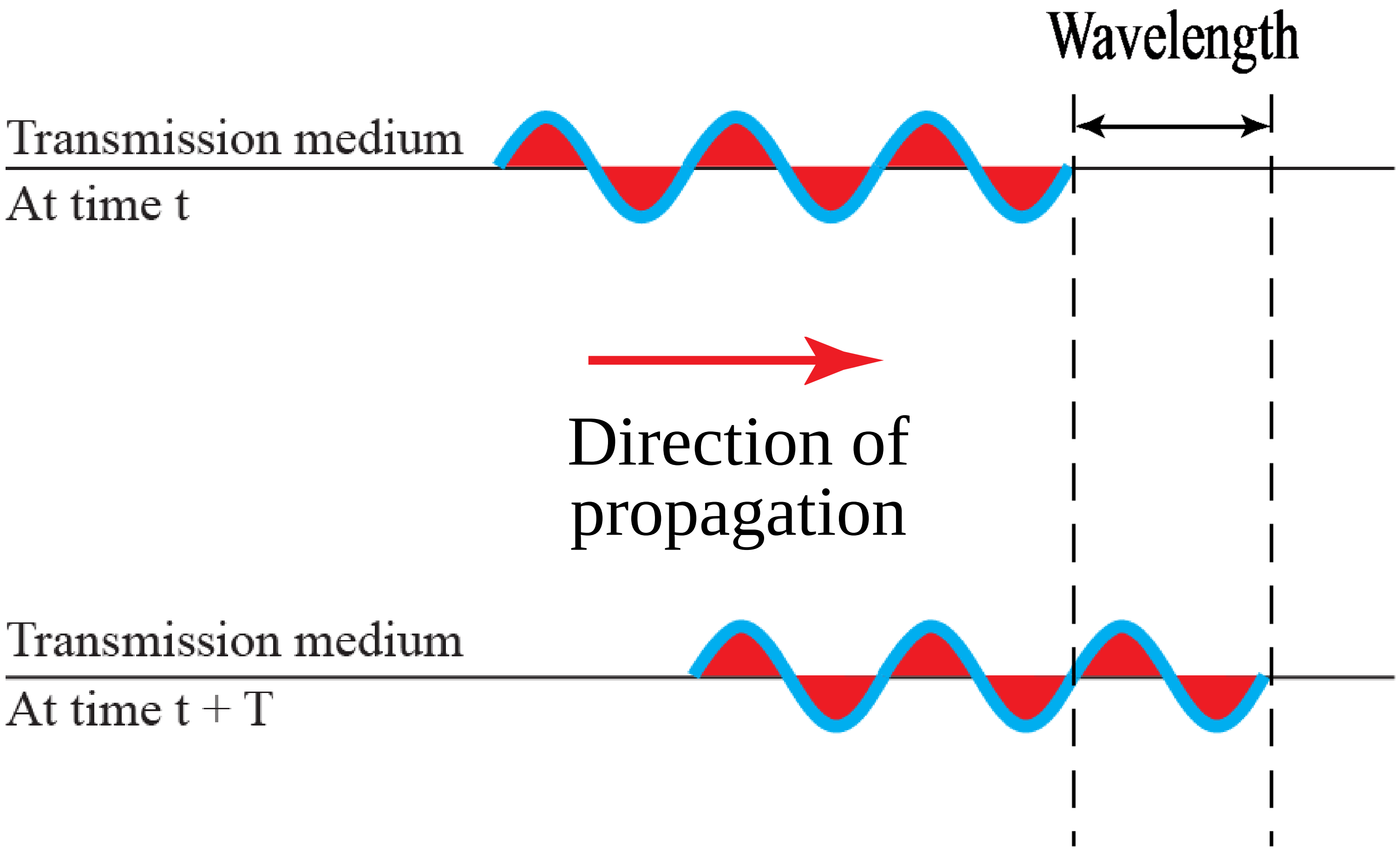
Figure 3.6: *Three sine waves with different phases*



Wavelength

Wavelength binds the period or the frequency of a simple sine wave to the propagation speed of the medium.

Figure 3.7: Wavelength and period



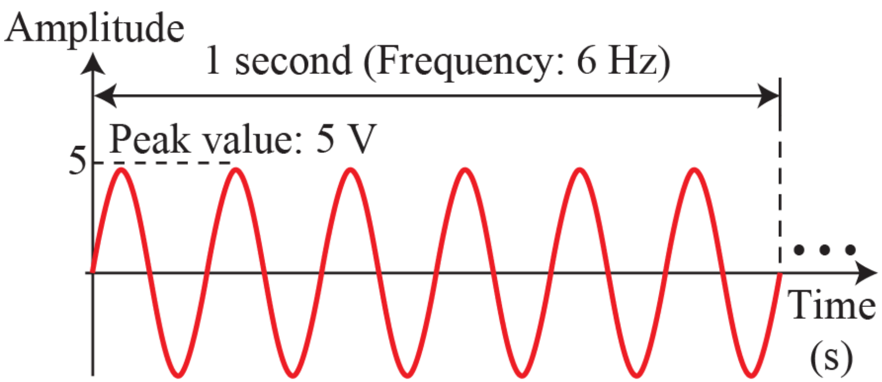
Time and Frequency Domains

A sine wave is comprehensively defined by its amplitude, frequency, and phase.

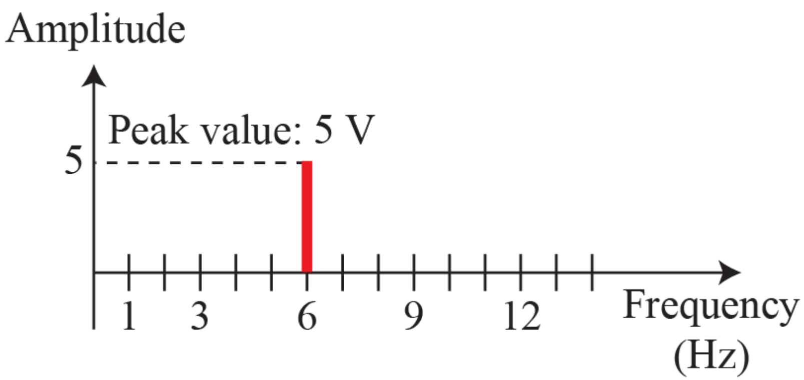
We have been showing a sine wave by using what is called a time domain plot. The time-domain plot shows changes in signal amplitude with respect to time (it is an amplitude-versus-time plot).

Phase is not explicitly shown on a time-domain plot.

Figure 3.8: *The time-domain and frequency-domain plots of a sine wave*



a. A sine wave in the time domain

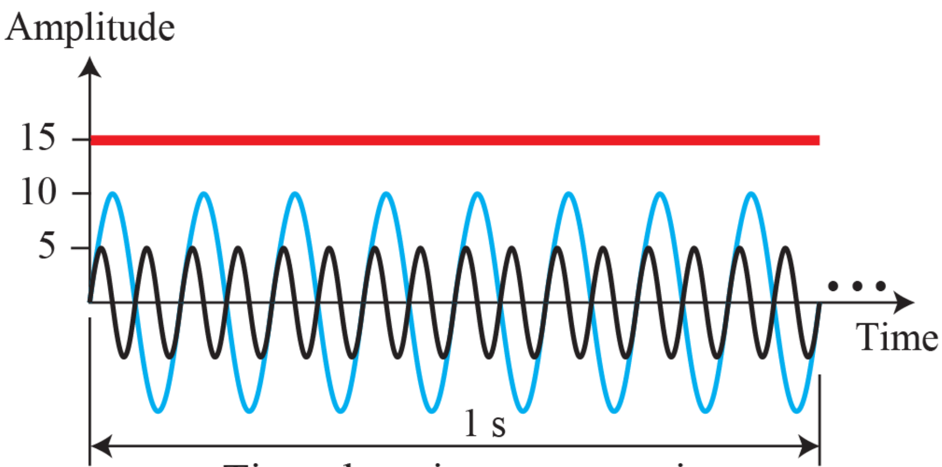


b. The same sine wave in the frequency domain

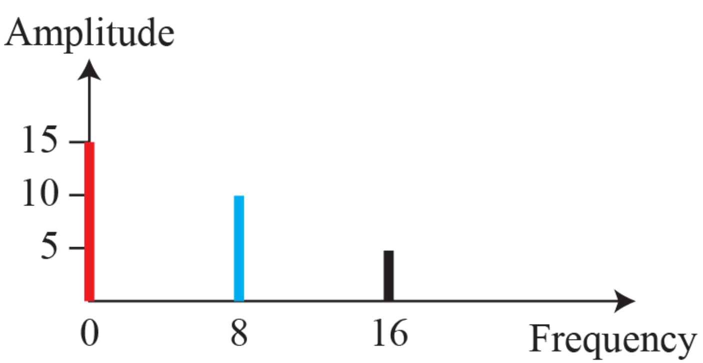
Example

The frequency domain is more compact and useful when we are dealing with more than one sine wave. For example, Figure 3.9 shows three sine waves, each with different amplitude and frequency. All can be represented by three spikes in the frequency domain.

Figure 3.9: *The time domain and frequency domain of three sine waves*



a. Time-domain representation



b. Frequency-domain representation

Bandwidth

The bandwidth is normally a difference between two numbers. For example, if a composite signal contains frequencies between 1000 and 5000, its bandwidth is 5000 − 1000, or 4000.

Example

If a periodic signal is decomposed into five sine waves with frequencies of 100, 300, 500, 700, and 900 Hz, what is its bandwidth?

Solution

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

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

Example

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.

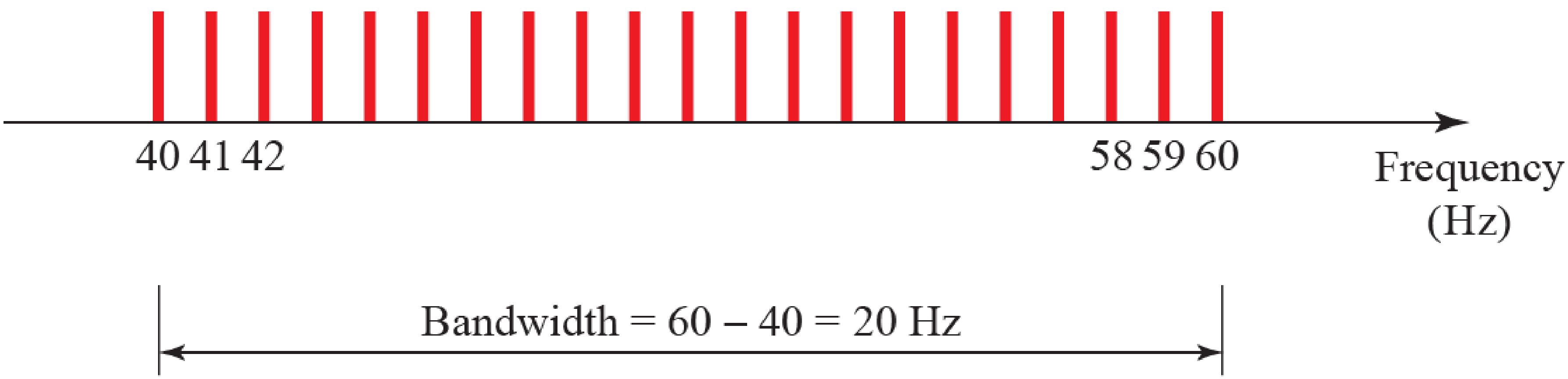
Solution

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

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

The spectrum contains all integer frequencies. We show this by a series of spikes (see Figure 3.15).

Figure 3.15: *The bandwidth for example 3.11*



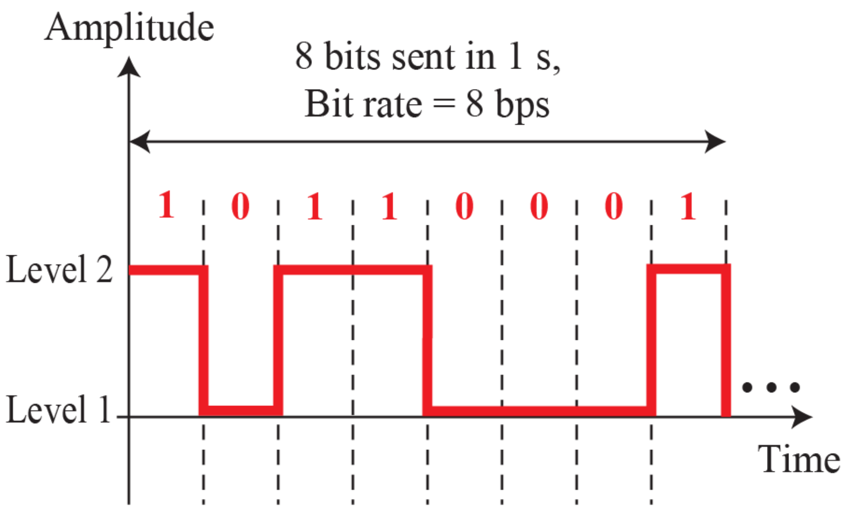
DIGITAL SIGNALS

- *In addition to being represented by an analog signal, information can also be represented by a digital signal.*

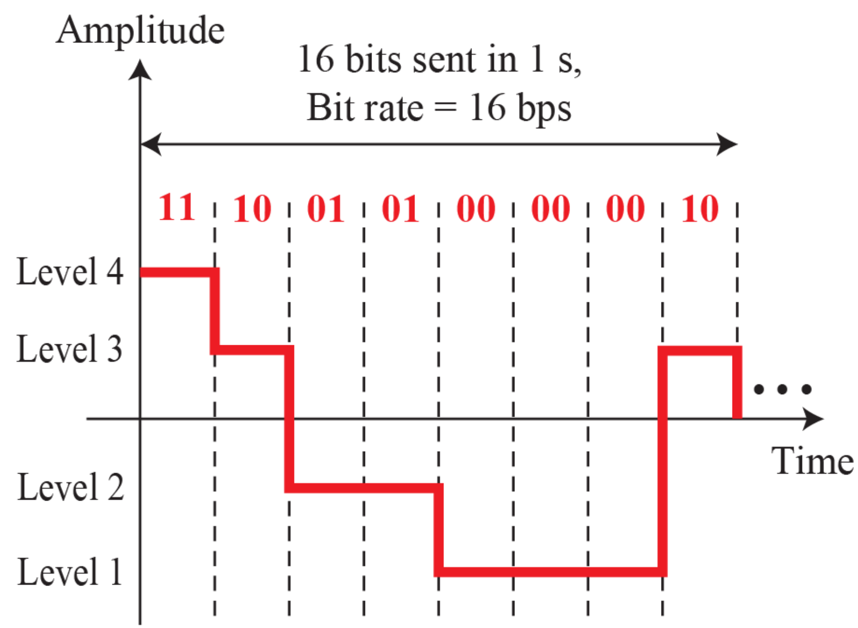
  For example, a 1 can be encoded as a positive voltage and a 0 as zero voltage.

- *A digital signal can have more than two levels. In this case, we can send more than 1 bit for each level.*

Figure 3.17: 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

Example

A digital signal has eight levels. How many bits are needed per level? We calculate the number of bits from the following formula. Each signal level is represented by 3 bits.

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

Example

A digital signal has nine levels. How many bits are needed per level?

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.

Bit Rate

Most digital signals are nonperiodic, and thus period and frequency are not appropriate characteristics. Another term— bit rate (instead of frequency)—is used to describe digital signals.

The bit rate is the number of bits sent in 1s, expressed in bits per second (bps).

TRANSMISSION IMPAIRMENT

- *What is sent is not what is received*

- *Three causes of impairment are attenuation, distortion, and noise*

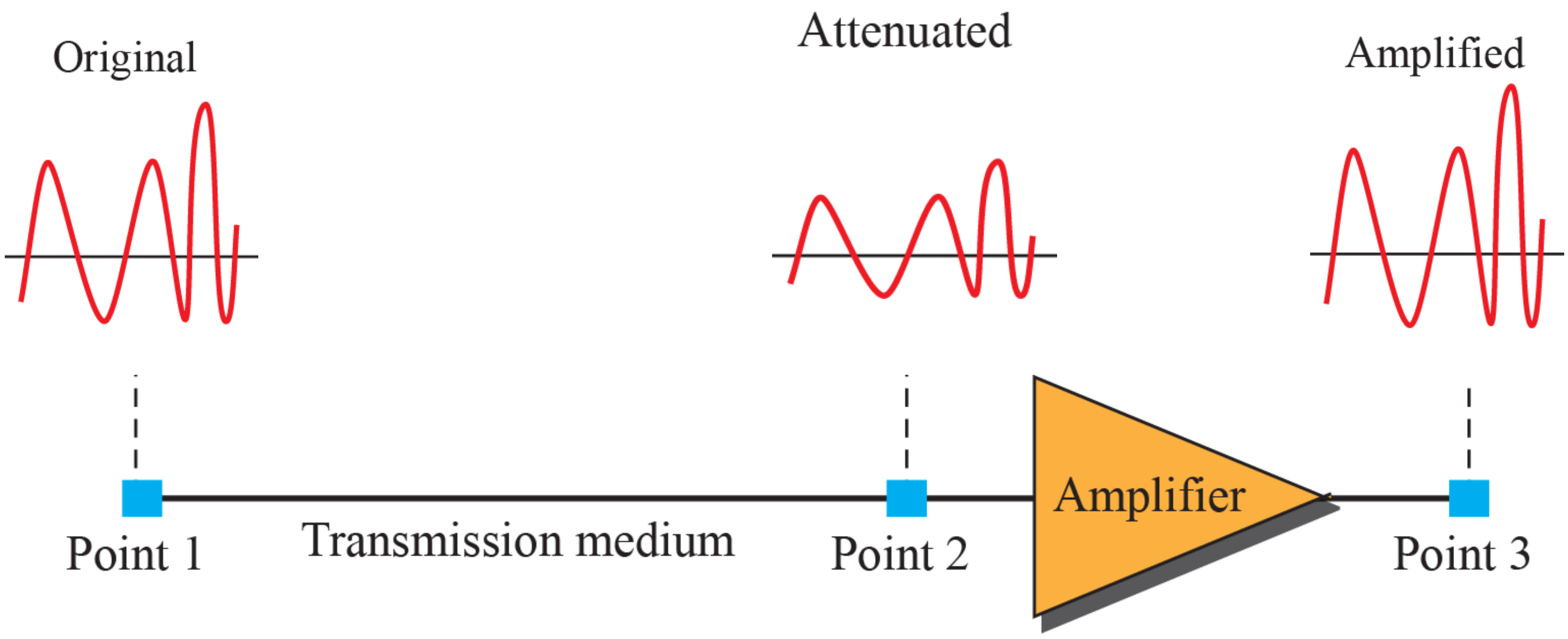
3.4.1 Attenuation

- *Attenuation means a loss of energy.*

- *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, amplifiers are used to amplify the signal.*

Figure 3.27: Attenuation and amplification



Example

Suppose a signal travels through a transmission medium and its power is reduced to one half. This means that P2 = 0.5 P1. In this case, the attenuation (loss of power) can be calculated as

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

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

Distortion

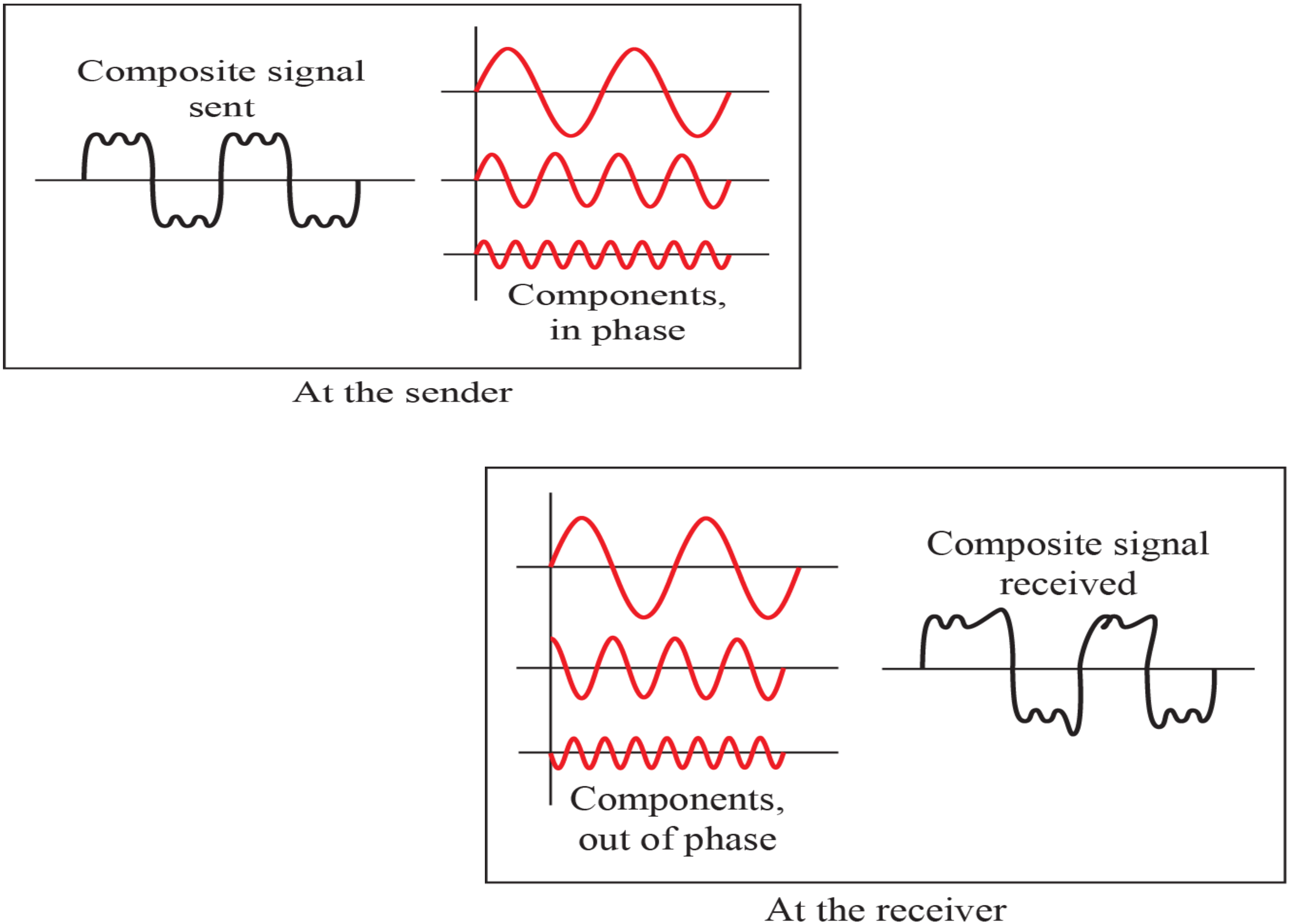
- *Signal changes its form or shape.*

- *Distortion can occur in a composite signal made of different frequencies.*

- *Each signal component has its own propagation speed through a medium and, therefore, its own delay in arriving at the final destination.*

- *Differences in delay may create a difference in phase if the delay is not exactly the same as the period duration.*

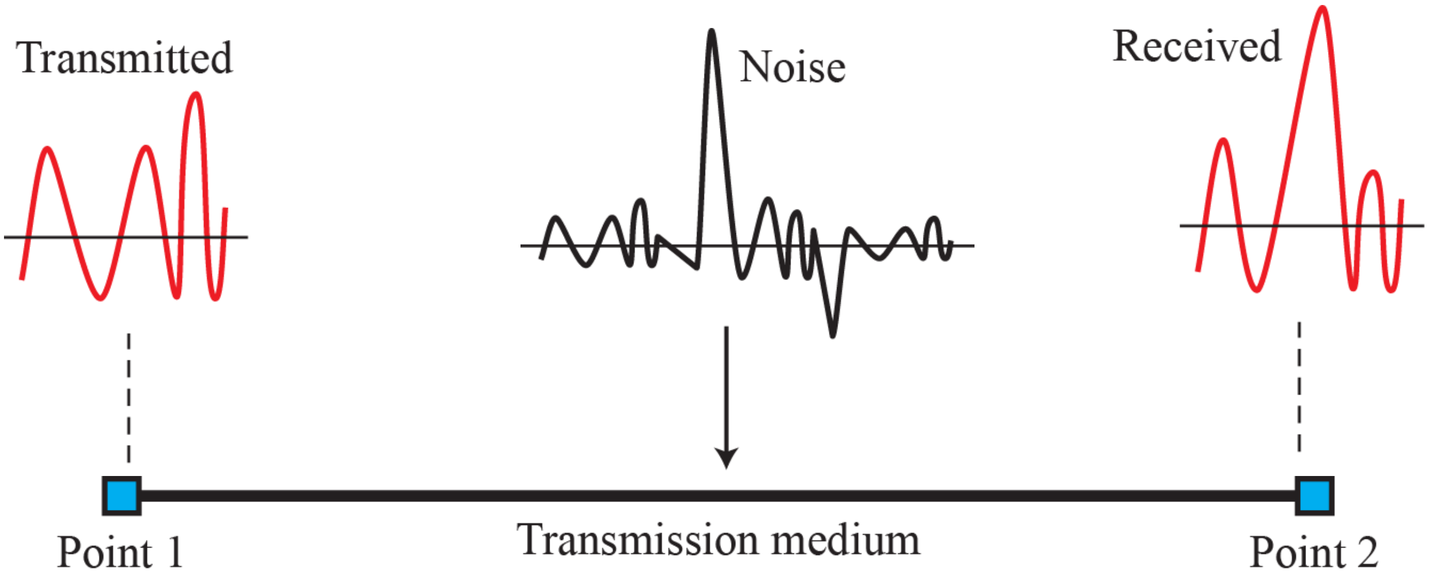
Figure 3.29: *Distortion*



Noise

- *Noise is another cause of impairment.*
- *Several types of noise, such as thermal noise, induced noise, crosstalk, and impulse noise, may corrupt the signal.*
- *Thermal noise is the random motion of electrons in a wire, which creates an extra signal not originally sent by the transmitter.*
- *Induced noise comes from sources such as motors.*
- *Crosstalk is the effect of one wire on the other.*

Figure 3.30: Noise



DATA RATE LIMITS

- *How fast we can send data, in bits per second, over a channel.*

- *Two theoretical formulas were developed to calculate the data rate:*

  Nyquist for a noiseless channel

  Shannon for a noisy channel.

Noiseless Channel: Nyquist Rate

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

$$\text{BitRate} = 2 \times \text{bandwidth} \times \log_2 L$$

Example

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

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

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:

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

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.

Noisy Channel: Shannon Capacity

In reality, we cannot have a noiseless channel; the channel is always noisy. In 1944, Claude Shannon introduced a formula, called the Shannon capacity, to determine the theoretical highest data rate for a noisy channel:

$$\text{Capacity} = \text{bandwidth} \times \log_2(1 + \text{SNR})$$

Example

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

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

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

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

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

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

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

Using Both Limits

In practice, we need to use both methods to find the limits and signal levels.

Example

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.

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

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

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

PERFORMANCE

One important issue in networking is the performance of the network— how good is it?

Bandwidth

- *One characteristic that measures network performance*

- *can be used in two different contexts with two different measuring values:*

  bandwidth in hertz

  bandwidth in bits per second

Throughput

a measure of how fast we can actually send data through a network.

Throughput

- *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 can say that latency is made of four components: propagation time, transmission time, queuing time and processing delay.*

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

Example

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

$$\text{Throughput} = (12{,}000 \times 10{,}000) / 60 = 2 \text{ Mbps}$$

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

Example

What is the propagation time if the distance between the two points is 12,000 km? Assume the propagation speed to be 2.4 × 108 m/s in cable.

Solution

We can calculate the propagation time as

$$\text{Propagation time} = (12{,}000 \times 10{,}000) / (2.4 \times 2^8) = 50 \text{ ms}$$

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

What are the propagation time and the transmission time for a 2.5-KB (kilobyte) message 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 × 108 m/s.

Solution

We can calculate the propagation and transmission time as

$$\textbf{Propagation time} = (12{,}000 \times 1000) / (2.4 \times 10^8) = 50 \text{ ms}$$

$$\textbf{Transmission time} = (2500 \times 8) / 10^9 = 0.020 \text{ ms}$$

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.

Example

What are the propagation time and the transmission time for a 5-MB (megabyte) 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 × 108 m/s.

Solution

We can calculate the propagation and transmission times as

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

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

We can calculate the propagation and transmission times as

Bandwidth-Delay Product

- *Bandwidth and delay are two performance metrics of a link.*

- *What is very important in data communications is the product of the two, the bandwidth-delay product.*

Figure 3.32: Filling the links with bits for Case 1

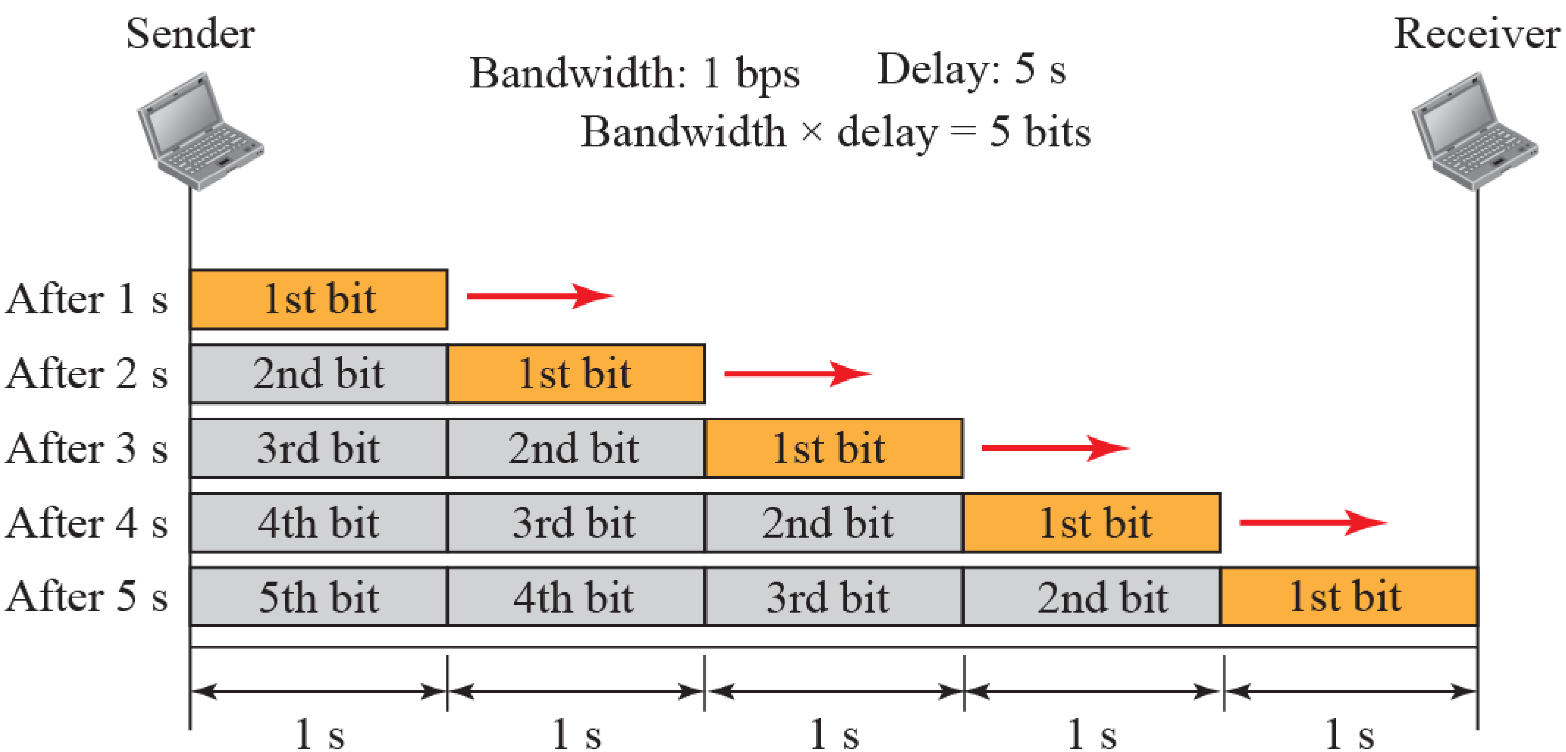
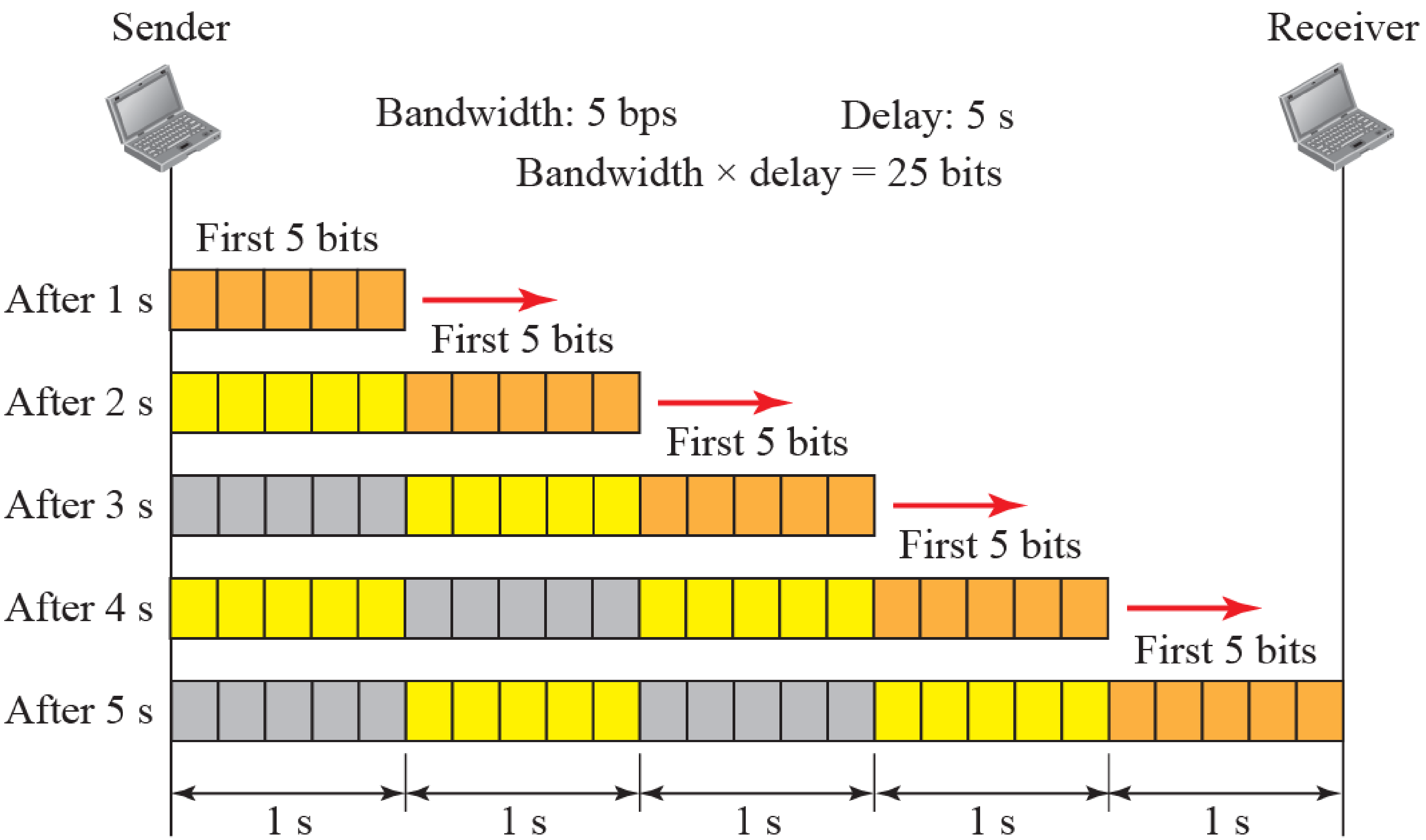


Figure 3.33: Filling the pipe with bits for Case 2



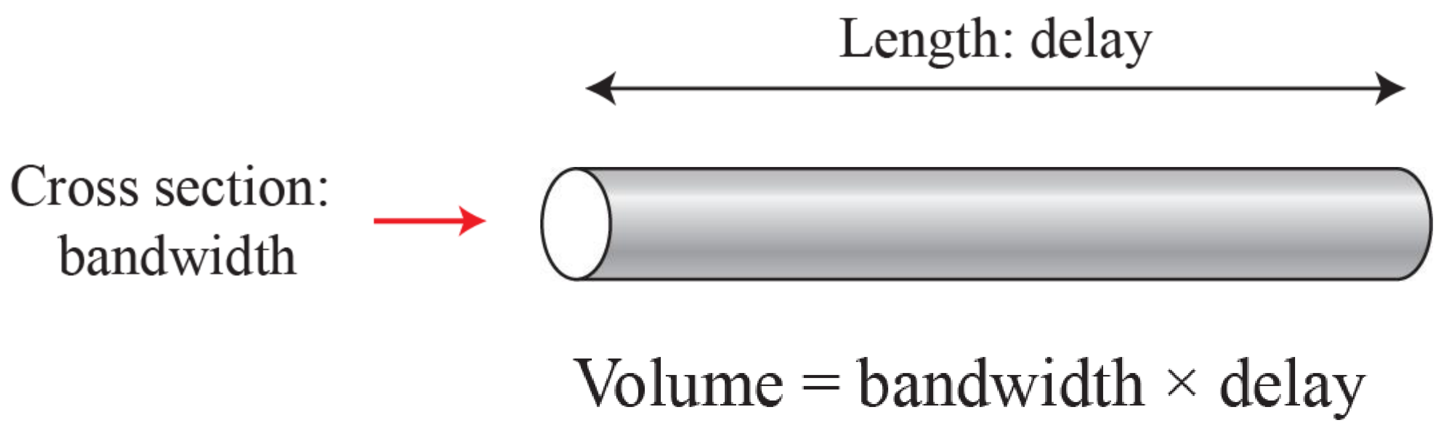
Example

- 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

Figure 3.34: ***Concept of bandwidth-delay product***



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).*