

# Data Communications and Networking Fourth Edition



# **Chapter 3**Data and Signals



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



Data can be analog or digital.

Analog data are continuous and take continuous values.

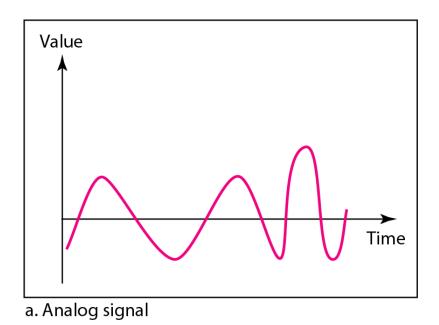
Digital data have discrete states and take discrete values.

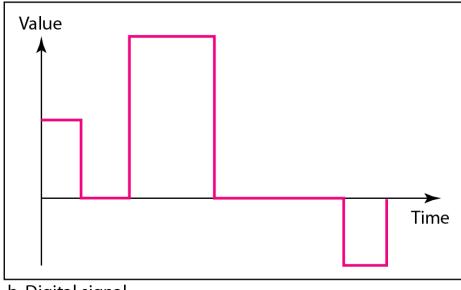


Signals can be analog or digital.

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







In data communications, we commonly use periodic analog signals and non-periodic 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

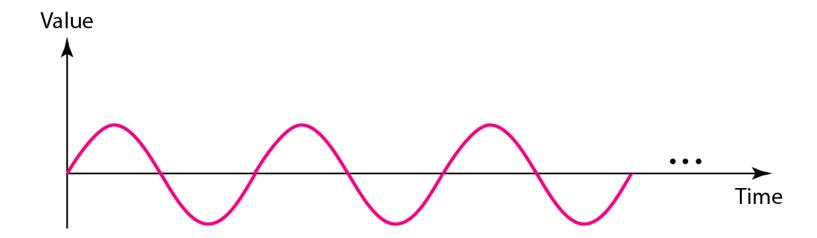
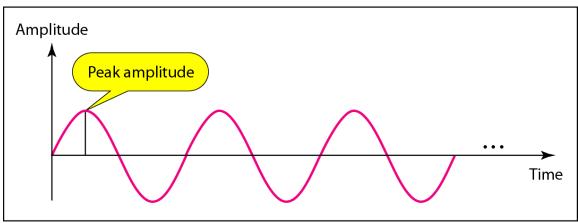
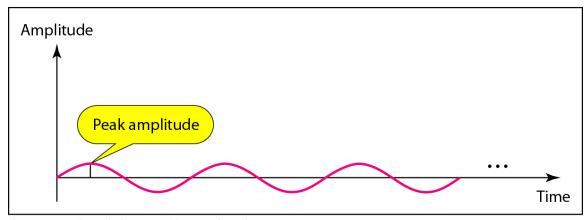


Figure 3.3 Two signals with the same phase and frequency, but different amplitudes



a. A signal with high peak amplitude

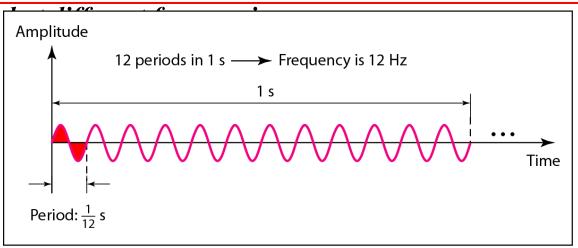


b. A signal with low peak amplitude

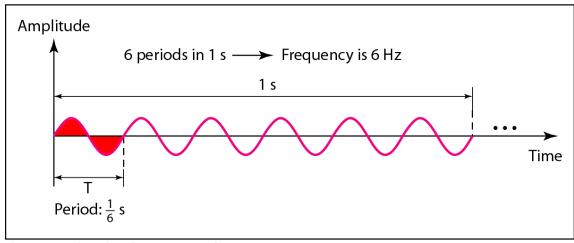
# Frequency and period are the inverse of each other.

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

# Figure 3.4 Two signals with the same amplitude and phase,



a. A signal with a frequency of 12 Hz



b. A signal with a frequency of 6 Hz



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 3.5

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).

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

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



# Frequency is the rate of change with respect to time.

Change in a short span of time means high frequency.

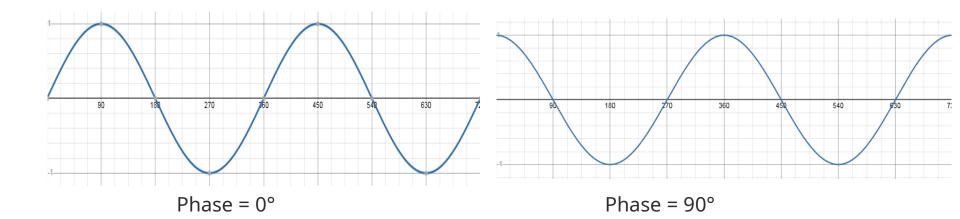
Change over a long span of time means low frequency.

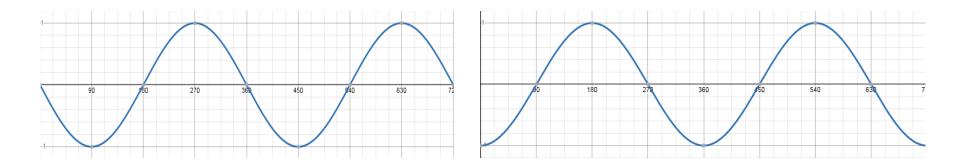
If a signal does not change at all, its frequency is zero.

If a signal changes instantaneously, its frequency is infinite.



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

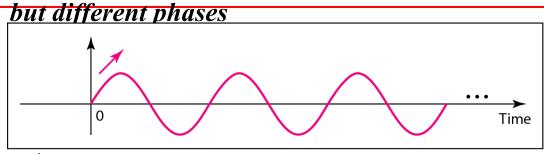




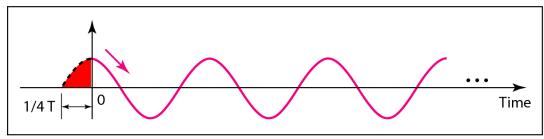
Phase = 270°

Phase = 180°

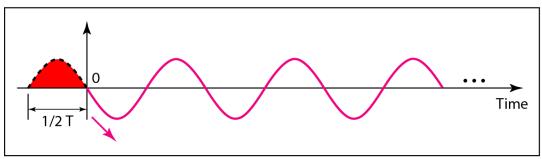
# Figure 3.5 Three sine waves with the same amplitude and frequency,



a. 0 degrees

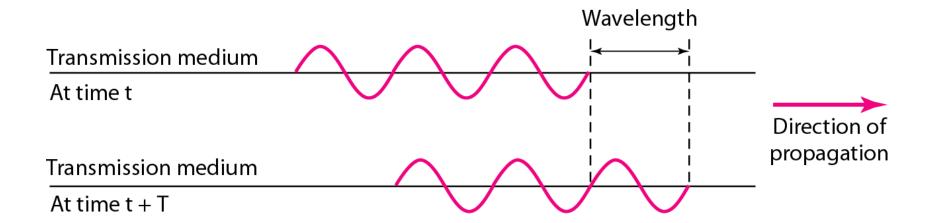


b. 90 degrees

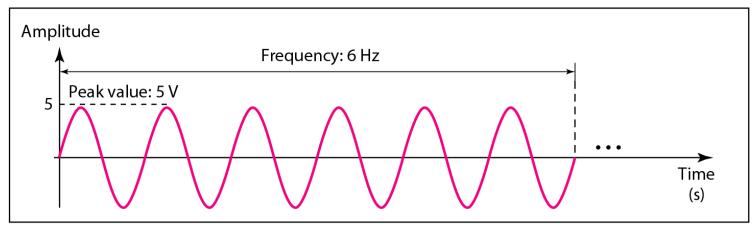


c. 180 degrees

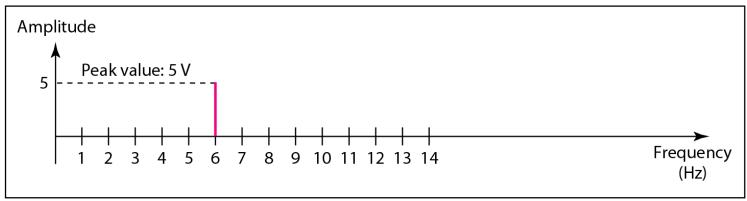
### Figure 3.6 Wavelength and period



#### 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)

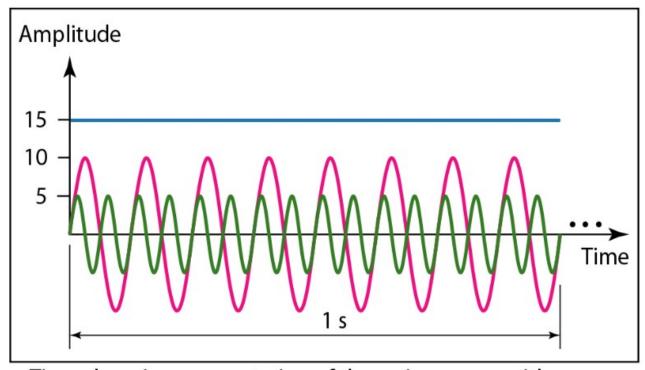


b. The same sine wave in the frequency domain (peak value: 5 V, frequency: 6 Hz)

# **Example 3.7**

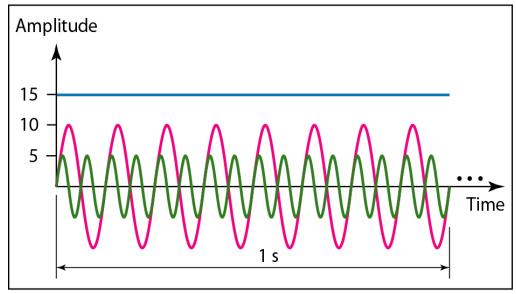
The frequency domain is more compact and useful when we are dealing with more than one sine wave. For example, Figure 3.8 shows three sine waves, each with different amplitude and frequency. All can be represented by three spikes in the frequency domain.

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

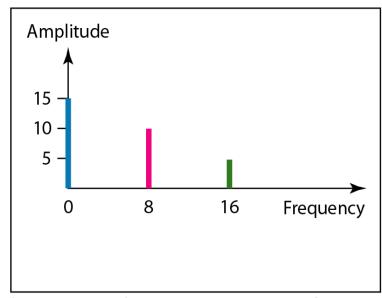


a. Time-domain representation of three sine waves with frequencies 0, 8, and 16

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



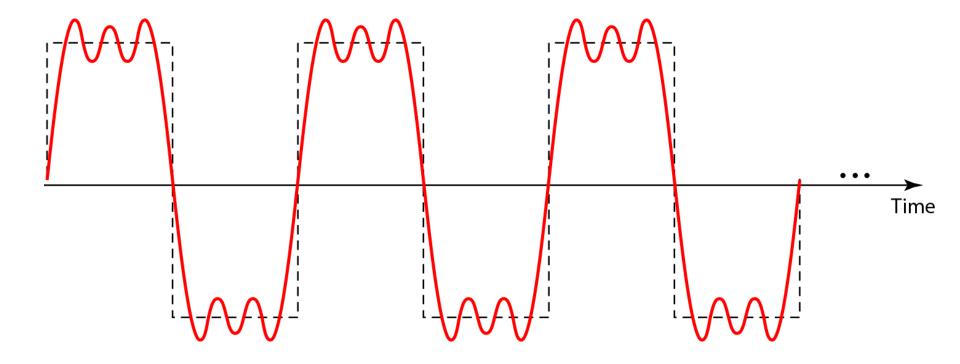
a. Time-domain representation of three sine waves with frequencies 0, 8, and 16



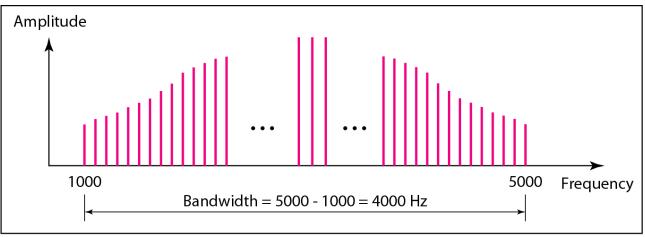
b. Frequency-domain representation of the same three signals

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.

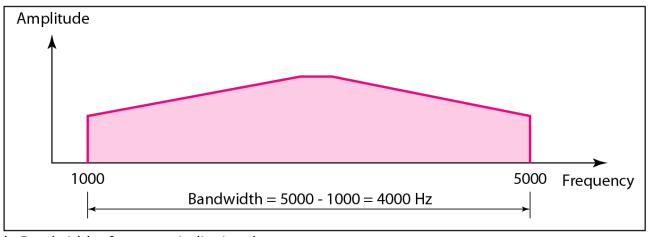
Figure 3.9 A composite periodic signal



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



a. Bandwidth of a periodic signal



b. Bandwidth of a nonperiodic signal



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.

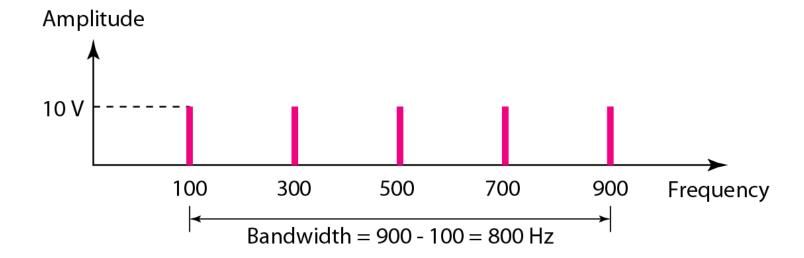
#### Solution

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



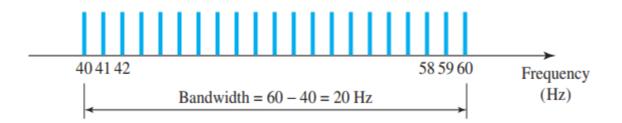


## Example 3.11

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 same amplitude.

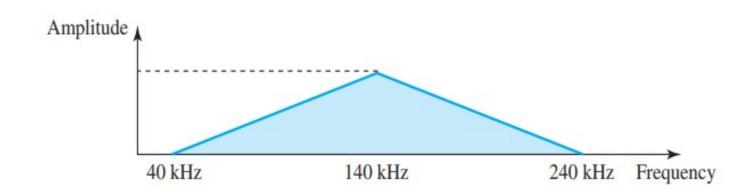
#### Solution

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



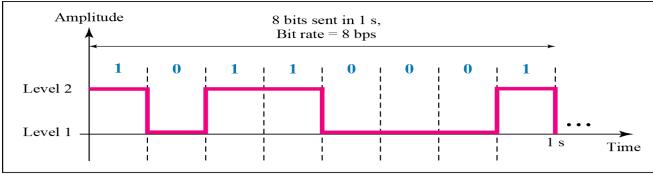


A non-periodic composite signal has a bandwidth of 200 kHz, with a middle frequency of 140 kHz and peak amplitude of 20V. The two extreme frequencies have an amplitude of 0. Draw the frequency spectrum. Solution

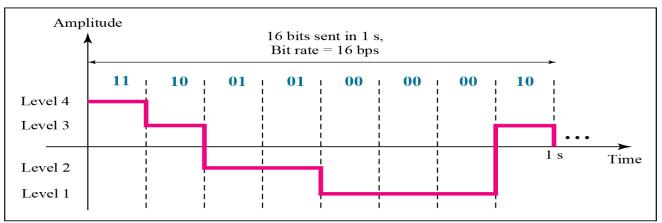


# Figure: Two digital signals: one with two signal levels and the other with four signal levels

- Figure shows two signals, one with two levels and the other with four. We send 1 bit per level in part a of the figure and 2 bits per level in part b of the figure.
- In general, if a signal has L levels, each level needs  $\log_2 L$  bits. For this reason, we can send  $\log_2 4 = 2$  bits in part b.



a. A digital signal with two levels



b. A digital signal with four levels

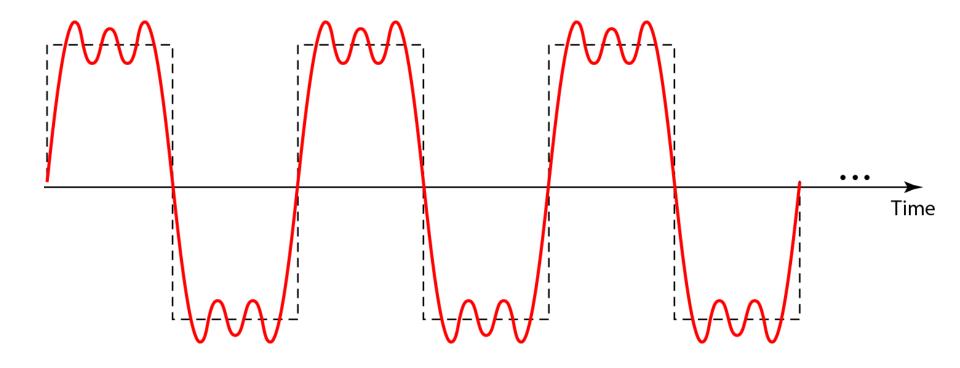
# **Example 3.16**

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

Number of bits per level =  $log_2 8 = 3$ 

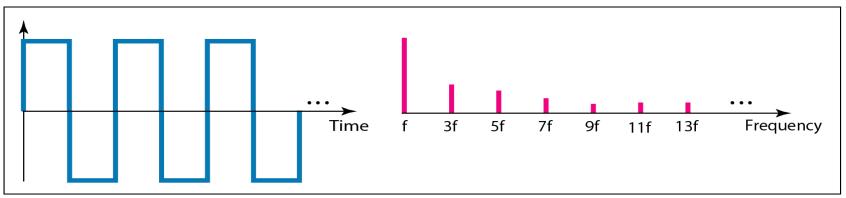
Each signal level is represented by 3 bits.

### Digital Signal as Composite Analog Signal

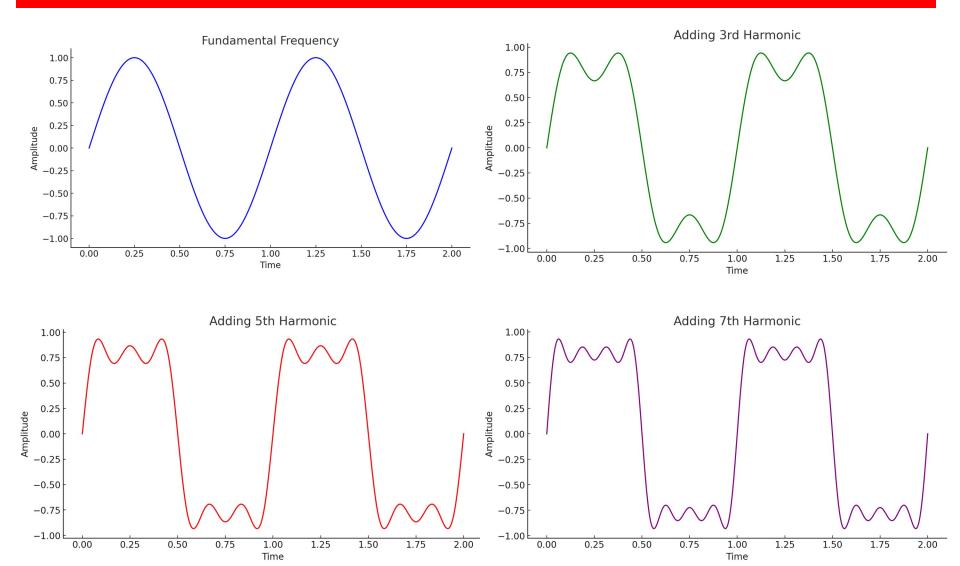


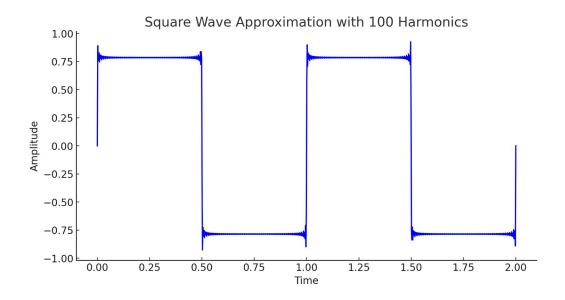
# Figure 3.17 The time and frequency domains of periodic and nonperiodic digital signals

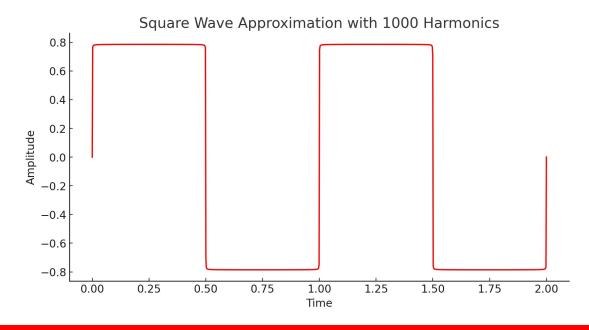
If the digital signal is periodic, which is rare in data communications, the decomposed signal has a frequency domain representation with an infinite bandwidth and discrete frequencies.



a. Time and frequency domains of periodic digital signal

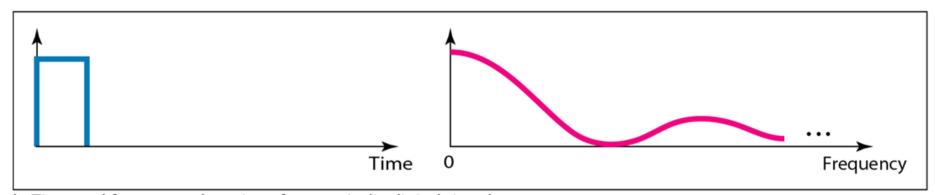




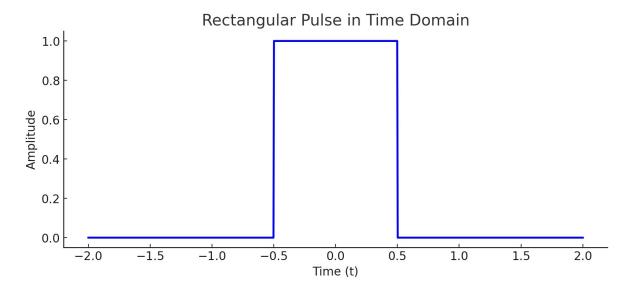


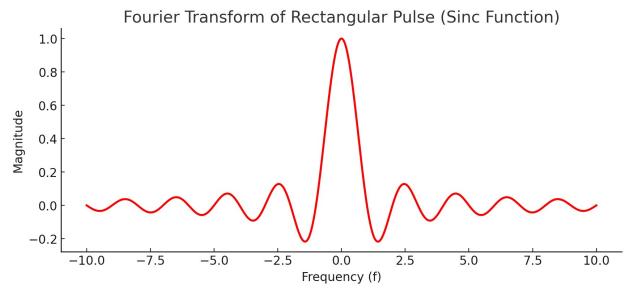
### Figure 3.17 The time and frequency domains of periodic and nonperiodic digital signals

If the digital signal is non-periodic, the decomposed signal still has an infinite bandwidth, but the frequencies are continuous.



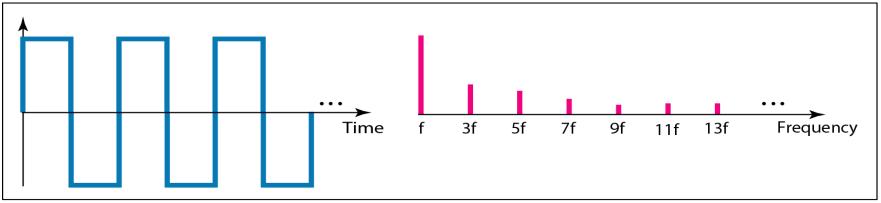
b. Time and frequency domains of nonperiodic digital signal



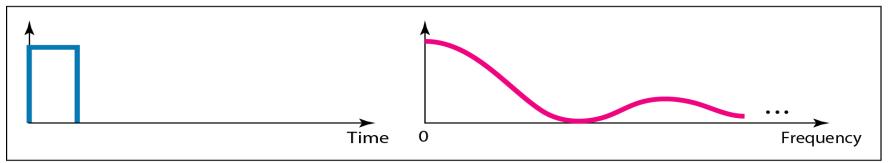


### Figure 3.17 The time and frequency domains of periodic and nonperiodic digital signals

Note that both bandwidths are infinite, but the periodic signal has discrete frequencies while the non-periodic signal has continuous frequencies.



a. Time and frequency domains of periodic digital signal

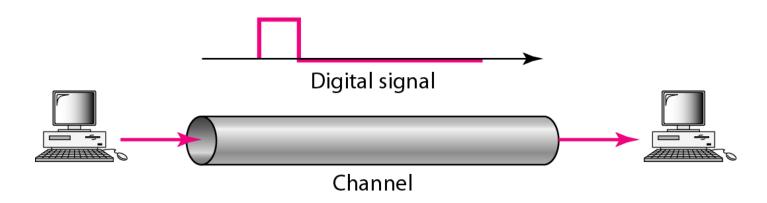


b. Time and frequency domains of nonperiodic digital signal

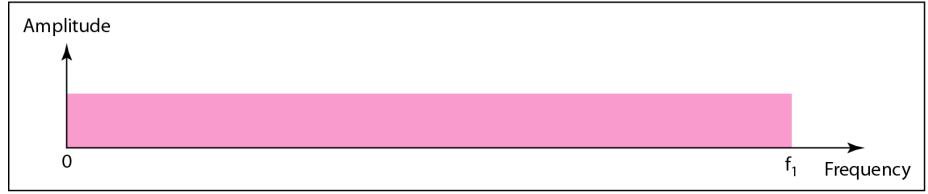
#### Transmission of digital signals

We can transmit a digital signal by one of two different approaches:

- 1. Baseband Transmission
- 2. Broadband Transmission (using modulation)
- ☐ Baseband transmission means sending a digital signal over a channel without changing the digital signal to an analog signal.
- ☐ Baseband transmission requires a low-pass channel, a channel with a bandwidth that starts from zero.



#### Figure: Bandwidths of two low-pass channels



a. Low-pass channel, wide bandwidth

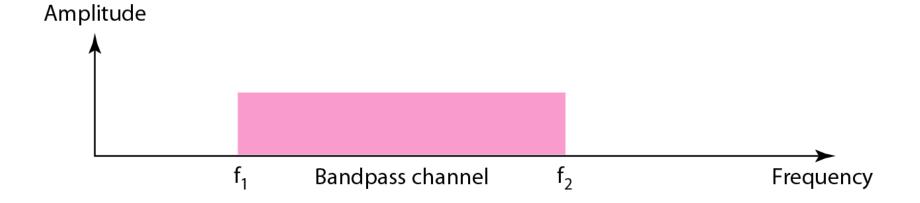


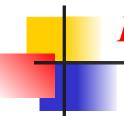
b. Low-pass channel, narrow bandwidth

#### **Broadband Transmission**

- Broadband transmission or modulation means changing the digital signal to an analog signal for transmission.
- Modulation allows us to use a bandpass channel— a channel with a bandwidth that does not start from zero.
- This type of channel is more available than a low-pass channel.
- 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: Bandwidth of a bandpass channel





#### Example: Low Pass Channel

We have a low-pass channel with bandwidth 200 kHz. What is the maximum frequency of this channel?

#### Solution:

Here, bandwidth, B = 200 kHz

We know, low-pass channel's bandwidth starts from 0 Hz,

And bandwidth = highest frequency – lowest frequency So, maximum frequency = 200 kHz

# **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 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

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



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**

An FHD monitor has an aspect ratio of 16:9. There are 1920 by 1080 pixels per screen, and the refresh rate is 120 Hz, meaning the screen is renewed 120 times per second. If each color pixel is represented by 24 bits, calculate the bit rate.

#### 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:

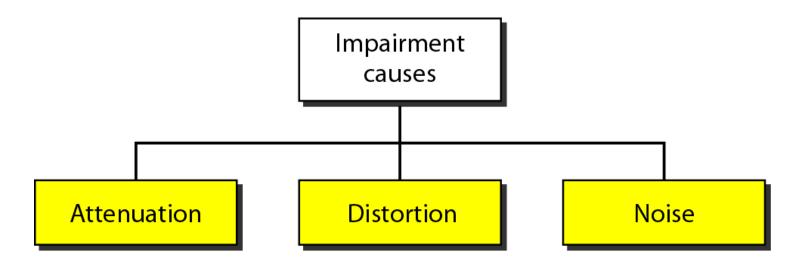
Attenuation Distortion Noise

### The World if there were no Transmission Impairment



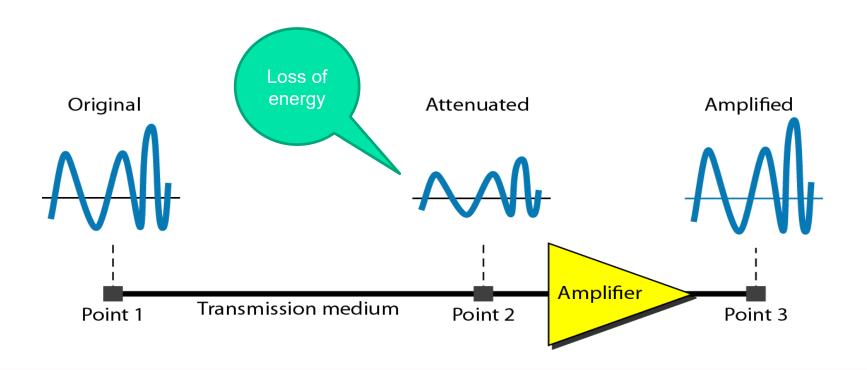
### Figure 3.25 Causes of

*impairment* 

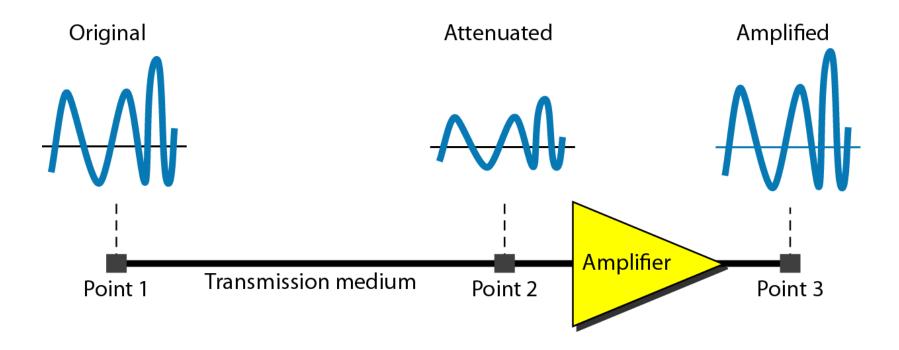


#### **Attenuation**

- It means loss of energy -> weaker signal
- When a signal travels through a medium it loses energy overcoming the resistance of the medium.
- This is also known as attenuated signal.
- Amplifiers are used to amplify the attenuated signal which gives the original signal back.



#### 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

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

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



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

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

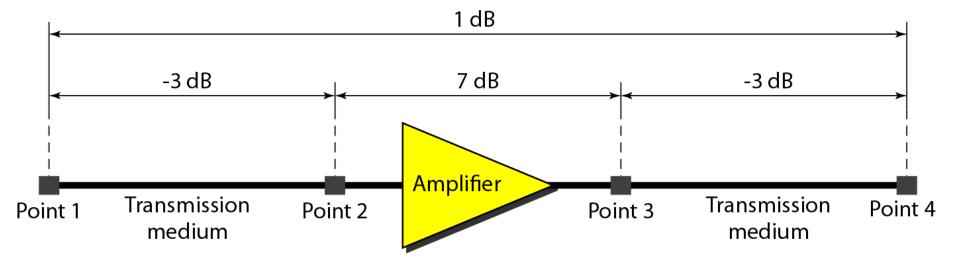
$$= 10 \log_{10} 10 = 10(1) = 10 \text{ dB}$$

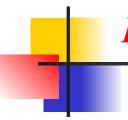


One reason that engineers use the decibel to measure the changes in the strength of a signal is that decibel numbers can be added (or subtracted) when we are measuring several points (cascading) instead of just two. In Figure 3.27 a signal travels from point 1 to point 4. In this case, the decibel value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

$$dB = -3 + 7 - 3 = +1$$

Figure 3.27 Decibels for Example 3.28





#### Example: Attenuation

A fiber-optic communication system transmits data from a source to a destination 12 km away. The input power at the transmitter is 5 mW, and the attenuation coefficient of the fiber is 0.2 dB/km.

- (A) Find the total attenuation (in dB) over the 12 km fiber length.
- (B) Calculate the output power (in mW) at the receiver.

#### Solution:

(A) Total attenuation over 12 km fiber length = 0.2\*12 = 2.4 dB



### Example: Attenuation

(B) We know, attenuation =  $10*log_{10} \frac{P_2}{P_1}$  Here, attenuation over 12 km = 2.4 dB  $P_1 = 5 \text{ mW}$  The output power at the receiver,  $P_2 = 8.689 \text{ mW}$ 

## **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  $5 \times (-0.3) = -1.5 \, dB$ . We can calculate the power as

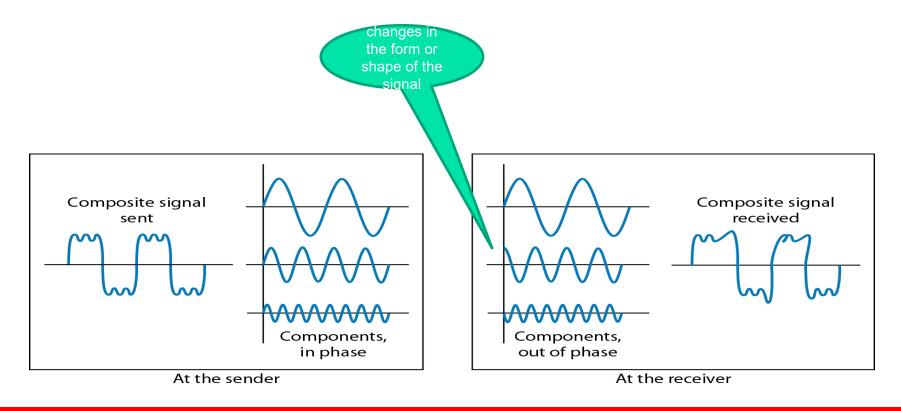
$$dB = 10 \log_{10} \frac{P_2}{P_1} = -1.5$$

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

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

#### **Distortion**

- It means change in the shape of signal.
- Distortion occurs in composite signals with different frequencies.
- Each frequency component has its own propagation speed traveling through a medium.
- The different components therefore arrive with different delays at the receiver.
- That means that the signals have different phases at the receiver end from what they had at sender's end.



#### **Noise**

The random or unwanted signal that mixes up with the original signal is called noise.

There are different types of noise

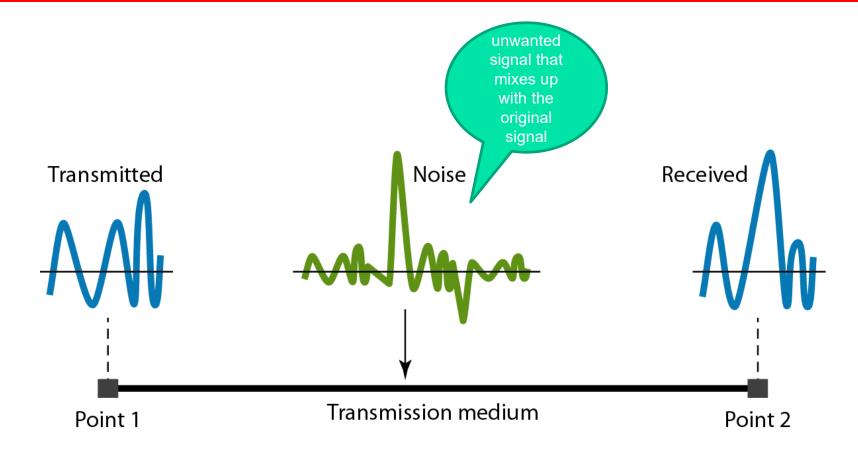
Thermal - noise random movement of electrons in the wire creates an extra signal

Induced – comes from sources such as motors and appliances. These devices act as sending antenna and transmission medium act as receiving antenna.

Crosstalk – when one wire affects the other wire.

Impulse - Spikes that result from power lines, lightning, or comes from high energy etc.

### **Figure:** Noise



#### Signal to Noise Ratio (SNR)

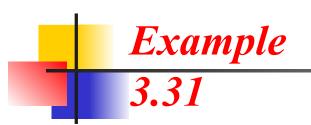
- To measure the quality of a system the SNR is often used. It indicates the strength of the signal with the noise power in the system.
- SNR is actually the ratio of what is wanted (signal) to what is not wanted (noise).
- A high SNR means the signal is less corrupted by noise; a low SNR means the signal is more corrupted by noise.

$$SNR = \frac{P_{signal}}{P_{noise}}$$
 Unwanted component

- It is the ratio between two powers.
- It is usually described in dB unit and referred to as SNR<sub>dB.</sub>

$$SNR(dB) = 10 \log_{10} \left( \frac{Signal\ Power}{Noise\ Power} \right)$$

$$SNR_{dB} = 10 \log_{10} SNR$$



The power of a signal is 10 mW and the power of the noise is 1  $\mu$ W; what are the values of SNR and SNR<sub>dB</sub>?

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

$$SNR = \frac{10,000 \ \mu\text{W}}{1 \ \text{mW}} = 10,000$$
$$SNR_{dB} = 10 \log_{10} 10,000 = 10 \log_{10} 10^4 = 40$$

1 W =  $10^3$  mW 1 mW =  $10^{-3}$  W 10 mW =  $10^{-2}$  W 1 W =  $10^6$   $\mu$ W

# **Example 3.32**

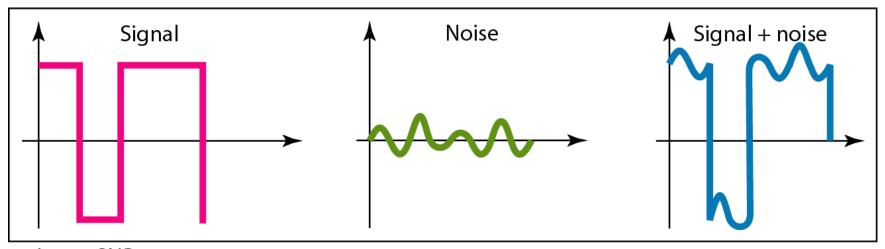
The values of SNR and  $SNR_{dB}$  for a noiseless channel are

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

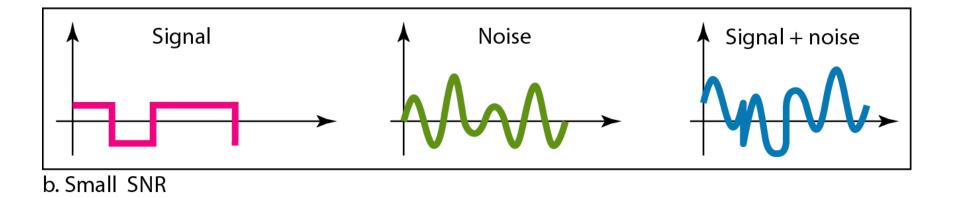
We can never achieve this ratio in real life; it is an ideal.

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

**SNR** 



a. Large SNR



#### 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** 



### Noiseless Channel: Nyquist Bit Rate

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

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

Here L is the number of signal levels used.



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

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

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



Note

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

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:

$$265,000 = 2 \times 20,000 \times \log_2 L$$
  
 $\log_2 L = 6.625$   $L = 2^{6.625} = 98.7$  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, the theoretical maximum bit rate can be calculated using the following formula:

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

Here SNR is the signal to noise ratio, and capacity is the capacity of the channel in bits per second.

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

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

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.

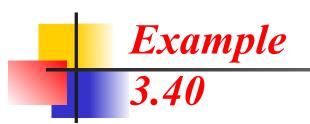
We can calculate the theoretical highest bit rate of a regular telephone line. A telephone line normally has a bandwidth of 3000. The signal-to-noise ratio is usually 3162. For this channel the capacity is calculated as

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

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.

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

$$SNR_{dB} = 10 \log_{10} SNR$$
  $\longrightarrow$   $SNR = 10^{SNR_{dB}/10}$   $\longrightarrow$   $SNR = 10^{3.6} = 3981$   $C = B \log_2 (1 + SNR) = 2 \times 10^6 \times \log_2 3982 = 24 \text{ Mbps}$ 



For practical purposes, when the SNR is very high, we can assume that 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: Using Both Limits

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.

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



#### Note

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

### Practice |

Suppose, you are sending a PDF at a speed of 64 kbps through a noiseless channel. The PDF contains 5 pages; each page contains 8 characters. The channel uses 16 signal levels. The signal strength of the channel is 245W.

- Calculate the bandwidth of the channel (in Hz). [Ans: 8 kbps]
- Suppose the channel becomes noisy, with only 75% of the bitrate of the noiseless channel. Calculate the power of the noise. [Ans: 3.89W]

#### 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)



### 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.

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.

#### Throughput

- The throughput is a measure of how fast we can actually send data through a network.
- A link may have a bandwidth of B bps, but we can only send T bps through this link with T always less than B.
- In other words, the bandwidth is a potential measurement of a link; the throughput is an actual measurement of how fast we can send data.
- For example, we may have a link with a bandwidth of 1 Mbps, but the devices connected to the end of the link may handle only 200 kbps. This means that we cannot send more than 200 kbps through this link.

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

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

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

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  $2.4 \times 10^8$  m/s.

Total delay = Transmission delay + Queueing delay + Processing delay + Propagation delay

Solution

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



- ☐ Propagation delay = Distance/propagation speed
- ☐ Transmission delay = Data size/bandwidth

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

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



### END