Department of Computer science and Information Technology

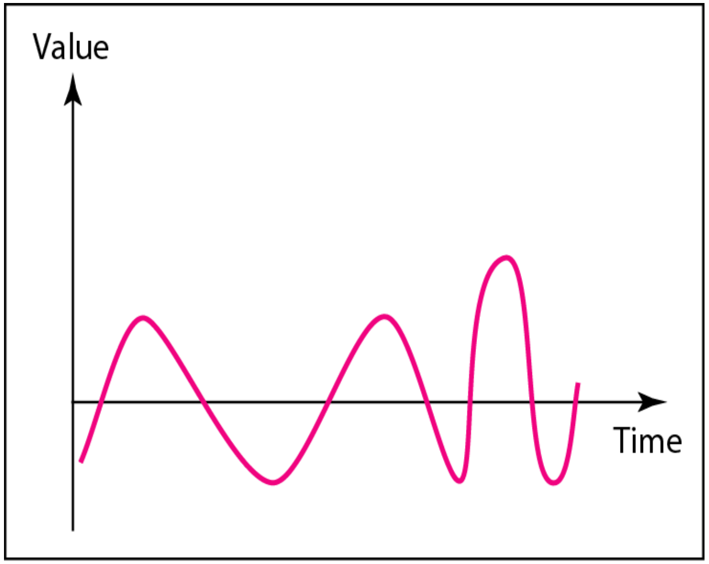
Introduction to Physical Layer

3-1 ANALOG AND DIGITAL

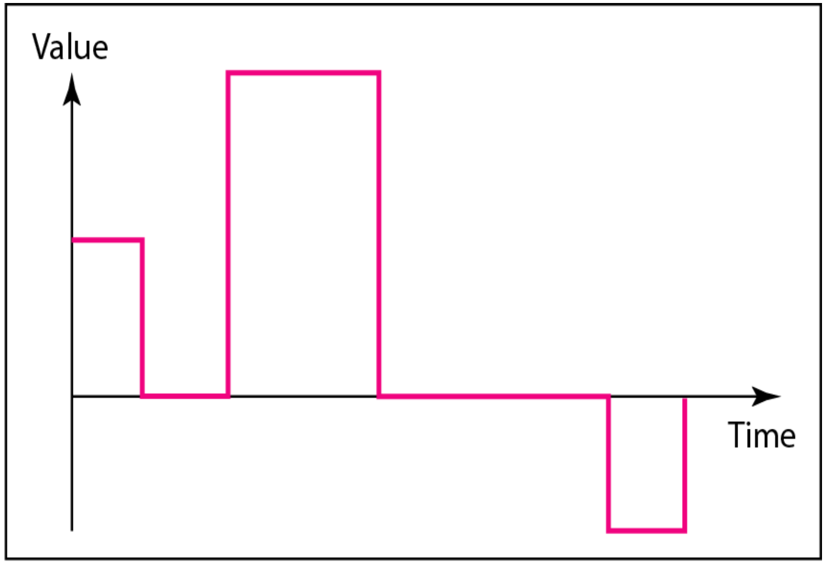
- Data can be **analog** or **digital.** The term **analog data** refers to information that is continuous; **digital data** refers to information that has discrete states. Analog data take on continuous values. Digital data take on discrete values.
- Analog and Digital Signals:

  signals can be either analog or digital. An **analog signal** has infinitely many levels of intensity over a period of time. A **digital signal**, on the other hand, can have only a limited number of defined values (Usually 1 and 0).

Figure 3.1 Comparison of analog and digital signals



a. Analog signal



b. Digital signal

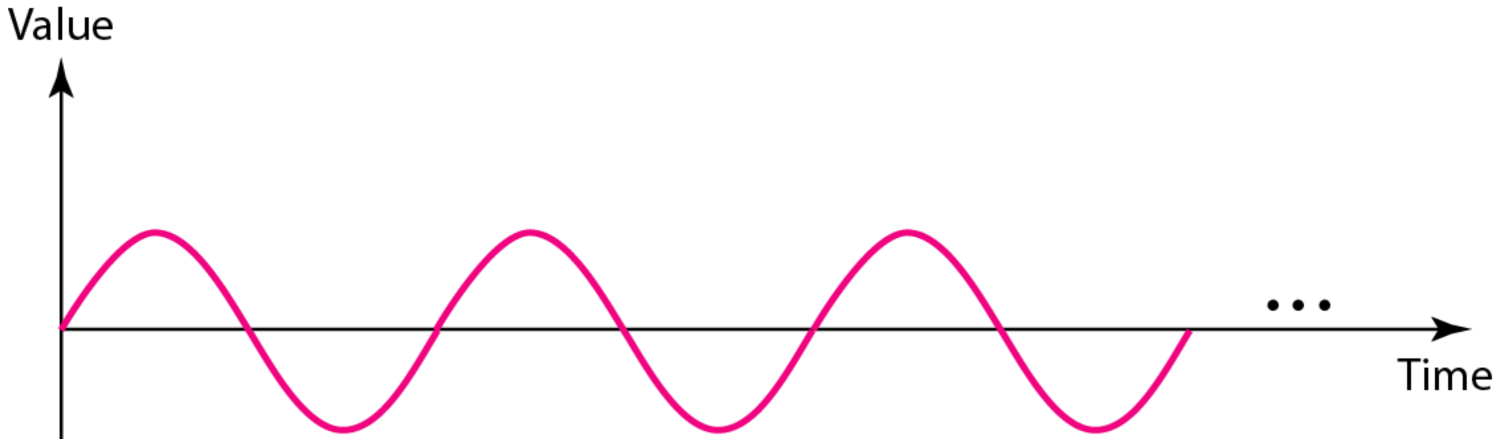
Periodic and Nonperiodic:

- 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.

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.
- Sine wave can be visualized as a simple oscillating curve, its change over the course of a cycle is smooth and consistent, a continuous, rolling flow.

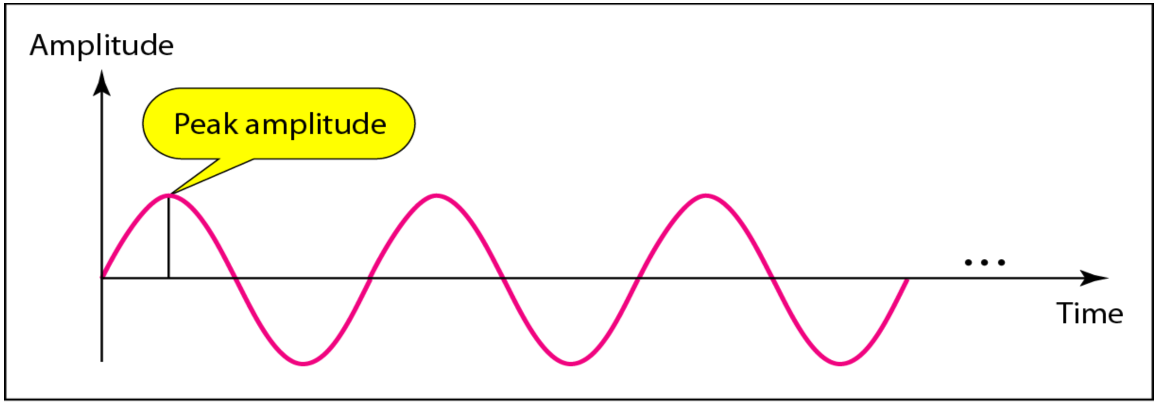
Figure 3.2 *A sine wave*



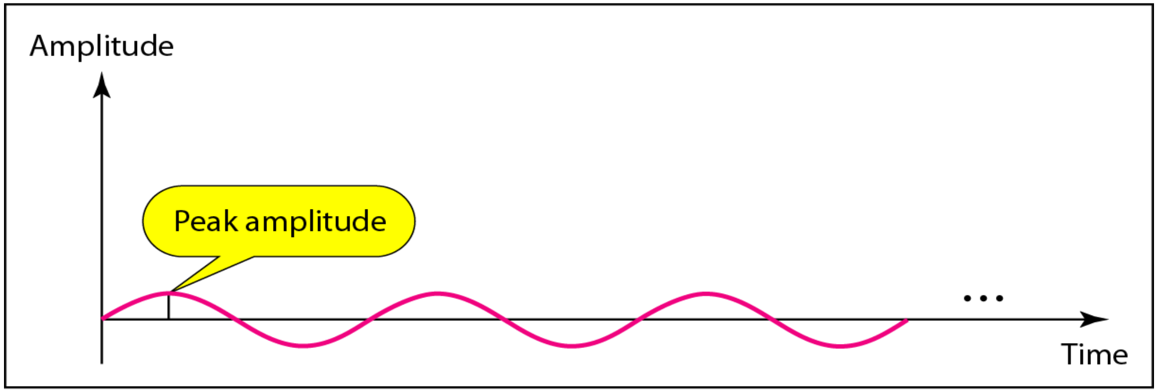
Parameters of Sine waves:

- A sine wave can be represented by three parameters: the peak amplitude, the frequency, and the phase.
- The **peak amplitude** of a signal is the absolute value of its highest intensity, proportional to the energy it carries. It is measured in volts.

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



a. A signal with high peak amplitude

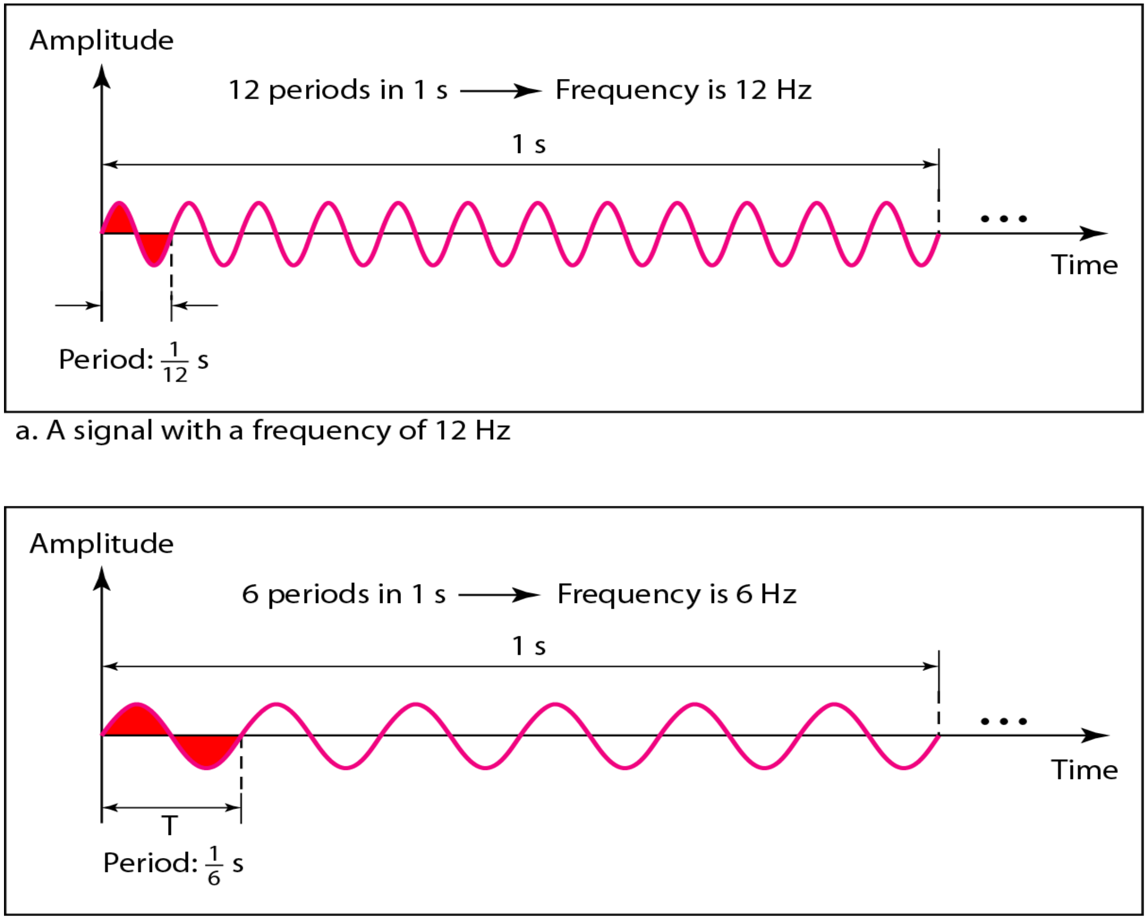


b. A signal with low peak amplitude

Period and Frequency:

- **Period** refers to the amount of time, in seconds, a signal needs to complete 1 cycle.
- **Frequency** refers to the number of periods in 1 s.
- Period is formally expressed in **seconds**.
- Frequency is formally expressed in **Hertz (Hz),** which is cycle per second.
- $\boxed{T = (1 / F) \quad \text{OR} \quad F = (1 / T)}$

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

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

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} μs). We make the following substitutions:

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

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 Hz = 10^{-3} kHz).

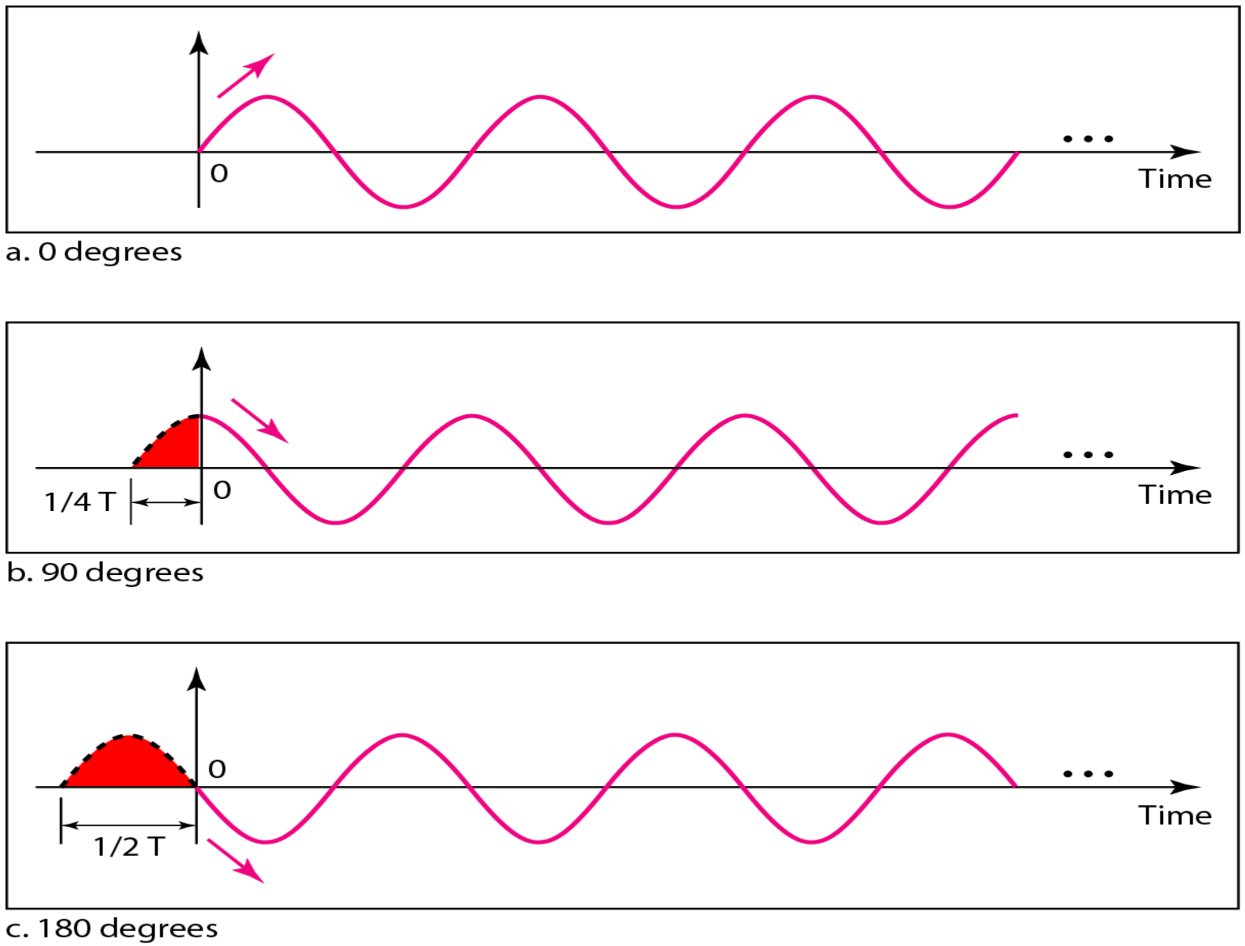
$$100 \text{ ms} = 100 \times 10^{-3} \text{ s} = 10^{-1} \text{ s}$$

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

Phase :

- The term **phase**, or **phase shift**, describes the position of the waveform relative to time 0.
- Phase is measured in **degrees** or **radians** [360º is 2π rad; 1º is 2π/360 rad, and 1 rad is 360/(2π)].

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



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

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

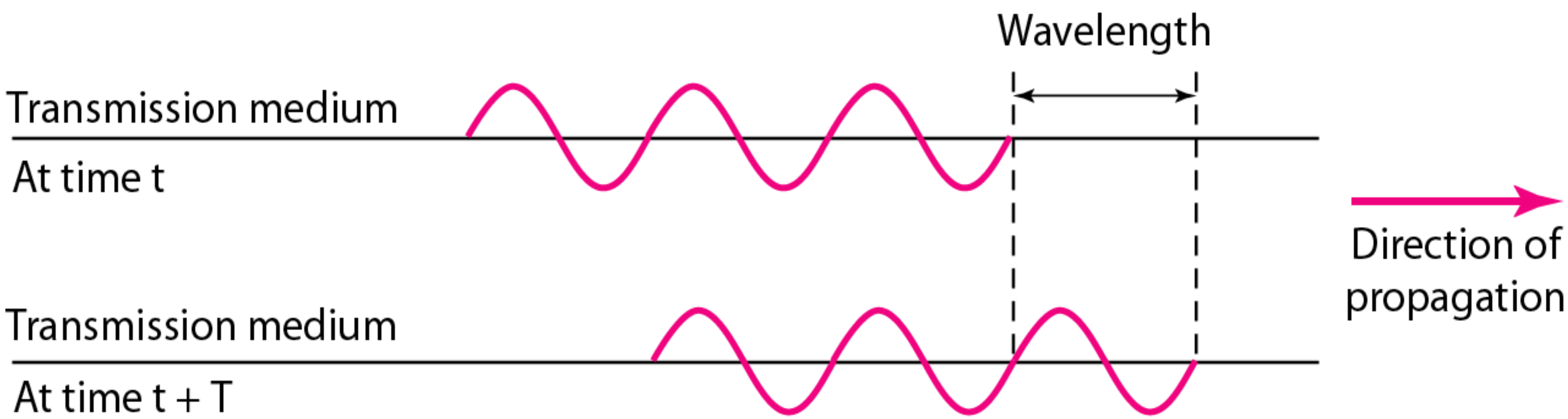
Wavelength:

- **Wavelength** binds the period or the frequency of a simple sine wave to the propagation speed of the medium.
- The wavelength is the distance a simple signal can travel in one period.
- Wavelength can be calculated if one is given the propagation speed (the speed of light) and the period of the signal.

$$\text{Wavelength} = (\text{propagation speed}) \times \text{period} = \frac{\text{propagation speed}}{\text{frequency}}$$

$$\lambda = \frac{c}{f}$$

Figure 3.6 Wavelength and period



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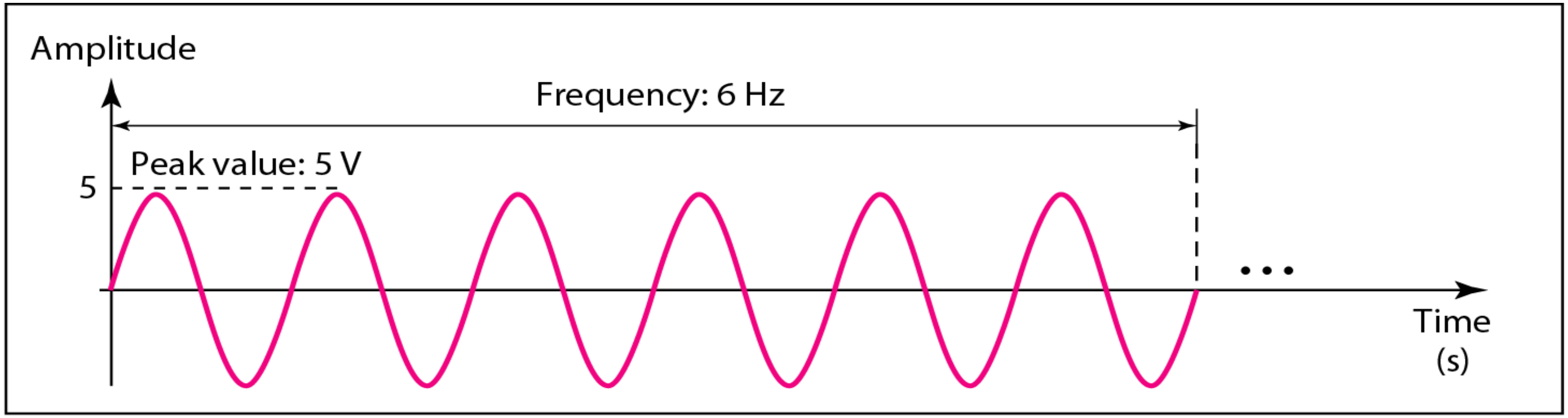
- The wavelength is normally measured in **micrometers (microns)** instead of meters.
- For example, the wavelength of red light (frequency = 4×10^{14}) in air is:

$$\lambda = \frac{c}{f} = \frac{3 \times 10^{8}}{4 \times 10^{14}} = 0.75 \times 10^{-6}\ \text{m} = 0.75\ \mu\text{m}$$

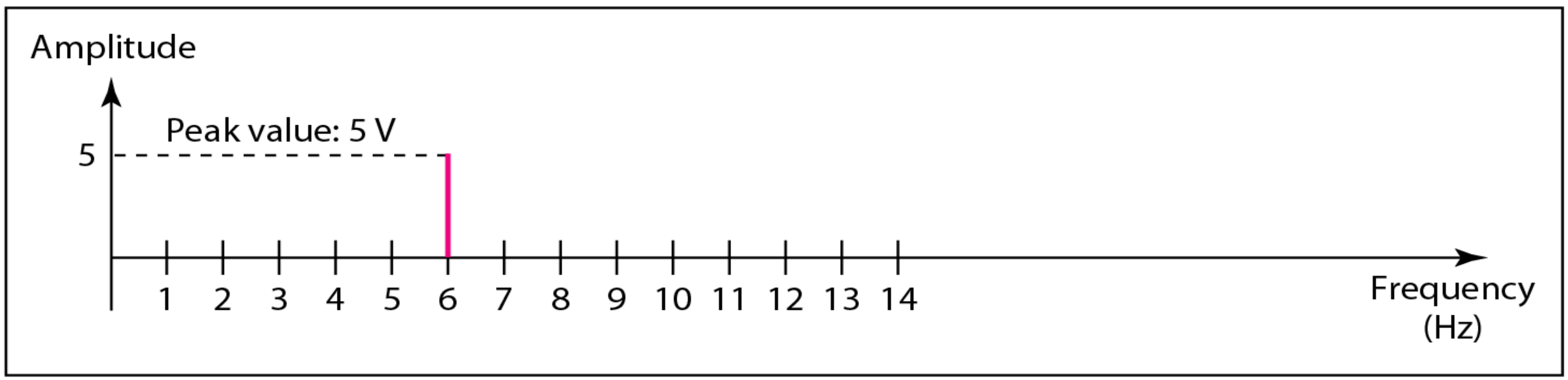
Time and Frequency Domains:

- **Time-domain plot** shows changes in signal amplitude with respect to time (it is an amplitude-versus-time plot).
- A **frequency-domain plot** is concerned with only the peak value and the frequency.

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

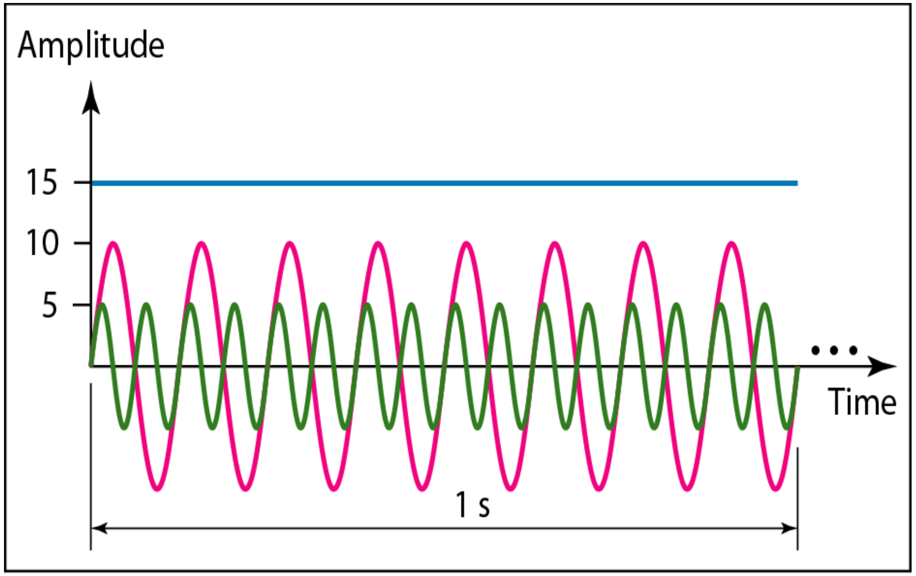


a. A sine wave in the time domain (peak value: 5 V, frequency: 6 Hz)

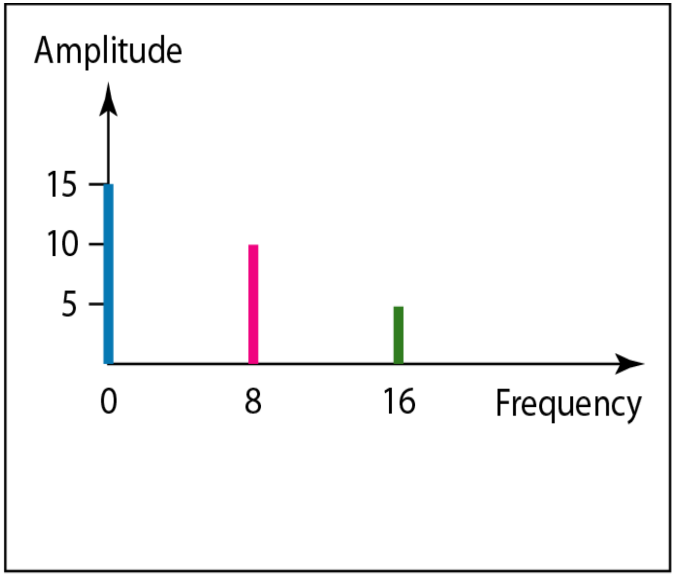


b. The same sine wave in the frequency domain (peak value: 5 V, frequency: 6 Hz)

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

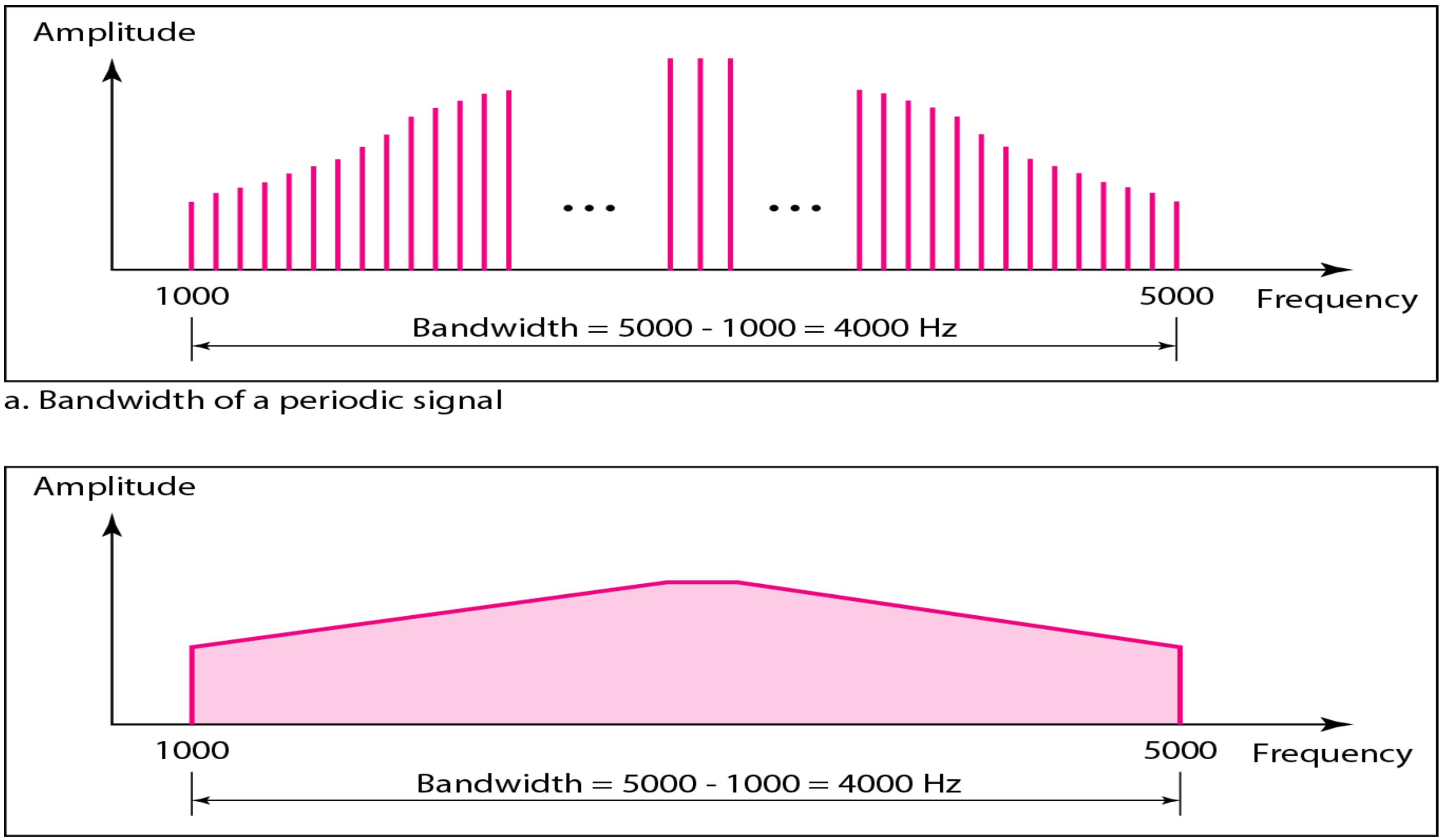


b. Frequency-domain representation of the same three signals

Bandwidth:

- 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

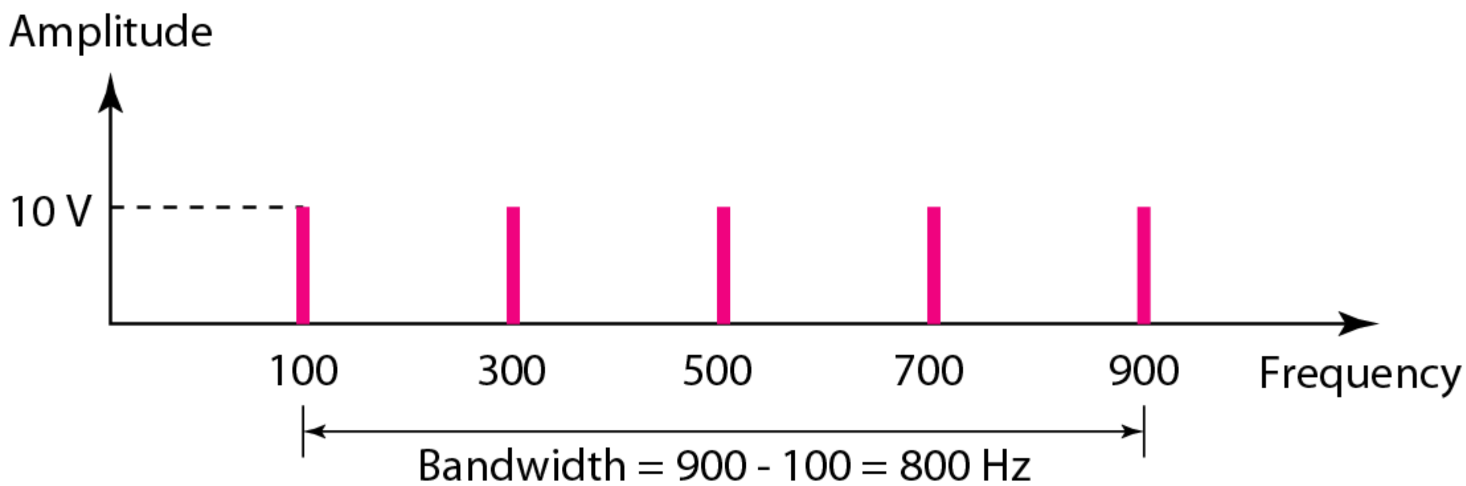
- If a periodic signal is decomposed into five sine waves with frequencies of 100, 300, 500, 700, and 900 Hz, what is its bandwidth? Draw the spectrum, assuming all components have a maximum amplitude of 10 V.

Solution

- Let f_h be the highest frequency, f_l the lowest frequency, and B the bandwidth. Then
- The spectrum has only five spikes, at 100, 300, 500, 700, and 900 Hz (see Figure 3.13).

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

Figure 3.13 The bandwidth for Example 3.10



Example 3.11

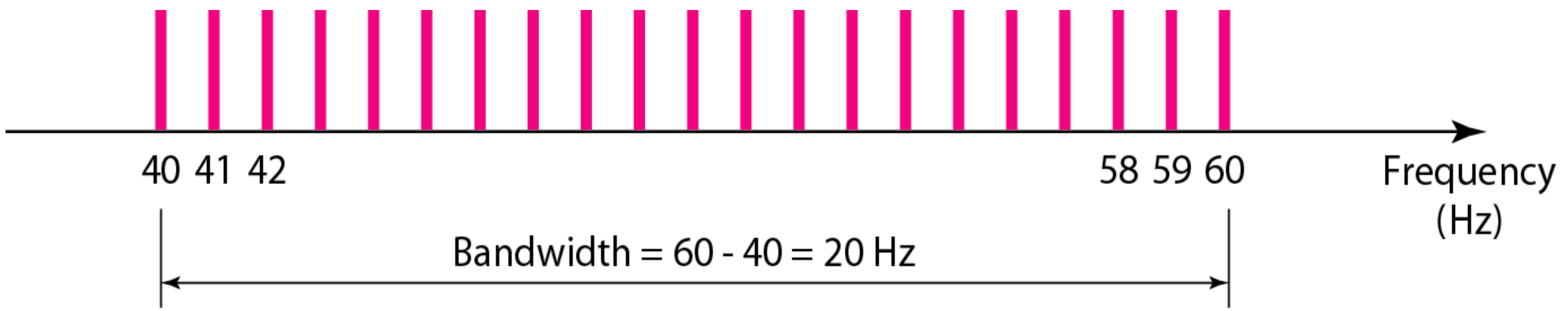
- A periodic signal has a bandwidth of 20 Hz. The highest frequency is 60 Hz. What is the lowest frequency? Draw the spectrum if the signal contains all frequencies of the same amplitude.

Solution

- Let f_h be the highest frequency, f_l the lowest frequency, and B the bandwidth. Then
- The spectrum contains all integer frequencies. We show this by a series of spikes (see Figure 3.14).

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

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.

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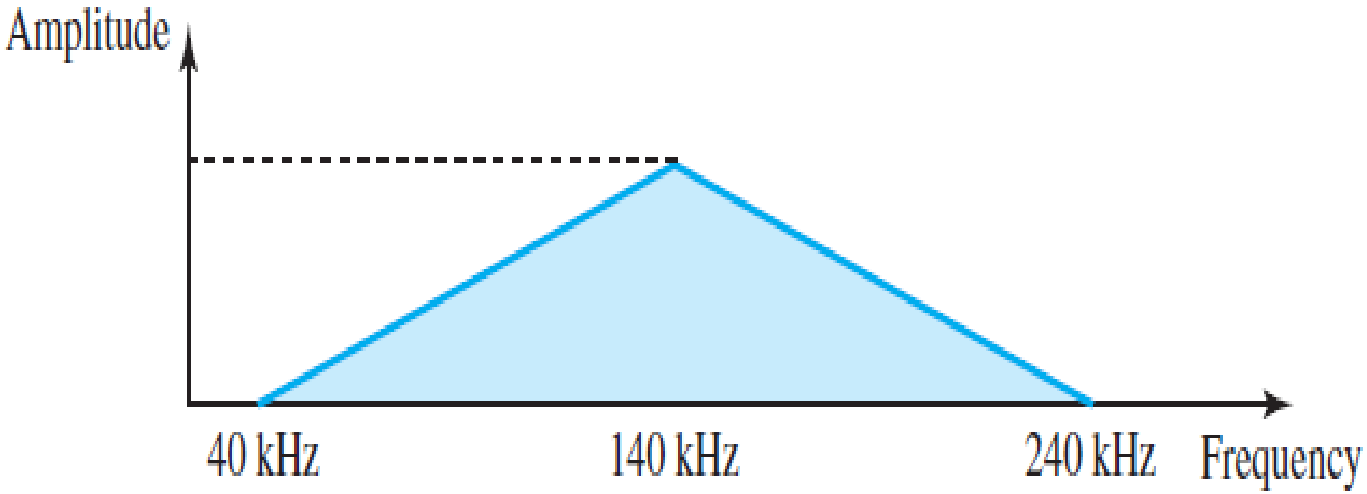
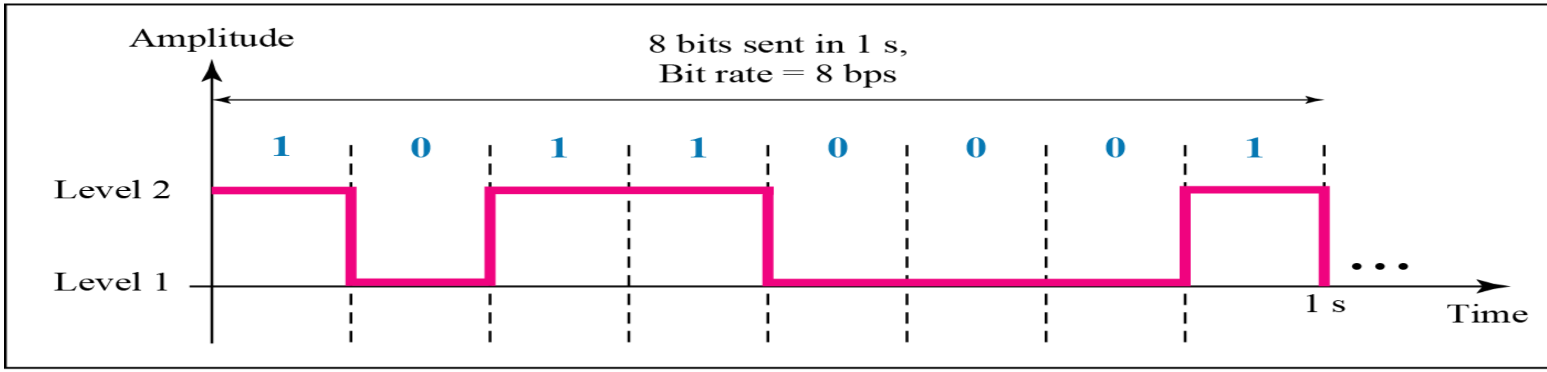
Figure 3.16 *The bandwidth for Example 3.12*



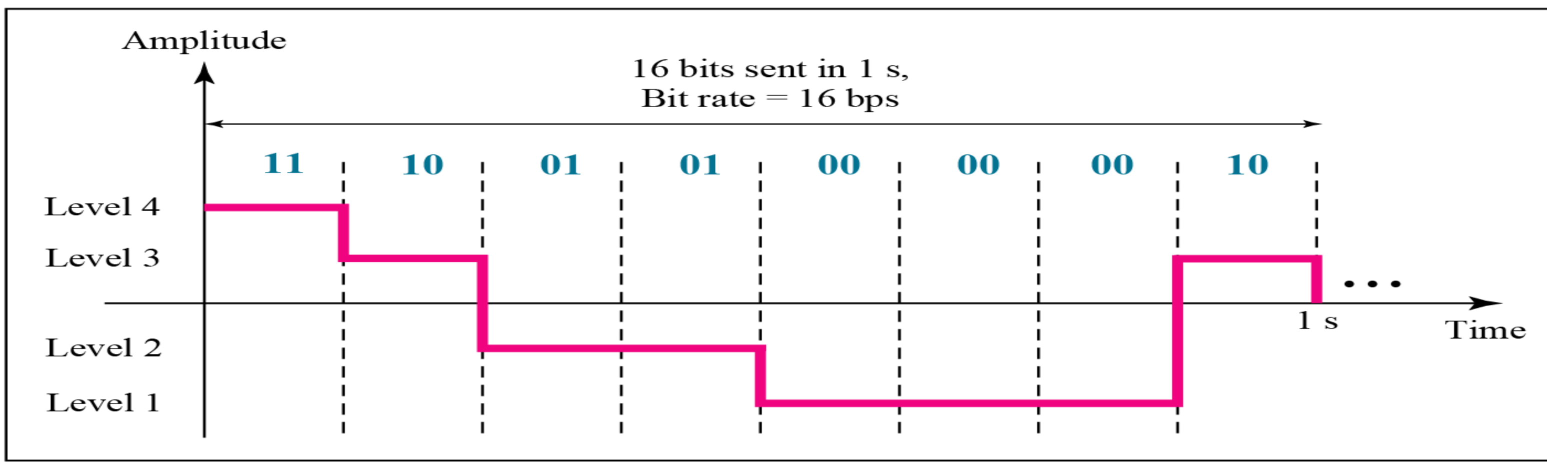
3-3 DIGITAL SIGNALS

- 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. if a signal has **L** levels, each level needs **log2 L bits**.

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

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
- **Solution:**

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

- Each signal level is represented by 3 bits.

Bit Rate:

- The **bit rate** is the number of bits sent in 1s,expressed in **bits per second (bps).** bit rate is used in digital signal (instead of frequency in analog signal) as most of the digital signals are nonperiodic and hence period and frequency are inappropriate characteristics for it.

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

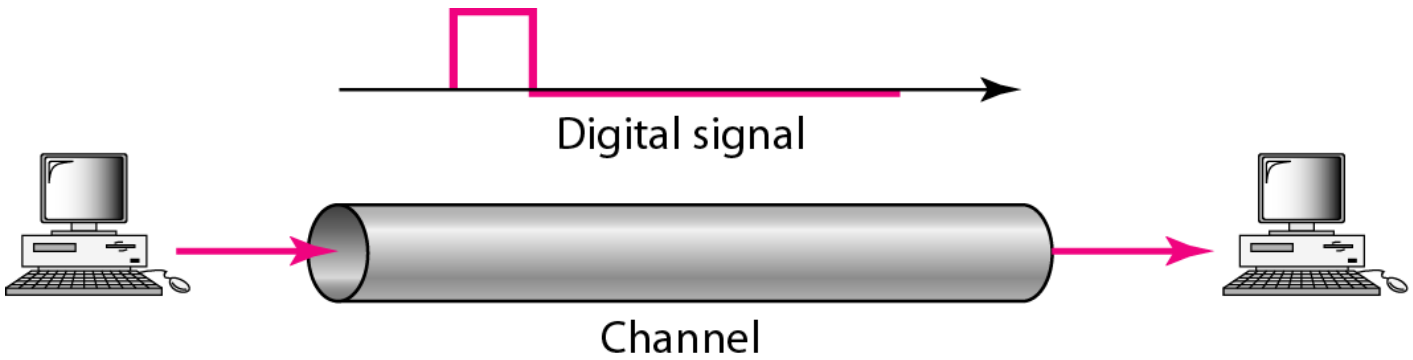
$$\boxed{100 \times 24 \times 80 \times 8 = 1{,}636{,}000 \text{ bps} = 1.636 \text{ Mbps}}$$

Transmission of Digital Signals:

- We can transmit a digital signal by using one of two different approaches: **baseband transmission** or **broadband transmission** (using modulation).

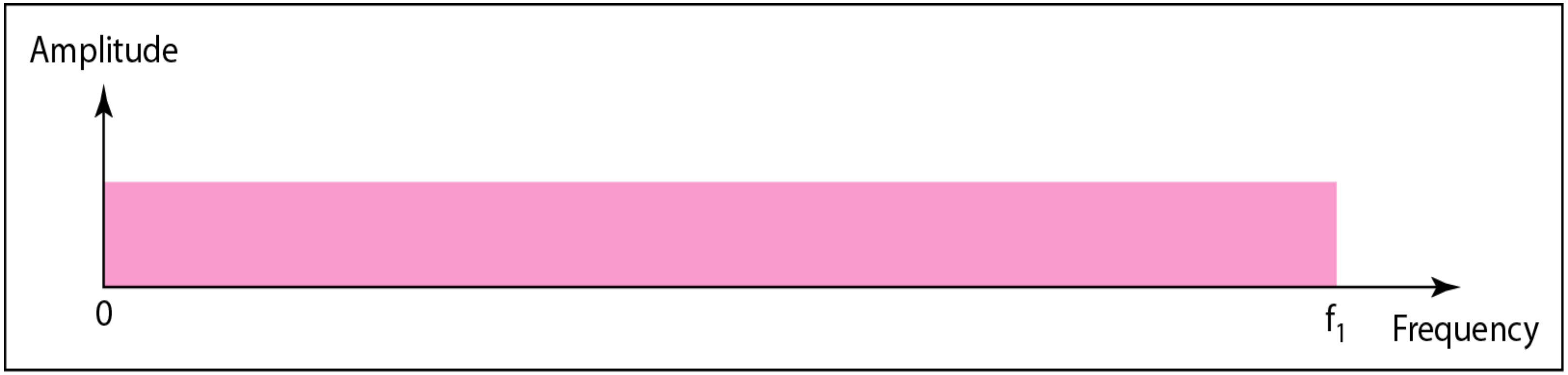
- **Baseband Transmission:**
- **Baseband transmission** means sending a digital signal over a channel without changing the digital signal to an analog signal.

Figure 3.18 Baseband transmission



- Baseband transmission requires that we have a **low-pass channel**, a channel with a bandwidth that starts from zero.

Figure 3.19 Bandwidths of two low-pass channels



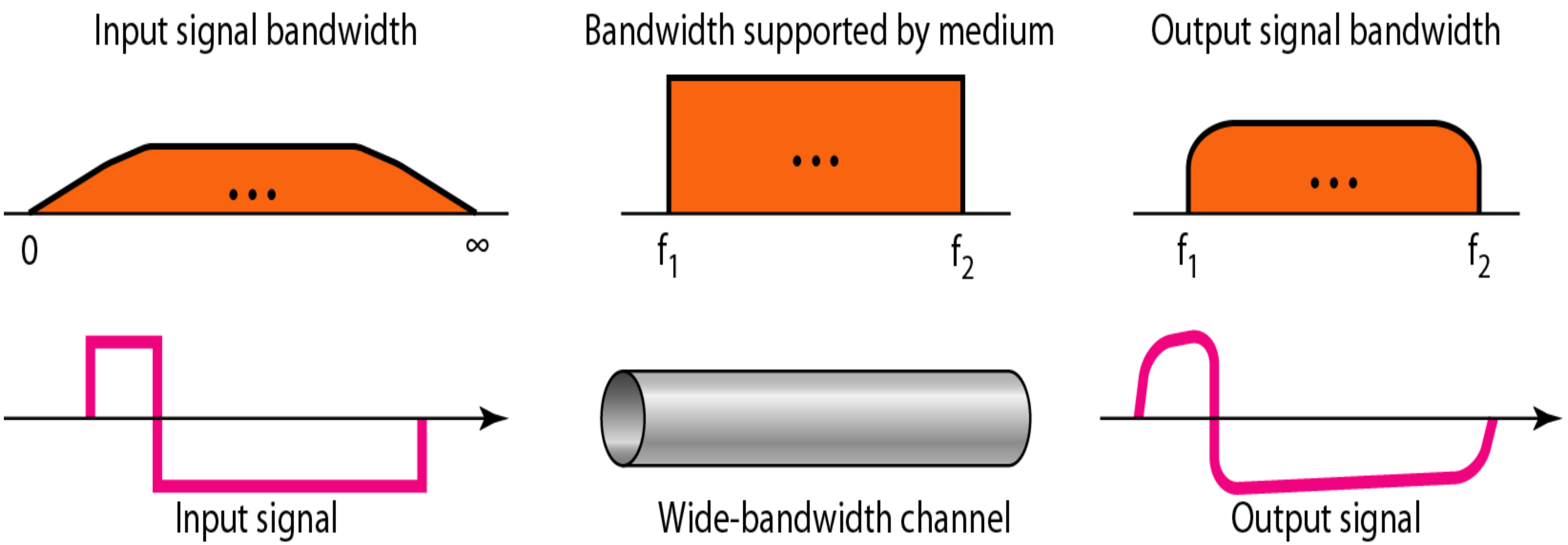
a. Low-pass channel, wide bandwidth

b. Low-pass channel, narrow bandwidth

Case 1: Low-Pass Channel with Wide Bandwidth:

- 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.
- An example of a dedicated channel where the entire bandwidth of the medium is used as one single channel is a LAN.

Figure 3.20 Baseband transmission using a dedicated medium



Example 3.22

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

- Solution
- The bit rate is 2 times the available bandwidth, or 200 kbps.

Figure 3.23 Bandwidth of a bandpass channel

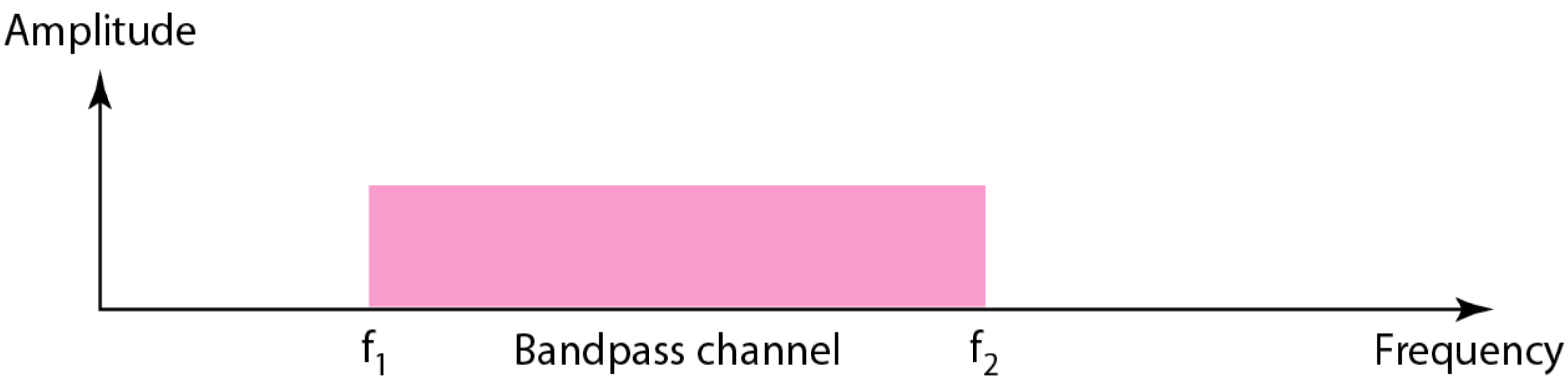
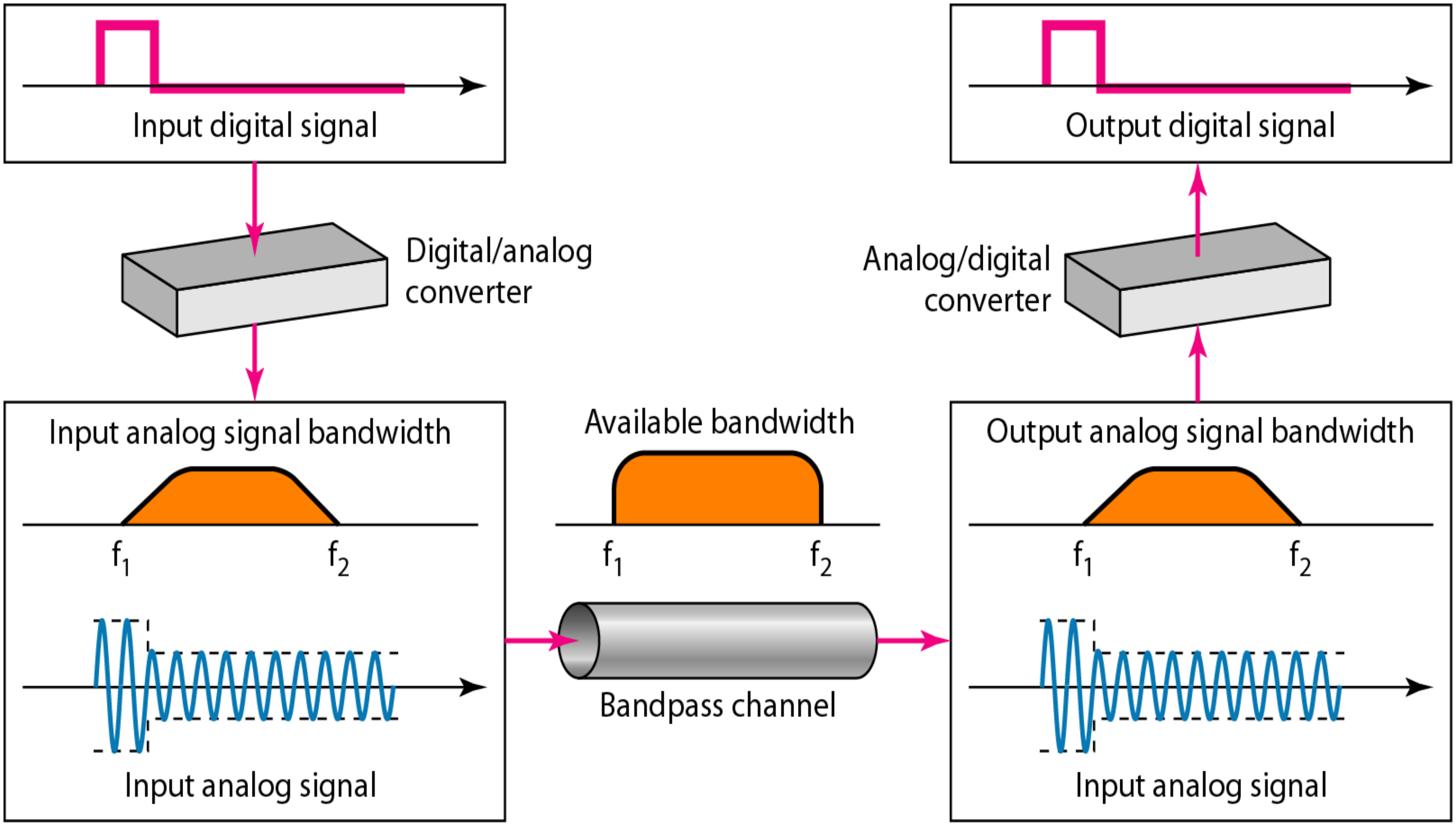


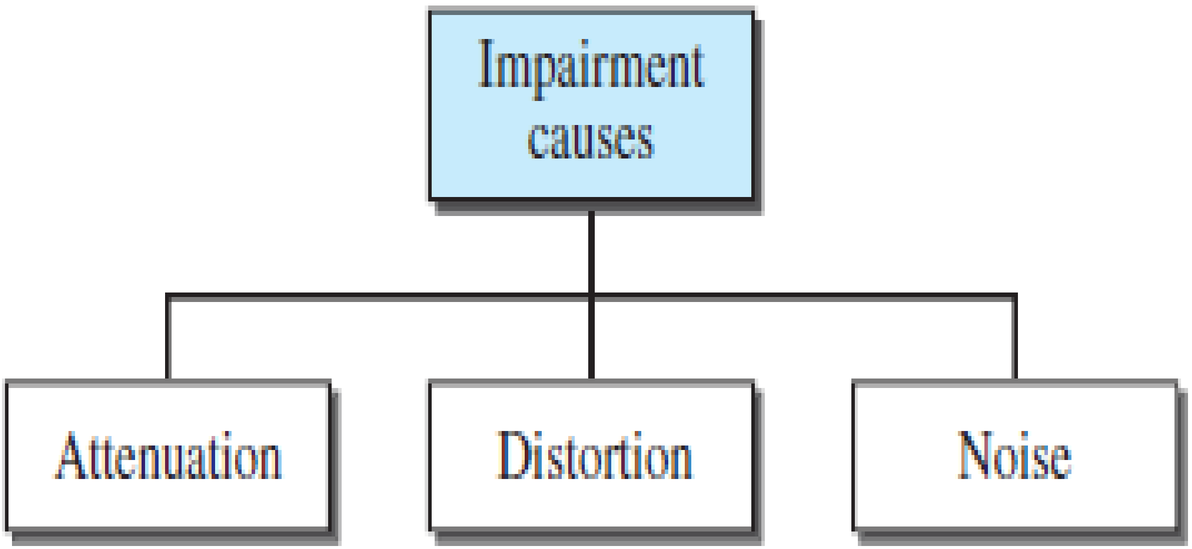
Figure 3.24 Modulation of a digital signal for transmission on a bandpass channel



3-4 TRANSMISSION IMPAIRMENT

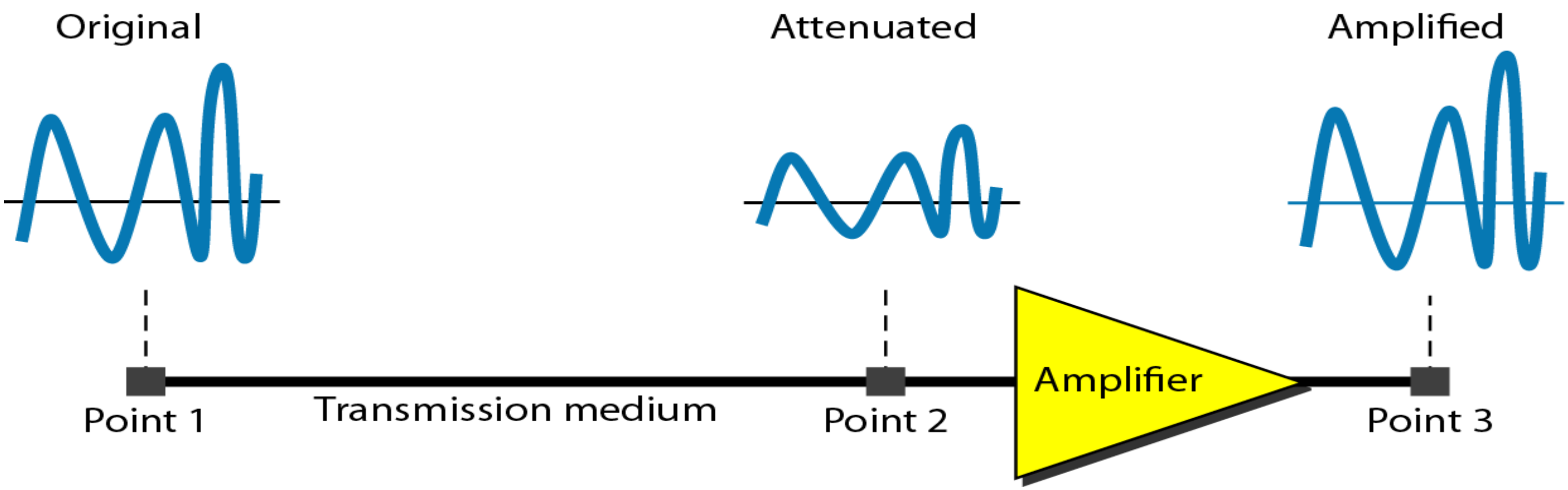
- Signals travel through transmission media, which are not perfect. The imperfection causes signal impairment. Three causes of impairment are **attenuation**, **distortion**, and **noise**.

Figure 3.25 Causes of impairment



Attenuation:

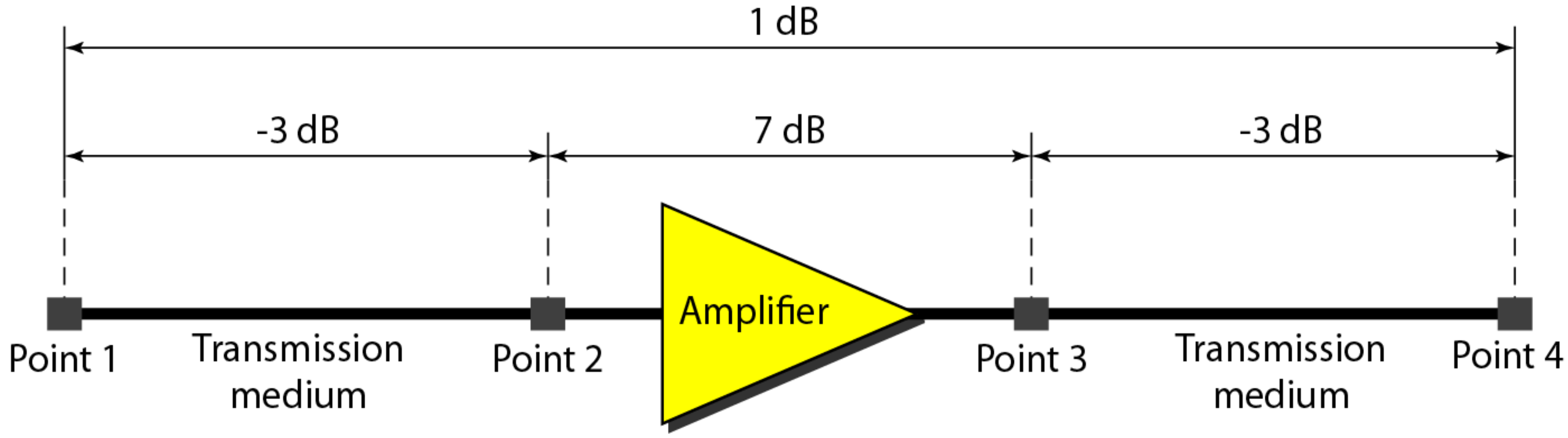
- **Attenuation** means a loss of energy. When a signal, simple or composite, travels through a medium, it loses some of its energy in overcoming the resistance of the medium. To compensate for this loss, **amplifiers** are used to amplify the signal.



Decibel:

- The decibel (dB) measures the relative strengths of two signals or one signal at two different points.
- **decibel** is negative if a signal is attenuated and positive if a signal is amplified.

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



Example 3.26

- Suppose a signal travels through a transmission medium and its power is reduced to one-half. This means that P2 is (1/2)P1. In this case, the attenuation (loss of power) can be calculated as

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

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

$$\boxed{\mathrm{dB} = -3 + 7 - 3 = +1}$$

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 $dB_m = 10 \log10 P_m$, 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

$$\mathrm{dB_m} = 10 \log_{10} P_m = -30$$

$$\log_{10} P_m = -3 \qquad P_m = 10^{-3}\ \mathrm{mW}$$

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 × (−0.3) = −1.5 dB. We can calculate the power as

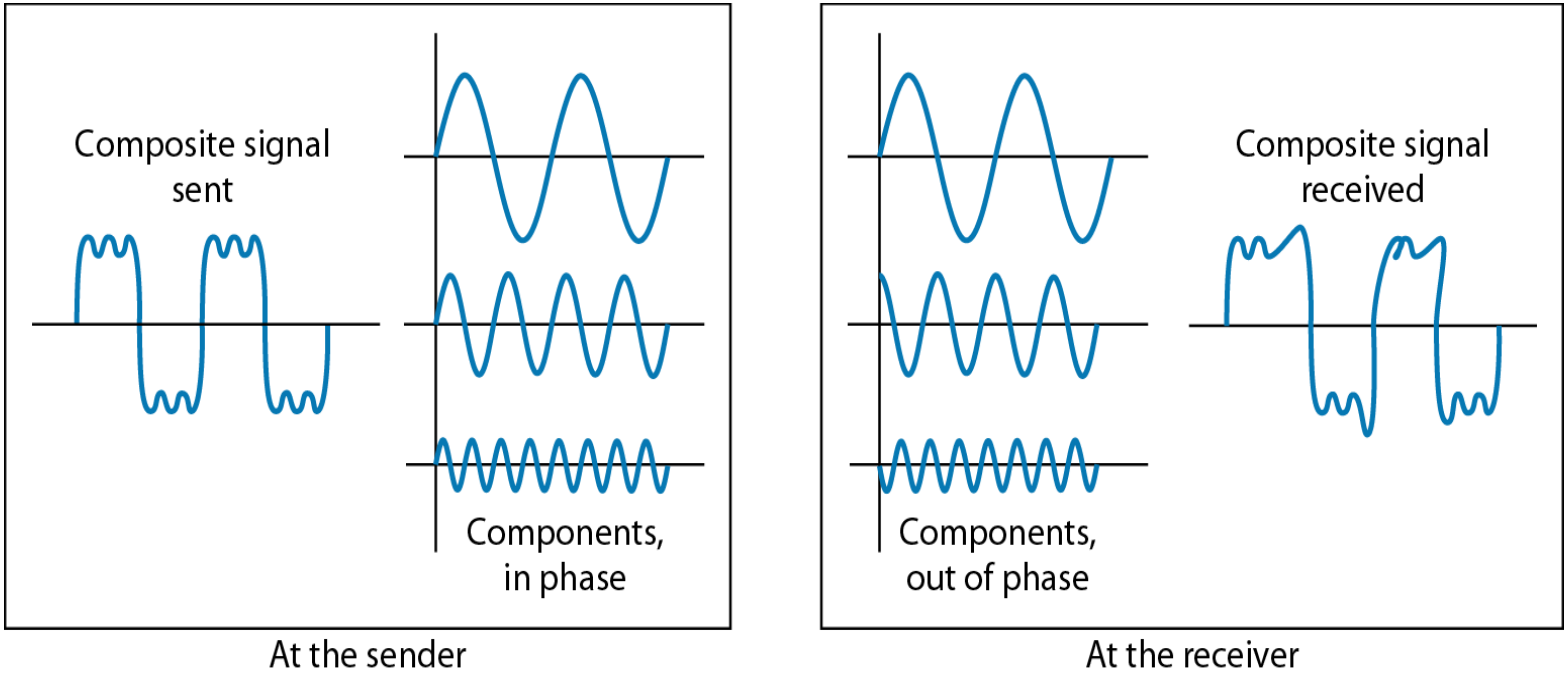
$$\text{dB} = 10 \log_{10} \frac{P_2}{P_1} = -1.5$$

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

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

Distortion:

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



Noise:

- Several types of noise, such as thermal noise, induced noise, crosstalk, and impulse noise, may corrupt the signal.
  - thermal noise: random motion of electrons in a wire, creates an extra signal
  - Induced noise comes from sources such as motors and appliances.
  - Crosstalk is the effect of one wire on the other.
  - Impulse noise is a spike that comes from power lines, lightning, and so on.

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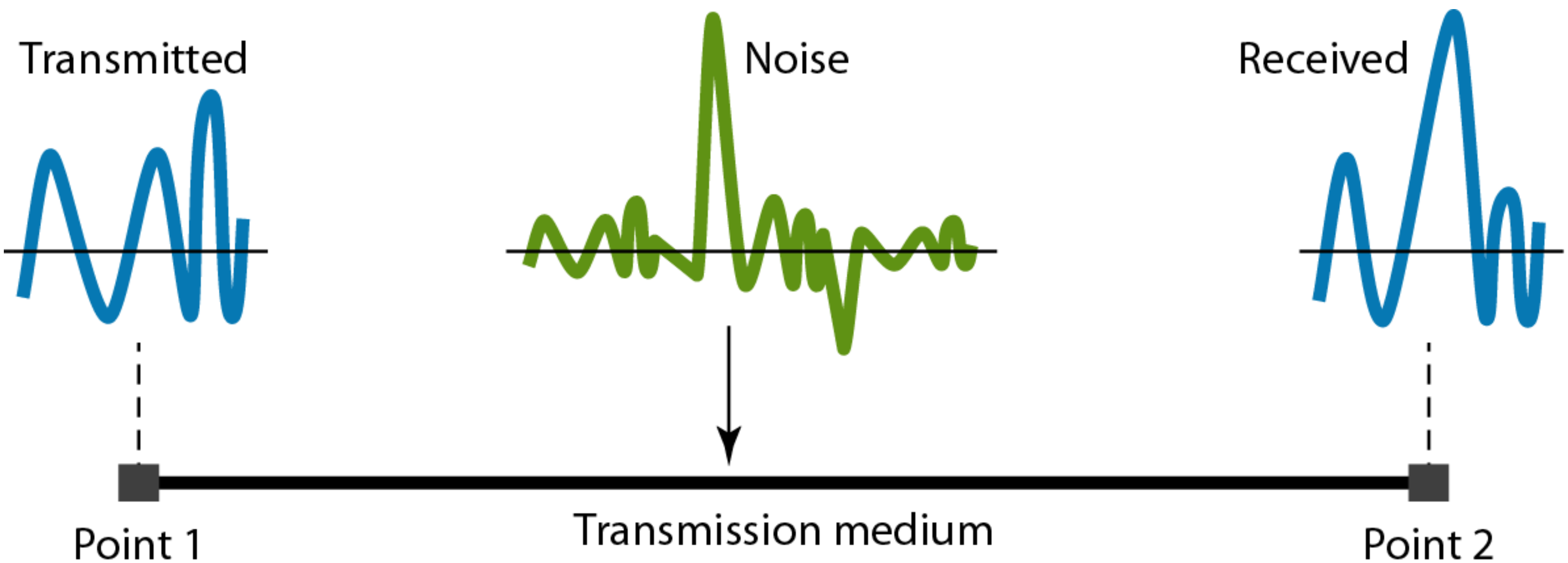

Transmitted
Noise
Received
Point 1
Transmission medium
Point 2

Signal-to-Noise Ratio:

- to find the theoretical bit rate limit, we need to know the ratio of the signal power to the noise power. The **signal-to-noise** ratio is defined as

$$\mathrm{SNR} = \frac{\text{average signal power}}{\text{average noise power}}$$

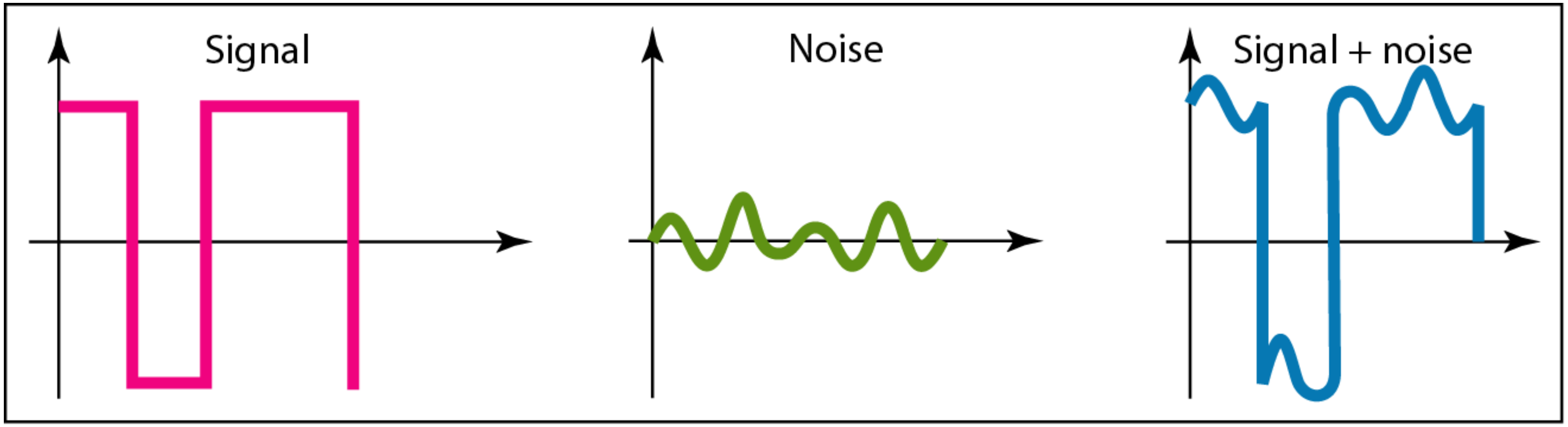
Example 3.31

- 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} ?

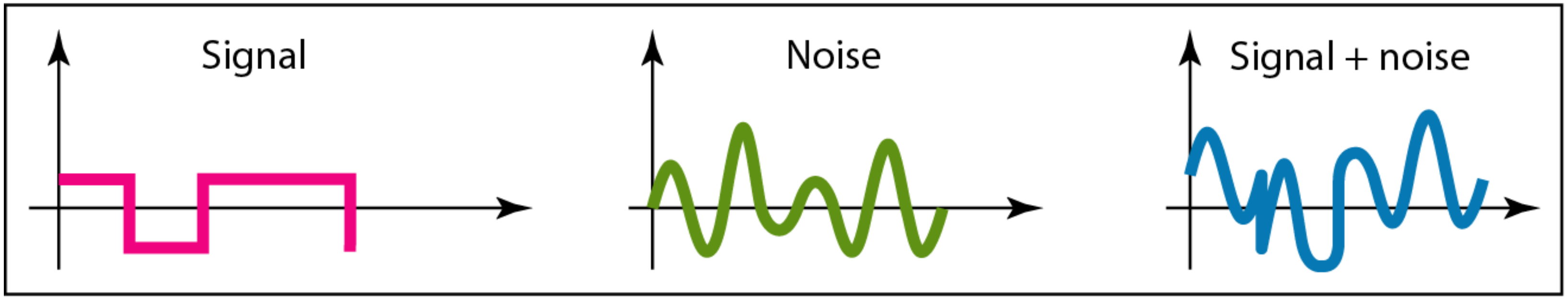
- Solution
- The values of SNR and SNRdB can be calculated as follows:

$$SNR = (10{,}000\ \mu w) / (1\ \mu w) = 10{,}000 \quad SNR_{dB} = 10 \log_{10} 10{,}000 = 10 \log_{10} 10^4 = 40$$

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:
  - The bandwidth available
  - The level of the signals we use
  - The quality of the channel (the level of noise)

Noiseless Channel: Nyquist Bit Rate:

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

$$\textbf{BitRate} = 2 * \textbf{bandwidth} * \log_2 L$$

- In this formula, bandwidth is the bandwidth of the channel, L is the number of signal levels used to represent data, and BitRate is the bit rate in bits per second.

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

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

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

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

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:

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

- 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:

Capacity = bandwidth * log2(1 + SNR)

- In this formula, bandwidth is the bandwidth of the channel, SNR is the signal-to-noise ratio, and capacity is the capacity of the channel in bits per second. The formula defines a characteristic of the channel, not the method of transmission.

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

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

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

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

- 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 3.41

- 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.

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

Continue..

- 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.

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

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.

Bandwidth:

- One characteristic that measures network performance is bandwidth.
- **Bandwidth in Hertz:** Bandwidth in hertz is the range of frequencies contained in a composite signal or the range of frequencies a channel can pass.
- **Bandwidth in Bits per Seconds:** The term bandwidth can also refer to the number of bits per second that a channel, a link, or even a network can transmit.

- Note: an increase in bandwidth in hertz means an increase in bandwidth in bits per second.

Throughput:

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

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

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

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.
- **Latency** = **propagation time + transmission time + queuing time + processing delay**

- **Propagation time** measures the time required for a bit to travel from the source to the destination.
- **Propagation time = Distance / (Propagation Speed)**

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

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

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- The **transmission time** of a message depends on the size of the message and the bandwidth of the channel.
- **Transmission time = (Message size) / Bandwidth**

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 × 108 m/s.

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

Continue..

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

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

Continue..

- **queuing time**, is the time needed for each intermediate or end device to hold the message before it can be processed. The queuing time is not a fixed factor; it changes with the load imposed on the network. When there is heavy traffic on the network, the queuing time increases

Reference:

- Data Communications and Networking, Behrouz A. Forouzan, Fifth Edition, TMH, 2013.