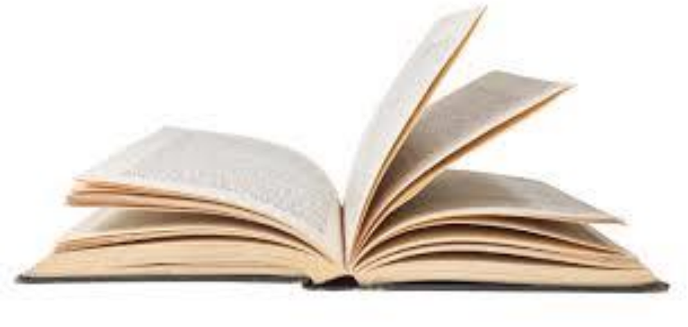
Data Communications and Networking

Lecture 2



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Outlines

- Introduction to Physical Layer: Data and Signals
  - Periodic Analog Signals
  - Digital Signals
  - Transmission Impairment
  - Data Rate Limits
  - Performance

Lecture Objectives

- To introduce
  - Data and signals
  - Periodic analog signals
  - Digital signals
  - Transmission impairment
  - Data rate limits
  - Performance
- What is analog data
- What is digital data
- To understand the basic concepts of data and signals
- To understand how to transform data to electromagnetic signals

Topic 1: Introduction to Physical Layer

Data and Signals

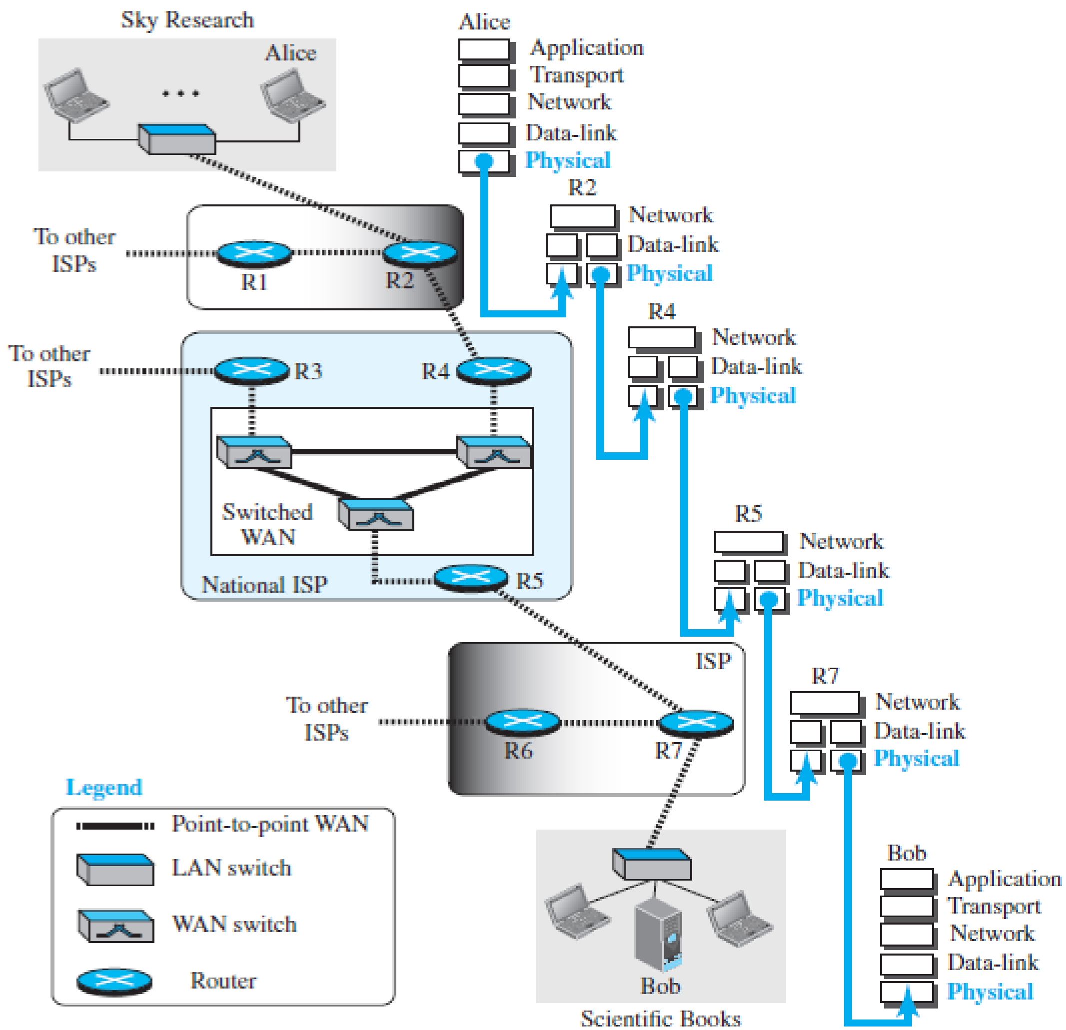

Figure 1. Communication at the Physical Layer

Data and Signals (Continue)

Analog and Digital Data

- Data can be analog or digital.
- Analog data refers to information that is continuous; digital data refers to information that has discrete states.

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.
- Although each value can be any number, it is often as simple as 1 and 0.

Data and Signals (Continue)

- The simplest way to show signals is by plotting them on a pair of perpendicular axes.
- The vertical axis represents the value or strength of a signal.
- The horizontal axis represents time.
- Figure 2 illustrates an analog signal and a digital signal.

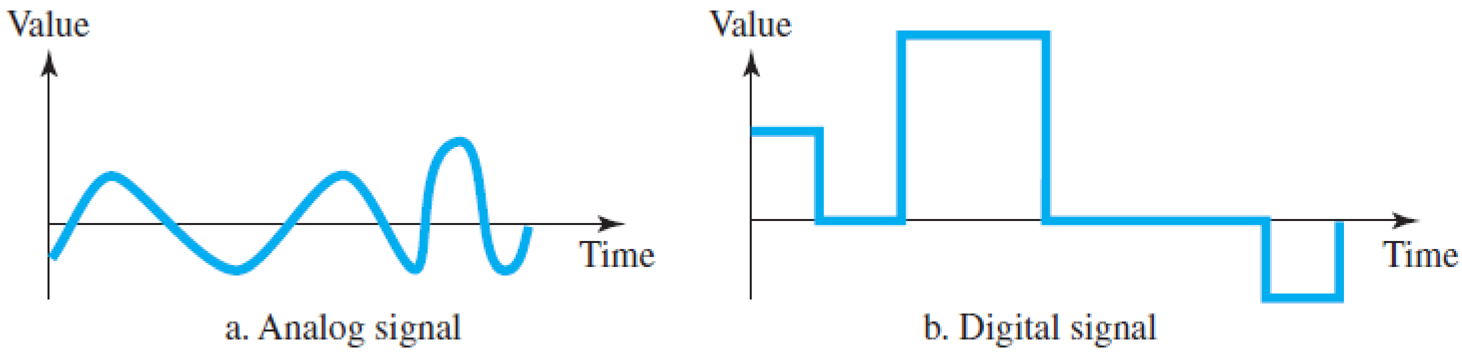

Figure 2. Comparison of Analog and Digital Signals

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

- The sine wave is the most fundamental form of a periodic analog signal as depicted in figure 3.
- A sine wave can be represented by three parameters: the peak amplitude, the frequency, and the phase.

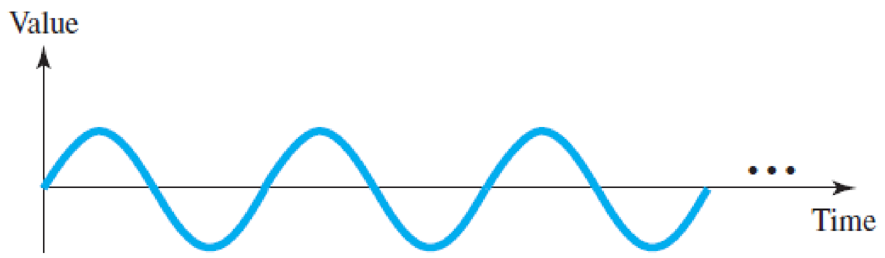

Figure 3. A Sine Wave

Periodic Analog Signals (Continue)

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 4 shows two signals and their peak amplitudes.

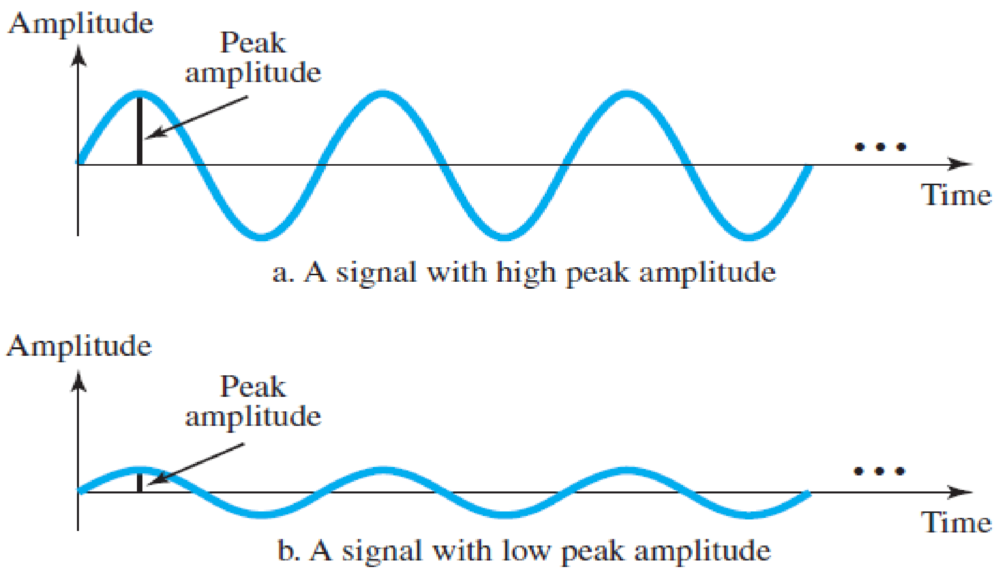

Figure 4. Two Signals with Same Phase and Frequency, But Different Amplitudes

Periodic Analog Signals (Continue)

Periodic 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, in Hertz (Hz).
- Frequency and period are the inverse of each other as the following formula.
- Figure 5 shows two signals and their frequencies.
- Period is formally expressed in seconds.
- Frequency is formally expressed in Hertz (Hz), which is cycle per second.

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

Periodic Analog Signals (Continue)

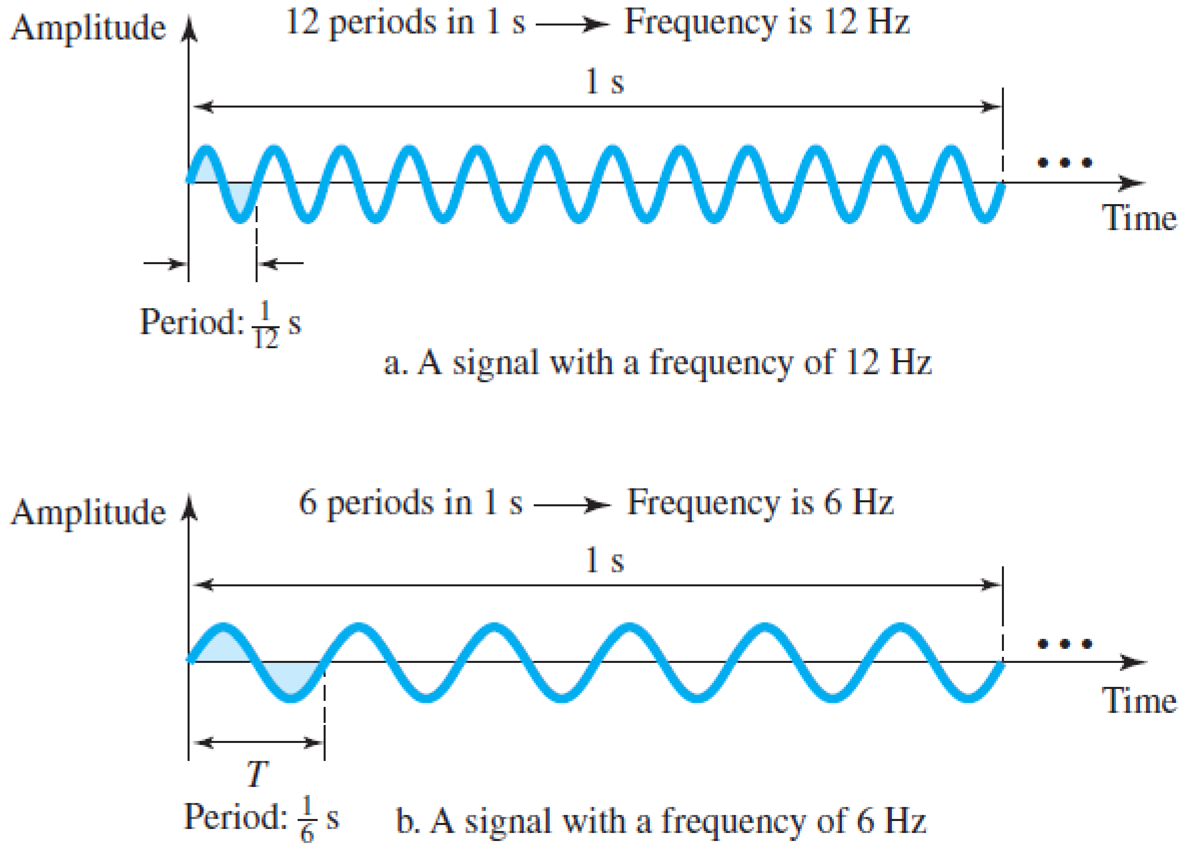

Figure 5. Two Signals with the Same Amplitude and Phase, but Different Frequencies

Periodic Analog Signals (Continue)

Example 1

The power we use at home has a frequency of 60 Hz (50 Hz in Europe). The period of this sine wave can be determined as follows:

Solution: $T = 1/f = 1/60 = 0.0166$ s = 16.6 ms

Example 2

The period of a signal is 100 ms. What is its frequency in kilohertz?

Solution: $f = 1/T$

$= 1/(100 \times 10^{-3})$

$= 10$ Hz $= 10^{-2}$ kHz (1Hz $= 10^{-3}$ kHz)

- Frequency is the rate or 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.

Periodic Analog Signals (Continue)

Phase

- Phase describes the position of the waveform relative to time 0.
- Phase is measured in degrees or radians ($360^{\circ} = 2\pi$ rad and $1^{\circ} = 2\pi/360$ rad as shown in figure 6.

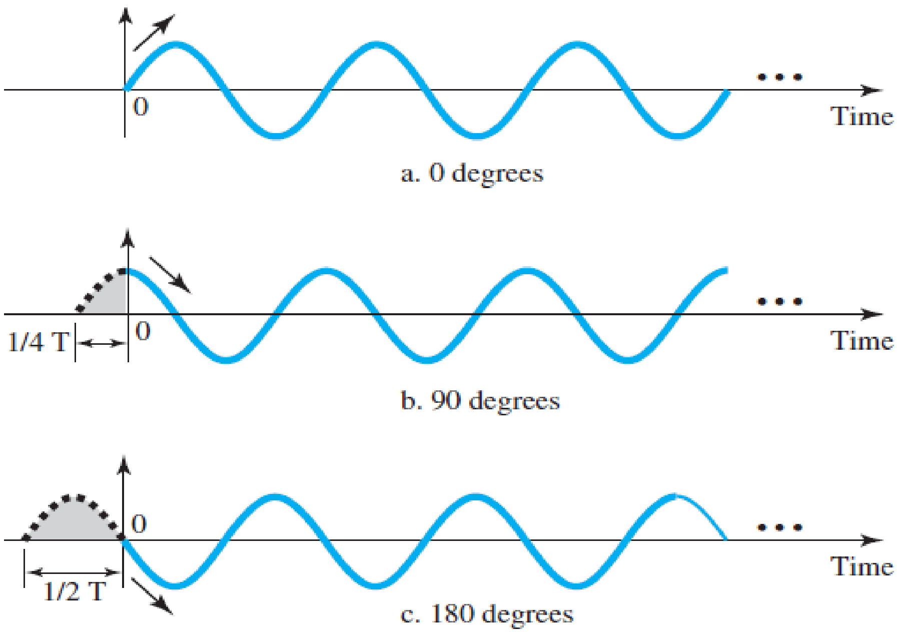

Figure 6. Three Sine Waves with the Same Amplitude and Frequency , But Different Phases

Periodic Analog Signals (Continue)

- Looking at Figure 6, it can say that
  a. A sine wave with a phase of 0° starts at time 0 with a zero amplitude. The amplitude is increasing.
  b. A sine wave with a phase of 90° starts at time 0 with a peak amplitude. The amplitude is decreasing.
  c. A sine wave with a phase of 180° starts at time 0 with a zero amplitude. The amplitude is decreasing.
- Another way to look at the phase is in terms of shift or offset. It can say that
  a. A sine wave with a phase of 0° is not shifted.
  b. A sine wave with a phase of 90° is shifted to the left by ¼ cycle. However, note that the signal does not really exist before time 0.
  c. A sine wave with a phase of 180° is shifted to the left by ½ cycle. However, note that the signal does not really exist before time 0.

Periodic Analog Signals (Continue)

Example 3

A sine wave offset 1/6 cycle with respect to time 0. What is its phase in degrees and radians?

Solution: $1/6 \times 360 = 60^{\circ}$

$$= 60 \times 2\pi /360 \text{ rad} = \pi/3 \text{ rad} = 1.046 \text{ rad}$$

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 as shown in figure 7.

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

-Where, λ = wavelength, c = propagation speed and f = frequency

Periodic Analog Signals (Continue)

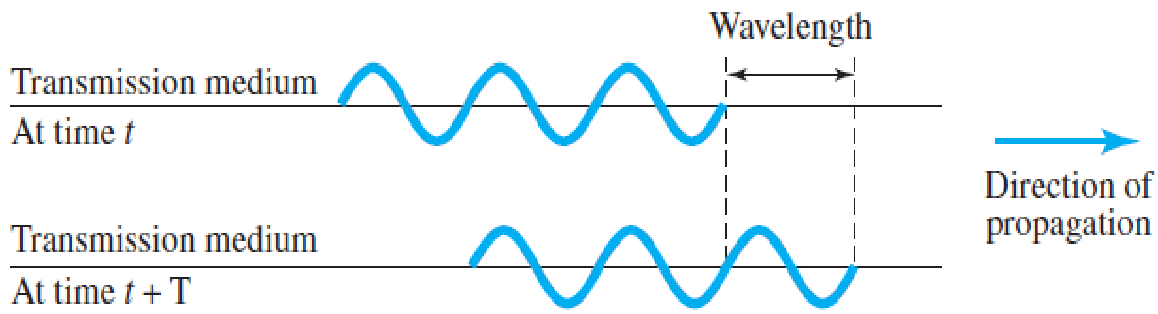

Figure 7. Wavelength and Period

- Wavelength can be calculated if one is given the propagation speed (the speed of light) and the period of the signal.
- However, since period and frequency are related to each other, if wavelength is represented by λ, propagation speed by *c* (speed of light), and frequency by *f*, the formula of wavelength is as follows:

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

Periodic Analog Signals (Continue)

Example 4

In a vacuum, light is propagated with a speed of 3×10^8 m/s. That speed is lower in air and even lower in cable. The wavelength is normally measured in micrometers (microns) instead of meters. For example, the wavelength of red light (frequency = 4×10^{14}) in air.

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

$= (3 \times 10^8) / (4 \times 10^{14})$

$= 0.75 \times 10^{-6}$ m

$= 0.75$ µm

Periodic Analog Signals (Continue)

Time and Frequency Domains

- The time-domain plot shows changes in signal amplitude with respect to time.
- A frequency-domain plot is concerned with only the peak value and the frequency as depicted in figure 8.

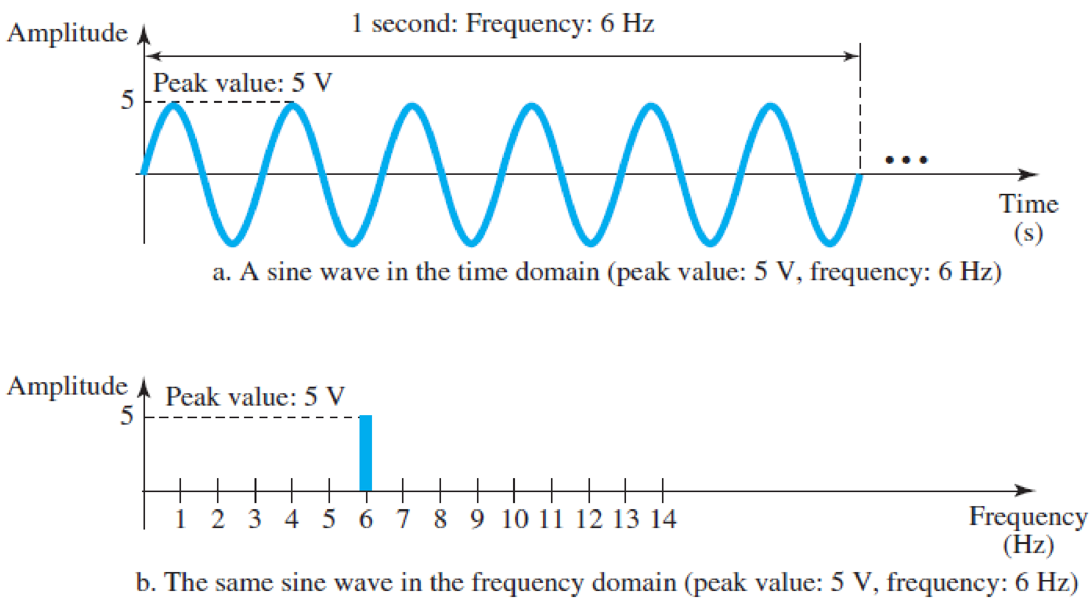

Figure 8. The Time-Domain and Frequency-Domain Plots of a Sine Wave

Periodic Analog Signals (Continue)

Composite Signals

- If the composite signal is periodic, the decomposition gives a series of signals with discrete frequencies; if the composite signal is nonperiodic, the decomposition gives a combination of sine waves with continuous frequencies.

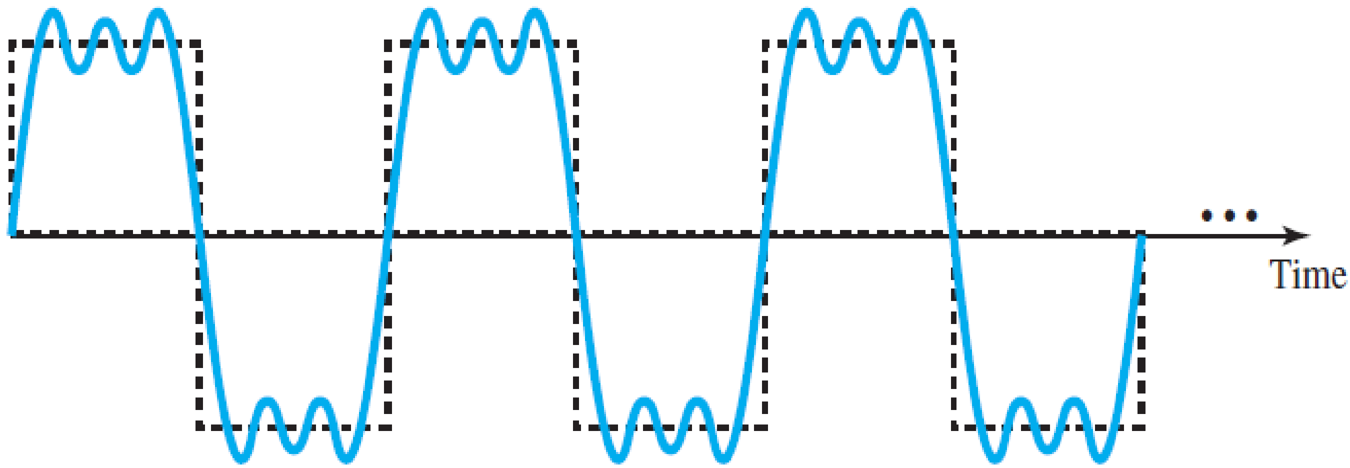

Figure 9. A Composite Periodic Signal

Periodic Analog Signals (Continue)

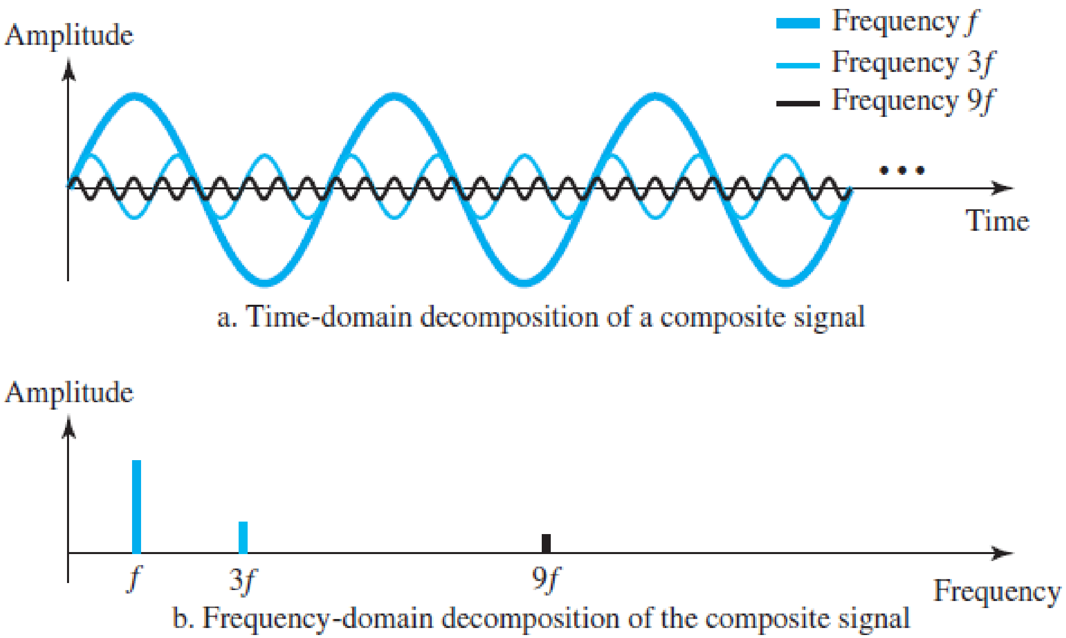

Figure 10. The Time-Domain and Frequency-Domain Plots of a Sine Wave

Bandwidth

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

Periodic Analog Signals (Continue)

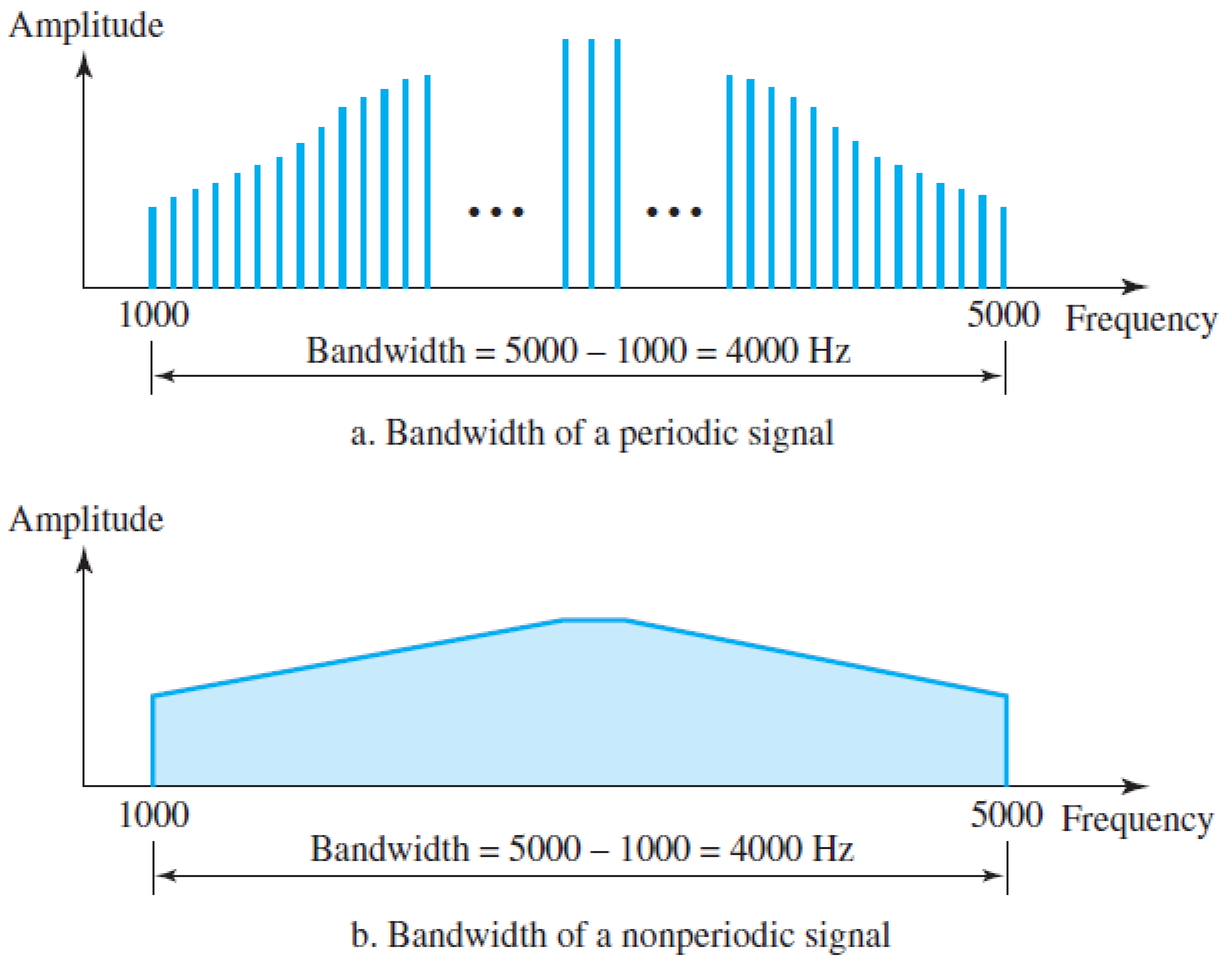

Figure 11. The bandwidth of Periodic and Nonperiodic Composite Signal

Periodic Analog Signals (Continue)

Example 5

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: $B = f_h - f_l$

$20 = 60 - f_l$

$f_l = 60 - 20 = 40$ Hz

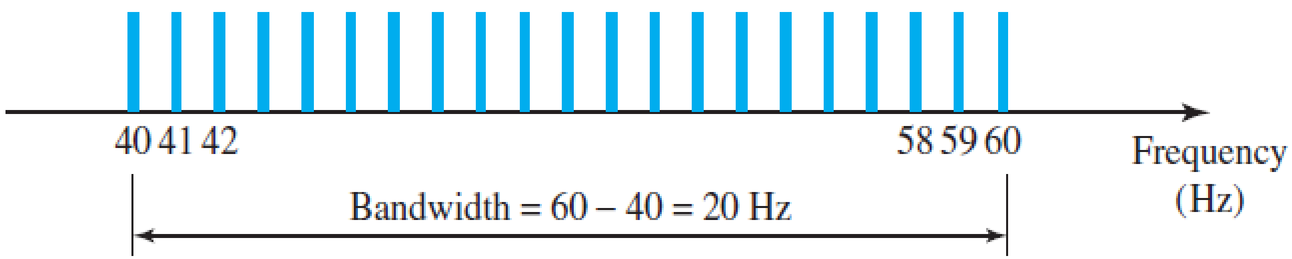

Figure 12. The Bandwidth

Periodic Analog Signals (Continue)

Example 6

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:

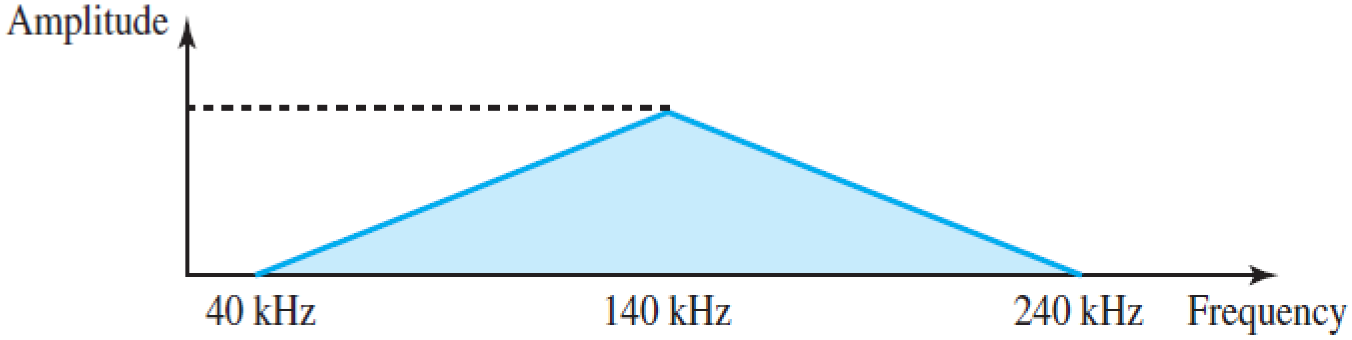

Figure 13. The Bandwidth

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, it can send more than 1 bit for each level.
- Figure 14 shows two signals, one with two levels and the other with four.
- It sends 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 $\text{Log}_2 L$ bits.
- For this reason, it can send $\text{Log}_2 4 = 2$ bits in part b.

Digital Signals (Continue)

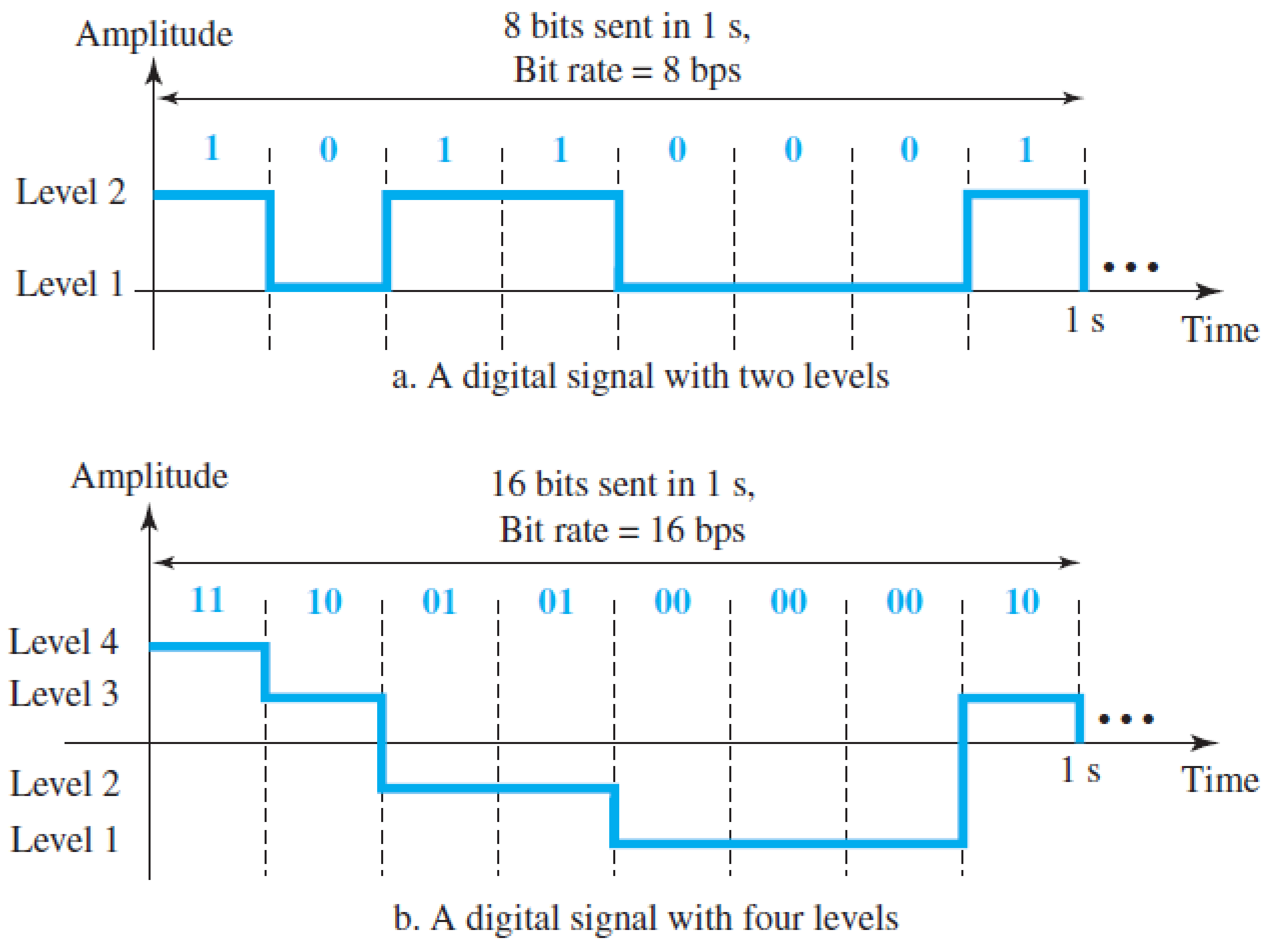

Figure 14. Two Digital Signals: One with Two Signal Levels and the Other with Four Signal Levels

Digital Signals (Continue)

Example 7

The digital signal has eight levels. How many bits are needed per level?

Solution: Number of bits per level = $\log_2 8 = 3$

Bit Rate

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

Example 8

A digitized voice channel, 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

$$2 \times 4000 \times 8 = 64,000 \text{ bps} = 64 \text{ kbps}$$

Digital Signals (Continue)

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 of Digital Signals

- A digital signal can be transmitted by using one of two different approaches: baseband transmission or broadband transmission.

Baseband Transmission

- Baseband transmission means sending a digital signal over a channel without changing the digital signal to an analog signal.
- Figure 15 shows baseband transmission.

Digital Signals (Continue)

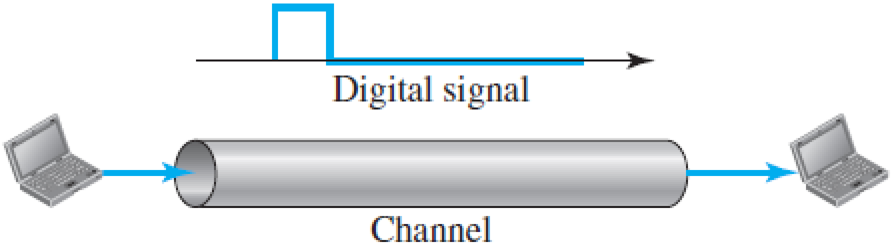

Figure 15. Baseband Transmission

- Baseband transmission requires that it has a low-pass channel, a channel with a bandwidth that starts from zero.
- Figure 16 shows two low-pass channels: one with a narrow bandwidth and the other with a wide bandwidth.

Digital Signals (Continue)

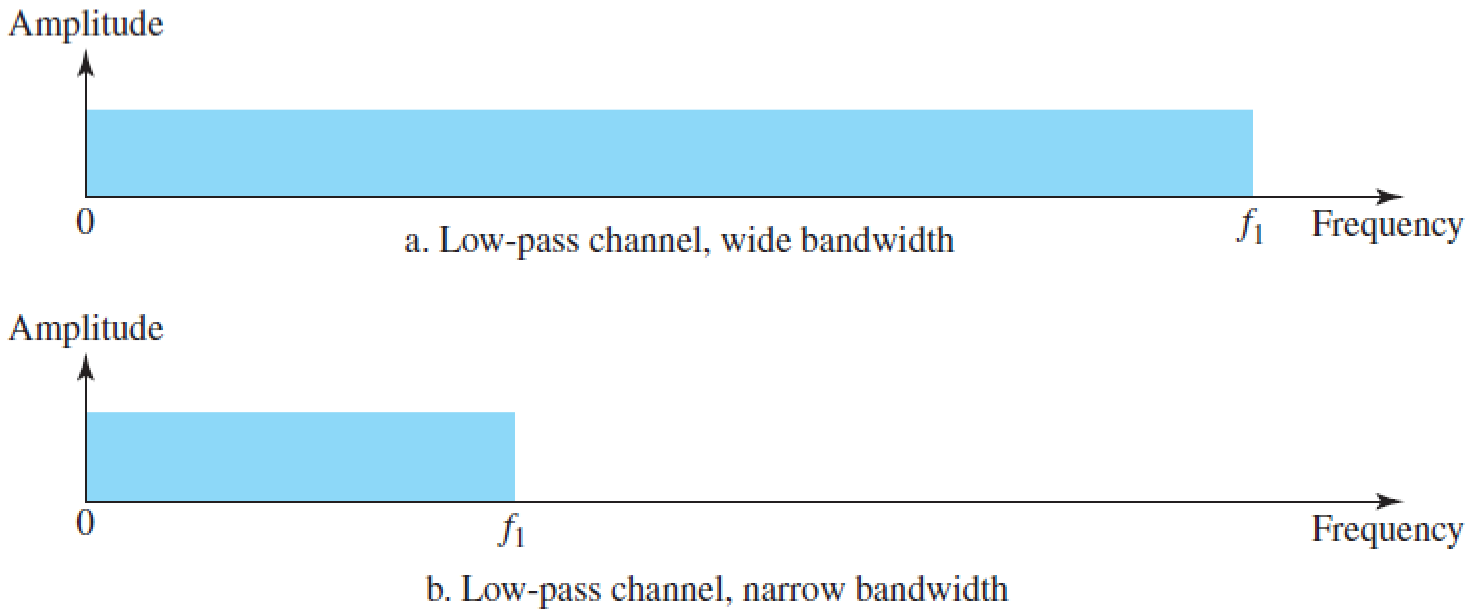

Figure 16. Bandwidths of Two Low-Pass Channels

Digital Signals (Continue)

Broadband Transmission (Using Modulation)

- Broadband transmission or modulation means changing the digital signal to an analog signal for transmission.
- Modulation allows 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.
- Figure 17 shows a bandpass channel.

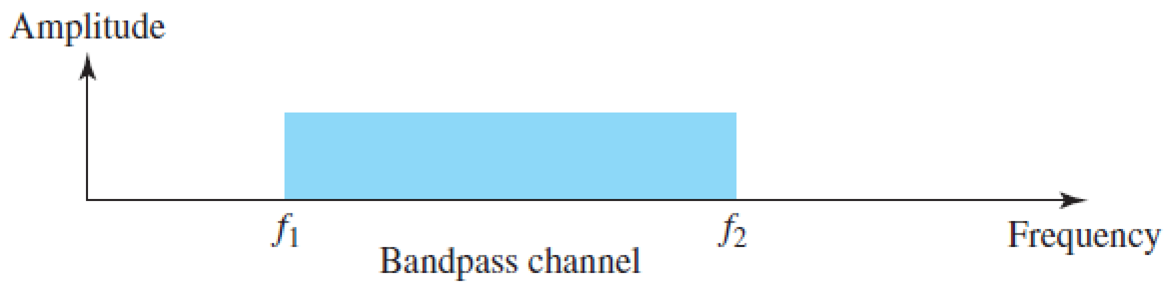

Figure 17. Bandwidth of a Bandpass Channel

Digital Signals (Continue)

- Figure 18 shows the modulation of a digital signal.
- In this figure, a digital signal is converted to a composite analog signal.

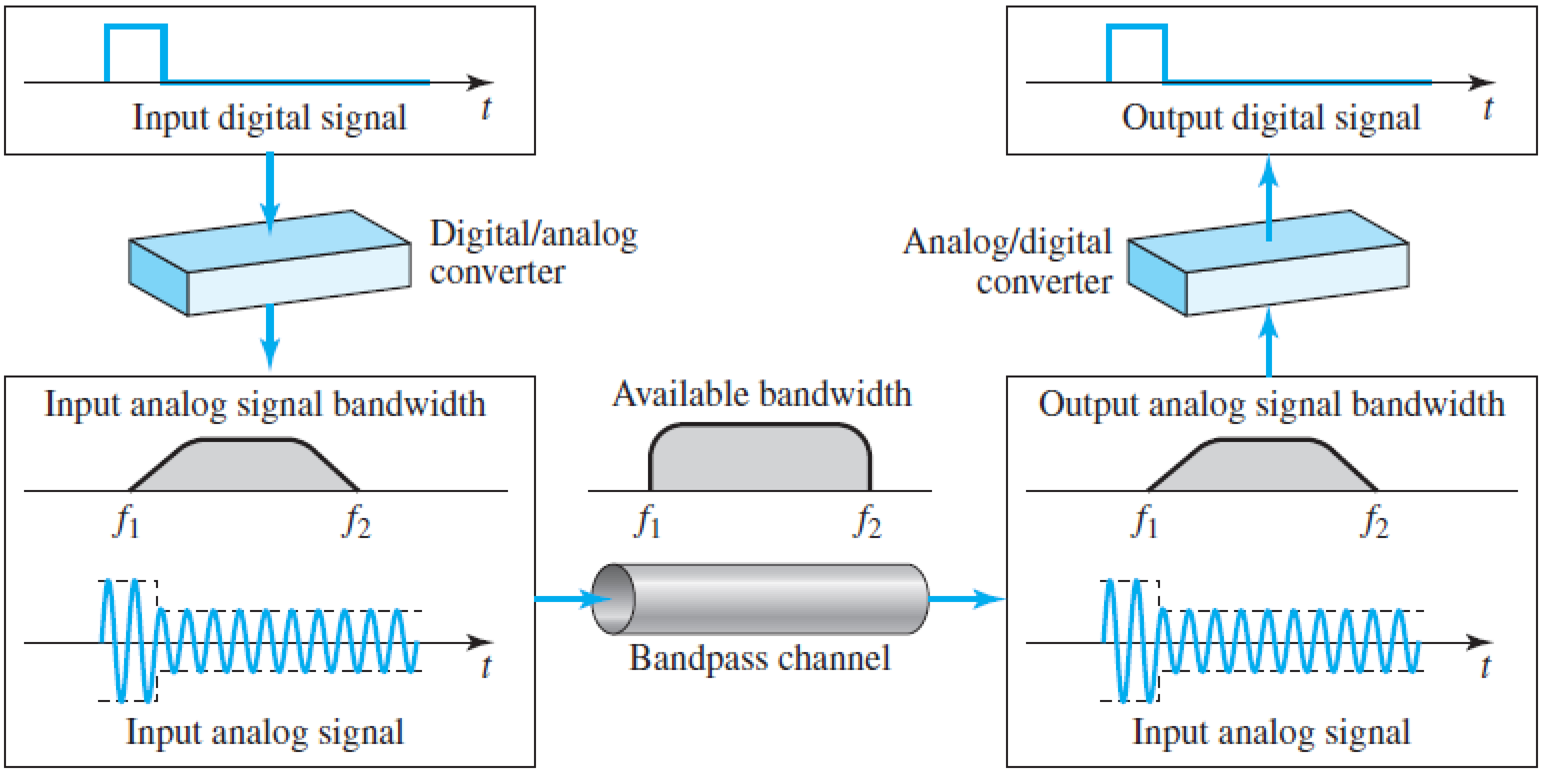

Figure 18. Modulation of A Digital Signal for Transmission on A Bandpass Channel

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 as shown in figure 19.

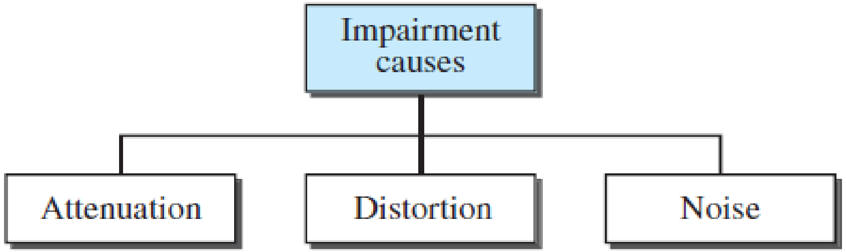

Figure 19. Causes of Impairment

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.

Transmission Impairment (Continue)

- That is why a wire carrying electric signals gets warm, if not hot, after a while.
- Some of the electrical energy in the signal is converted to heat.
- To compensate for this loss, amplifiers are used to amplify the signal.
- Figure 20 shows the effect of attenuation and amplification.

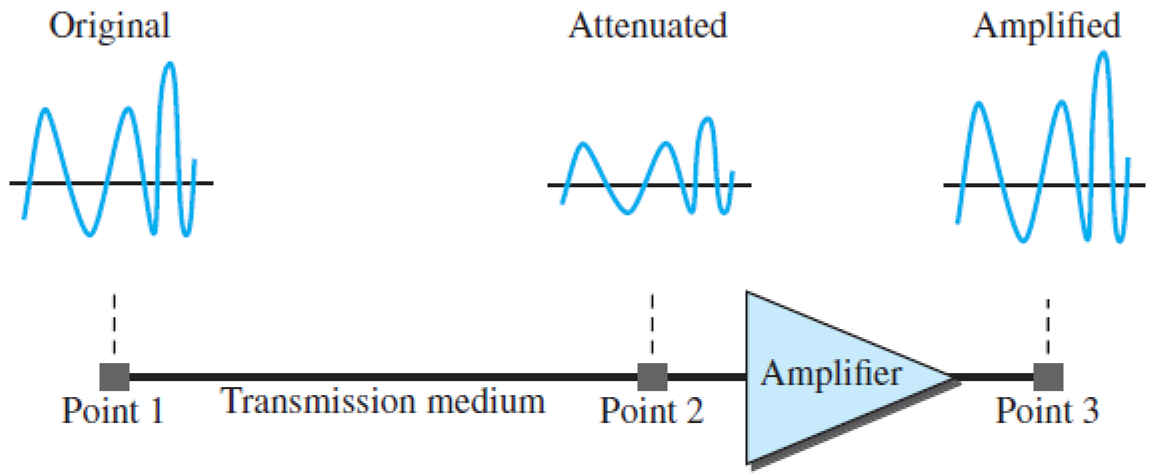

Figure 20. Attenuation

Transmission Impairment (Continue)

- The decibel (dB) measures the relative strengths of two signals or one signal at two different points.

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

- Variables P1 and P2 are the powers of a signal at points 1 and 2, respectively.

Example 9

Suppose a signal travels through a transmission medium and its power is reduced to one-half. This means that P2 = ½ P1. In this case, the attenuation (loss of power) can be calculated as

Solution: $10\ log_{10}\frac{P_2}{P_1} = 10\ log_{10}\frac{0.5P_1}{P_1}$

$= 10\ log_{10}0.5$

= - 3dB

Transmission Impairment (Continue)

Example 10

A signal travels through an amplifier, and its power is increased 10 times. This means that $P2 = 10P1$. In this case, the amplification (gain of power) can be calculated as

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

$$= 10\ log_{10} 10$$

$$= 10 \text{ dB}$$

Distortion

- Distortion means that the signal changes its form or shape.
- Distortion can occur in a composite signal made of different frequencies as shown in figure 21 .

Transmission Impairment (Continue)

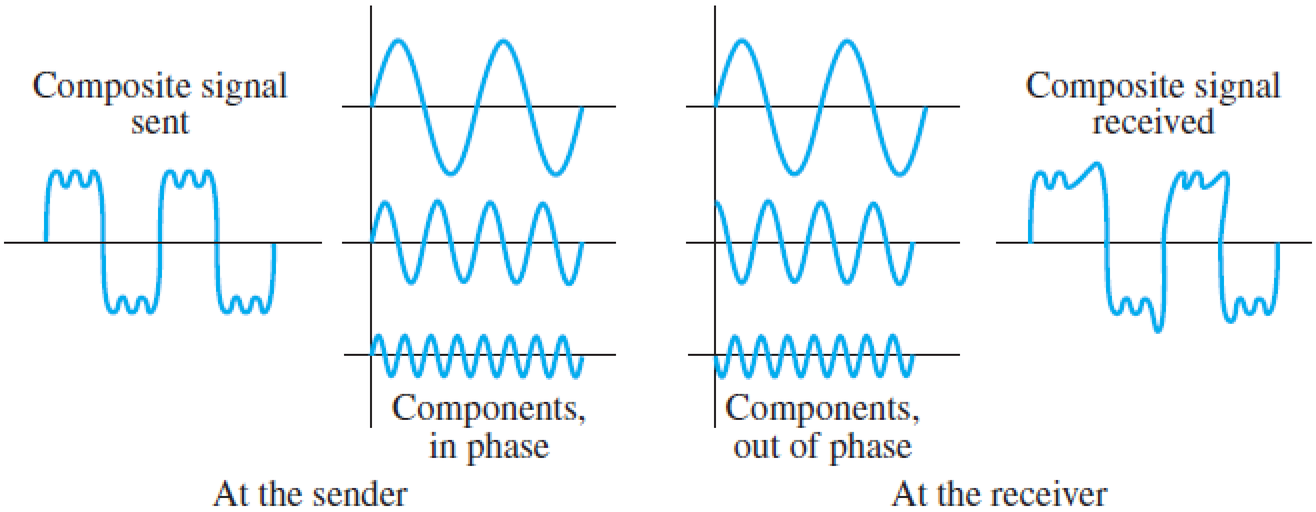

Figure 21. Distortion

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.

Transmission Impairment (Continue)

- Induced noise comes from sources such as motors and appliancses.
- 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 22 shows the effect of noise on a signal.

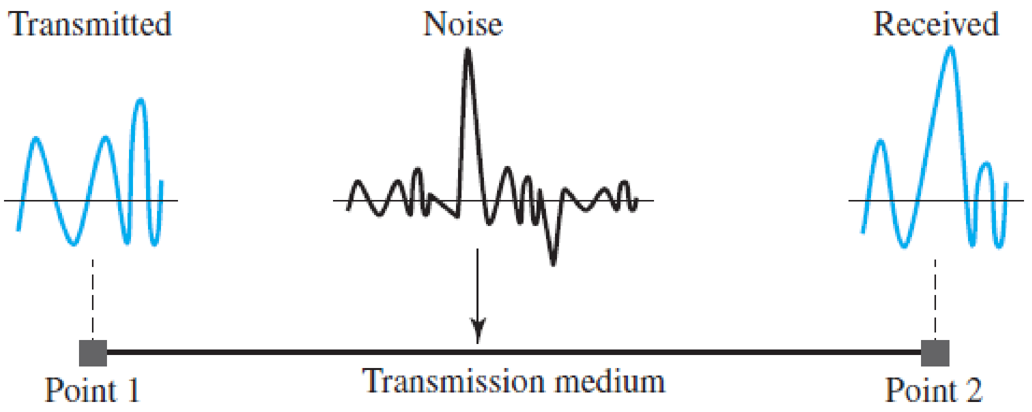

Figure 22. Noise

Transmission Impairment (Continue)

Signal-to-Noise Ratio (SNR)

- The signal-to-noise ratio is defined as

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

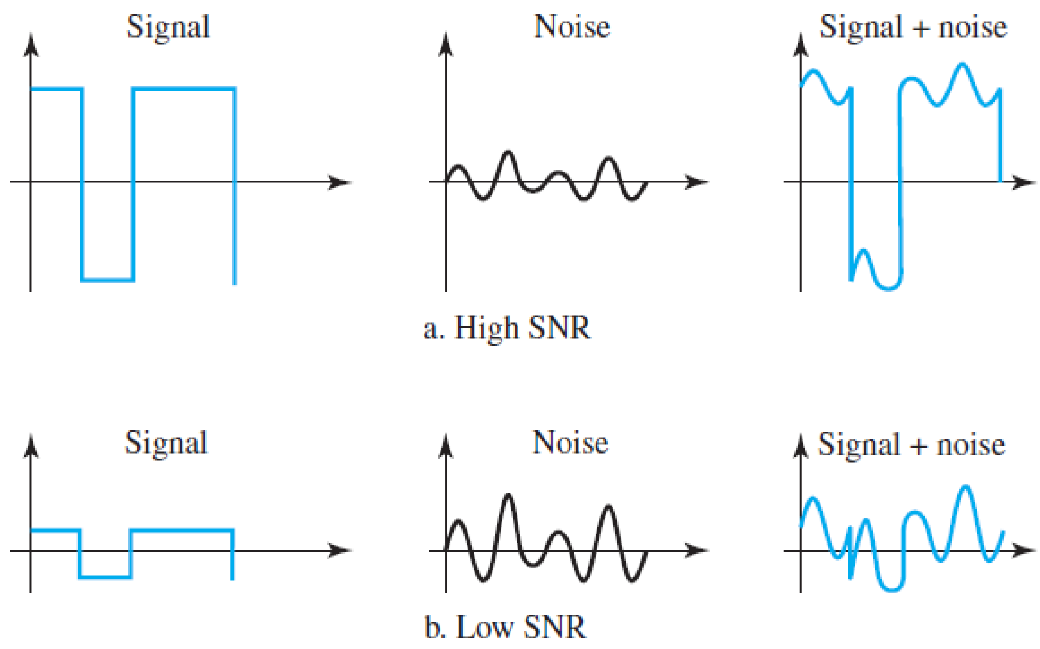

Figure 23. Two Cases of SNR: A High SNR and A Low SNR

Transmission Impairment (Continue)

- Because SNR is the ratio of two powers, it is often described in decibel units, SNR_{dB} , defined as

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

Example 11

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:

$$SNR = (10{,}000\ \mu w)/(1\mu w)$$

$$= 10{,}000$$

$$SNR_{dB} = 10\log_{10} 10{,}000$$

$$= 10\log_{10} 10^4$$

$$= 40$$

Data Rate Limits

- A very important consideration in data communications is how fast data can be sent, in bits per second, over a channel.
- Data rate depends on three factors:

  1. The bandwidth available

  2. The level of the signals we use

  3. The quality of the channel (the level of noise)
- Two theoretical formulas were developed to calculate the data rate: one by Nyquist for a noiseless channel, another by Shannon for a noisy channel.

Data Rate Limits (Continue)

Noiseless Channel: Nyquist Bit Rate

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

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

- Where, bandwidth is the bandwidth of the channel

  L is the number of signal levels used to represent data

  BitRate is the bit rate in bits per second
- Increasing the levels of a signal may reduce the reliability of the system.

Example 12

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

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

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

Data Rate Limits (Continue)

Noisy Channel: Shannon Capacity

- The shannon capacity, to determine the theoretical highest data rate for a noisy channel:

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

- Where, bandwidth is the bandwidth of the channel

  SNR is the signal-to-noise ratio

  capacity is the capacity of the channel in bits per second

Example 13

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 C is calculated as

Solution: $C = B \log_2 (1 + \text{SNR})$

$= 3000 \log_2 (1 + 3162)$

$= 3000 \times 11.62 = 34{,}860$ bps

Performance

- There are five performances in the network: bandwidth, throughput, latency, bandwidth-delay product and jitter.

Bandwidth

- One characteristic that measures network performance is bandwidth.

- However, the term can be used in two different contexts with two different measuring values: bandwidth in hertz and bandwidth in bits per second.

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

- Bandwidth in bits per second, refers to the speed of bit transmission in a channel or link.

Performance (Continue)

Throughput

- The throughput is a measure of how fast data can actually be sent through a network.

Example 14

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: Throughput = $(12000 \times 10000)/60 = 2$ 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.

Performance (Continue)

- Latency is made of four components: propagation time, transmission time, queuing time and processing delay.

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

Propagation Time

- Propagation time measures the time required for a bit to travel from the source to the destination.

Propagation time = Distance / (Propagation Speed)

Example 15

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

Performance (Continue)

Transmission Time

- 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 16

What are the propagation time and the transmission time for a 2.5-KB (kilobyte) message (an email) 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 2.4×10^8 m/s.

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

Transmission time = $(2500 \times 8) / 10^9 = 0.02$ ms

Performance (Continue)

Queuing Time

- The third component in latency is the queuing time, the time needed for each intermediate or end device to hold the message before it can be processed.

Bandwidth-Delay Product

- The bandwidth-delay product defines the number of bits that can fill the link.

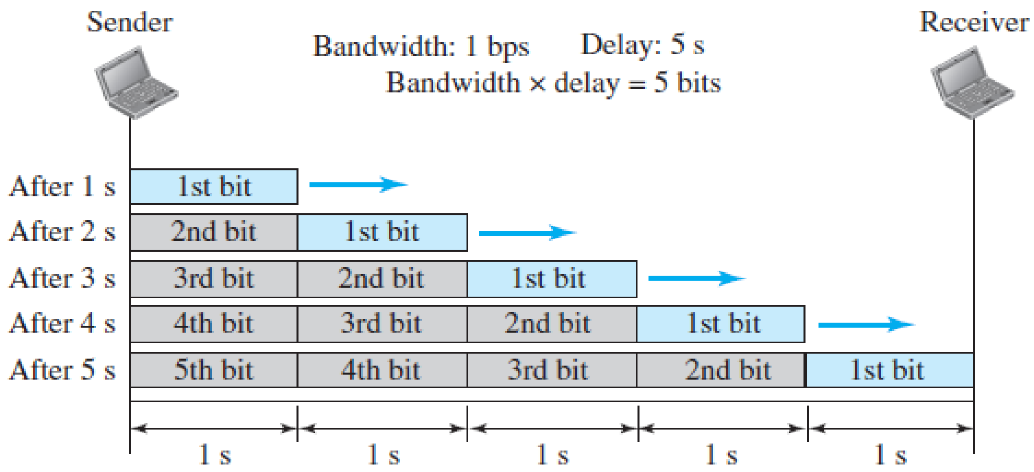

Figure 24. Filling the Link with Bits for Case 1

Performance (Continue)

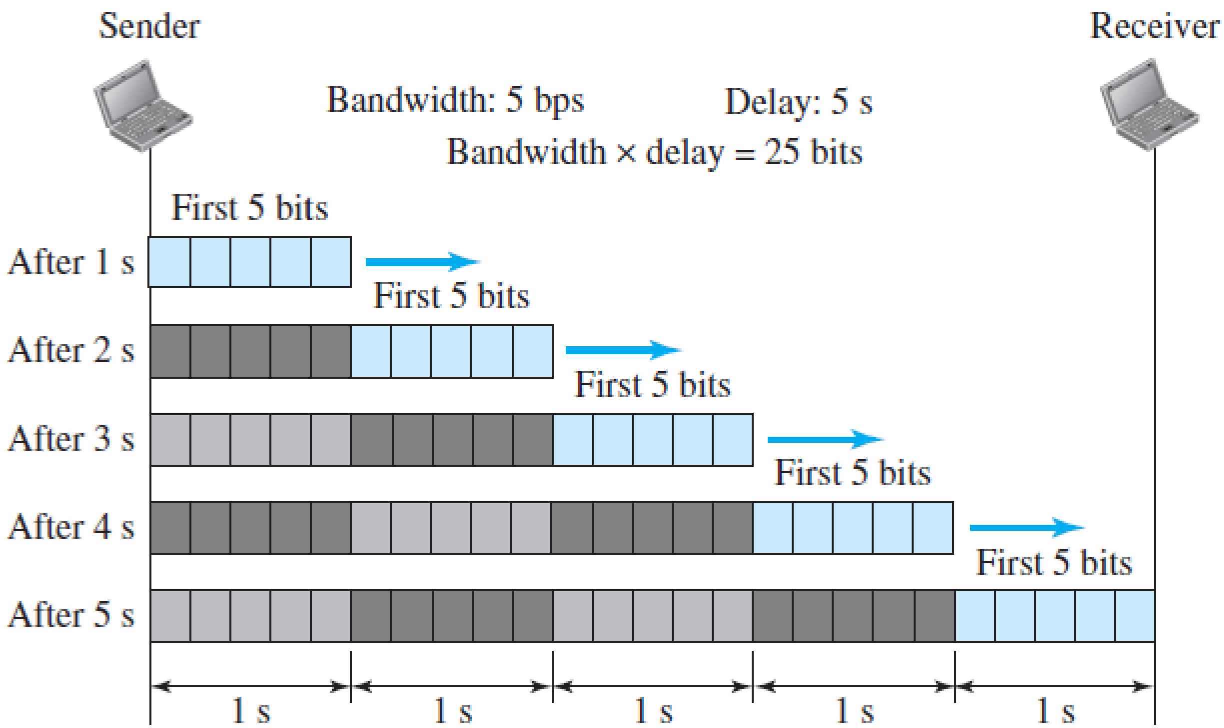

Figure 25. Filling the Link with Bits for Case 2

Jitter

- Another performance issue that is related to delay is jitter.

Questions for Topic 1

1. Answer the following questions.

   a. What is the relationship between period and frequency?

   b. What does the amplitude of a signal measure? What does the frequency of a signal measure? What does the phase of a signal measure?

   c. How can a composite signal be decomposed into its individual frequencies?

   d. Name three types of transmission impairment.

   e. Distinguish between baseband transmission and broadband transmission.

   f. Distinguish between a low-pass channel and a band-pass channel.

Next Week Lecture

- Digital Transmission
  - Digital-to-Digital Conversion
  - Analog-to-Digital Conversion
  - Transmission Modes
- Analog Transmission
  - Digital-to-Analog Conversion
  - Analog-to-Analog Conversion

Thank You