Chapter 2

Physical Layer

Prepared by :

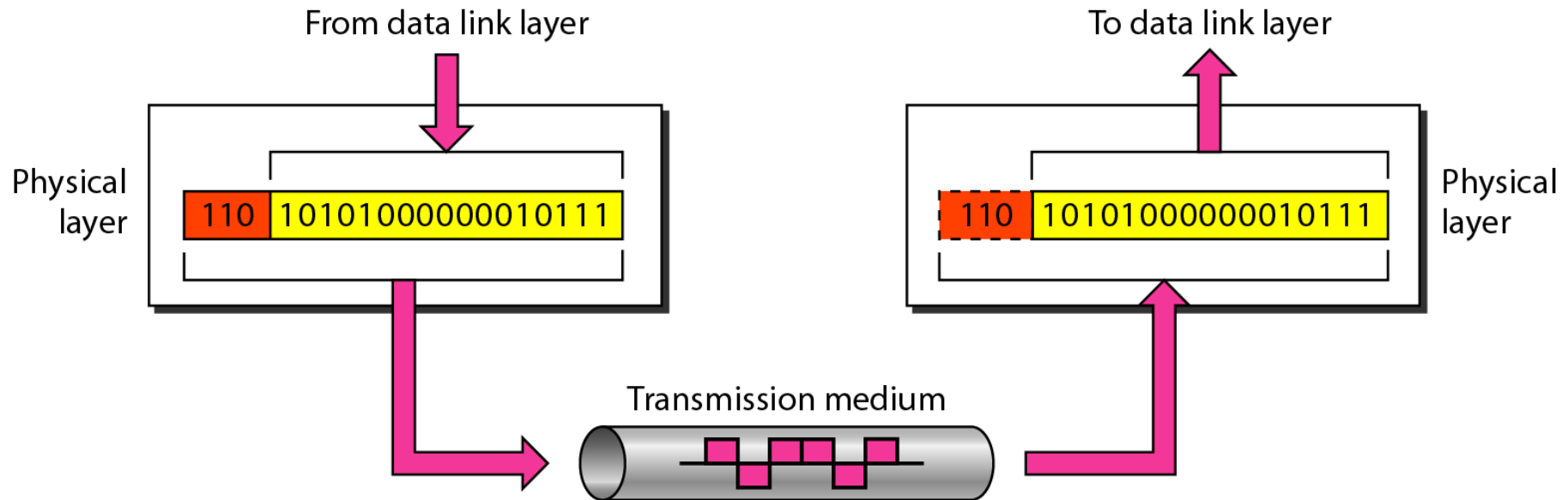## *Dr. Adel Soudani & Dr. Mznah Al-Rodhaan*

Outline

❑ 2.1 Analog and Digital

❑ 2.2 Transmission Media

❑ 2.3 Digital Modulation and Multiplexing

❑ 2.4 Transmission Impairment

❑ 2.5 Data-rate Limits

❑ 2.6 Performance

Lecture 1

Physical layer

Main functions of the physical layer
- Coding /decoding signals
- Modulation/Demodulation
- Adaptation of the signal to the physical medium properties

Data can be analog or digital

❑ Analog data refers to information that is continuous

❑ Analog data take on continuous values

❑ Analog signals can have an infinite number of values in a range

❑ Digital data refers to information that has discrete states

❑ Digital data take on discrete values

❑ Digital signals can have only a limited number of values

In data communications, we commonly use
periodic analog signals and nonperiodic digital signals.

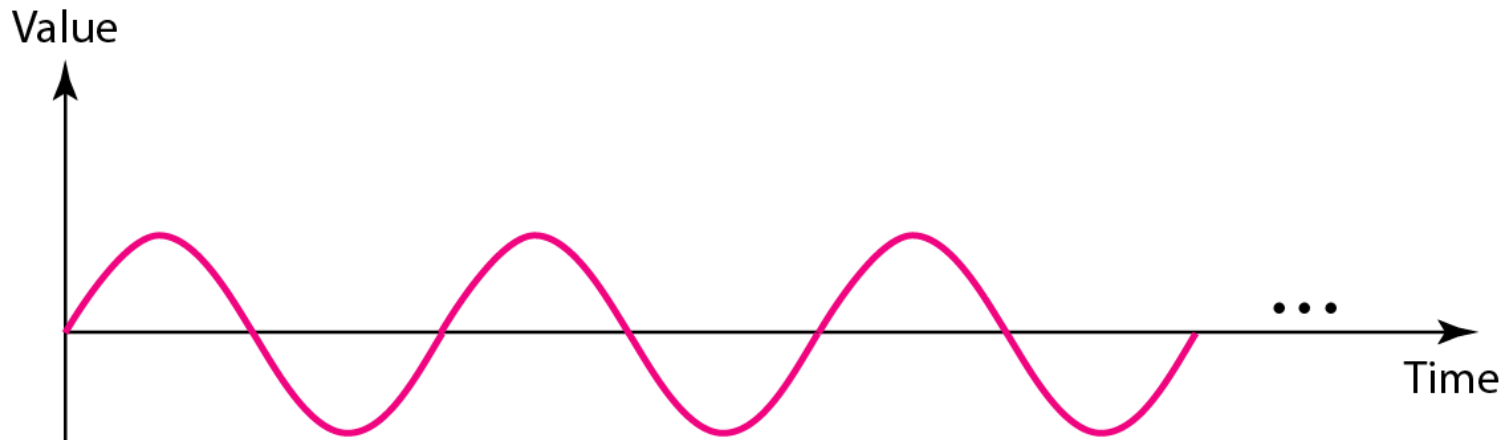# Comparison of analog and digital signals
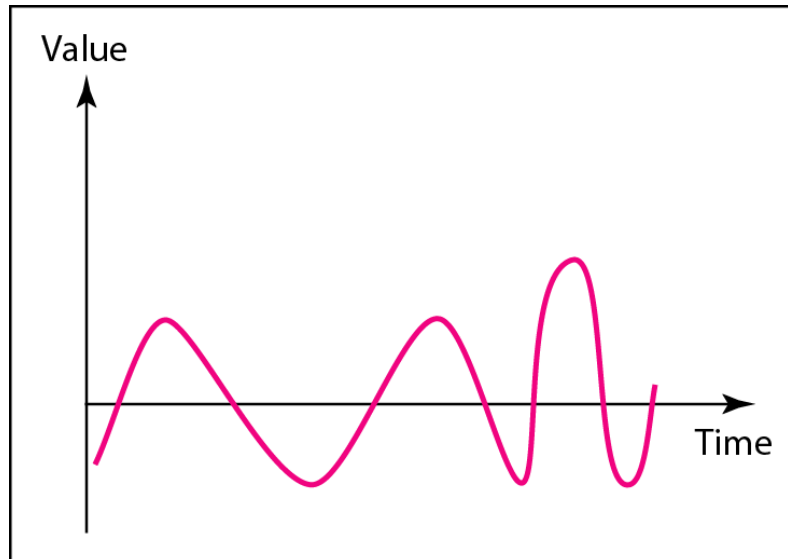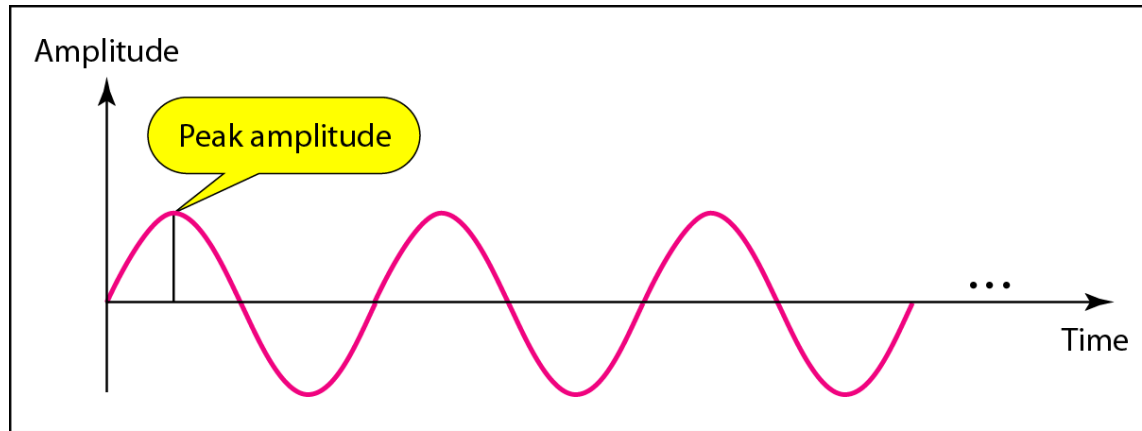

a. Analog signal
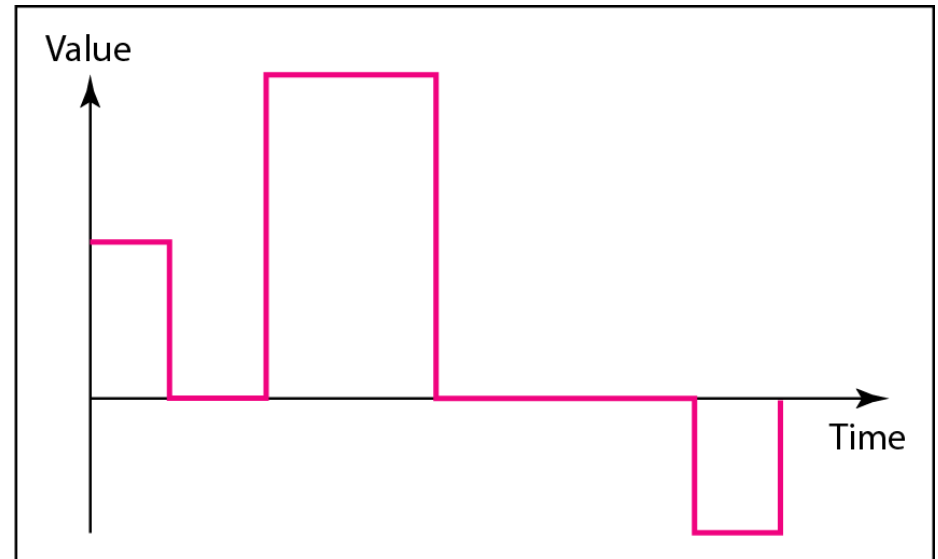
b. Digital signal

PERIODIC ANALOG SIGNALS

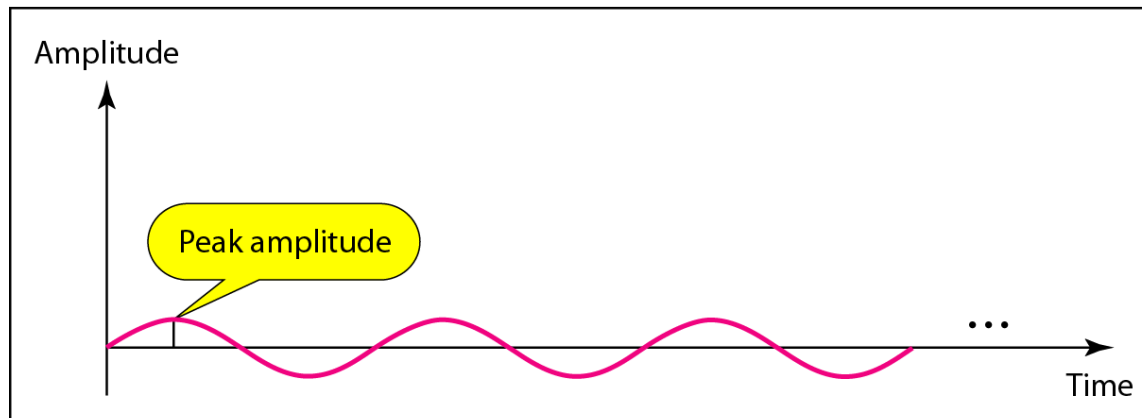*Periodic analog signals can be classified as simple or composite.*

❑ 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.

Signal amplitude

a. A signal with high peak amplitude

b. A signal with low peak amplitude

Frequency تردد

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.

Frequency and Period

Frequency and period are the inverse of each other.

$$f = \frac{1}{T} \text{ HZ} \quad \text{and} \quad T = \frac{1}{f} \text{ s}$$
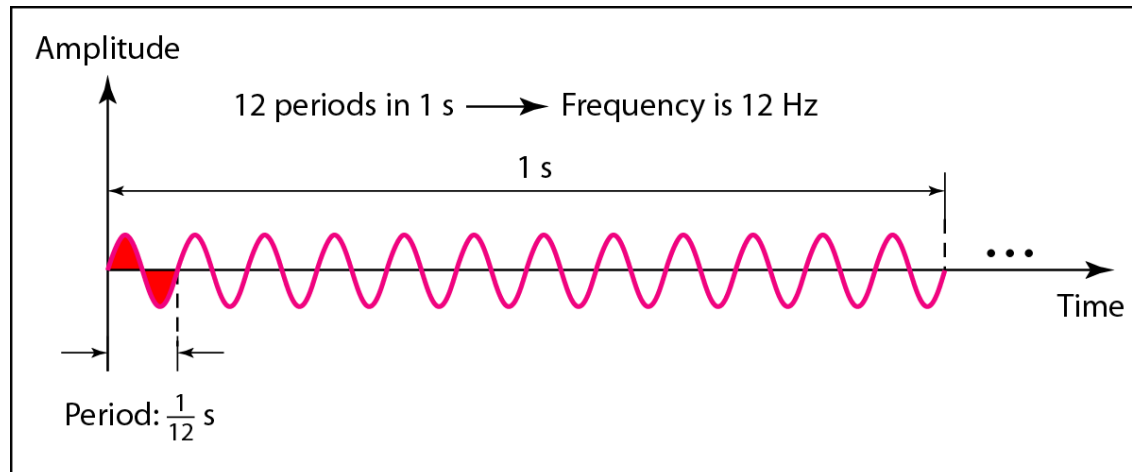
F = P / T

T = P / F

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

Two signals with the same amplitude, but different frequencies

P / F

F = P / T

Amplitude

12 periods in 1 s ⟶ Frequency is 12 Hz

1 s

... Time

Period: $\frac{1}{12}$ s

a. A signal with a frequency of 12 Hz

Amplitude

6 periods in 1 s ⟶ Frequency is 6 Hz

1 s

... Time

T

Period: $\frac{1}{6}$ s
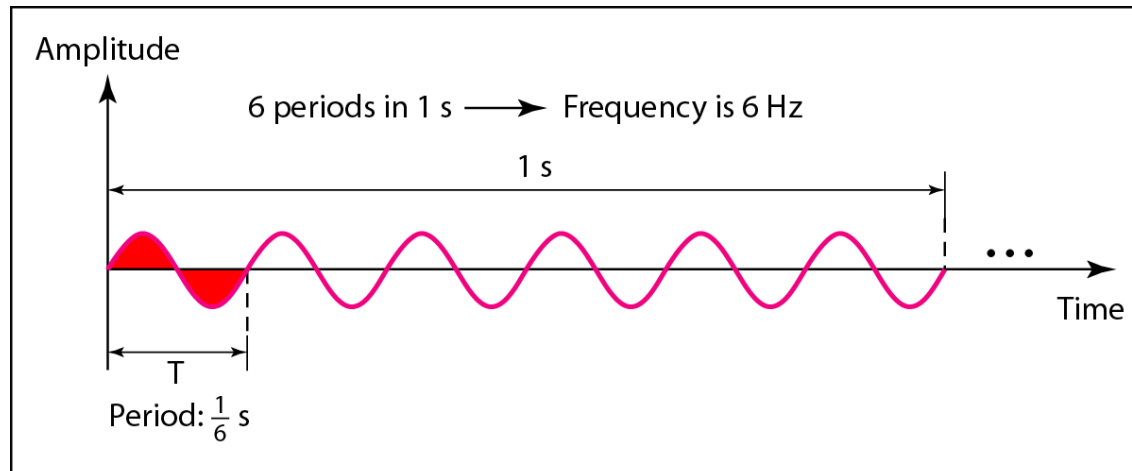
b. A signal with a frequency of 6 Hz

Examples

The power we use at home has a frequency of *60 Hz*. What is the period of this sine wave ?

$$T = \frac{1}{f} = \frac{1}{60} = 0.0166 \text{ s} = 0.0166 \times 10^3 \text{ ms} = 16.6 \text{ ms}$$
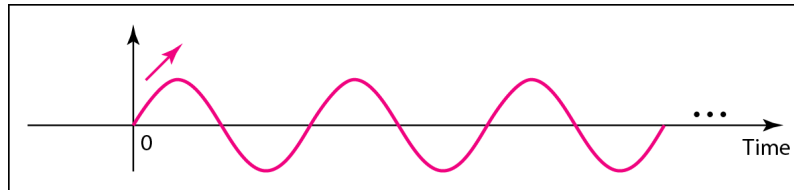
The period of a signal is 100 ms. What is its frequency in kilohertz?

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

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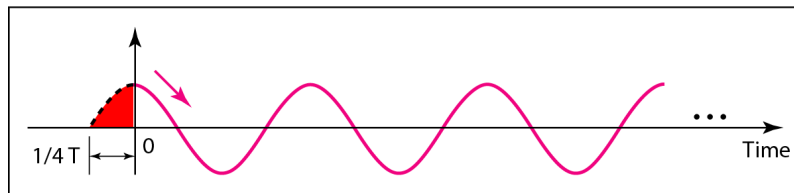
Phase

Phase describes the position of the waveform relative to time 0
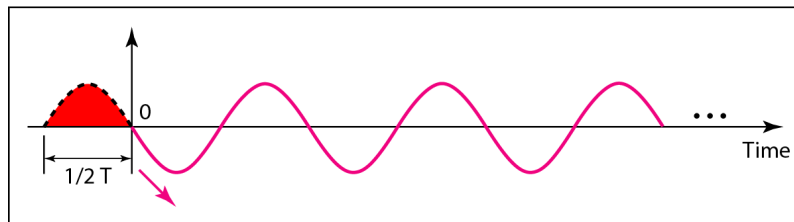
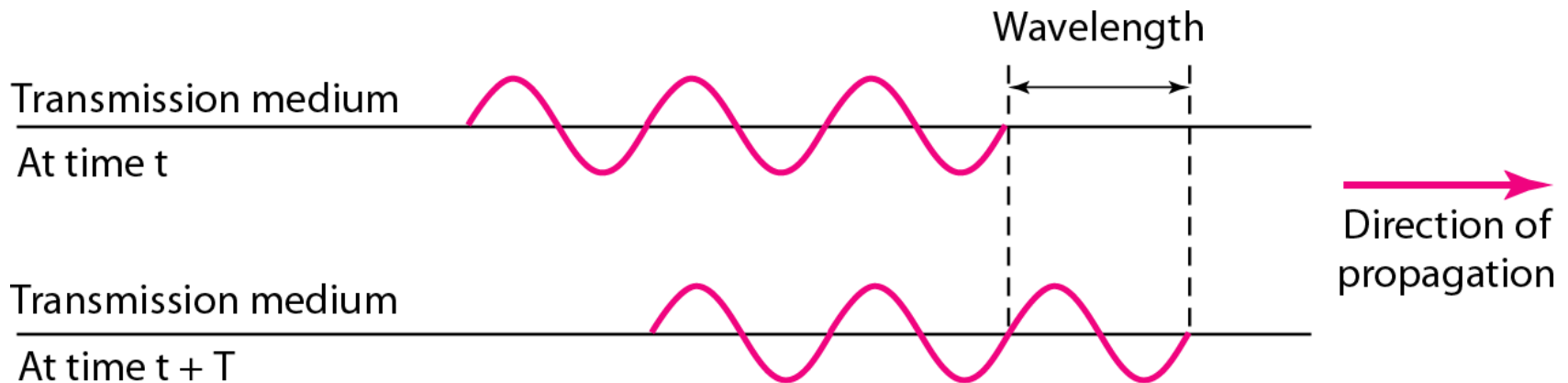Three sine waves with the same amplitude and frequency, but different phases
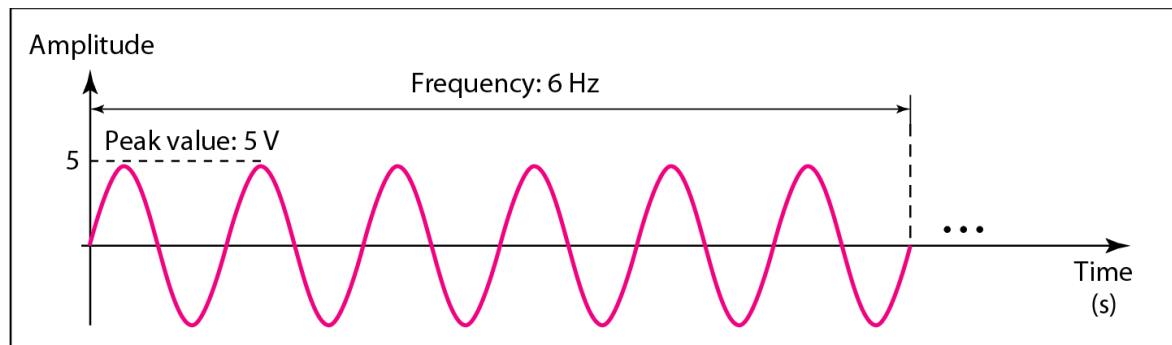
a. 0 degrees

b. 90 degrees

c. 180 degrees

Wavelength and period

Wavelength = Propagation speed x Period
= Propagation speed / Frequency

Time-domain and *frequency-domain* plots of a sine wave

A complete sine wave in the time domain can be represented by one single spike in the frequency domain.

Amplitude

Frequency: 6 Hz

Peak value: 5 V

5

Time (s)

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

Amplitude

Peak value: 5 V

5

1 2 3 4 5 6 7 8 9 10 11 12 13 14
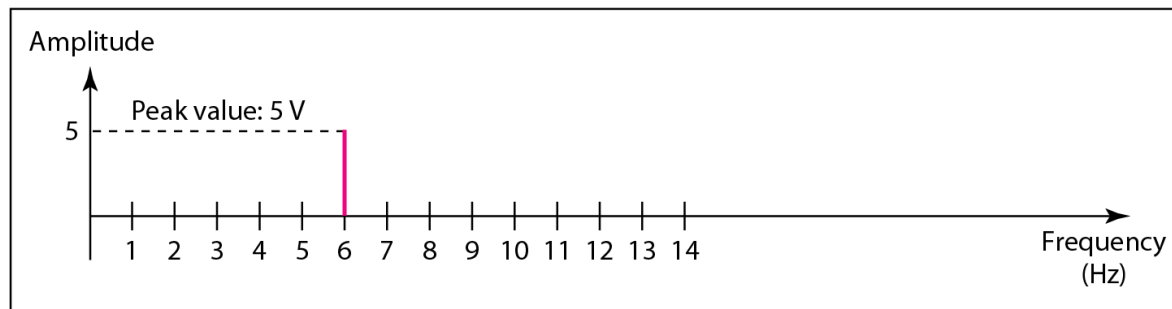
Frequency (Hz)

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

Frequency Domain
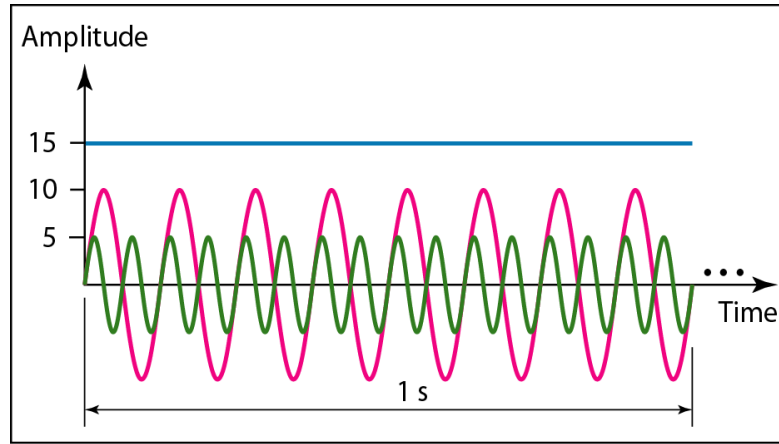
a. Time-domain representation of three sine waves with frequencies 0, 8, and 16
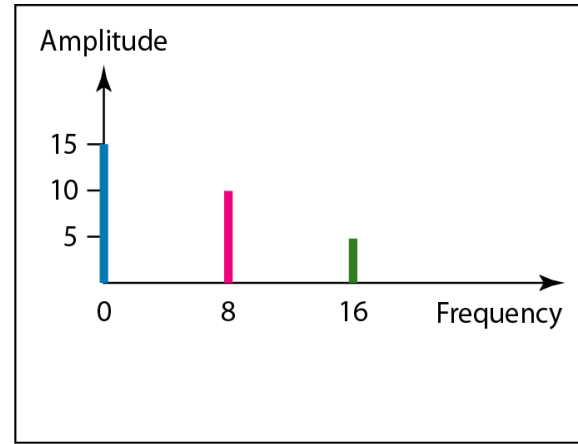
b. Frequency-domain representation of the same three signals

❑ The frequency domain is more compact and useful when we are dealing with more than one sine wave.

❑ A single-frequency sine wave is not useful in data communication
  ○ We need to send a composite signal, a signal made of many simple sine waves.

Fourier analysis

According to Fourier analysis,
any composite signal is a combination of simple sine
waves with different frequencies, amplitudes, and phases.

❑ 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*.

A composite periodic signal

Amplitude

Frequency f
Frequency 3f
Frequency 9f
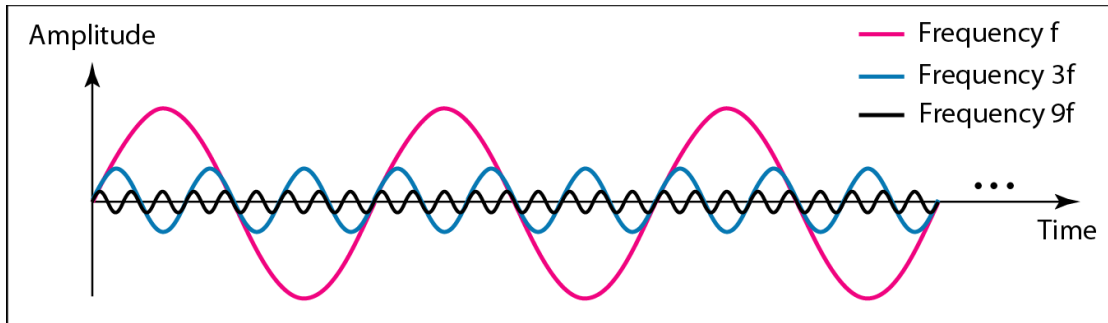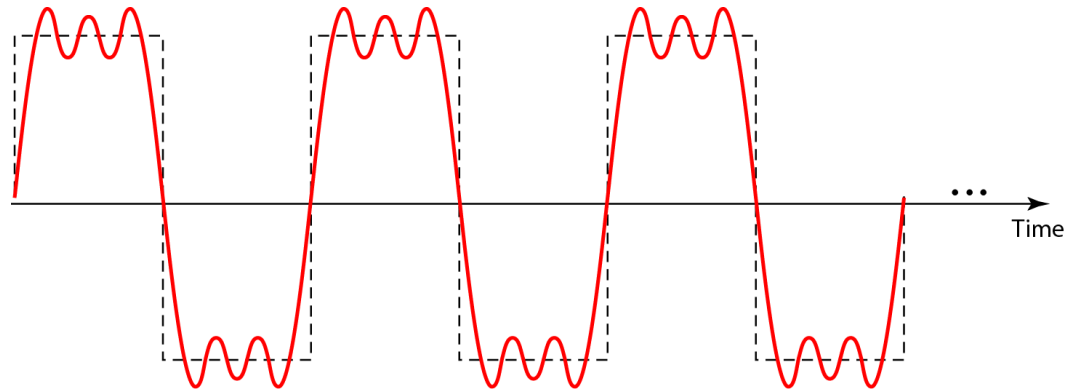
Time

a. Time-domain decomposition of a composite signal

Amplitude

f   3f   9f   Time
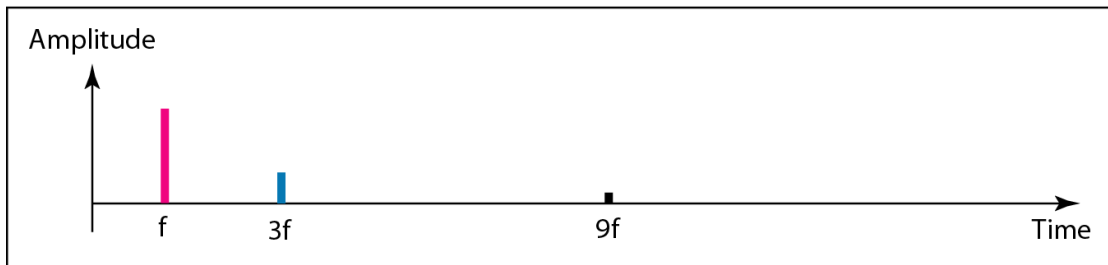
b. Frequency-domain decomposition of the composite signal

Decomposition of the composite periodic signal in the time and frequency domains

Time and frequency domains of a nonperiodic signal

❑ A nonperiodic composite signal

  ○ It can be a signal created by a microphone or a telephone set when a word or two is pronounced.

  ○ In this case, the composite signal cannot be periodic

    ➤ because that implies that we are repeating the same word or words with exactly the same tone.
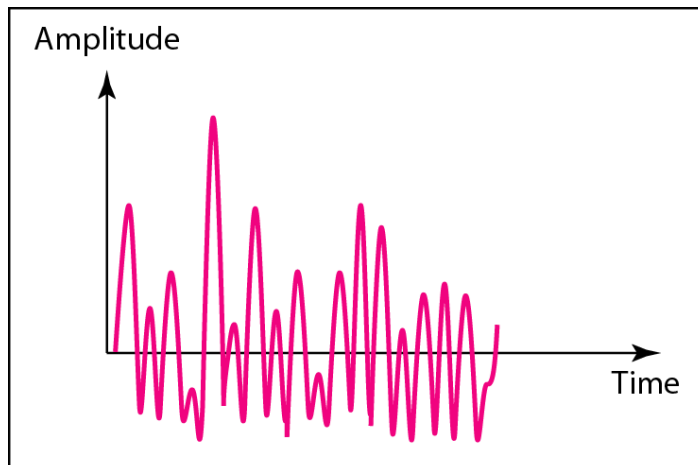
a. Time domain
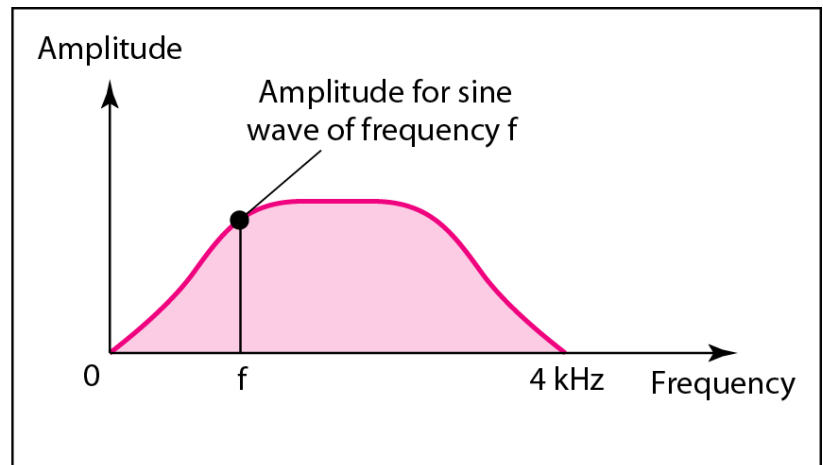
b. Frequency domain

Bandwidth

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

Amplitude

1000   5000   Frequency

Bandwidth = 5000 - 1000 = 4000 Hz
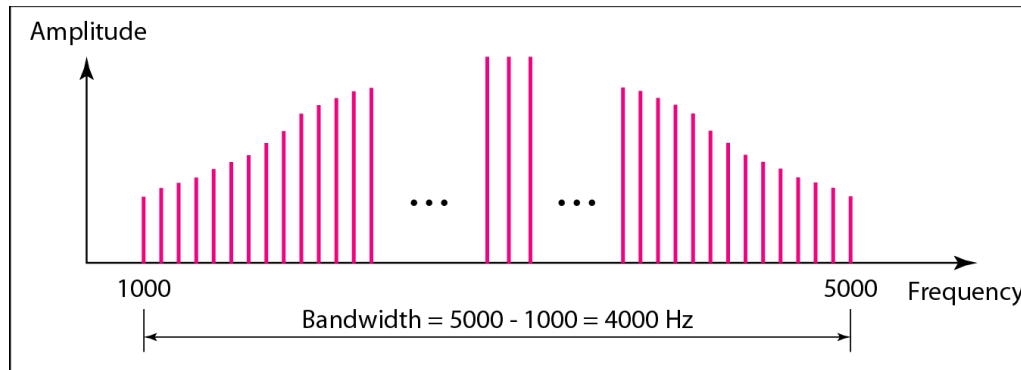
a. Bandwidth of a periodic signal

Amplitude

1000   5000   Frequency

Bandwidth = 5000 - 1000 = 4000 Hz
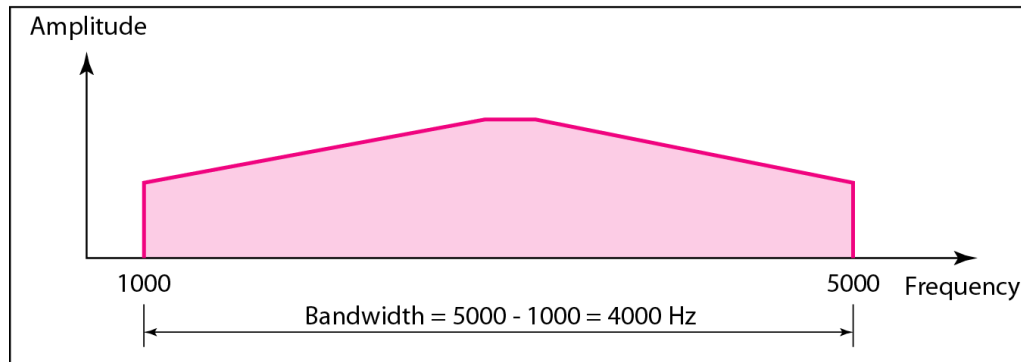
b. Bandwidth of a nonperiodic signal

Example

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.
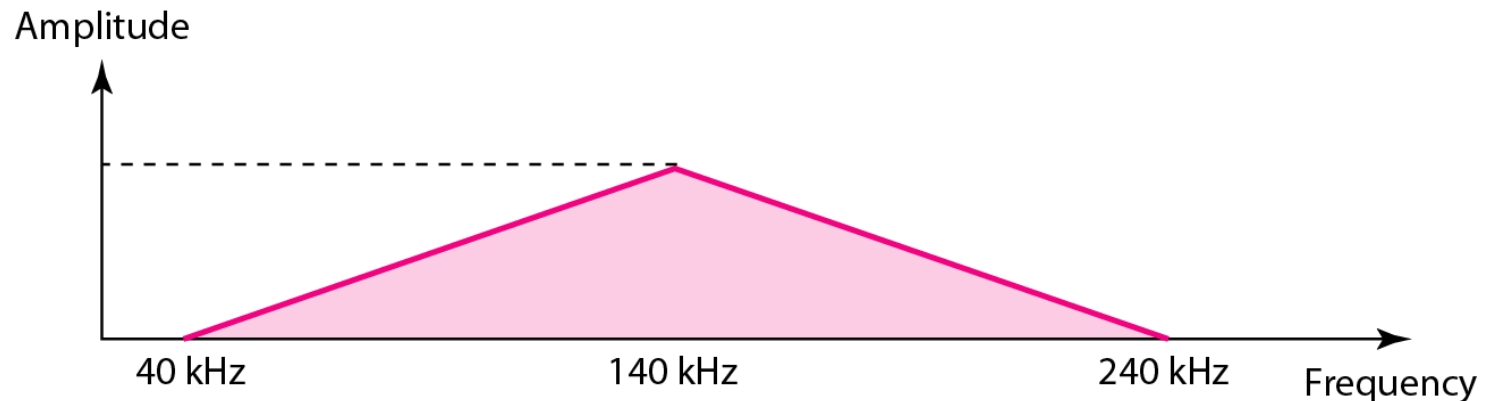
Lecture 2

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.

Two digital signals: one with two signal levels and the other with four signal levels
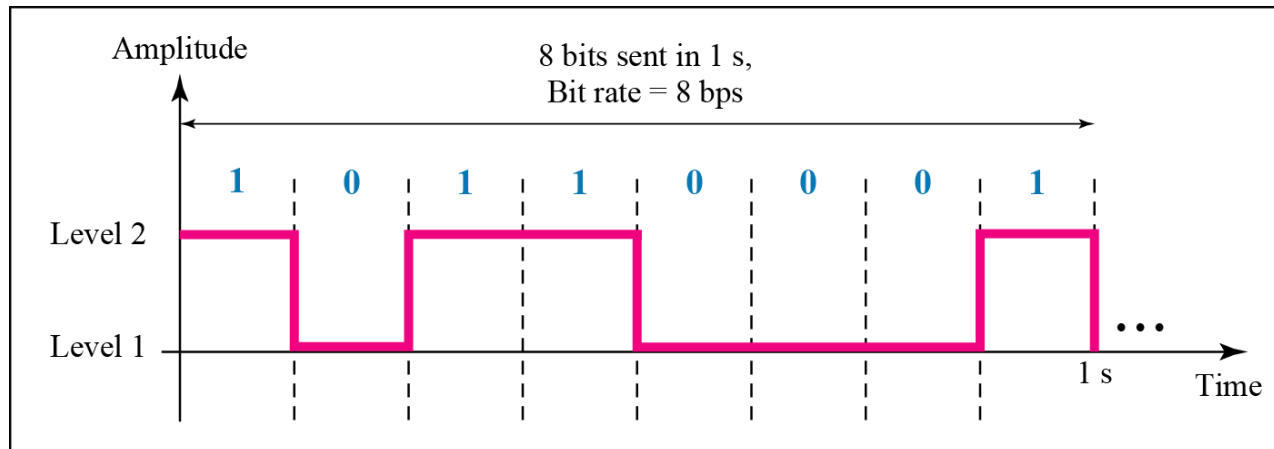
a. A digital signal with two levels
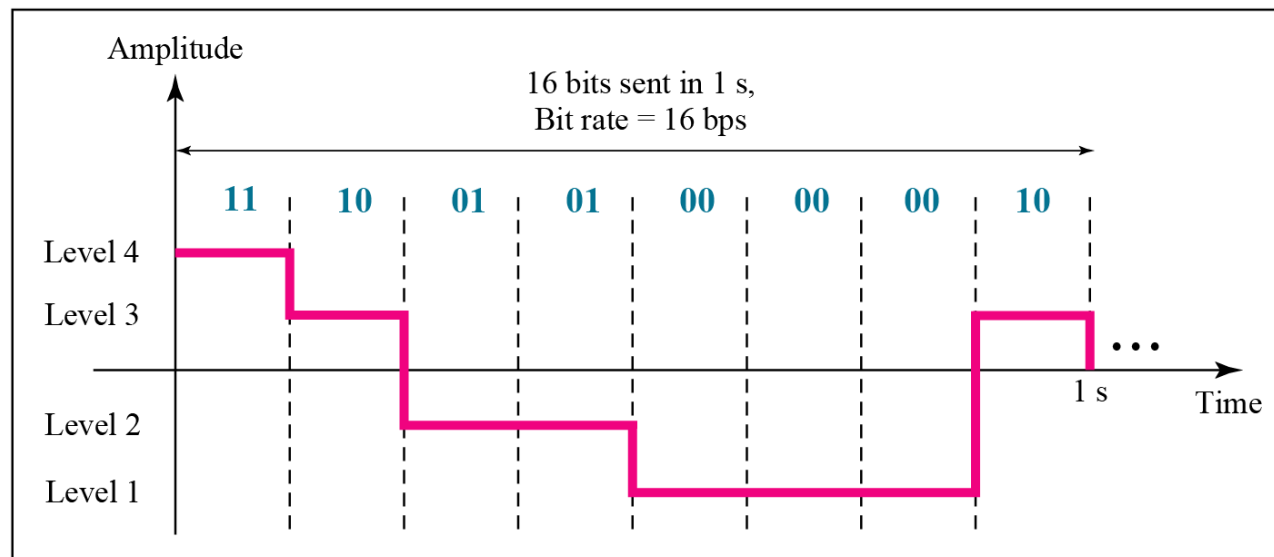
b. A digital signal with four levels

Examples

A digital signal has 8 levels. How many bits are needed per level?

We calculate the number of bits from the formula

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

Each signal level is represented by 3 bits.

A digital signal has 9 levels. How many bits are needed per level?

Each signal level is represented by 3.17 bits.
The number of bits sent per level needs to be an integer as well as a power of 2.
Hence, 4 bits can represent one level.

Examples

Assume we need to download files at a rate of 100 pages per minute. A page is an average of 24 lines with 80 characters in each line where one character requires 8 bits. What is the required bit rate of the channel?

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

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). Assume that each sample requires 8 bits. What is the required bit rate?

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

Example

HDTV uses digital signals to broadcast high quality video signals. There are 1920 by 1080 pixels per screen, and the screen is renewed 30 times per second. Also, 24 bits represents one color pixel.

What is the bit rate for high-definition TV (HDTV)?

$$1920 \times 1080 \times 30 \times 24 = 1{,}492{,}992{,}000 \text{ or } 1.5 \text{ Gbps}$$

The TV stations reduce this rate to 20 to 40 Mbps through compression.

The time and frequency domains of periodic and nonperiodic digital signals
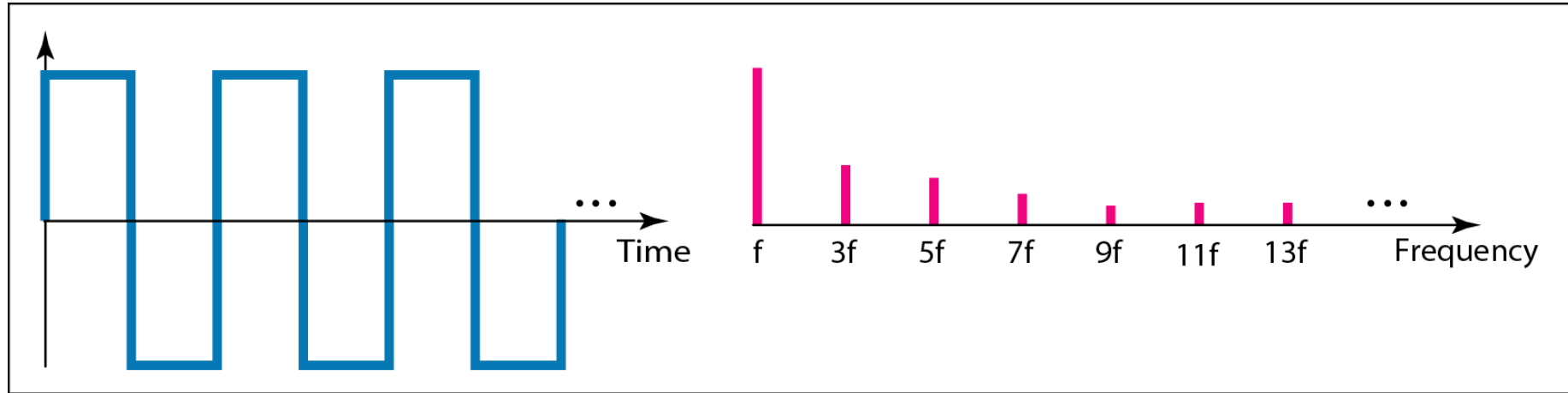
a. Time and frequency domains of periodic digital signal
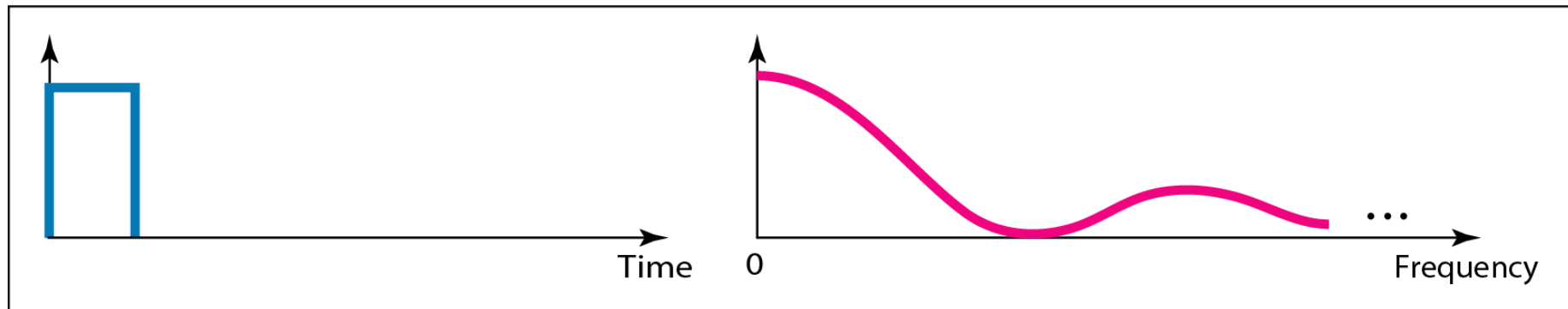
b. Time and frequency domains of nonperiodic digital signal

Baseband transmission

Digital signal
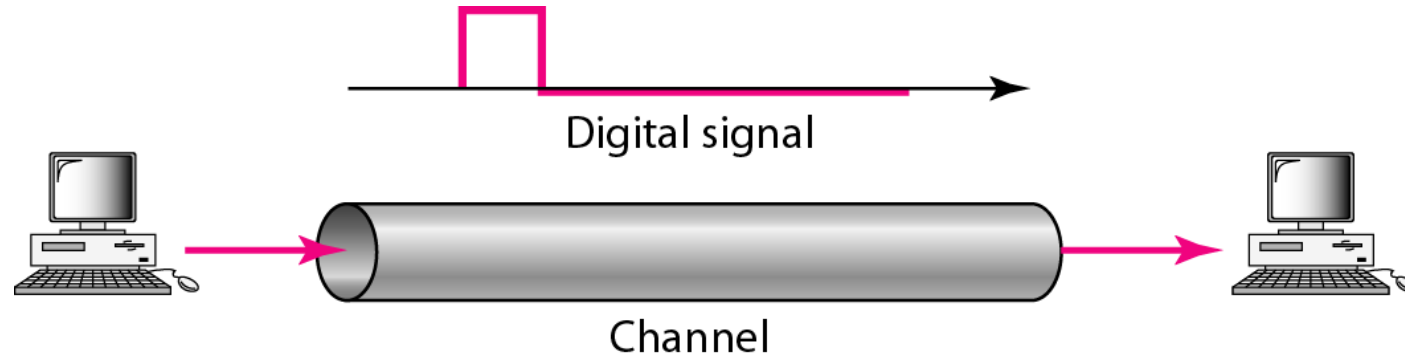
Channel

A digital signal is a composite analog signal with an infinite bandwidth.

Bandwidths of two low-pass channels
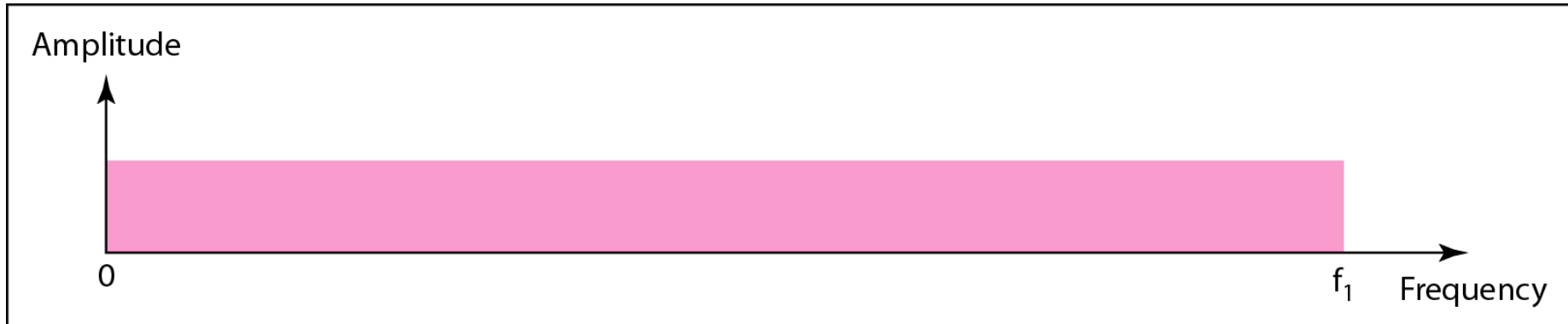
a. Low-pass channel, wide bandwidth
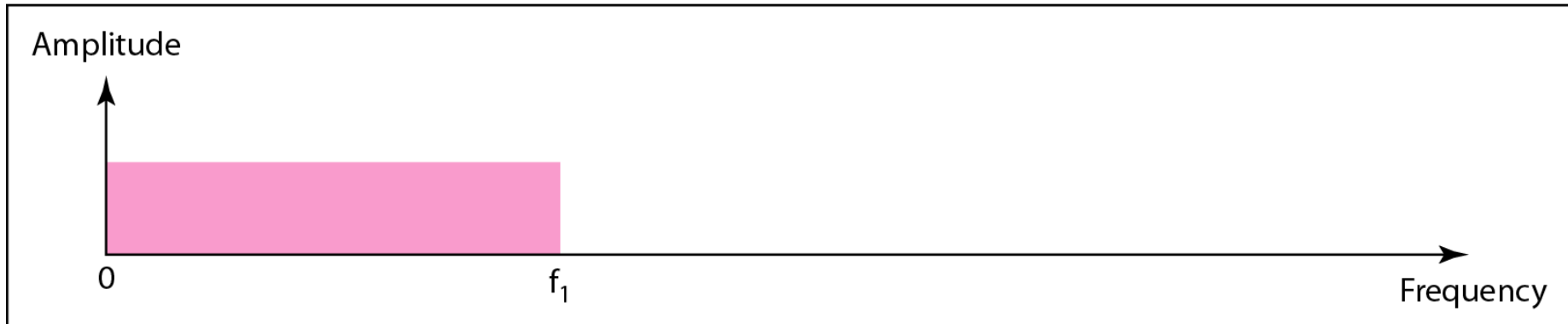
b. Low-pass channel, narrow bandwidth

Baseband transmission using a dedicated medium

Input signal bandwidth

Bandwidth supported by medium

Output signal bandwidth

0 ∞

f_1 f_2

f_1 f_2

Input signal

Wide-bandwidth channel

Output signal
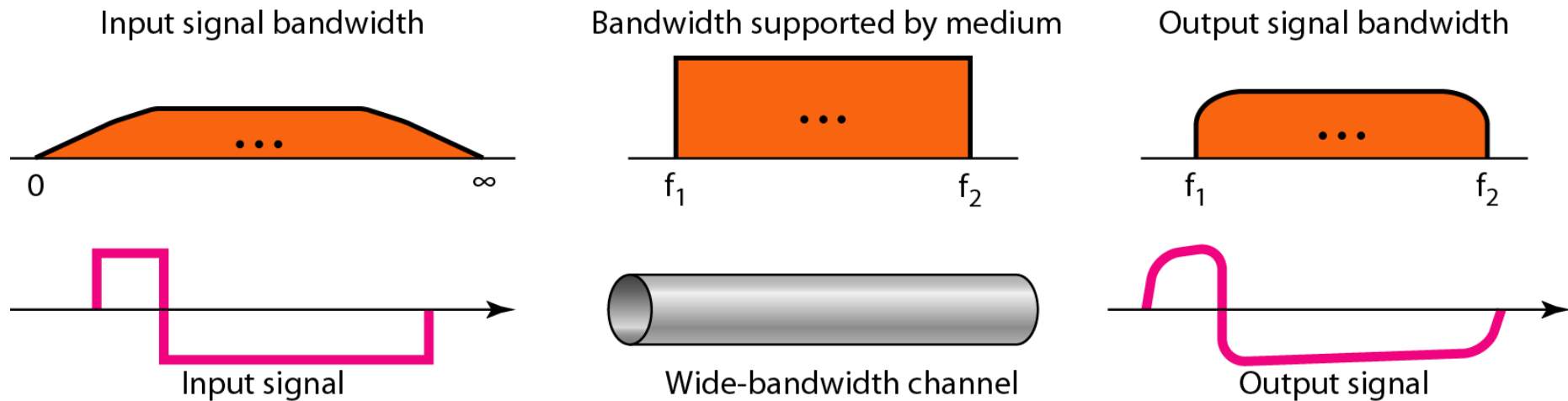
Baseband transmission of a digital signal that preserves the shape of the digital signal is possible only if we have a low-pass channel with an infinite or very wide bandwidth.

Bandwidth of a bandpass channel
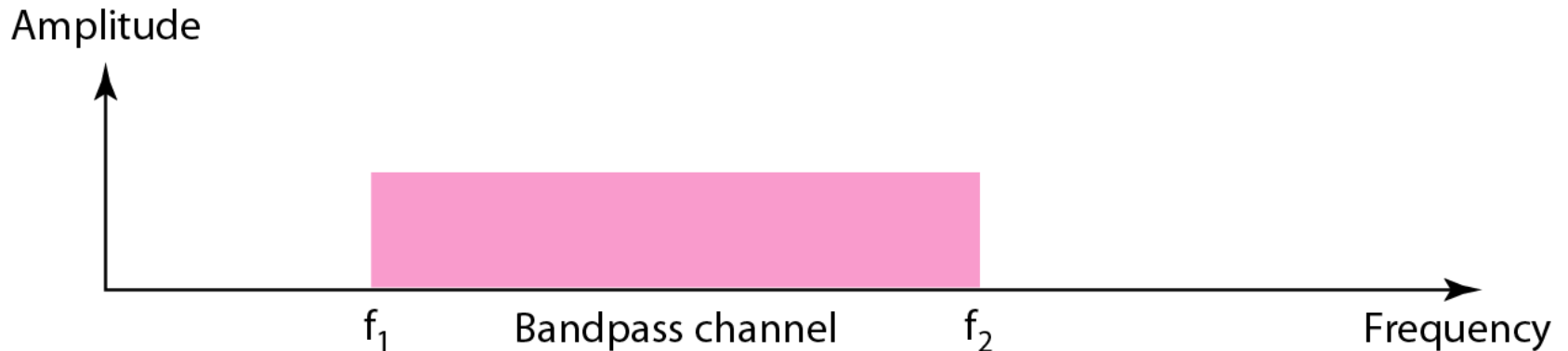
If the available channel is a bandpass channel, we cannot send the digital signal directly to the channel; we need to convert the digital signal to an analog signal before transmission.

Baseband Transmission
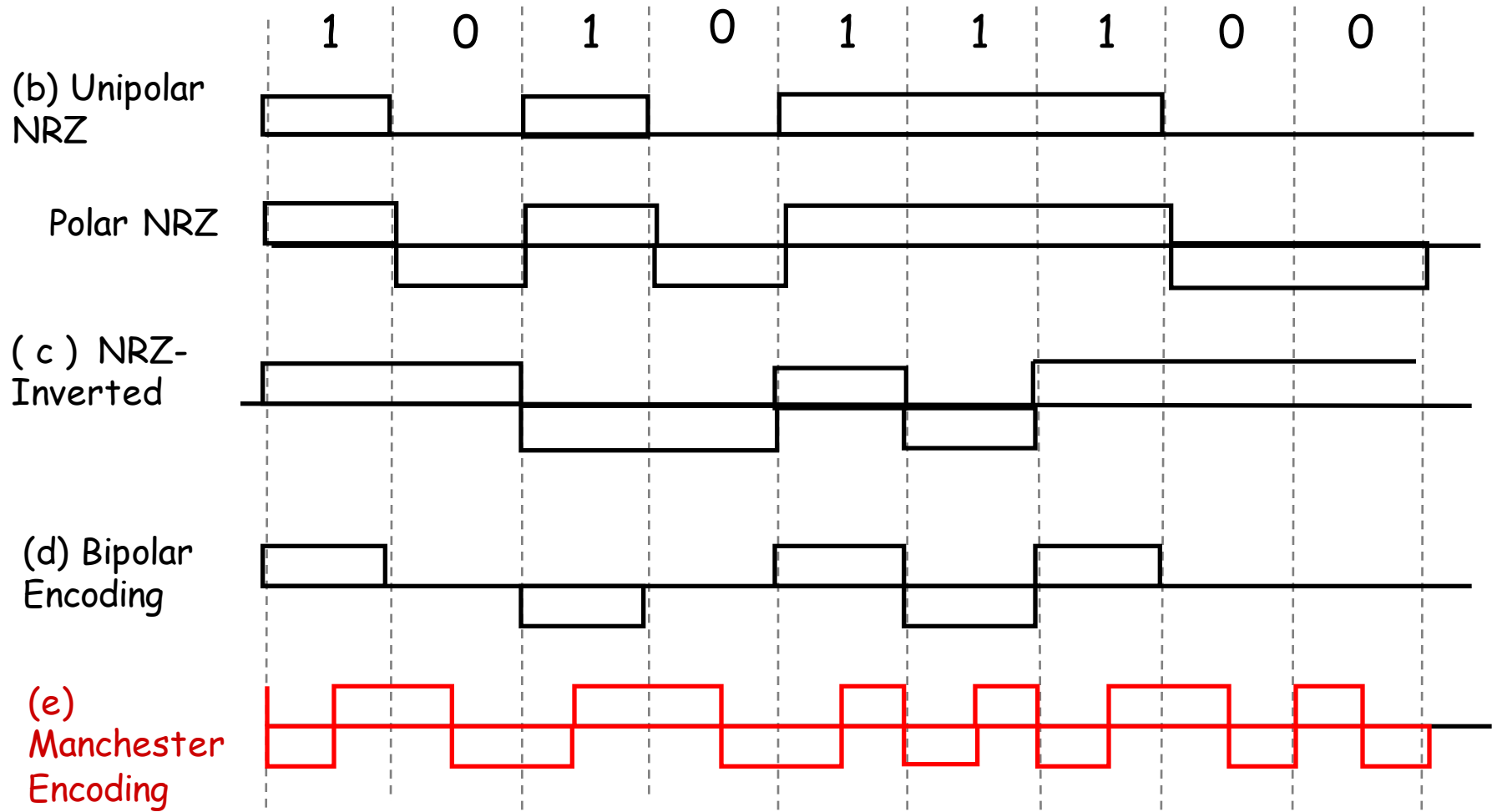
Line codes: (a) Bits, (b) NRZ, (c) NRZI, (d) Bipolar or AMI, (e) Manchester.

Passband Transmission
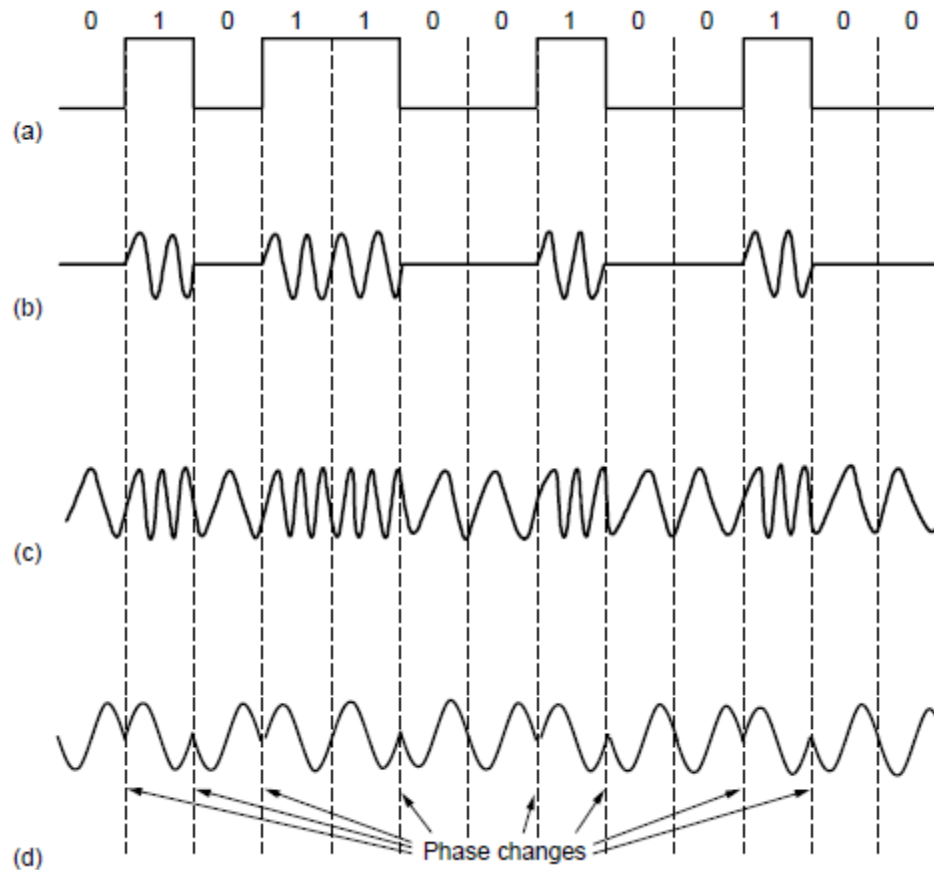
(a) A binary signal. (b) Amplitude shift keying.
(c) Frequency shift keying. (d) Phase shift keying.

Passband Transmission ((2
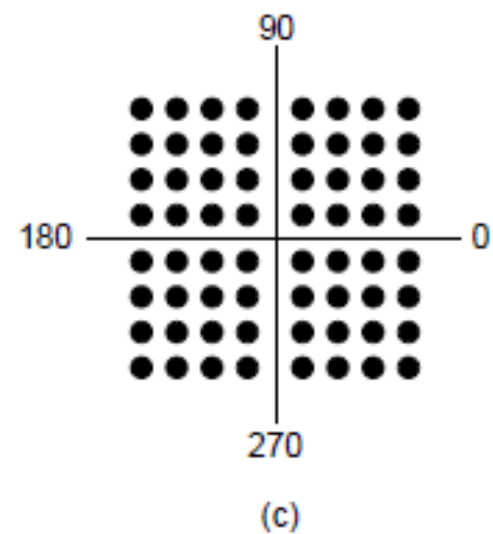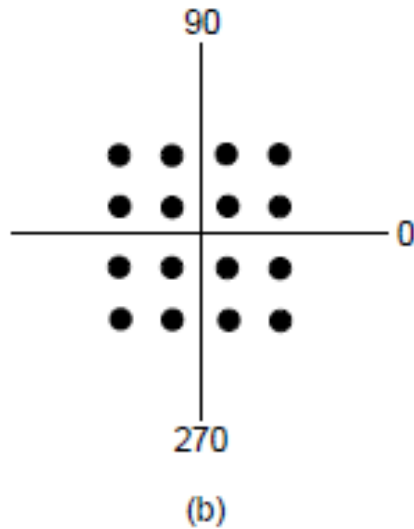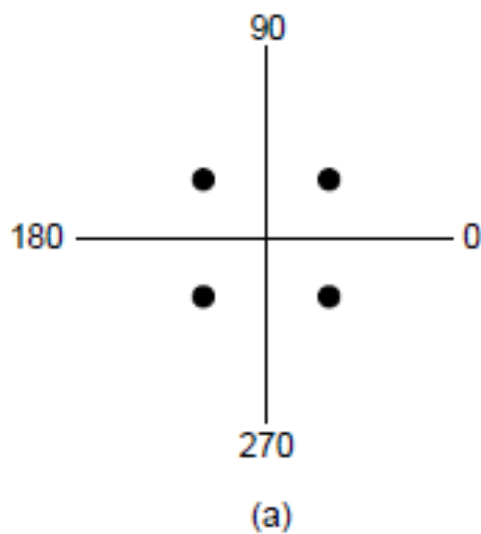
(a) QPSK. (b) QAM-16. (c) QAM-64.

Lecture 3

2-2 TRANSMISSION MEDIA

□ **Twisted pair (1)**

○ Simply two wires twisted together – thickness=1mm

The twisting cuts down on electrical interference.

○ Heavily used in the phone system

Typical office has four pairs for phones.

○ Until some Kilometers/ Some Mbps

○ For Analog and Digital

Transmission Media (2)

□ Twisted pair (2)
- ○ Bandwidth depends on thickness and distance
  Need repeater for long distances
- ○ Category 3 and 5 - with 5 having more twists and better insulation.
- ○ Popular by UTP (Unshielded Twisted Pair)
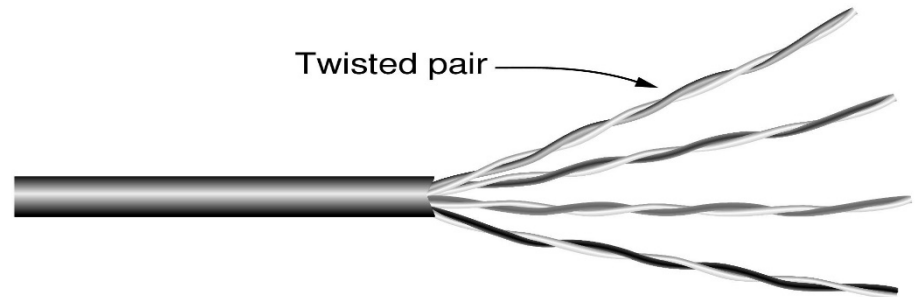
Twisted pair →

Category 5 UTP cable with four twisted pairs

Transmission Media (3)

❒ Baseband Coaxial cable

  ○ **Used for digital transmissions (called baseband.)**

  ○ **Good noise immunity.**

  ○ **Data rates as high as 2 Gbps for 1 Km distance.**

  ○ **Now being replaced by fiber.**

❒ Broadband Coaxial cable

  ○ **Used for analog transmissions (called broadband.)**

  ○ **Can run 300 MHz for long distances.**

  ○ **Analog signaling has better S/N than digital signaling.**

  ○ **Interfaces must convert digital signals to analog and vice versa.**

  ○ **Designed for long distances - can use amplifiers.**

Copper core   Insulating material   Braided outer conductor   Protective plastic covering
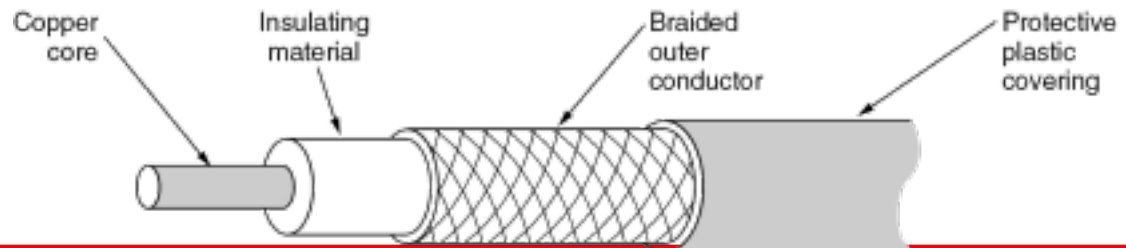
Transmission Media (4)

□ Fiber Optic (1)

○ Transmission of light through fiber

○ Bandwidth more than 50,000 Gbps !
  But now restricted to 1Gbps!
  Reason: Electrical and optical signal conversion

○ Including 3 components:
  1. Light source: Pulse of light=1, absence of light=0
  2. Transition medium: an ultra-thin fiber of glass
  3. detector: generate an electrical pulse when light falls on it

○ Similar to coax (without braid)

Core (glass)
Cladding (glass)
Jacket (plastic)

Sheath
Jacket
Core
Cladding
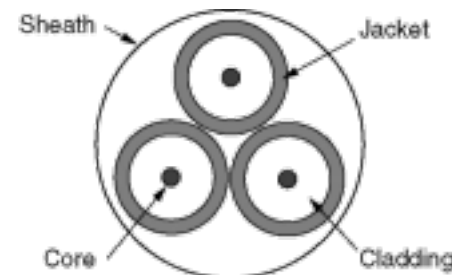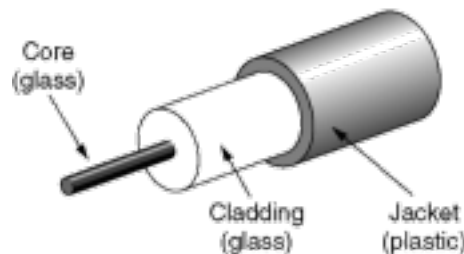
Transmission Media (5)

□ Fiber Optic (2)

○ Thickness of core: 8~10 microns or 50 microns

○ Two typically light sources:

1. LED (Light Emitting Diode)

   response time=1ns ➔ data rate = 1Gbps

2. Semiconductor laser

Item	LED	Semiconductor laser
Data rate	Low	High
Fiber type	Multimode	Multimode or single mode
Distance	Short	Long
Lifetime	Long life	Short life
Temperature sensitivity	Minor	Substantial
Cost	Low cost	Expensive

Transmission Media (6)

- Fiber Optic (3)
  - Properties include total internal reflection and attenuation of particular frequencies.
  - Fiber Optic Networks - can be used for LANs and long-haul.
  - A fiber-optic LAN
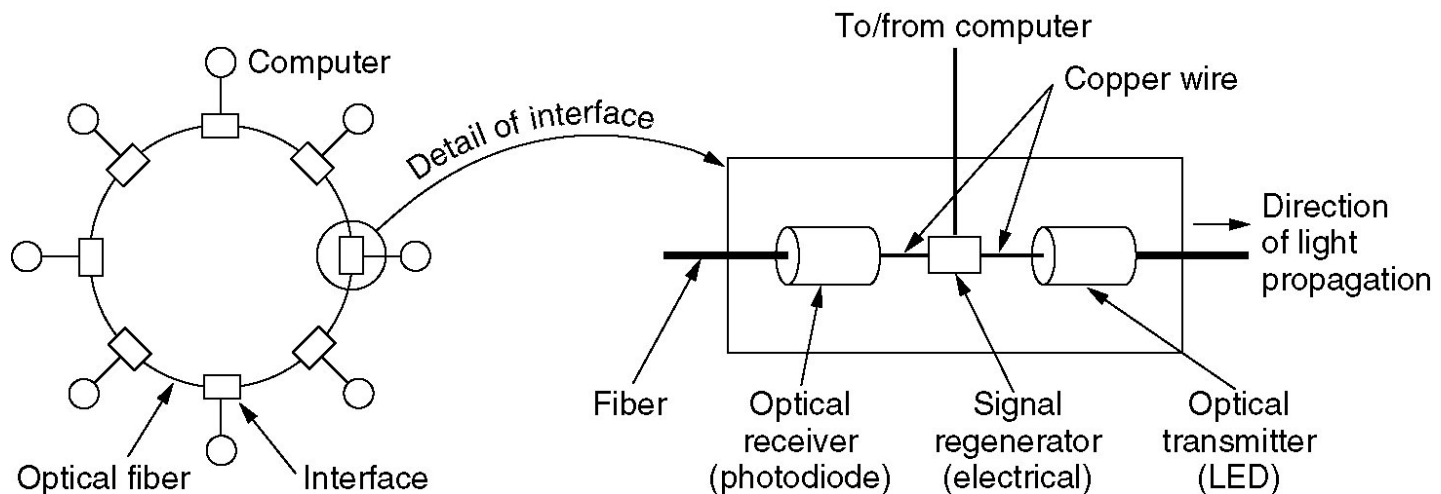
Transmission Media (7)

□ Comparison of fiber optic and copper wire

	Fiber	Copper
Bandwidth	Higher	Lower
Distance between repeaters	30 KM	5 Km
Interference	Low	High
Physical	Smaller/Lighter	-
Flow	Uni-directional	Bi-directional

Transmission Media (8)

□ Connector

□ Repeater

   ○ Signal Regeneration

   ○ Clean up

   ○ Amplify

   ○ Distance Extension

□ Hub

   ○ Repeater functionality, plus...

      • Concentration Point

      • Signal Distribution Device

      • Management Functions
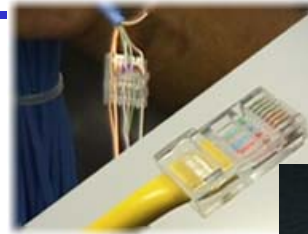
Wireless Transmission
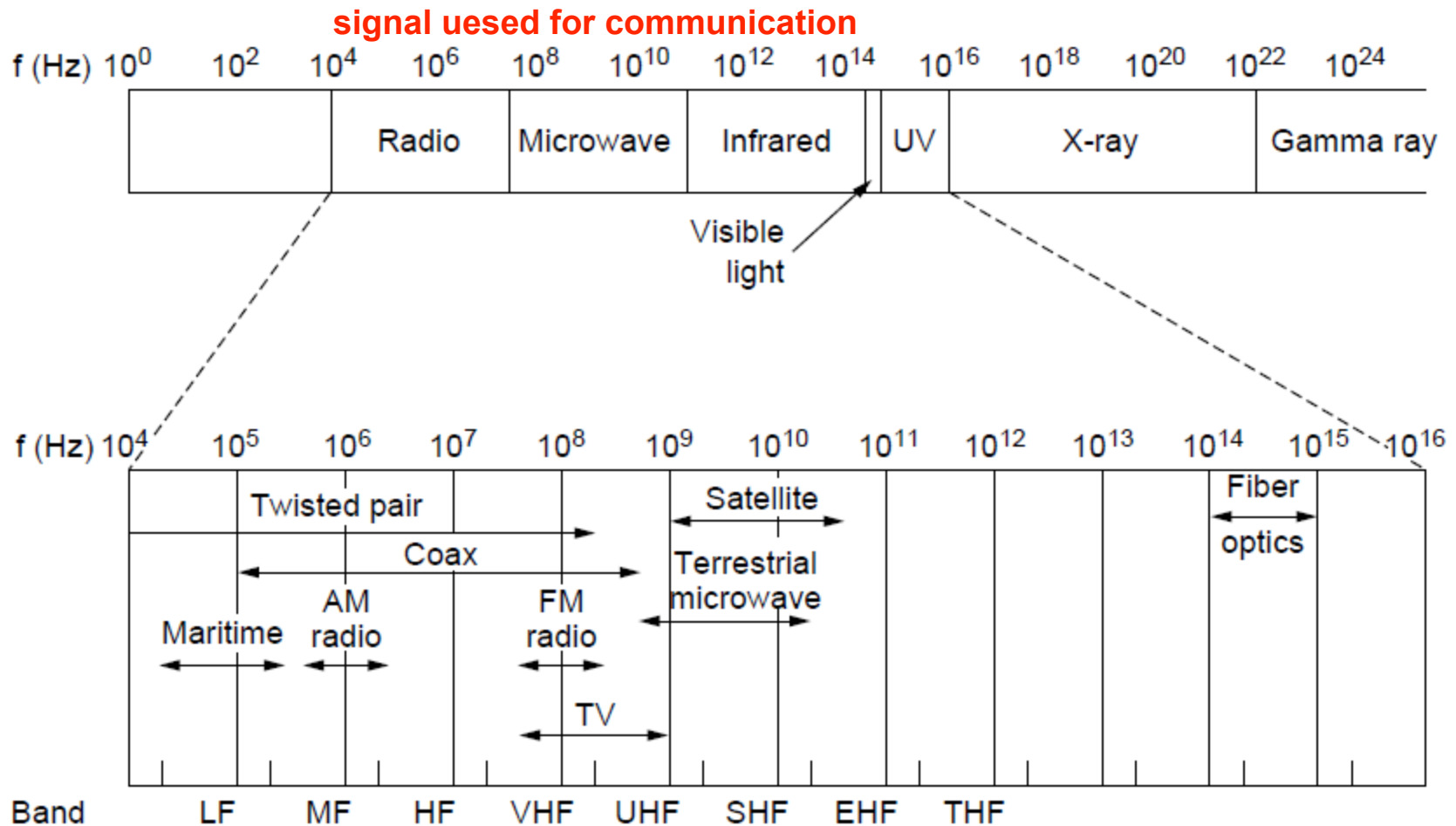
The electromagnetic spectrum and its uses for communication

Radio Transmission

Ground wave

Earth's surface

(a)
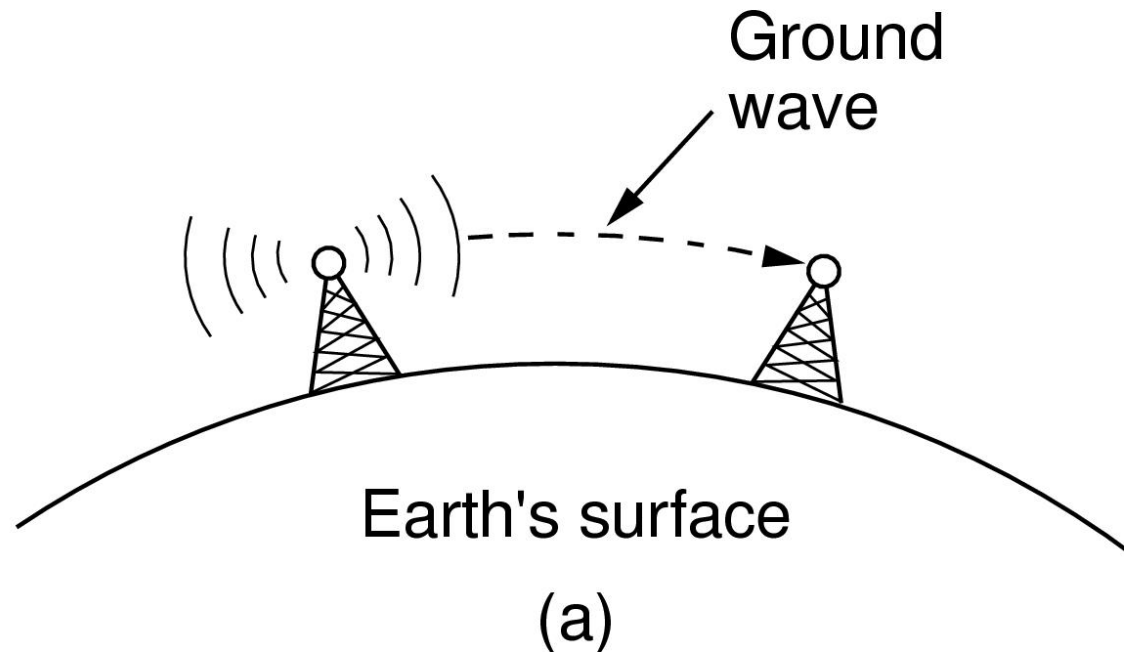
In the VLF, LF, and MF bands, radio waves follow the curvature of the earth

Radio Transmission ((2

Ionosphere

Earth's surface

(b)
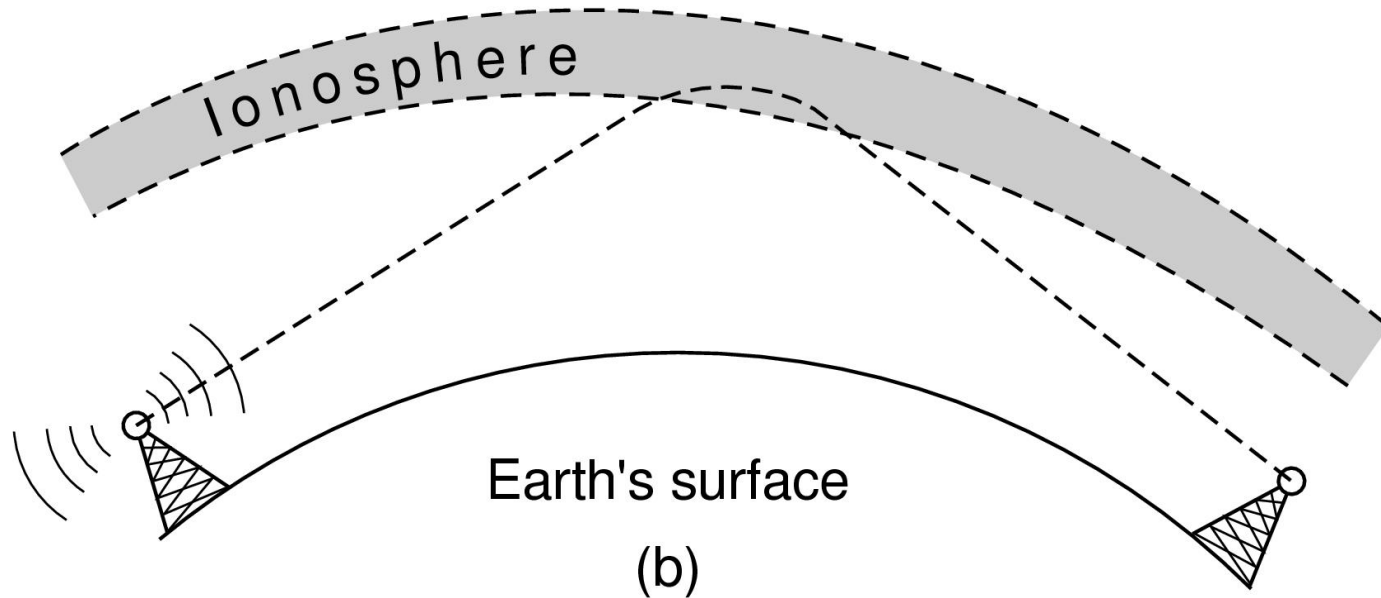
In the HF band, they bounce off the ionosphere.

Light Transmission

Photodetector   Region of turbulent seeing

Laser beam misses the detector

Laser

Heat rising off the building
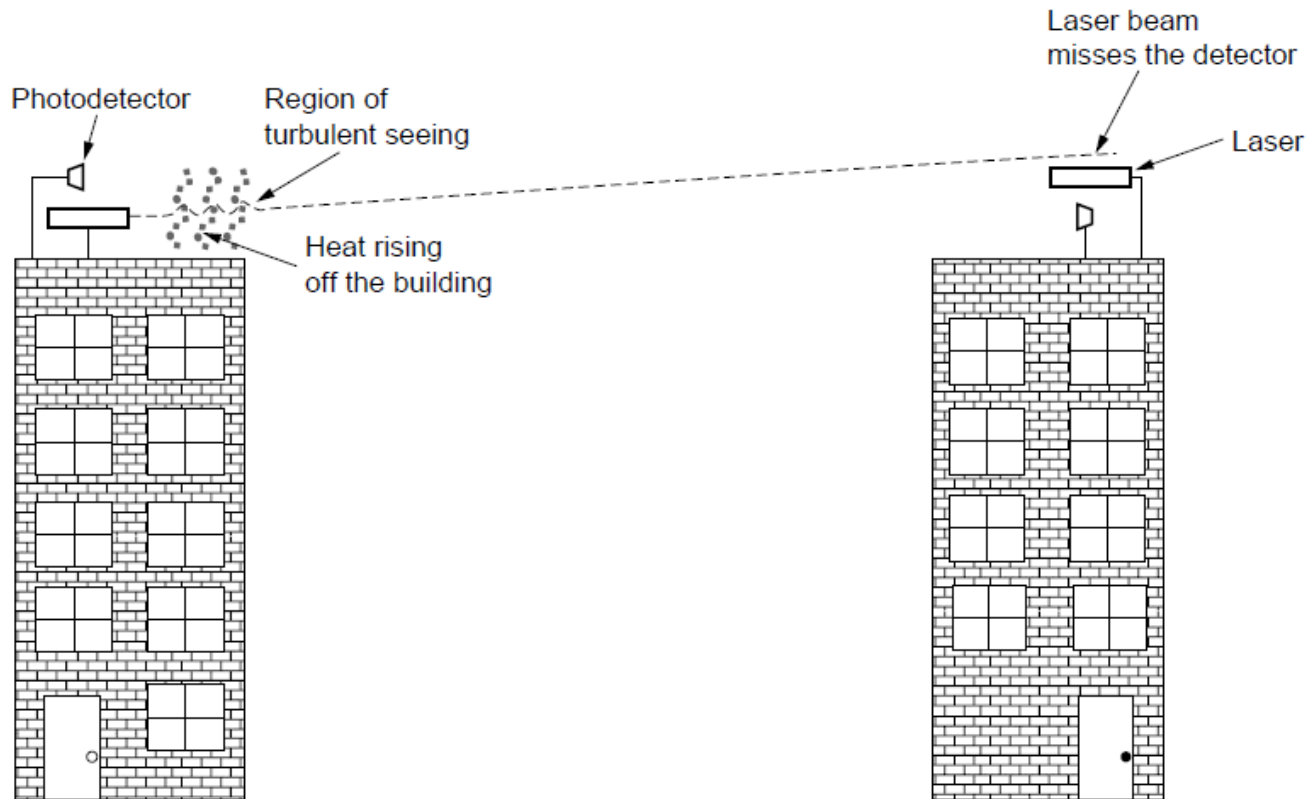
Convection currents can interfere with laser communication systems. A bidirectional system with two lasers is pictured here.

Communication Satellites

Altitude (km)		Type	Latency (ms)	Sats needed
35,000		GEO	270	3
30,000				
25,000				
20,000				
	Upper Van Allen belt			
15,000				
10,000		MEO	35–85	10
5,000				
	Lower Van Allen belt			
0			1–7	50
		LEO		
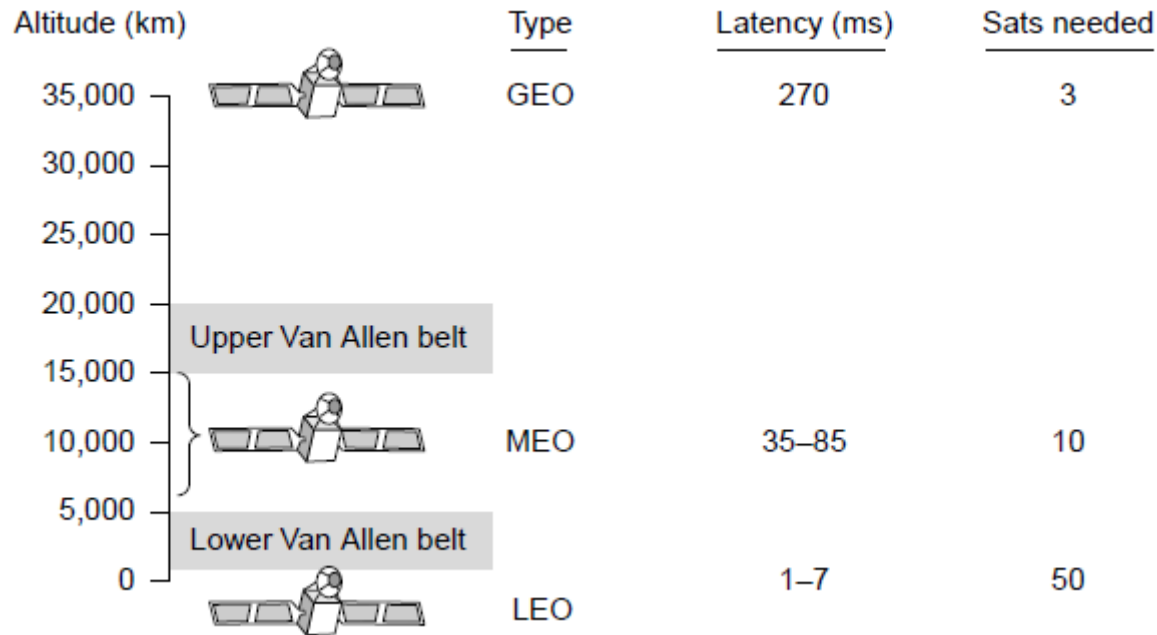
Communication satellites, some properties, including: altitude above earth, round-trip delay time, number of satellites for global coverage.

Geostathe, Satellites
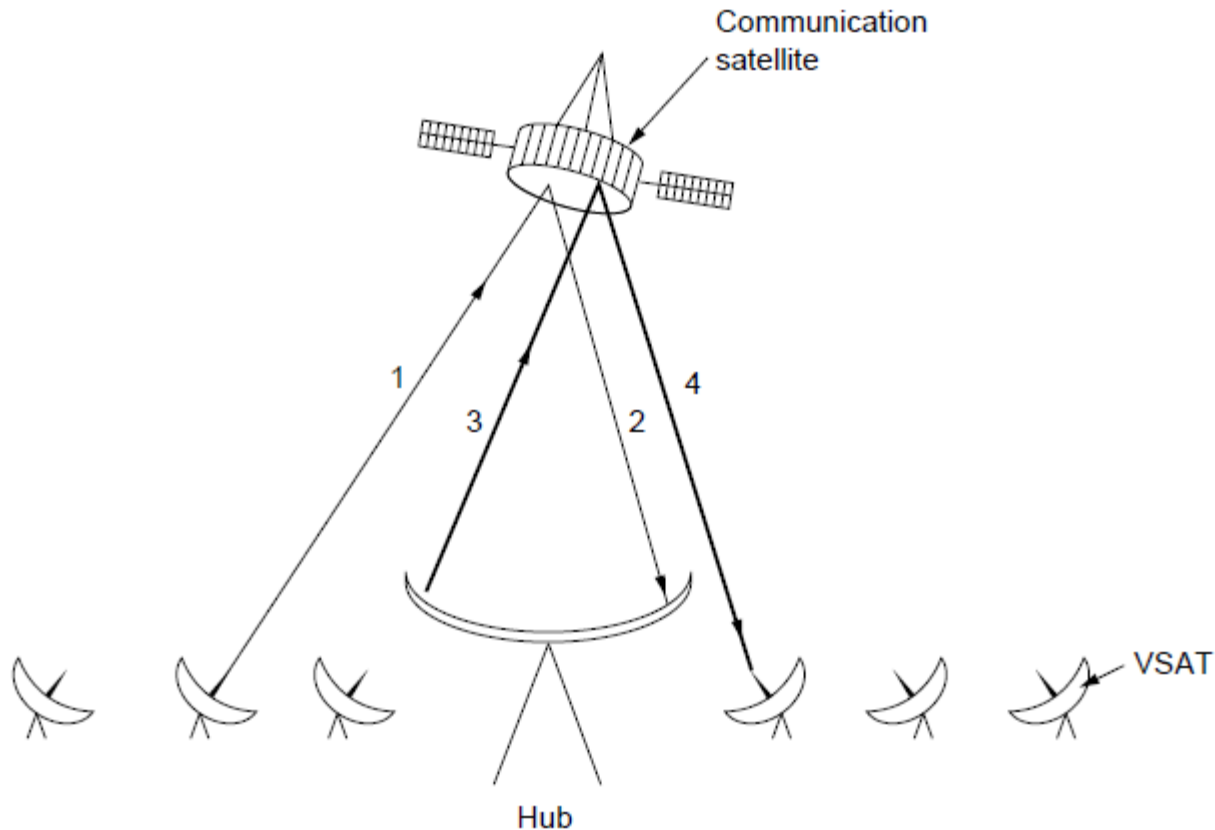
VSATs using a hub.

Low-Earth Orbit Satellites

Each satellite has four neighbors
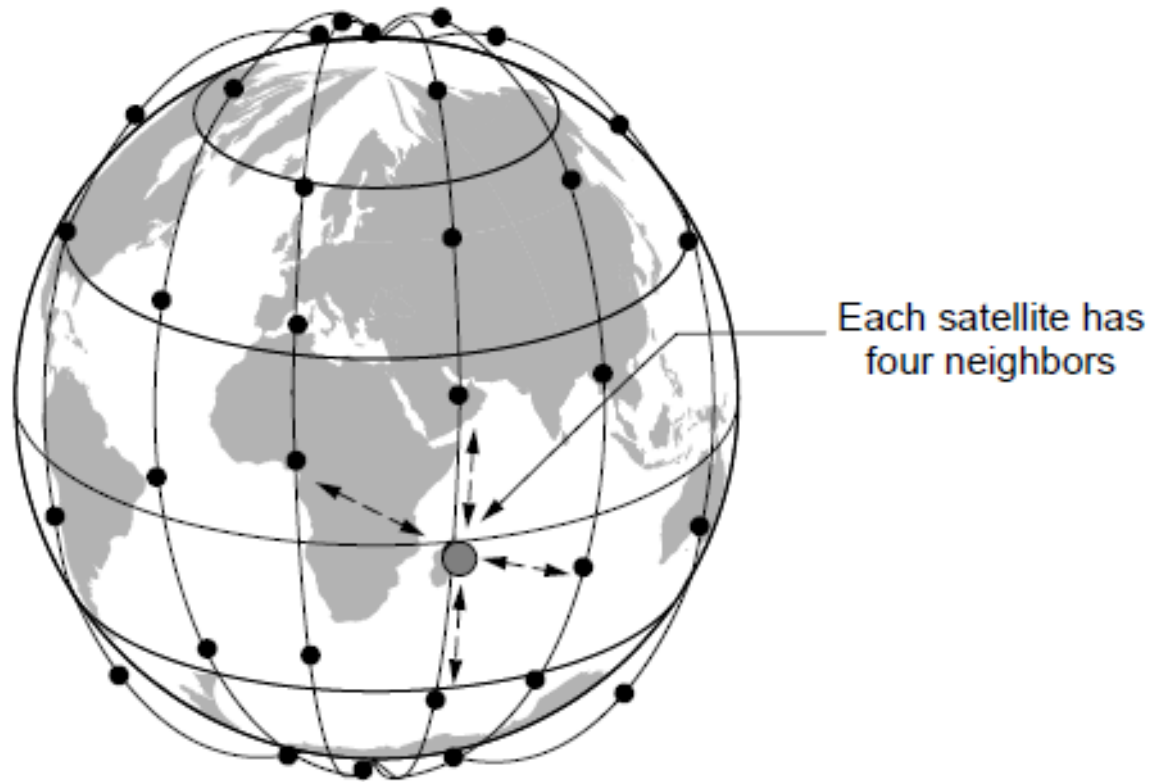
Lecture 4

Frequency Division Multiplexing
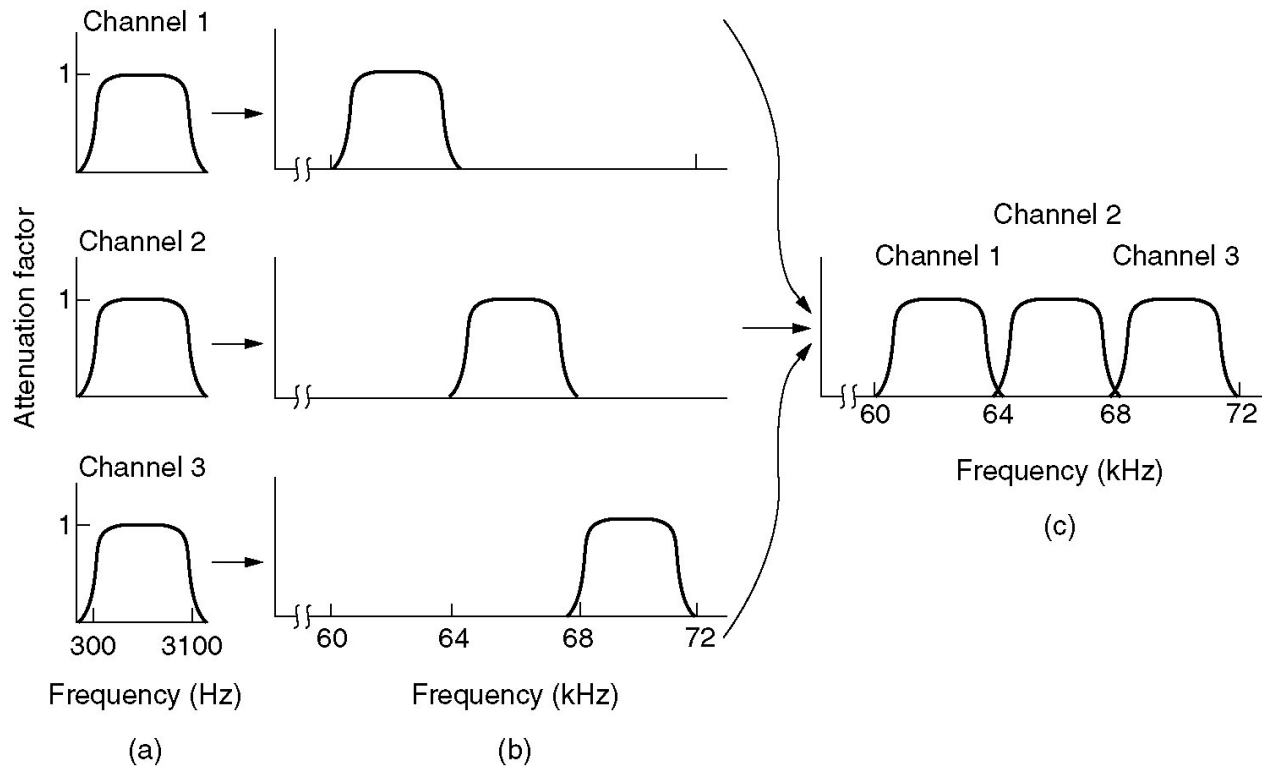
(a) The original bandwidths.
(b) The bandwidths raised in frequency.
(b) The multiplexed channel.

Frequency Division Multiplexing
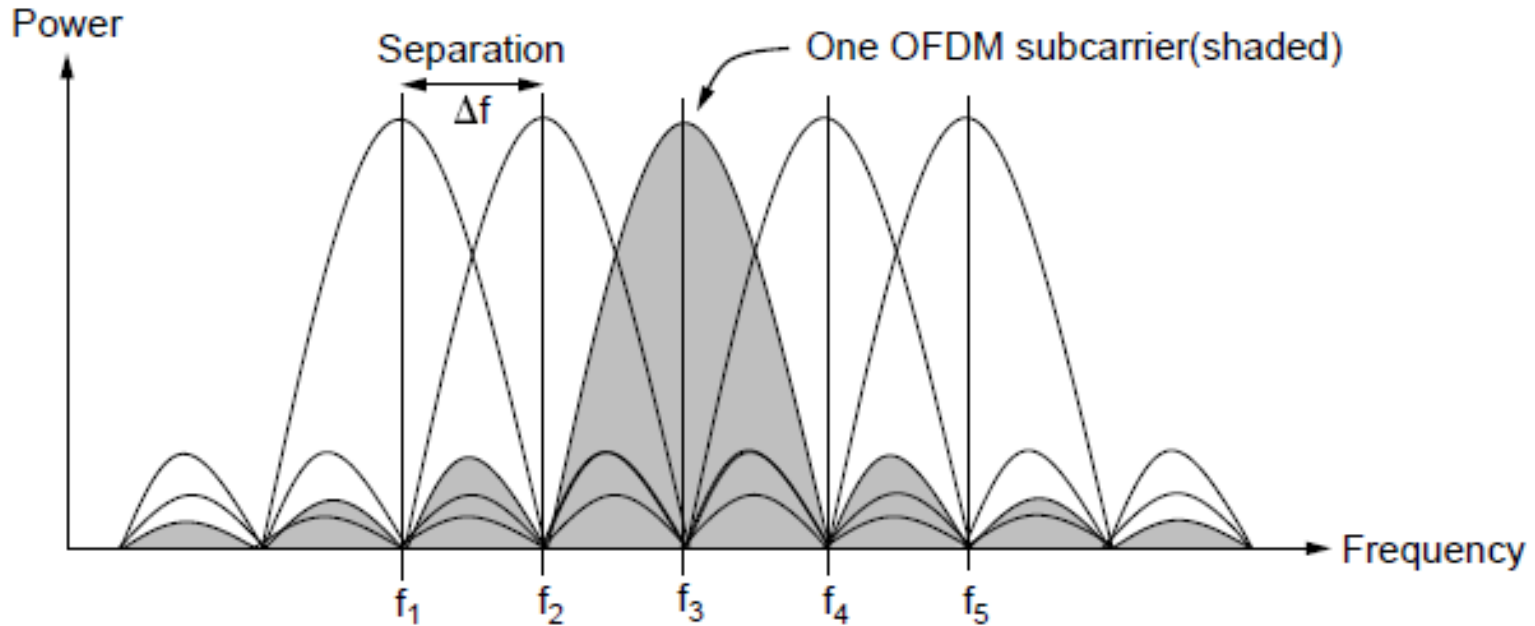
Orthogonal frequency division multiplexing (OFDM).

Time Division Multiplexing
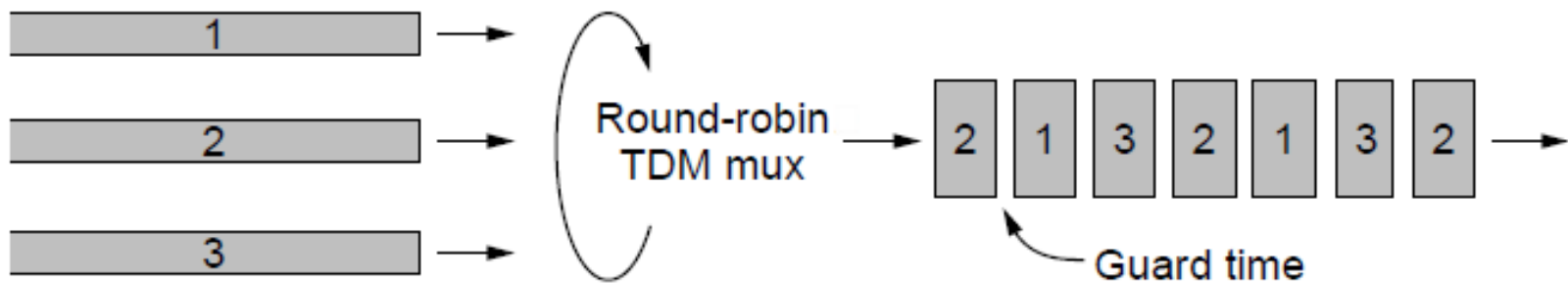
Time Division Multiplexing (TDM).

Code Division Multiplexing

$$A = (-1\ -1\ -1\ +1\ +1\ -1\ +1\ +1)$$
$$B = (-1\ -1\ +1\ -1\ +1\ +1\ +1\ -1)$$
$$C = (-1\ +1\ -1\ +1\ +1\ +1\ -1\ -1)$$
$$D = (-1\ +1\ -1\ -1\ -1\ -1\ +1\ -1)$$

(a)
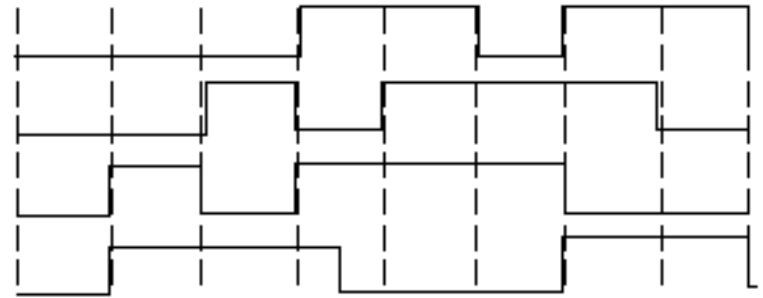
(b)

(a) Chip sequences for four stations.

(b) Signals the sequences represent.

2-4 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.
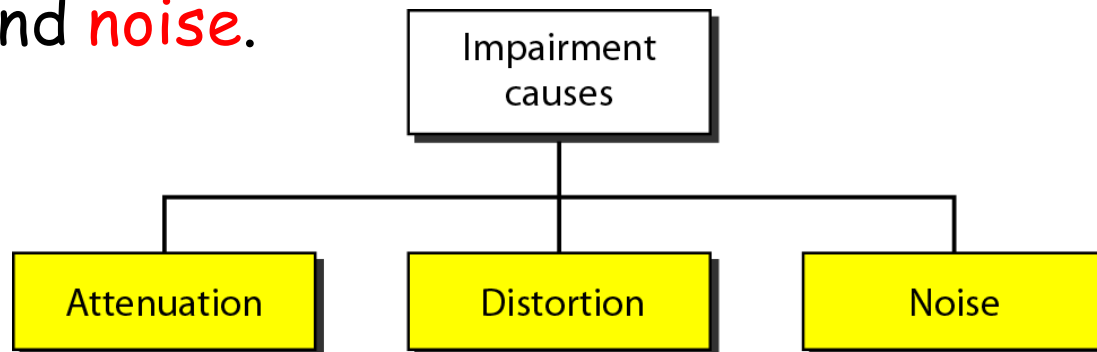
Attenuation
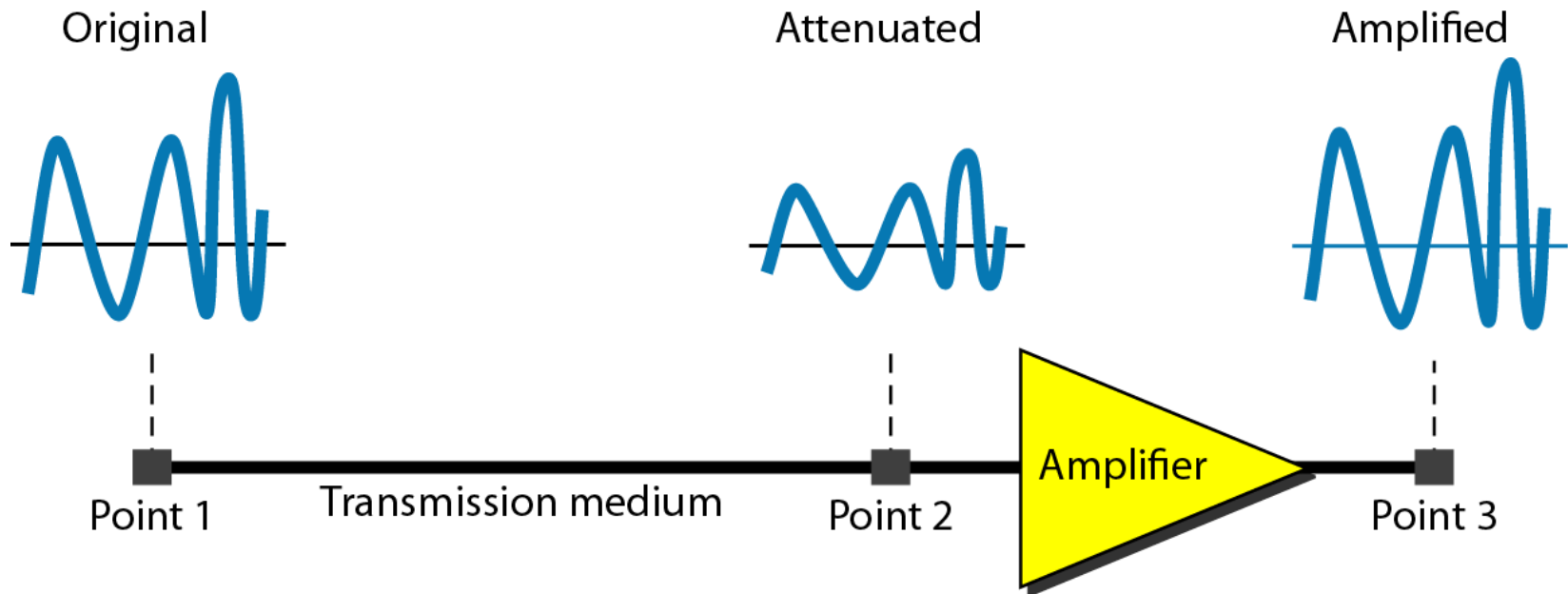
Example

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 <mark>attenuation</mark> (loss of power) can be <mark>calculated as</mark>

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

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

Example

A signal travels through an amplifier, and its power is increased 10 times.

This means that $P_2 = 10P_1$.

What is the amplification (gain of power)?

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

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

Example

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.
A signal travels from point 1 to point 4.
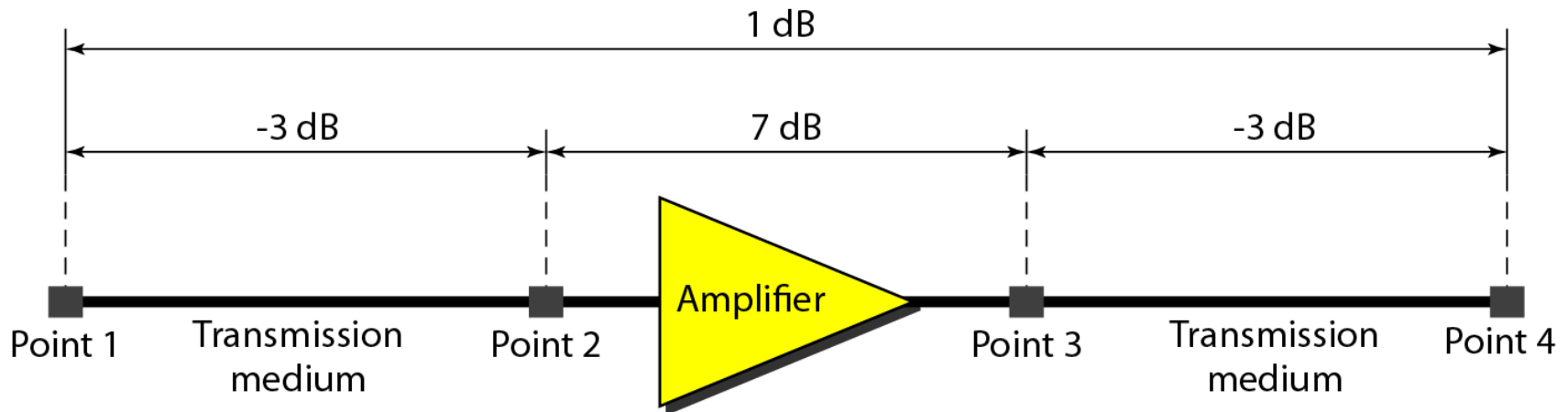
In this case, the decibel value can be calculated as

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

Distortion

Composite signal sent

Components, in phase

At the sender

Composite signal received

Components, out of phase
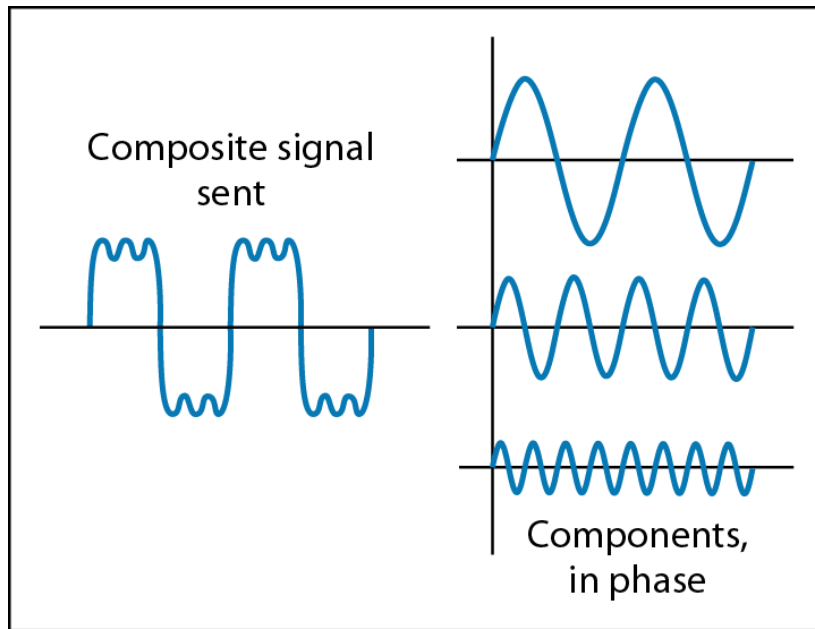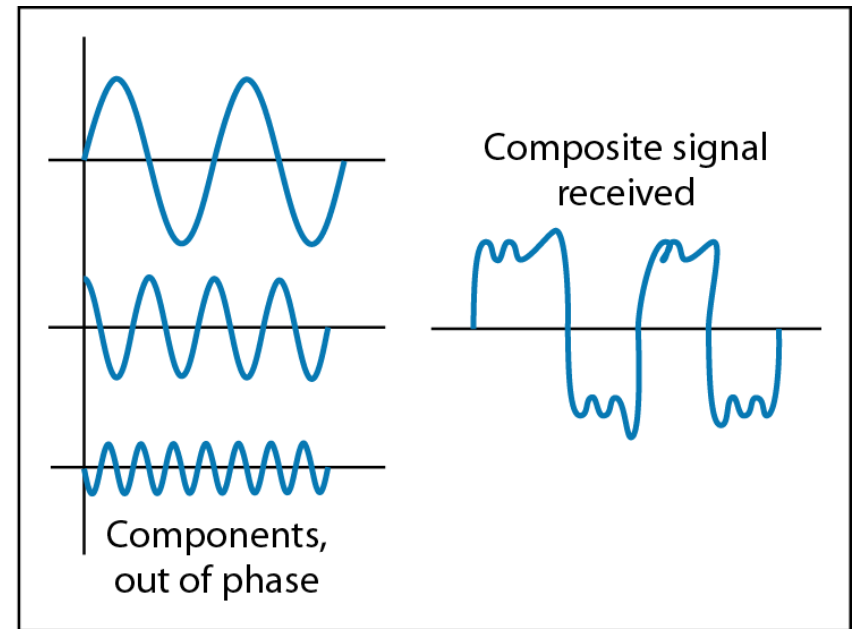
At the receiver
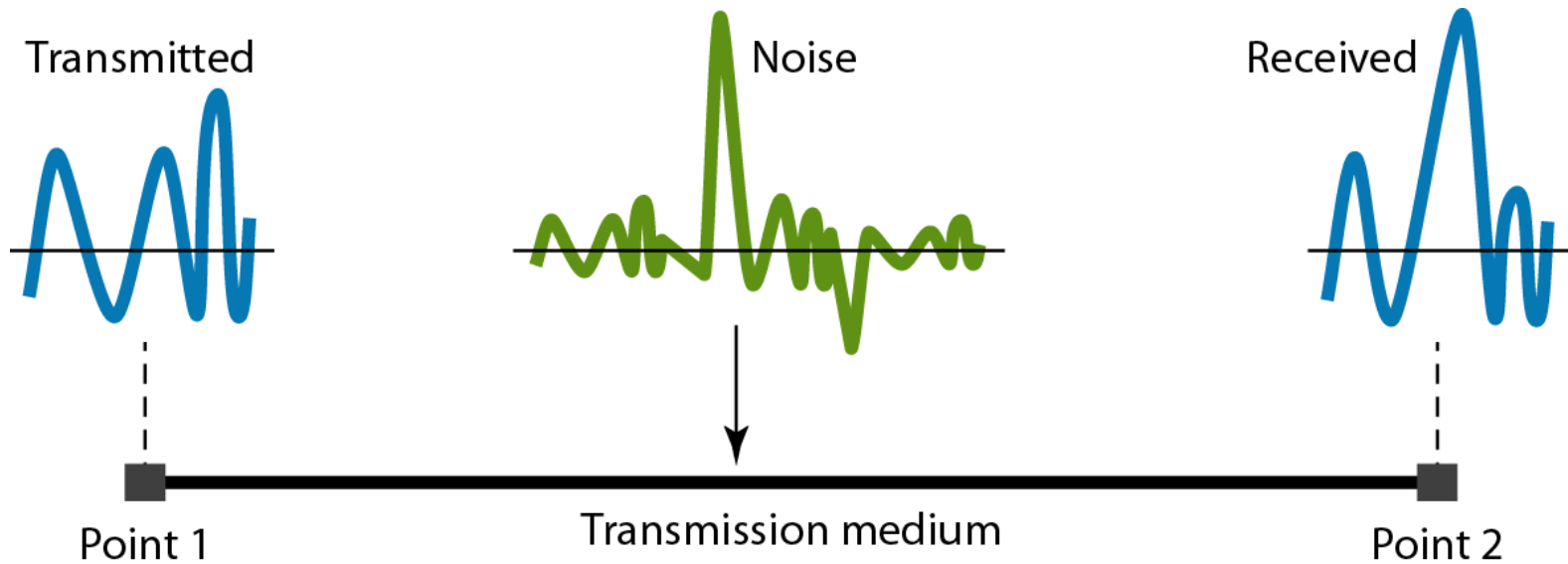
Noise

Example

$SNR = $ *average signal power / average noise power*
$SNR_{dB} = $ **10 log$_{10}$ SNR**

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:

$$SNR = \frac{10,000 \; \mu W}{1 \; mW} = 10,000$$

$$SNR_{dB} = 10 \log_{10} 10,000 = 10 \log_{10} 10^4 = 40$$

Two cases of SNR: a high SNR and a low SNR
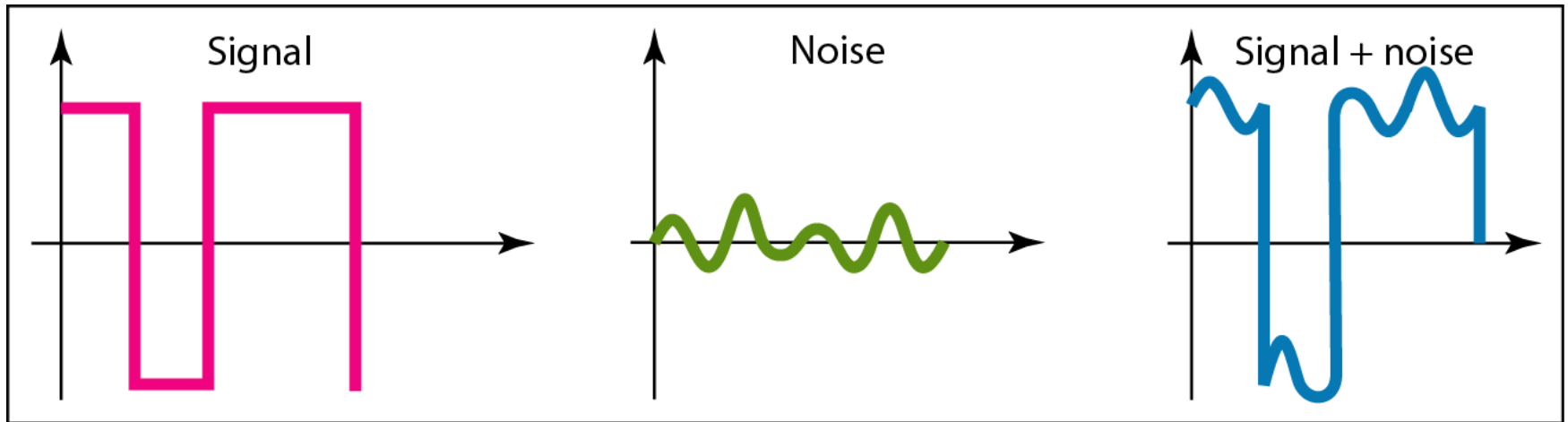
a. Large SNR
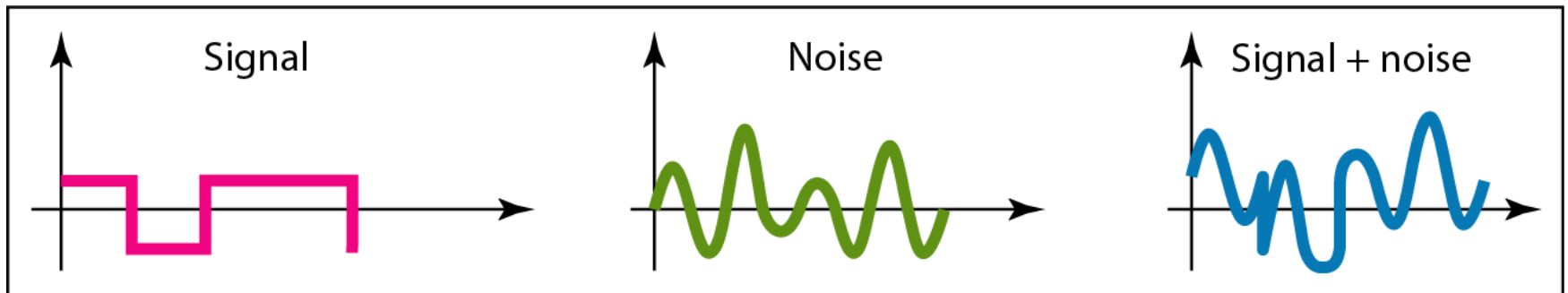
b. Small SNR

Example

The values of SNR and SNRdB 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.

Lecture 5

2-5   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)

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

Nyquist Theorem

For noiseless channel,

$$\text{BitRate} = 2 \times \text{Bandwith} \times \log_2 \text{Levels}$$

In baseband transmission, we said the bit rate is 2 times the bandwidth if we use only the first harmonic in the worst case.

However, the Nyquist formula is more general than what we derived intuitively; it can be applied to baseband transmission and modulation.

Also, it can be applied when we have two or more levels of signals.

Examples

Consider a noiseless channel with a bandwidth of 3000 Hz transmitting a signal with two signal levels. What is the maximum bit rate?

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

Consider the same noiseless channel transmitting a signal with four signal levels (for each level, we send 2 bits). What is the maximum bit rate?

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

Example

We need to send 265 kbps over a noiseless channel with a bandwidth of 20 kHz. How many signal levels do we need?

Solution
We can use the Nyquist formula as

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

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.

Shannon Capacity

In reality, we can not have a noisless channel

For noisy channel,

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

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

Example

Consider an extremely noisy channel in which the value of the signal-to-noise ratio is almost zero.

In other words, the noise is so strong that the signal is faint. What is the channel capacity?

Solution

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

This means that the capacity of this channel is zero regardless of the bandwidth.

In other words, we cannot receive any data through this channel.

Example

Let's 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.

What is the channel capacity?

Solution

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

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.

Example

The signal-to-noise ratio is often given in decibels.

Assume that SNR_{dB} = 36 and the channel bandwidth is 2 MHz.

What is the theoretical channel capacity?

Solution

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

Example

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 simplifiedto

$$C = B \times \frac{SNR_{dB}}{3}$$

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

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.

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

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.

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

2-6   PERFORMANCE

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

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.

Message Latency

- Latency is the delay to send a message over a link
  - Transmission delay: time to put M-bit message "on the wire"

    T-delay = M (bits) / Rate (bits/sec) = M/R seconds

  - Propagation delay: time for bits to propagate across the wire

    P-delay = Length / speed of signals = D seconds

  - Combining the two terms we have: Latency = M/R + D

Metric Units

❐ The main prefixes we use:

Prefix	Exp.	prefix	exp.
K(ilo)	10^3	m(illi)	10^{-3}
M(ega)	10^6	μ(micro)	10^{-6}
G(iga)	10^9	n(ano)	10^{-9}

❐ Use powers of 10 for rates, 2 for storage
  ○ 1 Mbps = 1,000,000 bps, 1 KB = 1024 bytes
❐ "B" is for bytes, "b" is for bits

Examples

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.

If the telephone company improves the quality of the
line and increases the bandwidth to 8 kHz,
we can send 112,000 bps.

Example

A network with bandwidth of 10 Mbps can pass only an average of 12,000 frames per minute with each frame carrying an average of 10,000 bits. What is the throughput of this network?

Solution
We can calculate the throughput as

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

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

Example

What is the propagation time if the distance between the two points is 12,000 km? Assume the propagation speed to be 2.4×10^{8} m/s in cable.

Solution
We can calculate the propagation time as

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

The example shows that a bit can go over the Atlantic Ocean in only 50 ms if there is a direct cable between the source and the destination.

Example

What are the propagation time and the transmission time
for a 2.5-kbyte message if the bandwidth of the network
is 1 Gbps? Assume that the distance is 12,000 km and that
light travels at 2.4×10^8 m/s.

Solution

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

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

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.

Example

What are the propagation time and the transmission time for a 5-Mbyte message if the bandwidth of the network is 1 Mbps? Assume that the distance is 12,000 km and that light travels at 2.4×10^8 m/s.

Solution

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

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

Note that in this case, because the message is very long and the bandwidth is not very high, the dominant factor is the transmission time, not the propagation time.
The propagation time can be ignored.