ANALOG AND DIGITAL SIGNALS

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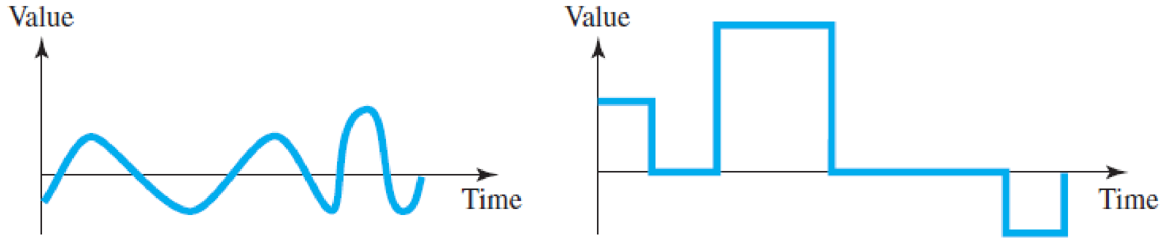
ANALOG AND DIGITAL DATA

- 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.
- For example, an analog clock that has hour, minute, and second hands gives information in a continuous form; the movements of the hands are continuous.
- On the other hand, a digital clock that reports the hours and the minutes will change suddenly from 8:05 to 8:06.

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, on the other hand, can have only a limited number of defined values. Although each value can be any number, it is often as simple as 1 and 0.

Figure 3.2 *Comparison of analog and digital signals*

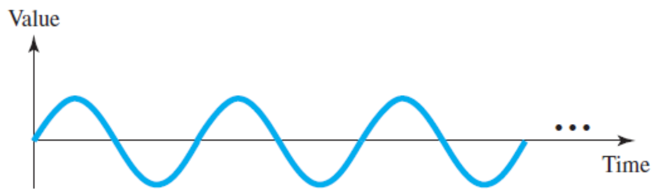


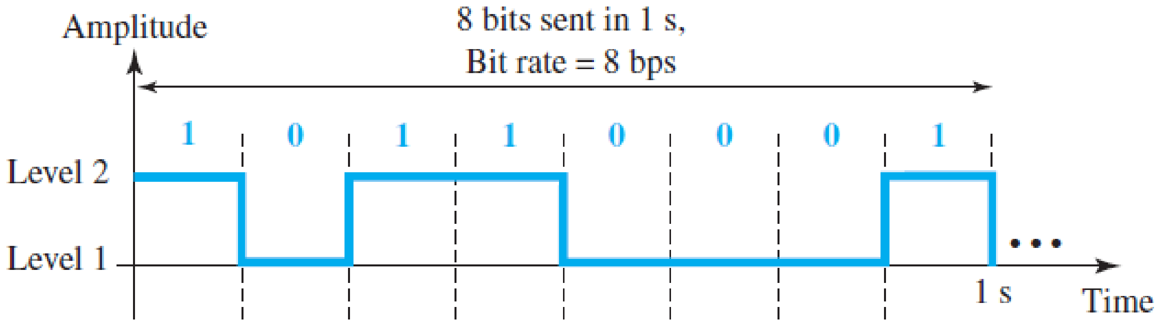
a. Analog signal   b. Digital signal

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.

Figure 3.3 *A sine wave*





a. A digital signal with two levels

PERIODIC ANALOG SIGNALS & SINE WAVE

- 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*

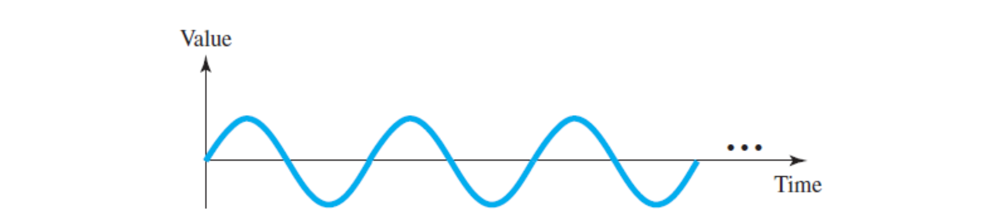
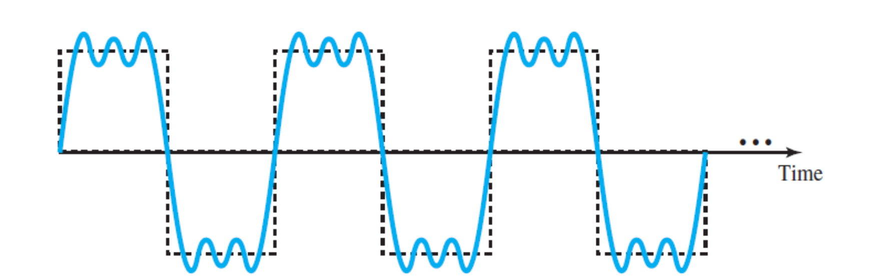


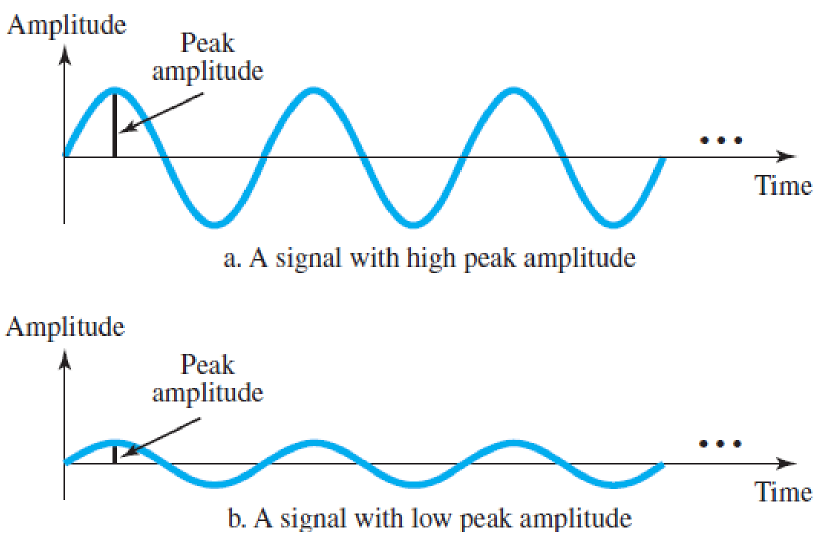
Figure 3.10 *A composite periodic signal*



SINE WAVE : PEAK AMPLITUDE

- The peak amplitude of a signal is the absolute value of its highest intensity, proportional to the energy it carries. For electric signals, peak amplitude is normally measured in volts.

Figure 3.4 *Two signals with the same phase and frequency, but different amplitudes*



SINE WAVE : PERIOD AND FREQUENCY

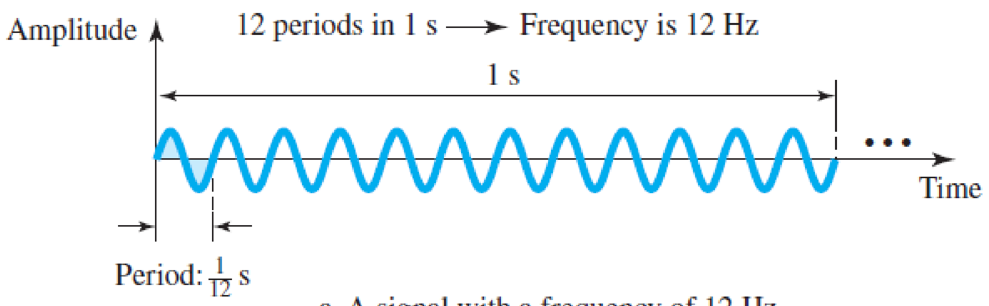
- Period refers to the amount of time, in seconds, a signal needs to complete 1 cycle. Frequency refers to the number of periods in 1 s. Note that period and frequency are just one characteristic defined in two ways. Period is the inverse of frequency, and frequency is the inverse of period, as the following formulas show.

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

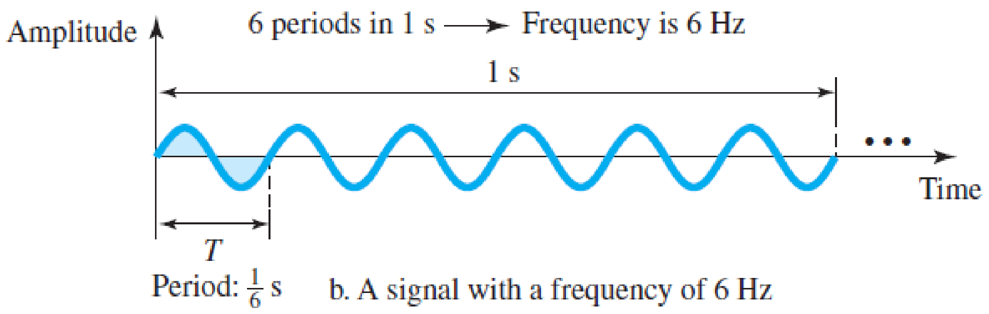
- Period is formally expressed in seconds. Frequency is formally expressed in Hertz (Hz), which is cycles per second.

SINE WAVE : PERIOD AND FREQUENCY

Figure 3.5 *Two signals with the same amplitude and phase, but different frequencies*



a. A signal with a frequency of 12 Hz

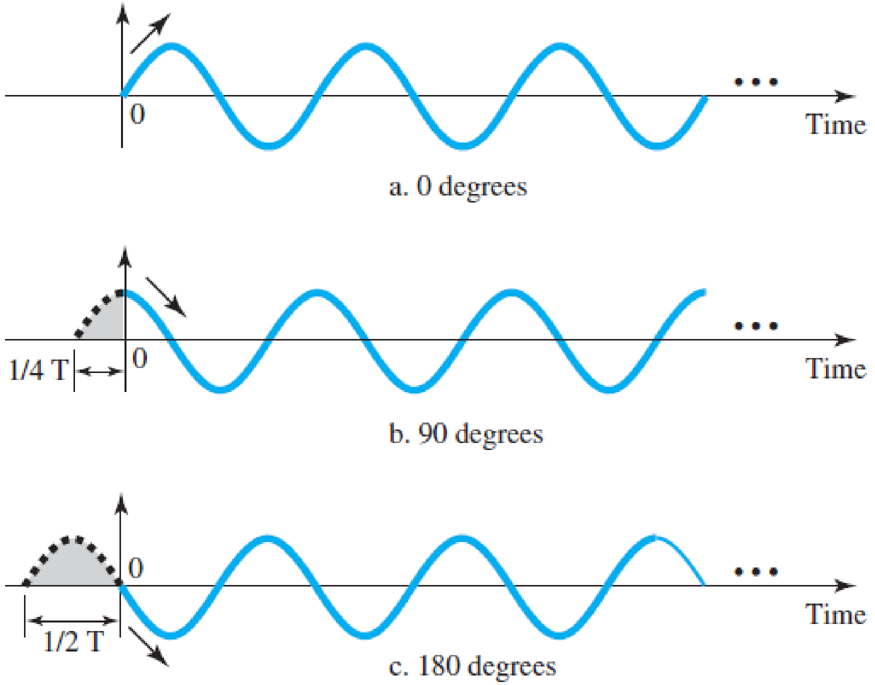


b. A signal with a frequency of 6 Hz

SINE WAVE : PHASE

- The term **phase,** or phase shift, describes the position of the waveform relative to time 0. It indicates the status of the first cycle.
- A phase shift of 360º corresponds to a shift of a complete period; a phase shift of 180° corresponds to a shift of one-half of a period; and a phase shift of 90º corresponds to a shift of one-quarter of a period.

Figure 3.6 *Three sine waves with the same amplitude and frequency, but different phases*



SINE WAVE : UNITS OF PERIOD AND FREQUENCY

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

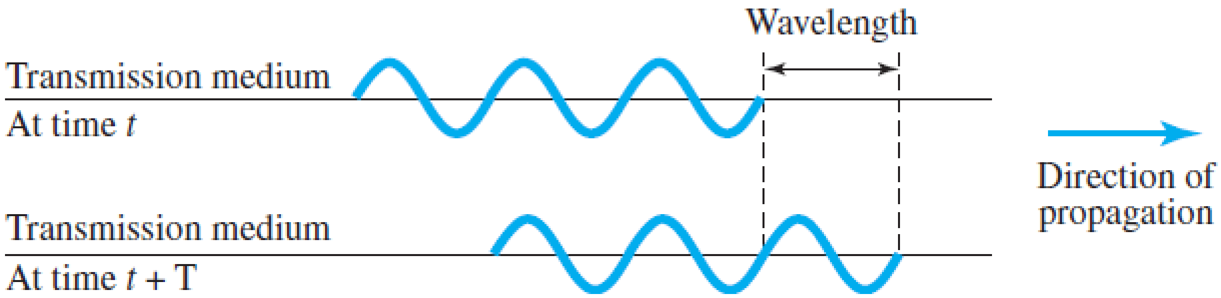
SINE WAVE : WAVELENGTH

- Wavelength is another characteristic of a signal traveling through a transmission medium. Wavelength binds the period or the frequency of a simple sine wave to the propagation speed of the medium. The wavelength is normally measured in micrometers.

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

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

Figure 3.7 *Wavelength and period*



BANDWIDTH

- The range of frequencies contained in a composite signal is its bandwidth. The bandwidth is normally the difference between two numbers. For example, if a composite signal contains frequencies between 1000 and 5000, its bandwidth is 5000 − 1000, or 4000.
- The bandwidth of a composite signal is the difference between the highest and the lowest frequencies contained in that signal.

Figure 3.10 *A composite periodic signal*

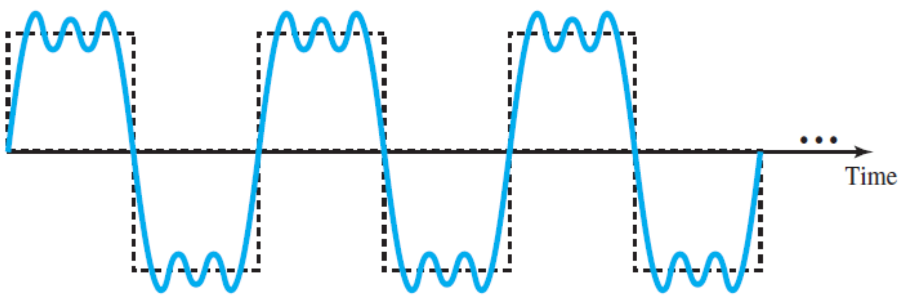
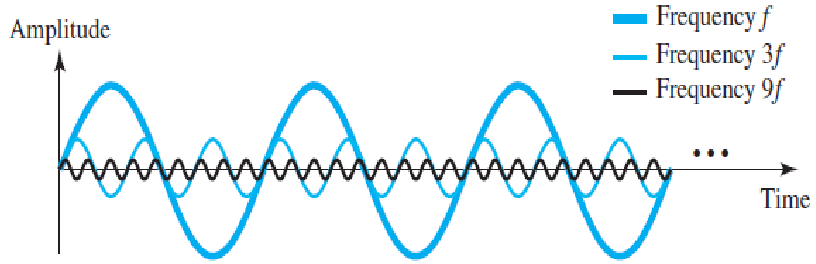


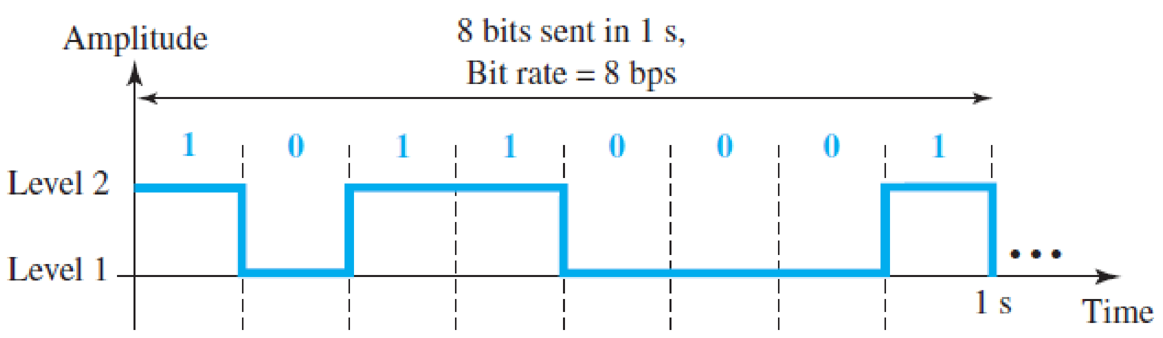
Figure 3.11 *Decomposition of a composite periodic signal in the time and frequency domains*



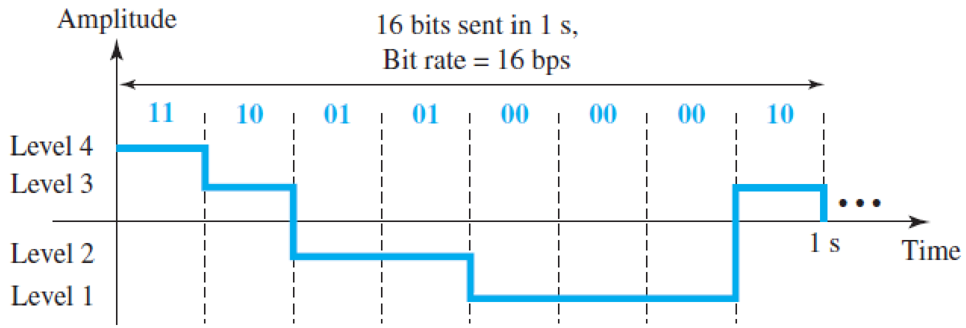
a. Time-domain decomposition of a composite signal

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.
- In general, if a signal has L levels, each level needs $\log_2 L$ bits.



a. A digital signal with two levels



b. A digital signal with four levels

DIGITAL SIGNALS : 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).

Example 3.16

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 3.18

Assume we need to download text documents at the rate of 100 pages per second. 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

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

DIGITAL SIGNALS : BIT LENGTH

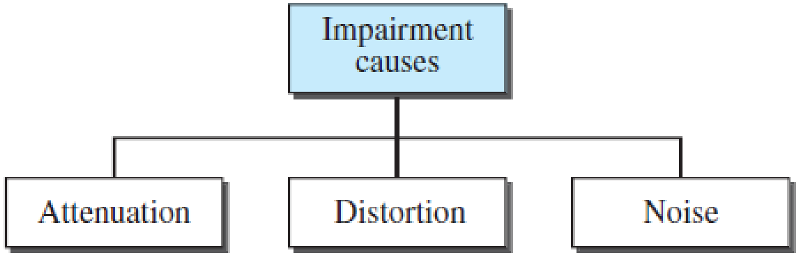
- The bit length is the distance one bit occupies on the transmission medium.

$$\text{Bit length} = \text{propagation speed} \times \text{bit duration}$$

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.

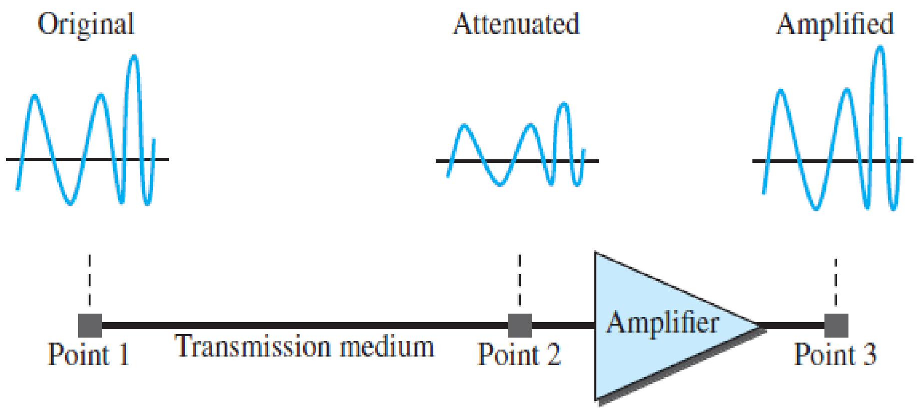
Figure 3.26 *Causes of impairment*



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

Figure 3.27 *Attenuation*

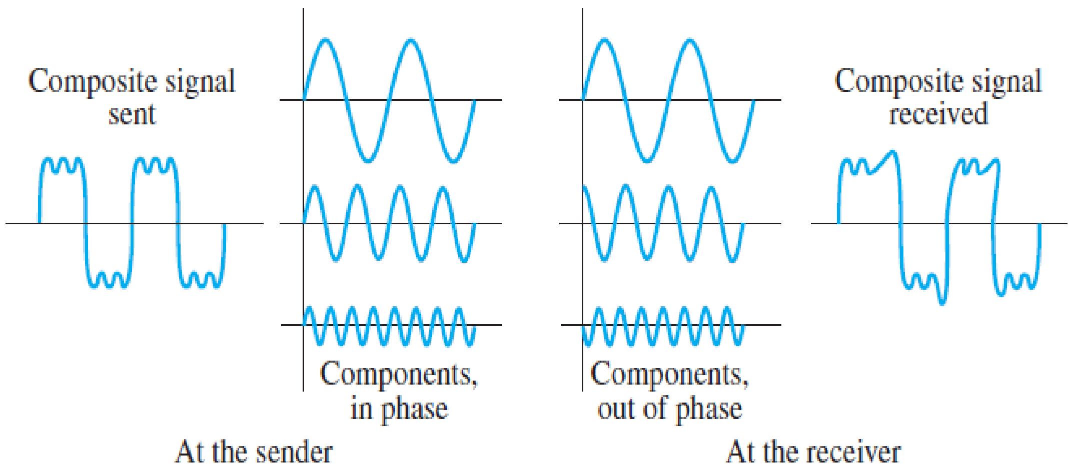


$$\mathrm{dB} = 10 \log_{10} \frac{P_2}{P_1}$$

DISTORTION

- Distortion means that the 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. In other words, signal components at the receiver have phases different from what they had at the sender. The shape of the composite signal is therefore not the same.

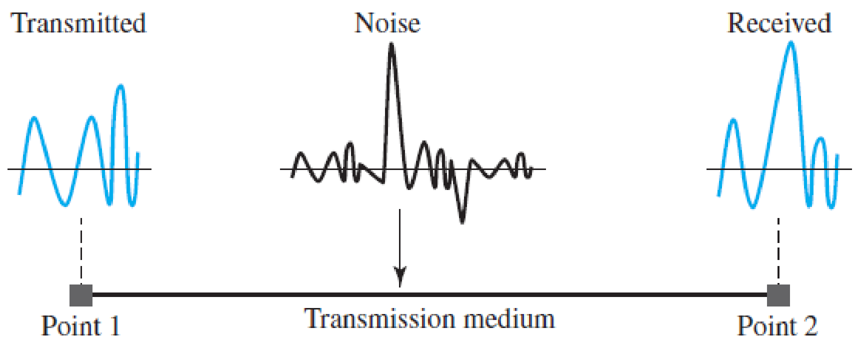
Figure 3.29 *Distortion*



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 and appliances. These devices act as a sending antenna, and the transmission medium acts as the receiving antenna. Crosstalk is the effect of one wire on the other. One wire acts as a sending antenna and the other as the receiving antenna. Impulse noise is a spike (a signal with high energy in a very short time) that comes from power lines, lightning, and so on.

Figure 3.30 *Noise*

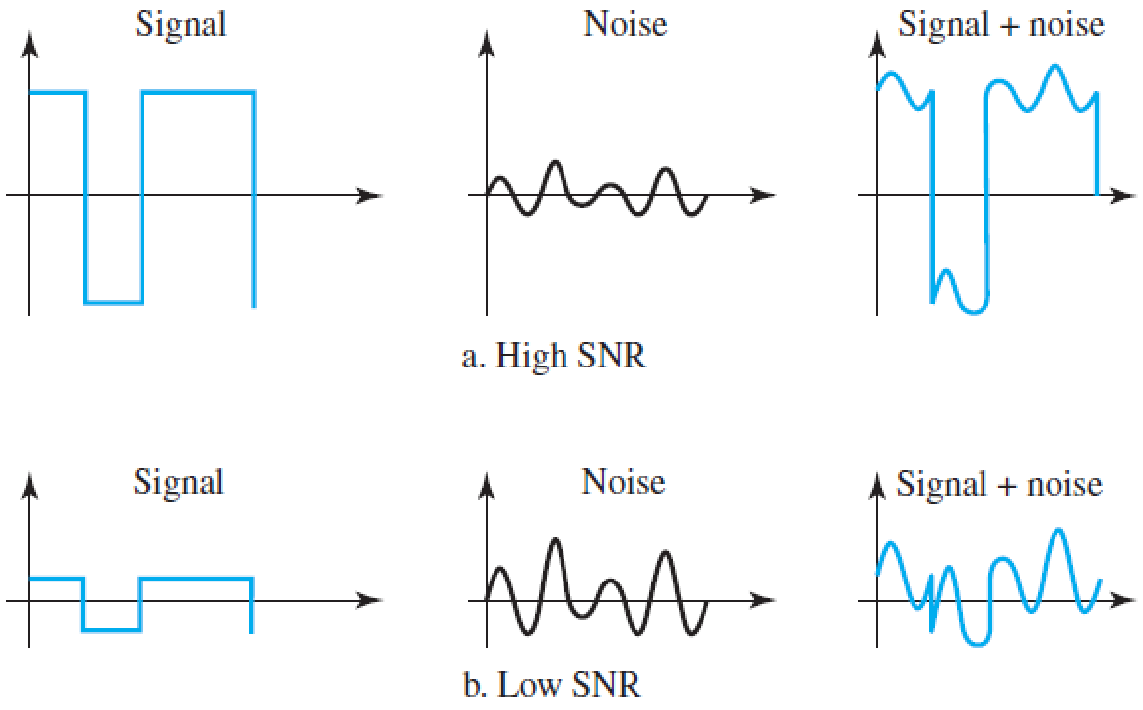


$$\text{SNR} = \frac{\text{average signal power}}{\text{average noise power}}$$

$$\text{SNR}_{\text{dB}} = 10 \log_{10} \text{SNR}$$

NOISE: SNR CASES

Figure 3.31 *Two cases of SNR: a high SNR and a low SNR*



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)

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

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

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

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

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:
- 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. Note that in the Shannon formula, there is no indication of the signal level, which means that no matter how many levels we have, we cannot achieve a data rate higher than the capacity of the channel. In other words, the formula defines a characteristic of the channel, not the method of transmission.

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

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

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

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