D_C_Chapter_01_Topic 1 to 17.pptx

D_C_Chapter_02_Topic 18 to 28.pptx

D_C_Chapter_03_Topic 29 to 53 (Complete).pptx

D_C_Chapter_04_1Topic 54 to 60.pptx

D_C_Chapter_04_2_Topic 61 to 75.pptx

D_C_Chapter_05_Topic 76 to 88.pptx

D_C_Chapter_06_Topic 89 to 100.pptx

D_C_Chapter_07_Topic 101 to 113.pptx

D_C_Chapter_08_Topic 114 to 123.pptx

D_C_Chapter_09_Topic 124 to 134.pptx

D_C_Chapter_10_Topic 135 to 148.pptx

D_C_Chapter_11_Topic 149 to 165.pptx

D_C_Chapter_12_Topic 166 to 179.pptx

D_C_Chapter_13_Topic 180 to 190.pptx

D_C_Chapter_14_1_Topic 191 to 196.pptx

D_C_Chapter_14_2_Topic 197 to 204.pptx

D_C_Chapter_15_1_Topic 205 to 210.pptx

D_C_Chapter_15_2_Topic 211 to 212.pptx

D_C_Chapter_16_Topic 213 to 220.pptx

Introduction to the Course

The Need for Communication

Trends and Advancements

What is taught in this course?

What is NOT taught in this course?

Tips and Tricks to do well

Text and References

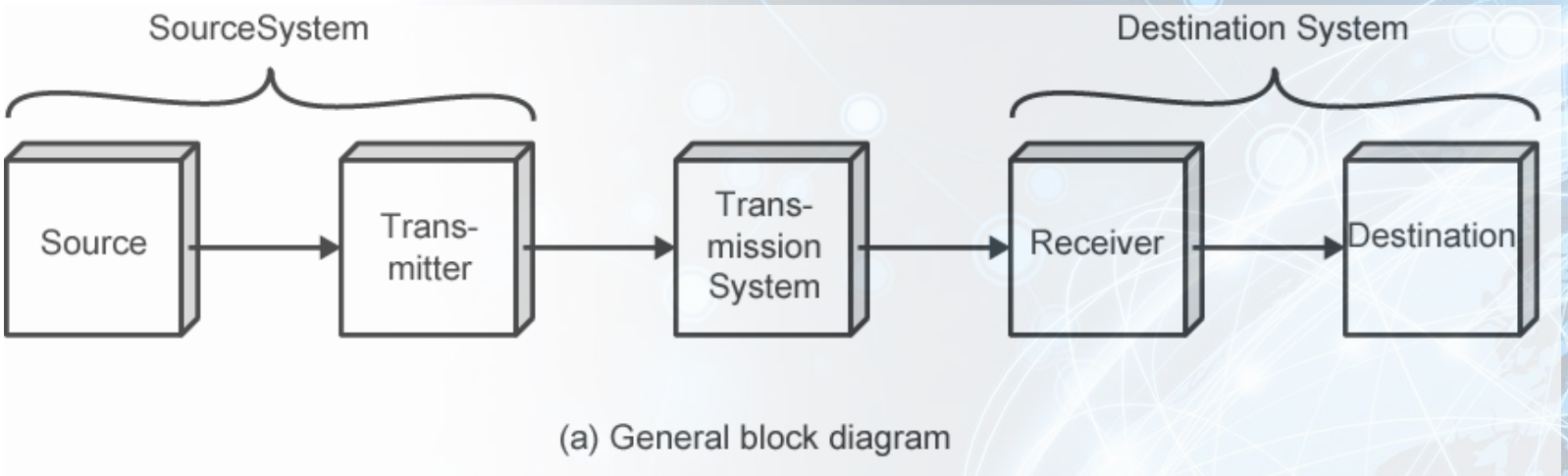
Introduction to Data Communications

Communication: Sharing of Information (Local or remote)

Telecommunications: Communication at a Distance (includes telephony, telegraph, and television etc.)

Data communications: Exchange of data between two devices via some form of transmission media

A Simple Communication Model



(a) General block diagram

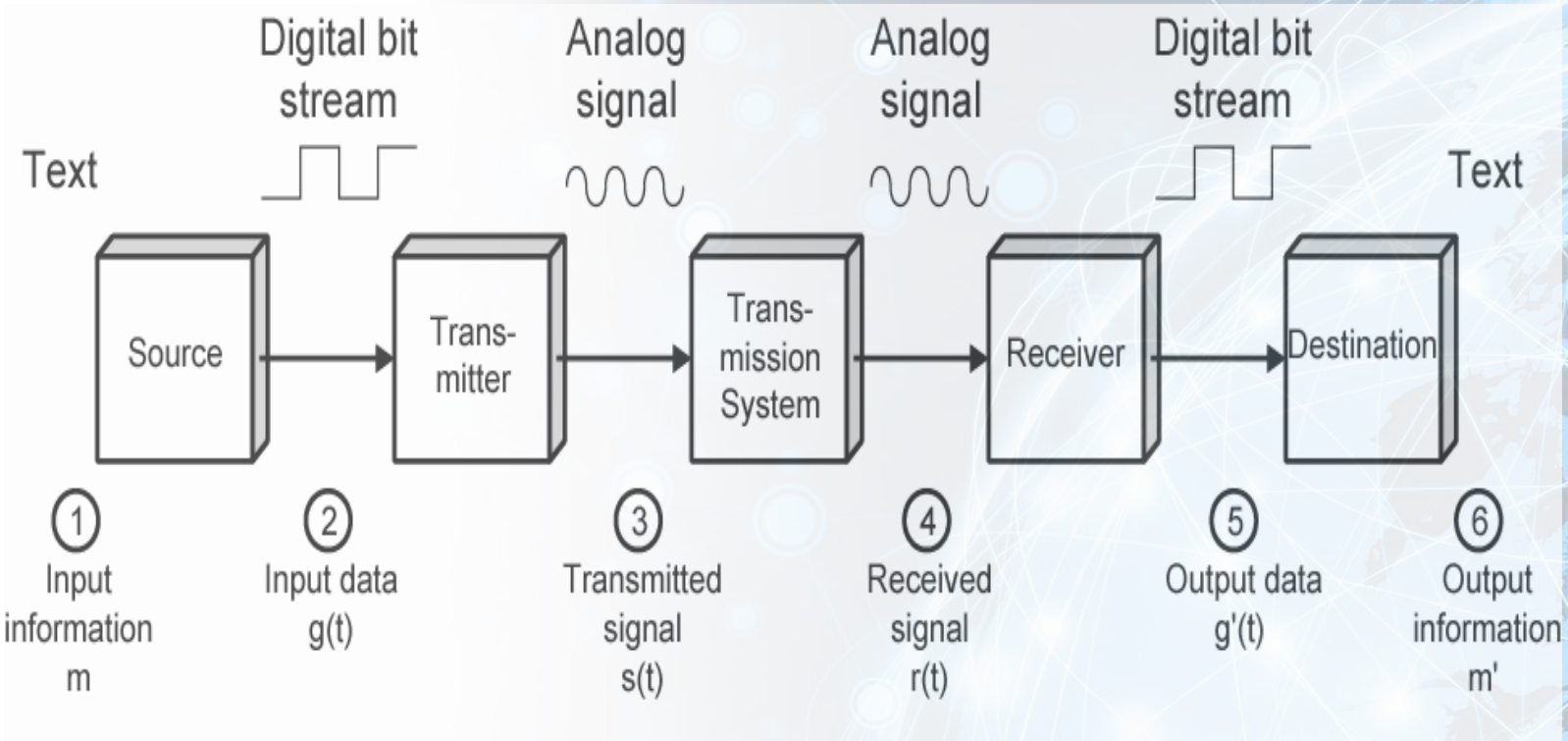
(b) Example

Characteristics of a Data Communication System

Effectiveness of a Data Communication System:

- **Delivery**
- **Accuracy**
- **Timeliness**
- **Jitter**

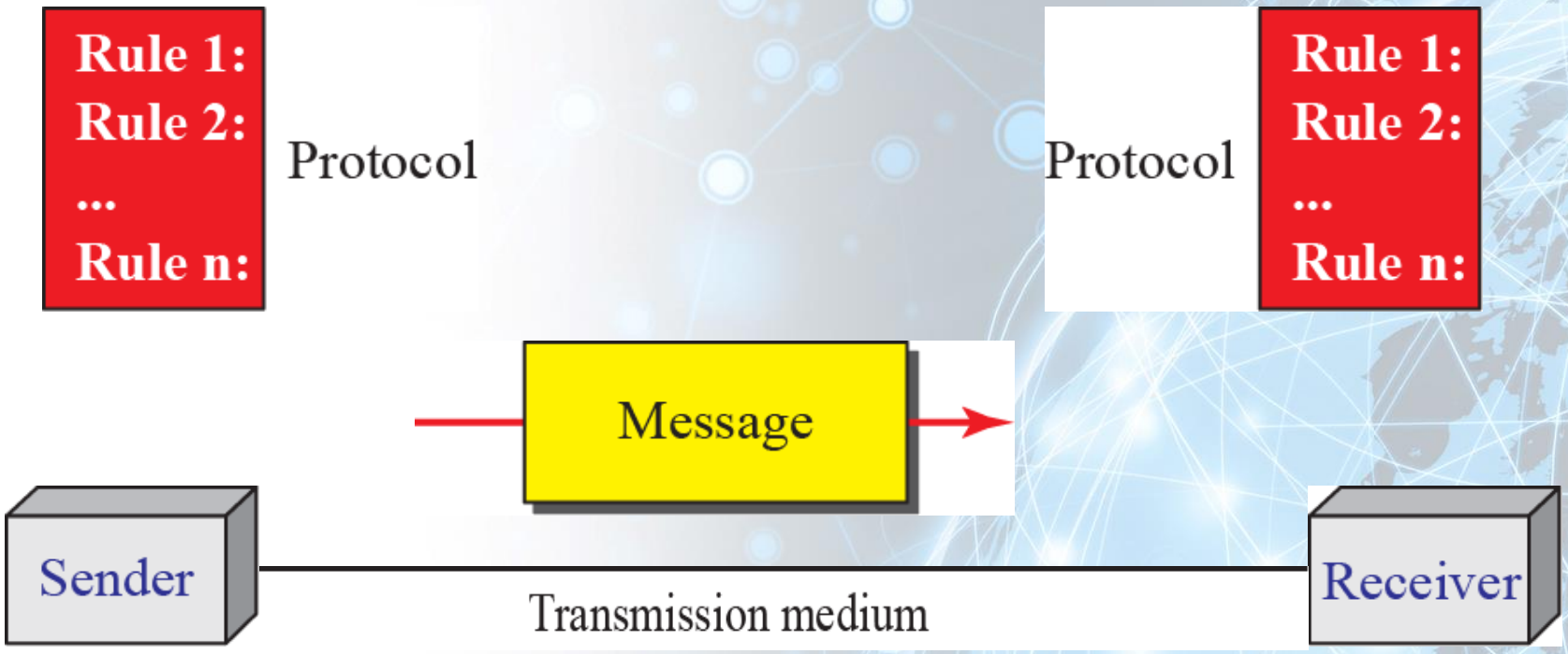
Characteristics of a Data Communication System



Components of a Data Communication system

A data communications system has five components

Components of Data Communication system



Data Representation and Data Flow

Forms of Information

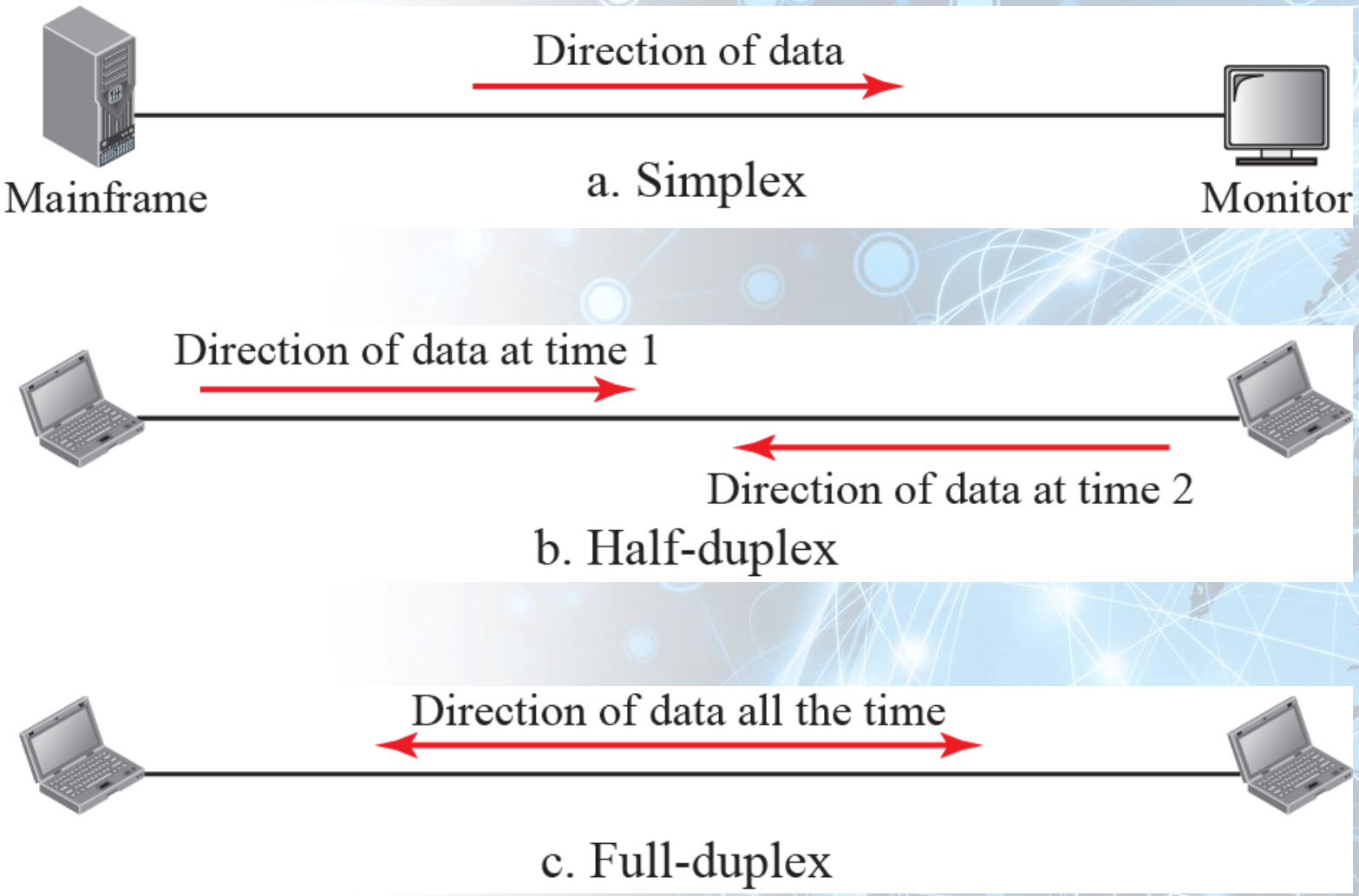
- **Text**
- **Numbers**
- **Images**
- **Audio**
- **Video**

Data Representation and Data Flow

Data Flow between two devices:

- **Simplex**
- **Half-Duplex**
- **Full-Duplex**

Data Flow


Direction of data
Mainframe
Monitor
a. Simplex
Direction of data at time 1
Direction of data at time 2
b. Half-duplex
Direction of data all the time
c. Full-duplex

Networks

- **Network:**
  Interconnection of a set of devices capable of communication
- **Host**
- **Connecting Device**

Network Criteria

A network must be able to meet a certain number of criteria:

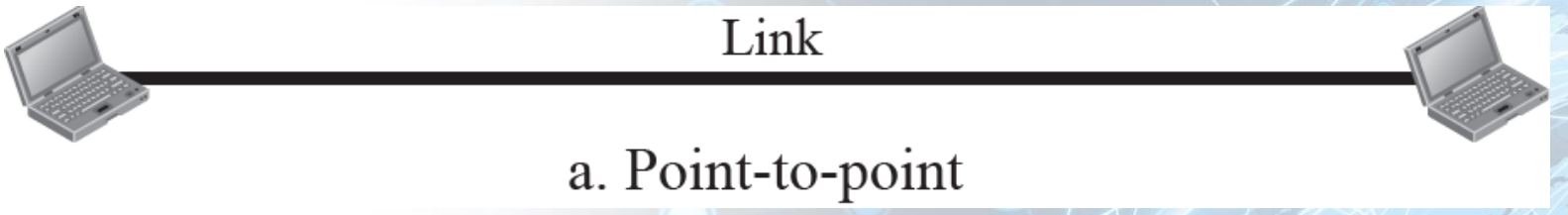
- **Performance**
  - ✓ Throughput
  - ✓ Delay
- **Reliability**
- **Security**

Physical Structures

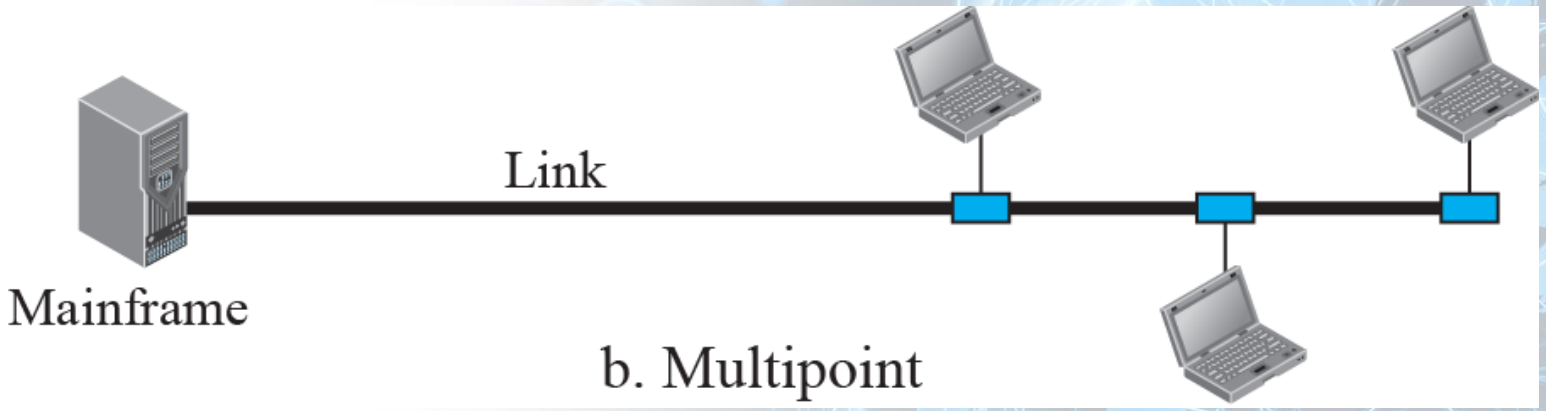
Physical Network Attributes

- Link
- Type of Connection
  - ✓ Point-to-Point
  - ✓ Multipoint

Physical Structures



a. Point-to-point

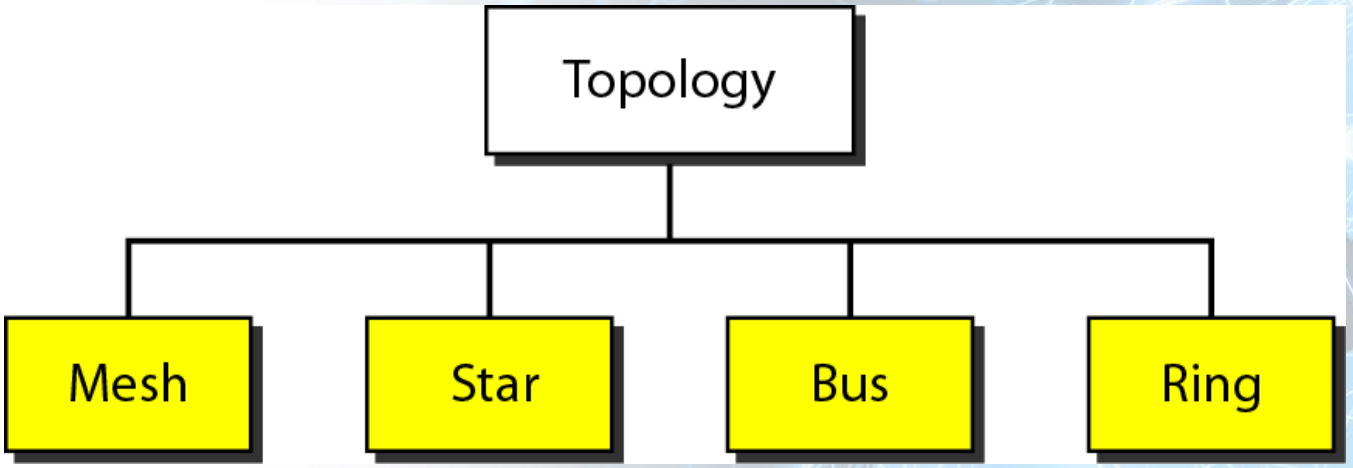


b. Multipoint

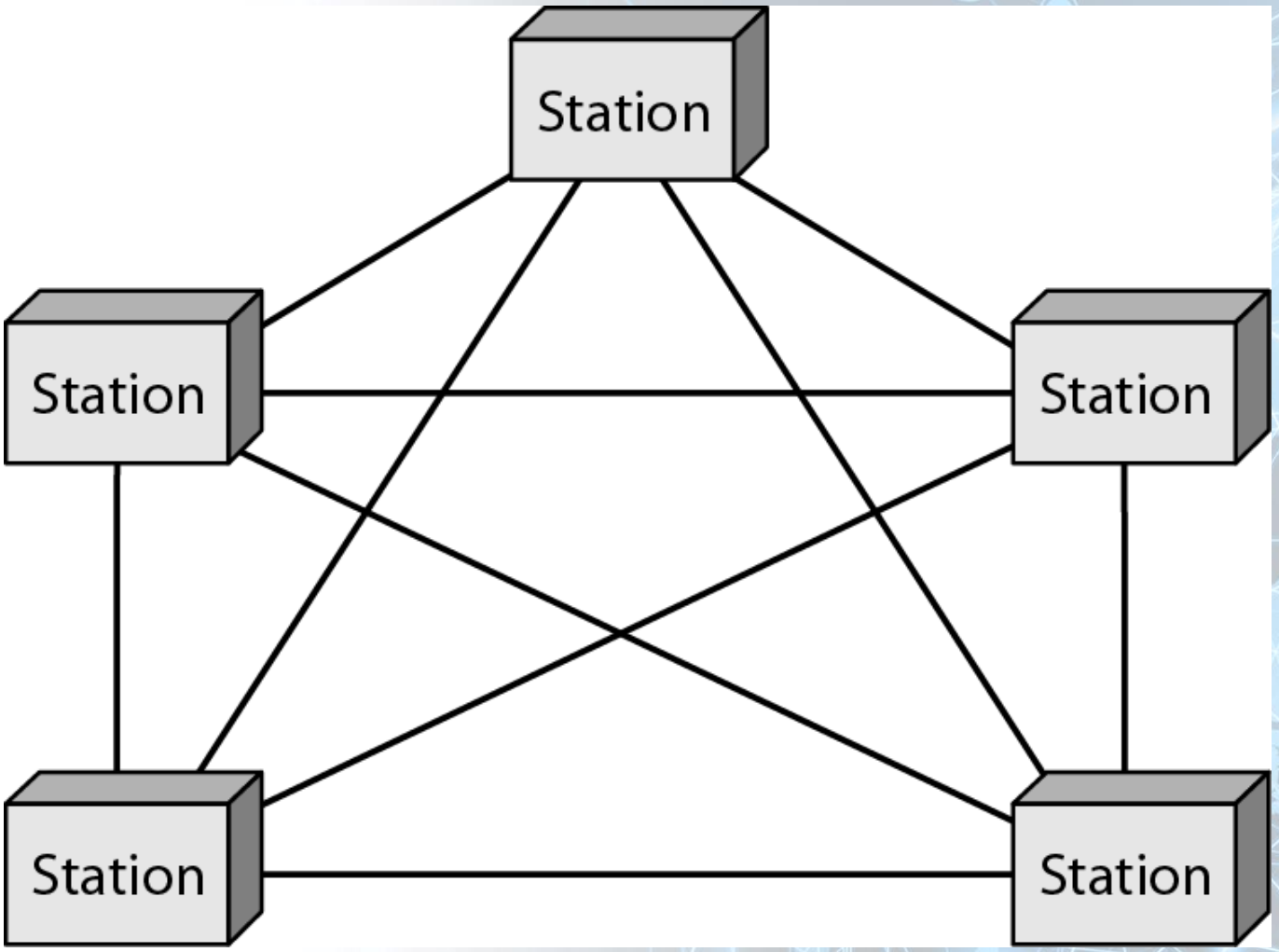
Physical Topologies

- Physical Layout of Network
- Links + Nodes = Topology
- Physical Topologies:
  - ✓ Mesh
  - ✓ Star
  - ✓ Bus
  - ✓ Ring

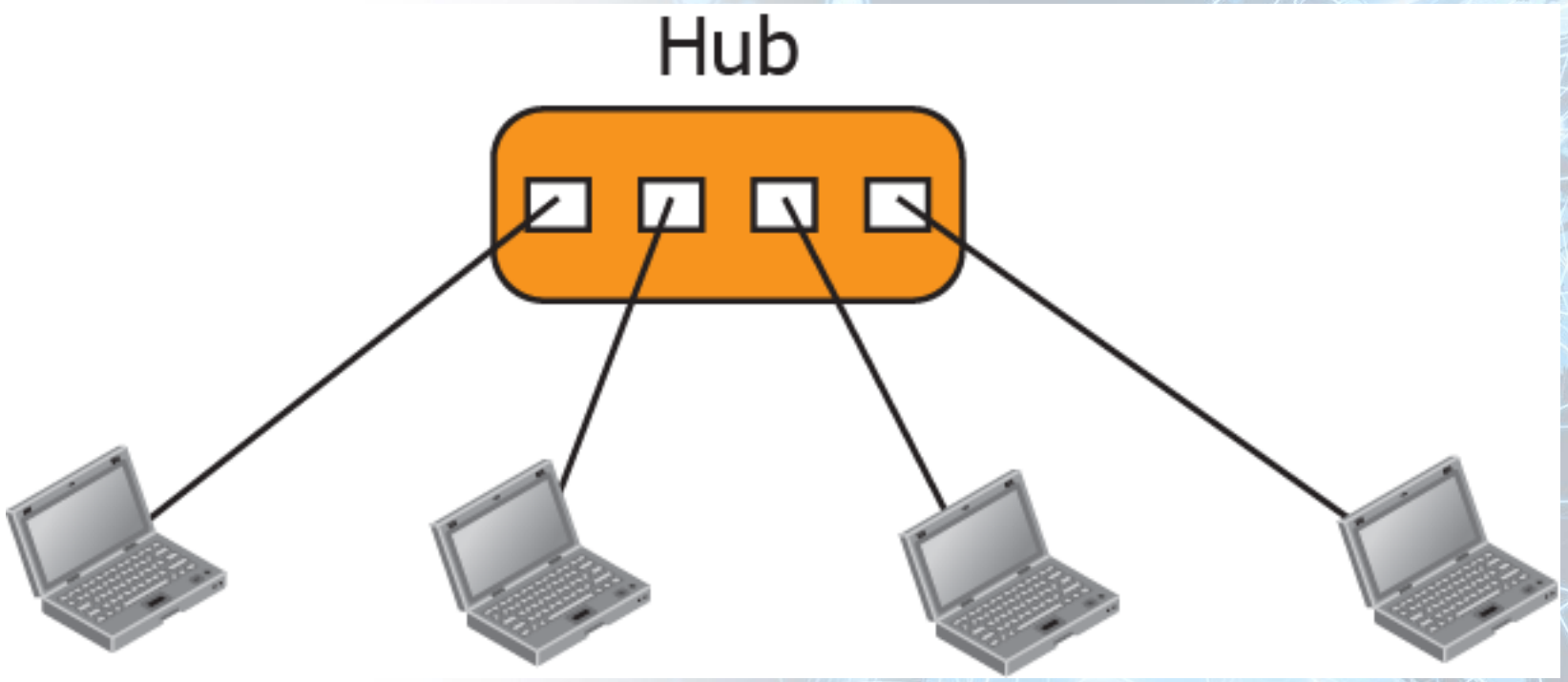
Physical Topologies



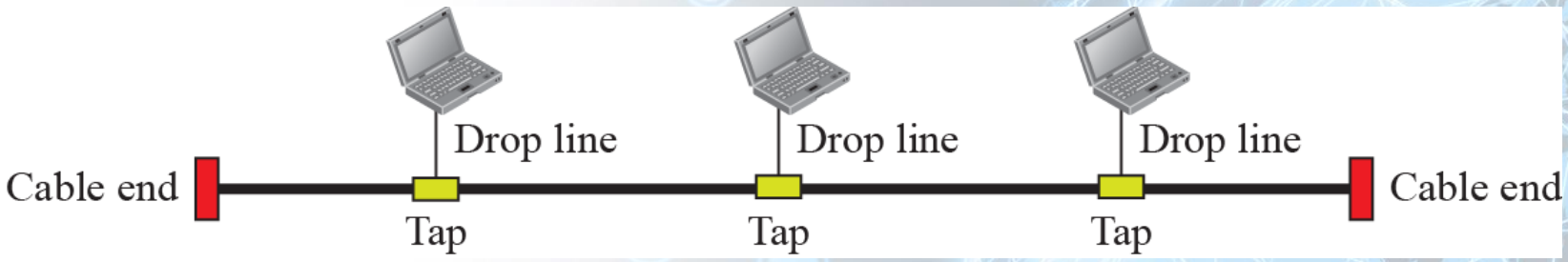
Mesh Topology



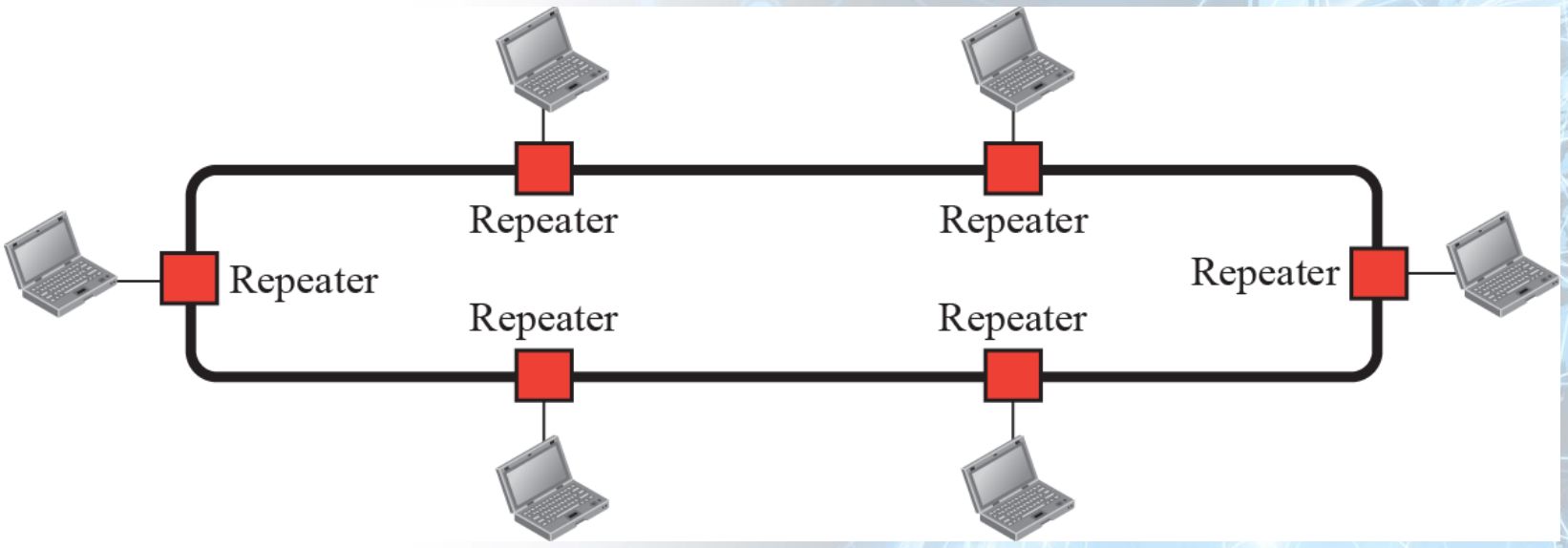
Star Topology



Bus Topology



Ring Topology



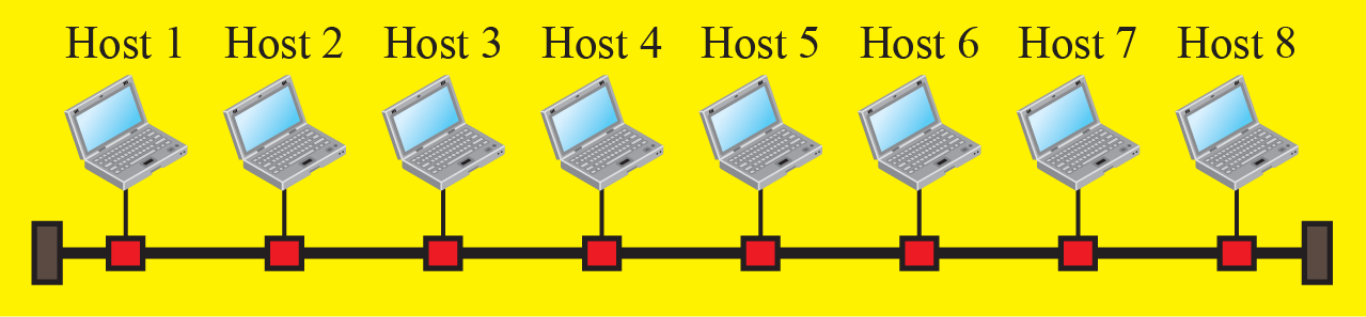
Networks Types

- **Network classification:**
  - ✓ **Size**
  - ✓ **Geographical Coverage**
  - ✓ **Ownership**
- **Local Area Networks (LANs)**
- **Wide Area Networks (WANs)**

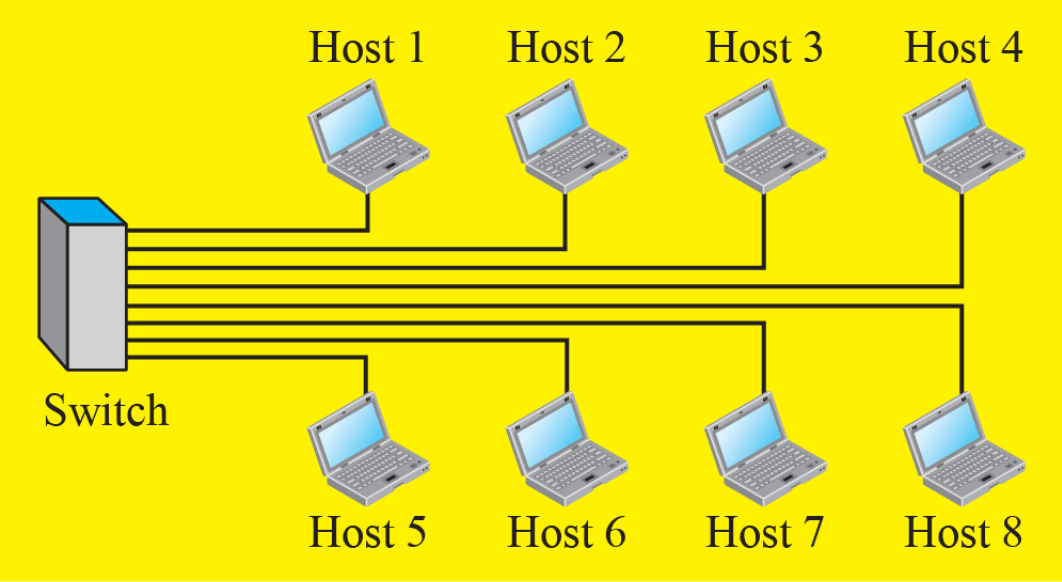
Local Area Networks

- Usually Privately owned
- Connects some hosts in a single office, building, or campus
- Can be as simple as two PCs and a printer in someone's home office
- Can extend throughout a company
- Host Address

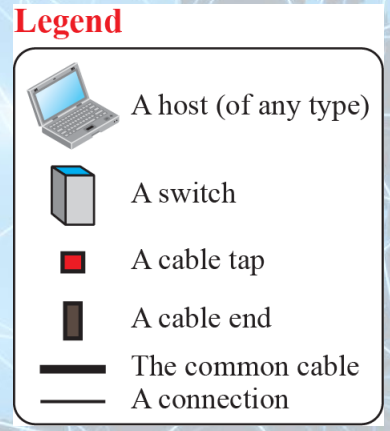
Local Area Networks



a. LAN with a common cable (past)



b. LAN with a switch (today)



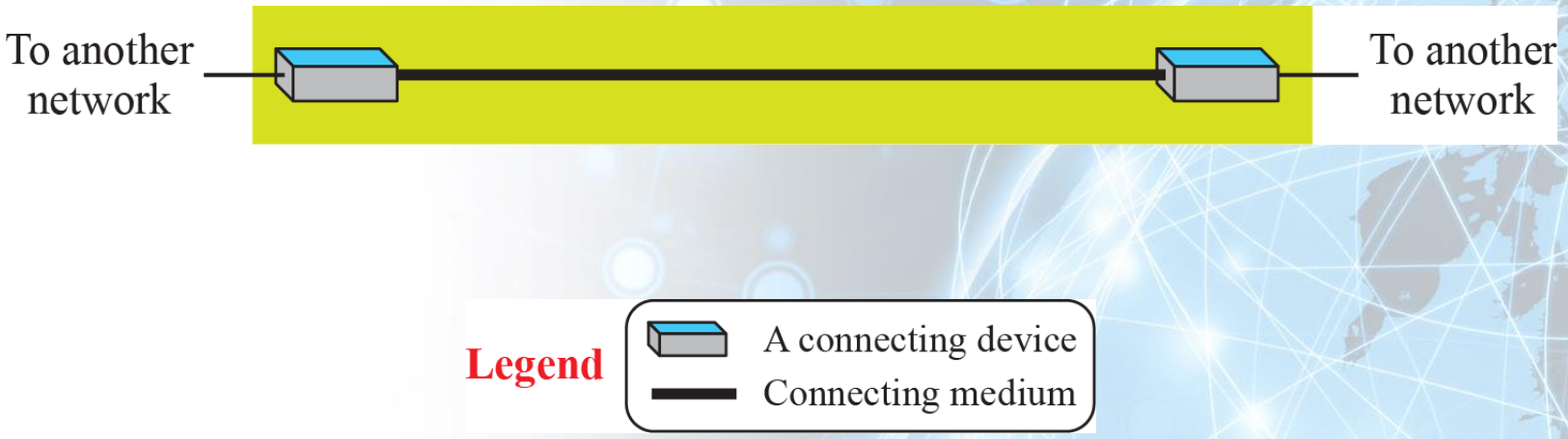
Wide Area Network

- Wider geographical span than a LAN
- Spans a town, a state, a country, or even the world
- Interconnects connecting devices such as switches, routers, or modems
- Normally created and run by communication companies

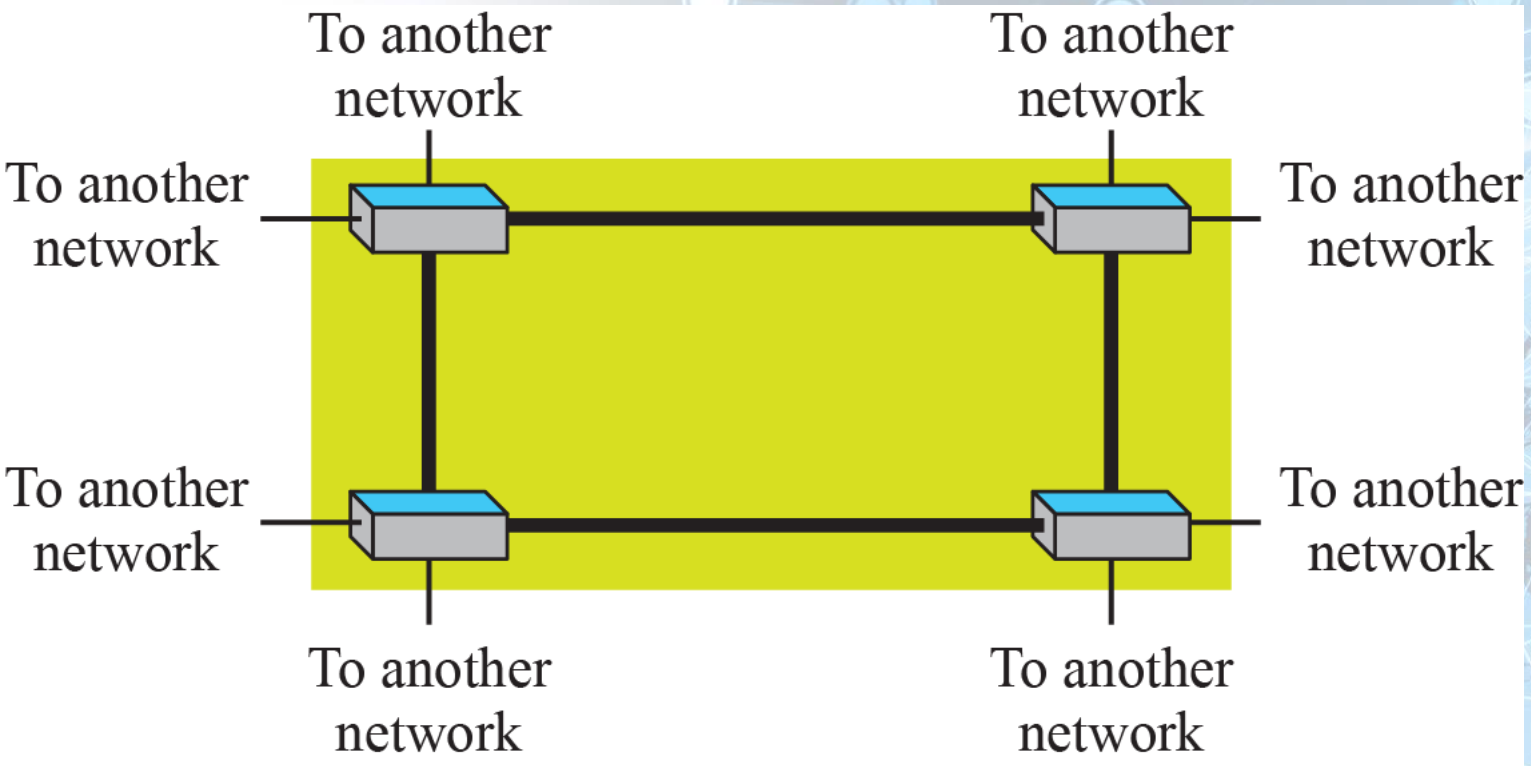
Wide Area Network

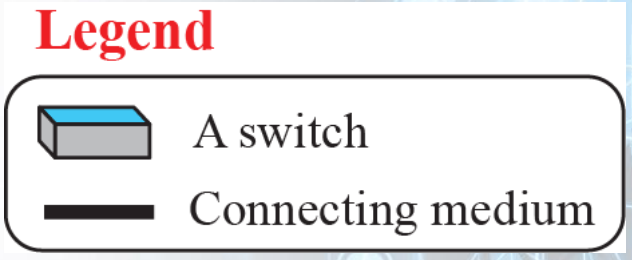
- Point-to-Point WAN
- Switched WAN
- Internetwork

Point-to-Point WANs

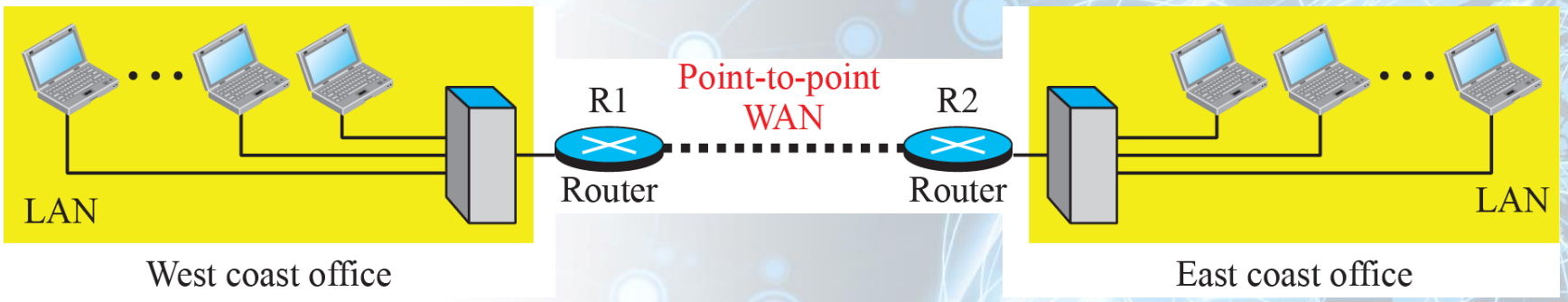


Switched WANs





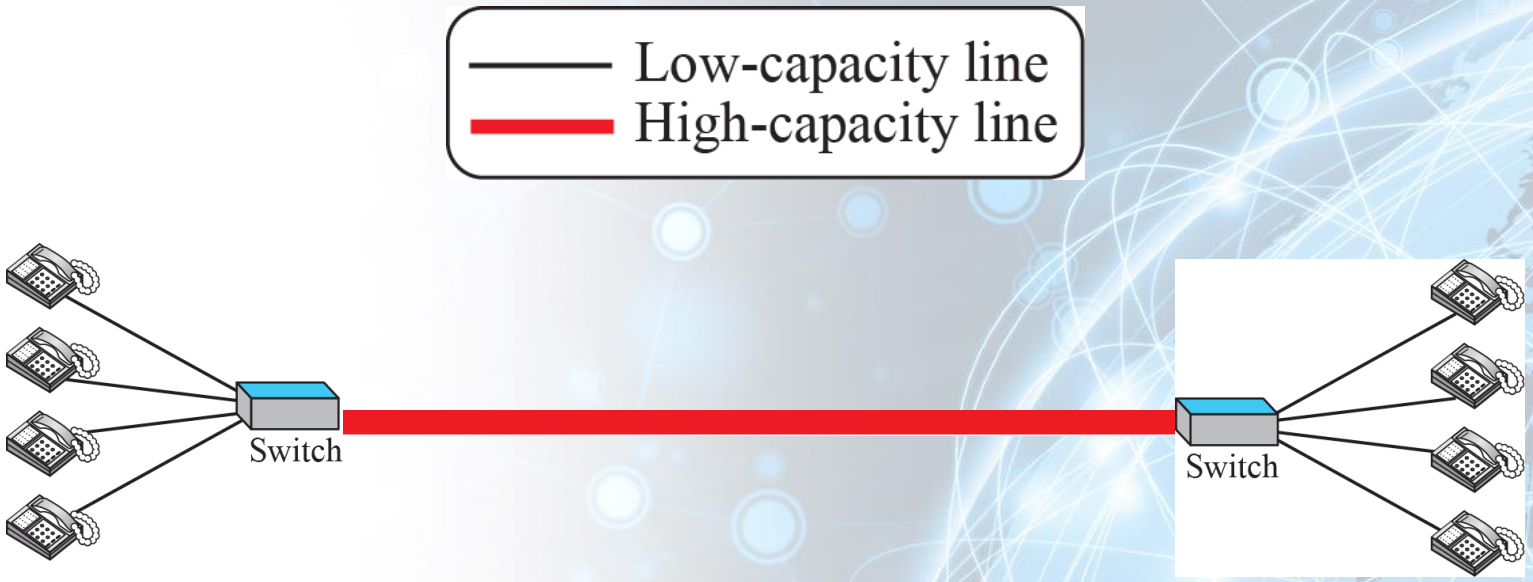
Internetwork



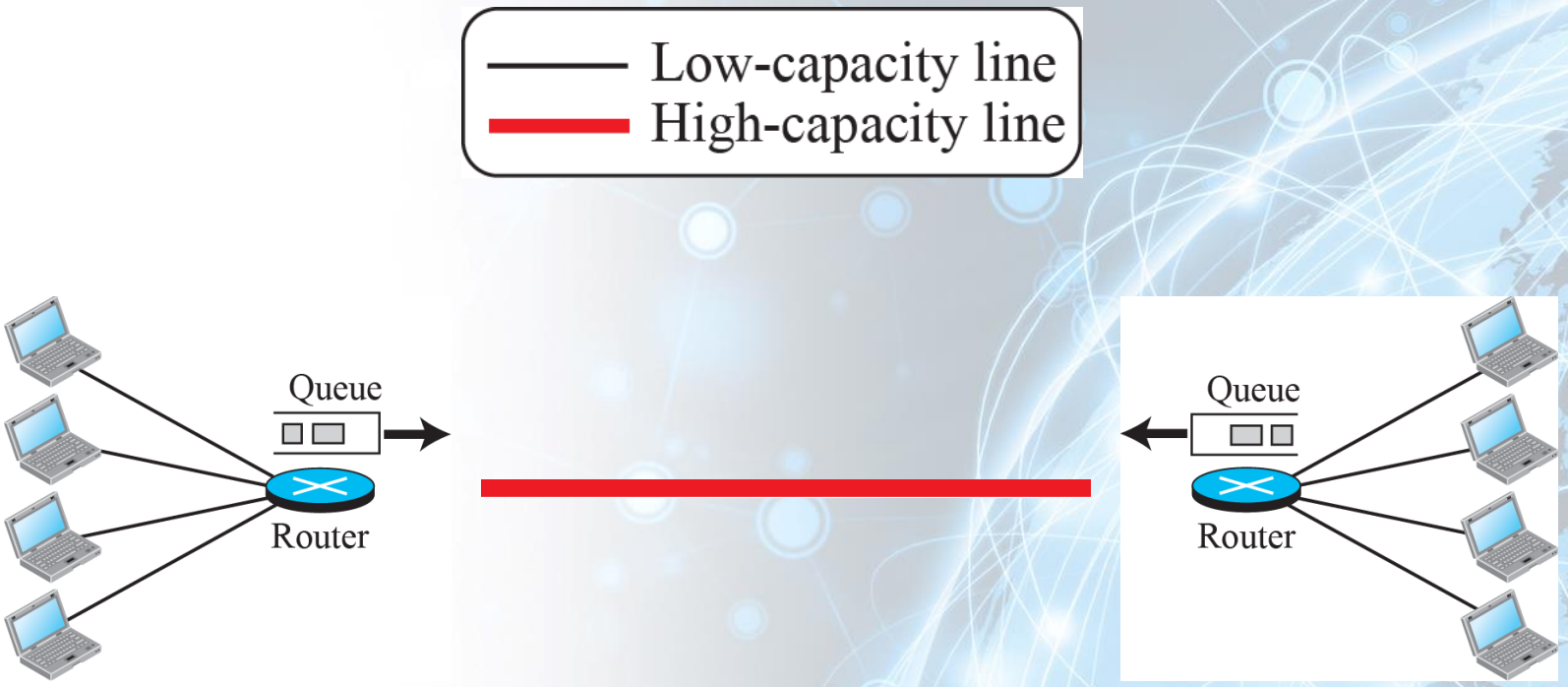
Switching

- **Switching**
  - ✓ **Circuit-Switched Network**
  - ✓ **Packet- Switched Network**

Circuit Switched Network



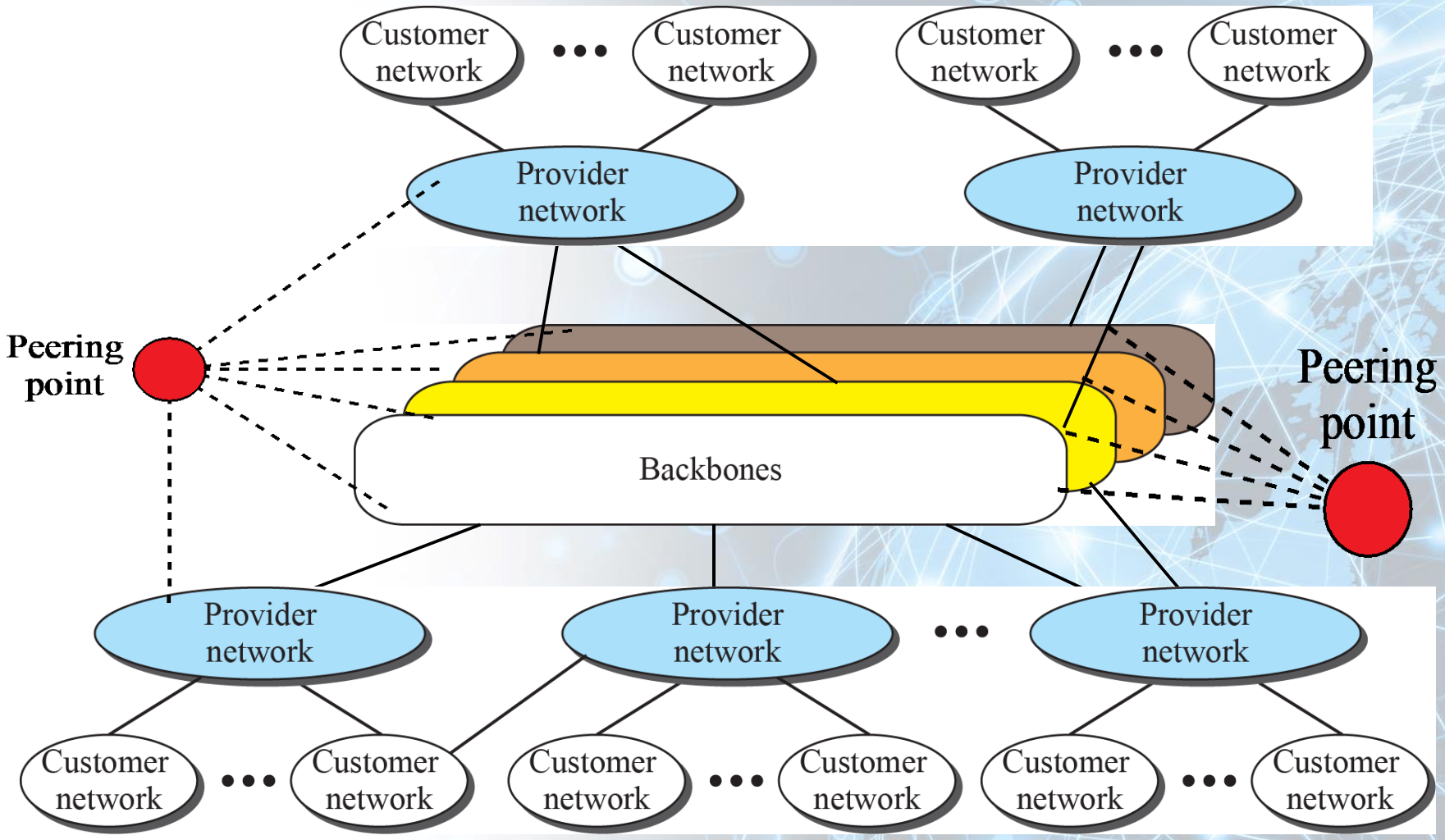
Packet Switched Network



The Internet

- An internet (note the lowercase i) is two or more networks that can communicate with each other
- The Internet (uppercase I), and is composed of thousands of interconnected networks.
- Accessing the Internet

The Internet



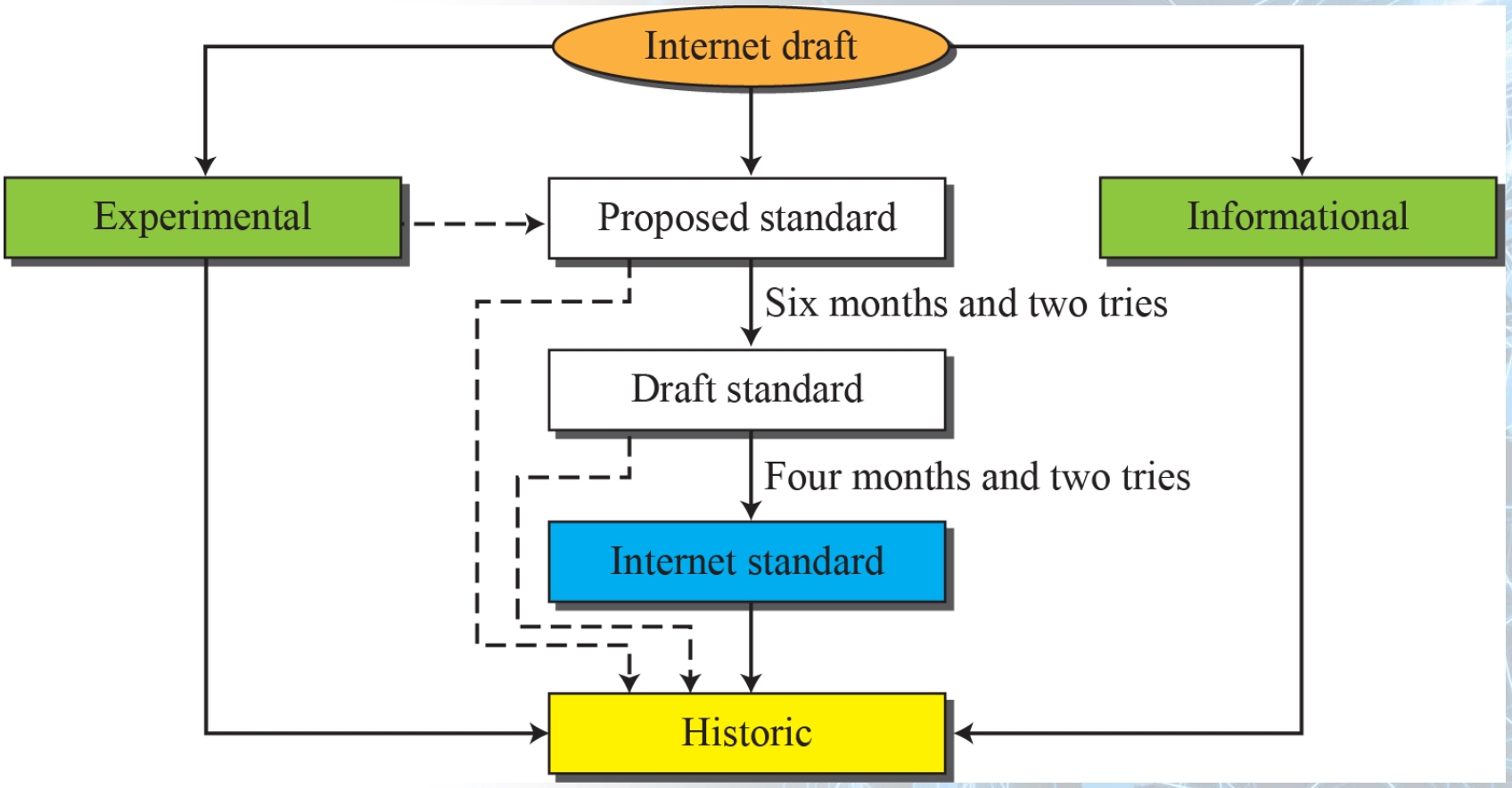
Internet History

- Telegraph and Telephone networks, before 1960:
  - ✓ Constant-rate communication only
- ARPANET- Packet Switched
- Birth of the Internet &TCP/IP
- MILNET
- CSNET
- NSFNET
- Internet Today

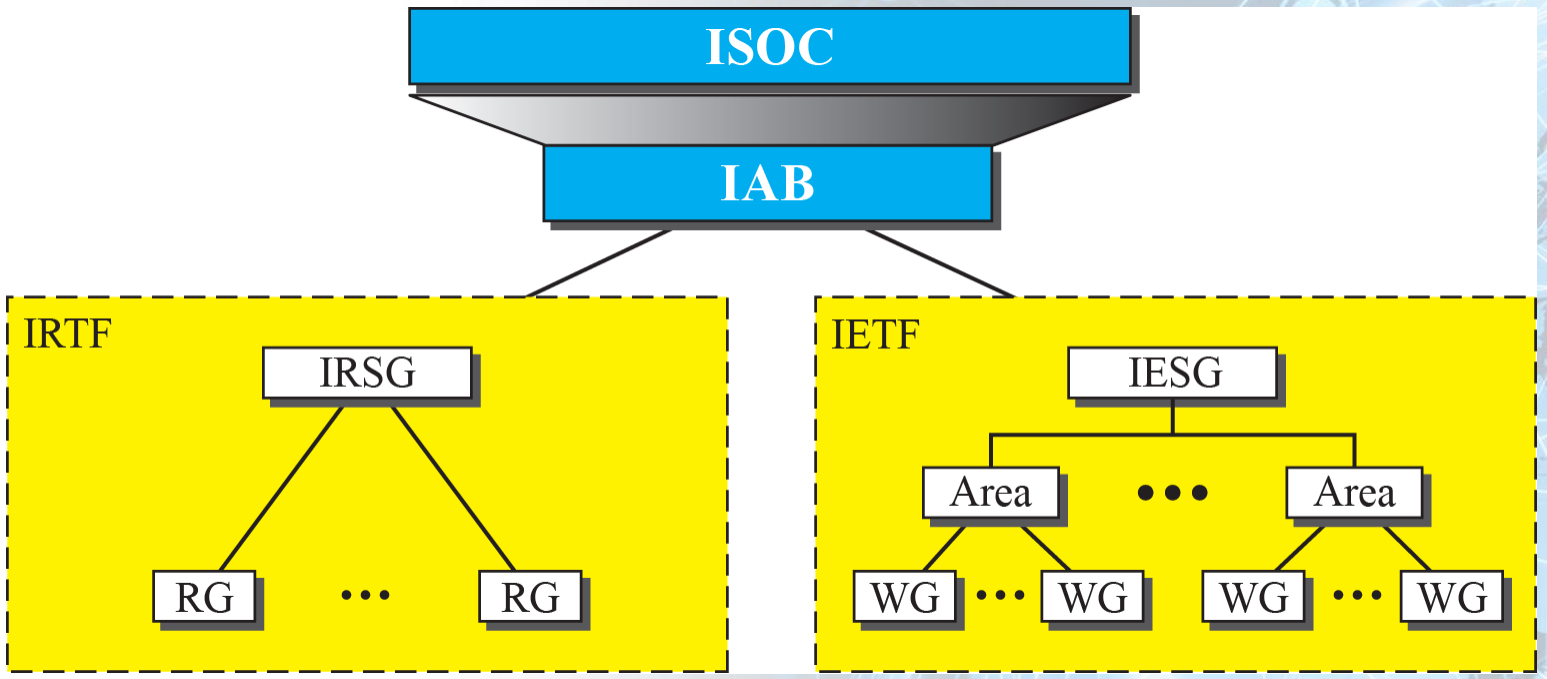
Internet Standards and Administration

- Internet draft
- Request for Comments (RFC)
  - ✓ Proposed Standard
  - ✓ Draft Standard
  - ✓ Internet Standard
  - ✓ Historic
  - ✓ Experimental
  - ✓ Informational

Internet Standards



Internet Administration



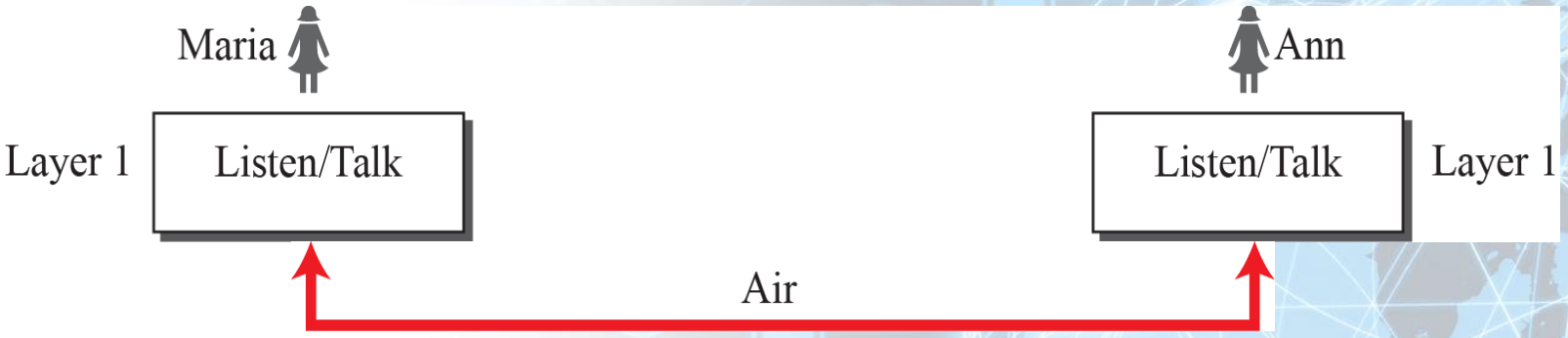
Protocol Layering - Introduction

- **Protocol**
  Rules that both the sender and receiver and all intermediate devices need to follow to be able to communicate effectively

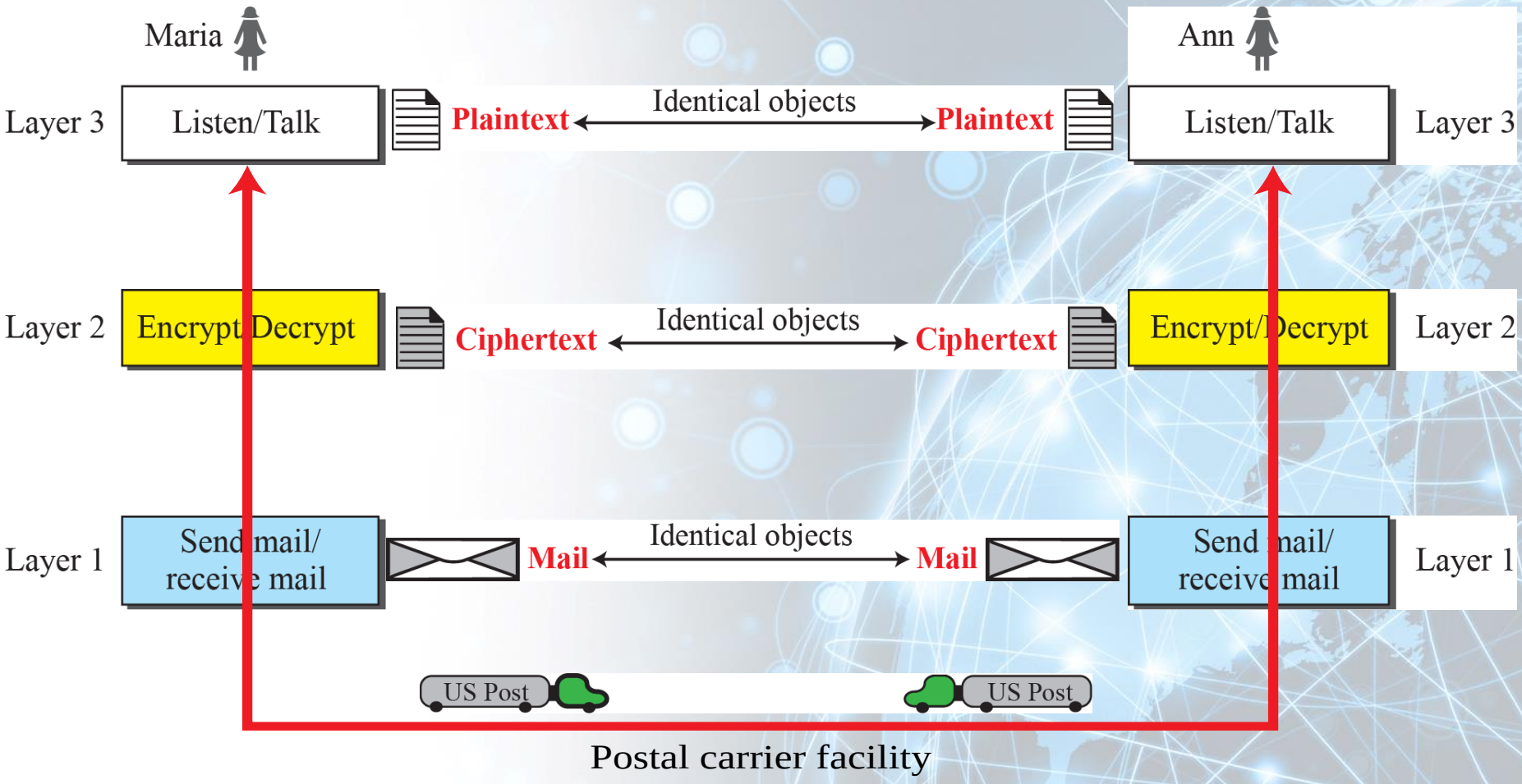
- **Protocol Layering**
  Simple Communication: only one simple protocol

  Complex Communication, we need a protocol at each layer, or Protocol Layering

Protocol Layering - Example Scenario 1



Protocol Layering - Example Scenario 2



Protocol Layering - Advantages and Disadvantages

- **Advantages**
  - ✓ Modularity
  - ✓ Separation of Service & Implementation
  - ✓ Reduced Complexity & Cost

- **Disadvantages**
  - ✓ None Really!

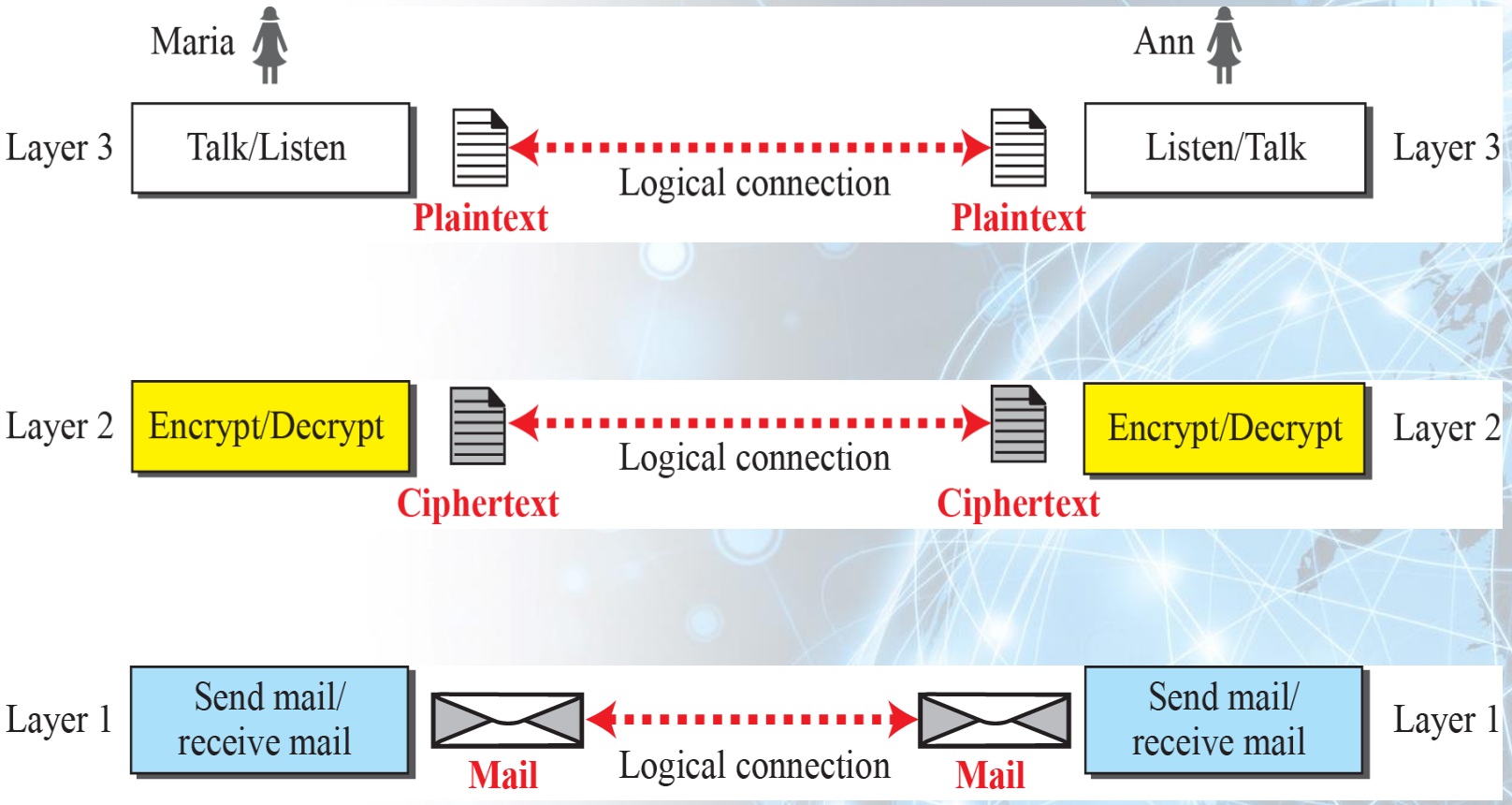
Protocol Layering - Principles

- **Two Principles**
  - ✓ Bidirectional Communication → Each Layer performs two opposite tasks in each direction
  - ✓ Two objects under each layer at both sites should be identical

Protocol Layering - Logical Connections

- **Logical Connections**
  - ✓ Imaginary connection between each layer

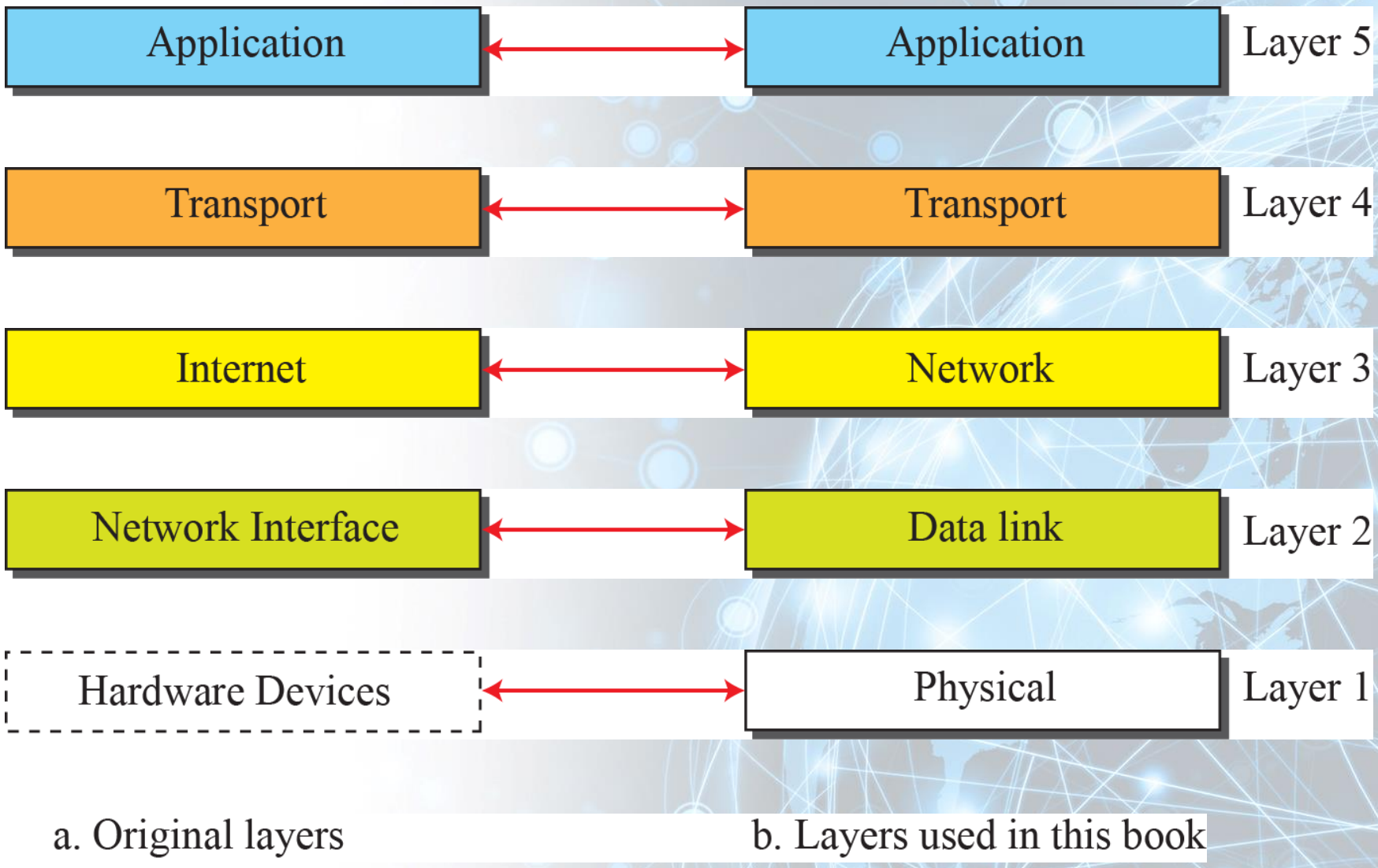
Protocol Layering



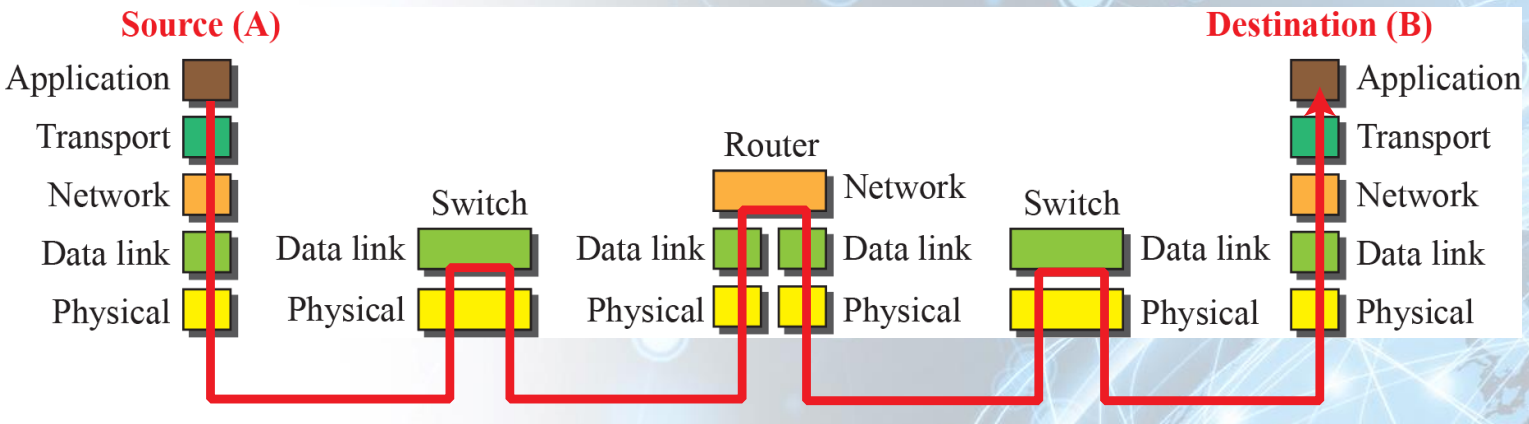
TCP/IP Protocol Suite

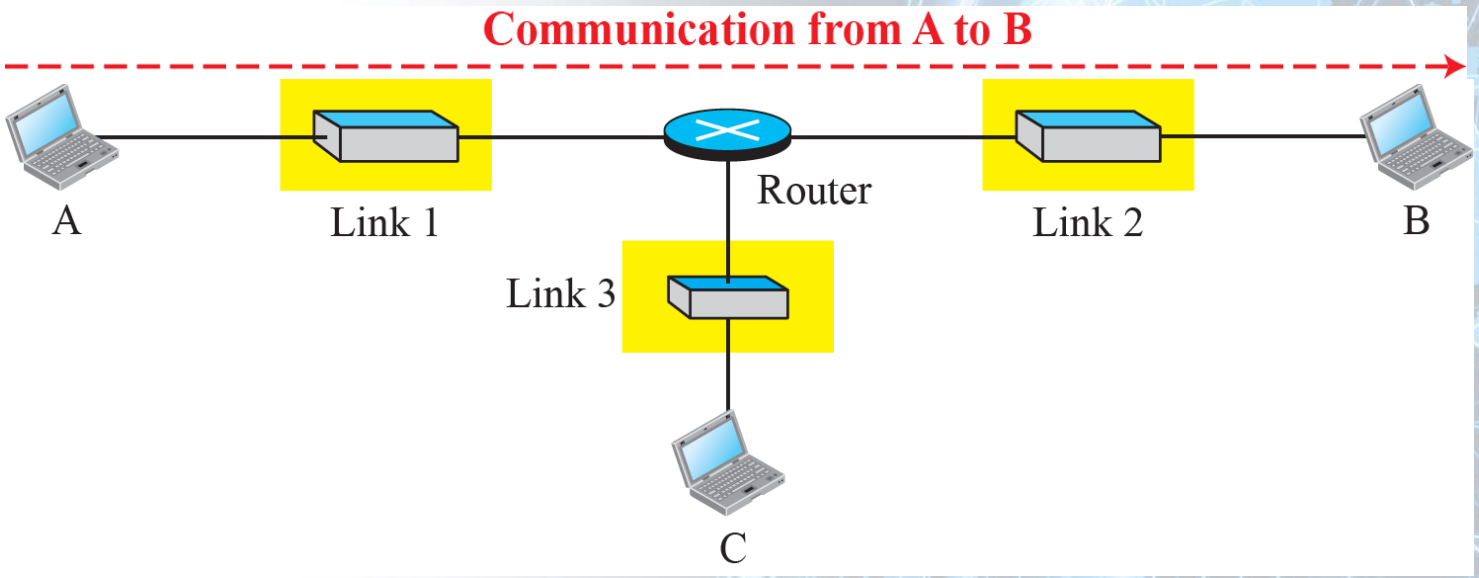
- **TCP/IP Protocol Suite**
  - ✓ Protocol suite used in Internet today
  - ✓ Each Layer provides specific functionality
  - ✓ Hierarchical Protocol
  - ✓ Presented in 1973 and chosen to be the official protocol of Internet in 1983

TCP/IP Protocol Suite



TCP/IP Protocol Suite - Layered Architecture

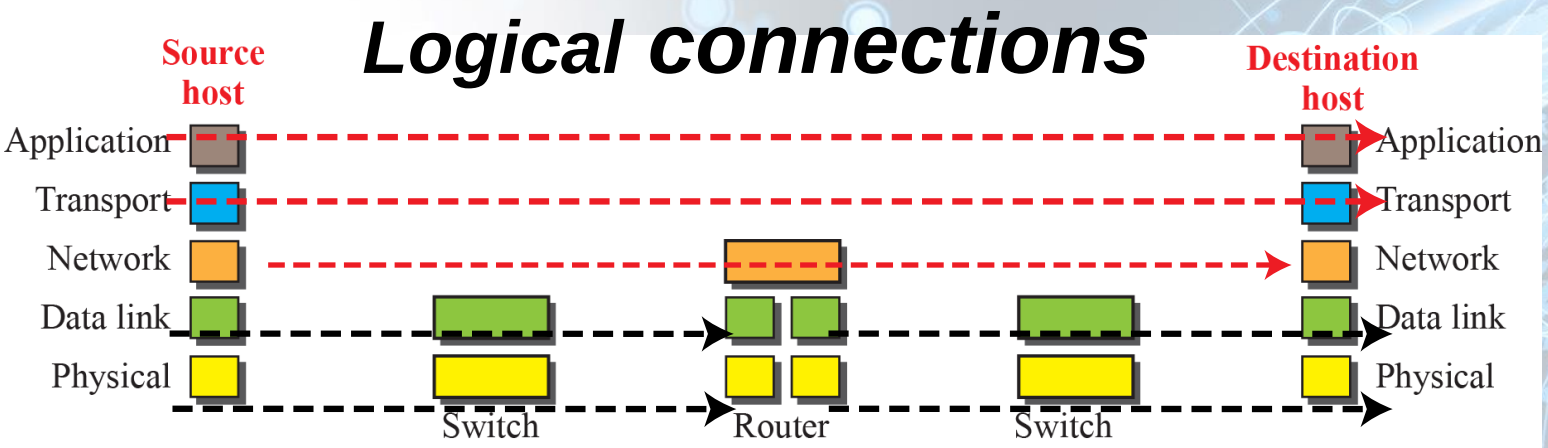


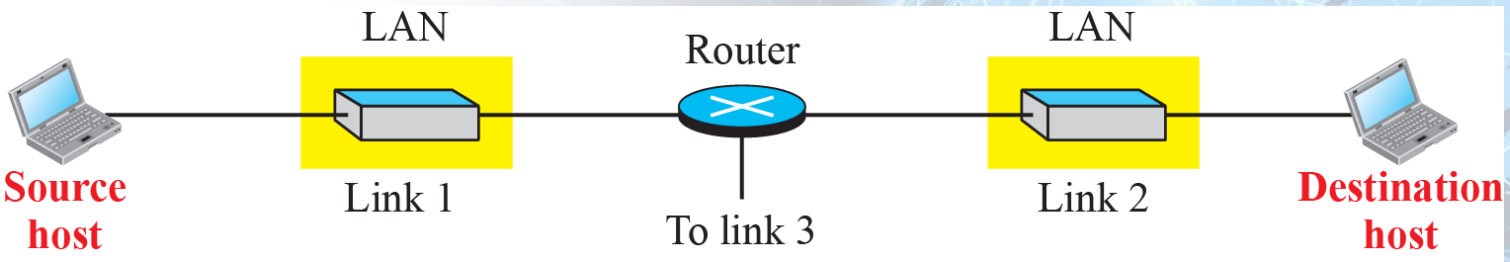


TCP/IP Protocol Suite – Function of Layers

- **Logical Connections between TCP/IP Layers**

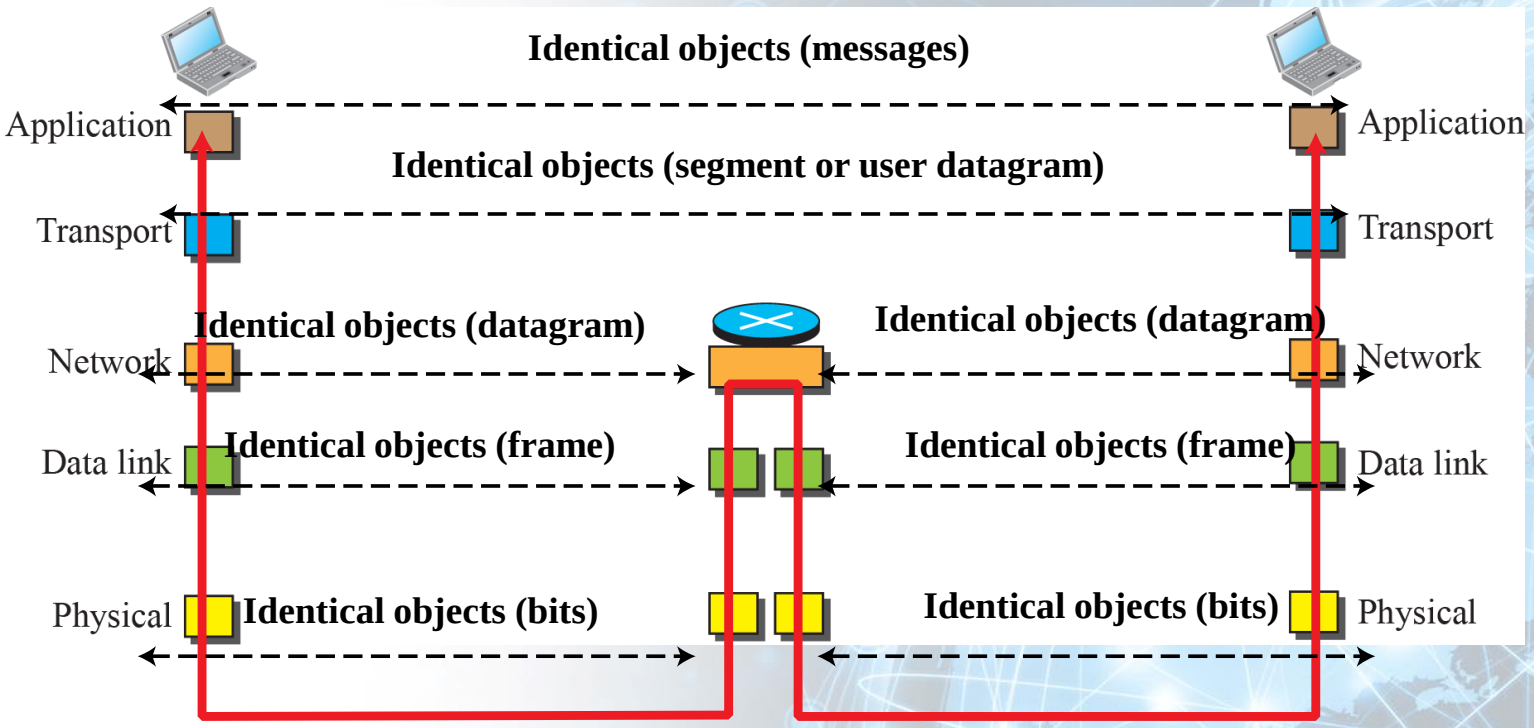
TCP/IP Protocol Suite – Function of Layers



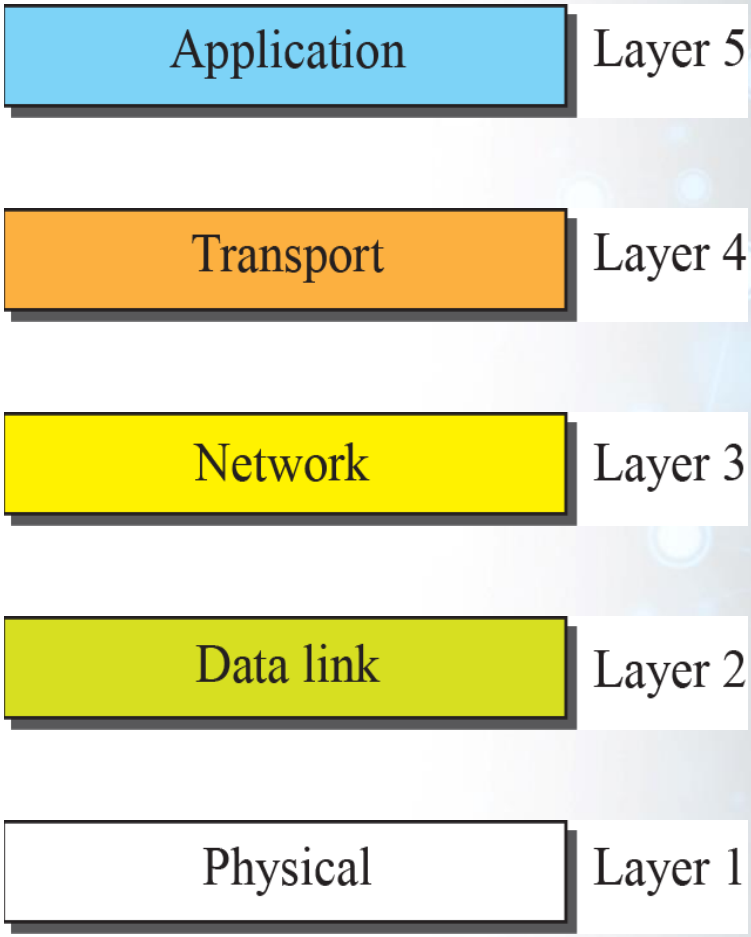


TCP/IP Protocol Suite – Function of Layers

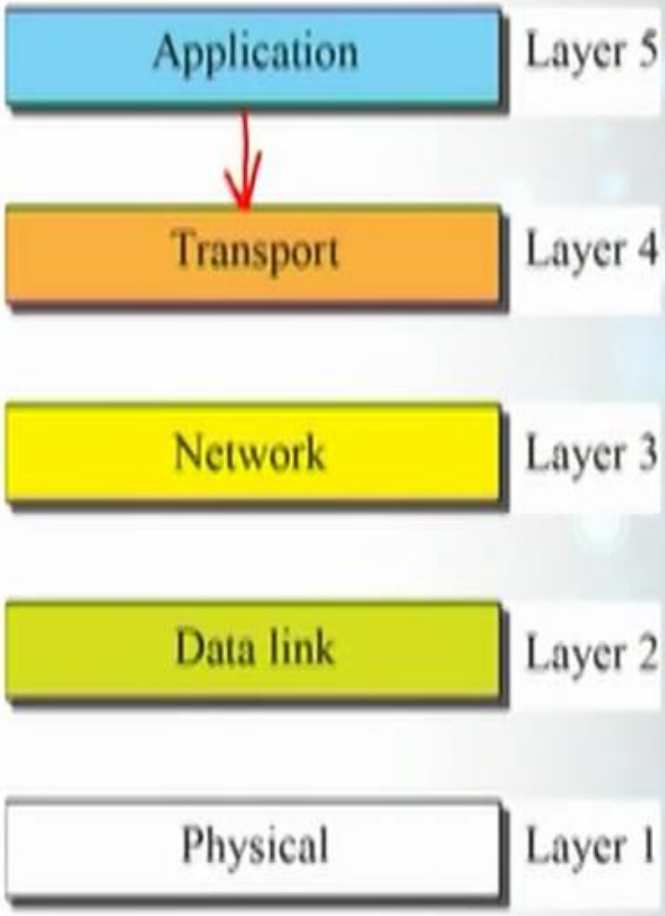
Notes: We have not shown switches because they don't change objects.



TCP/IP Protocol Suite – Layer Description



TCP/IP Protocol Suite – Layer Description



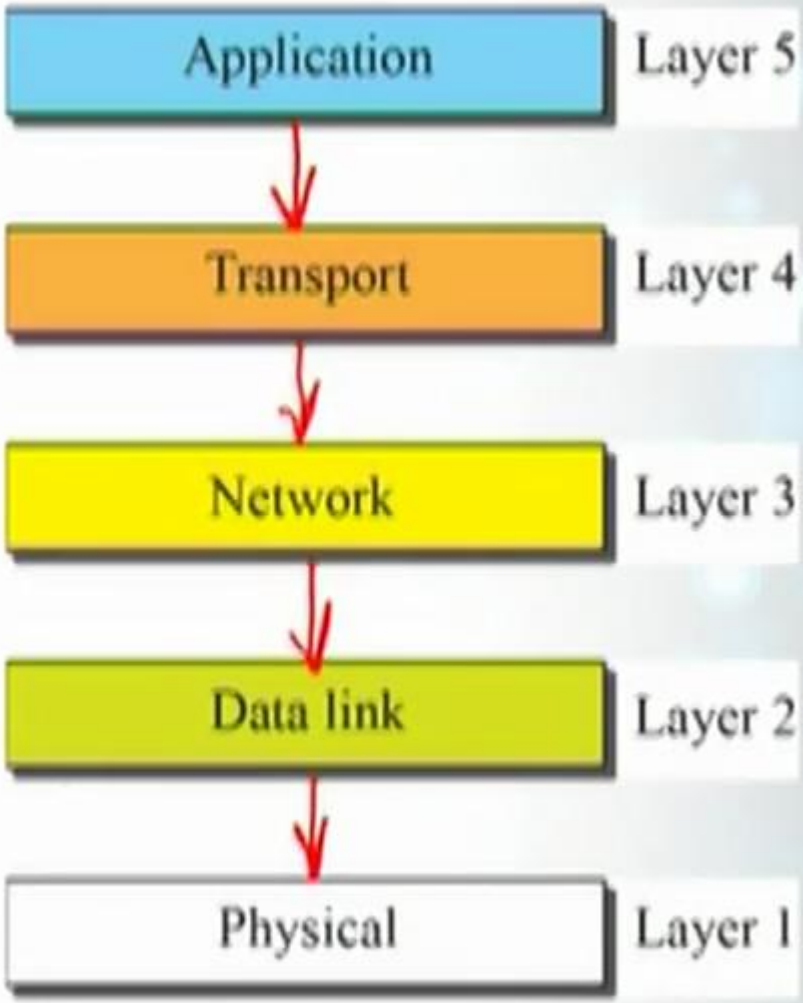
Message (object) HTTP, SMTP, FTP, ...

Segment (User Datagram) TCP, UDP

Datagram → Routing → IP

Double-click to go to fullscreen, ctrl+c

TCP/IP Protocol Suite – Layer Description



Message (object) HTTP, SMT

Segment (User Datagram) TC

Datagram → Routing →

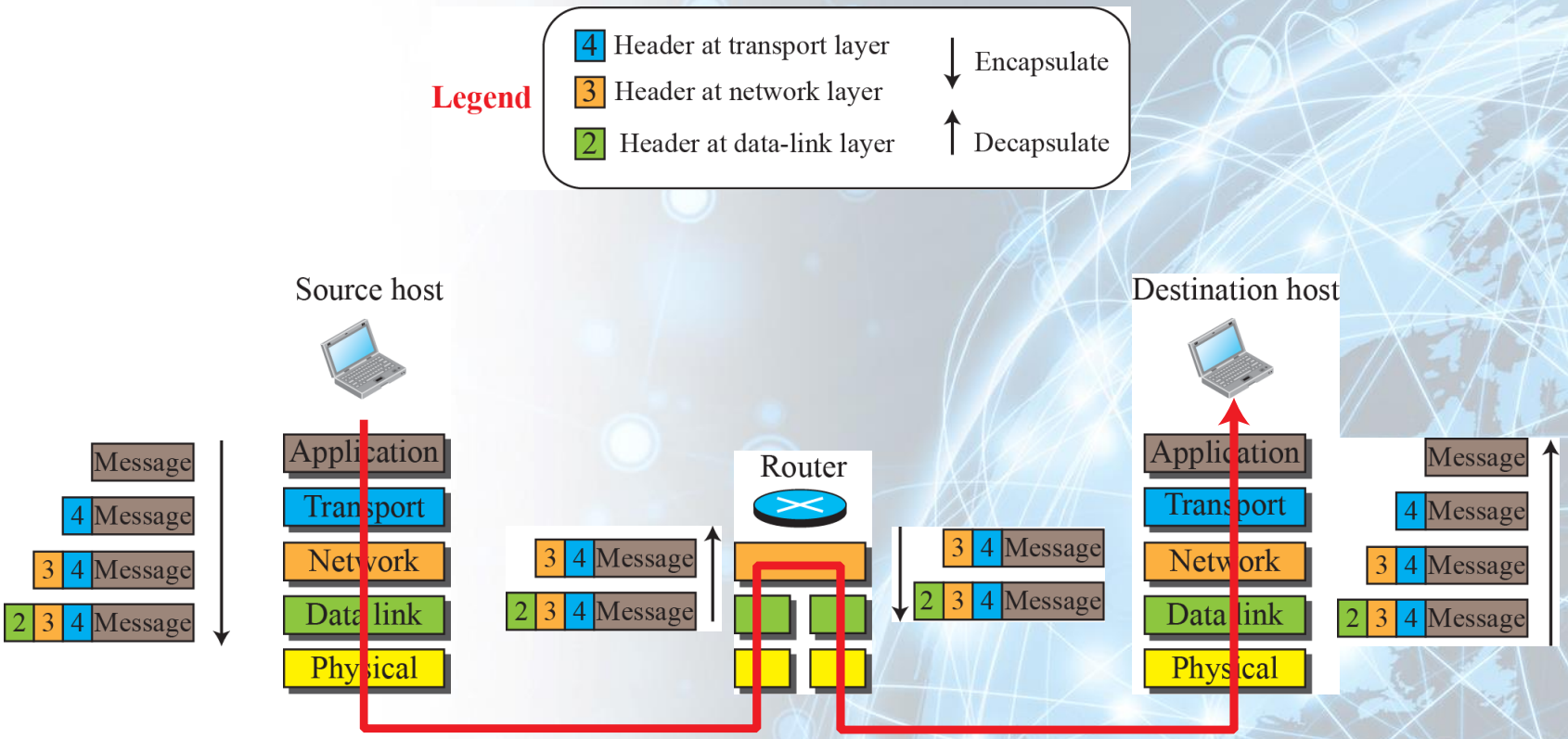
Frame (object) Standard,

Bits (object)

Encapsulation & Decapsulation

- **Important Concept in Internet Protocol Layering**
- **Layer Header**

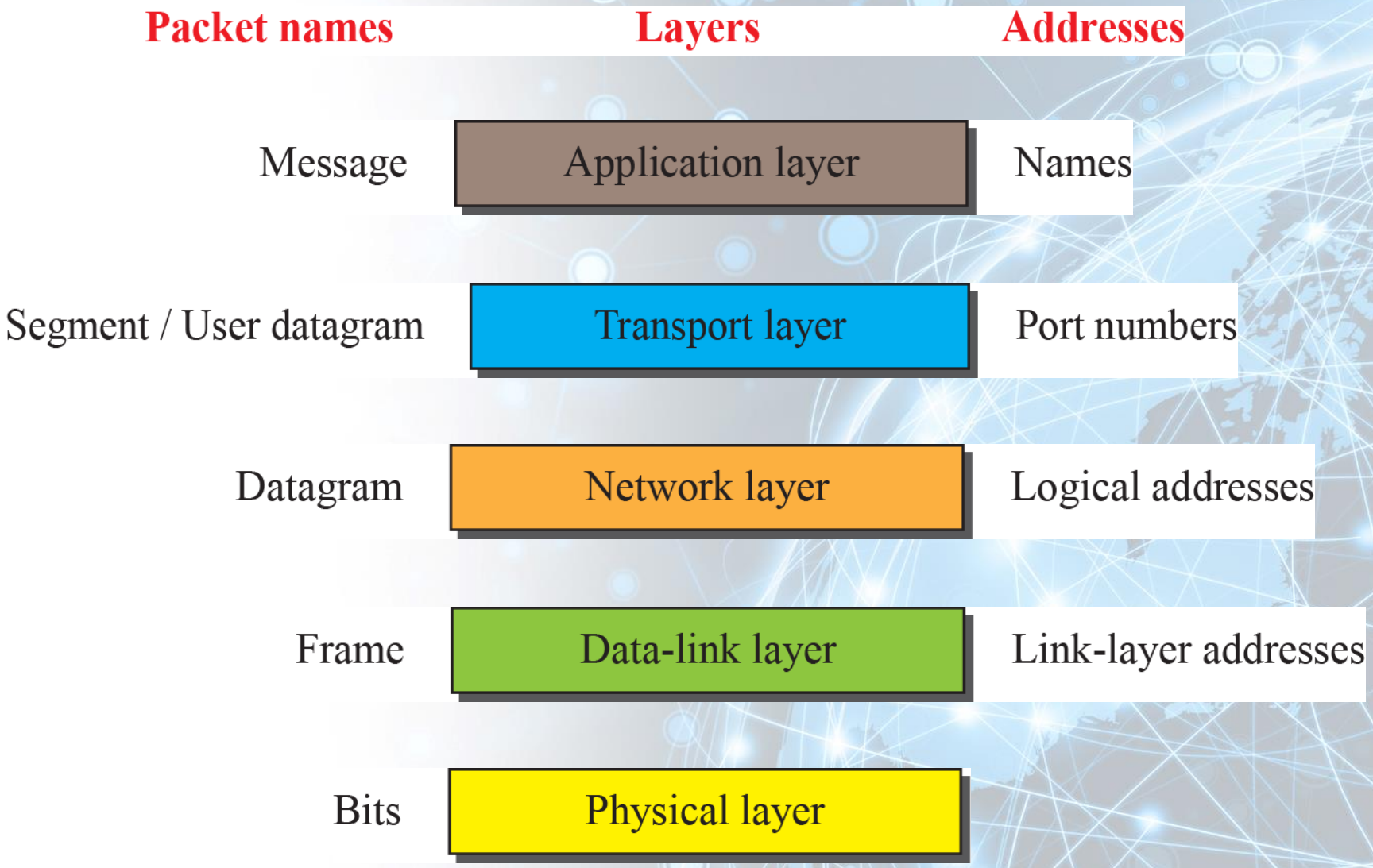
Encapsulation & Decapsulation



Addressing in TCP/IP Protocol Suite

- Every communication needs at least two addresses:
  - ✓ Source Address &
  - ✓ Destination Address
- Addressing by Layer
- Physical Layer is an exception

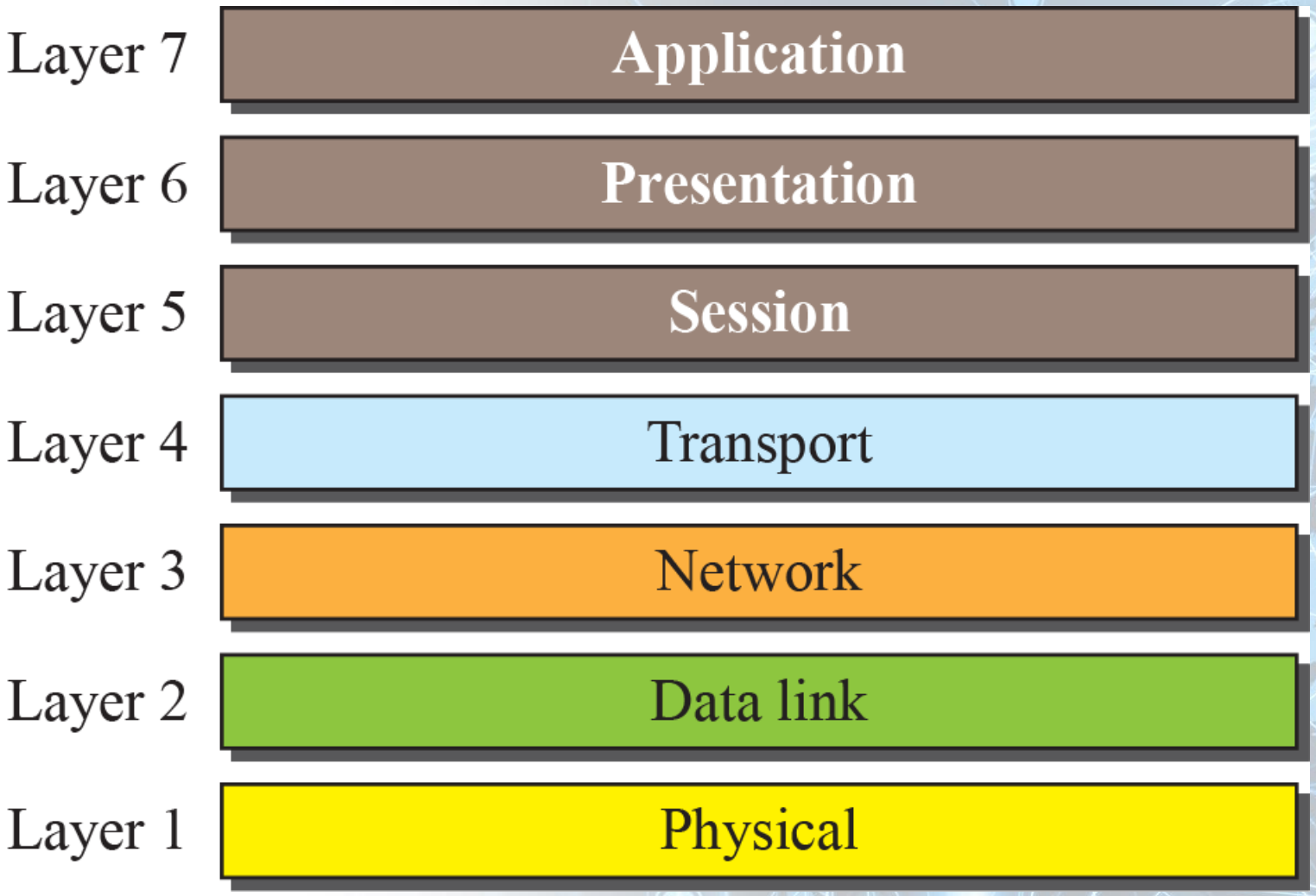
Addressing in TCP/IP Protocol Suite



The Open System Interconnection (OSI) Model

- International Organization for Standardization (ISO)
- ISO established in 1947
- Close to three-fourths of countries represented
- Introduced OSI Model in late 1970s
- OSI: a 7-Layer Model

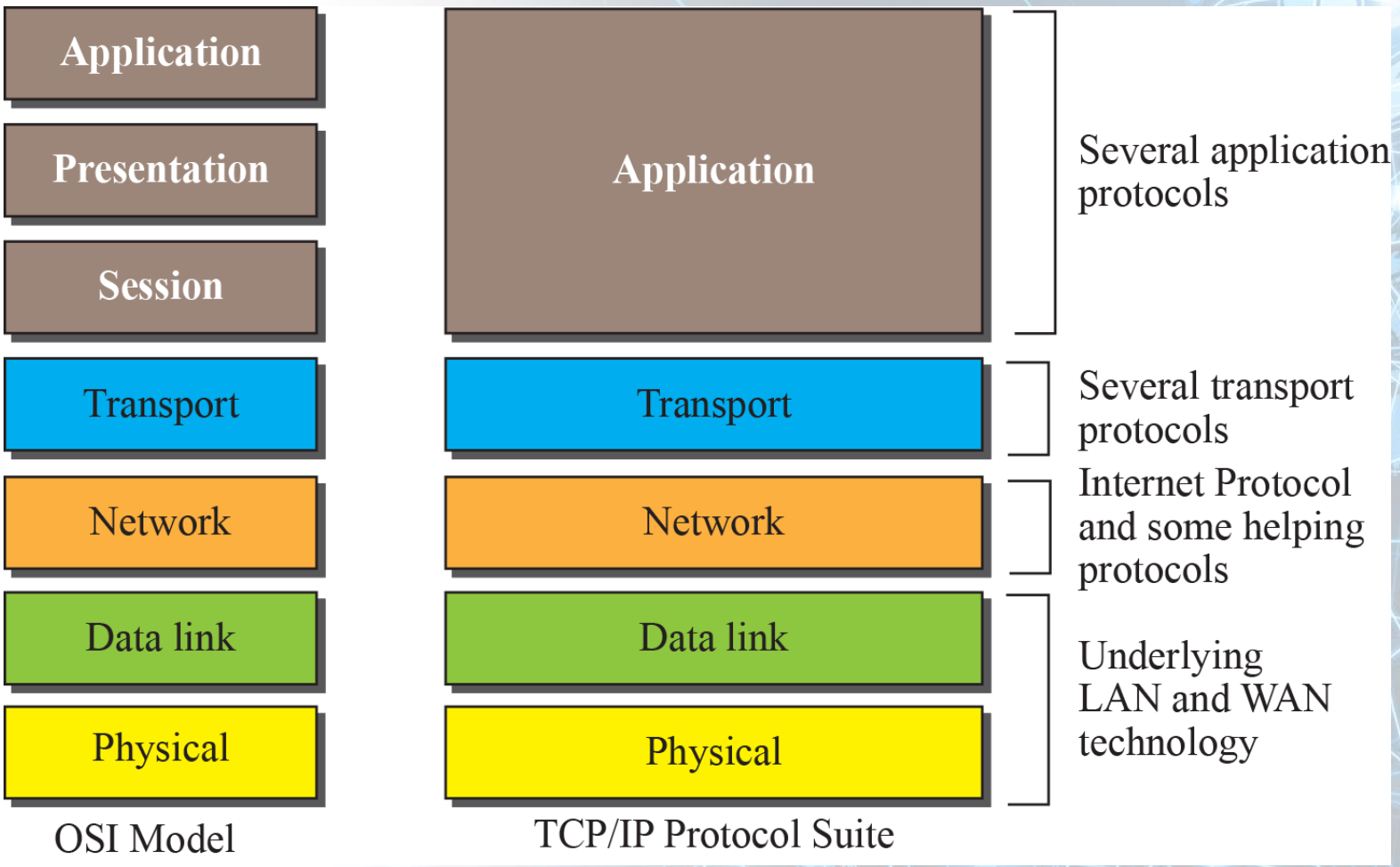
The Open System Interconnection (OSI) Model



OSI Model vs TCP/IP Protocol suite

- Two Layers of OSI missing from TCP/IP
- Application (TCP/IP) = Application + Presentation + Session (OSI)

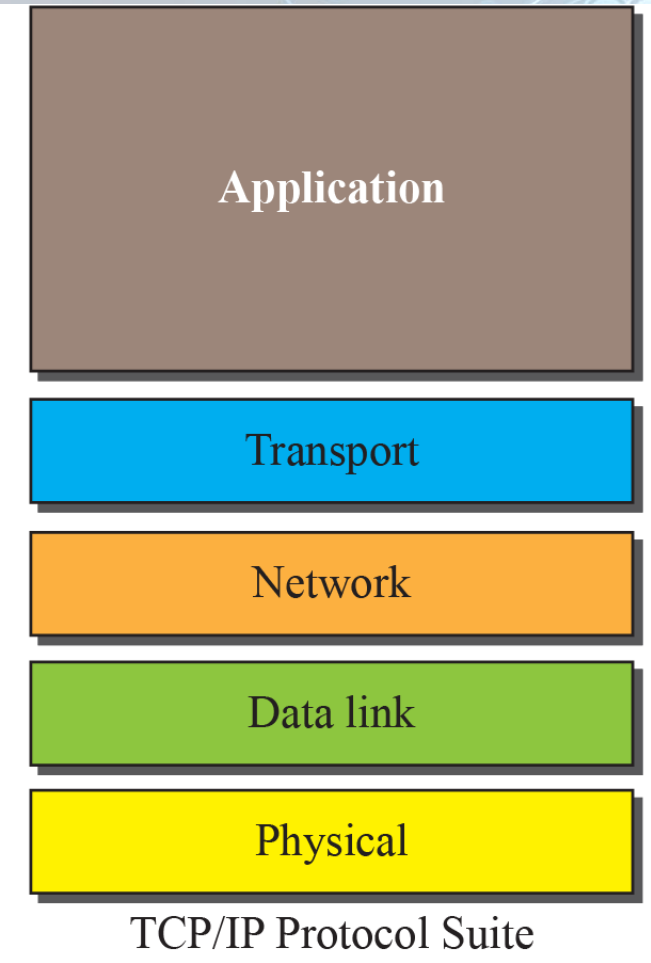
OSI Model vs TCP/IP Protocol suite



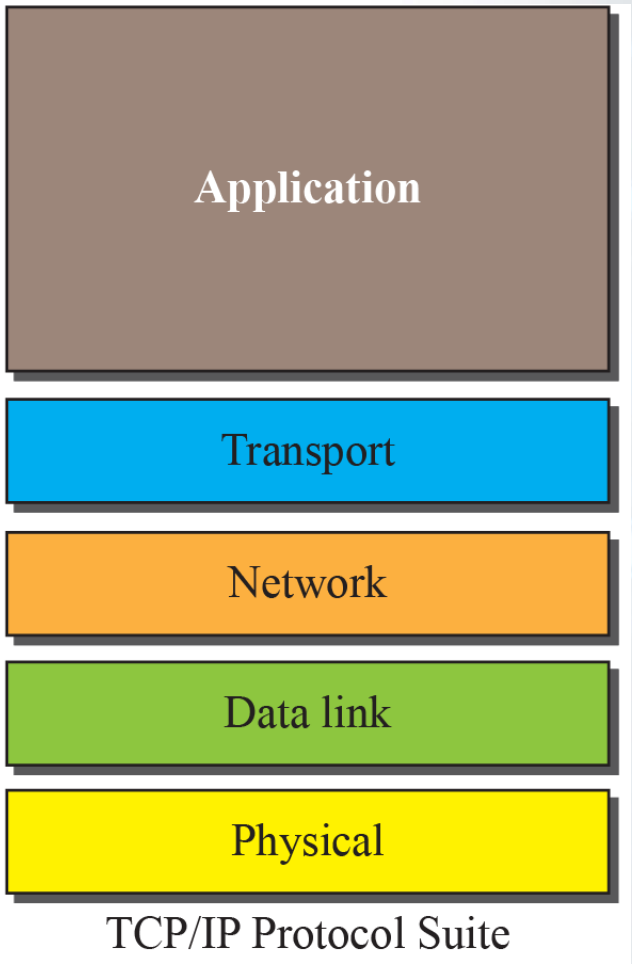
Lack of OSI Model's Success

- Three reasons OSI did not replace TCP/IP:
  - ✓ OSI was completed when TCP/IP was fully in place
  - ✓ Some layers in OSI not fully defined
  - ✓ Performance of TCP/IP better than that of OSI

Data Communication versus Computer Networks



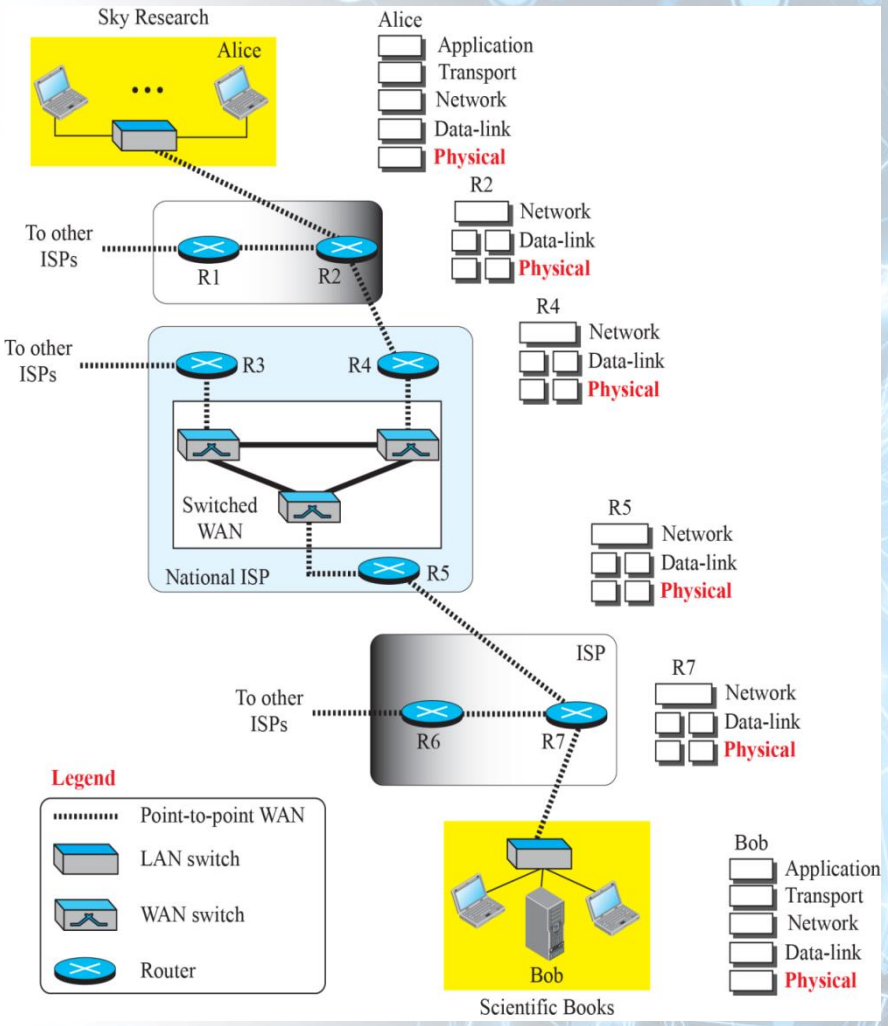
Data Communication versus Computer Networks



TCP/IP Protocol Suite

- Analog & Digital Transmission
- Transmission Media
- Switching
- Error Detection and Correction
- Media Access and Data Link Control
- Wired and Wireless LANs

Communication at Physical Layer



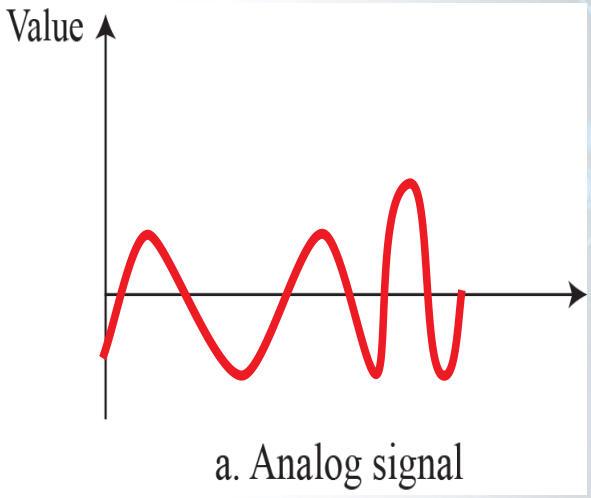
Analog & Digital Data

- Data → Analog or Digital
- Analog Data → Continuous
- Digital Data → Discrete
- Examples: Analog Clock vs. Digital Clock
- Human voice vs. Data in Computer

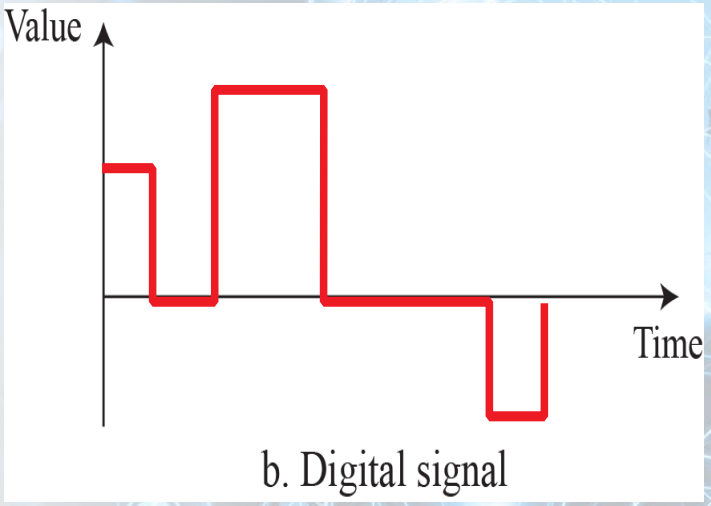
Analog & Digital Signals

- Signals represent Data
- Signals → Analog or Digital
- Analog Signal → Infinite Levels of Intensity over time
- Digital Signal → Limited number of defined values

Analog & Digital Signals



a. Analog signal



b. Digital signal

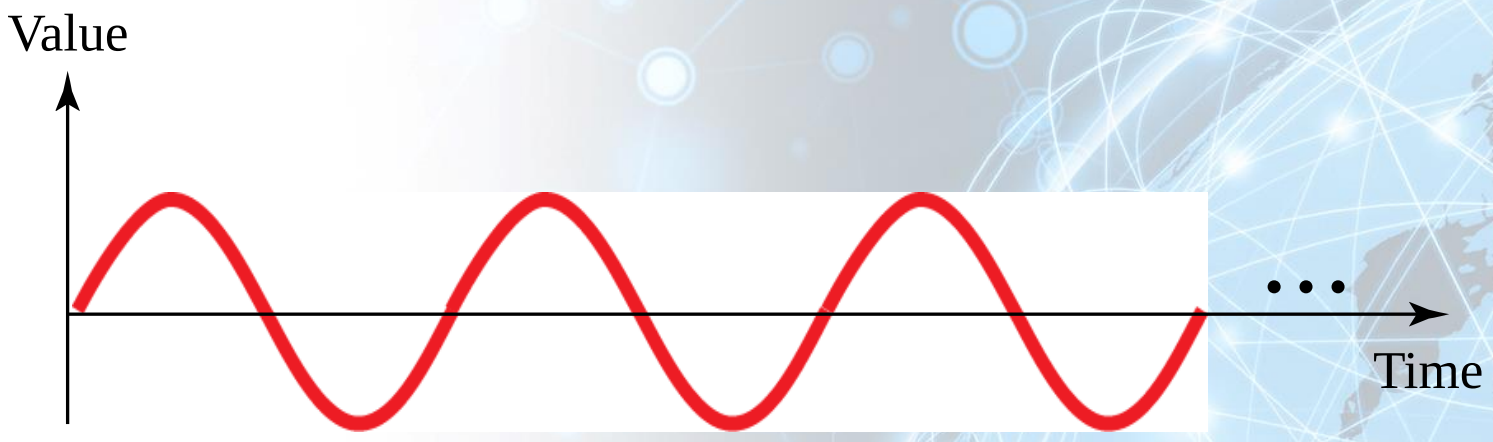
Periodic & Non-periodic Signals

- Analog/Digital Signal → Periodic or Non-periodic
- Periodic Signal → Pattern
- Period and Cycle
- Non-Periodic → No Pattern
- Periodic ANALOG Signals and Non-periodic DIGITAL Signals

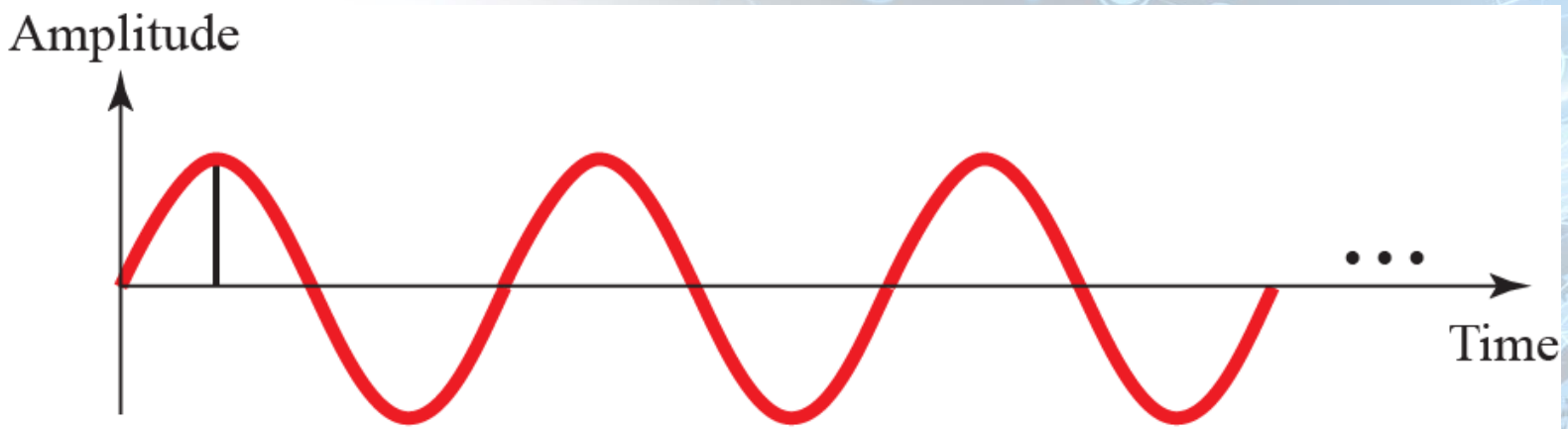
Periodic Analog Signals

- **Periodic Analog Signals → Simple or Composite**
- **Simple Periodic Analog signal→ Sine wave**
- **Composite Periodic Analog signal→ Composed of multiple sine waves**

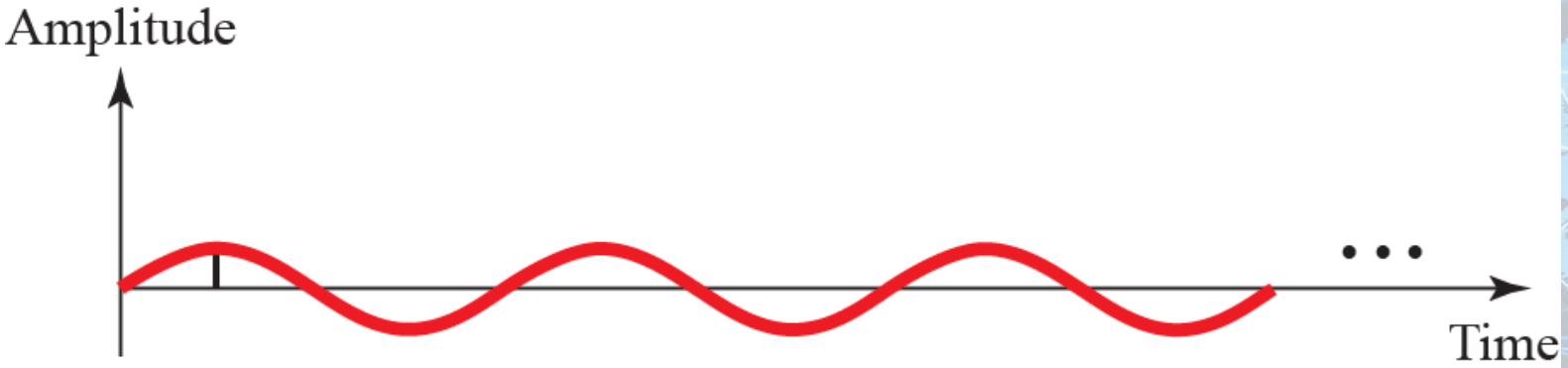
Sine Wave



Sine Wave – Peak Amplitude



a. A signal with high peak amplitude

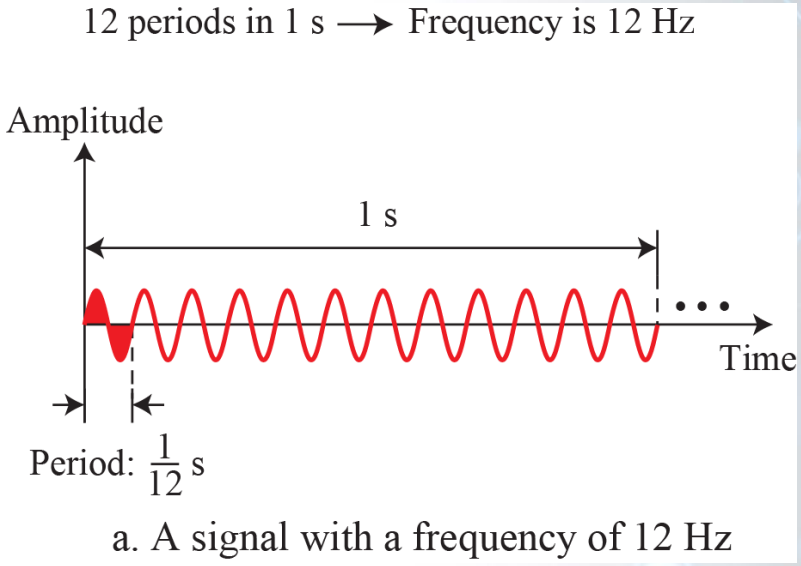


b. A signal with low peak amplitude

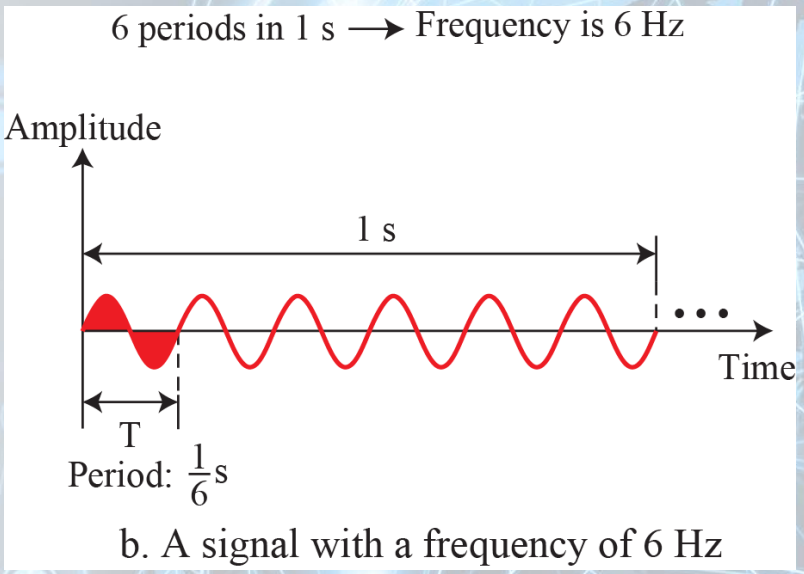
Sine Wave –Frequency

- Period (T) → Amount of time required to complete 1 cycle
- Frequency (f) → No. of Periods in 1 sec
- f = 1/T or T = 1/f

Sine Wave –Frequency



a. A signal with a frequency of 12 Hz



b. A signal with a frequency of 6 Hz

Sine Wave –Frequency

Period		*Frequency*	
Unit	*Equivalent*	*Unit*	*Equivalent*
Seconds (s)	1 s	Hertz (Hz)	1 Hz
Milliseconds (ms)	10^{-3} s	Kilohertz (kHz)	10^{3} Hz
Microseconds (μs)	10^{-6} s	Megahertz (MHz)	10^{6} Hz
Nanoseconds (ns)	10^{-9} s	Gigahertz (GHz)	10^{9} Hz
Picoseconds (ps)	10^{-12} s	Terahertz (THz)	10^{12} Hz

Example

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

Example

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

Phase (or Phase Shift)

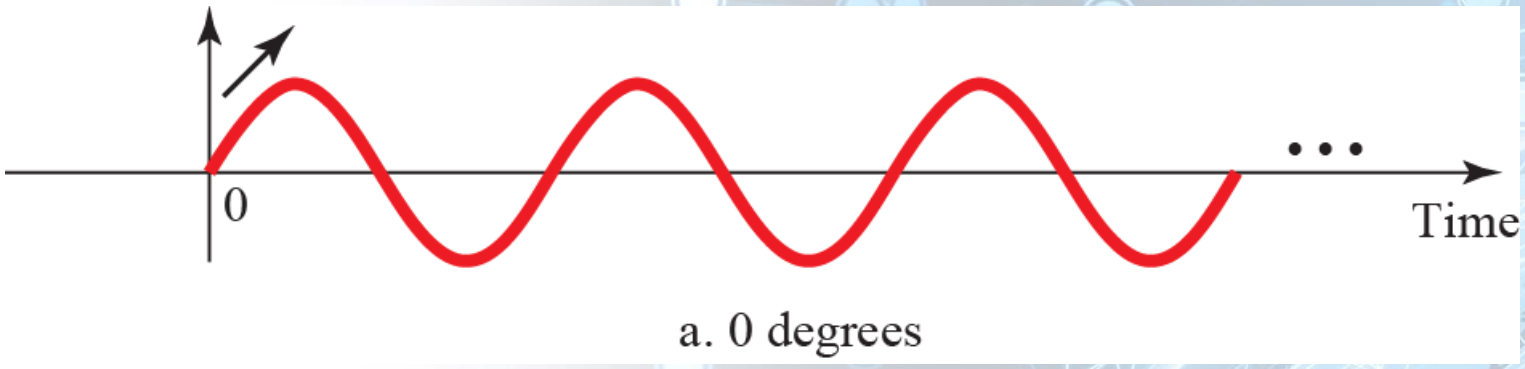
- Position of waveform relative to time 0
- Phase describes the amount of shift of the wave
- Indicates start of the first cycle

Phase

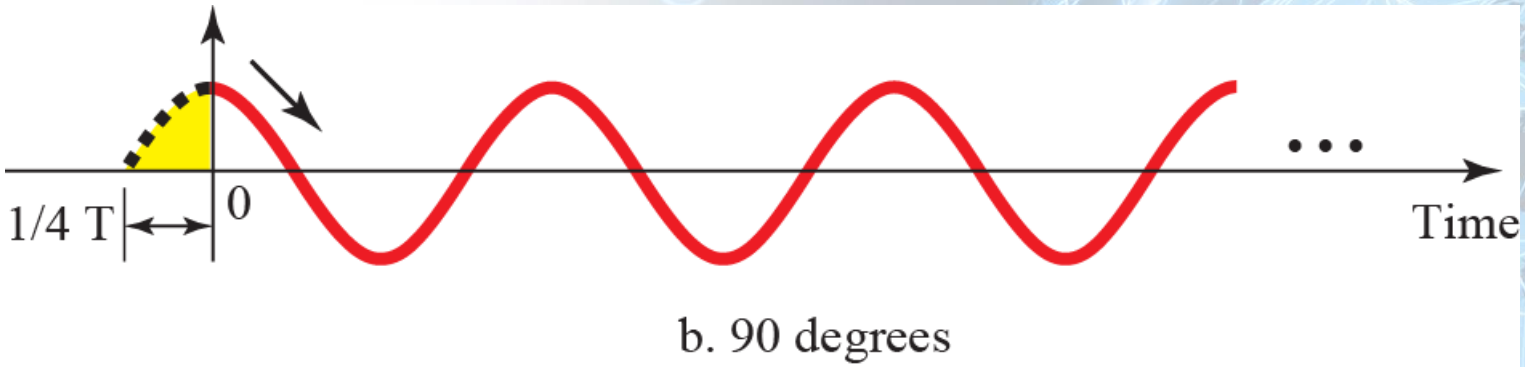
$$360^\circ = 2\pi \text{ radians}$$

$$1^\circ = \frac{2\pi}{360} \text{ rad}$$

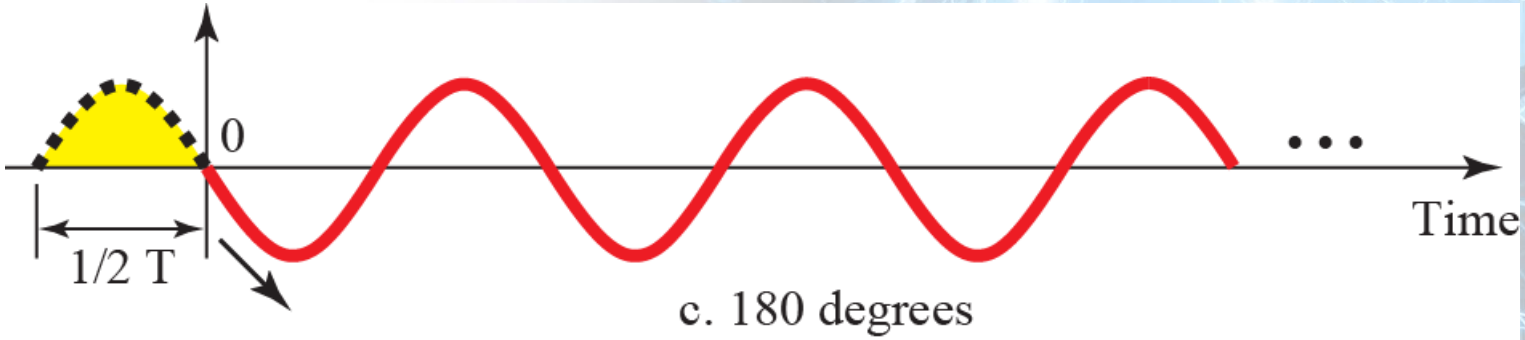
Phase



a. 0 degrees



b. 90 degrees



c. 180 degrees

Example

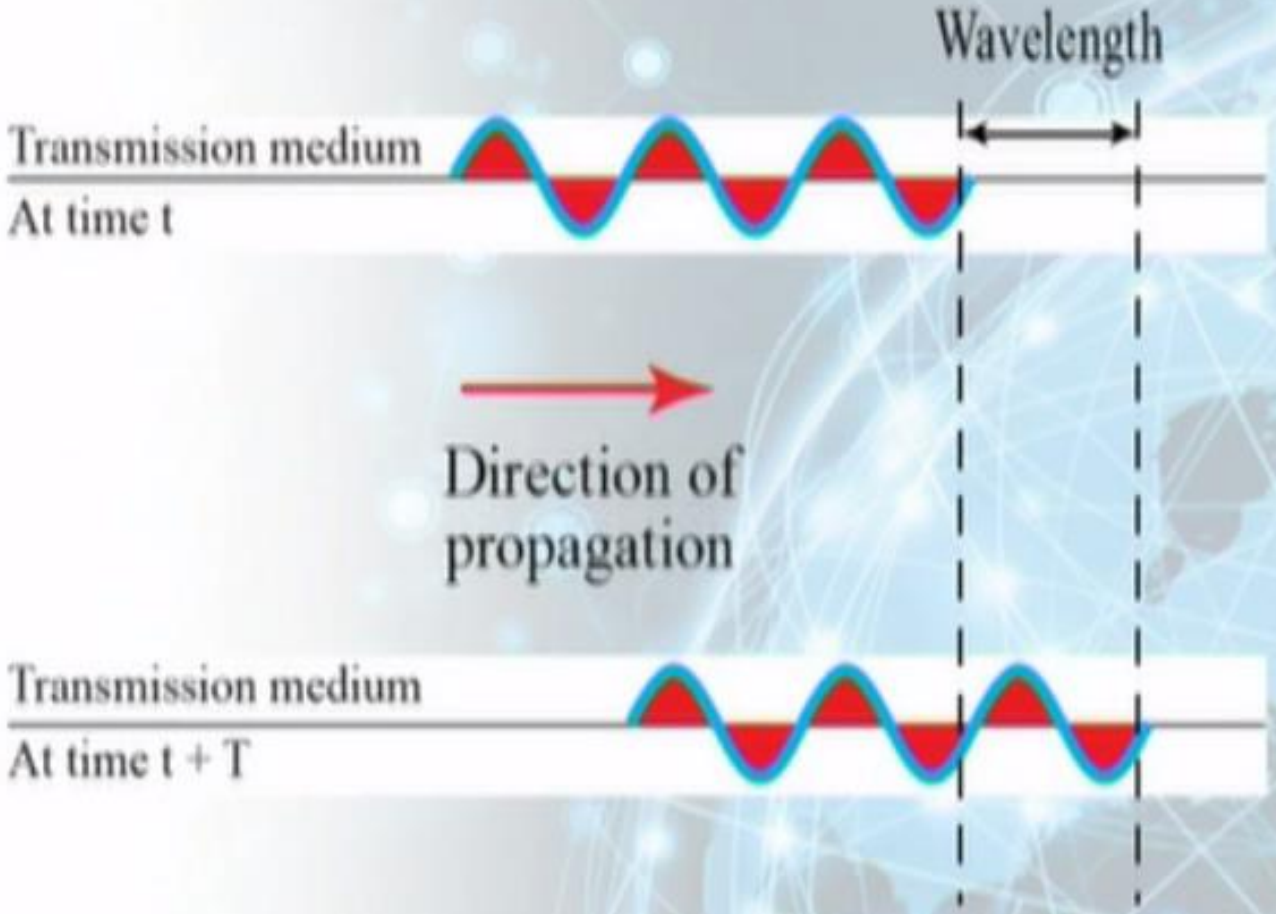
A sine wave is offset 1/6 cycle with respect to time 0. What is its phase in degrees and radians?

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 (see Figure 3.7).

Wavelength

Figure 3.7



Wavelength

Prop. Speed = c = Light (speed)

frequency = f

Wavelength = λ

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8 \text{ m/sec}}{f}$$

$$\lambda = \frac{3 \times 10^8}{4 \times 10^{14}}$$

Wavelength

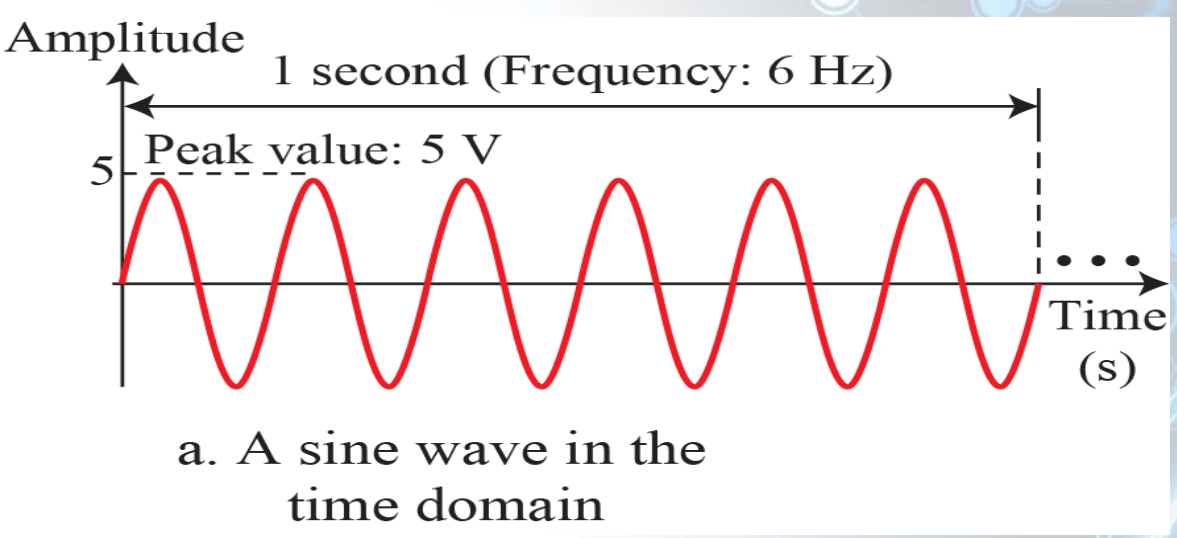
$$\lambda = 0.75 \times 10^{-6} \text{ m}$$

$$= 0.75 \mu\text{m}$$

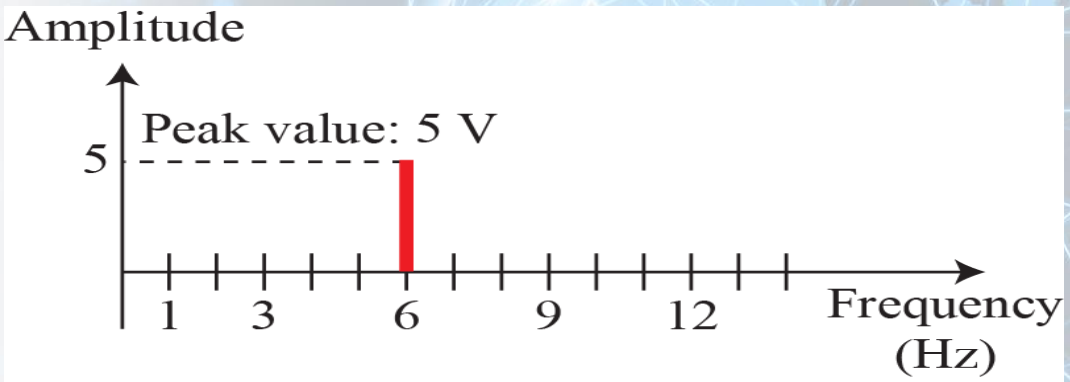
Time & Frequency Domains

A sine wave is comprehensively defined by its amplitude, frequency, and phase. We have been showing a sine wave by using what is called a time domain plot. The time-domain plot shows changes in signal amplitude with respect to time (it is an amplitude-versus-time plot). Phase is not explicitly shown on a time-domain plot.

Time & Frequency Domains



a. A sine wave in the time domain



b. The same sine wave in the frequency domain

Example 3.7

The frequency domain is more compact and useful when we are dealing with more than one sine wave. For example, Figure 3.9 shows three sine waves, each with different amplitude and frequency. All can be represented by three spikes in the frequency domain.

Time & Frequency Domains

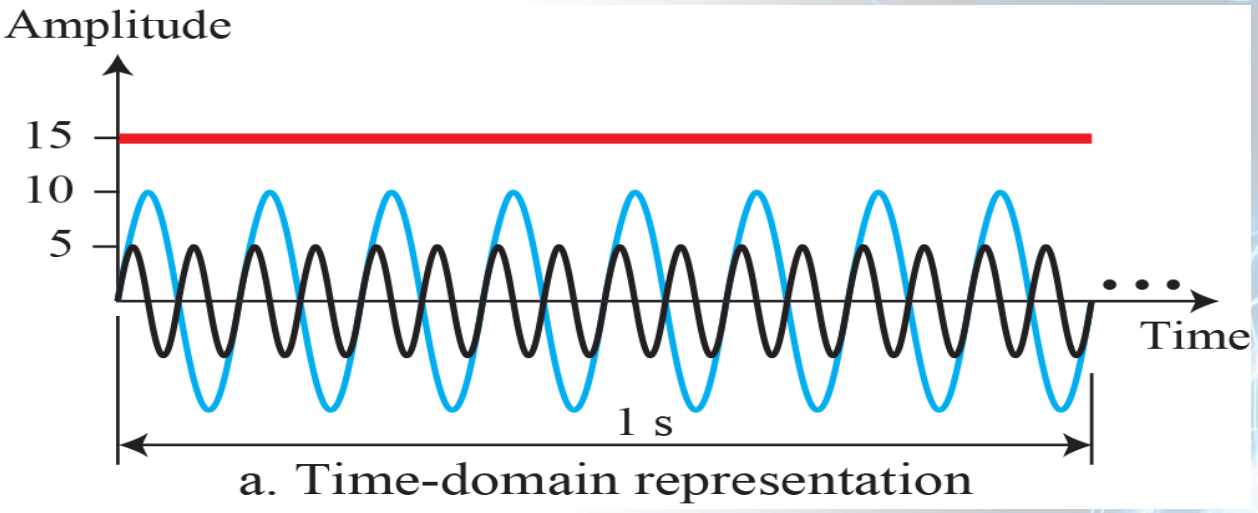
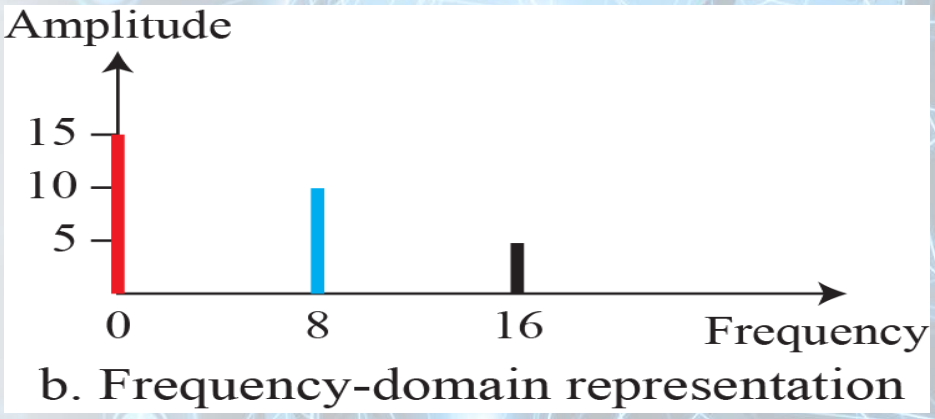


Figure 3.9



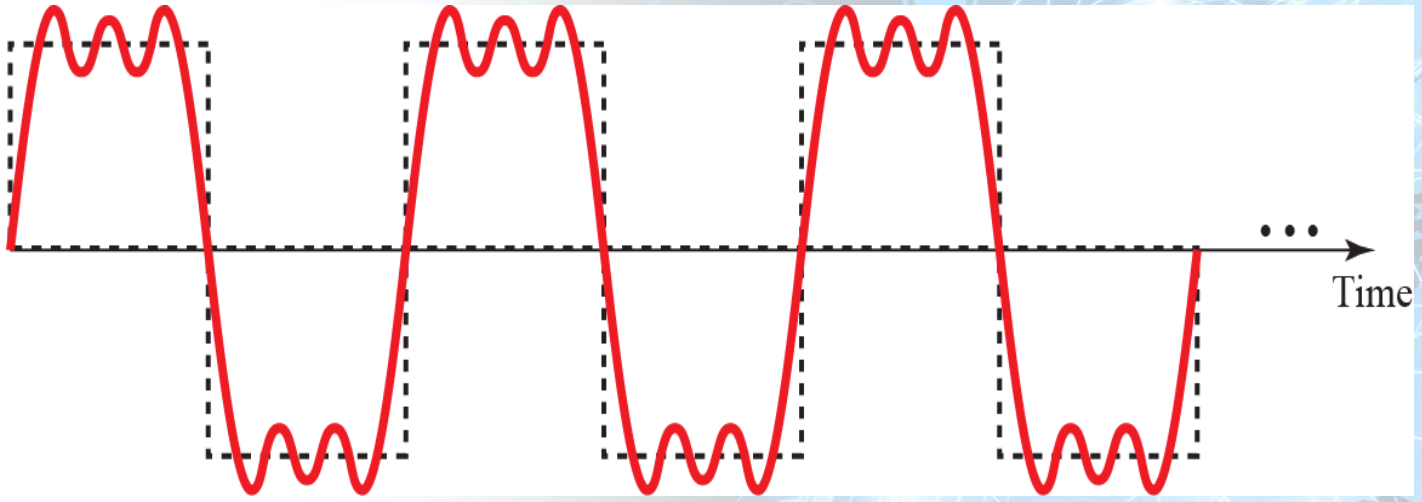
Composite Signals

So far, we have focused on simple sine waves. Simple sine waves have many applications in daily life. We can send a single sine wave to carry electric energy from one place to another. For example, the power company sends a single sine wave with a frequency of 60 Hz to distribute electric energy to houses and businesses.

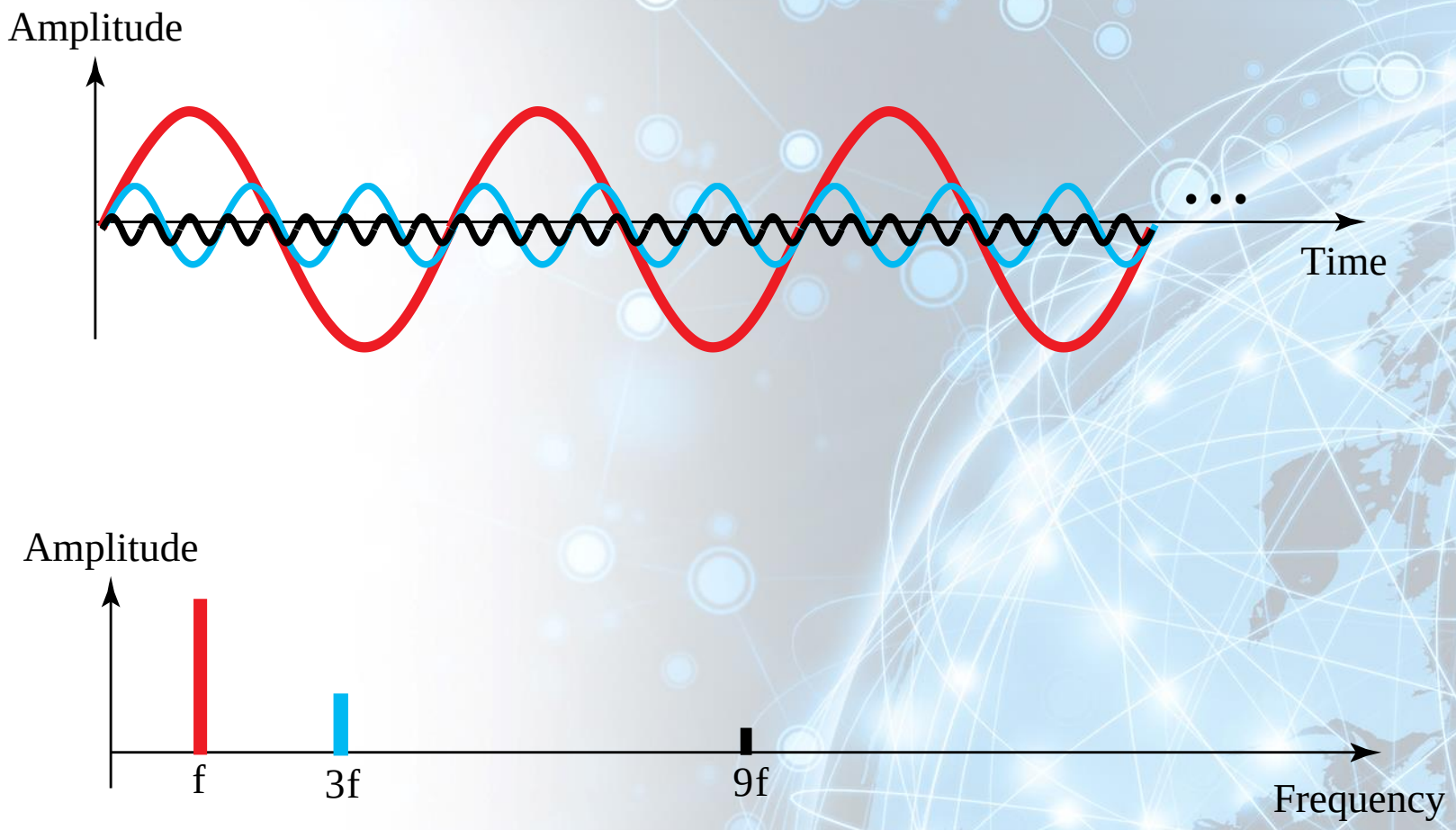
Composite Signals

- Single Sine Wave can only carry limited information
- Composite Signal is made up of multiple simple sine waves
- Can be periodic or non-periodic

A Composite Periodic Signal



Decomposition of Composite Periodic Signal

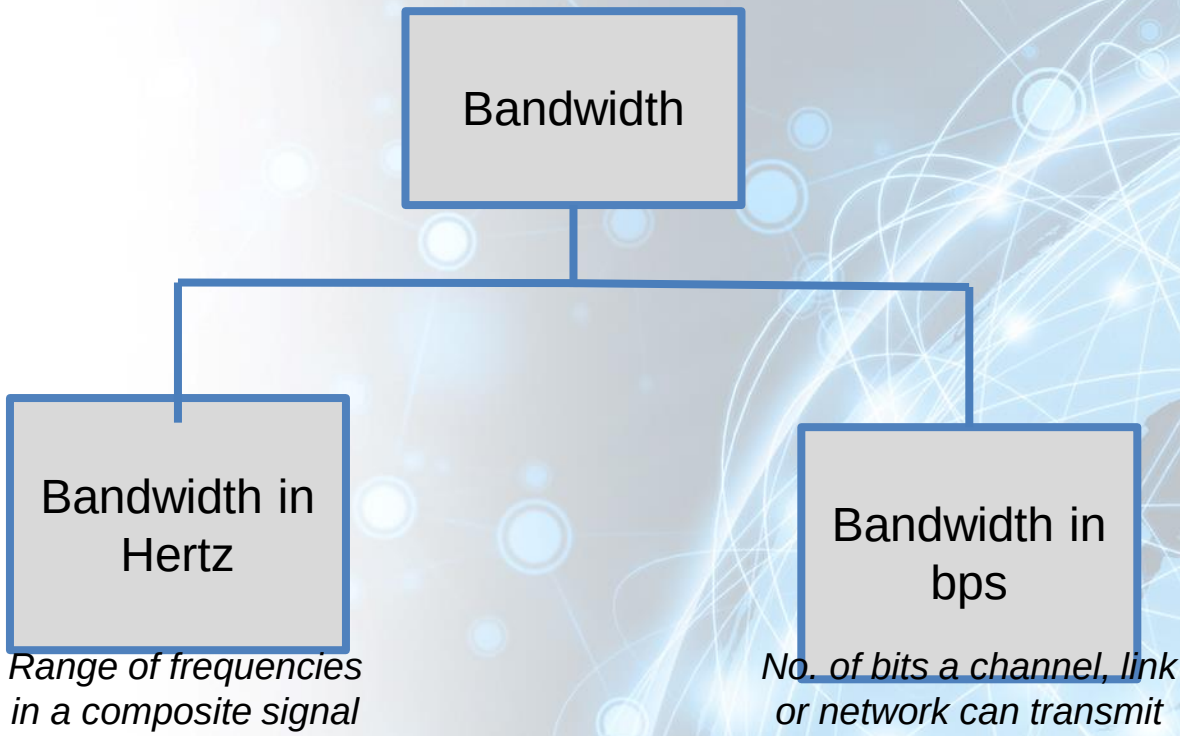


b. Frequency-domain decomposition of the composite signal

Bandwidth

- An important characteristic that measures Network Performance
- Bandwidth can be used in two different contexts with two different measuring values:
  - Bandwidth in Hertz
  - Bandwidth in bits per second

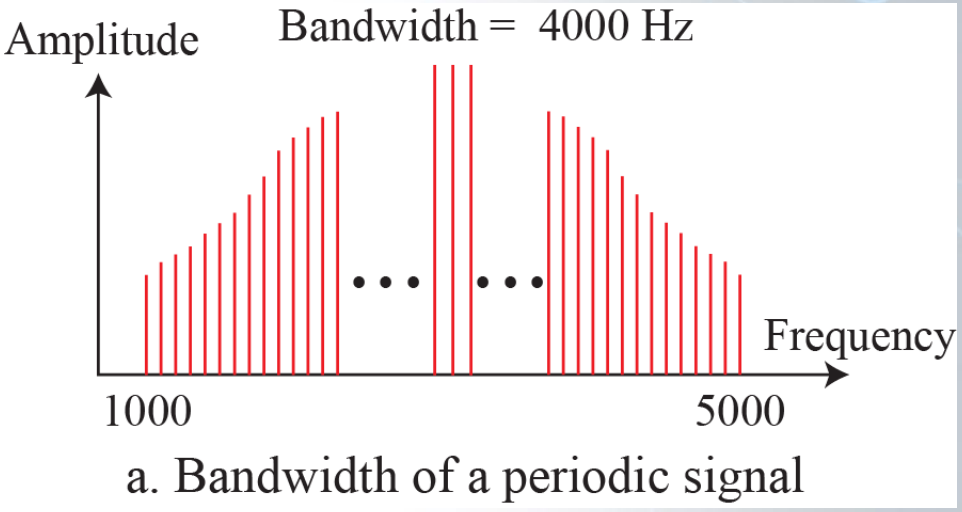
Bandwidth


Bandwidth
Bandwidth in Hertz
Range of frequencies in a composite signal
Bandwidth in bps
No. of bits a channel, link or network can transmit

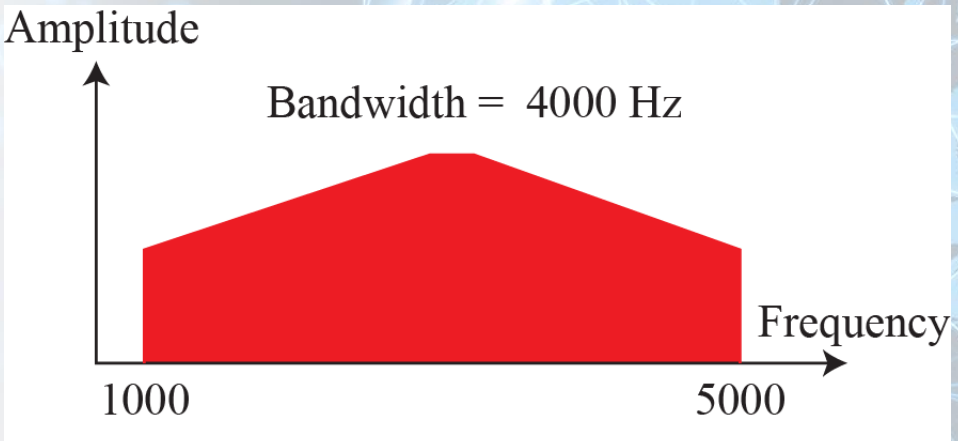
Bandwidth

- Range of frequencies contained in a Composite Signal
- The bandwidth is normally a difference between two frequencies (the highest and the lowest)

Bandwidth of a composite signal



a. Bandwidth of a periodic signal



b. Bandwidth of a nonperiodic signal

Example

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.

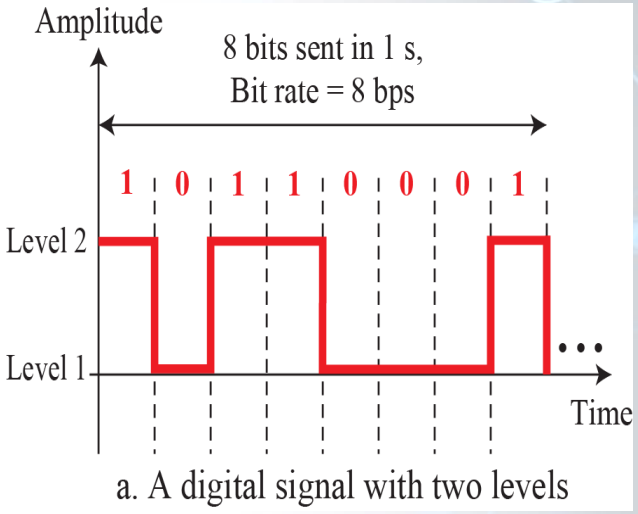
Digital Signals

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.

Digital Signals

- 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 so that we can send more than one bit for each level

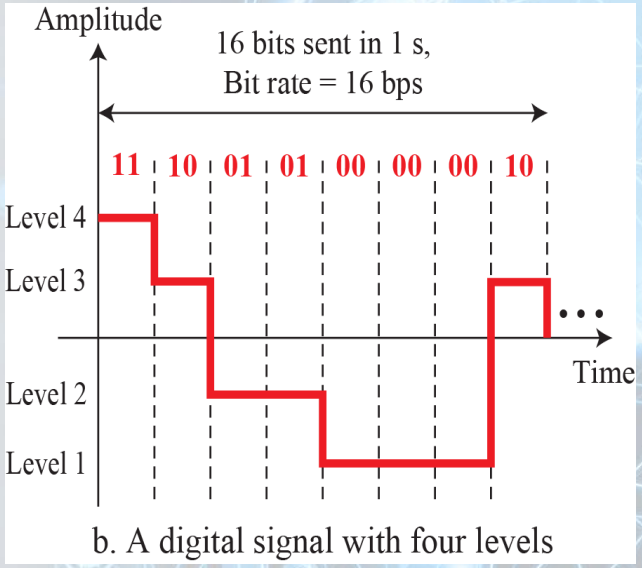
Digital Signals



a. A digital signal with two levels

In general, if a signal has L levels, each level needs $\log_2 L$ bits. So, we can send $\log_2 2 = 1$ bit per level

$\log_2 4 = 2$ bits



b. A digital signal with four levels

Digital Signals

In this case, we can send more than 1 bit for each level. Figure 3.17 shows two signals, one with two levels and the other with four.

Example 3.16

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

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

bits.

Example

A digital signal has eight levels. How many bits are needed per

$$\text{No of bits} = \log_2 L$$

$$= \log_2 8$$

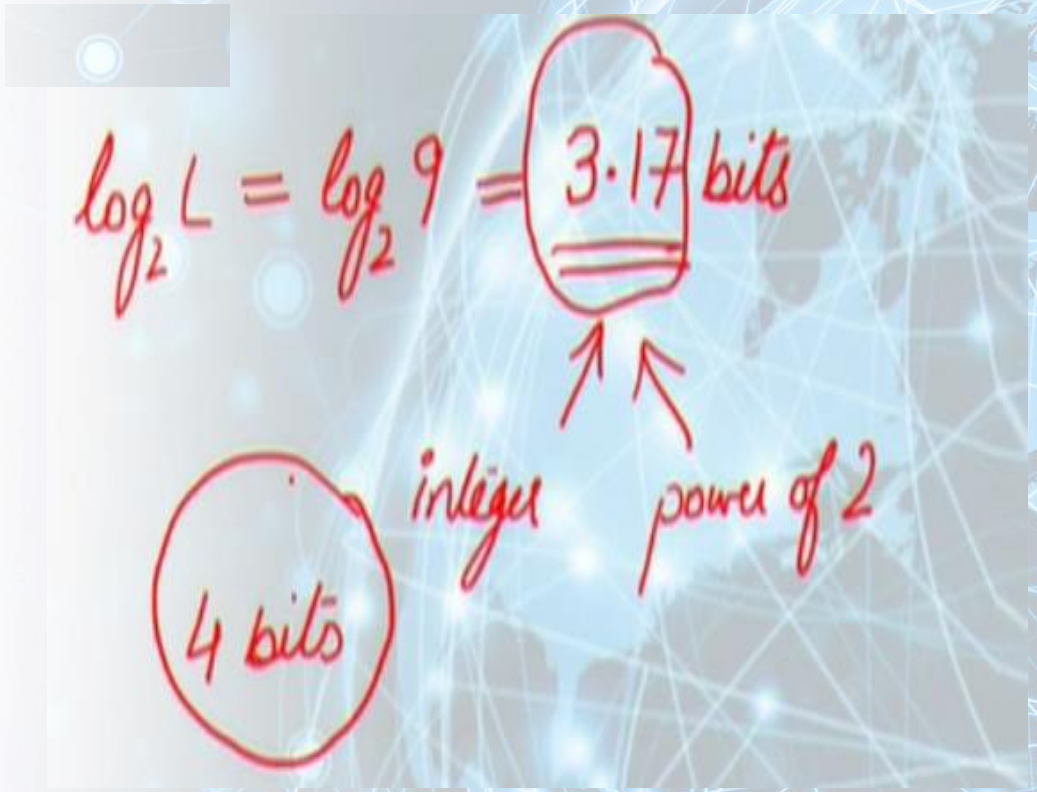
$$= 3 \text{ bits}$$

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

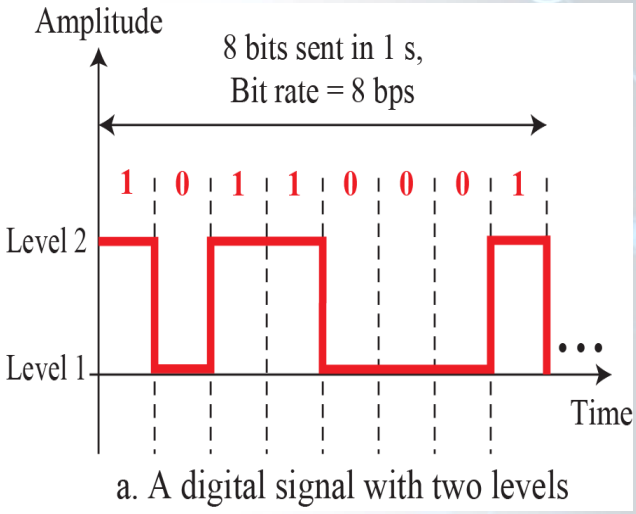
A digital signal has nine levels. How many bits are needed per level? We calculate the number of bits by using the formula.



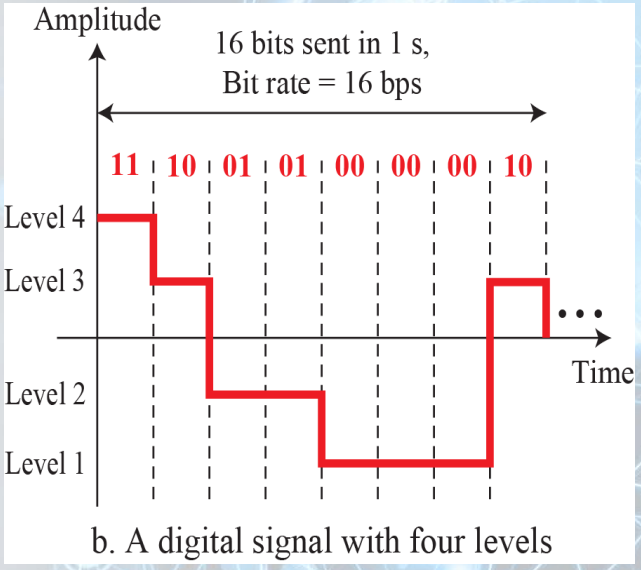
Bit Rate

- Number of bits sent in 1 second
- Bit Rate is expressed in bits per second (bps)
- Most digital signals are non-periodic, and thus period and frequency are not appropriate characteristics

Bit Rate

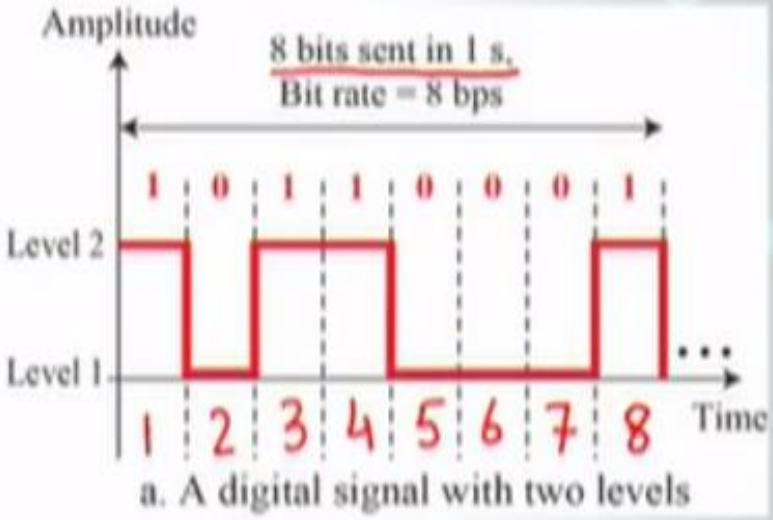


a. A digital signal with two levels



b. A digital signal with four levels

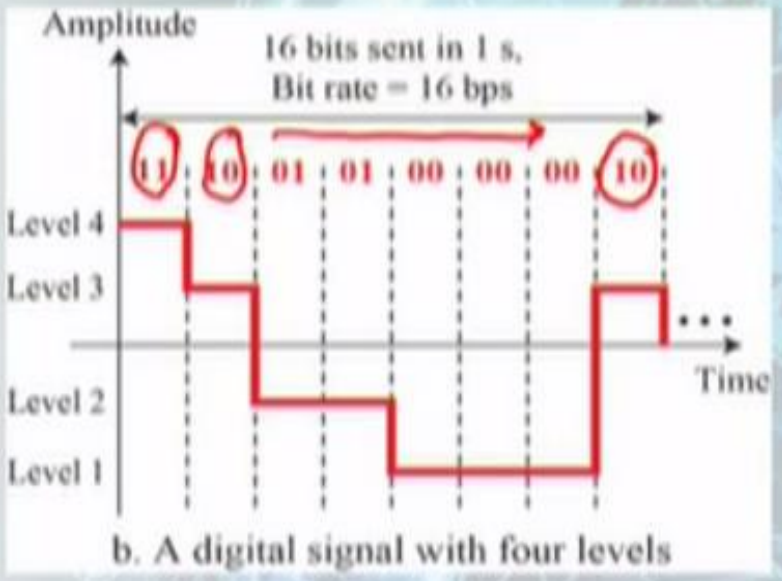
Bit Rate



a. A digital signal with two levels

Bit Rate = 8 bps

BR = 1



b. A digital signal with four levels

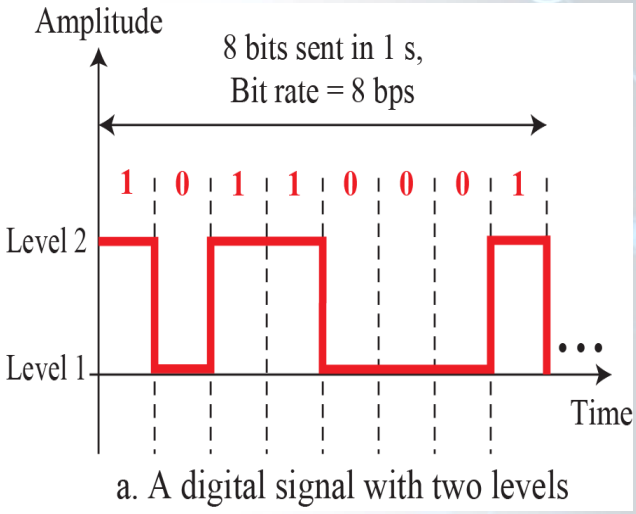
Bit Rate

Most digital signals are nonperiodic, and thus period and frequency are not appropriate characteristics. Another term—bit rate (instead of frequency)—is used to describe digital signals. The bit rate is the number of bits sent in 1s, expressed in bits per second (bps). Figure 3.17 shows the bit rate for two signals.

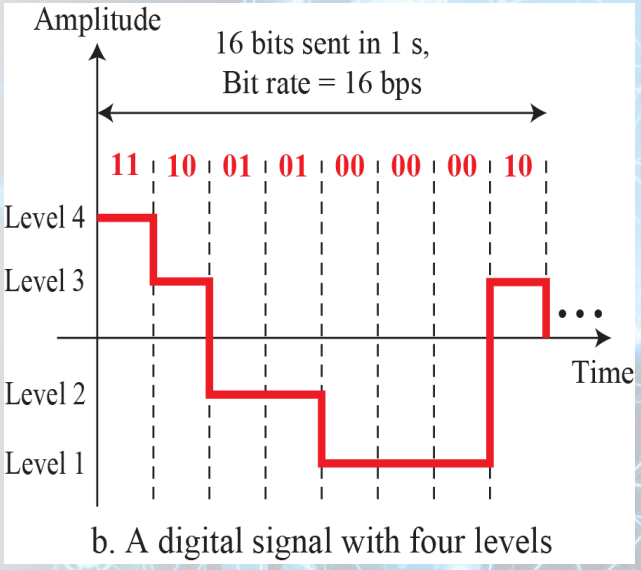
Bit Rate

- Number of bits sent in 1 second
- Bit Rate is expressed in bits per second (bps)
- Most digital signals are non-periodic, and thus period and frequency are not appropriate characteristics

Bit Rate



a. A digital signal with two levels



b. A digital signal with four levels

Example

Assume we need to download text documents at the rate of 100 pages per second. What is the required bit rate of the cl

1 page = 24 lines

1 line = 80 characters

1 ch = 8 bits

Bit Rate = 100 x 24 x 80 x 8

= 1.536 Mbps

Example 3.18

Solution

From Table 3.1 we find the equivalents of 1 ms (1 ms is 10–3 s) and 1 s (1 s is 106 µs). We make the

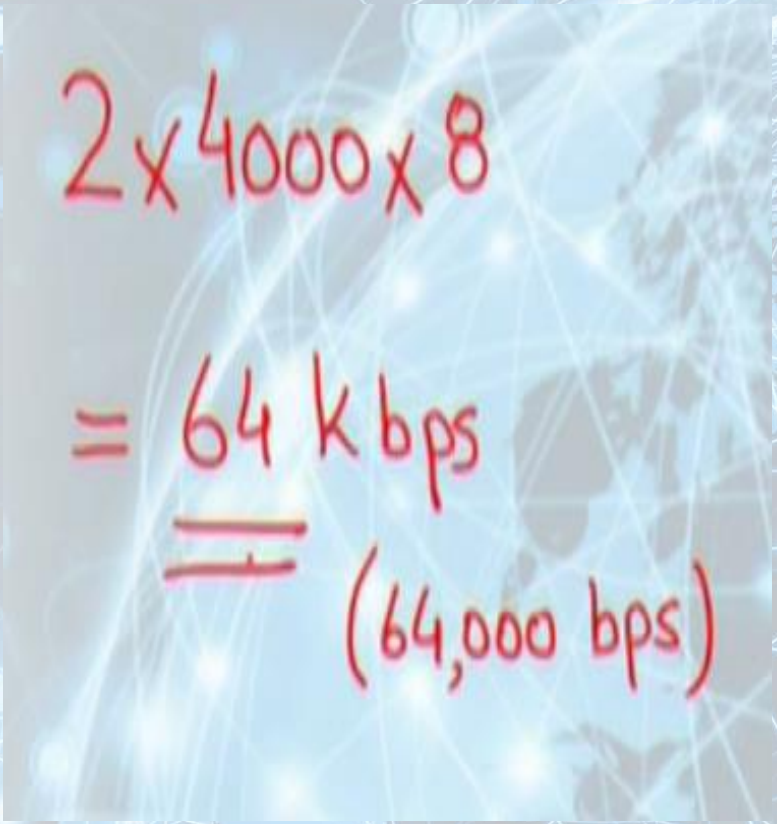
$$100 \times 24 \times 80 \times 8 = 1{,}536{,}000 \text{ bps}$$

subst

$$= 1.536 \text{ Mbps}$$

Example

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?



Example 3.19

Solution

A page is an average of 24 lines with 80 characters in each line. If we assume that one character requires

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

$$= 64 \text{ kbps}$$

Example 3.20

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

Solution

HDTV uses digital signals to broadcast high quality video signals. The HDTV screen is normally a ratio of 16 : 9 (in contrast to 4 : 3 for regular TV), which means the screen is wider. There are 1920 by 1080 pixels per screen, and the screen is renewed 30 times per second.

Example 3.20

Solution

Twenty-four bits represents one color pixel. We can calculate the bit rat

$$1920 \times 1080 \times 30 \times 24$$

$$= 1{,}492{,}992{,}000 \approx 1.5 \text{ Gbps}$$

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

Bit Length

We discussed the concept of the wavelength for an analog signal: the distance one cycle occupies on the transmission medium. We can define something similar for a digital signal: the bit length. The bit length is the distance one bit occupies on the transmission medium.

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

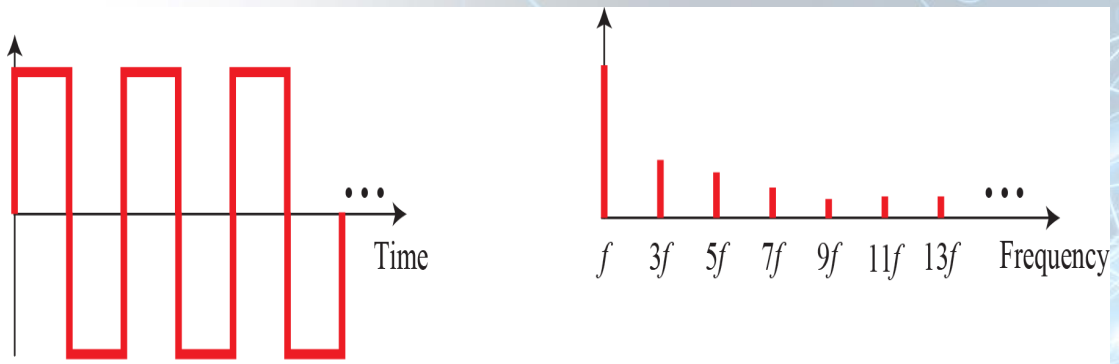
Digital Signal as Composite Analog Signal

- Based on Fourier analysis, a digital signal is a composite analog signal
- A digital signal, in the time domain, comprises connected vertical and horizontal line segments
- Infinite Bandwidth

Digital As Composite Analog

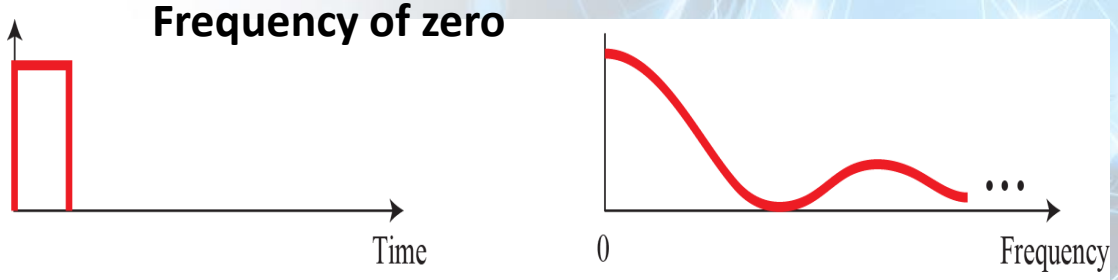
A vertical line in the time domain means a frequency of infinity: a horizontal line in the time domain means a frequency of zero. Going from a frequency of zero to a frequency of infinity implies all frequencies in between are part of the domain.

Digital Signal as Composite Analog Signal



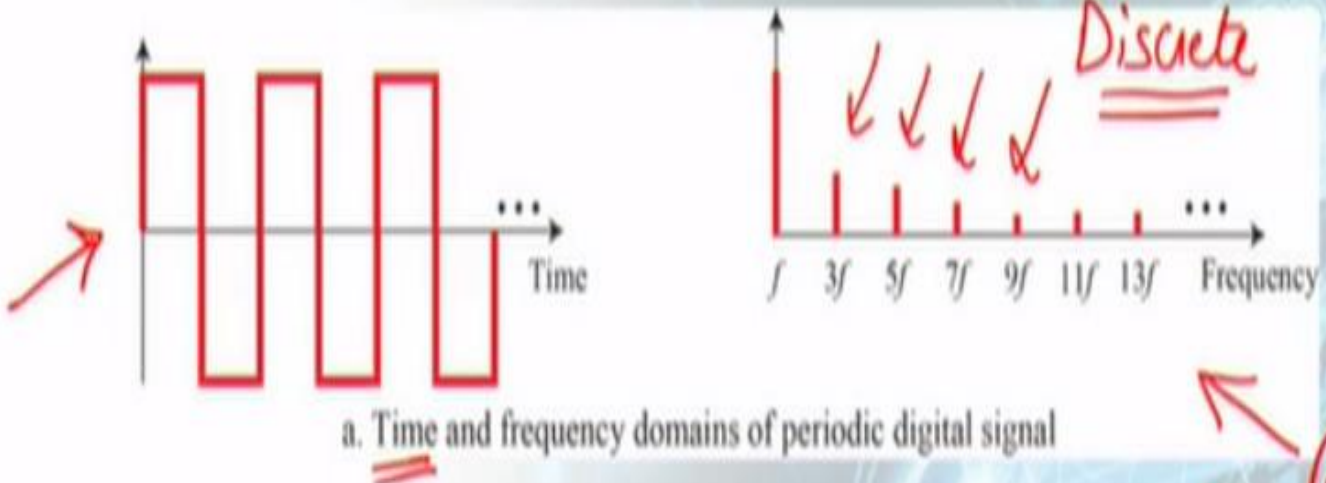
a. Time and frequency domains of periodic digital signal

Vertical line in the time domain:
Frequency of infinity
Horizontal line in the time domain:
Frequency of zero



b. Time and frequency domains of nonperiodic digital signal

Digital Signal as Composite Analog Signal

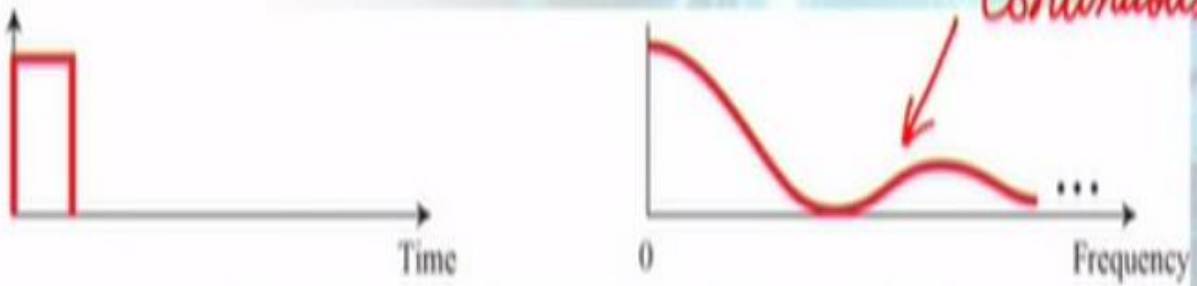


a. Time and frequency domains of periodic digital signal

Vertical line in the time domain: Frequency of infinity

Horizontal line in the time domain: Frequency of zero

$f \propto \frac{1}{T}$



b. Time and frequency domains of nonperiodic digital signal

Transmission of Digital Signals

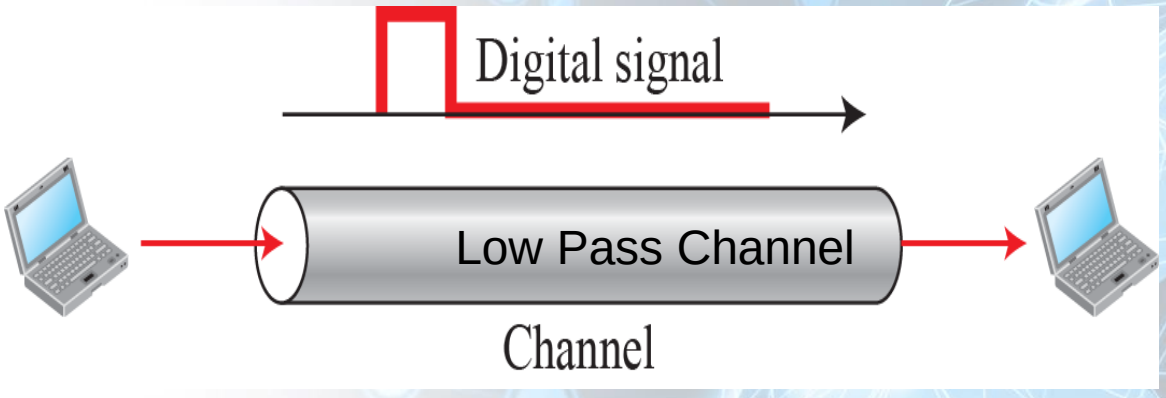
- Digital signal, periodic or non-periodic, is a composite analog signal with frequencies between zero and infinity (Infinite Bandwidth)

- Two approaches for transmission:
  - ✓ Baseband Transmission
  - ✓ Broadband Transmission

Transmission of Digital Signals

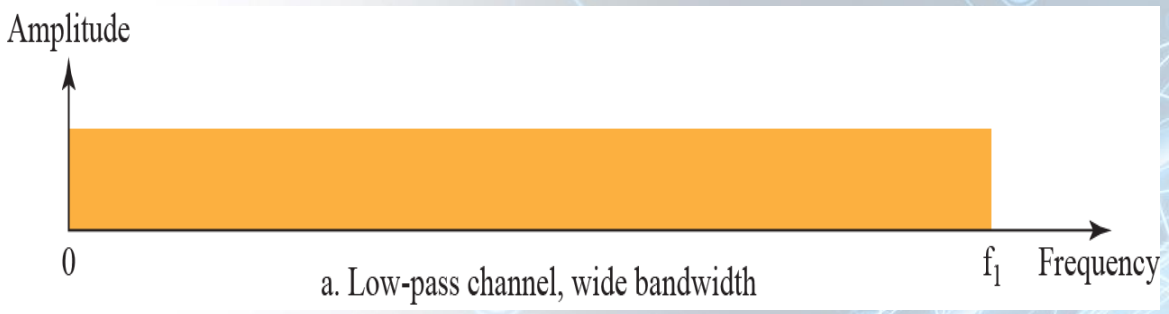
A vertical line in the time domain means a frequency of infinity: a horizontal line in the time domain means a frequency of zero. Going from a frequency of zero to a frequency of infinity implies all frequencies in between are part of the domain.

Baseband Transmission



Sending a **Digital Signal** without changing it to an **Analog Signal**

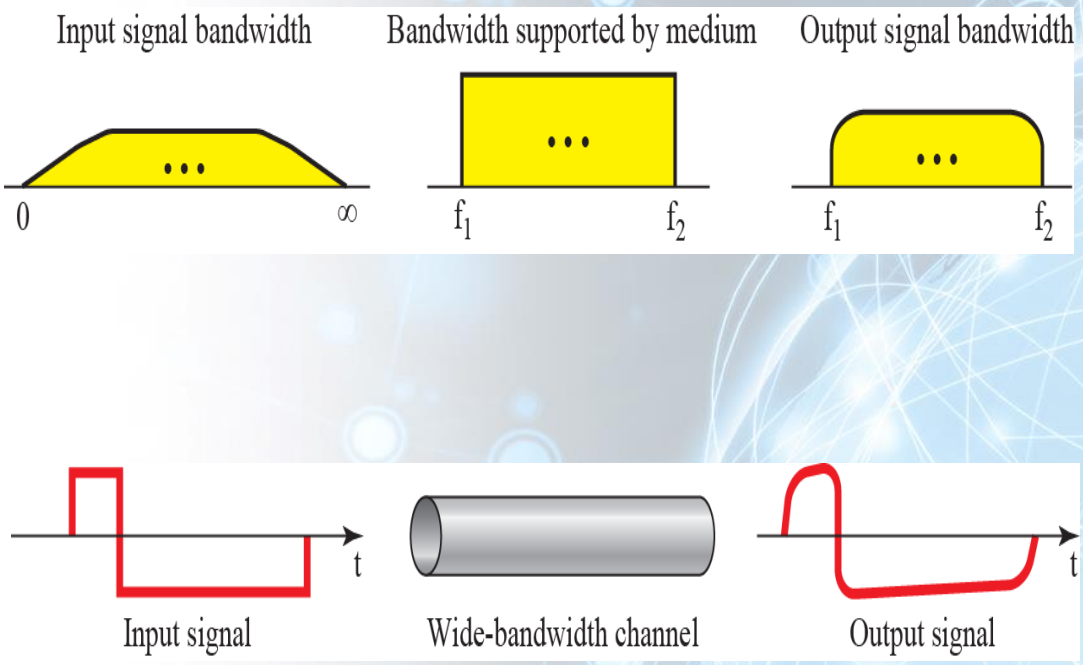
Baseband Transmission



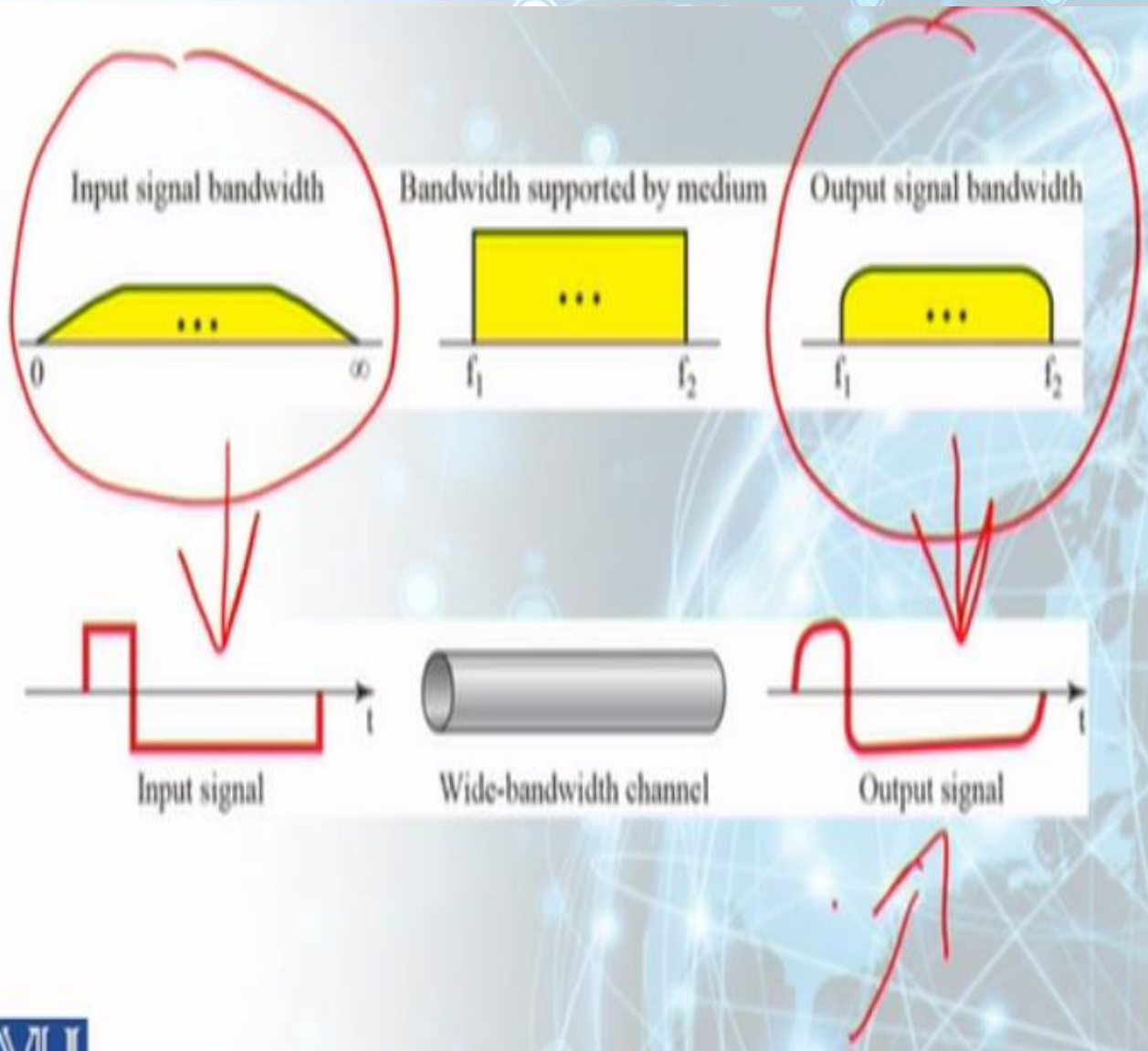
a. Low-pass channel, wide bandwidth

b. Low-pass channel, narrow bandwidth

Baseband Transmission



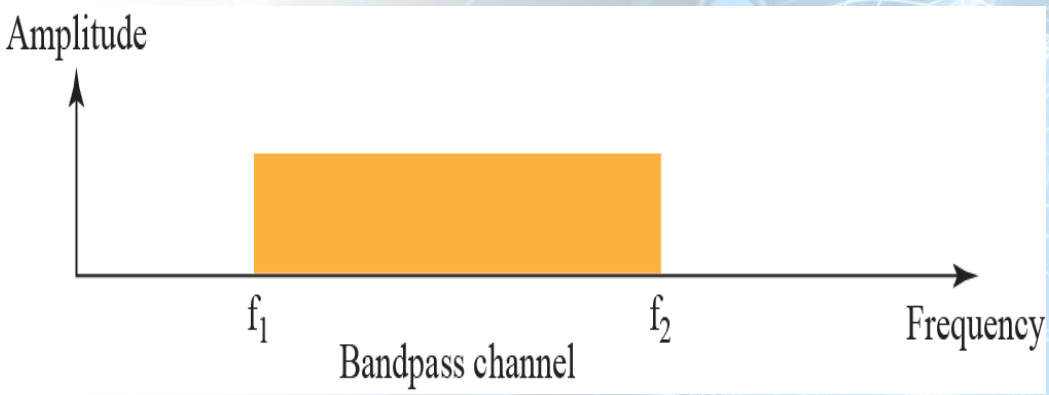
Baseband Transmission



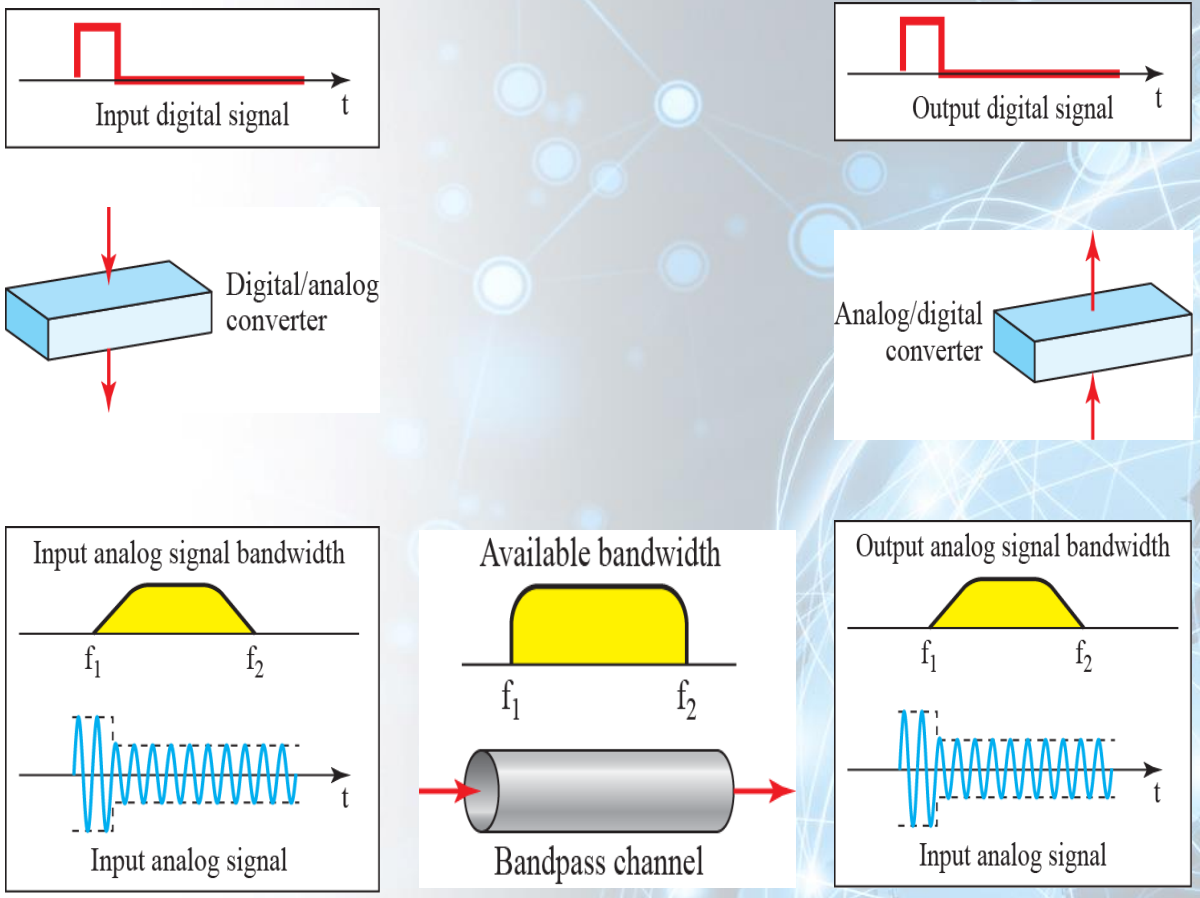
Broadband Transmission (Modulation)

- 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
- More available

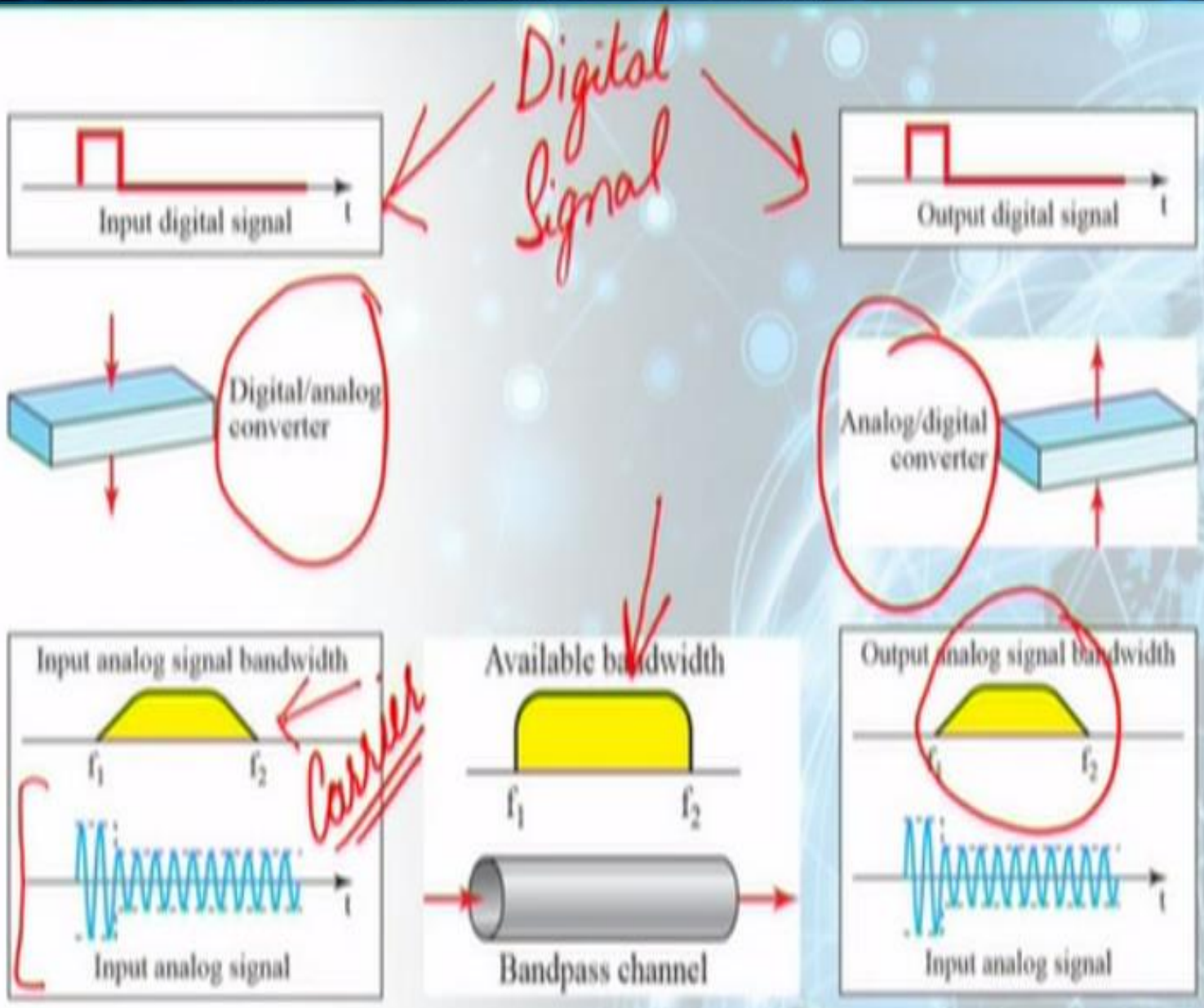
Broadband Transmission (Modulation)



Broadband Transmission (Modulation)



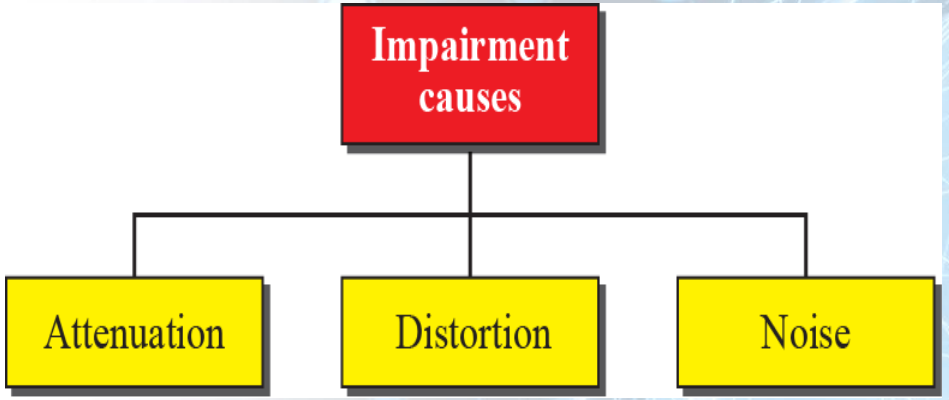
Broadband Transmission (Modulation)



Transmission Impairments

- Transmission media are not perfect
- Cause Signal impairments
- Signal sent is not the same as the signal received

Causes of Transmission Impairment



Transmission Impairment

What is sent is not what is received. Three causes of impairment are attenuation, distortion, and noise (see Figure 3.26).

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.

Attenuation

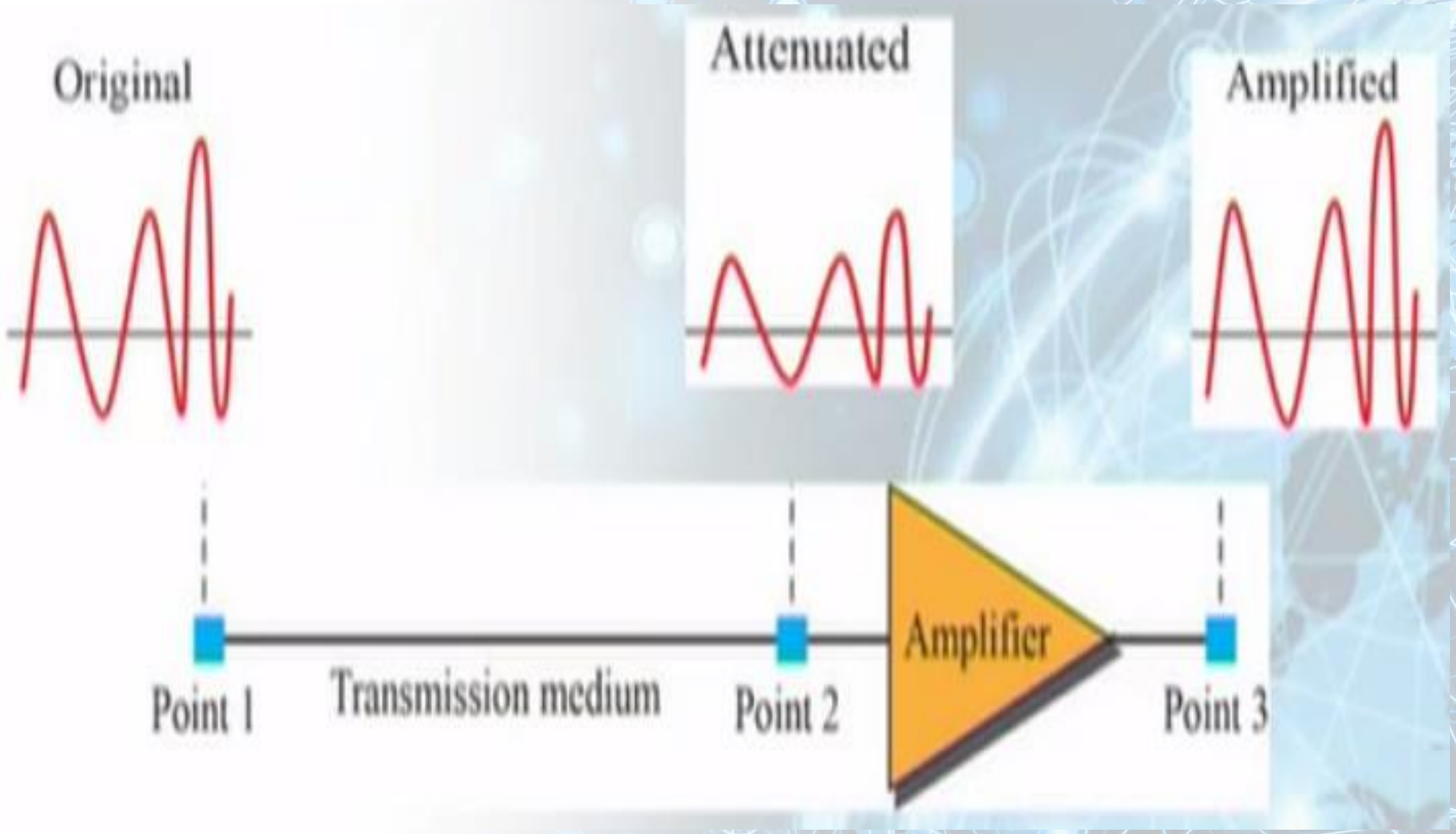
Attenuation means a loss of energy. When a signal, simple or composite, travels through a medium, it loses some of its energy in overcoming the resistance of the medium. That is why a wire carrying electric signals gets warm, if not hot, after a while. Some of the electrical energy in the signal is converted to heat.

Attenuation

To compensate for this loss, amplifiers are used to amplify the signal. Figure 3.27 shows the effect of attenuation and amplification..

Attenuation and amplification

Figure 3.27



Example 3.26

Suppose a signal travels through a transmission medium and its power is reduced to one half. This means that P2 = 0.5 P1. In this case, the attenuation (loss of power) can be calculated as

$$10 \log_{10} P_2/P_1 = 10 \log_{10} (0.5\, P_1)/P_1$$

$$= 10 \log_{10} 0.5 = 10 \times (-0.3) = -3 \text{ dB}.$$

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

Example 3.27

A signal travels through an amplifier, and its power is increased 10 times. This means that $P_2 = 10P1$. In this case, the amplification

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

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

Example 3.28

One reason that engineers use the decibel to measure the changes in the strength of a signal is that decibel numbers can be added (or subtracted) when we are measuring several points (cascading) instead of just two. In Figure 3.28 a signal travels from point 1 to point 4. The signal is attenuated by the time it reaches point 2.

Example 3.28

Between points 2 and 3, the signal is amplified. Again, between points 3 and 4, the signal is attenuated. We can find the resultant decibel value for the signal just by adding the decibel measurements between each set of points. In this case, the decibel value can be calculated as

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

Example 3.29

Sometimes the decibel is used to measure signal power in milliwatts. In this case, it is referred to as dB_m and is calculated as dBm = 10 log10 Pm, where Pm is the power in milliwatts. Calculate the power of a signal if its $dB_m = -30$.

Example 3.29

Solution

We can calculate the power in the signal as

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

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

Example 3.30

Sometimes the decibel is used to measure signal power in milliwatts. In this case, it is referred to as dB_m and is calculated as dBm = 10 log10 Pm, where Pm is the power in milliwatts. Calculate the power of a signal if its $dB_m = -30$.

Example 3.30

Solution

The loss in the cable in decibels is $5 \times (-0.3) = -1.5$ dB. We can

$$\text{dB} = 10 \log_{10} (P_2 / P_1) = -1.5$$

$$\longrightarrow \quad (P_2 / P_1) = 10^{-0.15} = 0.71$$

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

Attenuation and Amplification - Decibel

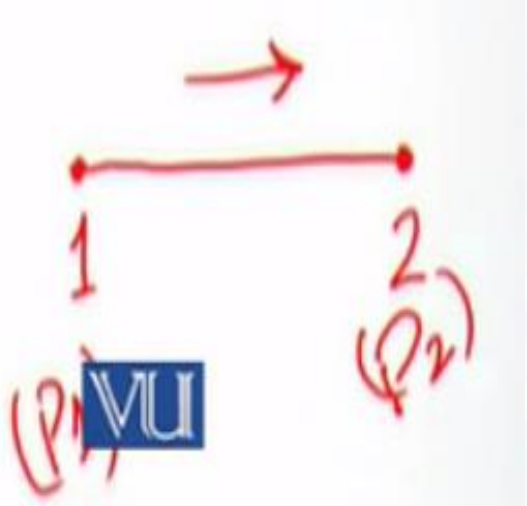
- Unit of Signal strength is Decibel or dB
- Decibel (dB) measures the relative strengths of two signals or one signal at two different points

$$10 \log_{10} P_2/P_1$$

- Decibel is negative if a signal is attenuated and positive if signal is amplified

Example

Suppose a signal travels through a transmission medium and its power is reduced to one half. This means that P2 = 0.5 P1. In this case, the a p c



$P_2 \rightarrow$ Power at point 2

$P_1 \rightarrow$ Power at point 1

$P_2 = 0.5\,P_1$

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

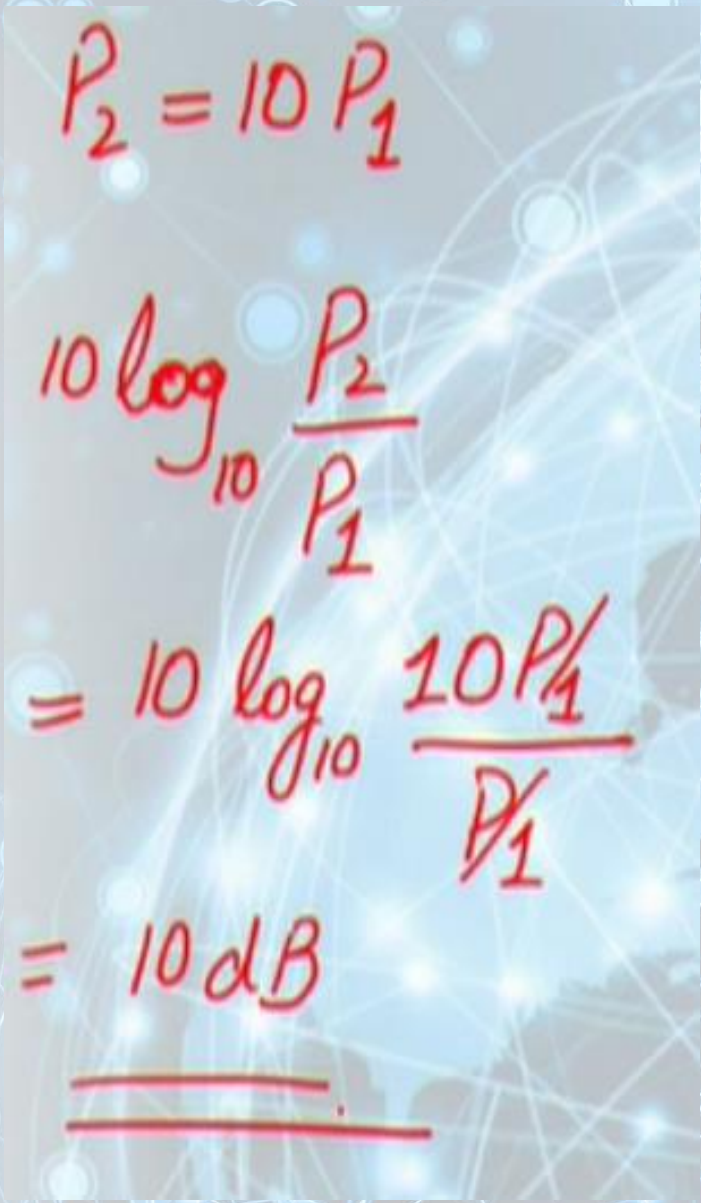
Signal has lost one half the power

$$= 10 \log_{10} 0.5$$

$$= -3 \text{ dB}$$

Example

A signal travels through an amplifier, and its power is increased 10 times. This means that $P_2 = 10P1$. In this case, the amplification (gain of power) can be calculated as



Distortion

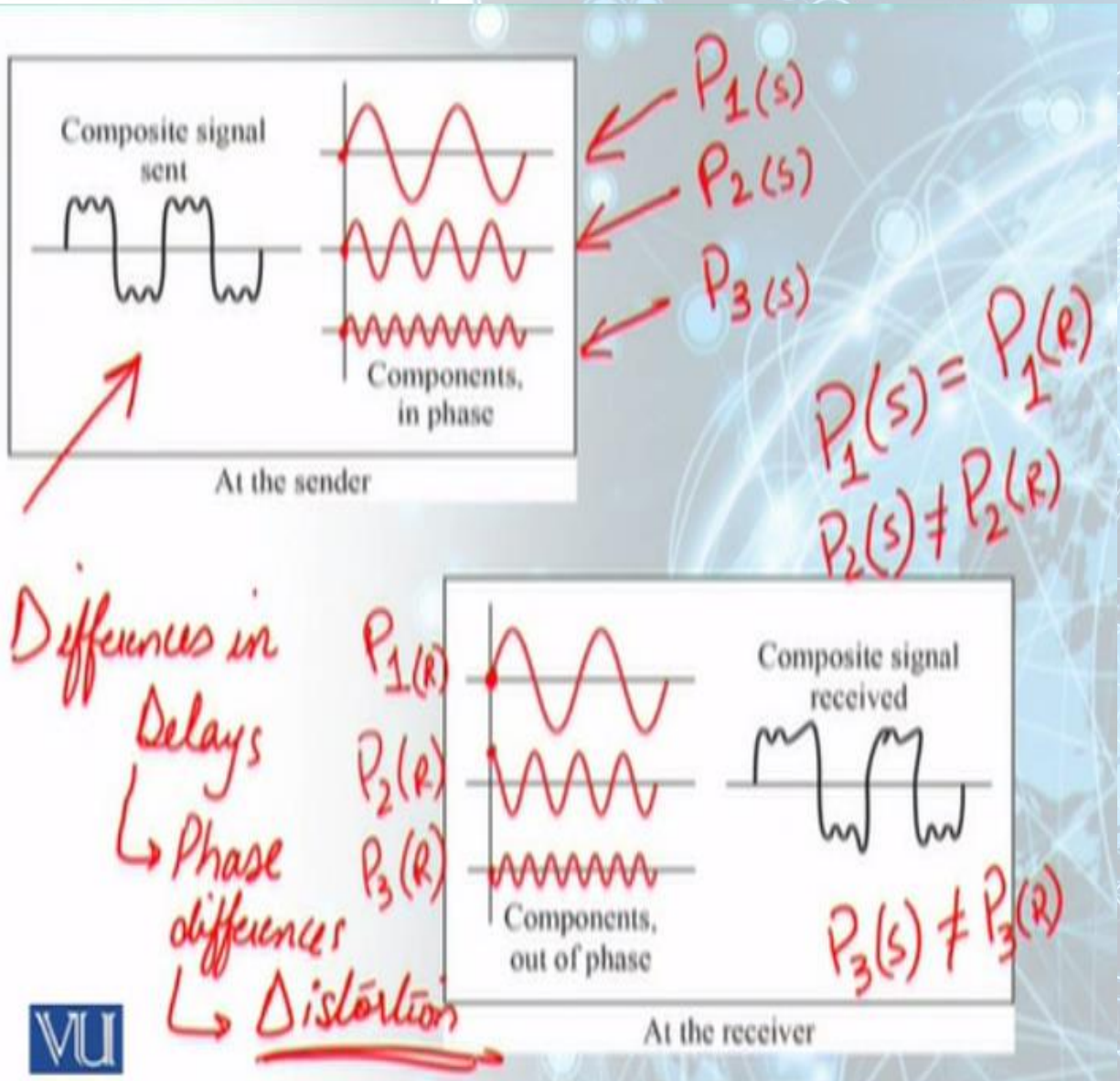
- Distortion means that the signal changes its form or shape.
- Distortion can occur in a composite signal made of different frequencies.
- Each signal component has its own propagation speed (see the next section) through a medium and, therefore, its own delay in arriving at the final destination.

Distortion

Differences in delay may create a difference in phase if the delay is not exactly the same as the period duration.

Distortion

Figure 3.2



Noise

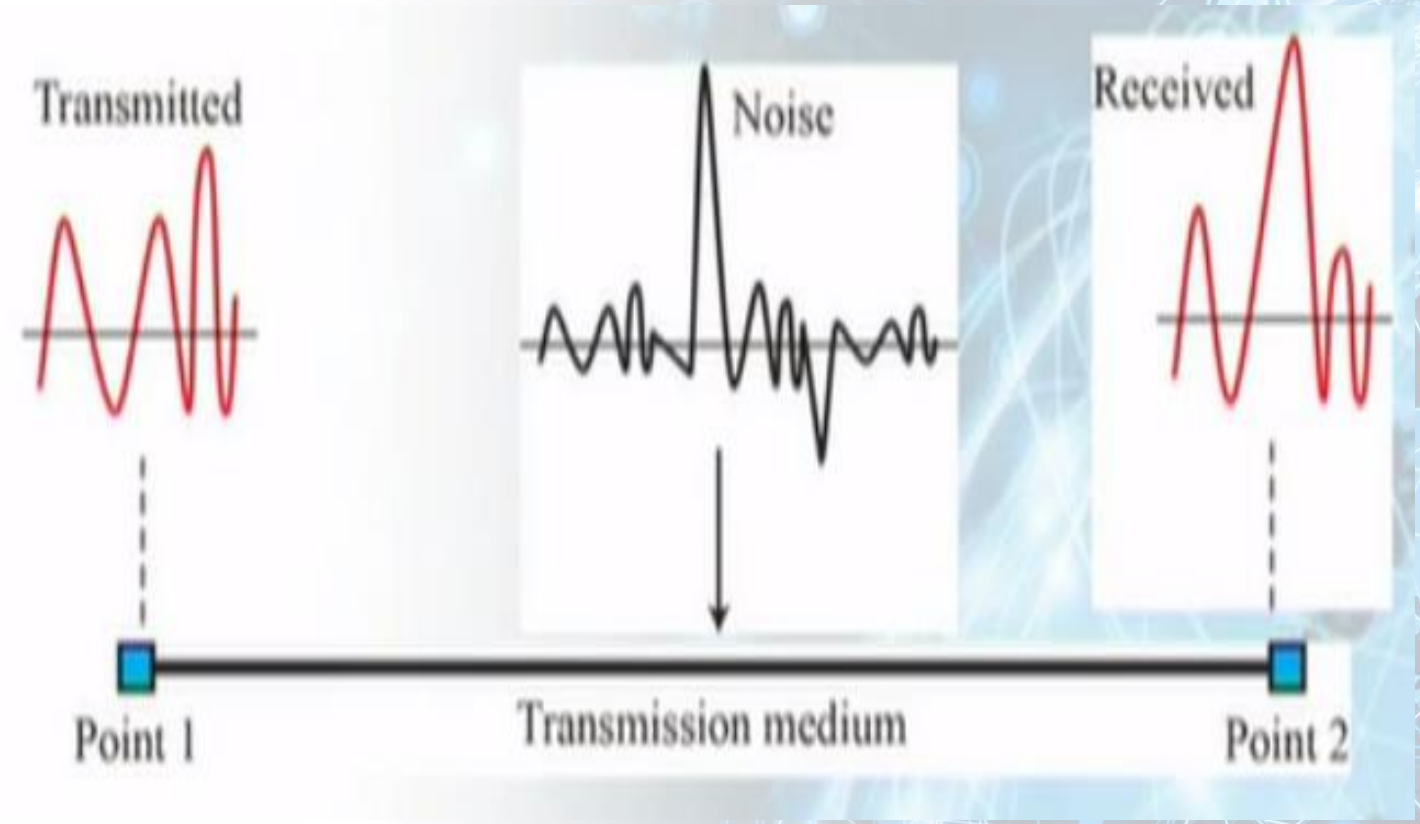
- Noise is another cause of impairment.
- Several types of noise, such as thermal noise, induced noise, crosstalk, and impulse noise, may corrupt the signal.

- Thermal noise is the random motion of electrons in a wire, which creates an extra signal not

Noise

- Induced noise comes from sources such as motors.
- Crosstalk is the effect of one wire on the other.

Noise


Transmitted
Noise
Received
Point 1
Transmission medium
Point 2

Noise

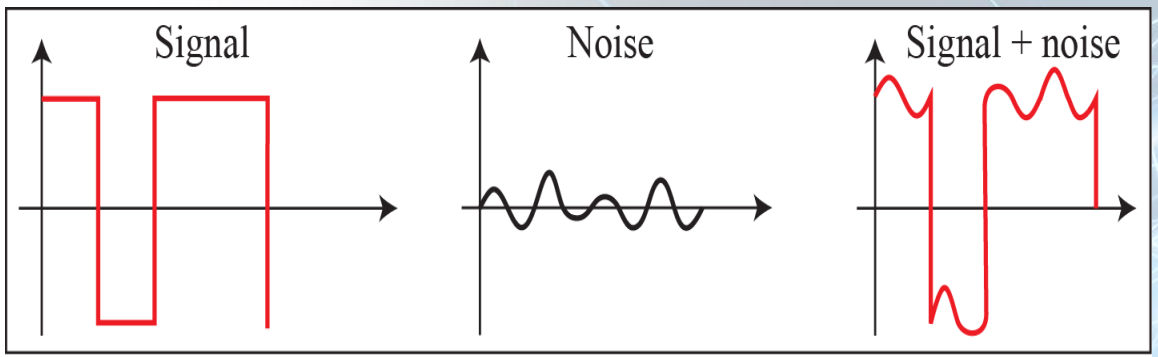
Figure 3.31

Noise – Signal to Noise Ratio (SNR)

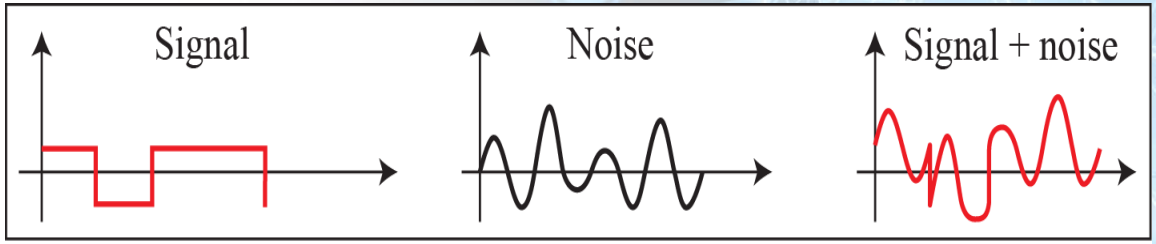
- Signal to Noise Ratio (SNR) is used to find the theoretical bit rate limit of a signal

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

Noise – Signal to Noise Ratio (SNR)



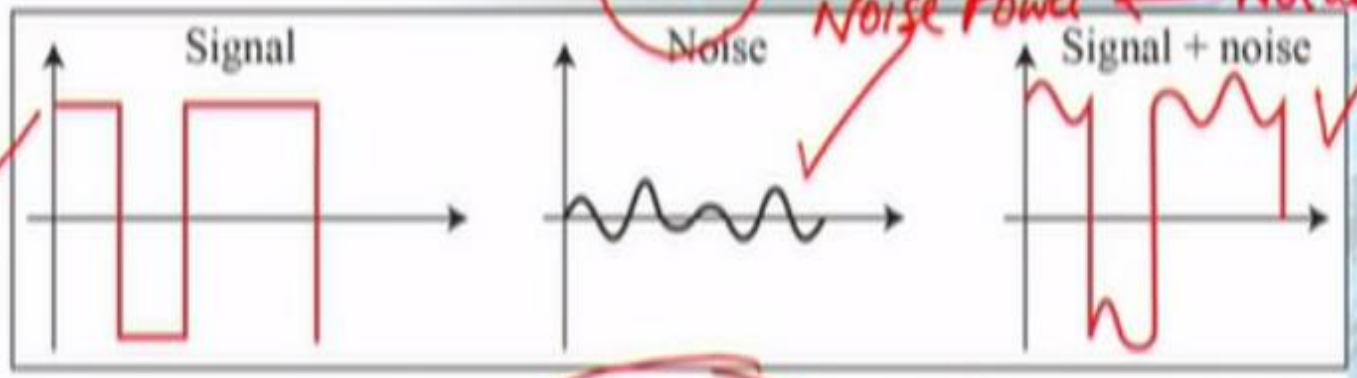
a. High SNR



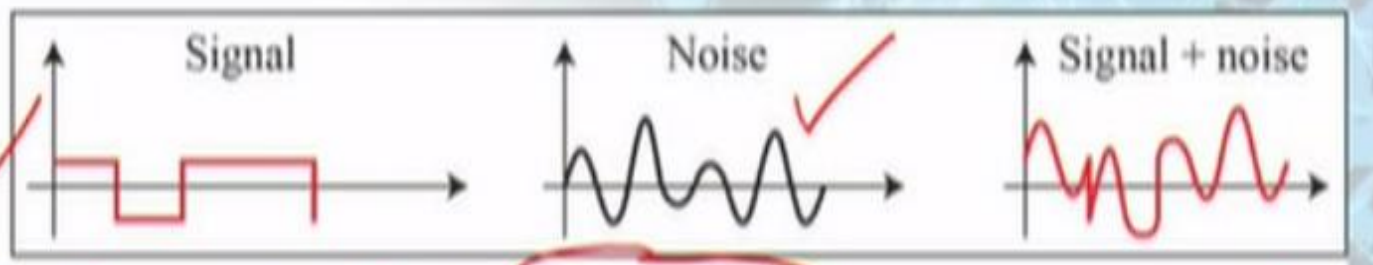
b. Low SNR

Noise – Signal to Noise Ratio (SNR)

$SNR = \frac{\text{Signal Power}}{\text{Noise Power}}$ ← wanted ← Not wanted



a. High SNR ✓ less corrupted



b. Low SNR ✓ more corrupted

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

Example

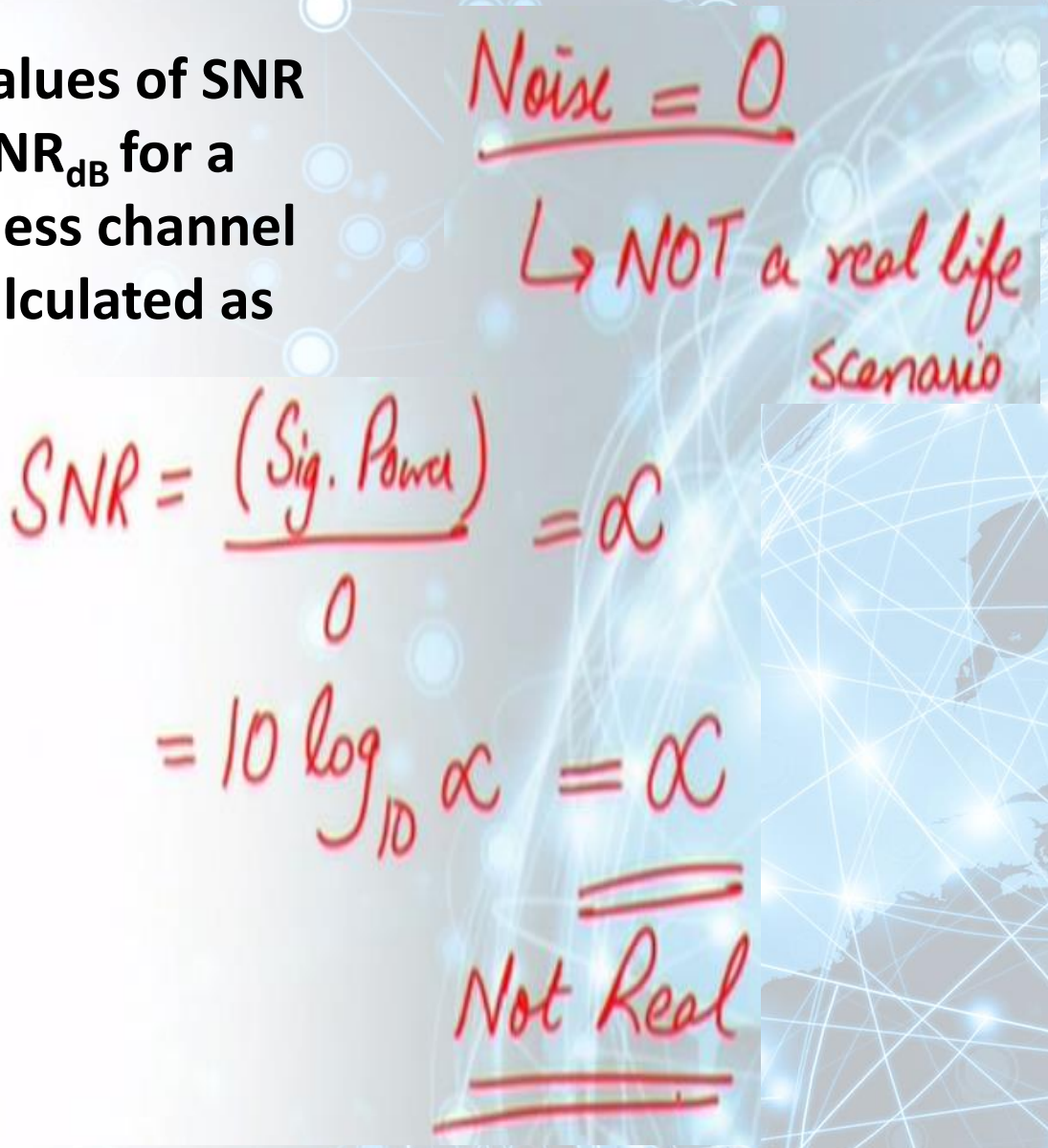
The power of a signal is 10 mW and the power of the noise is 1 µW; what are the values of SNR and SN

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

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

Example

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



Example 3.31

The power of a signal is 10 mW and the power of the noise is 1 µW; what are the values of SNR and SNR_{dB}?

Solution

The values of SNR and SNR_{dB} can be calculated as

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

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

Example 3.32

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

Solution

The values of SNR and SNRdB for a noiseless channel are

$$\text{SNR} = (\text{signal power}) / 0 = \infty$$

$$\longrightarrow \quad \text{SNR}_{\text{dB}} = 10 \log_{10} \infty = \infty$$

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

Data Rate Limits

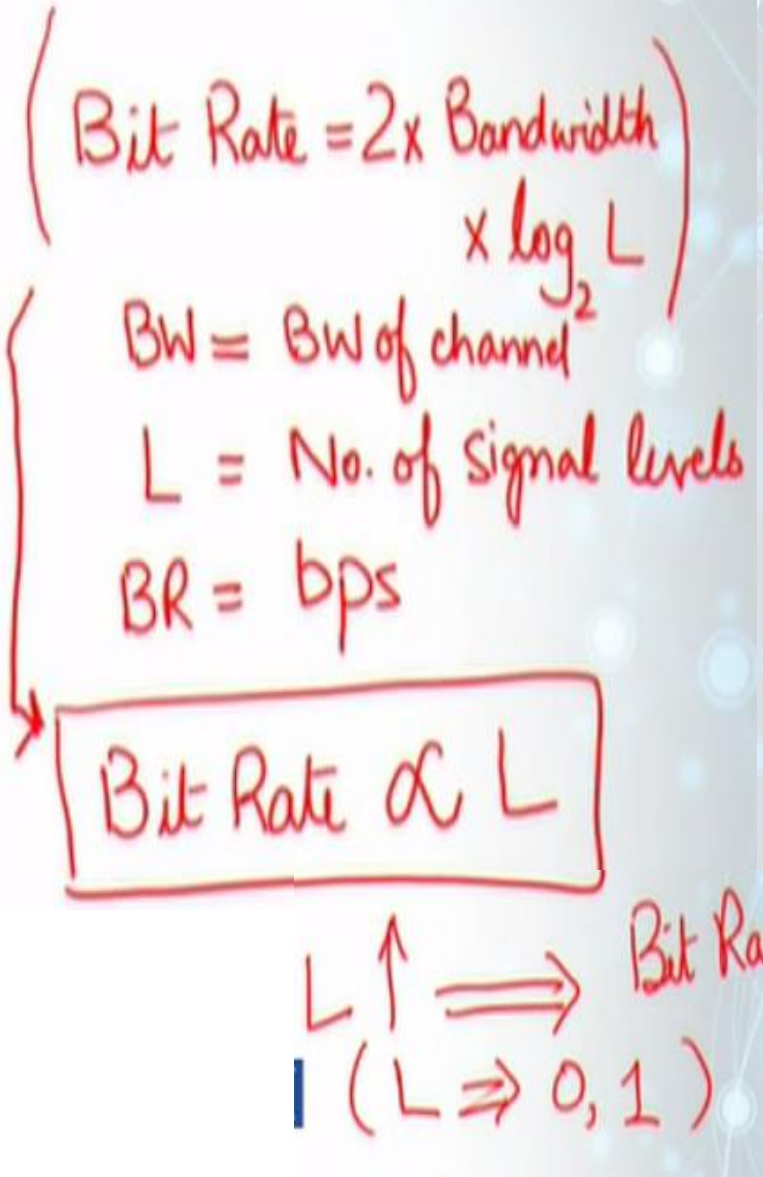
- How fast we can send data, in bits per second, over a channel?

- Data Rate depends on 3 factors:
  - ✓ The Bandwidth available
  - ✓ The level of the signals we use
  - ✓ The level of noise

Data Rate Limits

- Two theoretical formulas developed to calculate the data rate:
  - ✓ one by Nyquist for a noiseless channel
  - ✓ another by Shannon for a noisy channel

Noiseless Channel : Nyquist Rate



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

- Finding balance between Bit rate

Example

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

$$BR = 2 \times 3000 \times \log_2 2$$

$$= 6000 \text{ bps}$$

Example

Consider the same noiseless channel transmitting a signal with four signal levels (for each level, we send 2 bits). The n c a

$$BR = 2 \times 3000 \times \log_2 4$$

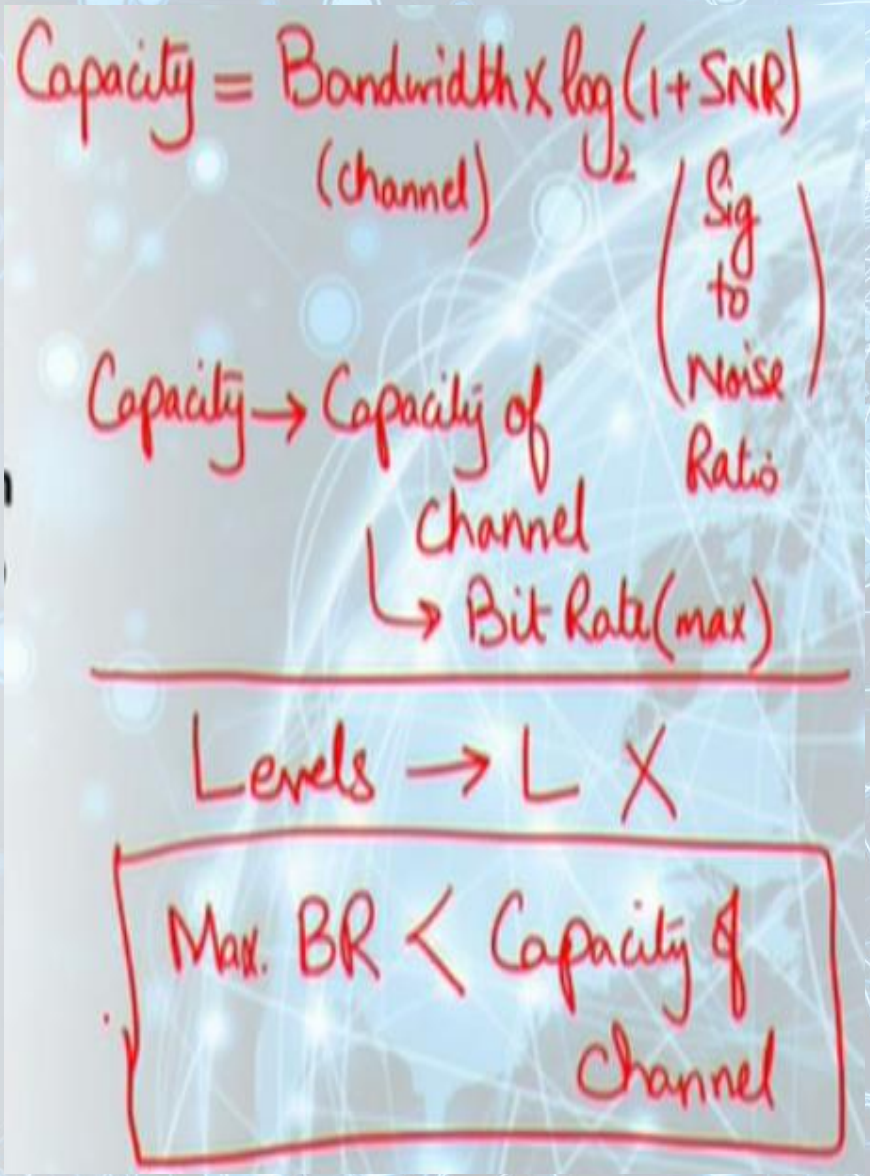
$$= 12{,}000 \text{ bps}$$

$$BR \propto L$$

(Reliability)

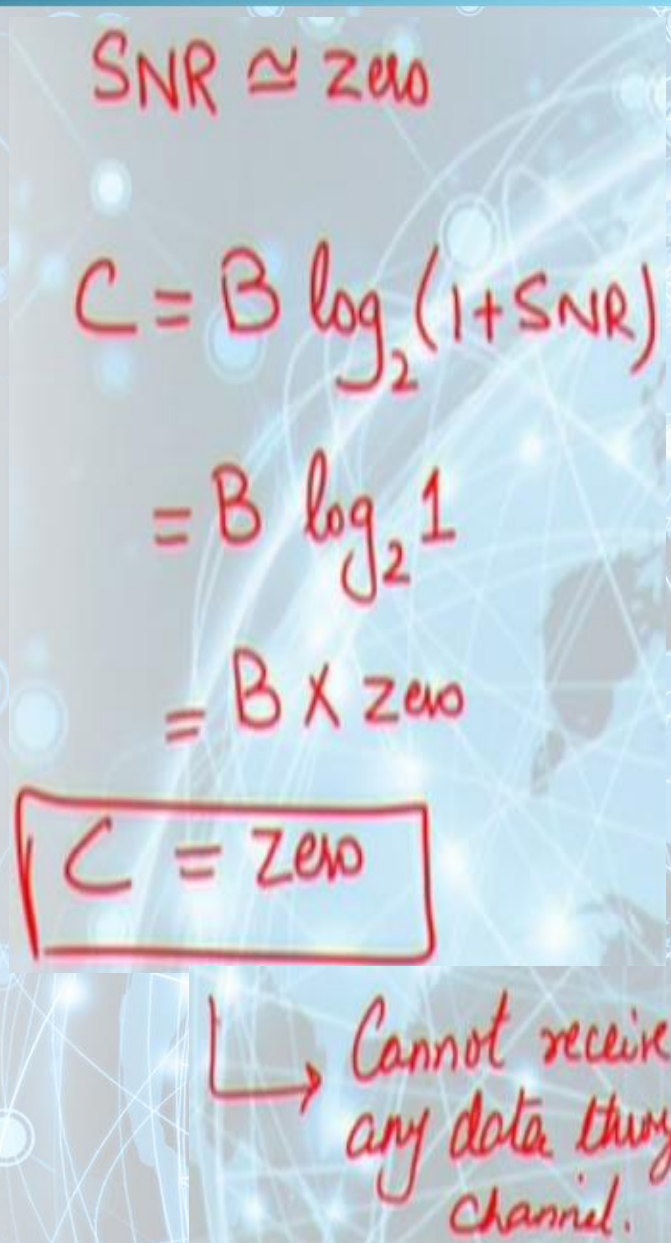
Noisy Channel : Shannon Capacity

- In reality, we cannot have a noiseless channel; the channel is always noisy
- In 1944, Claude Shannon introduced a formula, to determine the theoretical highest data rate for a noisy



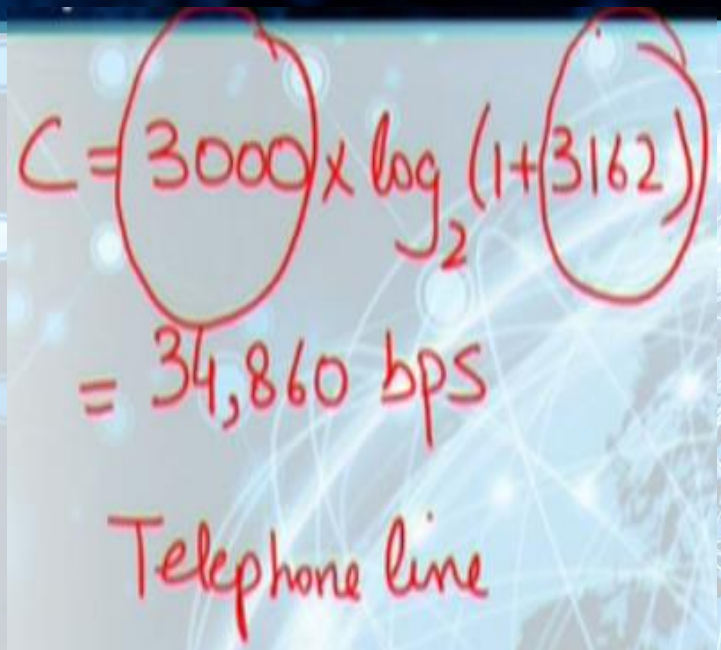
Example

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. For this channel the capacity C is calculated as



Example

Theoretical highest bit rate of a Telephone line with a Bandwidth of 3000 Hz assigned for data communication. SNR is usually 3162. The capacity is calculated as:



Using Both Limits

- In practice, we need to use both methods to find the limits and signal levels
- Shannon's formula gives us the upper limit while the Nyquist formula gives us the signal levels

Example 3.37

Consider an extremely noisy channel in which the value of the signal-to-noise ratio is almost zero. In other words, the noise is so strong that the signal is faint. For this channel the capacity C is calculated as

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

Example 3.37

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 3.38

This means that the capacity of this channel is zero regardless of the bandwidth. In other words, we cannot

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

$$3000 \log_2(1 + 3162) =$$

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

Example 3.38

This means that the highest bit rate for a telephone line is 34.860 kbps. If we want to send data faster than this, we can either increase the bandwidth of the line or improve the signal-to-noise ratio.

Example 3.39

The signal-to-noise ratio is often given in decibels. Assume that $SNR_{dB} = 36$ and the channel bandwidth is 2 MHz. The theoretical channel capacity can be calculated as

Example 3.39

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

$$\text{SNR} = 10^{\text{SNR}_{\text{dB}}/10} \longrightarrow$$

$$\text{SNR} = 10^{3.6} = 3981$$

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

$$2 \times 10^6 \times \log_2 3982$$

$$= 24 \text{ Mbps}$$

Example 3.40

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 5 B 3 $SNR_{dB.}$ For example, we can calculate the

$$C = 2\,\text{MHz} \times (36 / 3) = 24\,\text{Mbps}$$

of the previous example as

Using Both Limits

In practice, we need to use both methods to find the limits and signal levels. Let us show this with an example.

Example 3.41

We have a channel with a 1-MHz bandwidth. The SNR for this channel is 63. What are the appropriate bit rate and signal level?

Solution

First, we use the

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

a to

mit

$$10^6 \log_2(1 + 63) = 10^6 \log_2 64 =$$

6 Mbps

Example 3.41

The Shannon formula gives us 6 Mbps, the upper limit. For better performance we choose something lower, 4 Mbps. Then we use the Nyquist

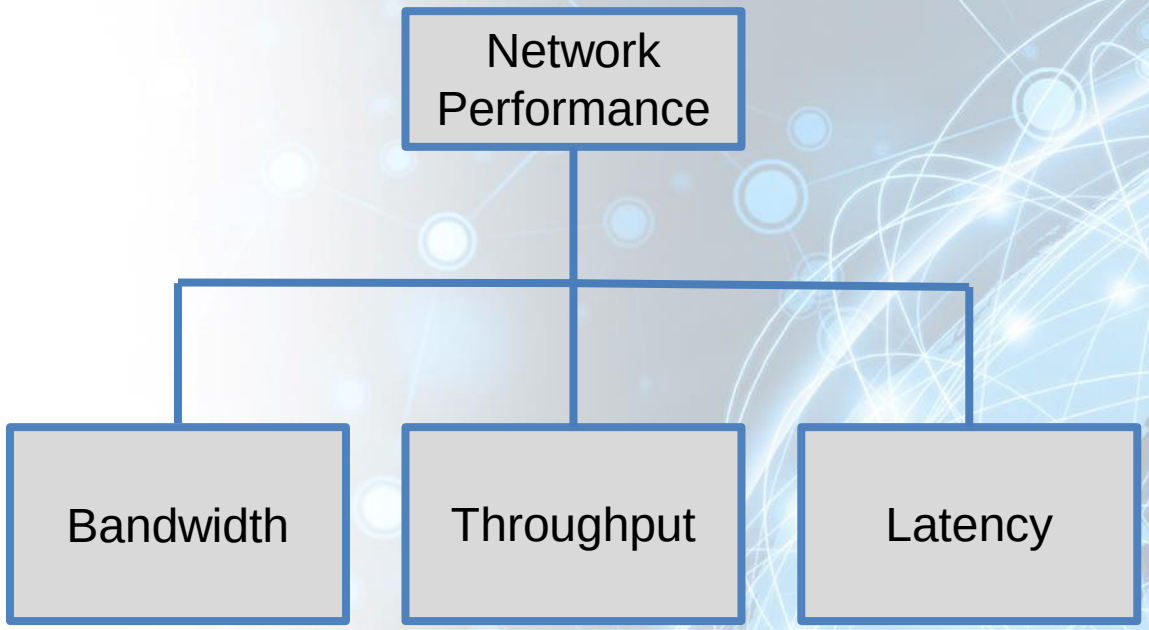
$$4 \text{ Mbps} = 2 \times 1 \text{ MHz} \times \log_2 L \longrightarrow L = 4$$

formula to find the number of signal levels

Network Performance

- Data transmission (in form of Signal) over a network and how network behaves is important
- More important is the performance of the network
- How good is our network?

Network Performance



- **There are 3 characteristics of network performance**

Bandwidth

- An important characteristic that measures Network Performance

- Bandwidth can be used in two different contexts with two different measuring values:
  - Bandwidth in Hertz
  - Bandwidth in

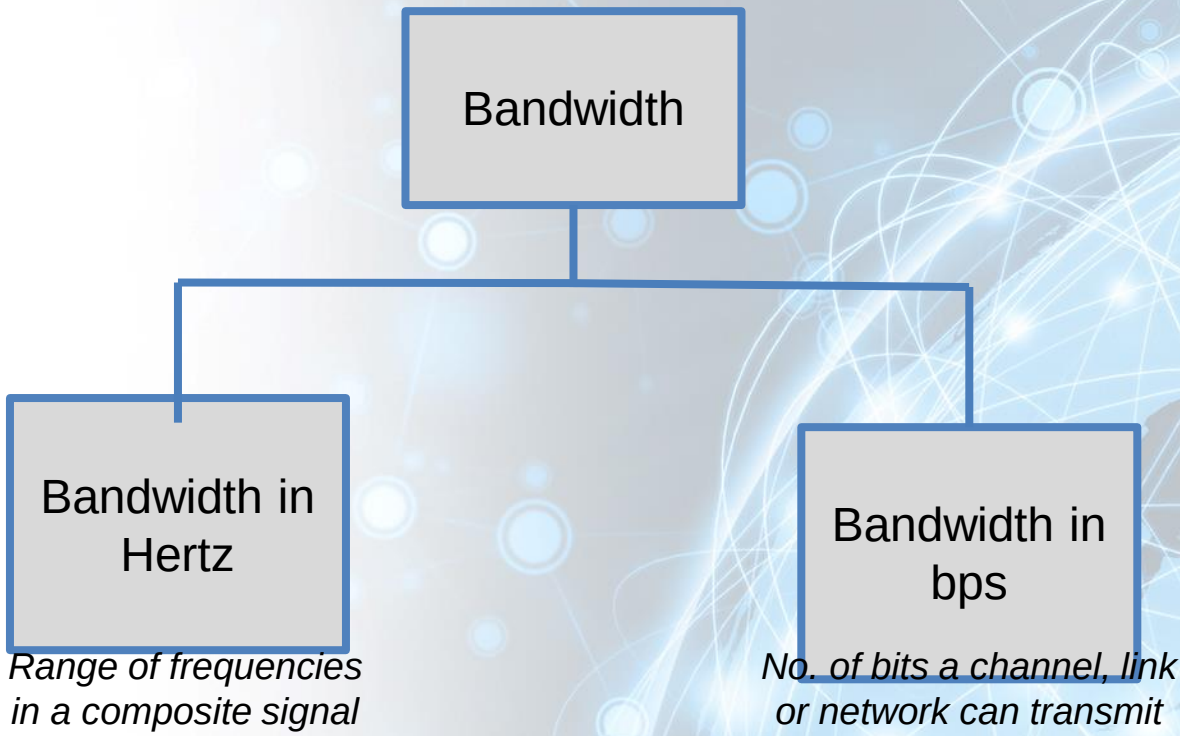
Example 3.42

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.

Example 3.43

If the telephone company improves the quality of the line and increases the bandwidth to 8 kHz, we can send 112,000 bps by using the same technology as mentioned in Example 3.42.

Bandwidth


Bandwidth
Bandwidth in Hertz
Range of frequencies in a composite signal
Bandwidth in bps
No. of bits a channel, link or network can transmit

Throughput

- Measure of how fast we can actually send data through a network.
- Bandwidth is not the same as Throughput
- A link may have a bandwidth of B bps, but we can only send T bps through this

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 the network?

$$T = \frac{(12{,}000 \times 10{,}000)}{60}$$

$$= 2\ \text{Mbps}$$

$T = 2\ \text{Mbps}$

$B = 10\ \text{Mbps}$

Throughput

The throughput is a measure of how fast we can actually send data through a network. Although, at first glance, bandwidth in bits per second and throughput seem the same, they are different. 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.

Throughput

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.

Throughput

We can say that latency is made of four components: propagation time, transmission time, queuing time and processing delay.

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

Example 3.44

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

Example 3.44

Solution

We can calculate the throughput as

Throughput =

(12,000X10,000)/60 = 2Mbps

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

Example 3.45

What is the propagation time if the distance between the two points is 12,000 km? Assume the propagation speed to be 2.4 × 108 m/s in cable.

Solution

We can calculate the propagation time as

Propagation time = (12,000X10,000)/(2 .4X2^{8})=

Example 3.45

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 3.46

What are the propagation time and the transmission time for a 2.5-KB (kilobyte) message if the bandwidth of the network is 1 Gbps? Assume that the distance between the sender and the receiver is 12,000 km and that light travels at 2.4 × 108 m/s.

Example 3.46

Solution

We can calculate the propagation and transmission time as

Propagation time = (12,000 X 1000)/ (2.4X 10^8) = 50 ms

Transmission time = (2500 X 8) / 10^9 = 0.020 ms

Example 3.46

Solution

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.

Example 3.47

What are the propagation time and the transmission time for a 5-MB (megabyte) message (an image) if the bandwidth of the network is 1 Mbps? Assume that the distance between the sender and the receiver is 12,000 km and that light travels at 2.4 × 108

Example 3.47

Solution

We can calculate the propagation and transmission times as

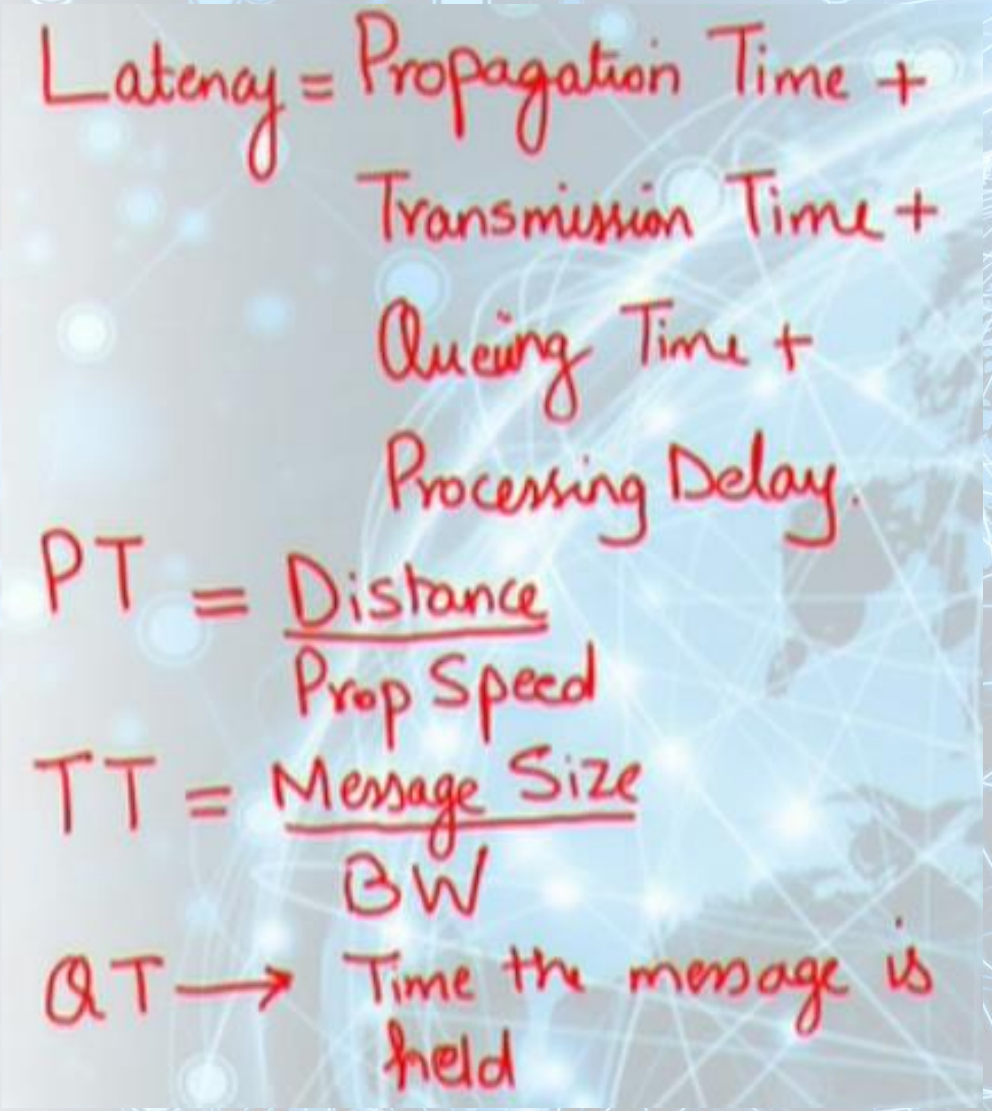
Propagation time = (12,000 X 1000) / (2.4 X 10^8) = 50 ms

Transmission time = (5,000,000 X 8) / 106 = 40s

We can calculate the propagation and transmission

Latency or Delay

- **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**



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.

$$PT = \frac{(12000 \times 1000)}{2.4 \times 10^8}$$

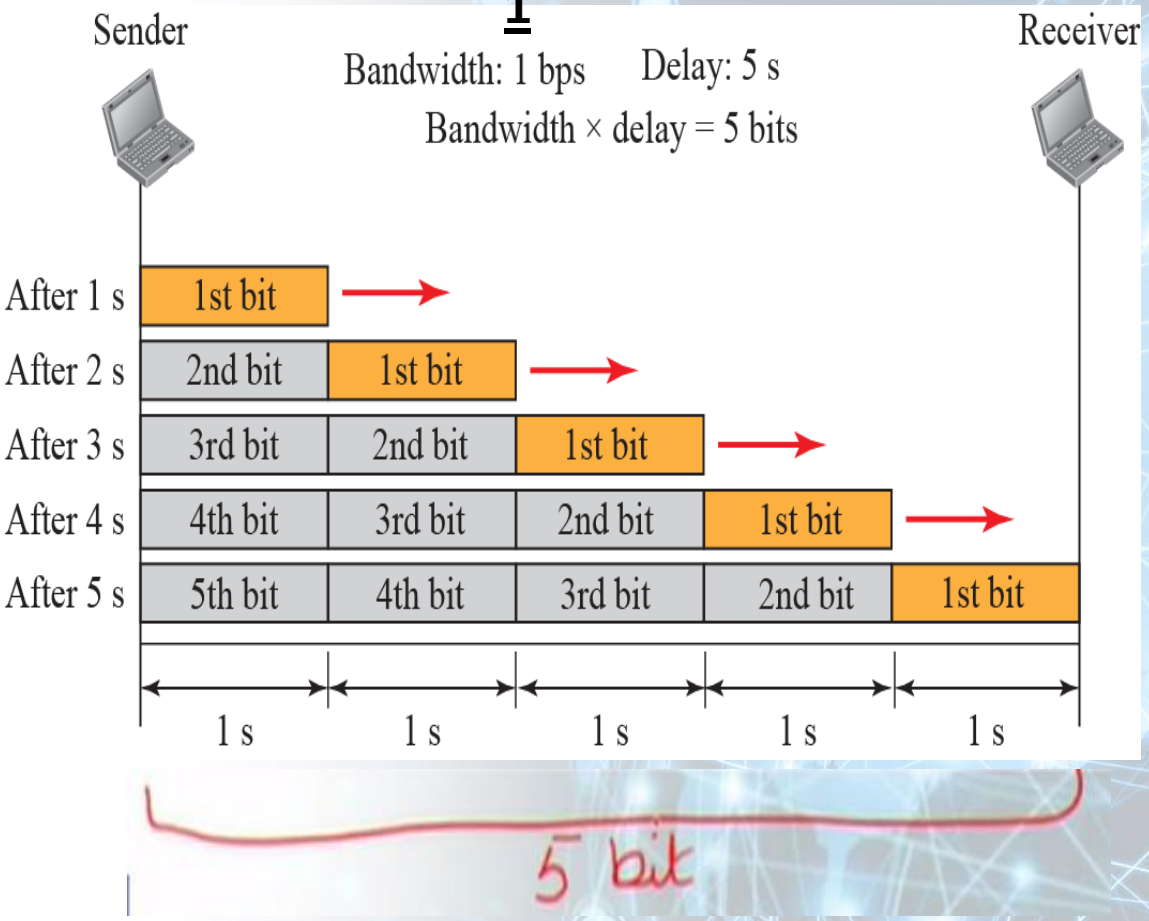
$$= 50 \text{ msec.}$$

Delay – Bandwidth Delay Product

- Bandwidth and delay are two performance metrics of a link
- Product of the two, The Bandwidth-Delay Product defines the number of bits that can fill a link

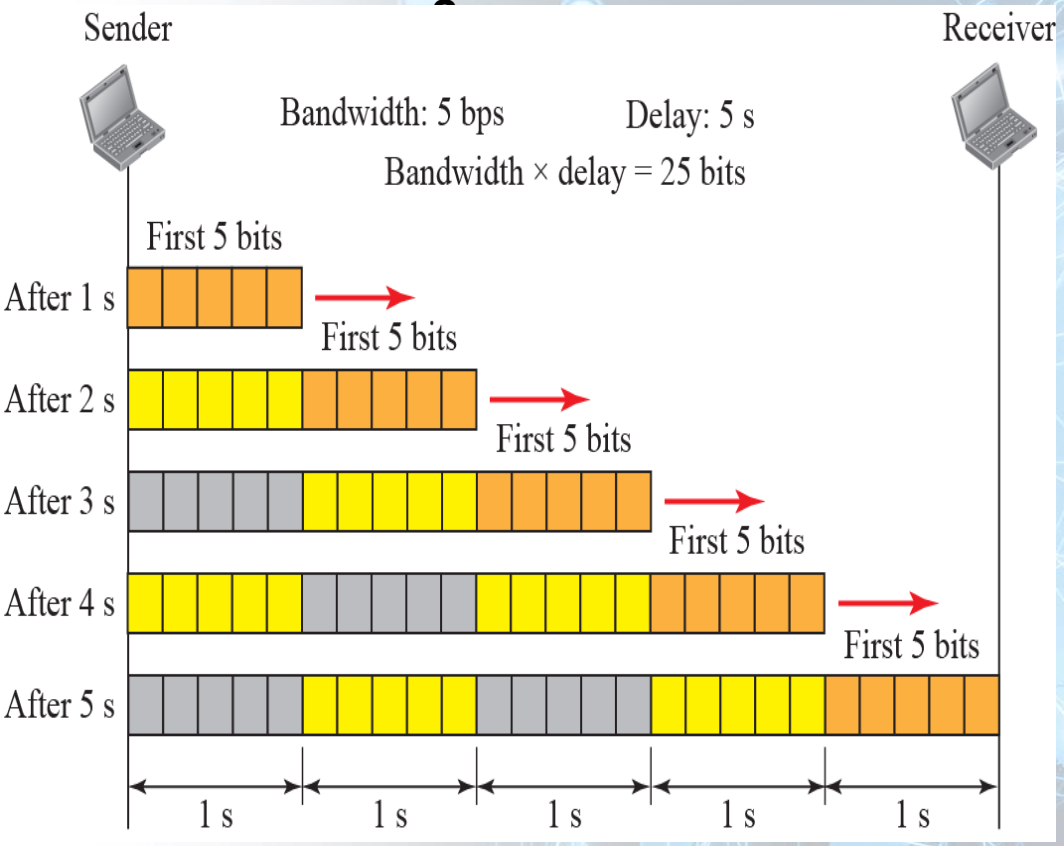
Bandwidth-Delay Product

Case 1

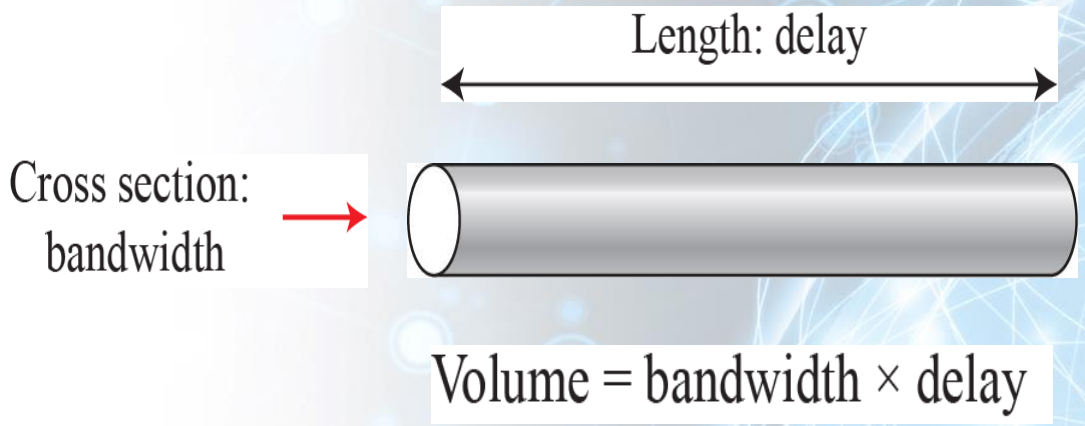


Bandwidth-Delay Product

Case



Bandwidth-Delay Product



Volume = bandwidth × delay

Example 3.48

We can think about the link between two points as a pipe. The cross section of the pipe represents the bandwidth, and the length of the pipe represents the delay. We can say the volume of the pipe defines the bandwidth-delay product, as shown in Figure 3.34.

Delay - Jitter

- Jitter is a problem if different packets of data encounter different delays and the application using the data at the receiver site is time-sensitive (audio and video data, for example)

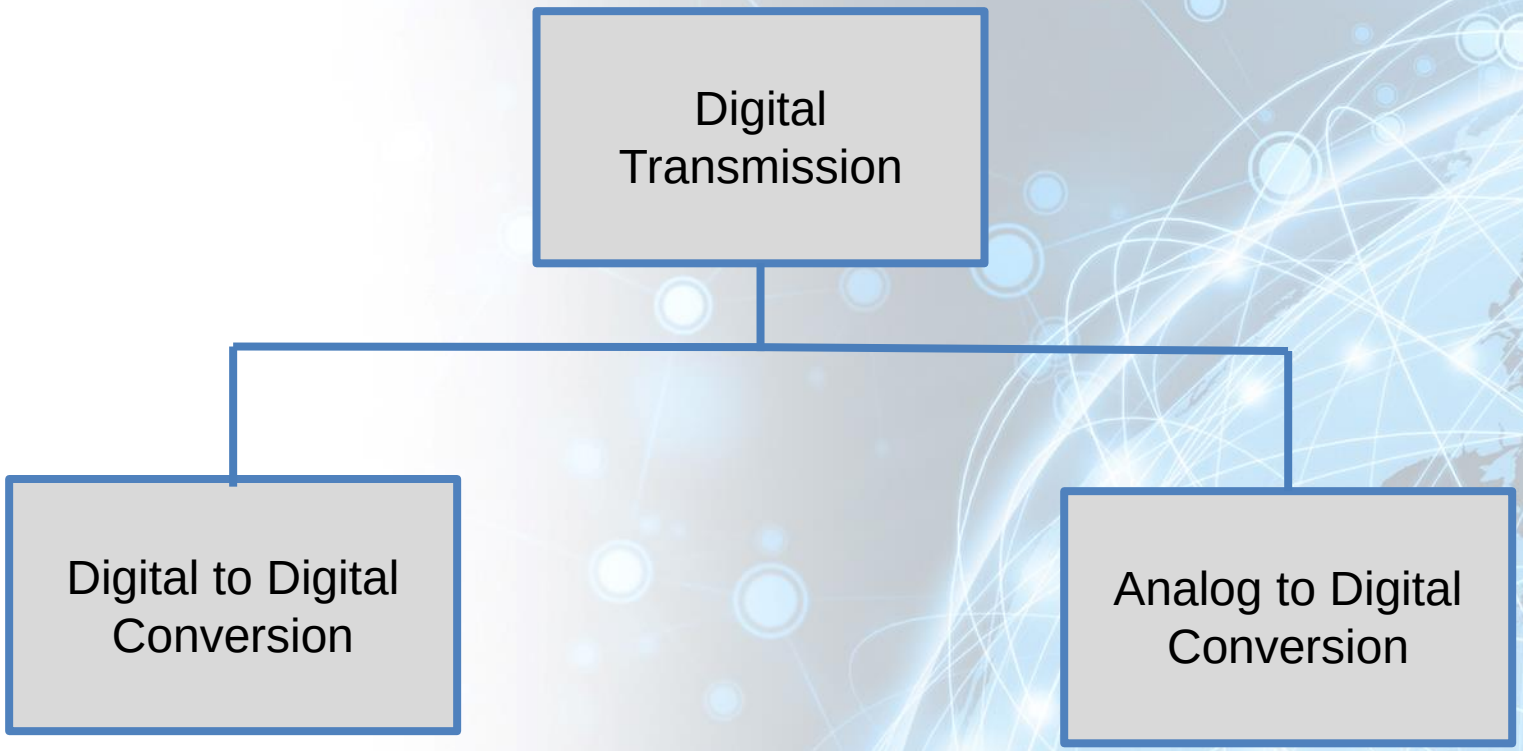
Delay - Jitter

- Delay for first packet is 20 ms for the second is 45 ms, and for the third is 40 ms, then the real-time application that uses the packets endures jitter

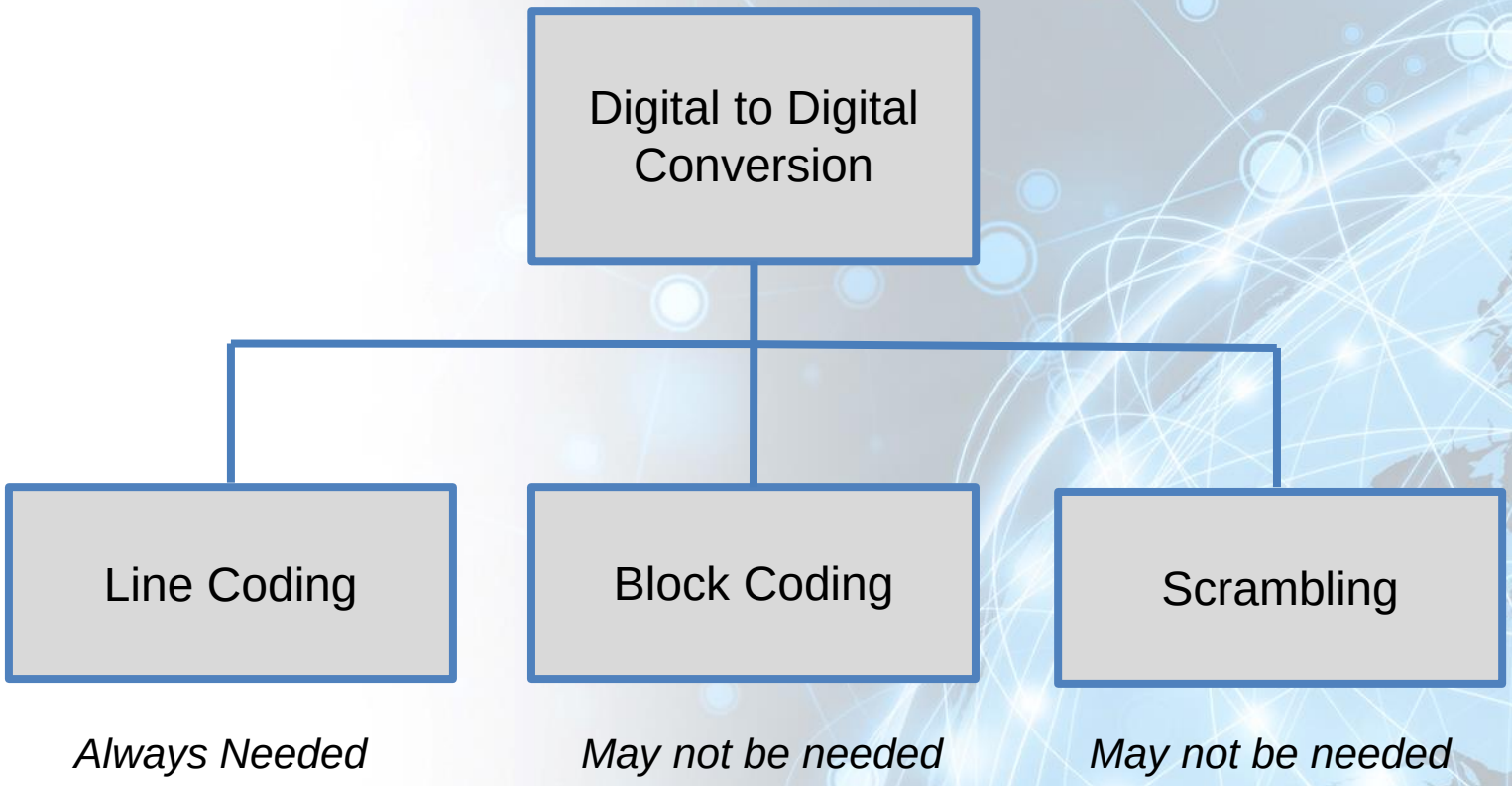
Digital-to-digital Conversion

- Data → Analog or Digital
- Signals → Analog or Digital
- Digital Transmission
- Analog Transmission

Digital Transmission



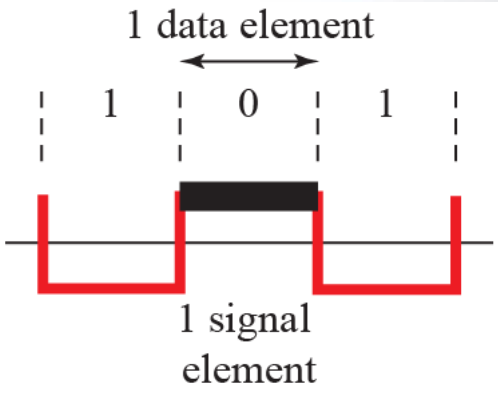
Digital to Digital Conversion



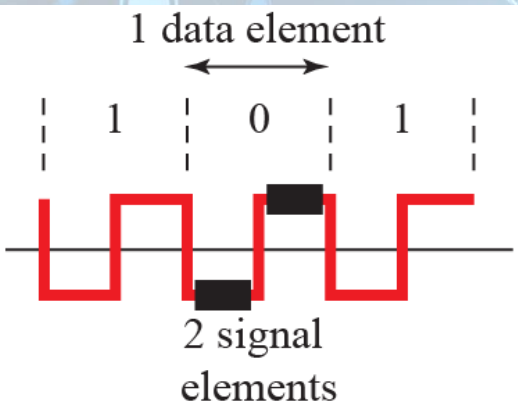
Signal Element versus Data Element

- A Data element is the smallest entity that can represent a piece of information → Bit
- A Signal element is the shortest unit of a digital signal
- Data Elements: Carried
- Signal Elements: Carriers

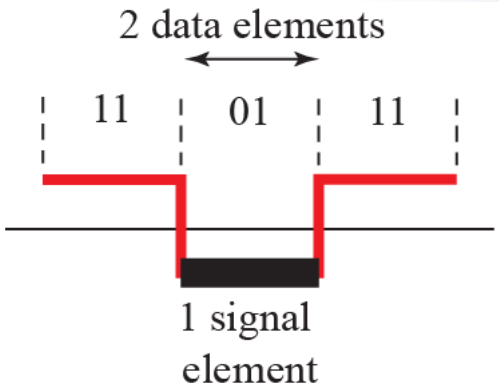
Signal Element versus Data Element



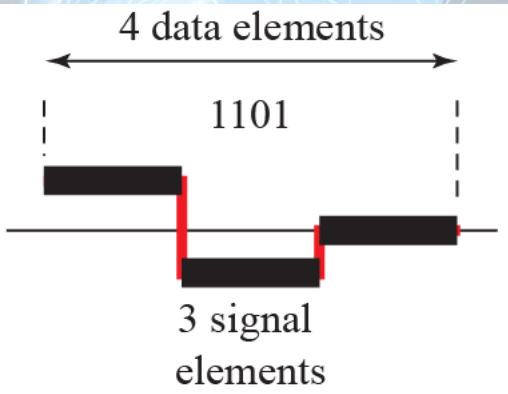
a. One data element per one signal element (r = 1)



b. One data element per two signal elements $\left(r = \frac{1}{2}\right)$



c. Two data elements per one signal element (r = 2)



d. Four data elements per three signal elements $\left(r = \frac{4}{3}\right)$

Data Rate versus Signal Rate

- Data Rate is number of data elements sent in 1 sec (bps)
- Signal Rate is number of signal elements sent in 1 sec (baud)
- Data Rate → Bit Rate
- Signal Rate → Pulse Rate, Modulation Rate or Baud Rate

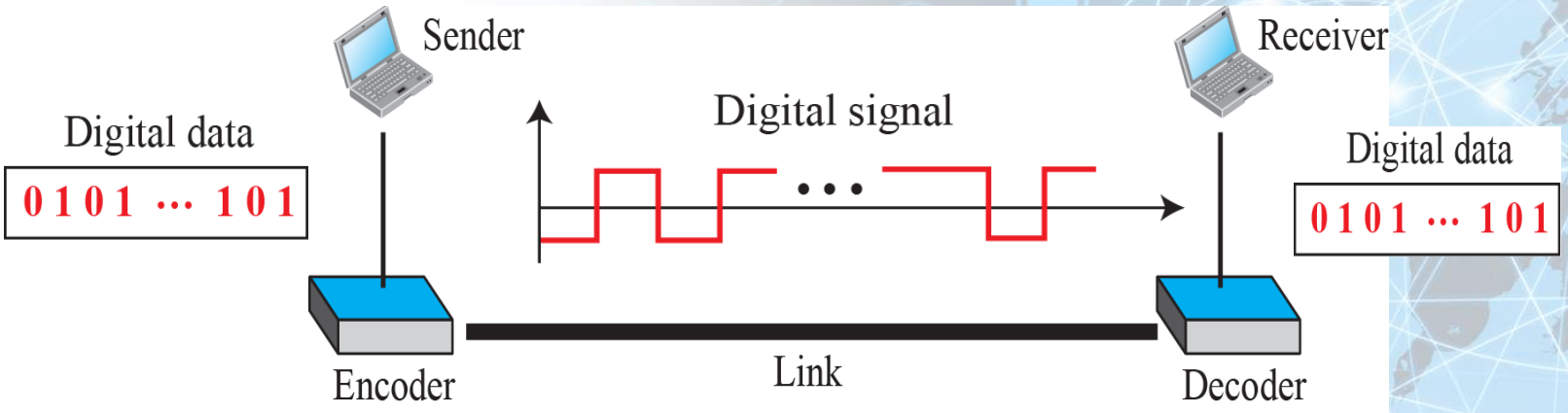
Example

A signal has a signal rate of 100 bauds. What is the Data rate if one data element is carried per signal element?

Line Coding

- Digital data to Digital signals
- Data (Text, Numbers, Pictures, Audio, or Video) is stored in computer memory as sequences of bits
- Line coding converts a sequence of Bits to a Digital Signal

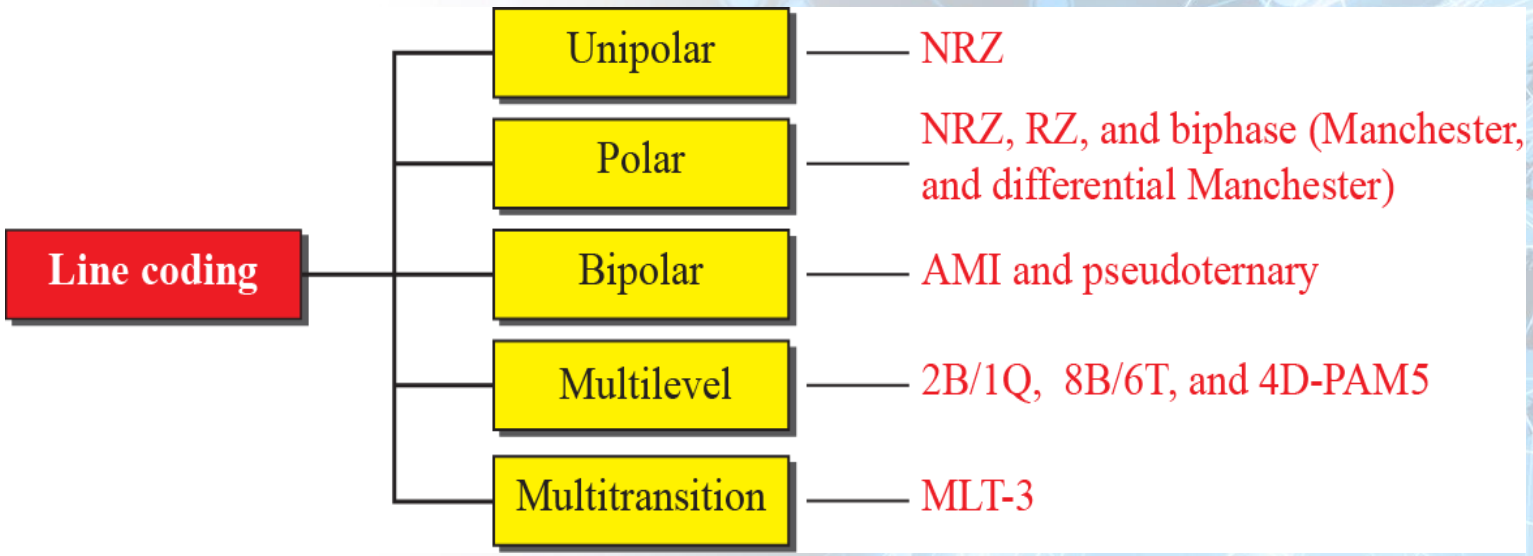
Line Coding and Decoding



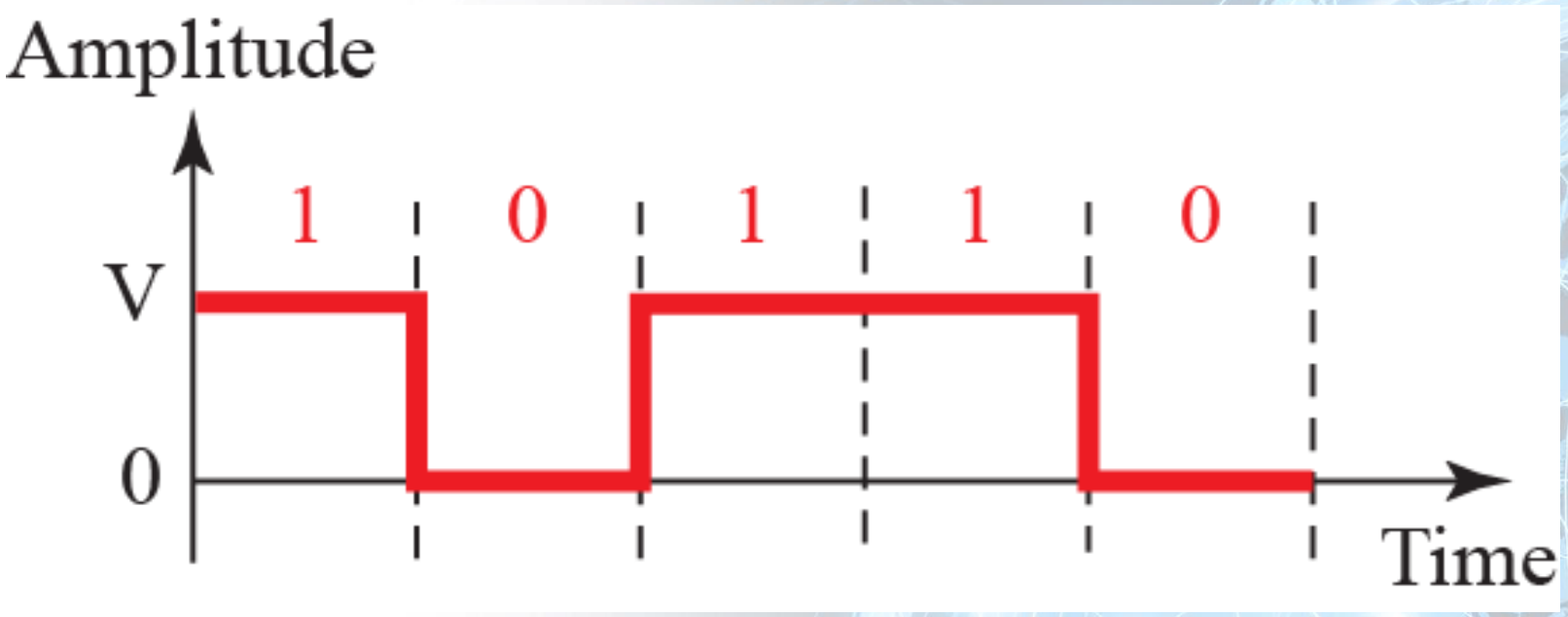
Line Coding Schemes

- We can roughly divide line coding schemes into five broad categories

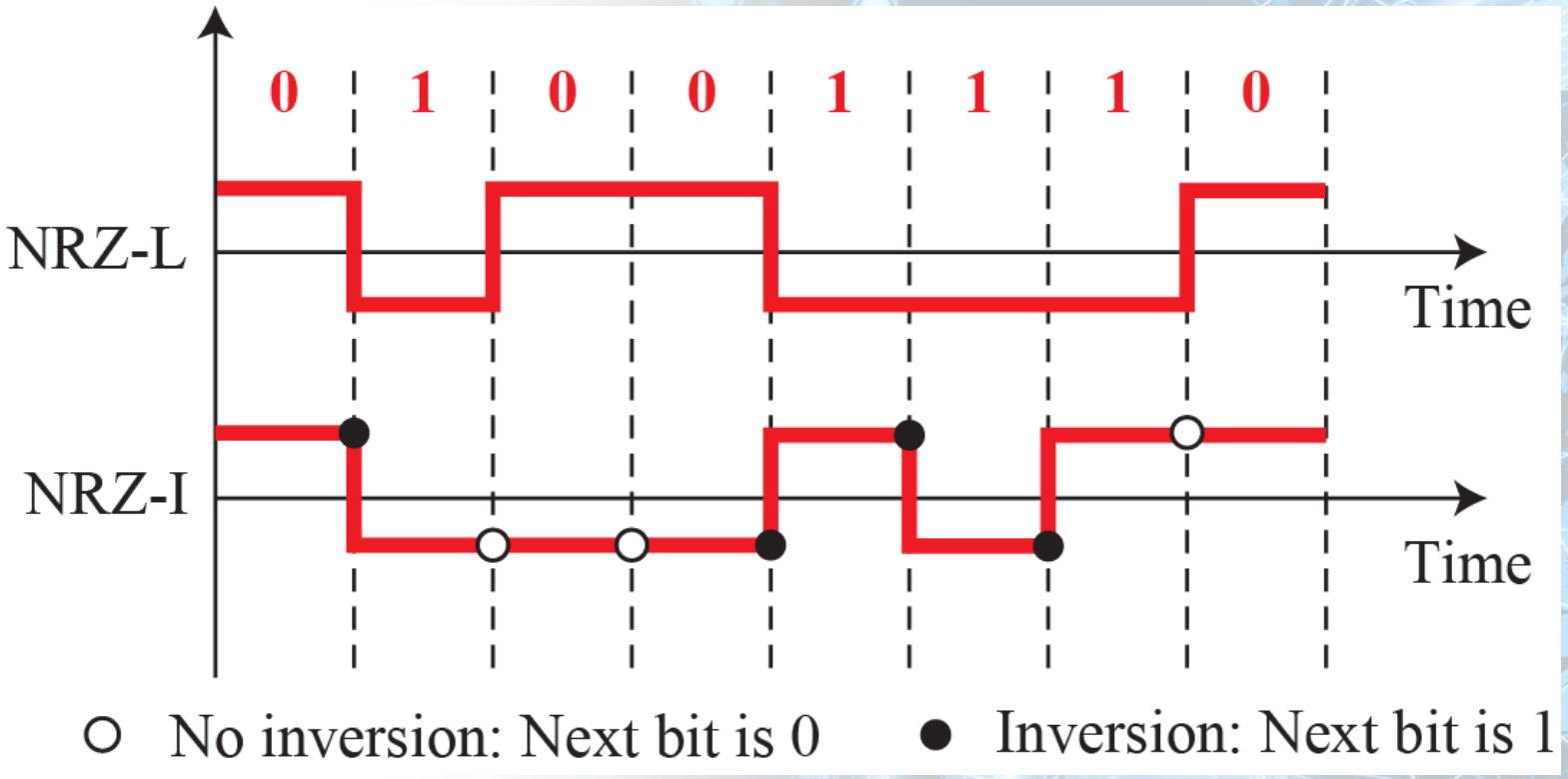
Line Coding Schemes



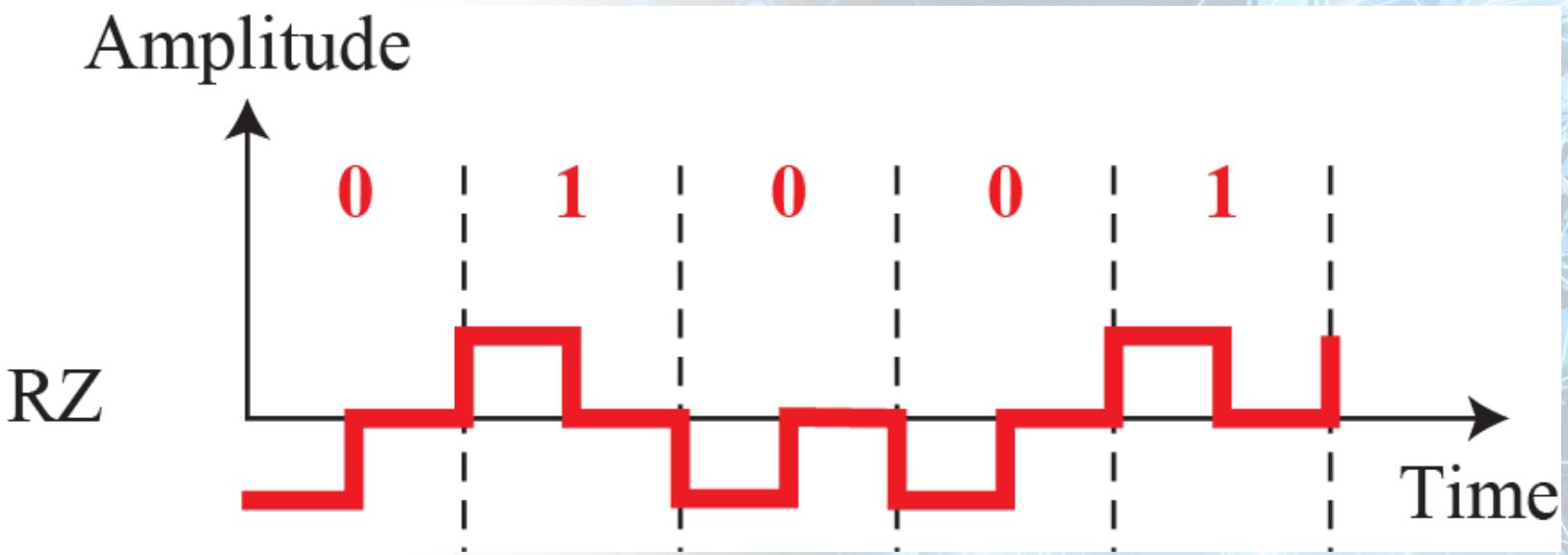
Unipolar NRZ scheme



Polar schemes (NRZ)



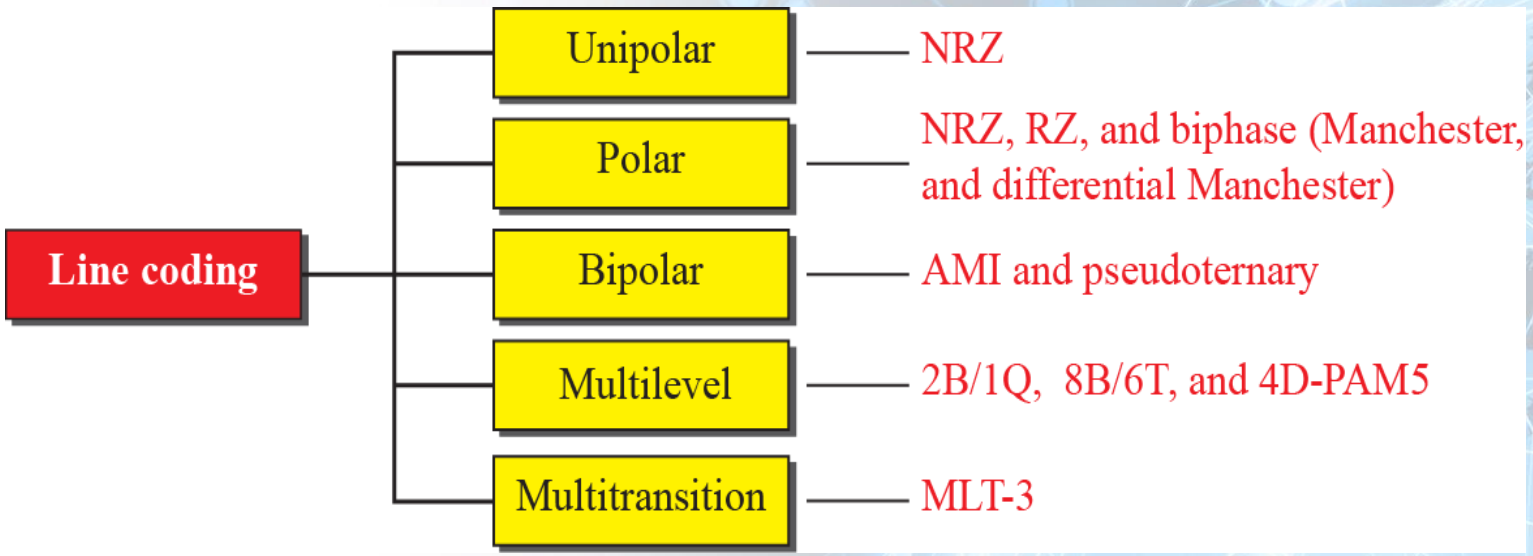
Polar schemes (RZ)



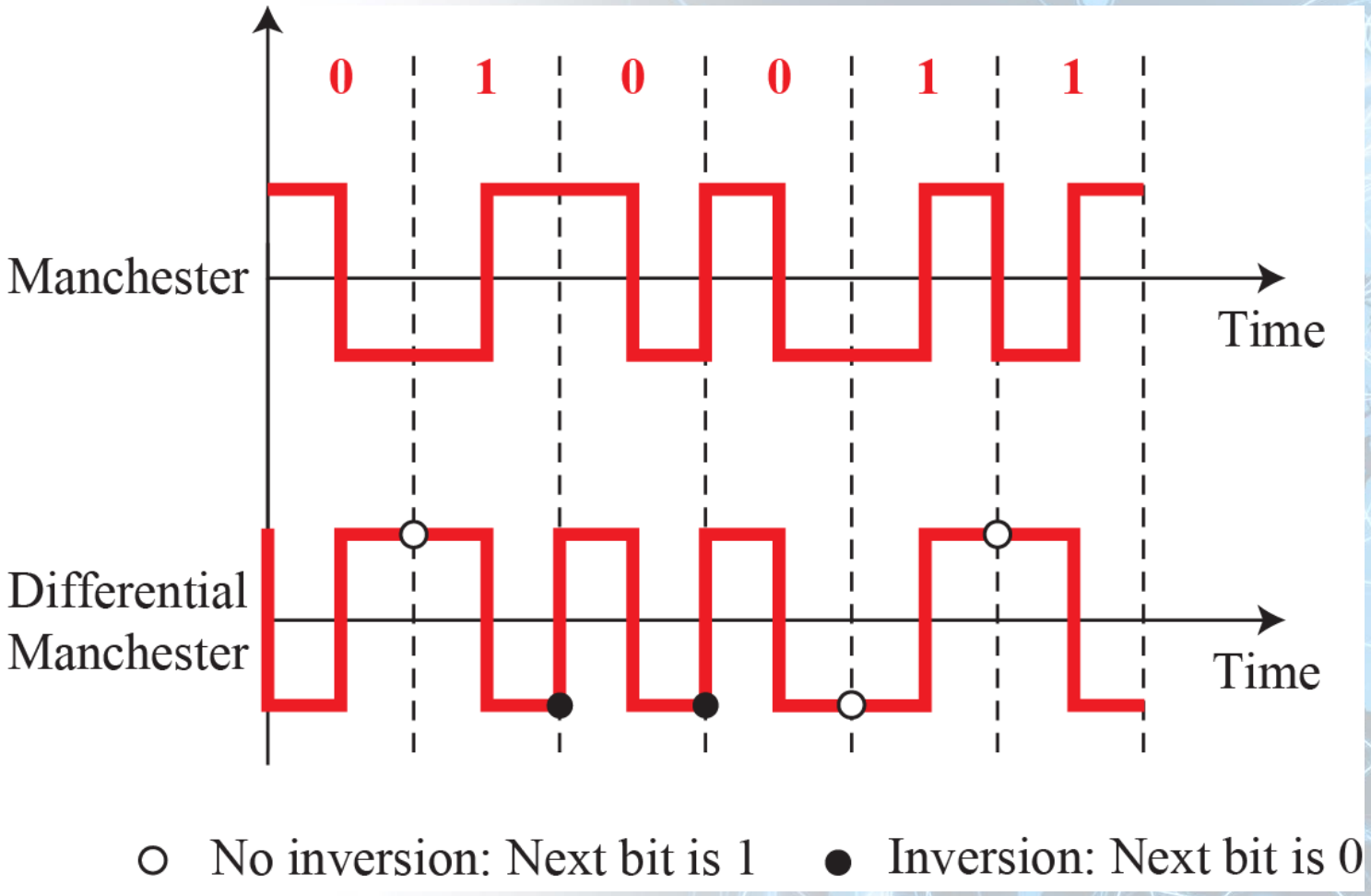
Line Coding Schemes

- We can roughly divide line coding schemes into five broad categories

Line Coding Schemes



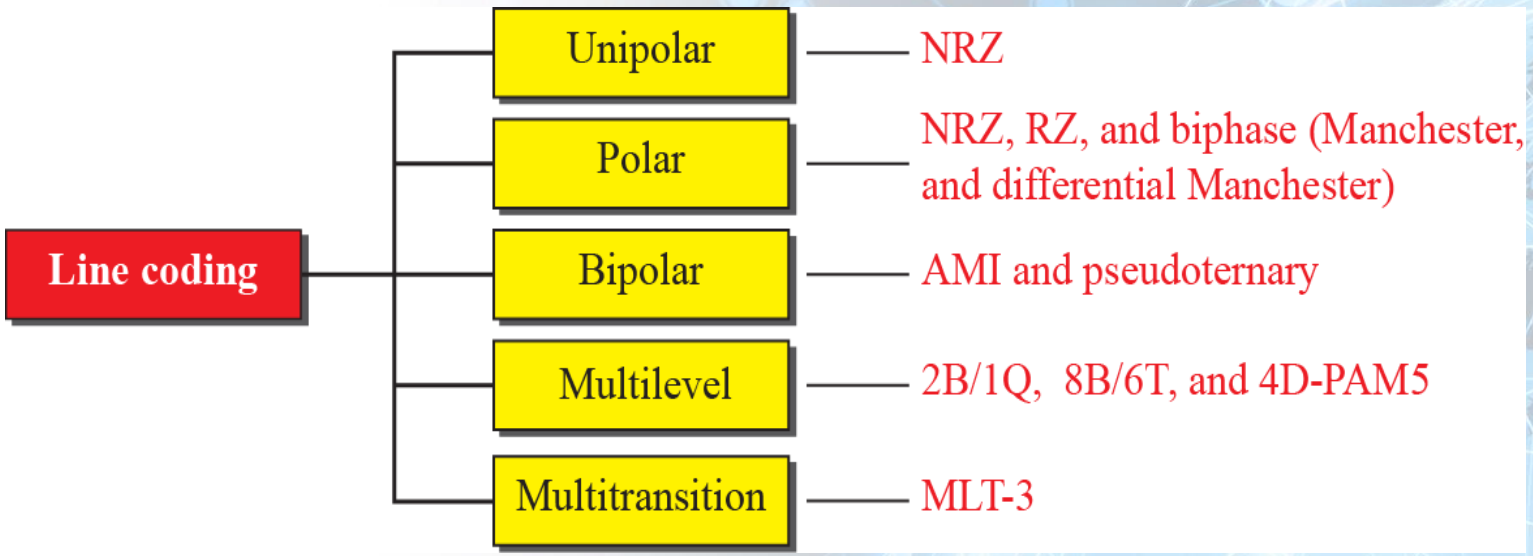
Polar Biphase



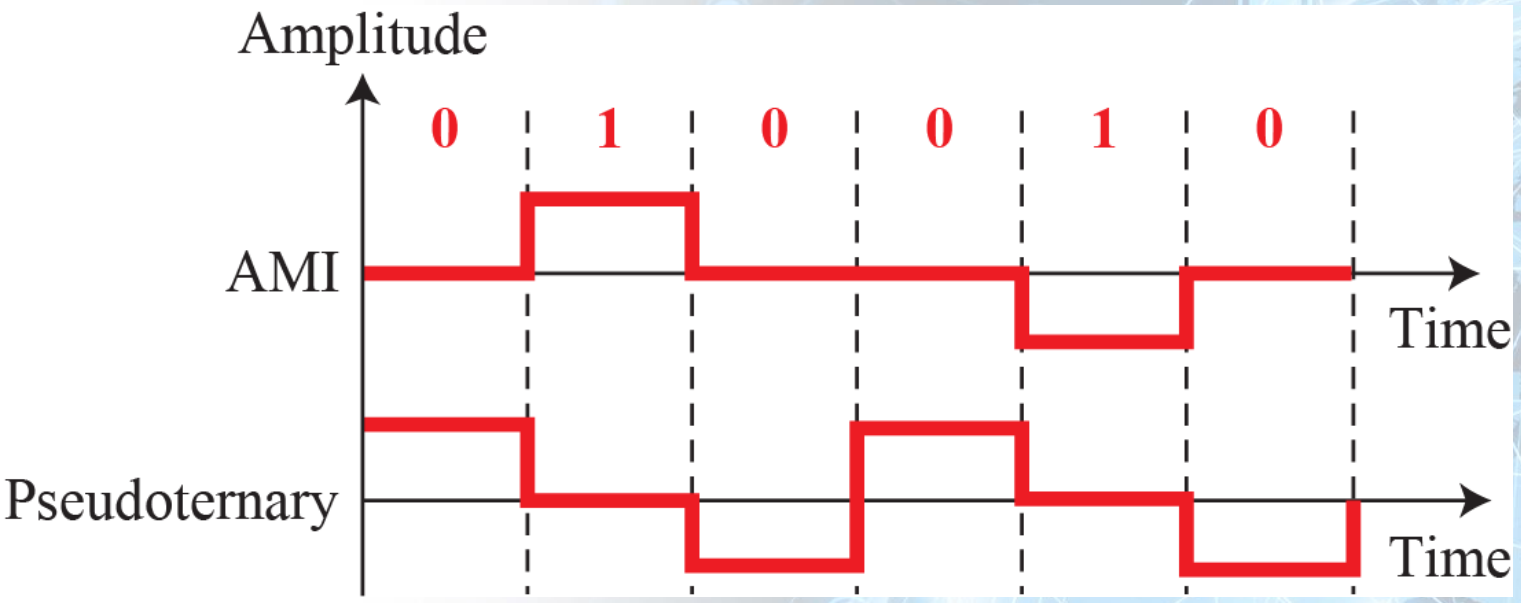
Line Coding Schemes

- We can roughly divide line coding schemes into five broad categories

Line Coding Schemes



Bipolar schemes: AMI & Pseudoternary



Multilevel: 2B1Q

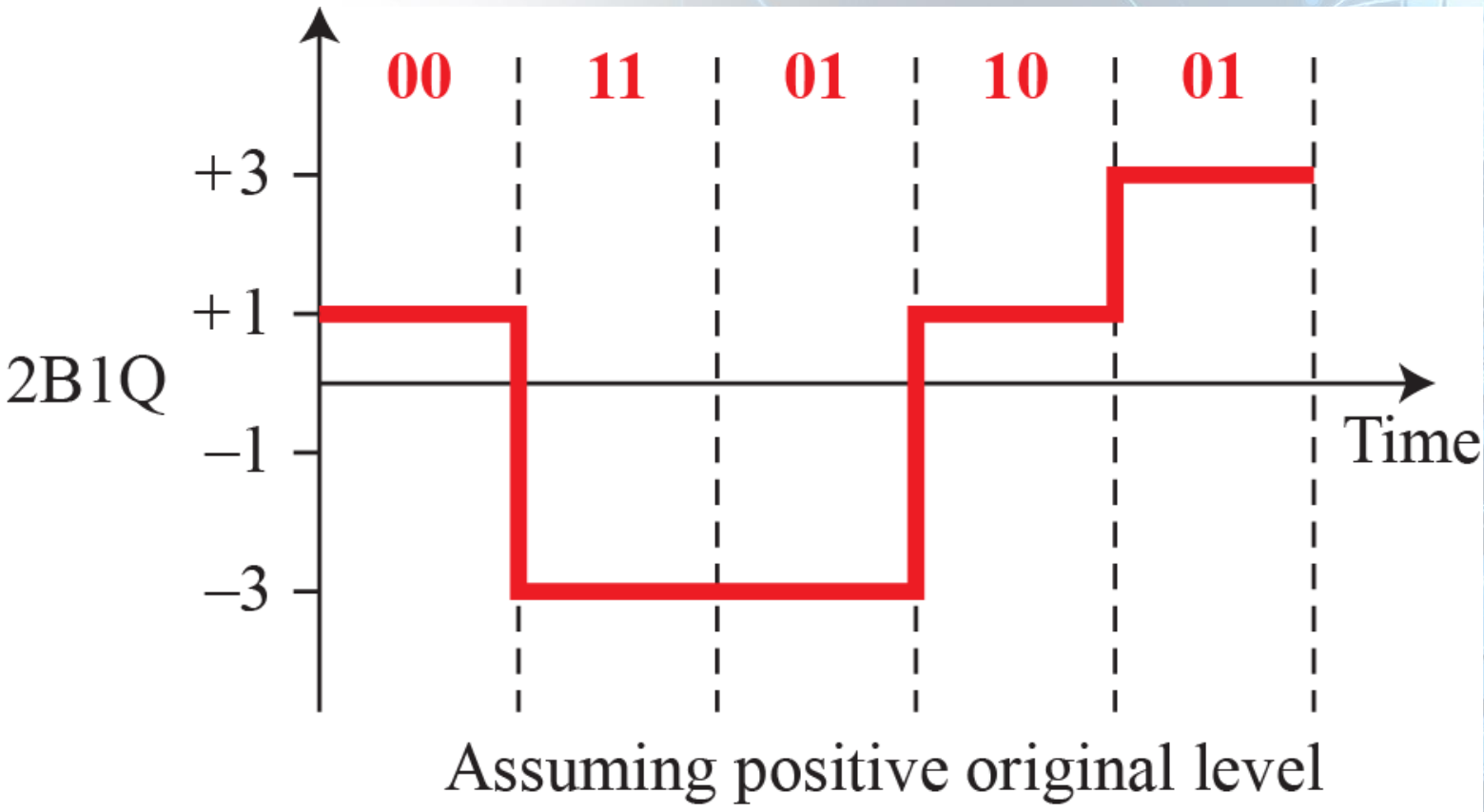


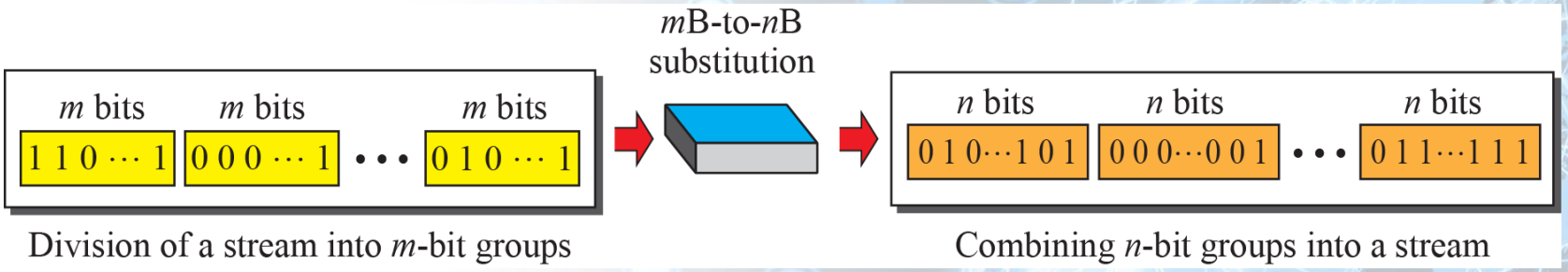
Table 4.1 : Summary of line coding schemes

Category	*Scheme*	*Bandwidth (average)*	*Characteristics*
Unipolar	NRZ	$B = N/2$	Costly, no self-synchronization if long 0s or 1s, DC
Polar	NRZ-L	$B = N/2$	No self-synchronization if long 0s or 1s, DC
	NRZ-I	$B = N/2$	No self-synchronization for long 0s, DC
	Biphase	$B = N$	Self-synchronization, no DC, high bandwidth
Bipolar	AMI	$B = N/2$	No self-synchronization for long 0s, DC
Multilevel	2B1Q	$B = N/4$	No self-synchronization for long same double bits
	8B6T	$B = 3N/4$	Self-synchronization, no DC
	4D-PAM5	$B = N/8$	Self-synchronization, no DC
Multitransition	MLT-3	$B = N/3$	No self-synchronization for long 0s

Block Coding

- Block coding changes a block of ‘m’ bits into a block of ‘n’ bits (n>m)
- mB/nB encoding technique
- We need Redundancy to ensure Synchronization
- Block coding gives us redundancy and improves line coding performance

Block coding concept



Block Coding

- Block coding changes a block of ‘m’ bits into a block of ‘n’ bits (n>m)
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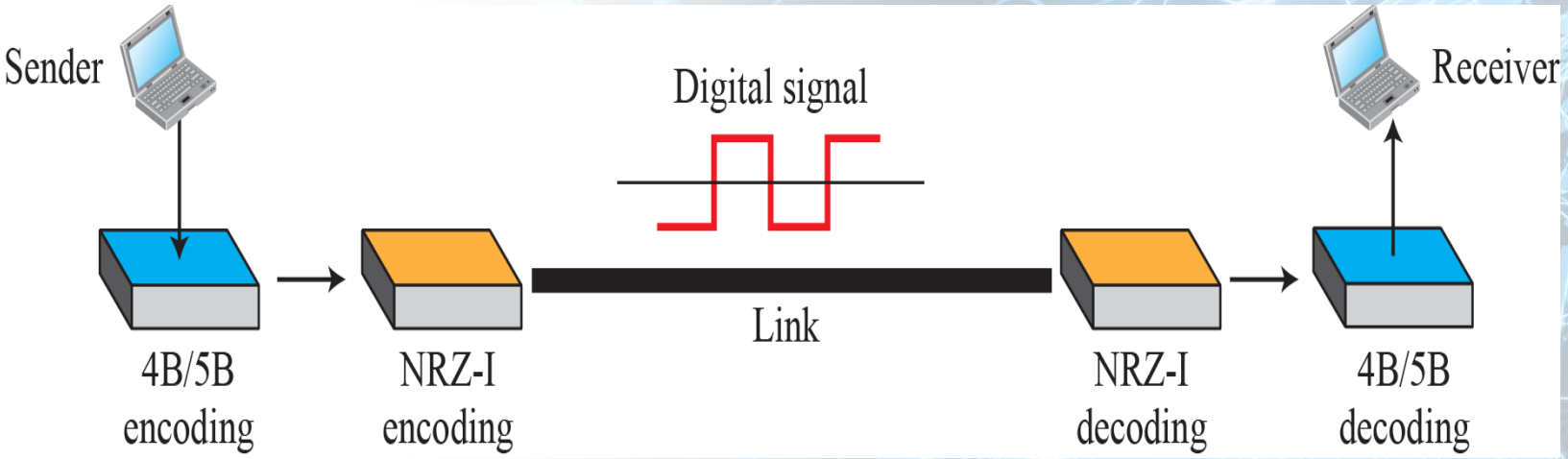
Using block coding 4B/5B with NRZ-I line coding



Block Coding

- Block coding changes a block of ‘m’ bits into a block of ‘n’ bits (n>m)
- mB/nB encoding technique
- We need Redundancy to ensure Synchronization
- Block coding gives us redundancy and improves line coding performance

4B/5B mapping codes

Data Sequence	*Encoded Sequence*	*Control Sequence*	*Encoded Sequence*
0000	11110	Q (Quiet)	00000
0001	01001	I (Idle)	11111
0010	10100	H (Halt)	00100
0011	10101	J (Start delimiter)	11000
0100	01010	K (Start delimiter)	10001
0101	01011	T (End delimiter)	01101
0110	01110	S (Set)	11001
0111	01111	R (Reset)	00111
1000	10010		
1001	10011		
1010	10110		
1011	10111		
1100	11010		
1101	11011		
1110	11100		
1111	11101		

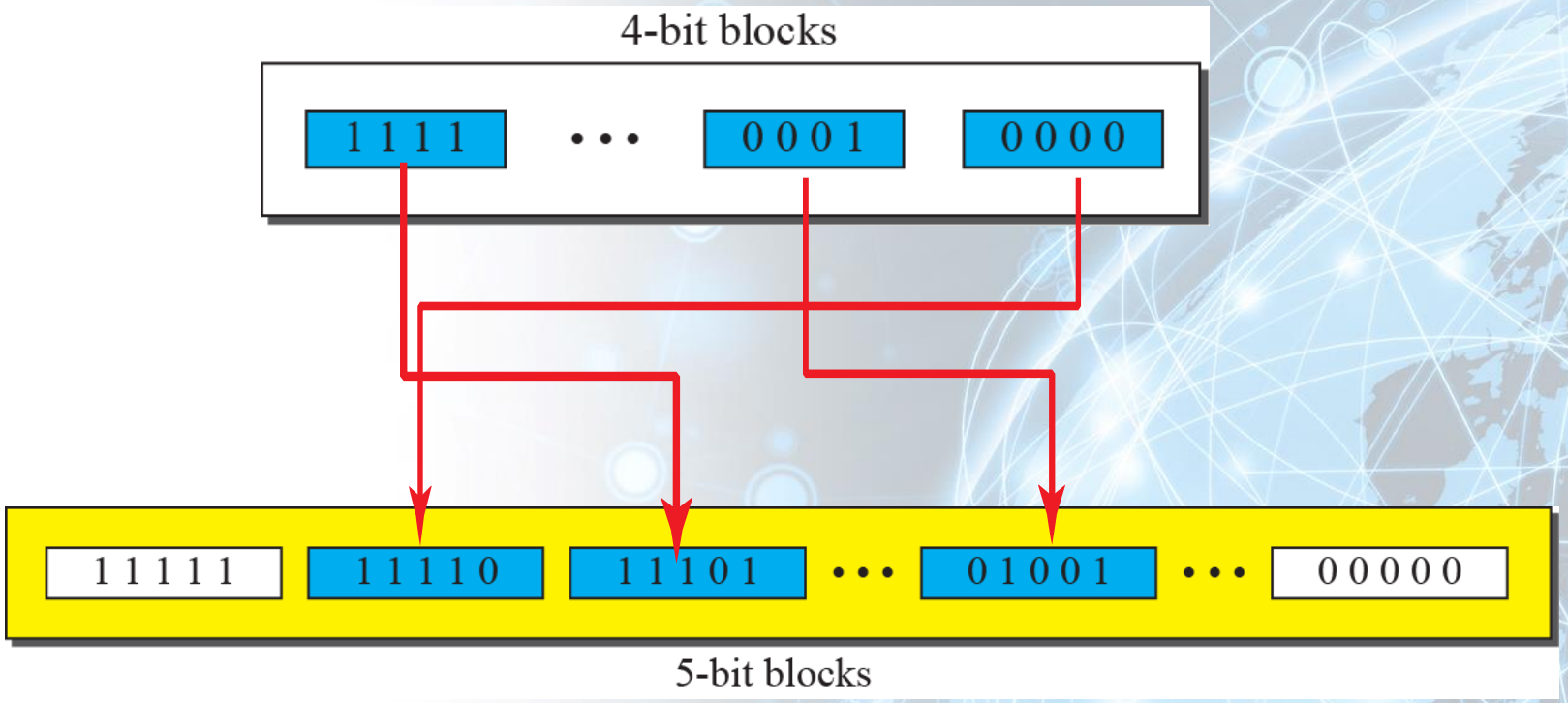
Block Coding

- Block coding changes a block of ‘m’ bits into a block of ‘n’ bits (n>m)
- mB/nB encoding technique
- We need Redundancy to ensure Synchronization
- Block coding gives us redundancy and improves line coding performance

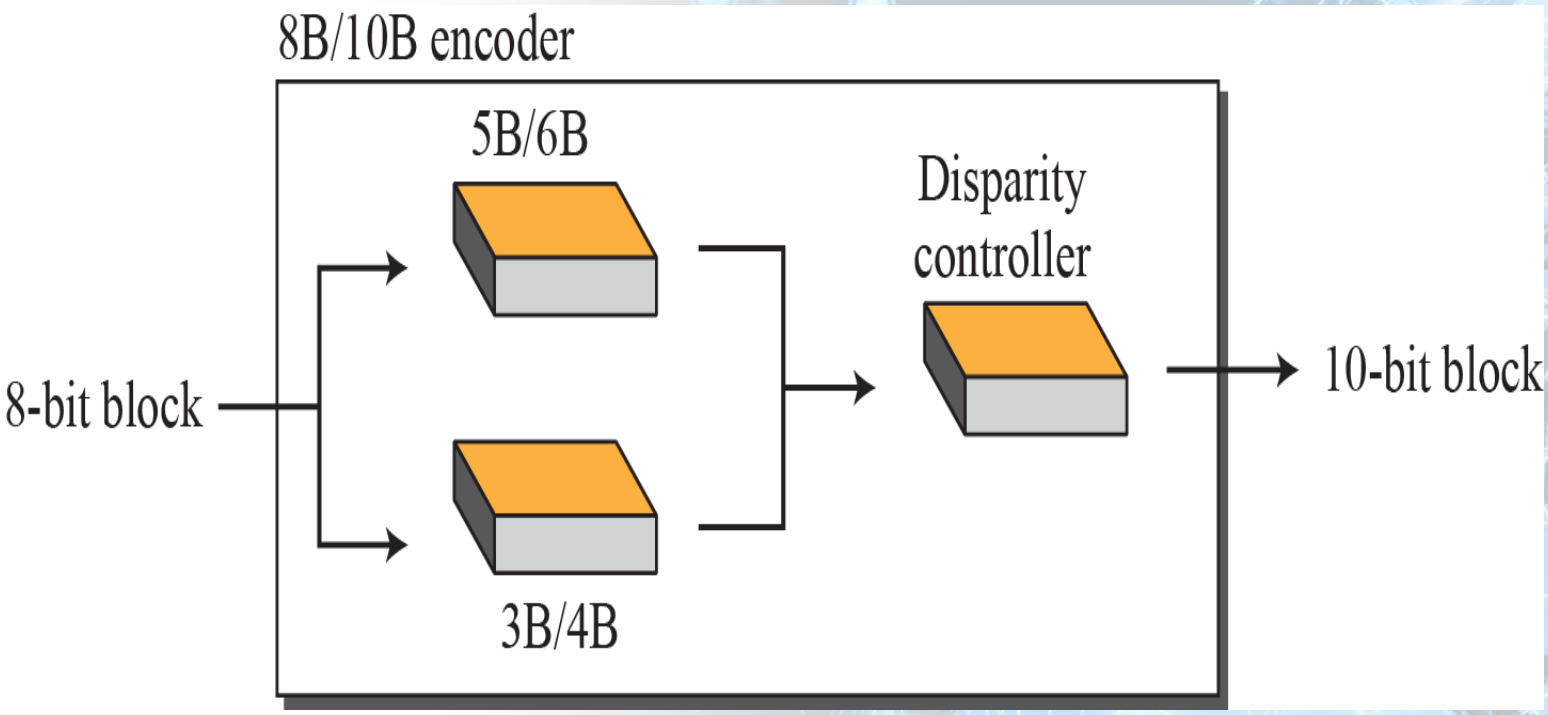
Example

We need to send data at a 1-Mbps rate. What is the minimum required bandwidth, using a combination of 4B/5B and NRZ-I or Manchester coding?

Example


4-bit blocks
1 1 1 1
0 0 0 1
0 0 0 0
1 1 1 1 1
1 1 1 1 0
1 1 1 0 1
0 1 0 0 1
0 0 0 0 0
5-bit blocks

8B/10B block encoding



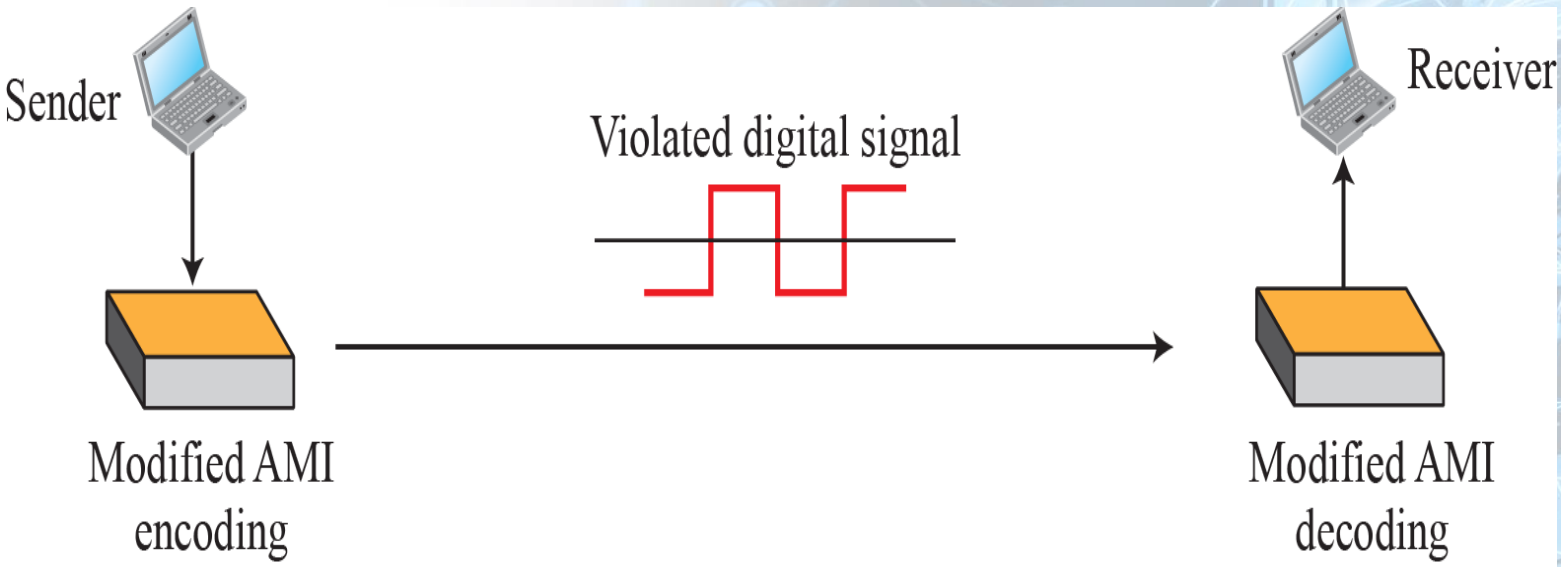
Scrambling

- Biphase schemes suitable for LAN but not for Long Distance
- Block Coding + NRZ-I solves synch issue but has DC component
- Bipolar AMI has a narrow bandwidth (no DC Component) but synch issue (long series of 0s)

Scrambling

- The system needs to insert the required pulses based on the defined scrambling rules

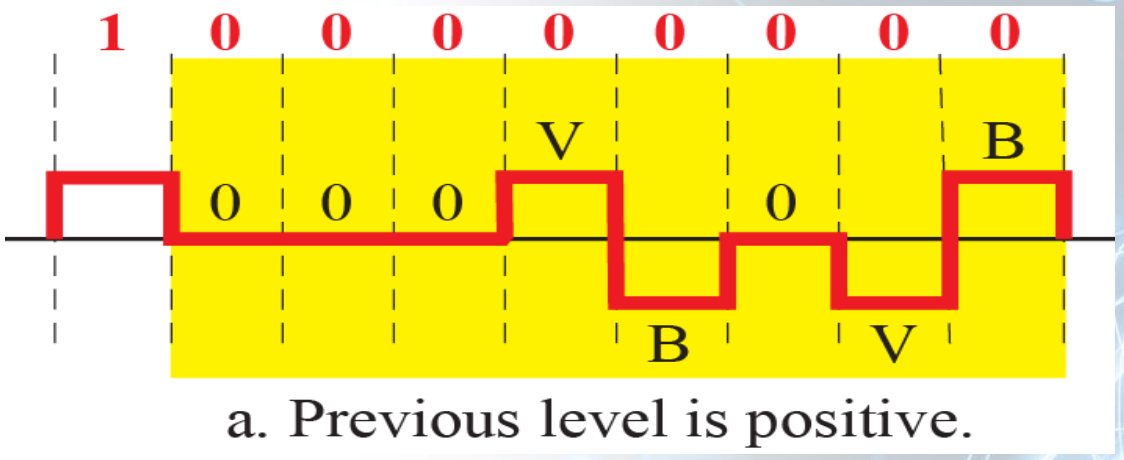
AMI used with scrambling



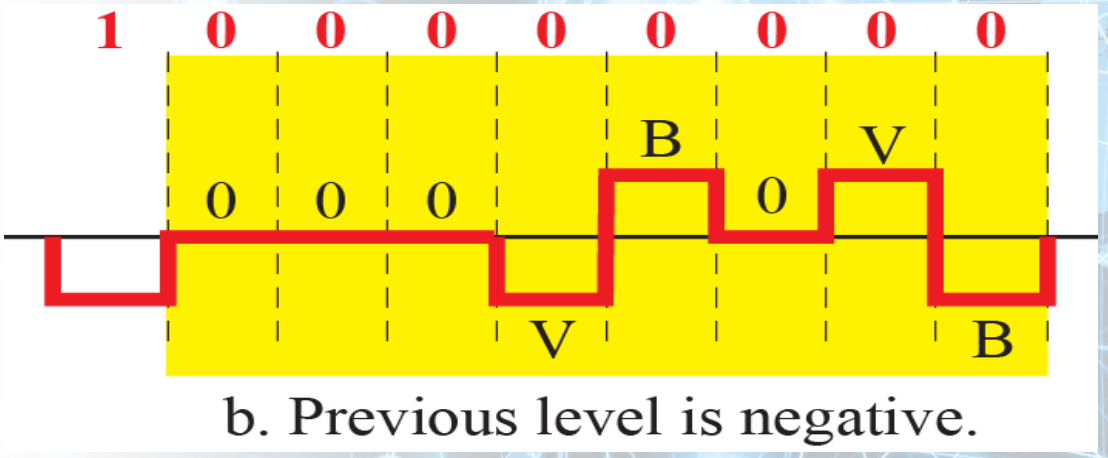
Types of Scrambling Techniques

- Two common scrambling techniques are B8ZS and HDB3
- Bipolar with 8-Zero Substitution (B8ZS)
- High-density bipolar 3-zero (HDB3)

Two cases of B8ZS scrambling technique



a. Previous level is positive.

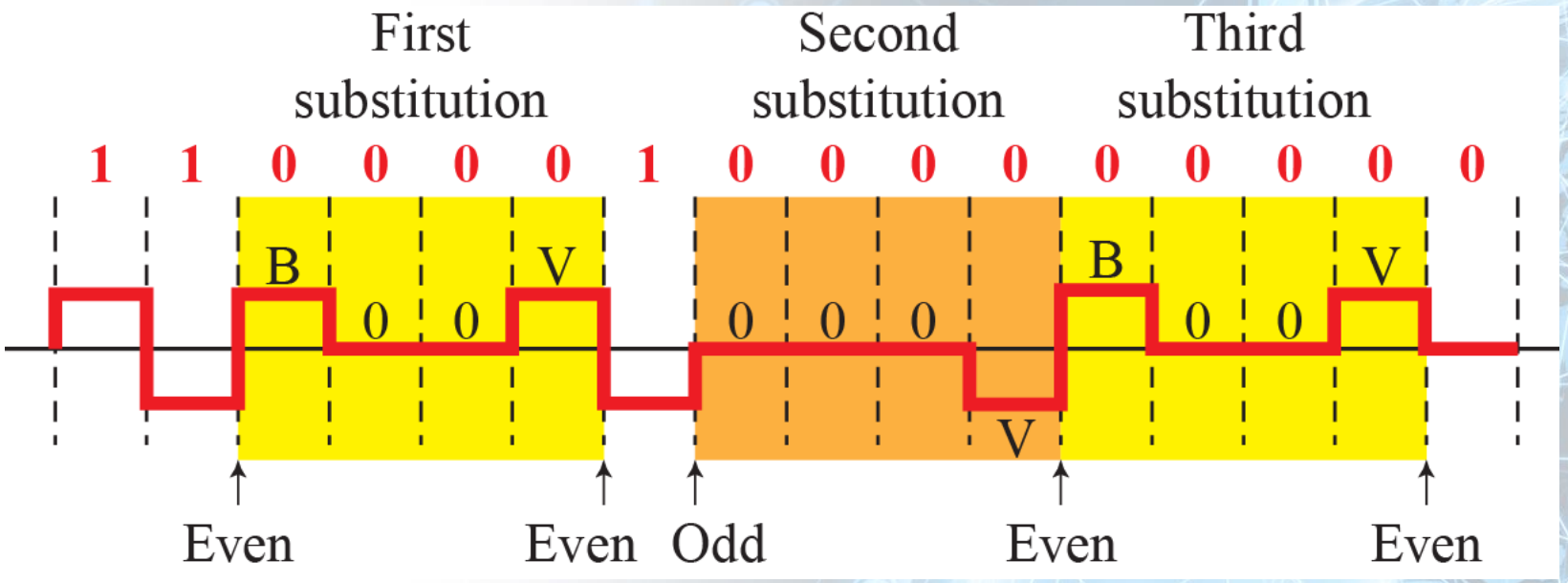


b. Previous level is negative.

Types of Scrambling Techniques

- Two common scrambling techniques are B8ZS and HDB3
- Bipolar with 8-Zero Substitution (B8ZS)
- High-density bipolar 3-zero (HDB3)

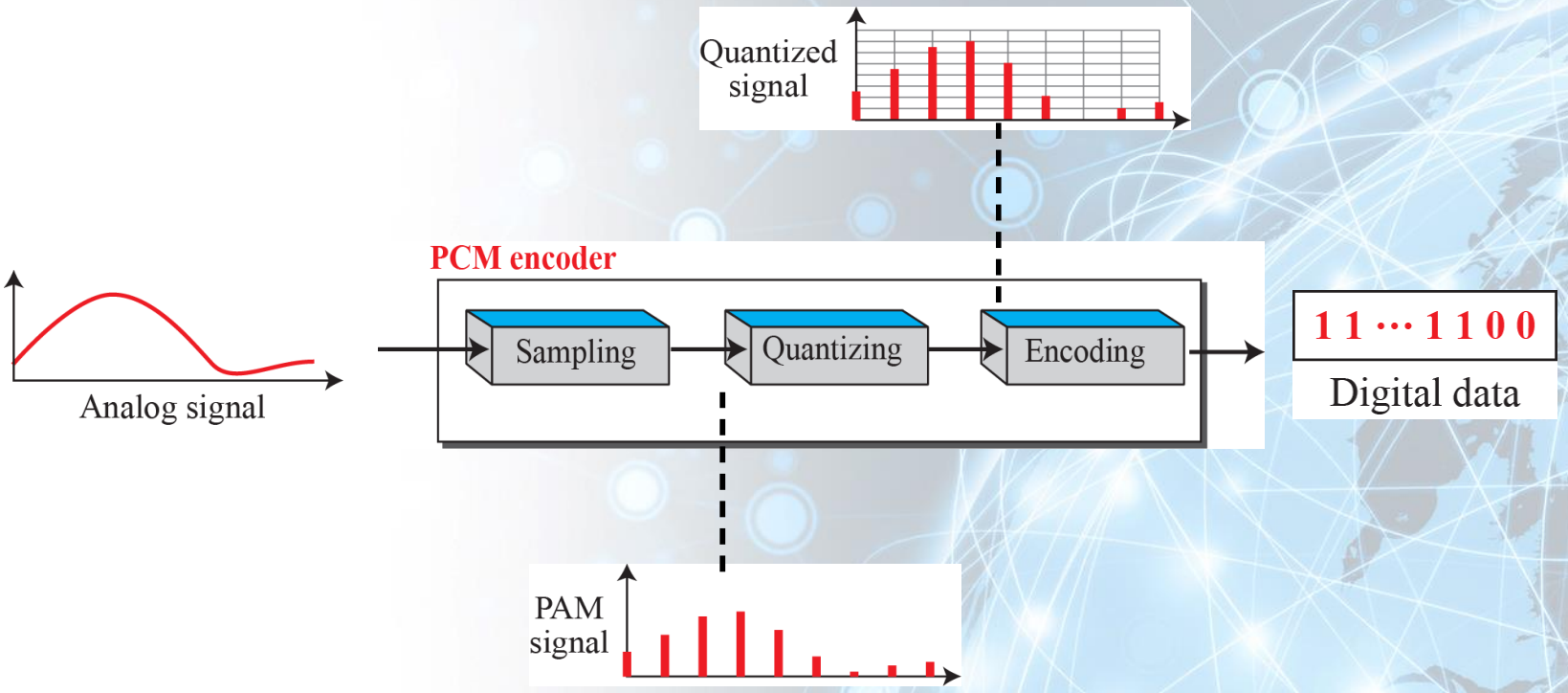
Different situations in HDB3 scrambling technique



Analog-to-digital Conversion

- Analog Data to Digital Data
- Process of Digitization
- Two techniques:
  - ✓ Pulse Code Modulation (PCM)
  - ✓ Delta Modulation (DM)

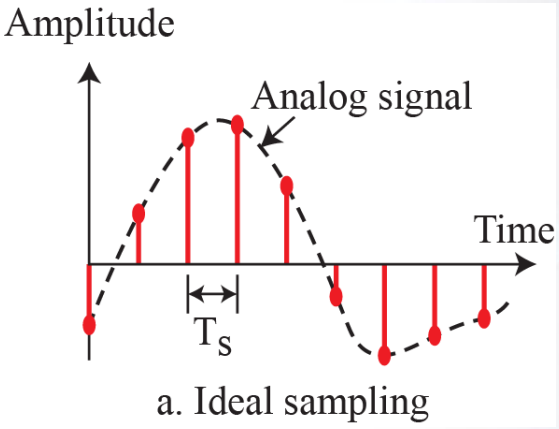
Pulse Code Modulation (PCM)



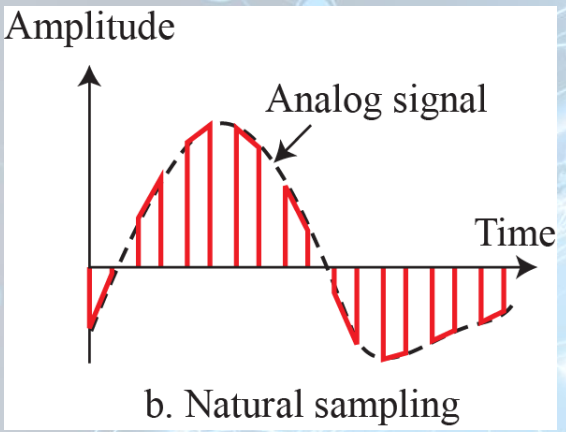
Pulse Code Modulation (PCM)

- Sampling
- Quantization
- Encoding

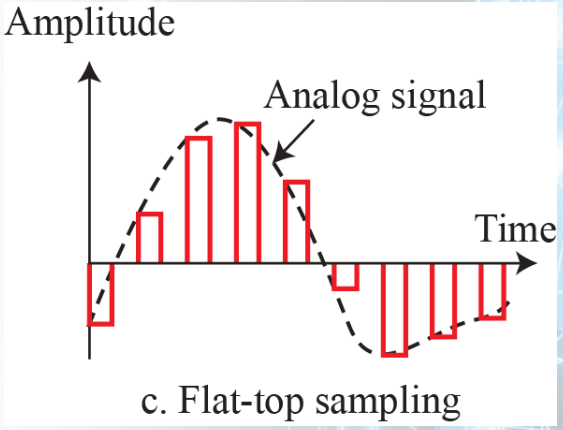
Three different sampling methods for PCM



a. Ideal sampling



b. Natural sampling

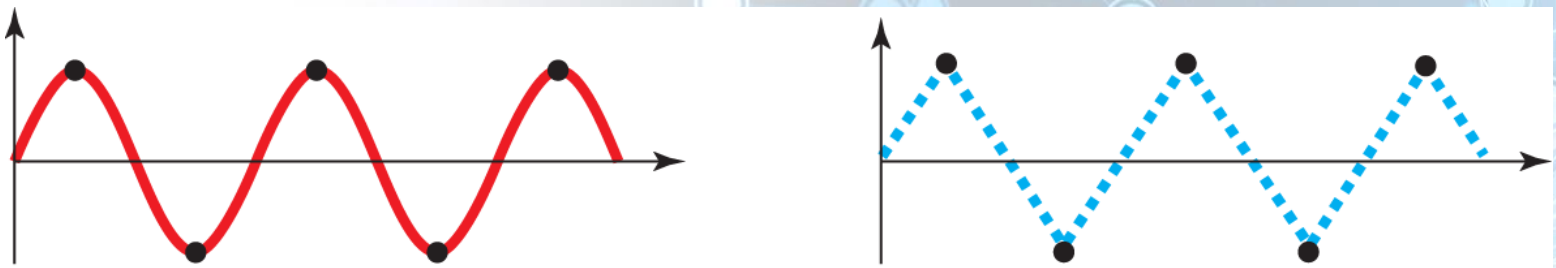


c. Flat-top sampling

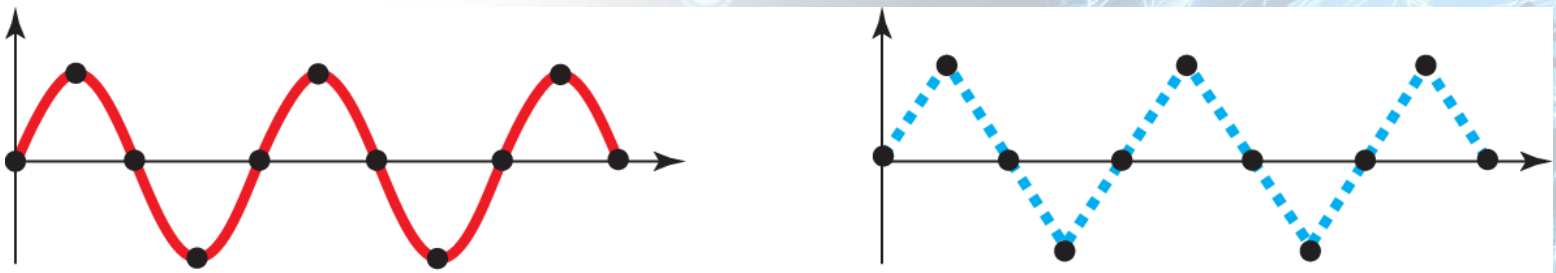
Nyquist Sampling Rate

- Nyquist → $f_s = 2f_h$
- Sampling sine wave at three sampling rates:
  - ✓ $f_s = 4f$ (2 times the Nyquist rate)
  - ✓ $f_s = 2f$ (Nyquist rate)
  - ✓ fs = f (one-half the Nyquist rate)

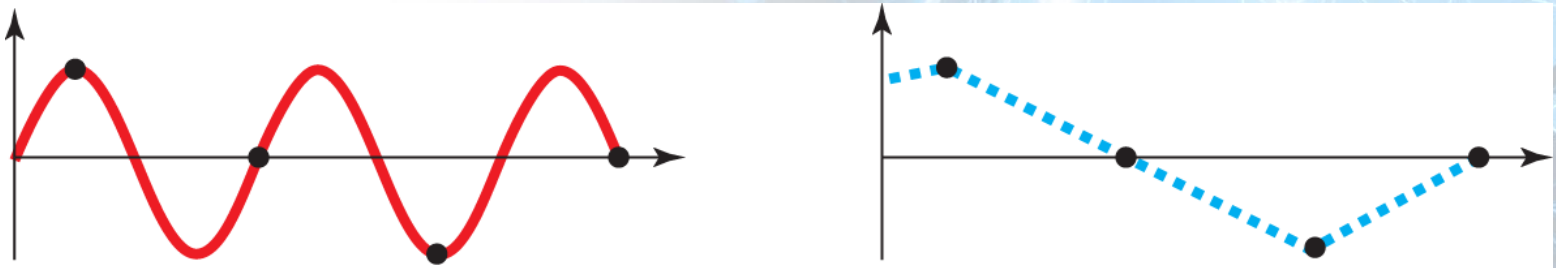
Nyquist Sampling Rate



a. Nyquist rate sampling: $f_s = 2\ f$



b. Oversampling: $f_s = 4\ f$

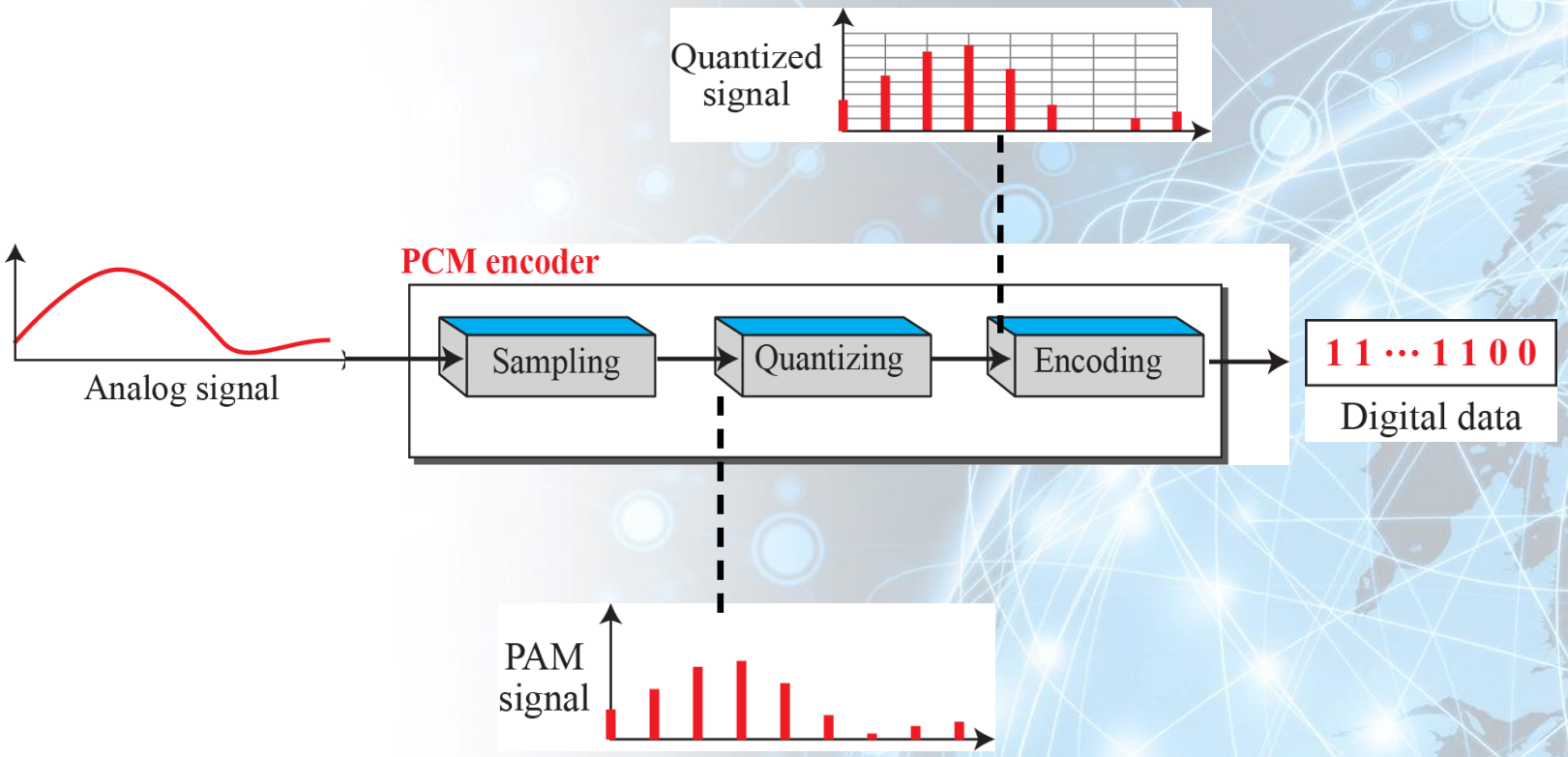


c. Undersampling: $f_s = f$

Pulse Code Modulation (PCM)

- Most common technique
- Employs a PCM Encoder
- A PCM encoder has three processes:
  - ✓ Sampling
  - ✓ Quantization
  - ✓ Encoding

Components of PCM encoder



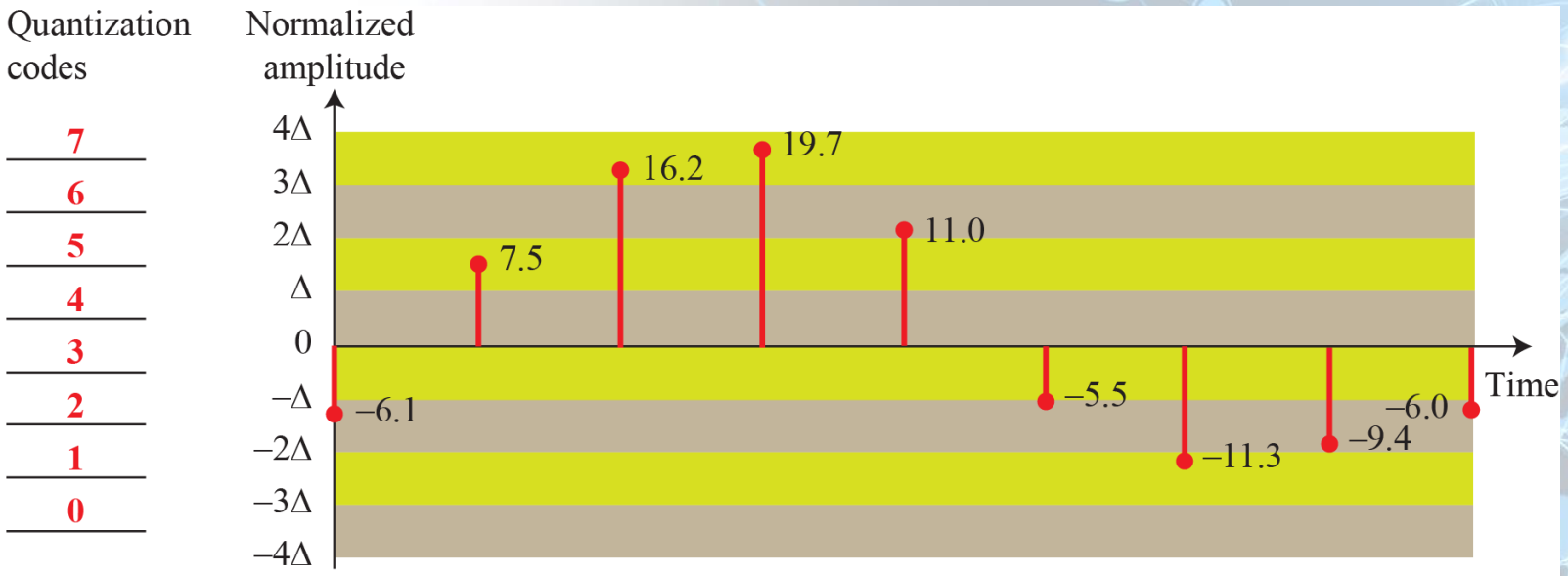
Pulse Code Modulation (PCM)

- Sampling
- Quantization
- Encoding

Quantization & encoding of a sampled signal

- Sampling → Series of pulses with amplitude values between min and max signal amplitude
- Infinite set with non-integral values not suitable for encoding
- We quantize the sampling output into certain levels based on range of amplitudes and how much accuracy is needed

Quantization & encoding of a sampled signal

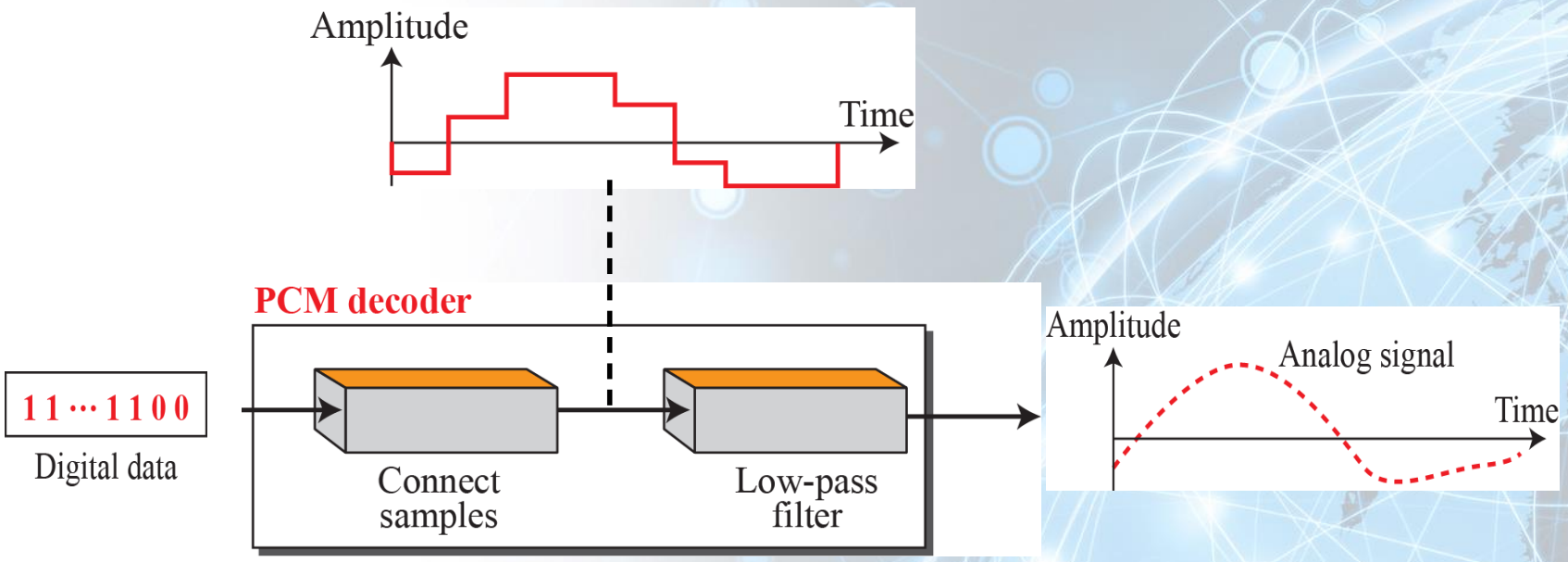


Normalized PAM values	−1.22	1.50	3.24	3.94	2.20	−1.10	−2.26	−1.88	−1.20
Normalized quantized values	−1.50	1.50	3.50	3.50	2.50	−1.50	−2.50	−1.50	−1.50
Normalized error	−0.28	0	+0.26	−0.44	+0.30	−0.40	−0.24	+0.38	−0.30
Quantization code	2	5	7	7	6	2	1	2	2
Encoded words	010	101	111	111	110	010	001	010	010

Pulse Code Modulation (PCM)

- Encoding
  - ✓ Sampling
  - ✓ Quantization
  - ✓ Encoding
- Decoding

Original Signal Recovery- PCM Decoder



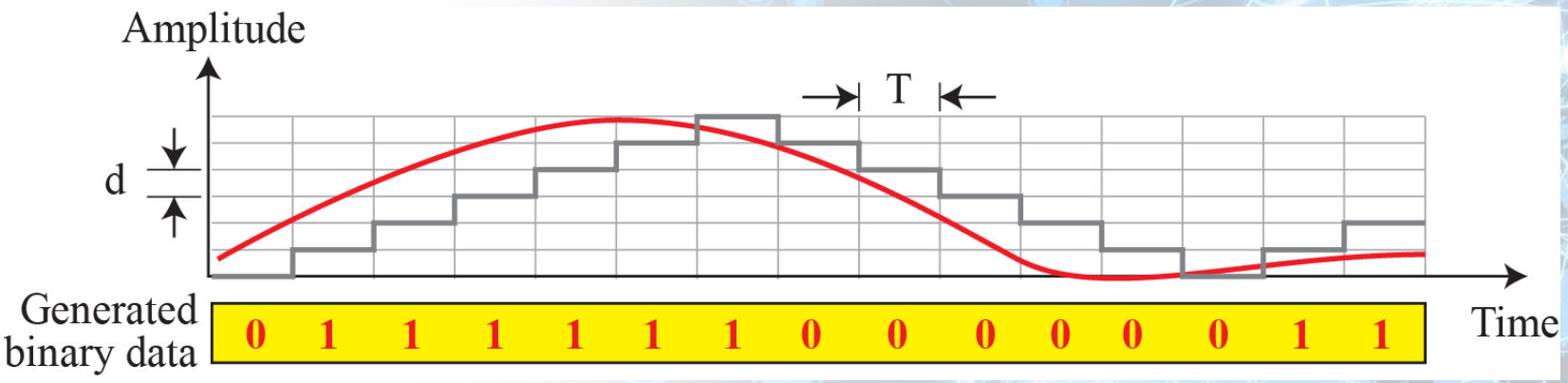
Analog-to-digital Conversion

- Analog Data to Digital Data
- Process of Digitization
- Two techniques:
  - ✓ Pulse Code Modulation (PCM)
  - ✓ Delta Modulation (DM)

Delta Modulation (DM)

- PCM is a very complex technique
- Delta modulation is a simpler technique
- PCM finds the value of the signal amplitude for each sample; DM finds the change from the previous sample
- No code words

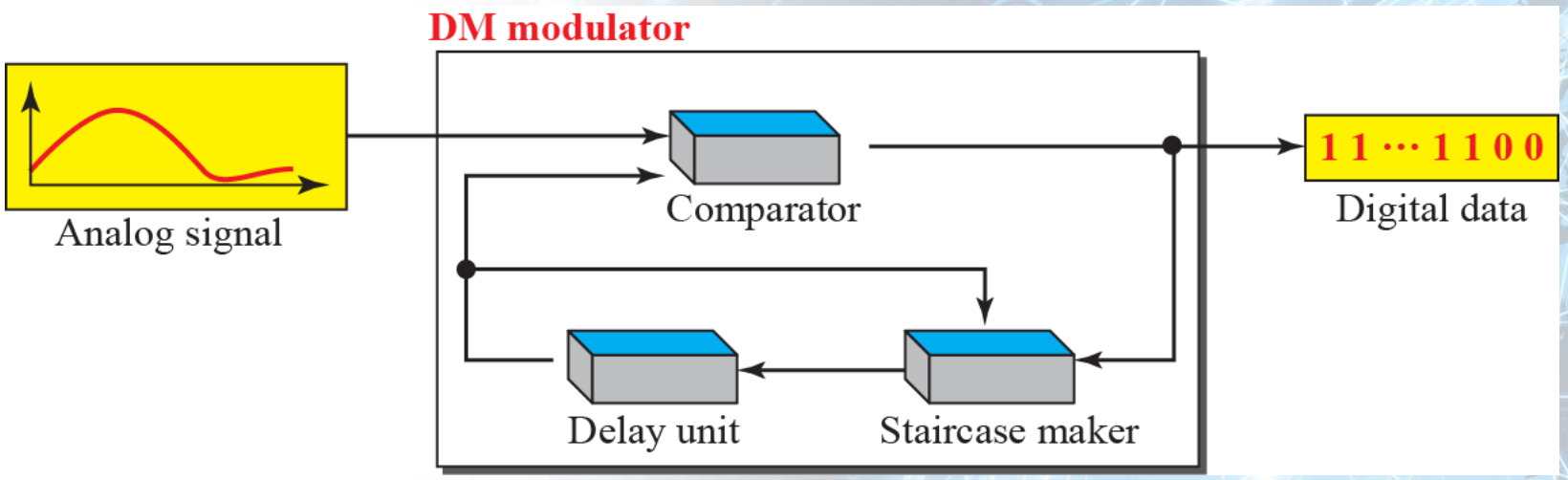
The process of delta modulation



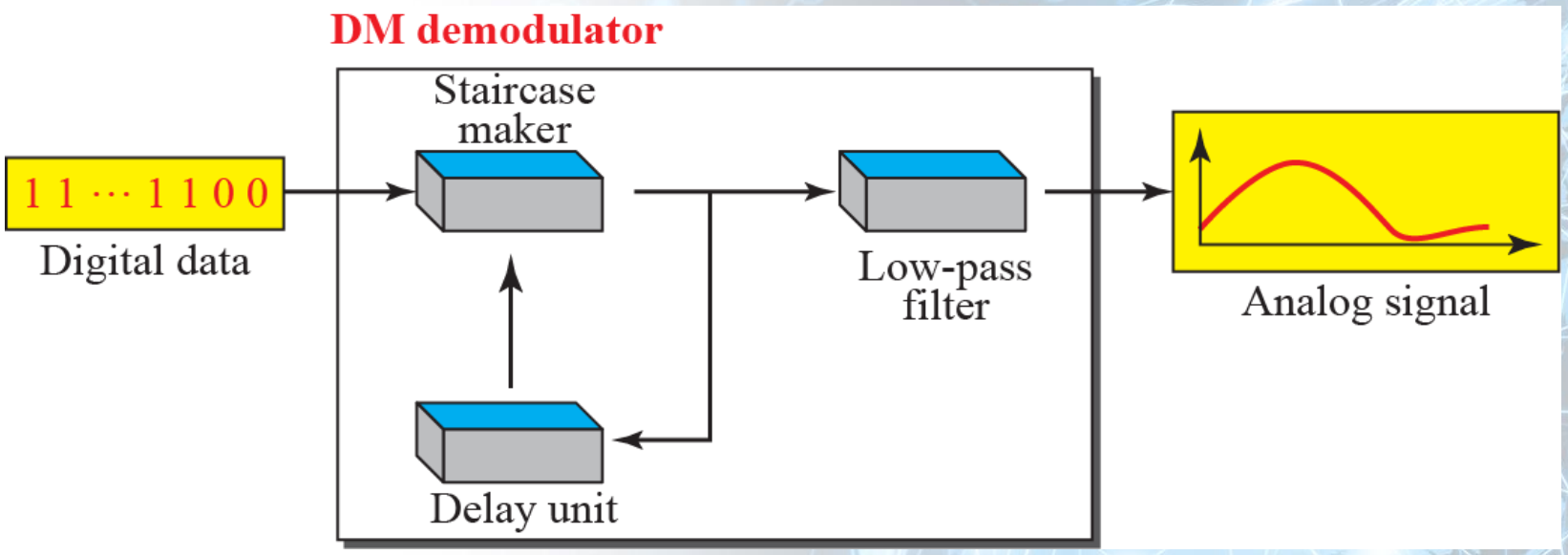
Delta Modulation (DM)

- Delta modulation is a simpler technique
- DM finds the change from the previous sample
- No code words

Delta Modulation Components



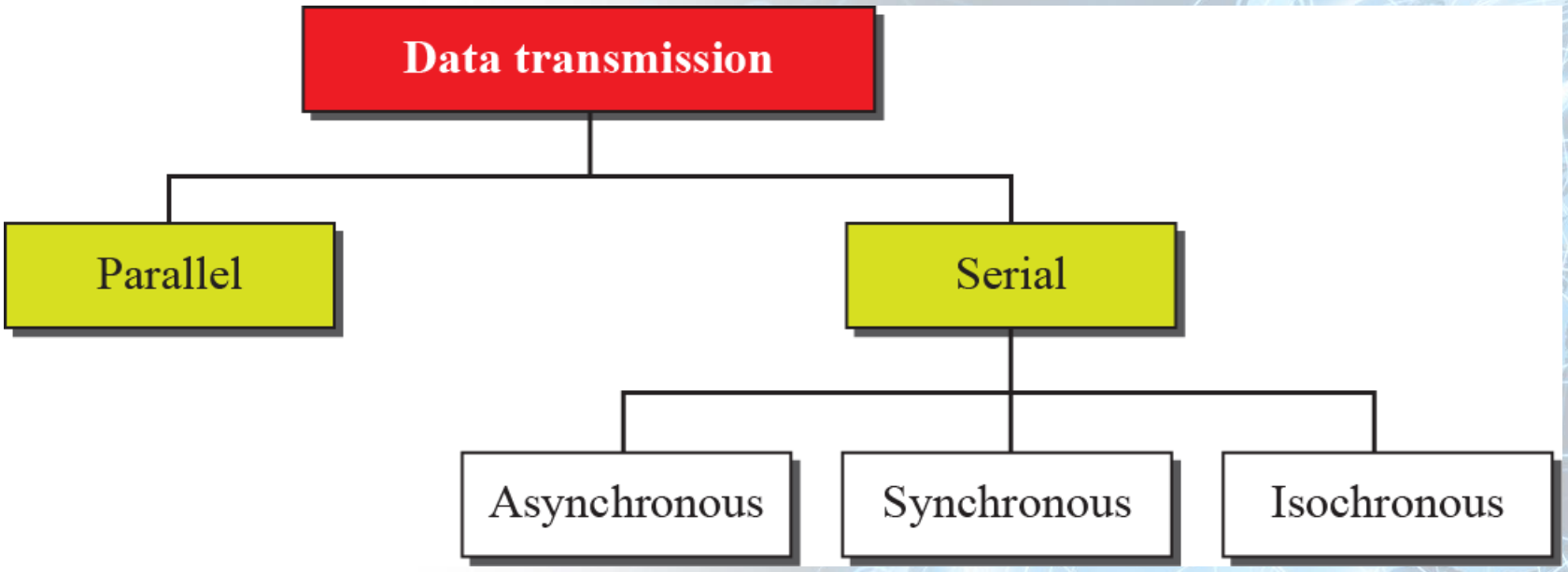
Delta Demodulation Components



Transmission Modes

- Transmission of Data:
  - ✓ Wiring
    - ➢ Data Stream
- Do we send 1 bit at a time; or do we group bits into larger groups and, if so, how?
- Parallel or Serial Transmission

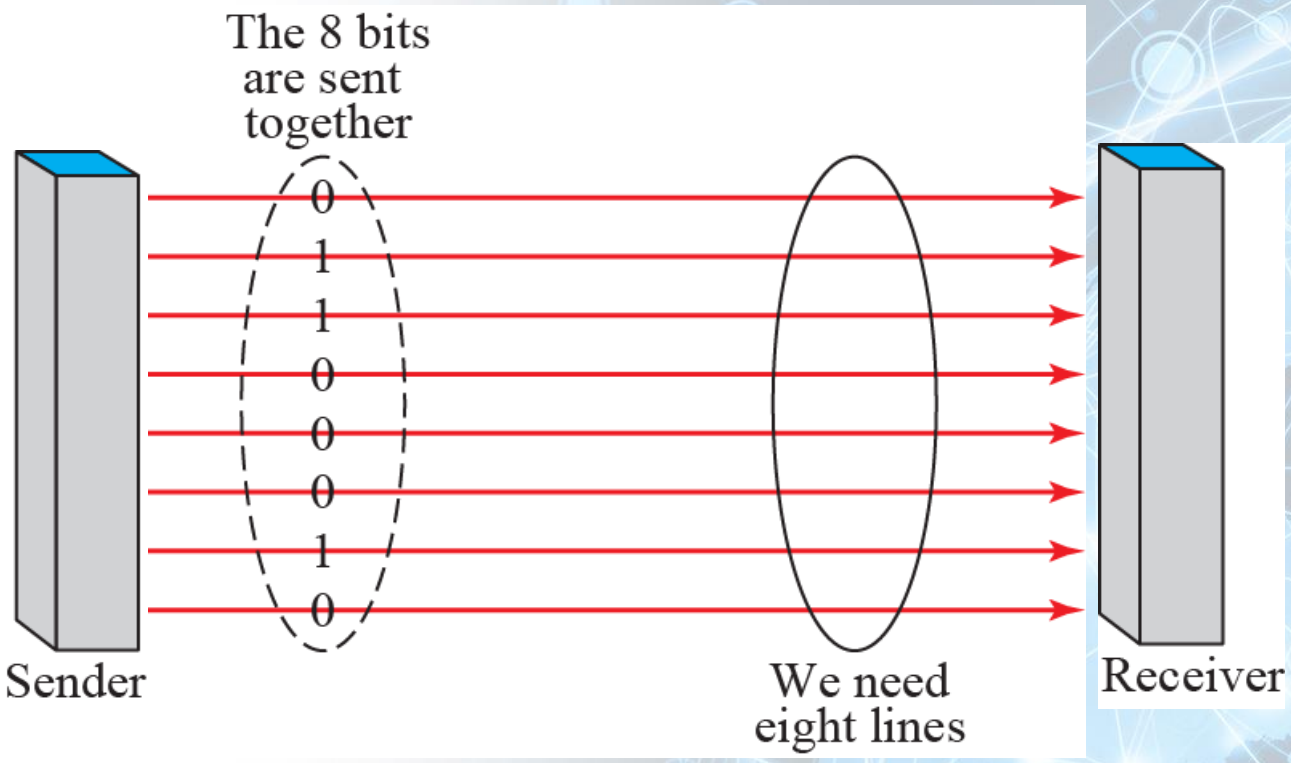
Data transmission modes



Parallel Transmission

- Binary data (1s ad 0s) organized in groups of ‘n’ bits
- We send ‘n’ bits at a time instead of just one
- ‘n’ wires required to send ‘n’ bits at one time

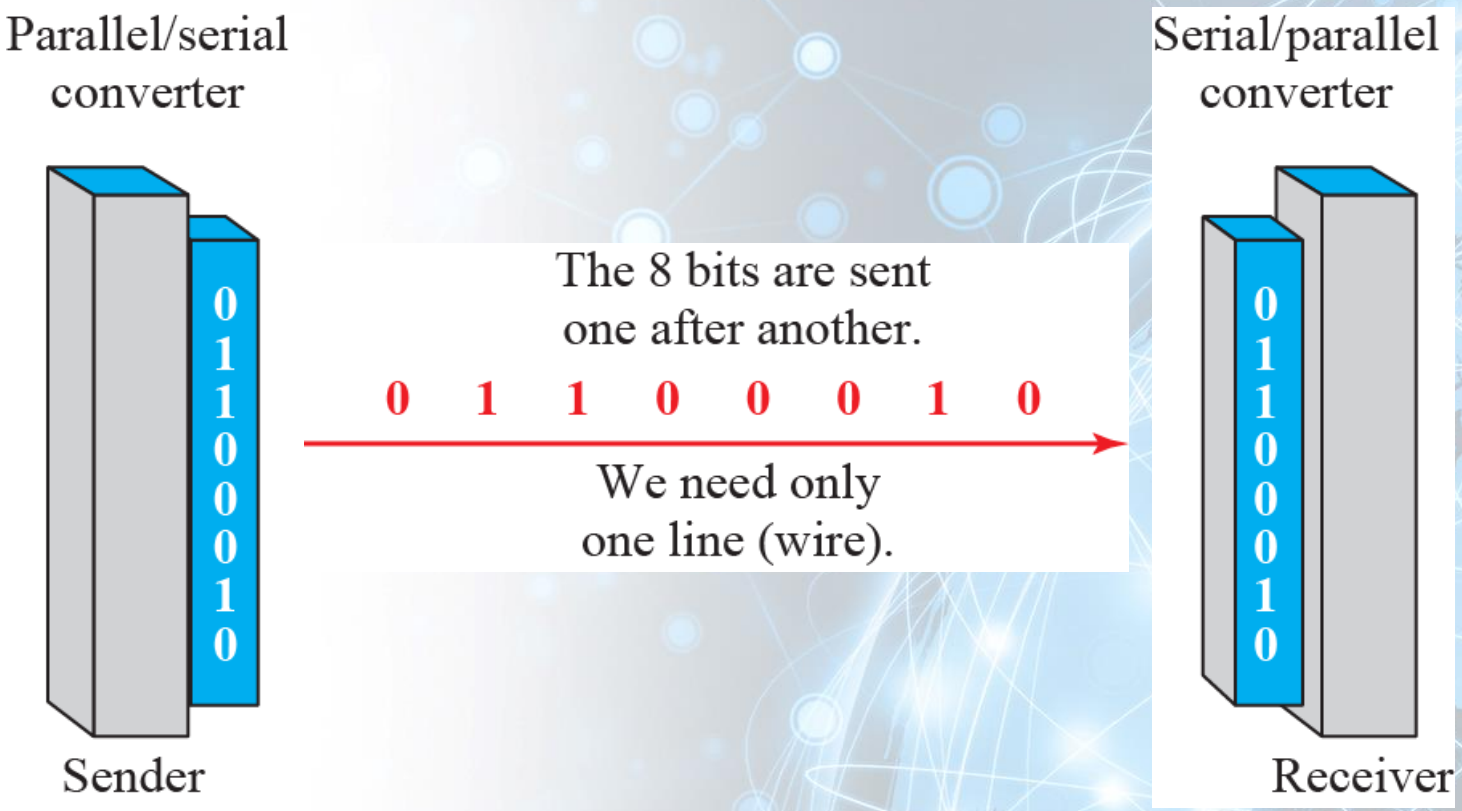
Parallel Transmission



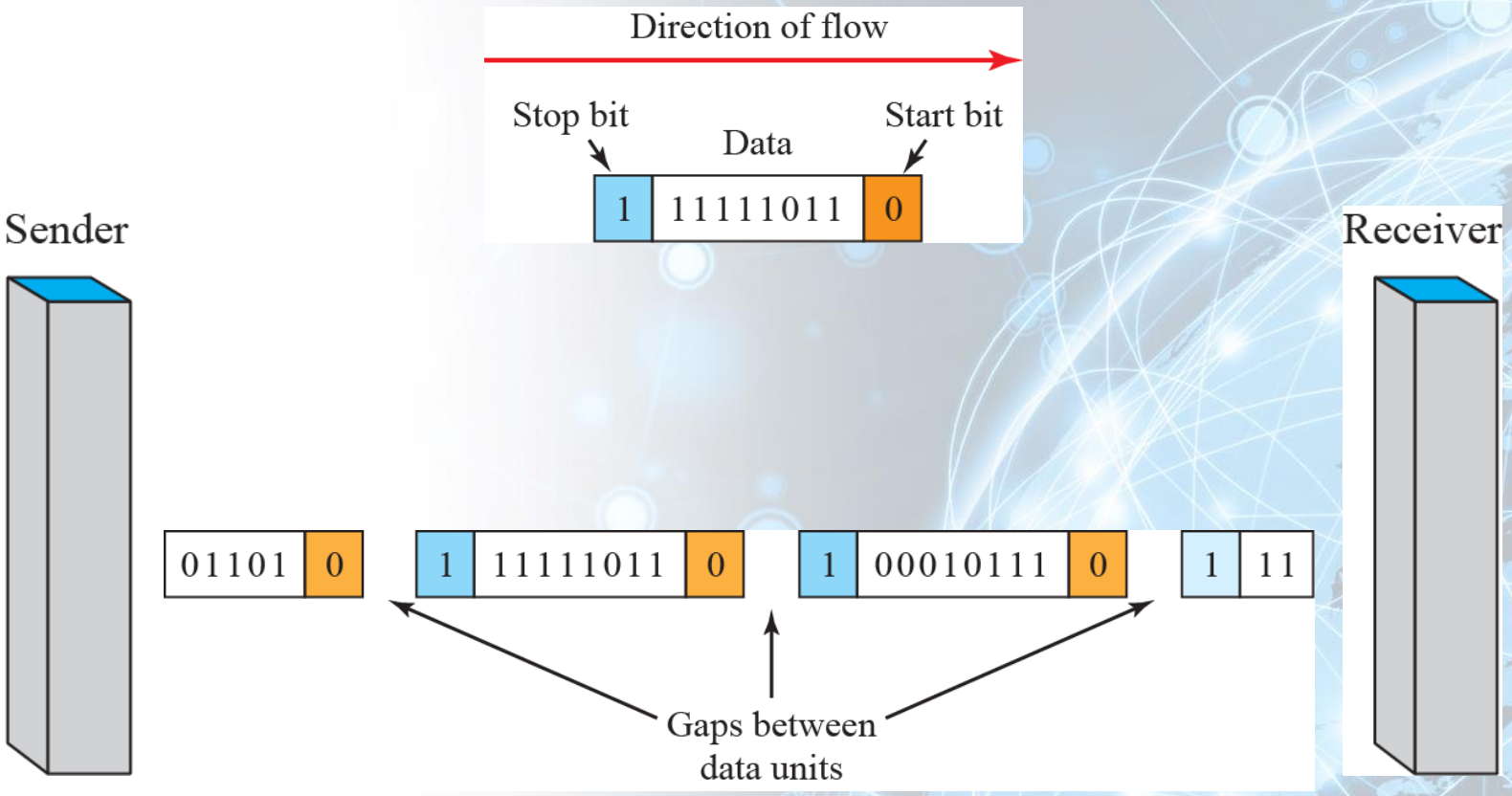
Serial Transmission

- In serial transmission one bit follows another
- Only one communication channel rather than ‘n’ to transmit data

Serial Transmission



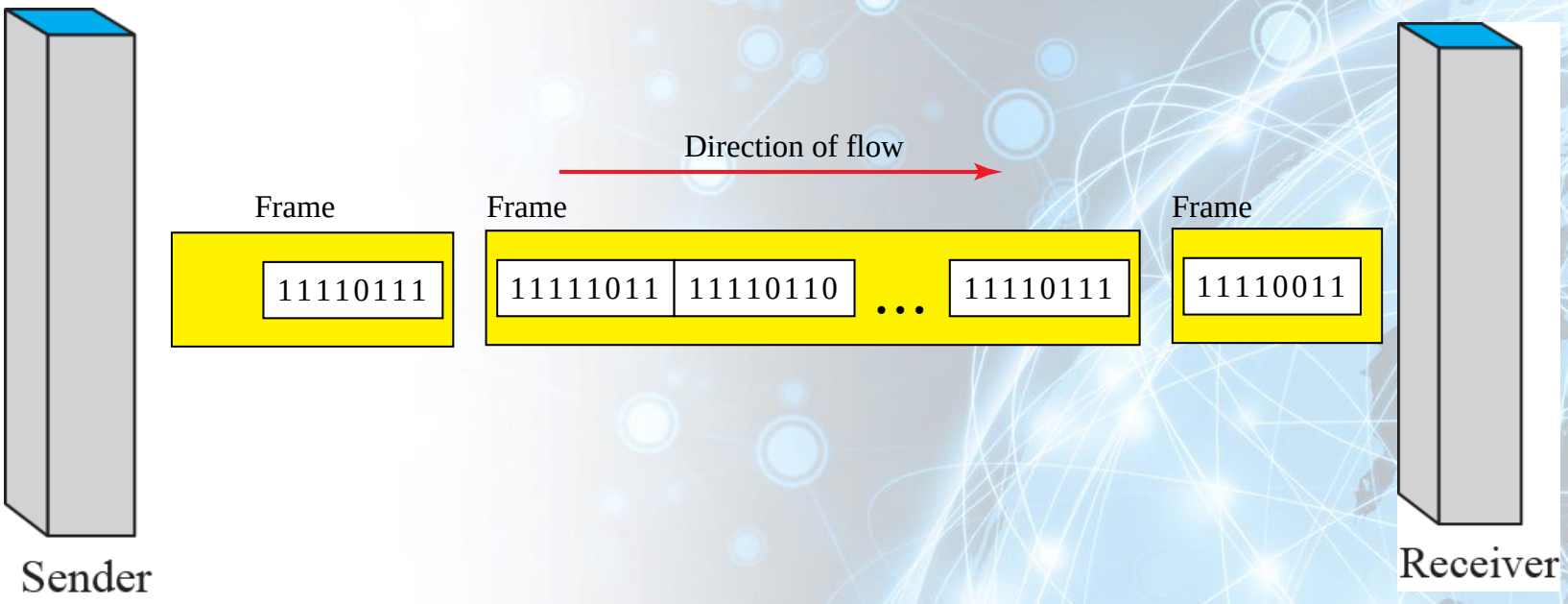
Asynchronous Transmission



Serial Transmission

- In serial transmission one bit follows another
- Only one communication channel rather than ‘n’ to transmit data

Synchronous Transmission



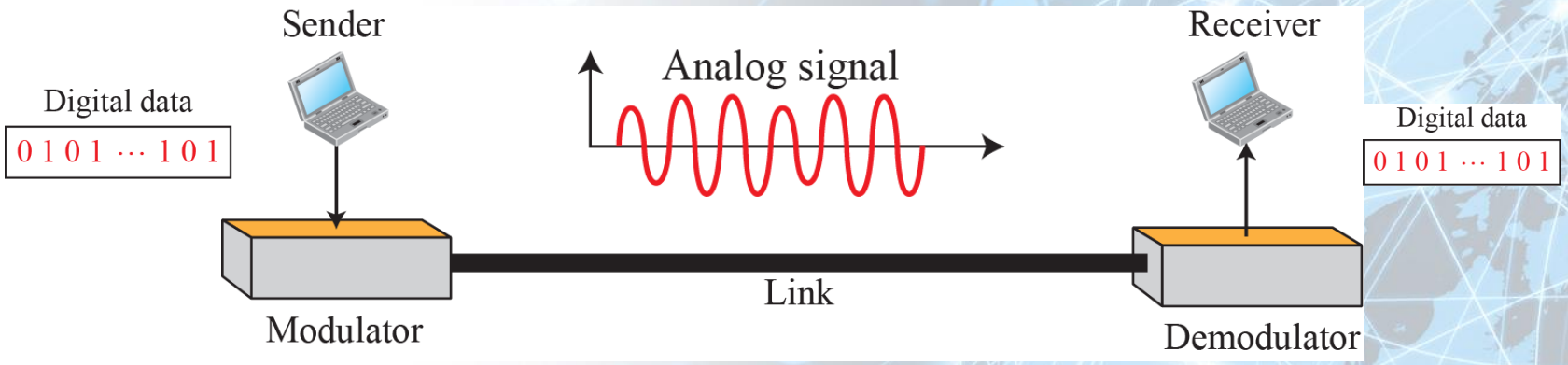
Isochronous Transmission

- Real time Audio and Video
- Synchronization between characters is not enough
- Entire stream should be synchronized
- Isochronous guarantees fixed rate data

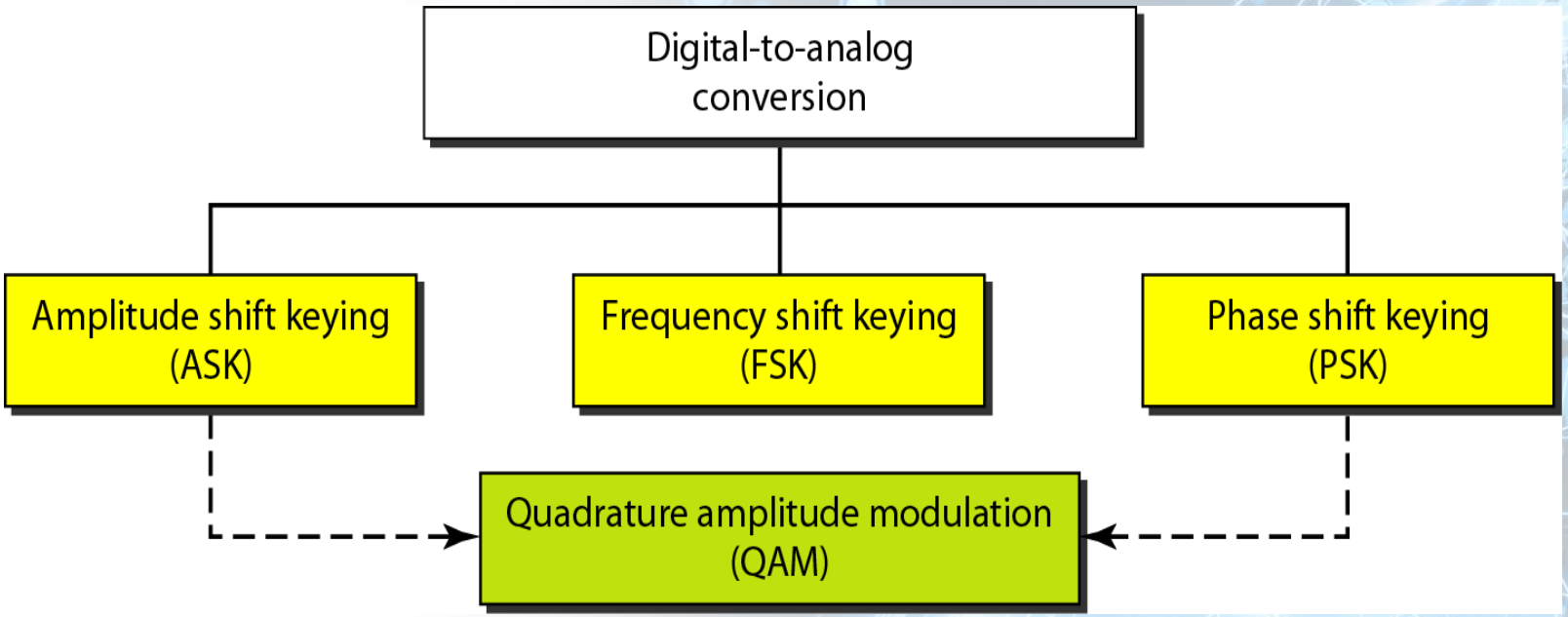
Digital-to-Analog Conversion

- Process of changing one of the characteristics of analog signal based on the information in digital data
- A sine wave is defined by 3 characteristics:
  - ✓ Amplitude
  - ✓ Frequency
  - ✓ Phase
- By changing one of these characteristics, we can use it to represent a digital signal

Digital-to-Analog Conversion



Types of Digital to Analog Conversion



Aspects of Digital to Analog Conversion

- **Before we discuss specific methods of digital-to-analog modulation, two basic issues must be reviewed:**
  - ✓ **Bit and Baud rates and**
  - ✓ **The Carrier Signal**

Aspects of Digital to Analog Conversion

- In Analog Transmission of Digital Data, Baud Rate is less than or equal to the Bit Rate
  - ✓ Data Element vs. Signal Element
  - ✓ Data Rate vs. Signal Rate
- Bandwidth Required $\propto$ Signal Rate (except FSK)
- Carrier Signal

Aspects of Digital to Analog Conversion

- **Before we discuss specific methods of digital-to-analog modulation, two basic issues must be reviewed:**
  - ✓ **Bit and Baud rates and**
  - ✓ **The Carrier Signal**

Example

An analog signal carries 4 bits per signal element. If 1000 signal elements are sent per second, find the bit rate?

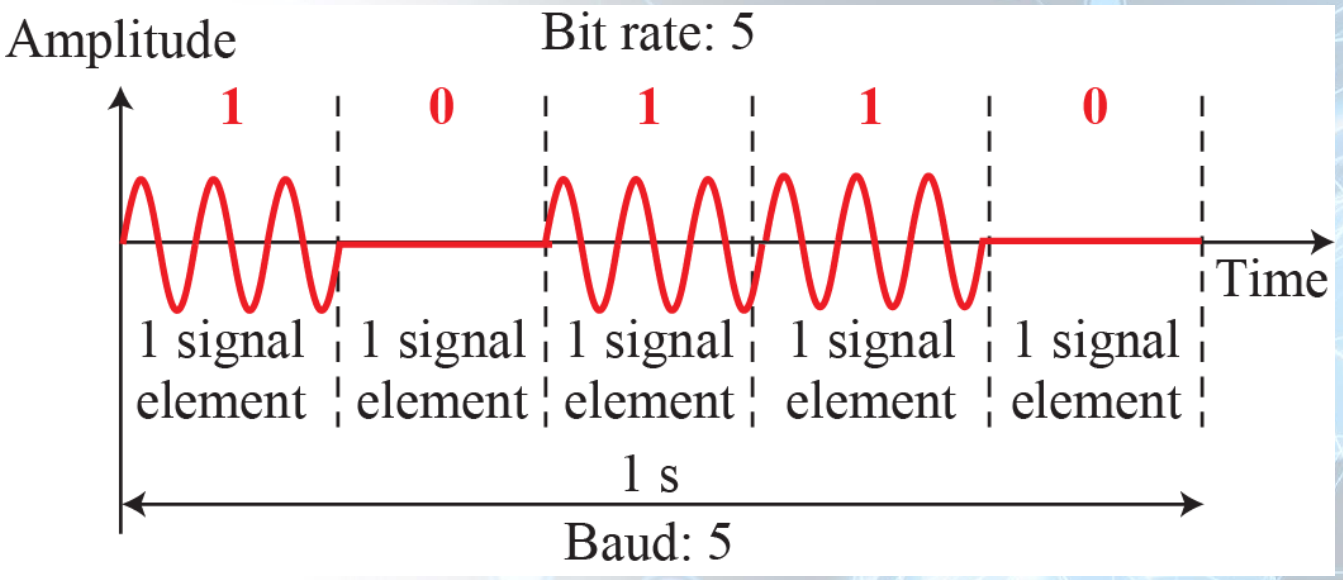
Example

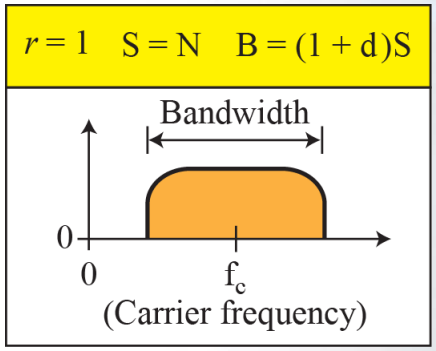
An analog signal has a bit rate of 8000 bps and a baud rate of 1000 baud. How many data elements are carried by each signal element? How many signal elements do we need?

Amplitude Shift Keying (ASK)

- The amplitude of the carrier signal is varied to create signal elements
- Both frequency and phase remain constant while the amplitude changes
- Binary ASK or On-Off Keying (OOK)

Binary Amplitude Shift Keying (Binary ASK)





Amplitude Shift Keying (ASK)

- The amplitude of the carrier signal is varied to create signal elements
- Both frequency and phase remain constant while the amplitude changes
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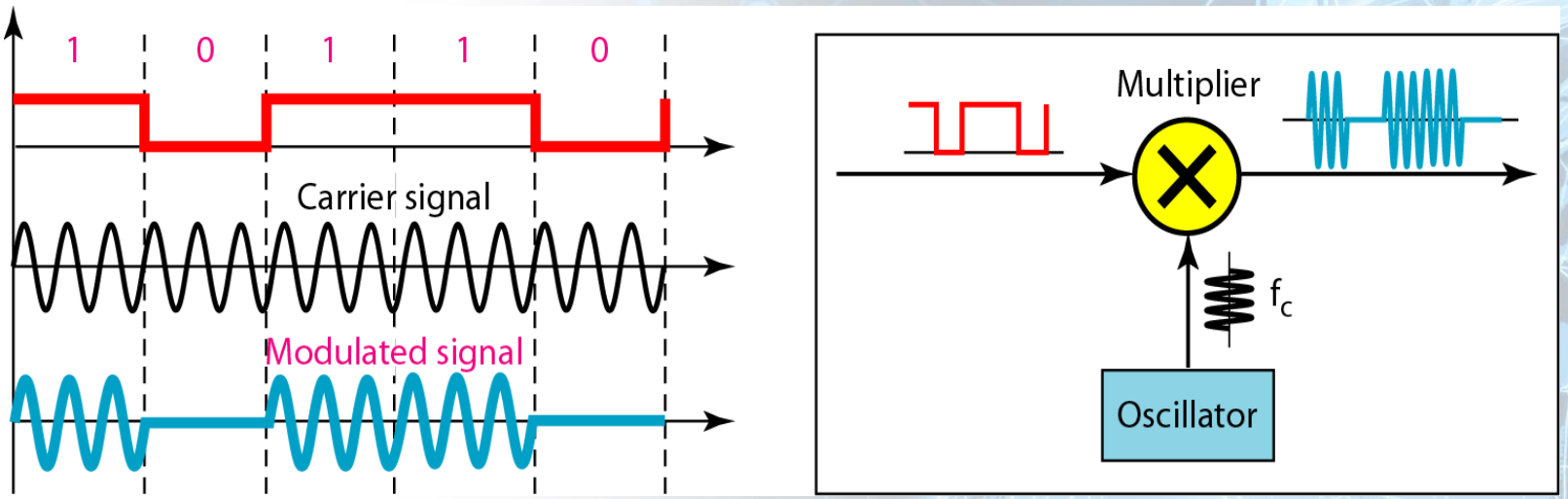
Implementation of Binary ASK



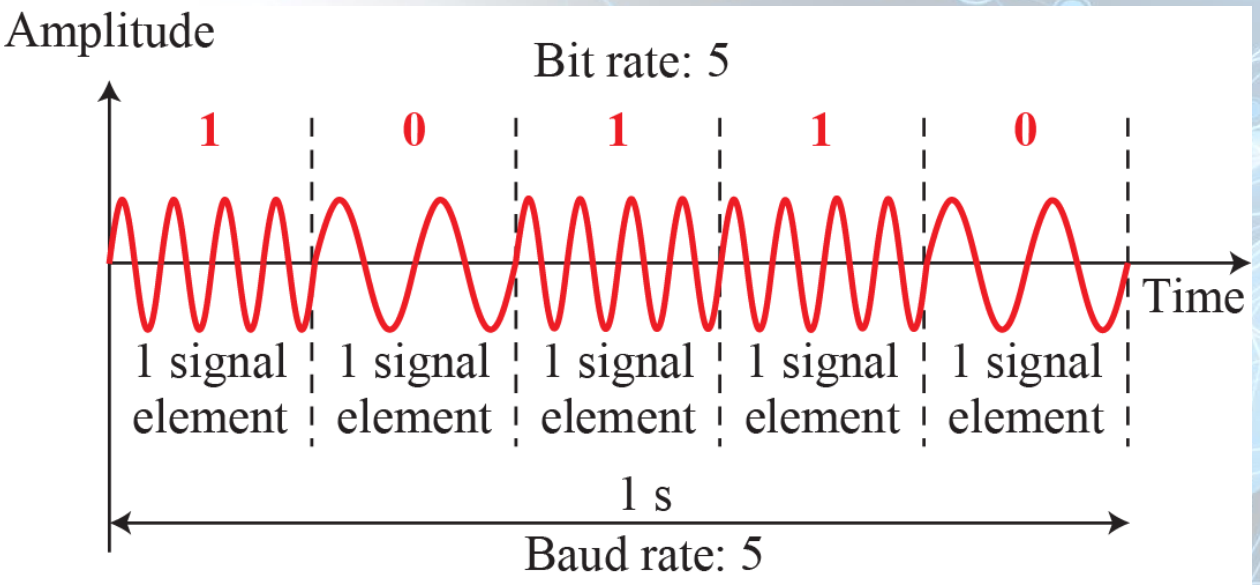
Example

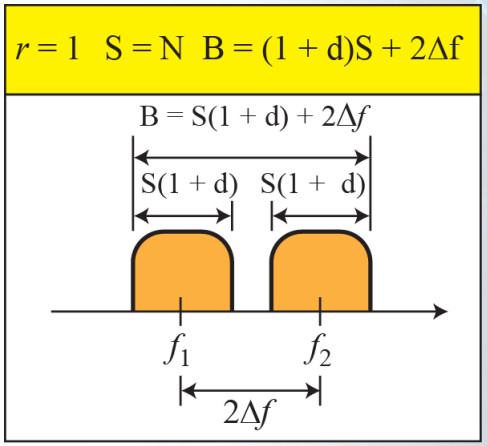
We have an available bandwidth of 100 kHz which spans from 200 to 300 kHz. What are the carrier frequency and the bit rate if we modulated our data by using ASK with d = 1?

Frequency Shift Keying (FSK)

- The frequency of the carrier signal is varied to represent data
- The frequency of the modulated signal is constant for the duration of one signal element, but changes for the next signal element if the data element changes
- Both peak amplitude and phase remain constant

Binary Frequency Shift Keying





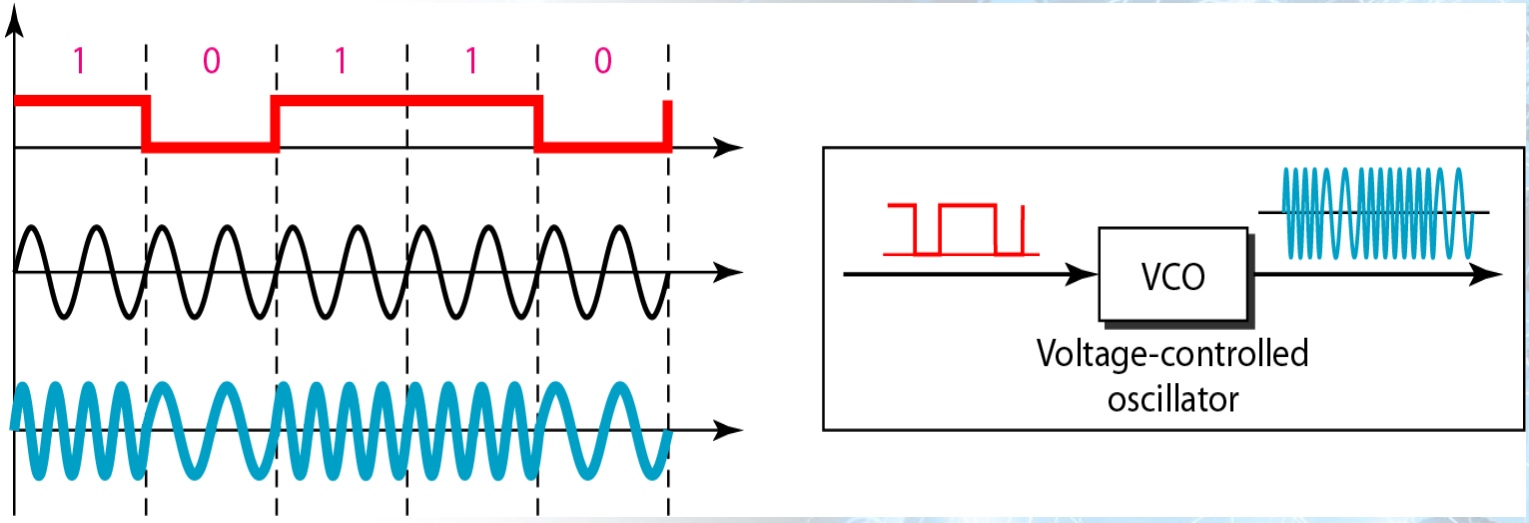
Frequency Shift Keying (FSK)

- The frequency of the carrier signal is varied to represent data
- Both peak amplitude and phase remain constant

Example

We have an available bandwidth of 100 kHz which spans from 200 to 300 kHz. What should be the carrier frequency and the bit rate if we modulated our data by using FSK with d = 1?

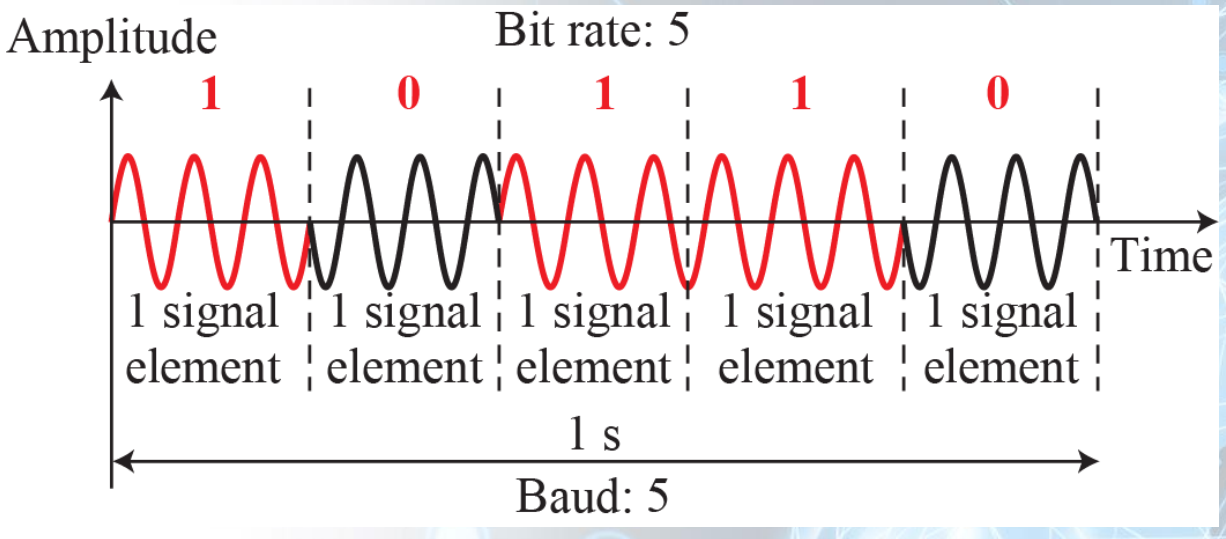
Implementation of BFSK

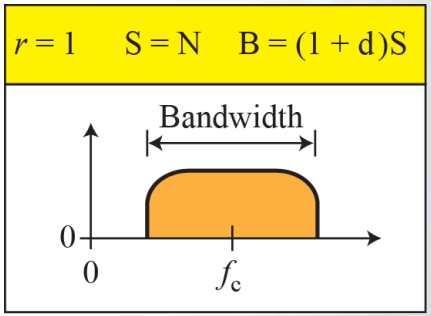


Phase Shift Keying (PSK)

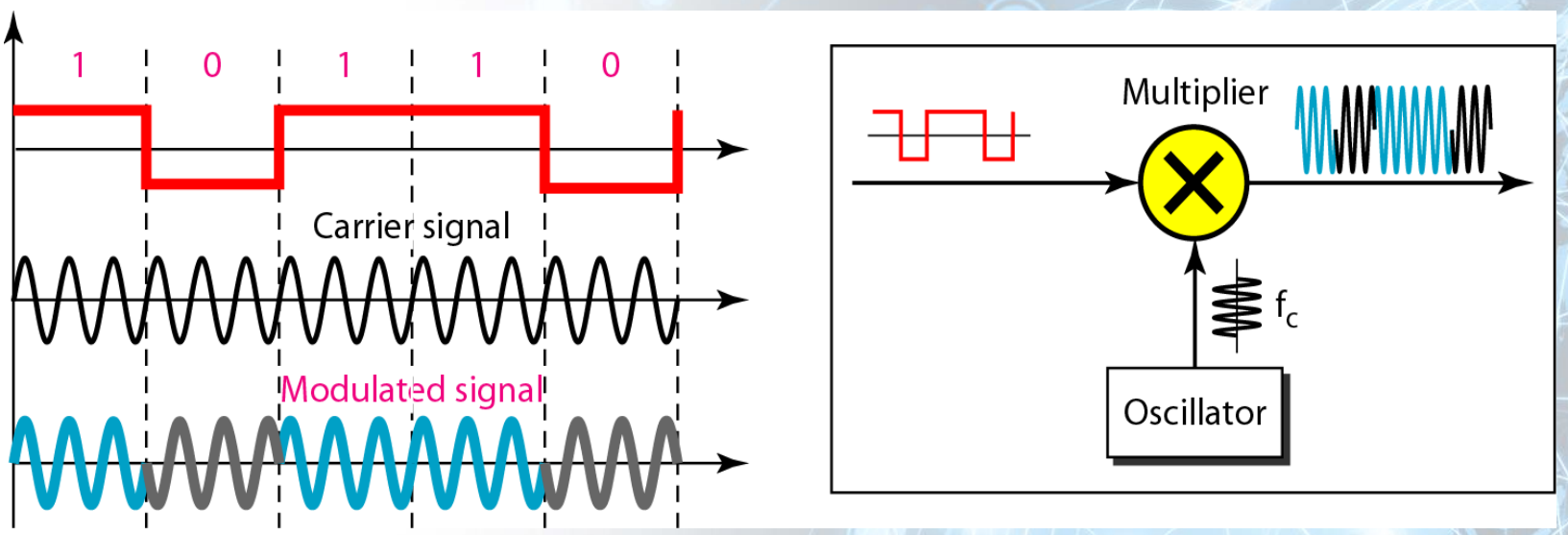
- The phase of the carrier is varied to represent two or more different signal elements
- Both peak amplitude and frequency remain constant
- PSK is relatively common than ASK or FSK

Binary Phase Shift Keying

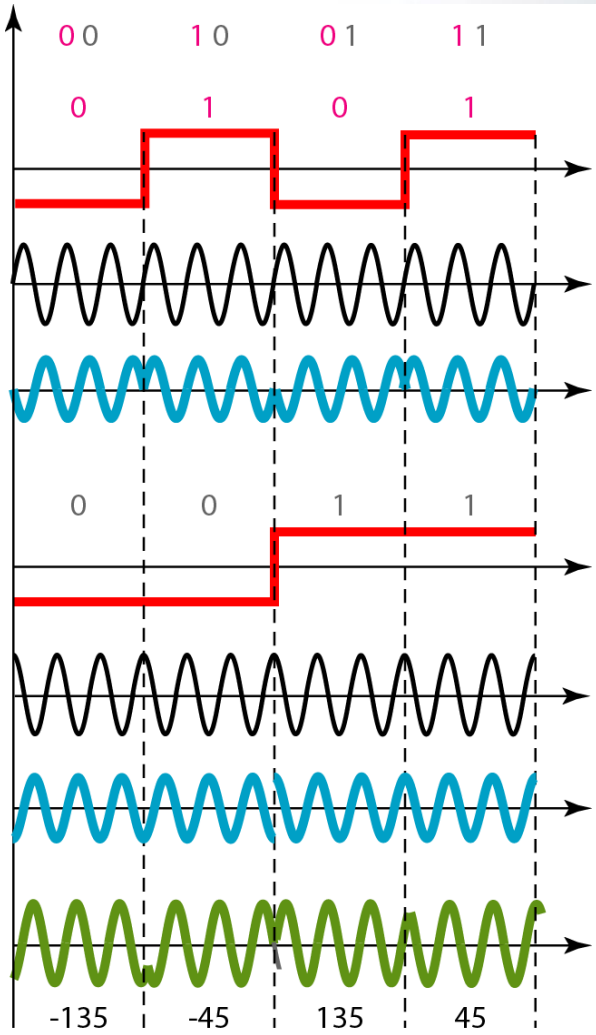


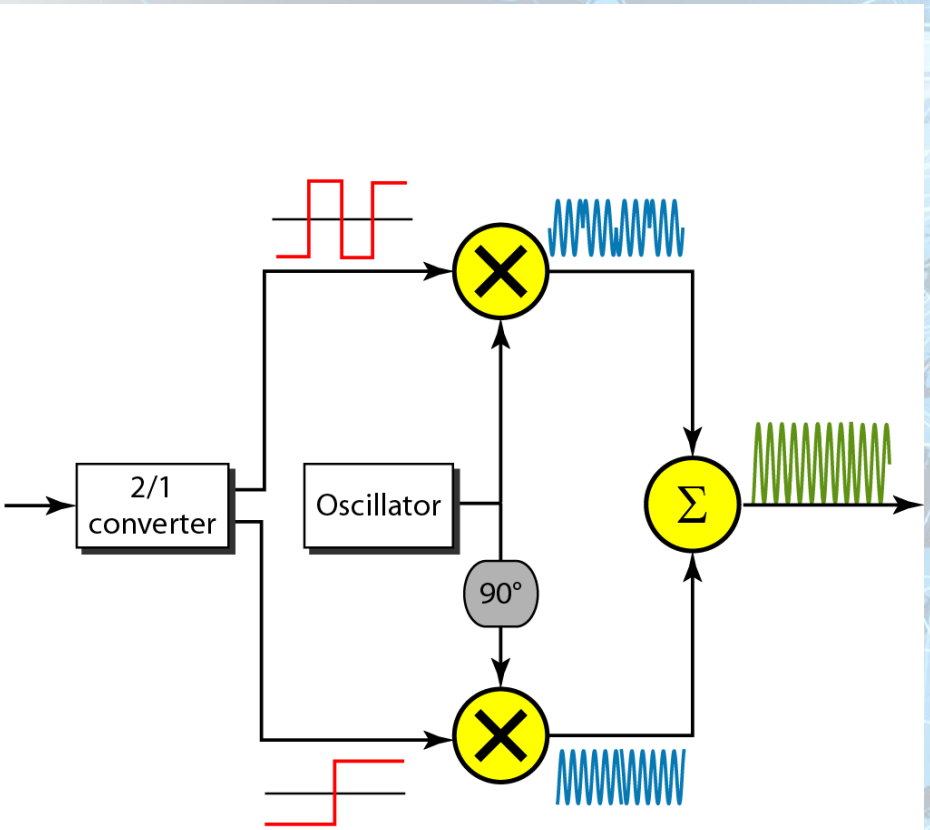


Implementation of BPSK



QPSK and its Implementation





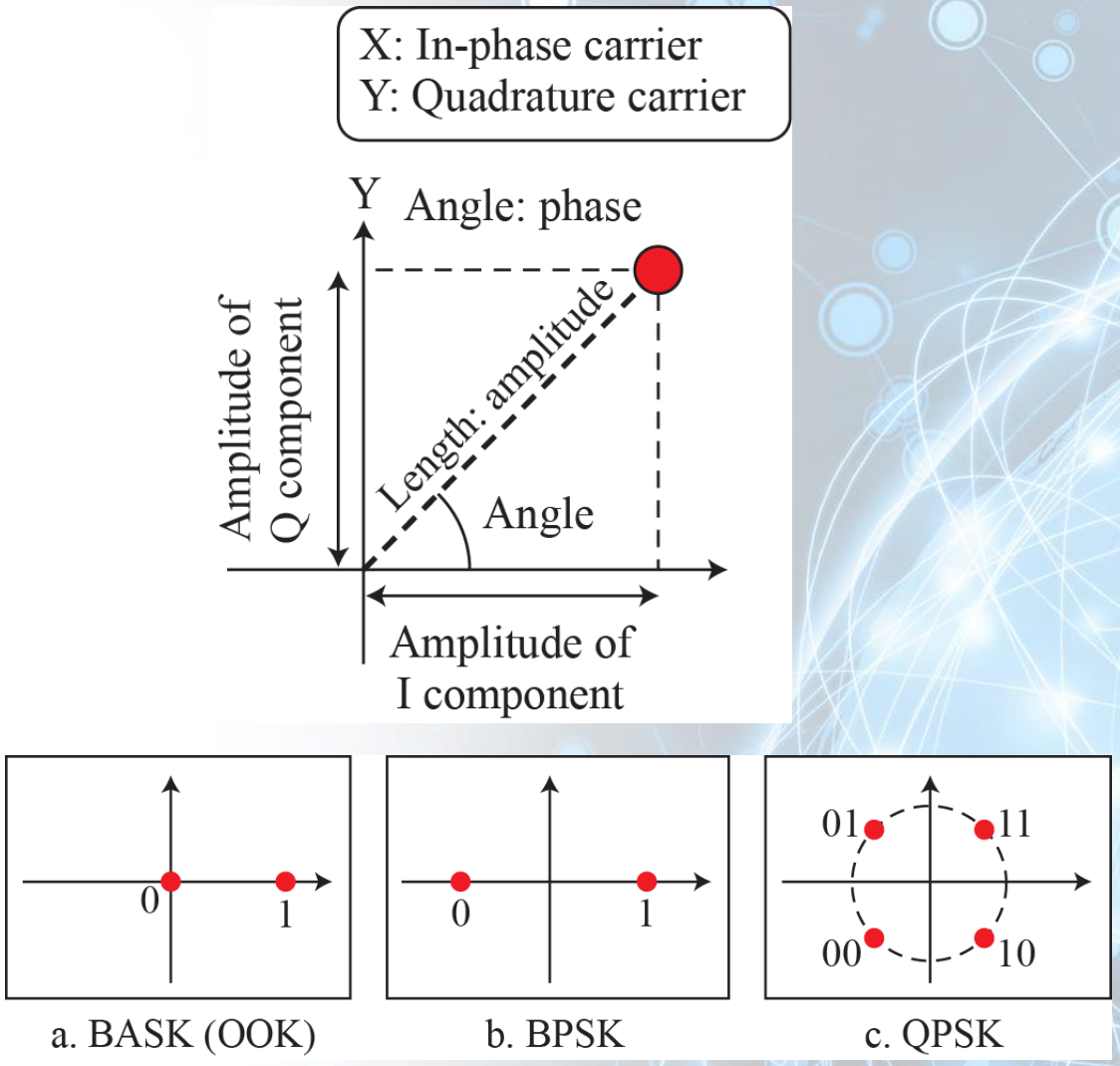
Example

Find the bandwidth for a signal transmitting at 12 Mbps for QPSK. The value of d = 0.

Constellation Diagram

- Helps us define the phase and amplitude of a signal element when we are using two carriers (one in phase and other in quadrature)
- Signal element is represented as a dot

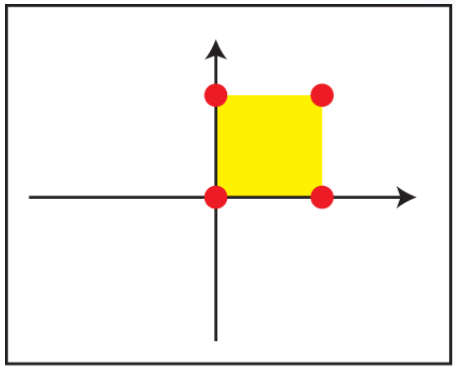
Constellation Diagram



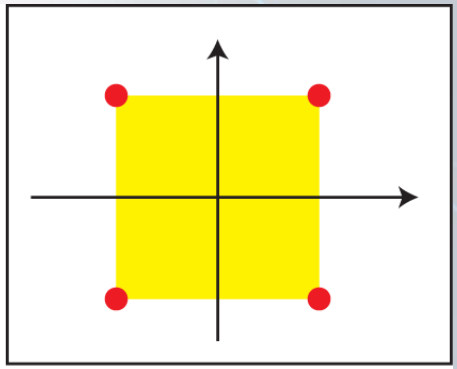
Quadrature Amplitude Modulation (QAM)

- PSK is limited by the ability of the equipment to distinguish small differences in phase which limits its potential bit rate
- We have been altering only one of the three characteristics of a sine wave at a time; but what if we alter two?
- Why not combine ASK and PSK?

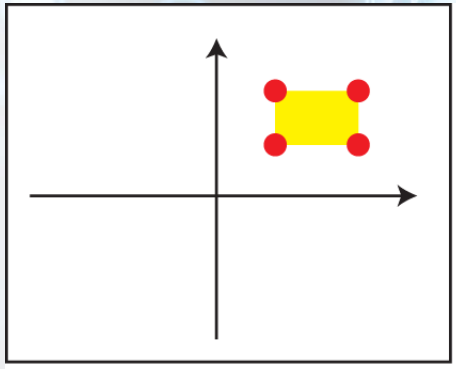
Constellation diagrams for some QAMs



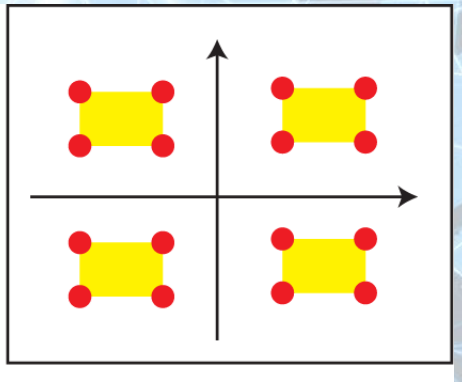
a. 4-QAM



b. 4-QAM



c. 4-QAM

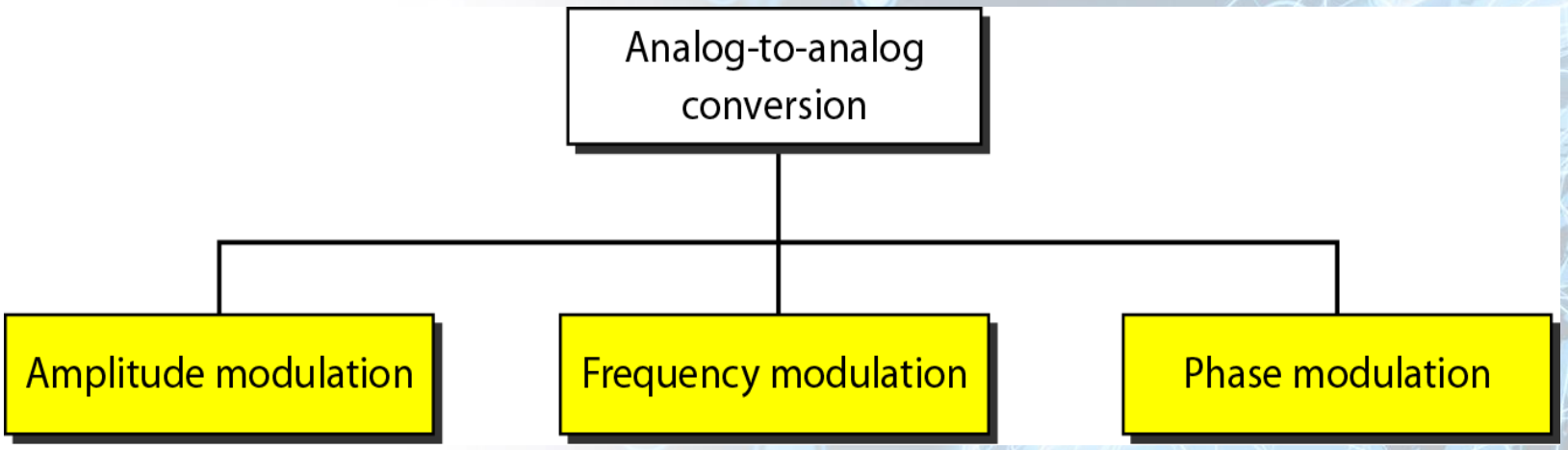


d. 16-QAM

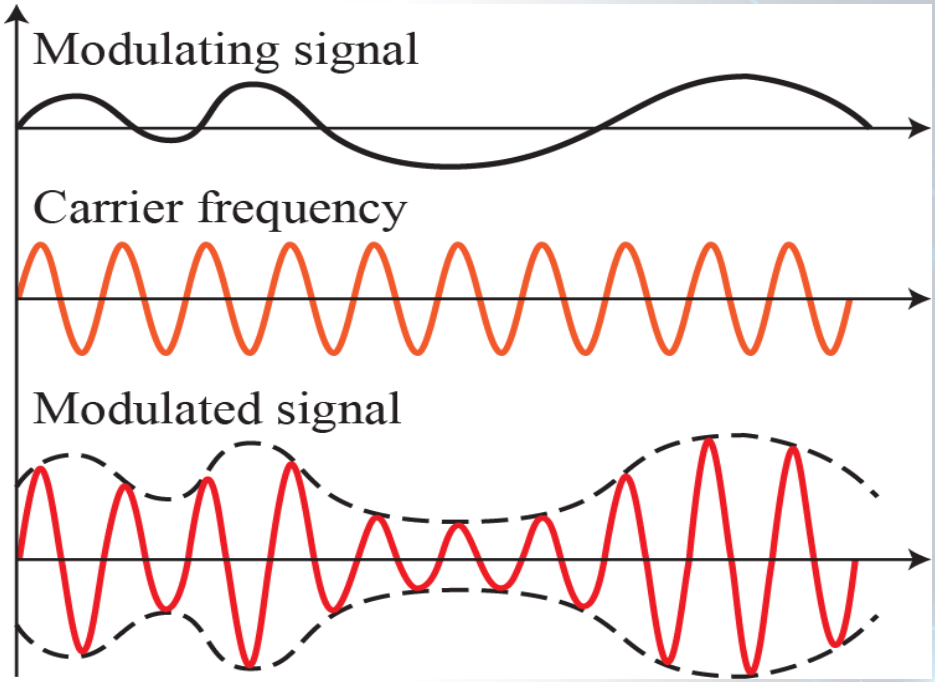
Analog-to-Analog Conversion

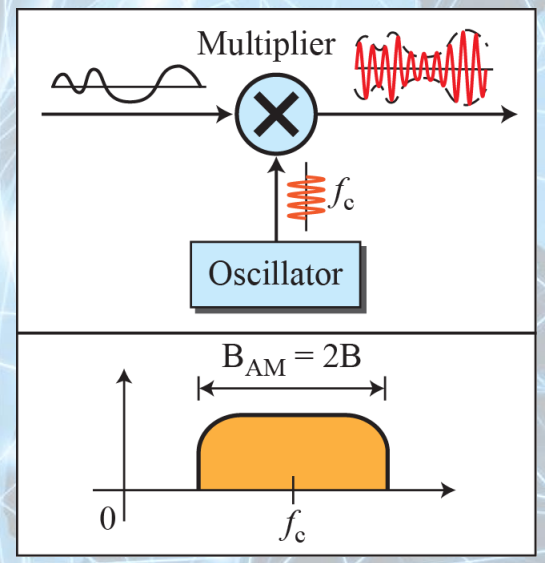
- Representation of Analog information by an Analog signal
- Amplitude Modulation (AM)
- Frequency Modulation (FM)
- Phase Modulation (PM)

Types of Analog-to-Analog Modulation

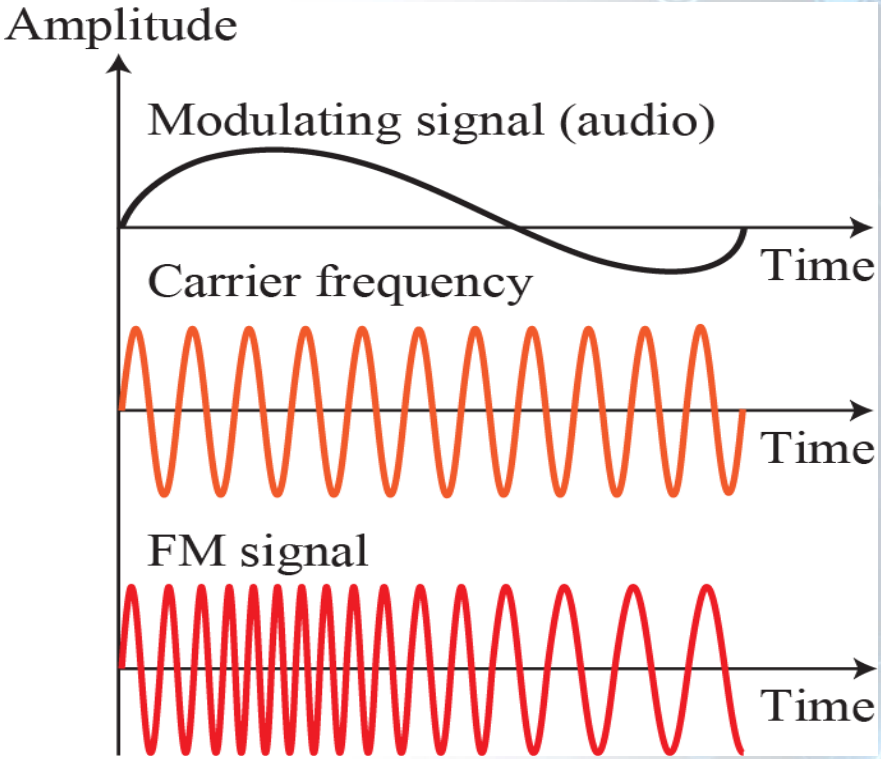


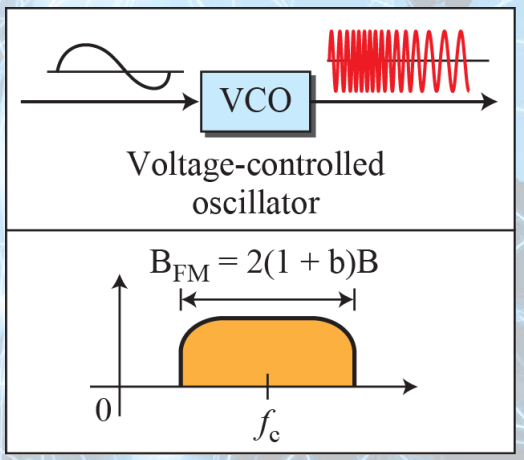
Amplitude modulation





Frequency Modulation





Analog-to-Analog Conversion

- Representation of Analog information by an Analog signal
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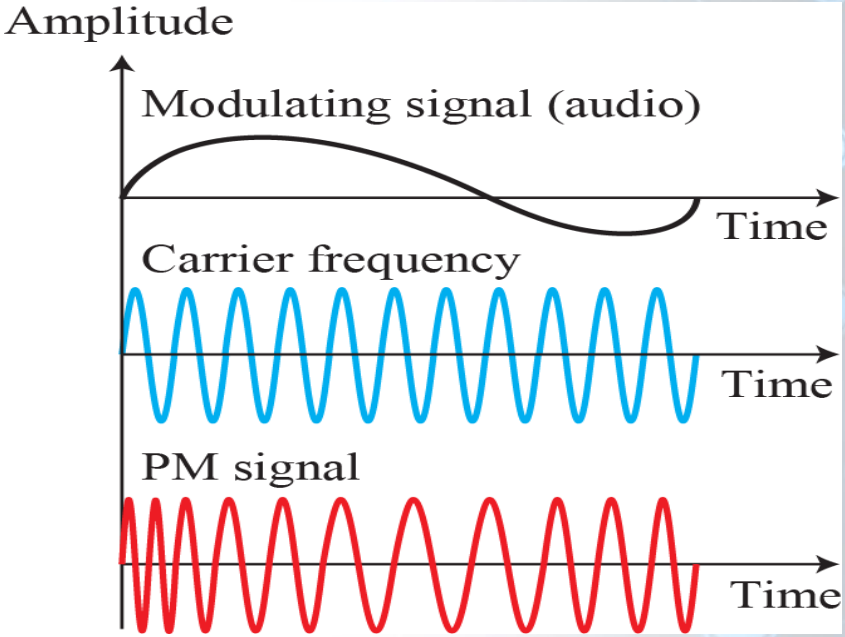
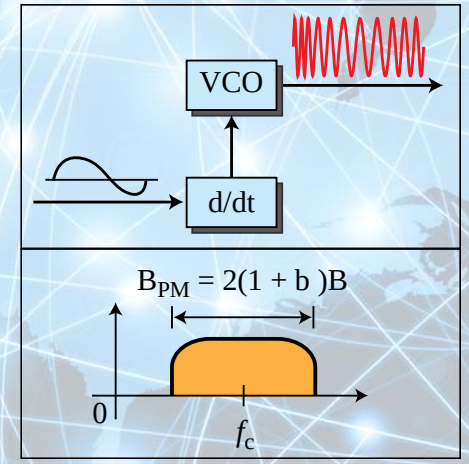
- Phase Modulation (PM)

Phase Modulation

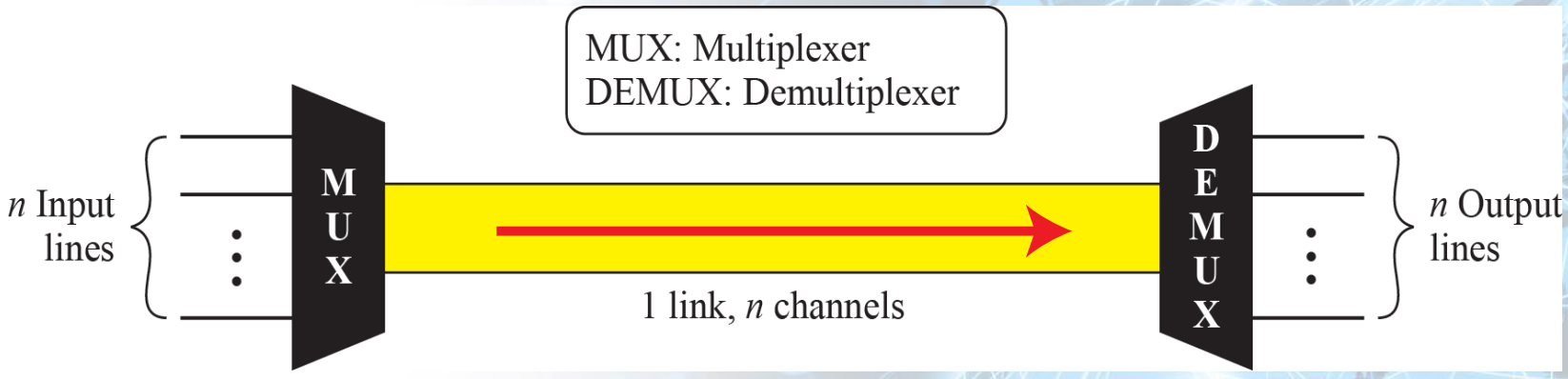




Multiplexing

- Simultaneous transmission of multiple signals across a single data link
- As data & telecomm use increases, so does traffic
  - ✓ Add individual links each time a new channel is needed
  - ✓ Install higher-bandwidth links and use each to carry multiple signals

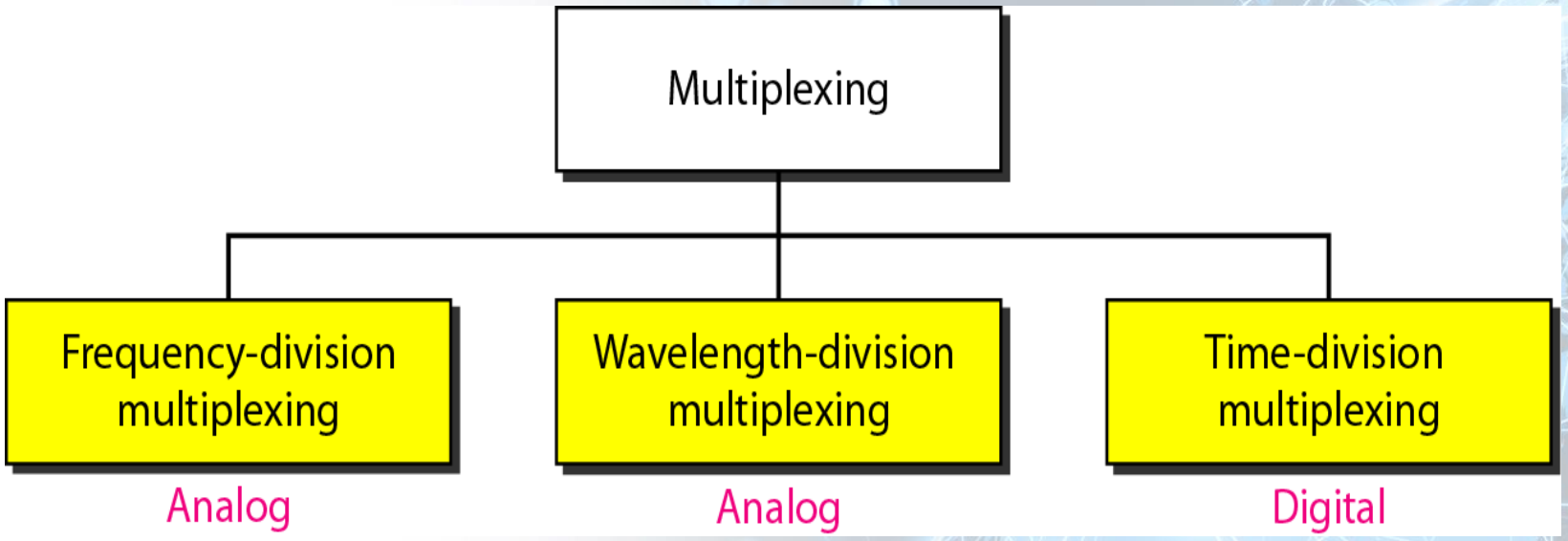
Dividing a Link into Channels



Multiplexing

- Simultaneous transmission of multiple signals across a single data link

Categories of Multiplexing



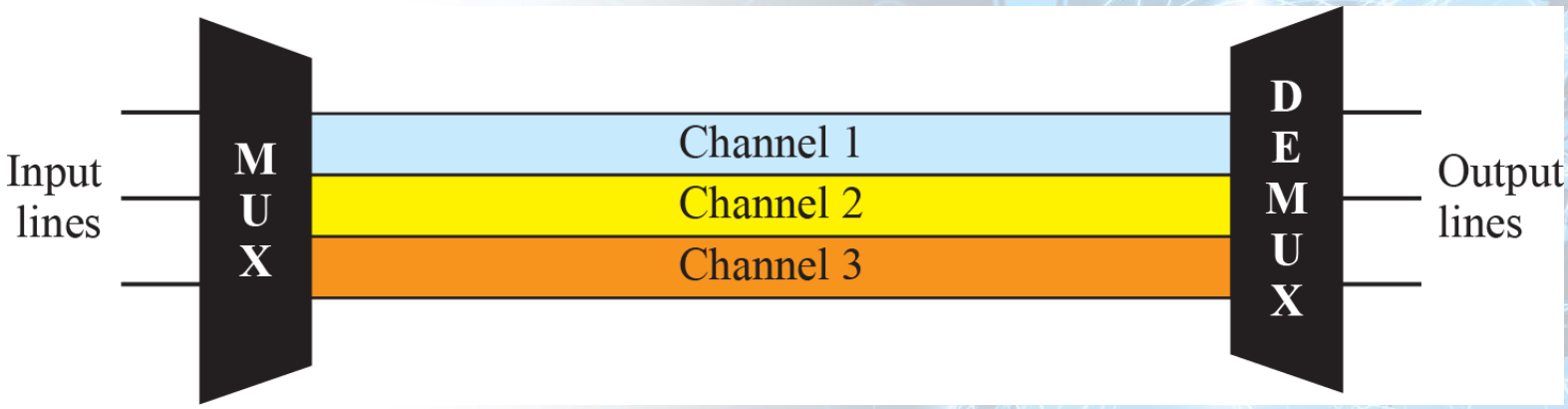
Frequency-Division Multiplexing

- An analog technique that can be applied when the bandwidth of a link (in hertz) is greater than the combined bandwidths of the signals to be transmitted
- Signals generated by each sending device modulate different carrier frequencies

Frequency-Division Multiplexing

These modulated signals are then combined into a single composite signal that can be transported by the link

Frequency-Division multiplexing



Frequency-Division Multiplexing

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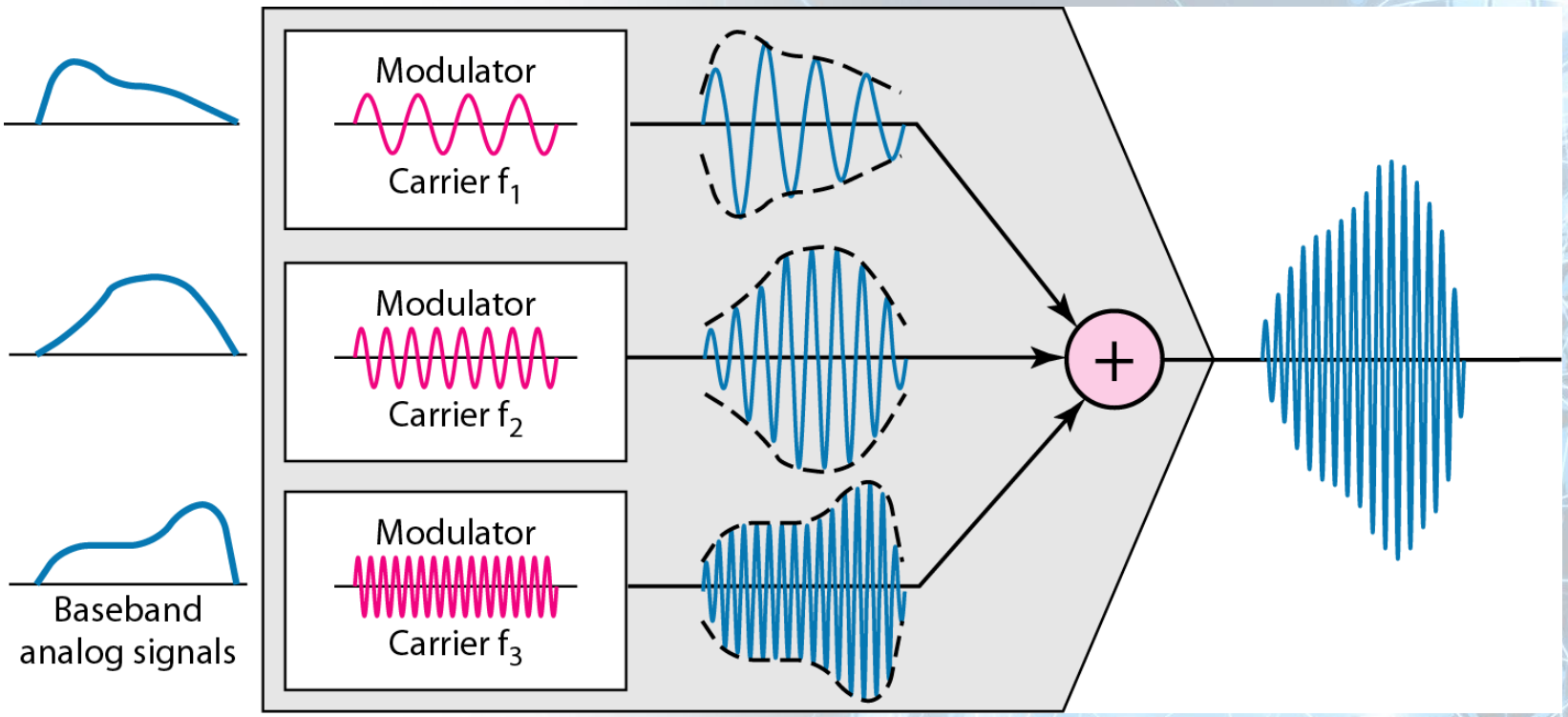
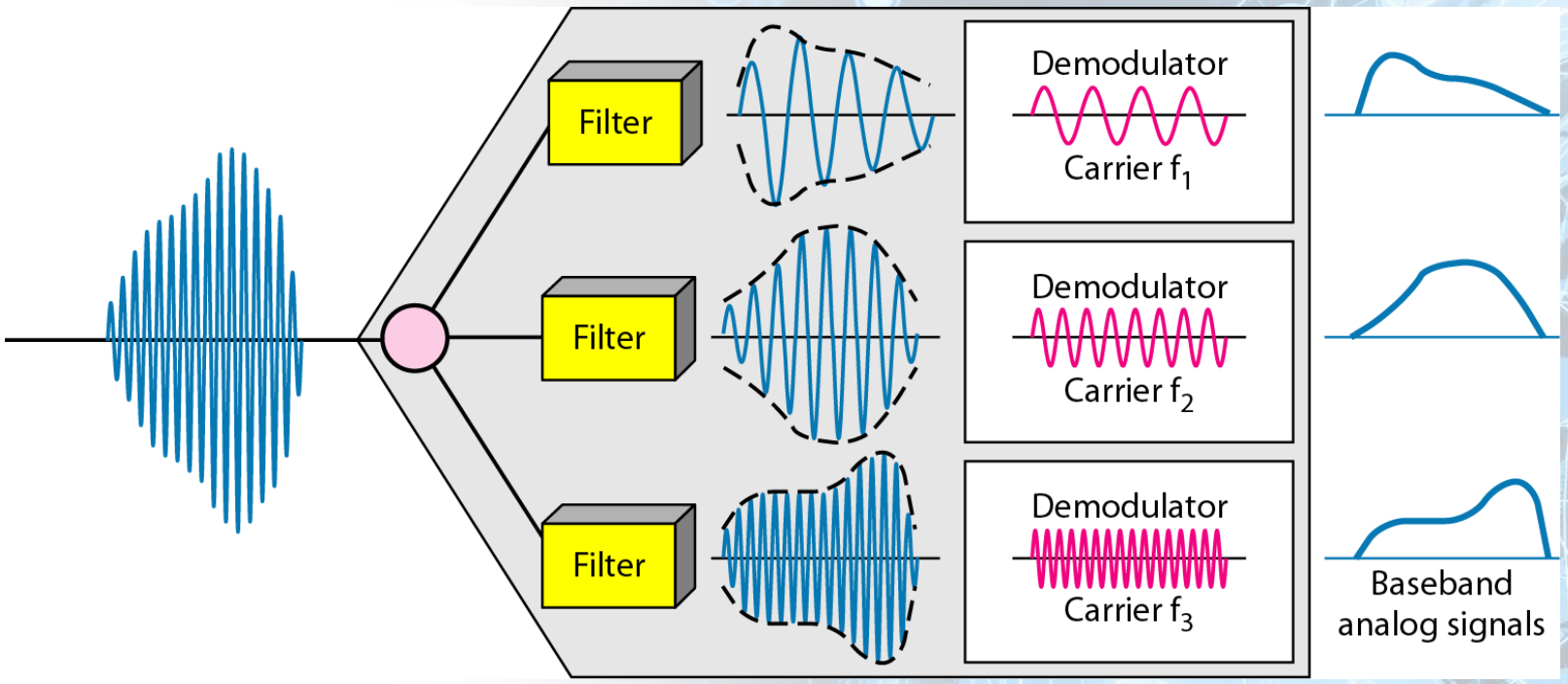
FDM Multiplexing

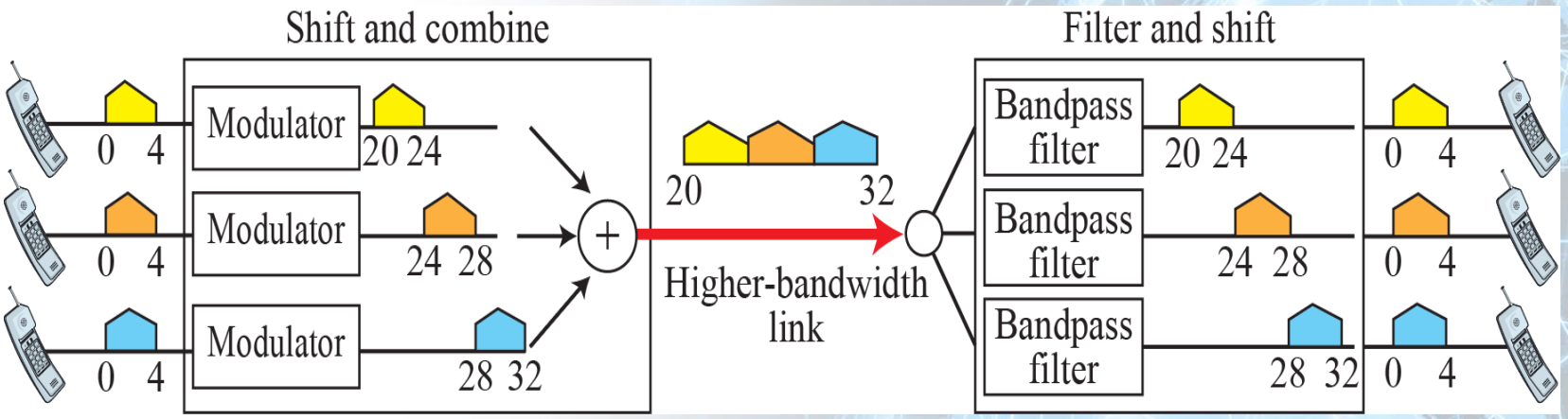


FDM De-Multiplexing



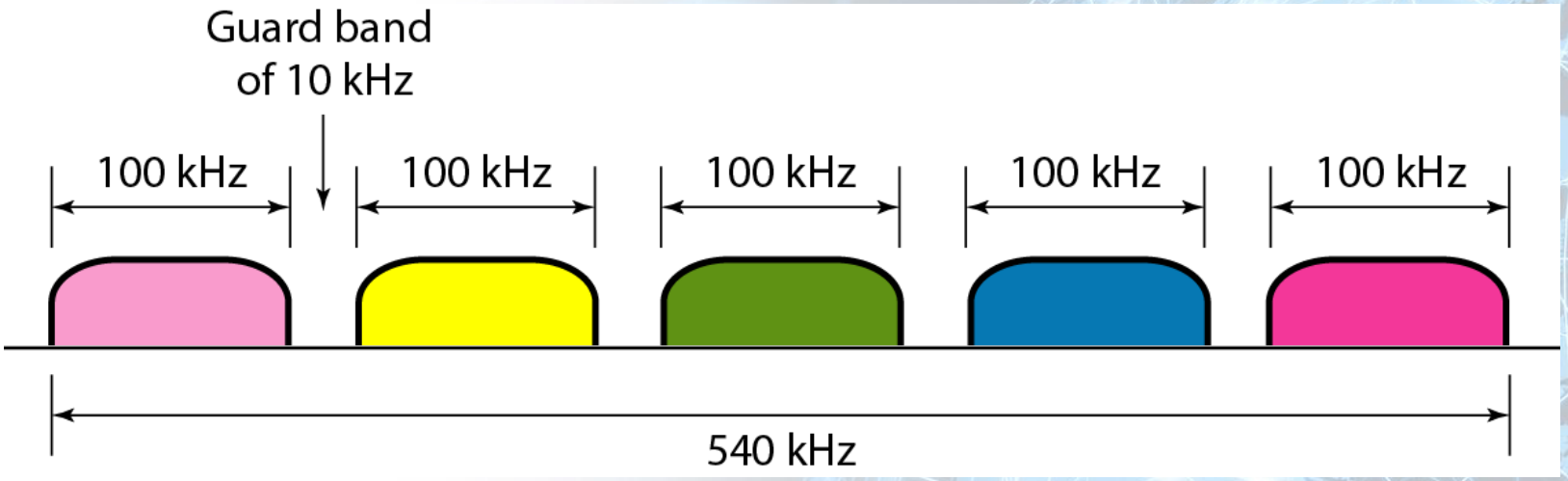
Example

Assume that a voice channel occupies a bandwidth of 4 kHz. We need to combine three voice channels into a link with a bandwidth of 12 kHz, from 20 to 32 kHz. Show the configuration, using the frequency domain. Assume there are no guard bands.



Example

Five channels, each with a 100-kHz bandwidth, are to be multiplexed together. What is the minimum bandwidth of the link if there is a need for a guard band of 10 kHz between the channels to prevent interference?

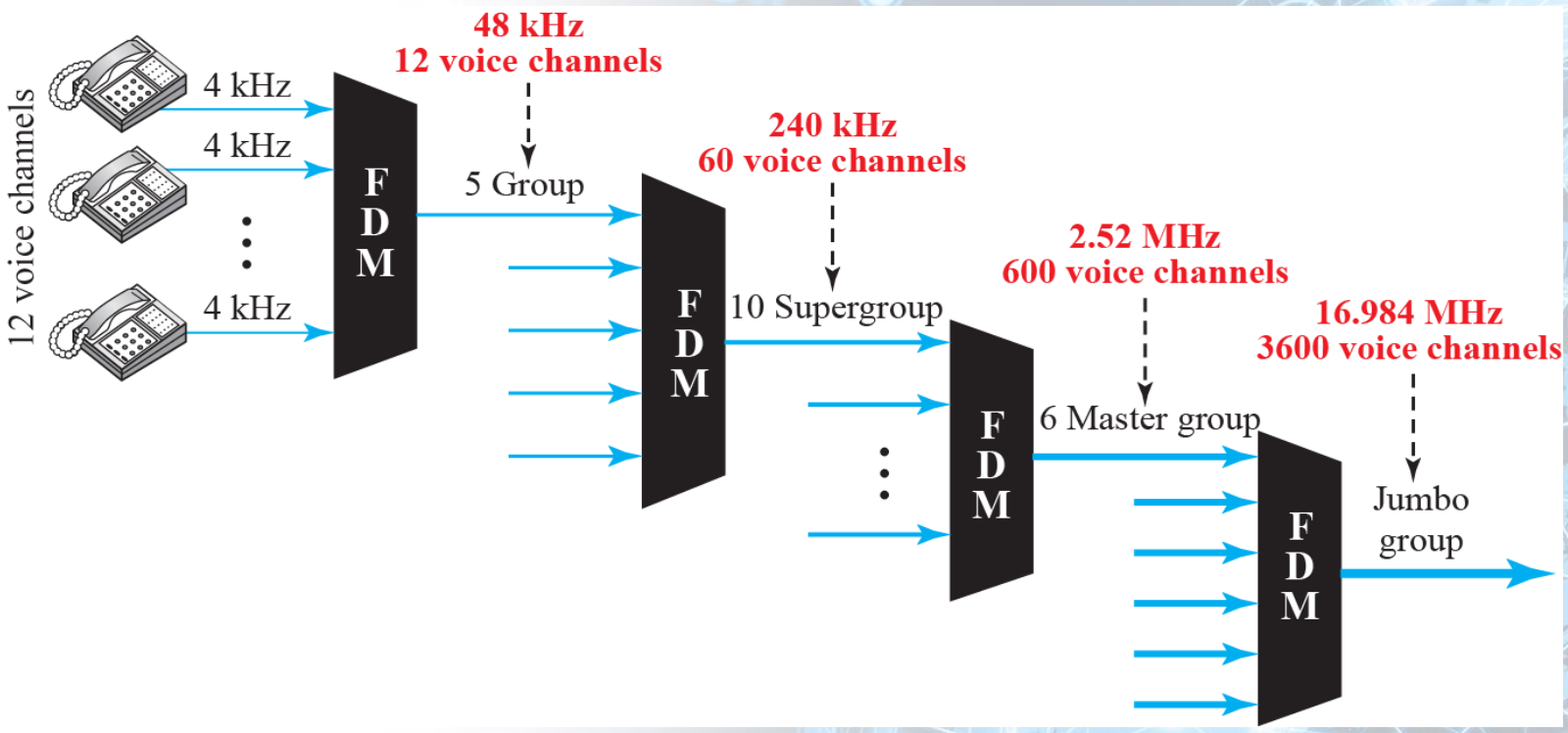


= 540 KHZ

The Analog Carrier System

- Telephone companies multiplex signals from lower-bandwidth lines on to higher-bandwidth lines
- For Analog, FDM is used

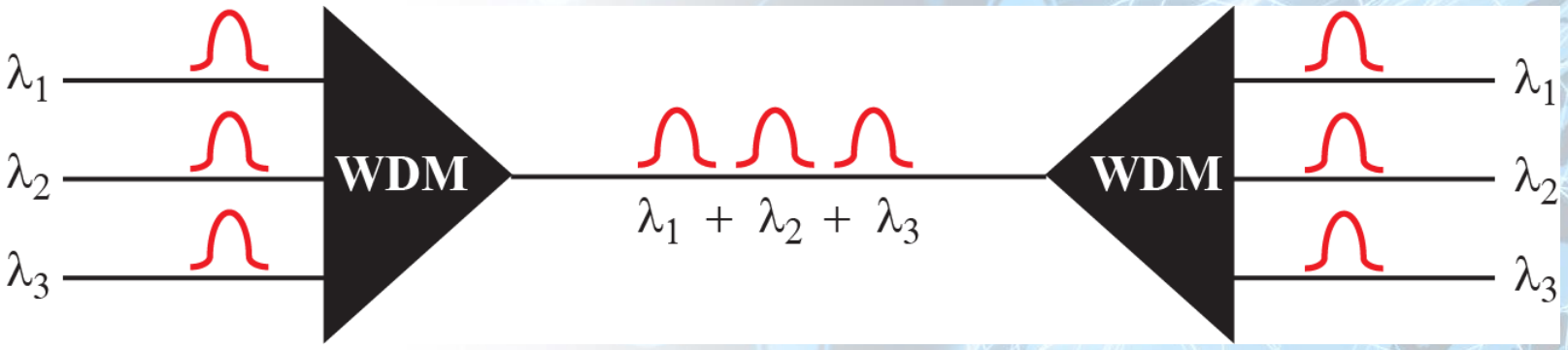
Analog Hierarchy



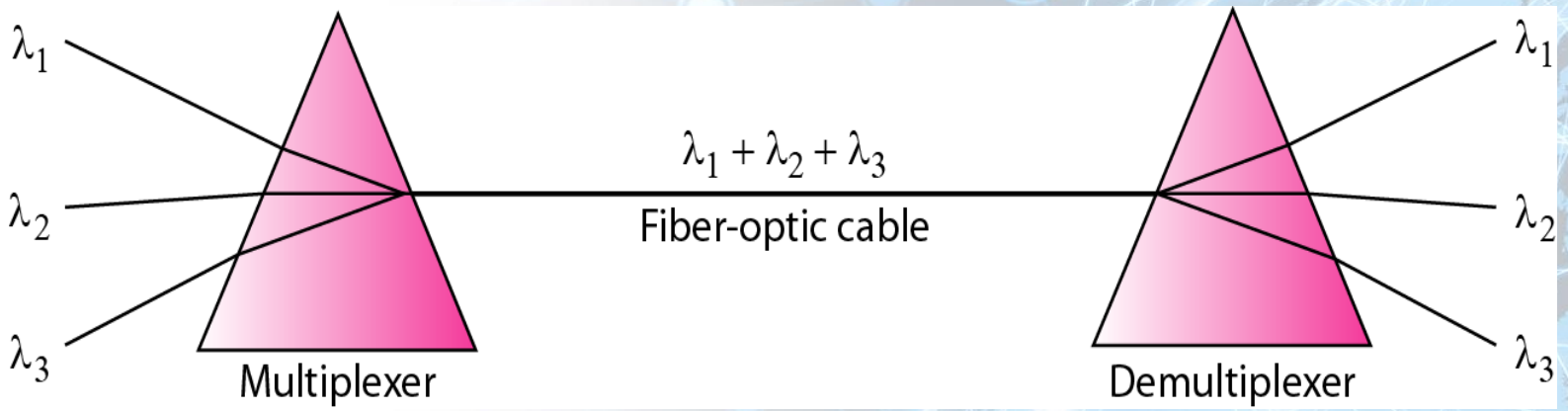
Wavelength-Division Multiplexing

- Designed to use the high-data-rate capability of fiber-optic cable
- Fiber data rate is higher than the data rate of metallic transmission cable
- Using a fiber-optic cable for a single line wastes the available bandwidth
- Multiplexing allows us to combine several lines into one

Wavelength-Division Multiplexing (WDM)



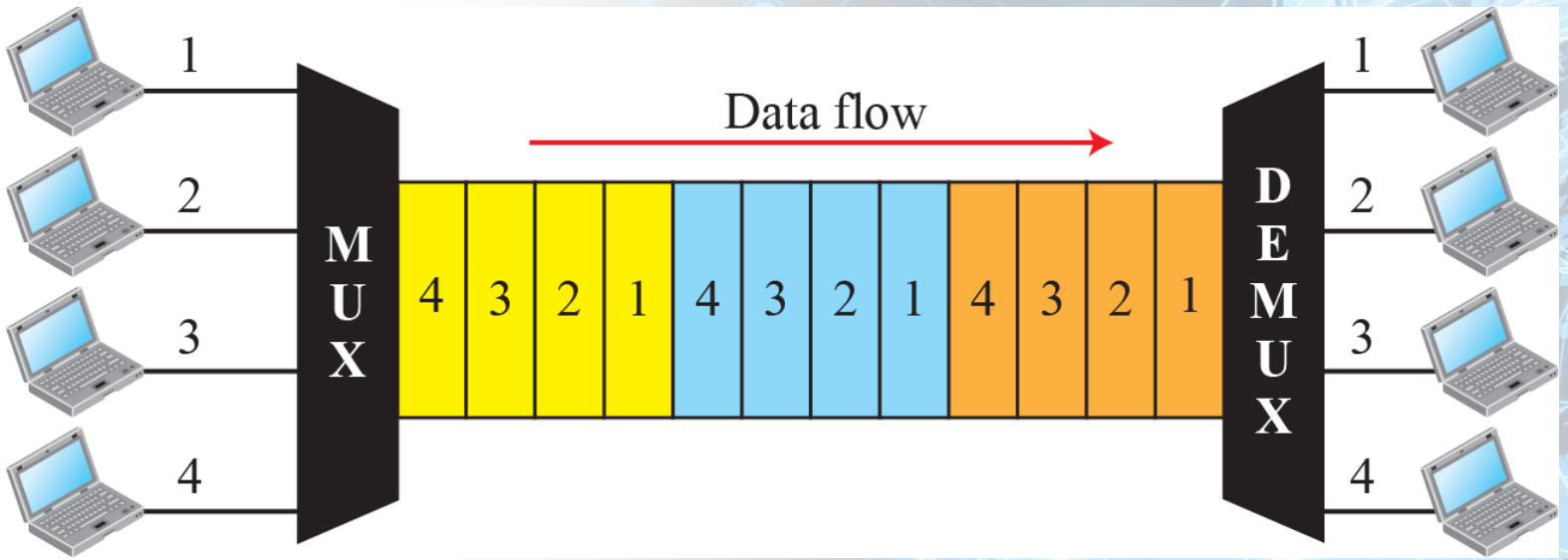
Prisms in Wave-Length Division Multiplexing



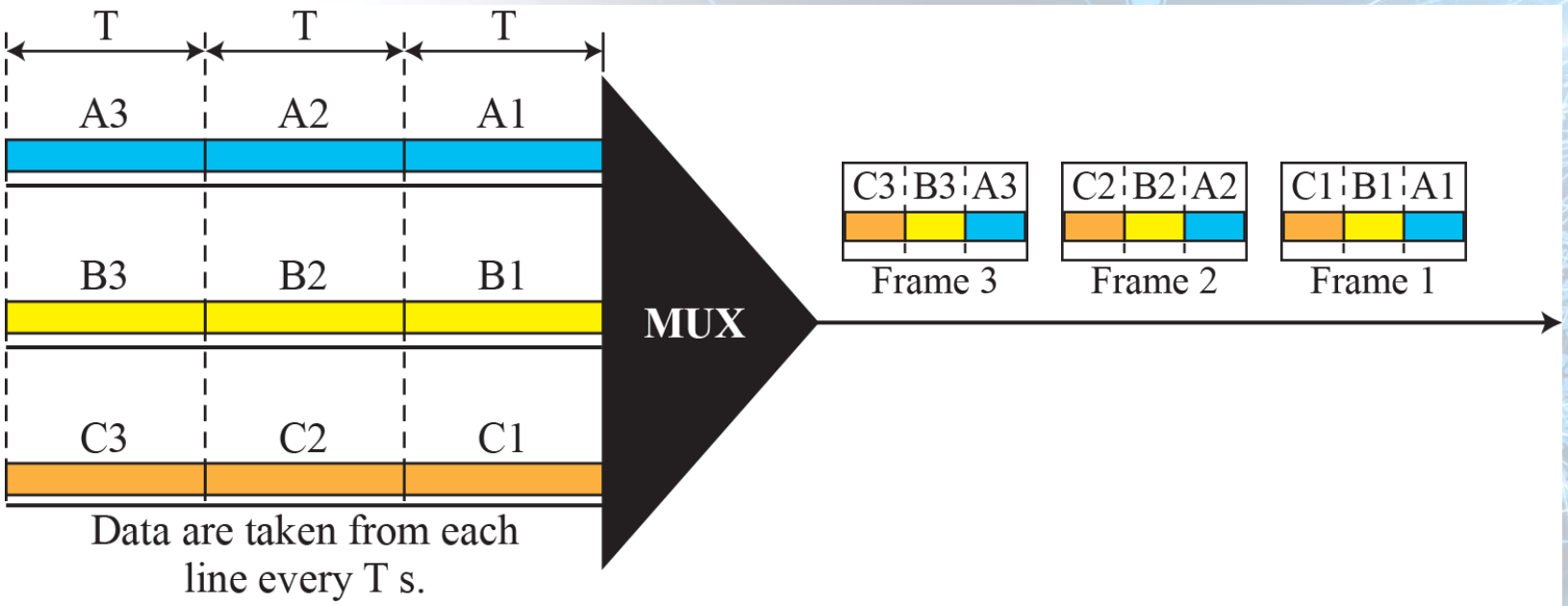
Time-Division Multiplexing

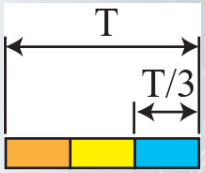
- Digital process that allows several connections to share the high bandwidth of a link
- Time is shared i.e. each connection occupies a portion of time in the link

TDM



Synchronous Time-Division Multiplexing





Each frame is 3 time slots.
Each time slot duration is T/3 s.

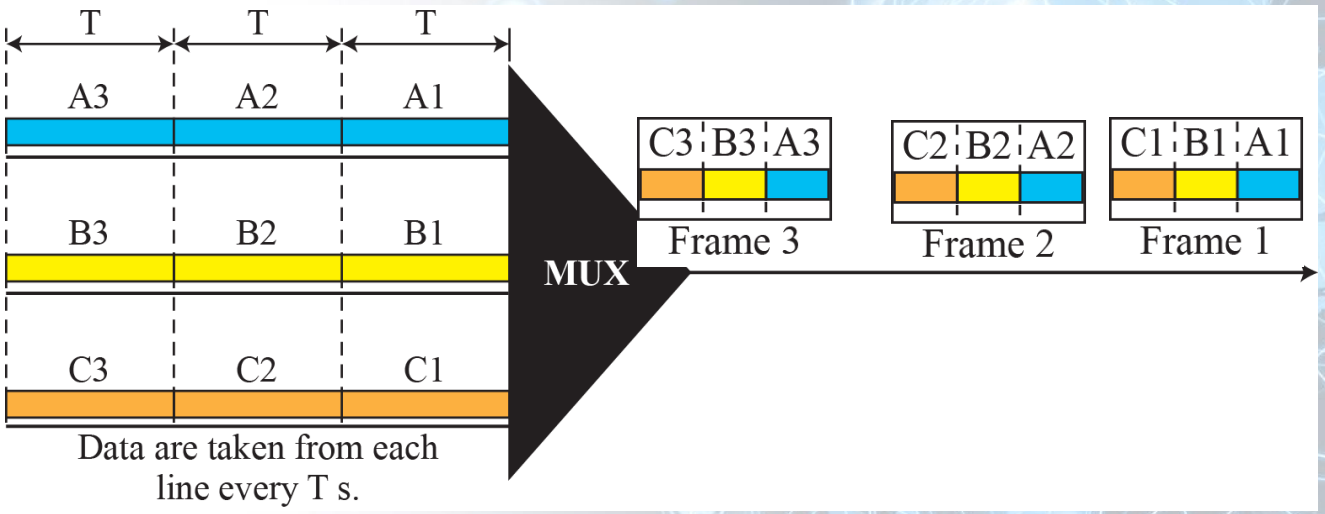
Time-Division Multiplexing

- Digital process that allows several connections to share the high bandwidth of a link
- Time is shared i.e. each connection occupies a portion of time in the link

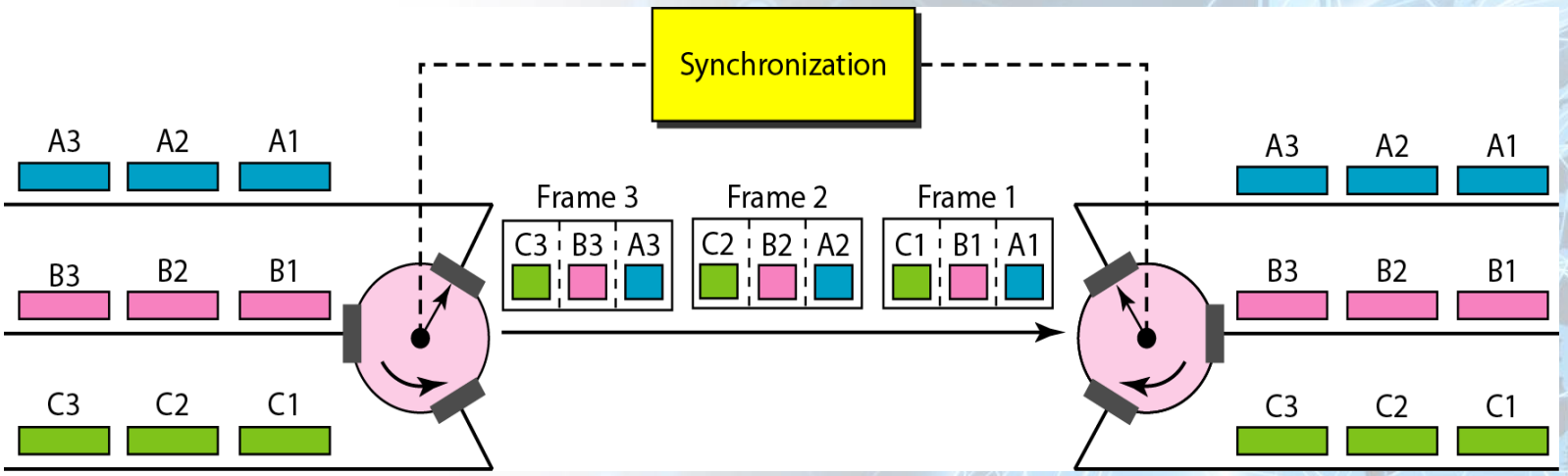
Example

In Figure the data rate for each input connection is 1 kbps. If 1 bit at a time is multiplexed (a unit is 1 bit), what is the duration of

- **each input slot,**
- **each output slot, and**
- **each frame?**



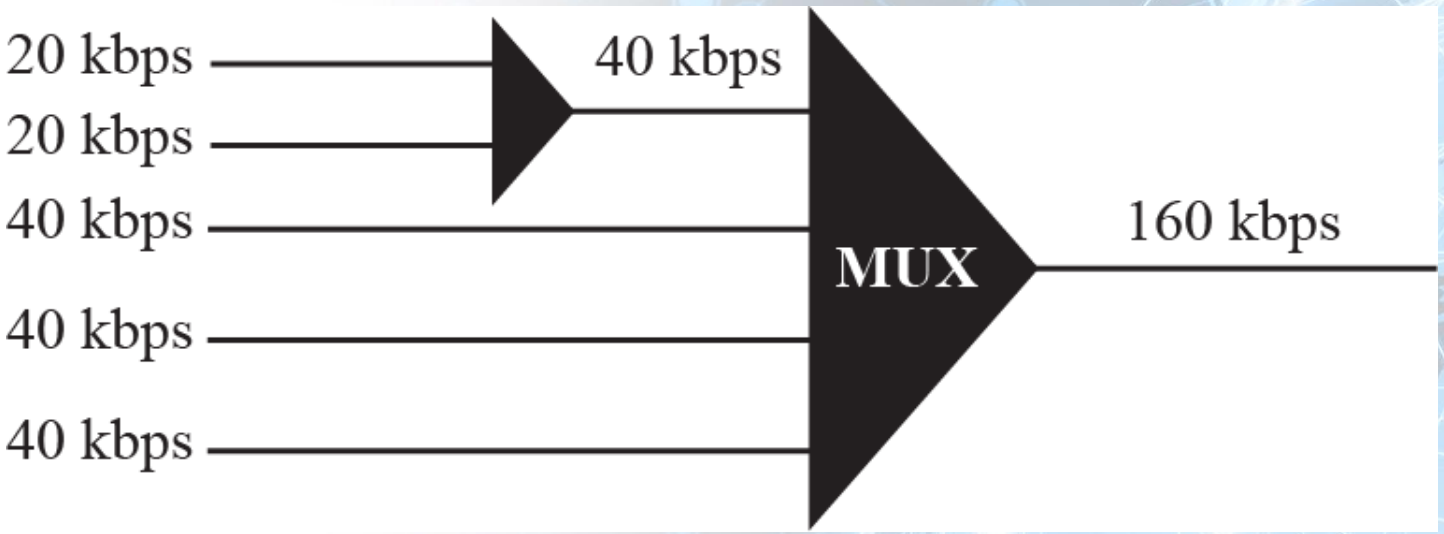
Interleaving



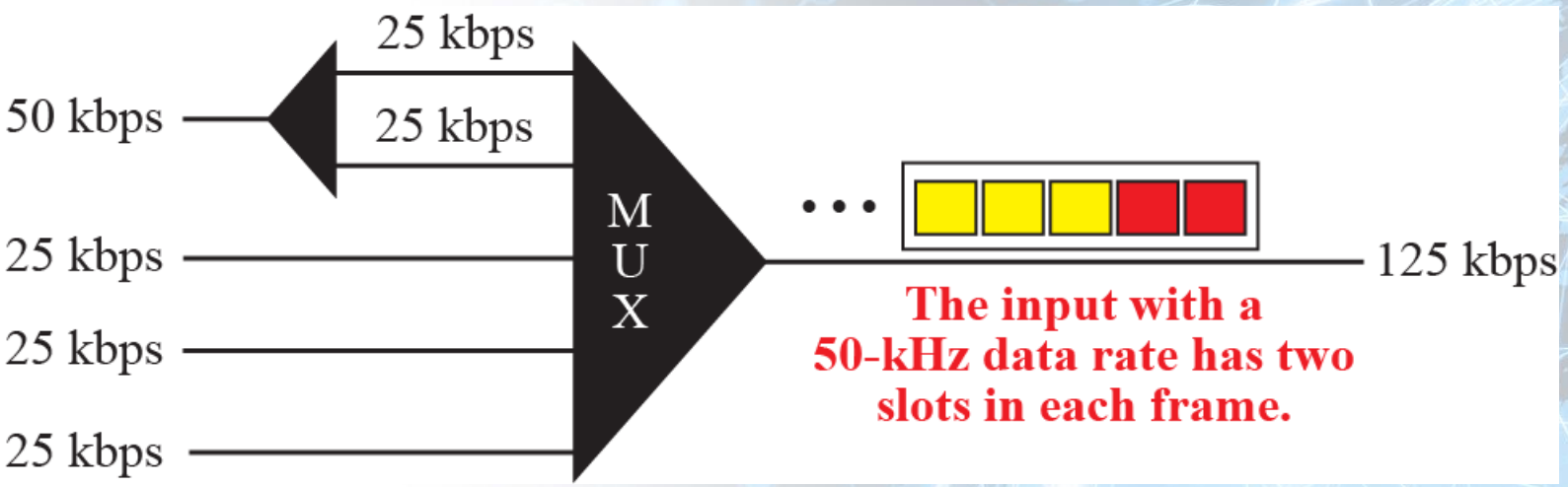
Time-Division Multiplexing

- Digital process that allows several connections to share the high bandwidth of a link
- Time is shared i.e. each connection occupies a portion of time in the link

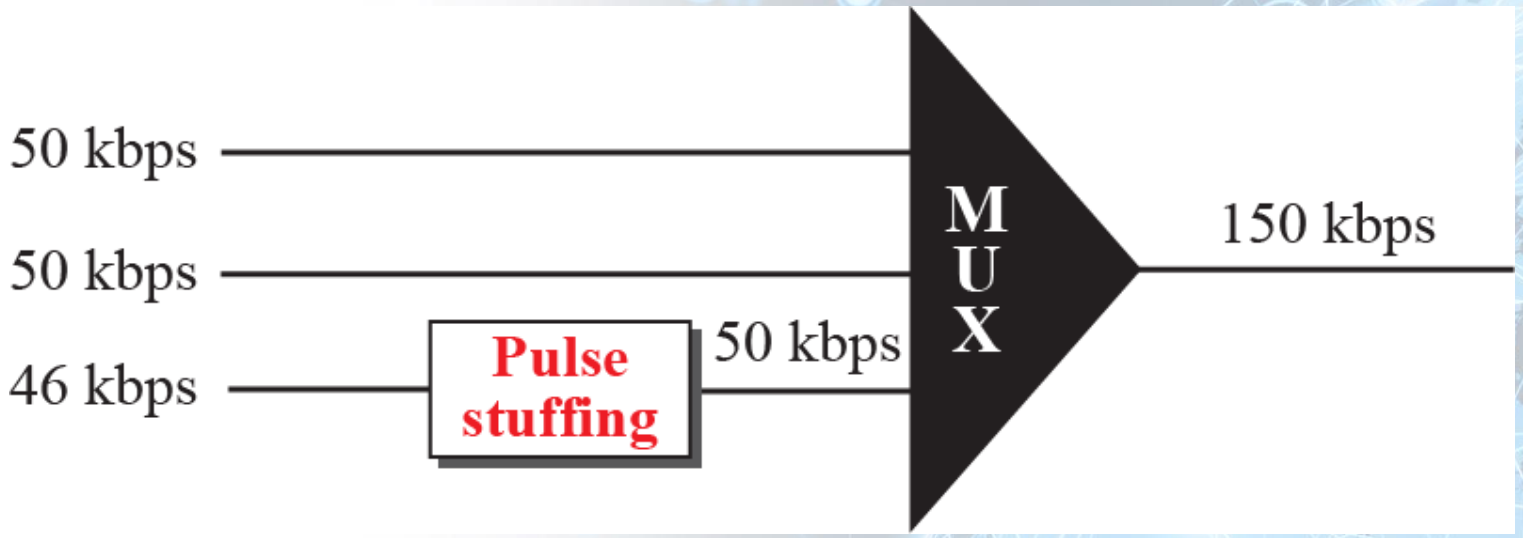
Multilevel Multiplexing



Multiple-SLot Multiplexing



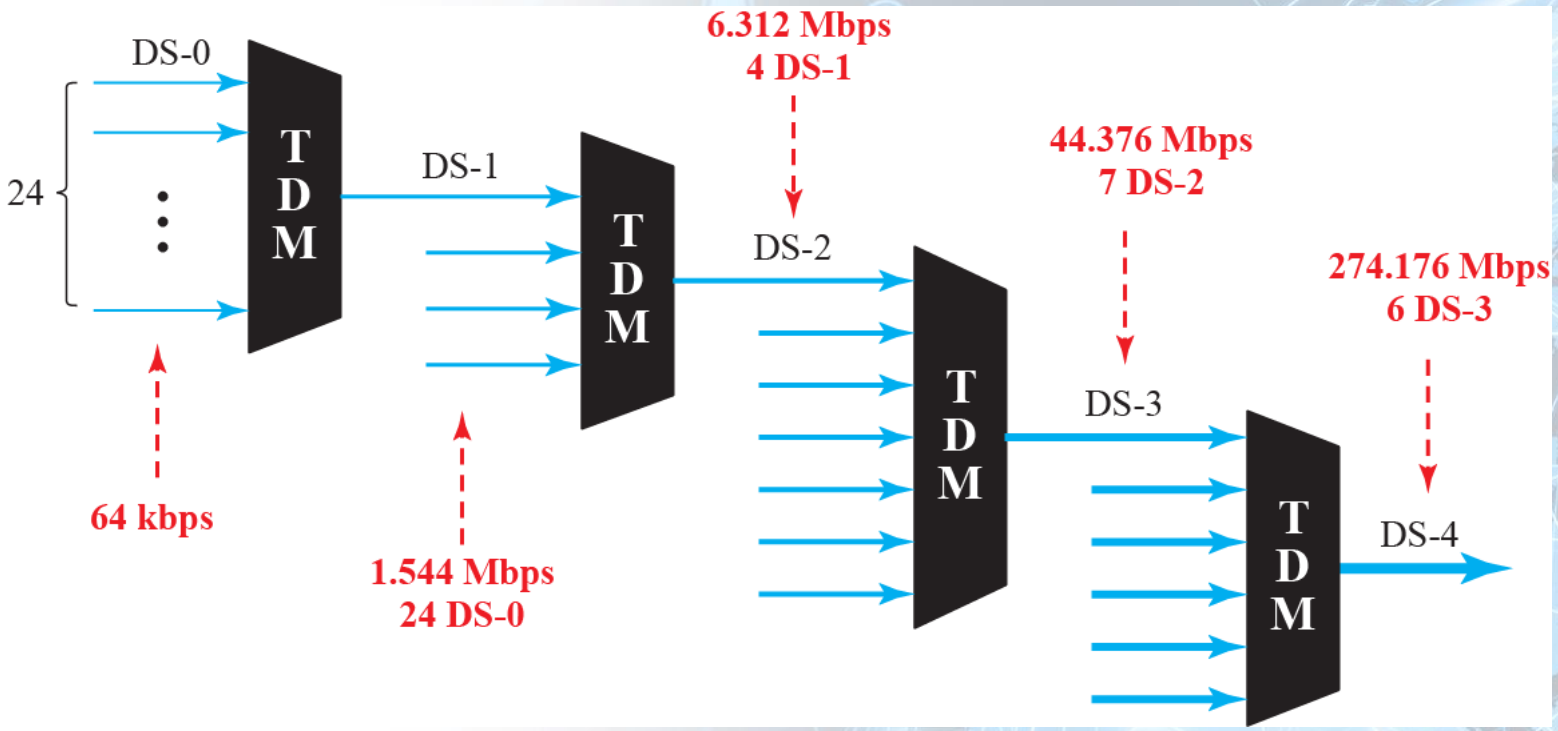
Pulse Stuffing



Time-Division Multiplexing

- Digital process that allows several connections to share the high bandwidth of a link
- Time is shared i.e. each connection occupies a portion of time in the link

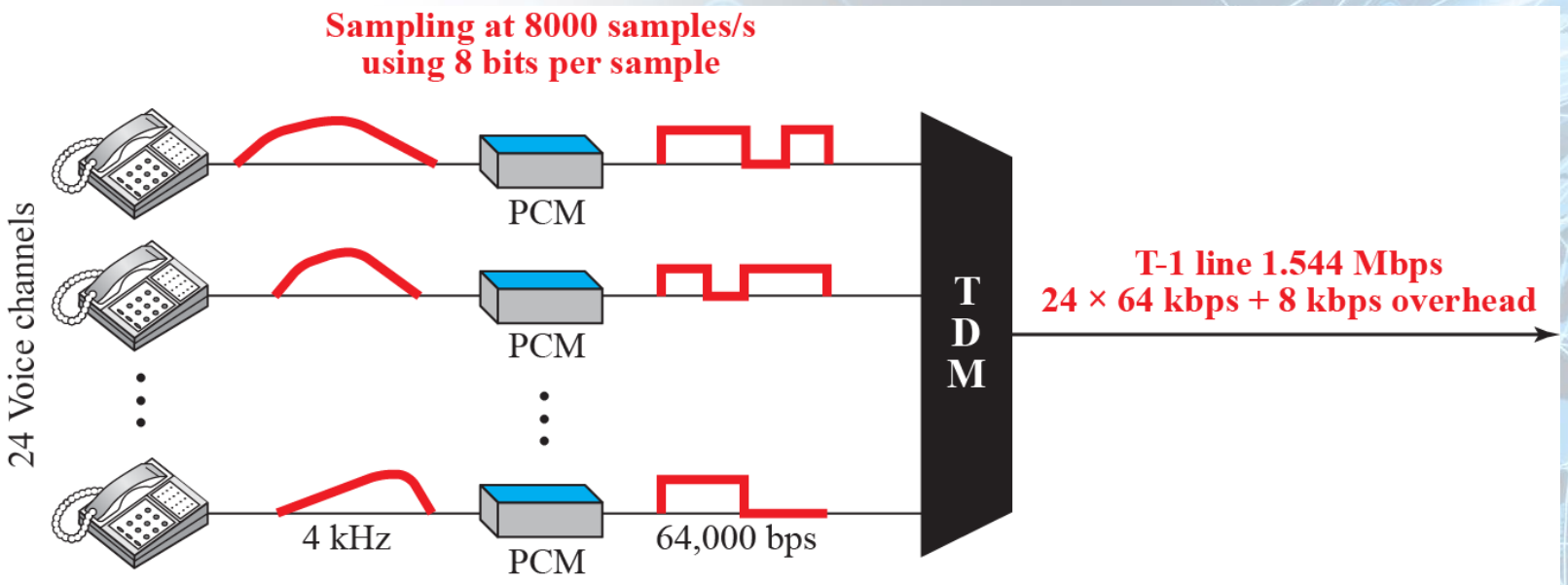
Digital Hierarchy



DS and T Line Rates

Service	*Line*	*Rate (Mbps)*	*Voice Channels*
DS-1	T-1	1.544	24
DS-2	T-2	6.312	96
DS-3	T-3	44.736	672
DS-4	T-4	274.176	4032

T-1 Line


Sampling at 8000 samples/s
using 8 bits per sample
24 Voice channels
PCM
PCM
PCM
4 kHz
64,000 bps
T
D
M
T-1 line 1.544 Mbps
24 × 64 kbps + 8 kbps overhead

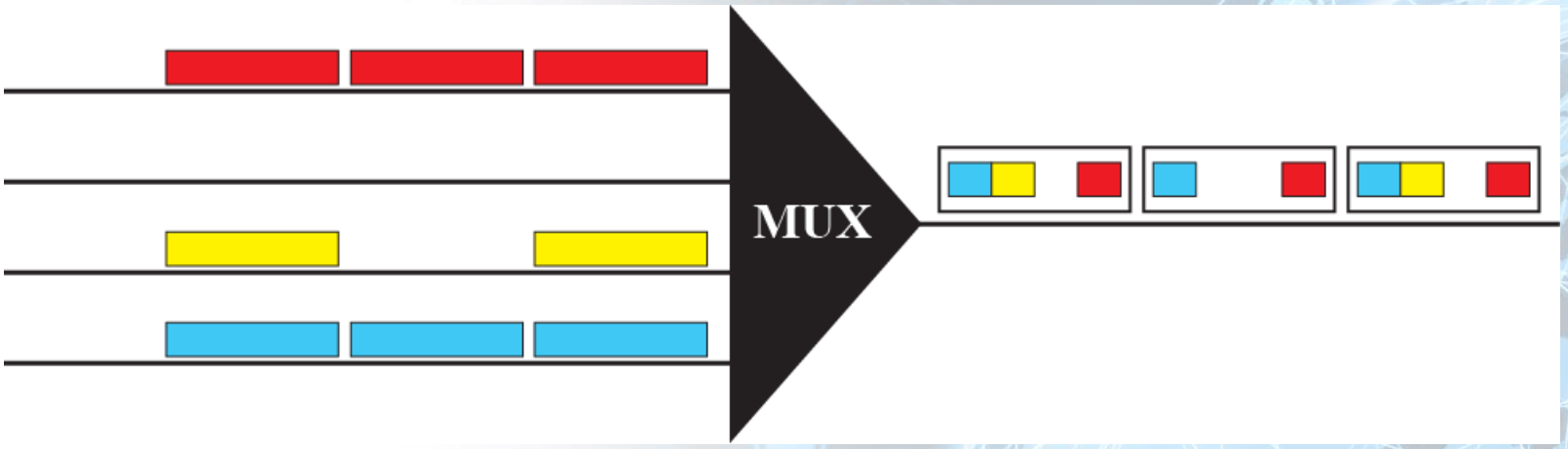
E Line Rates

Line	*Rate (Mbps)*	*Voice Channels*
E-1	2.048	30
E-2	8.448	120
E-3	34.368	480
E-4	139.264	1920

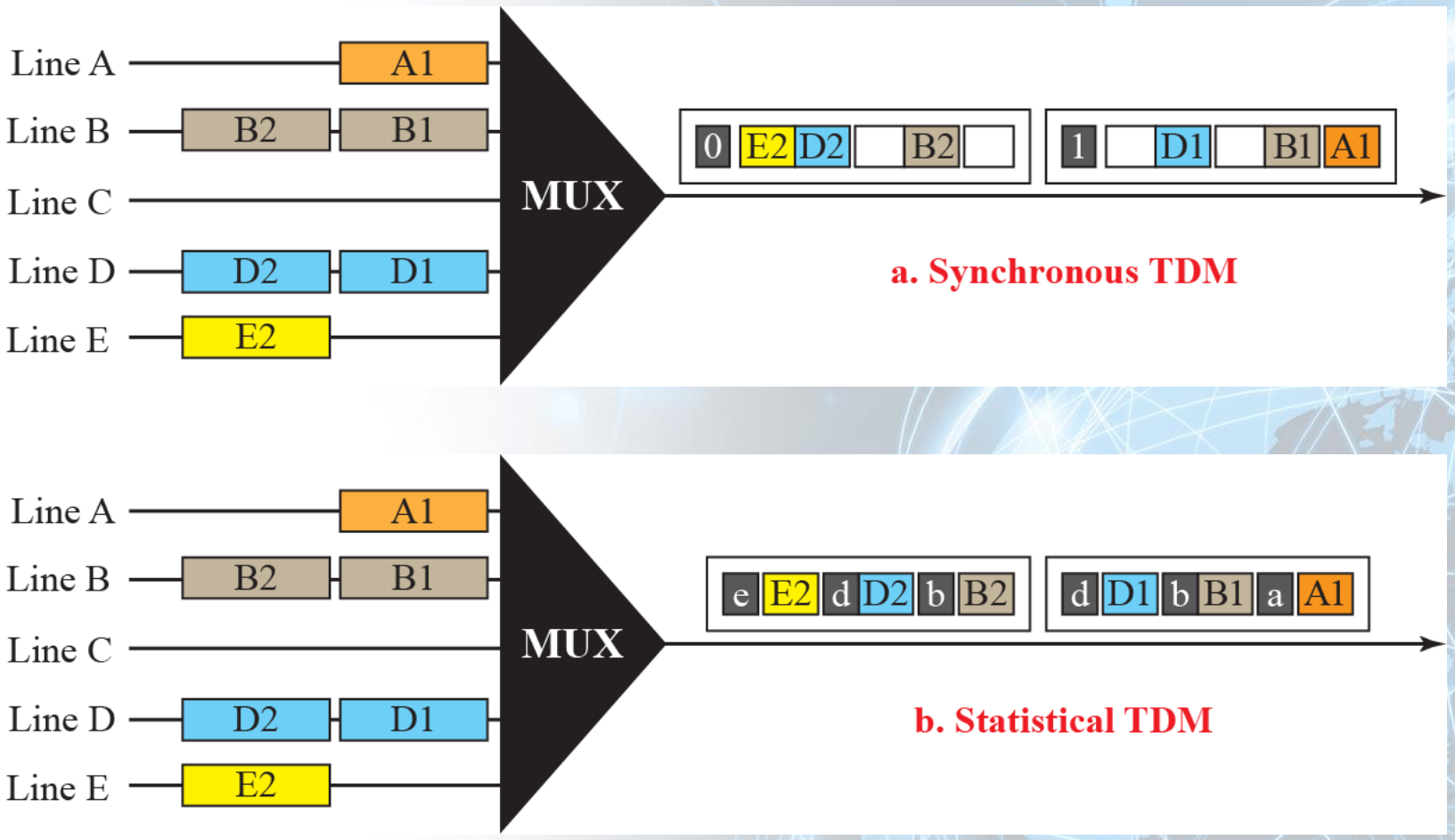
Time-Division Multiplexing

- Synchronous TDM
- Statistical TDM

Empty slots



Statistical TDM



SPREAD SPECTRUM

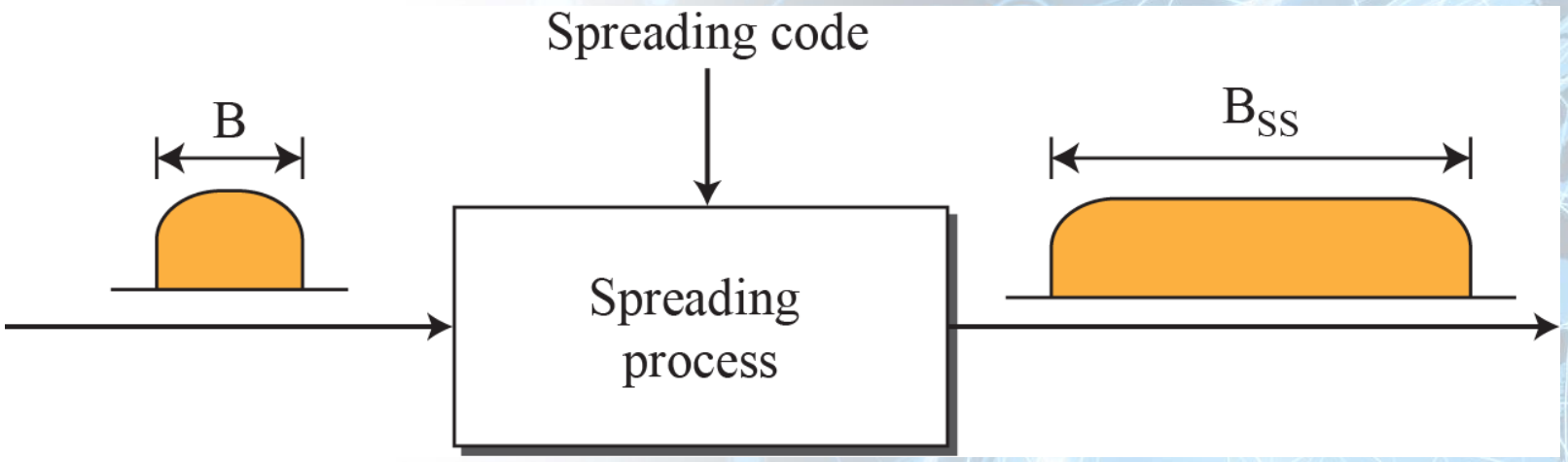
- In wireless applications, stations must be able to share the medium without interception by an eavesdropper and without being subject to jamming from a malicious intruder

- To achieve these goals, spread spectrum adds redundancy and spread original spectrum needed for each station

SPREAD SPECTRUM - Principles

- Bandwidth allocated to each station needs to be larger than what is needed to allow Redundancy
- Spreading process should be independent of the original signal

Spread Spectrum



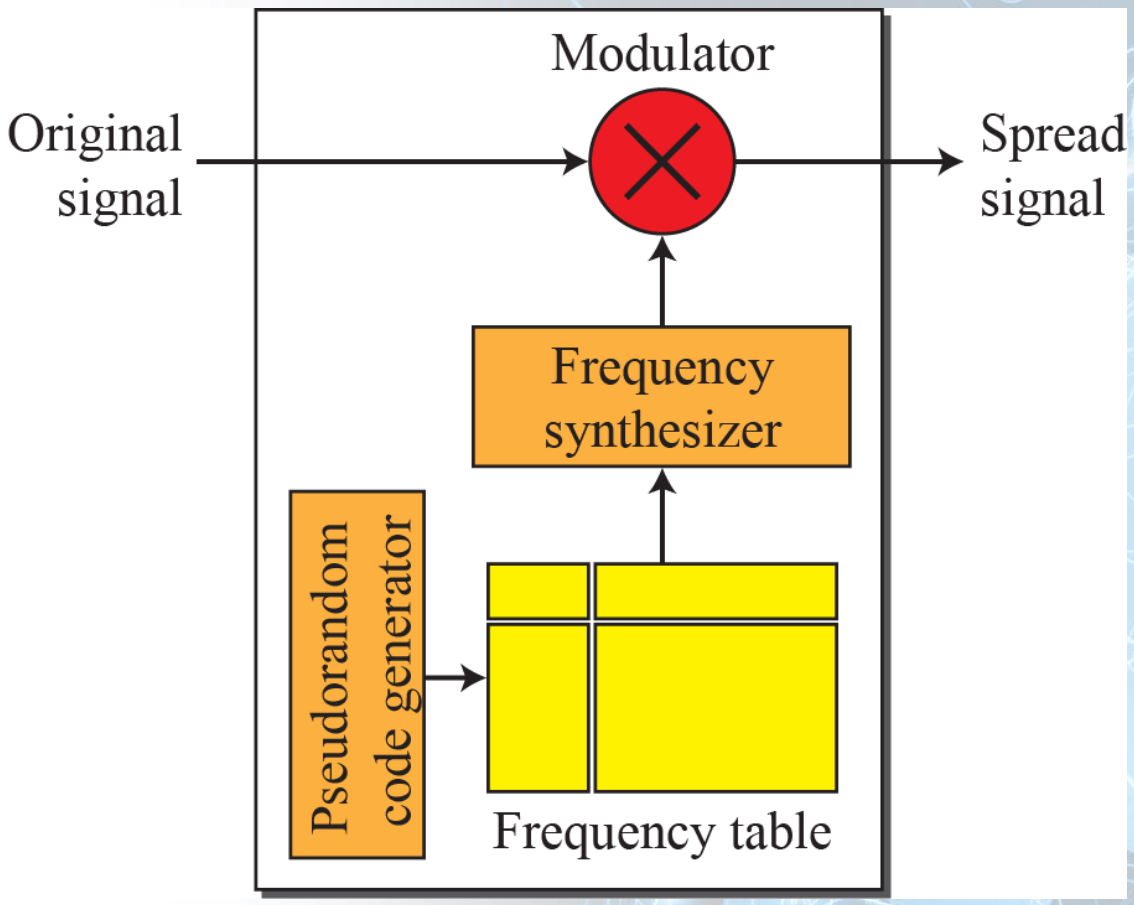
SPREAD SPECTRUM TECHNIQUES

- **Frequency Hopping Spread Spectrum (FHSS)**
- **Direct Sequence Spread Spectrum (DSSS)**

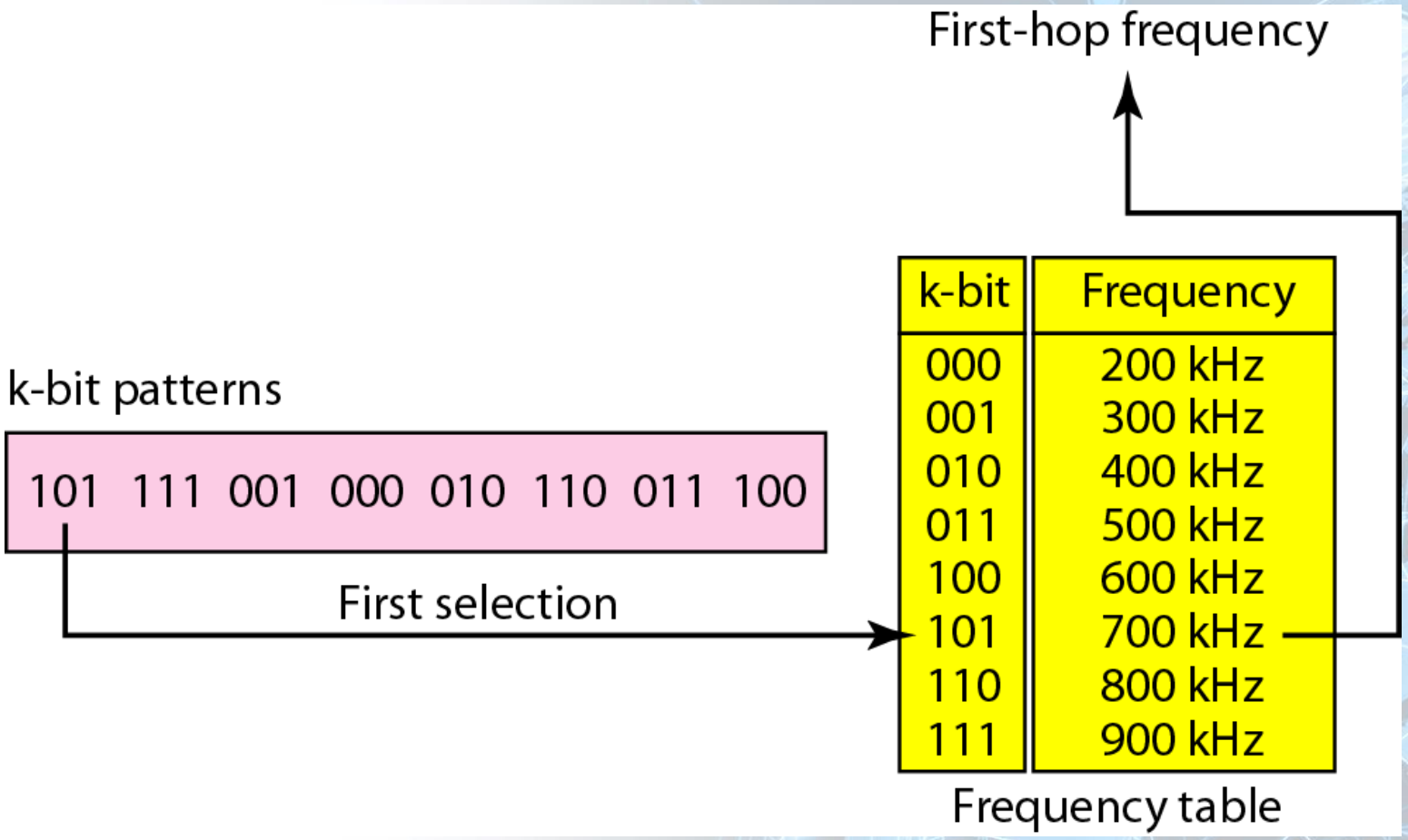
Frequency Hopping Spread Spectrum (FHSS)

- **‘M’ different carrier frequencies that are modulated by the source signal**
- **At one moment, signal modulates one carrier frequency and at next moment, it modulates another**

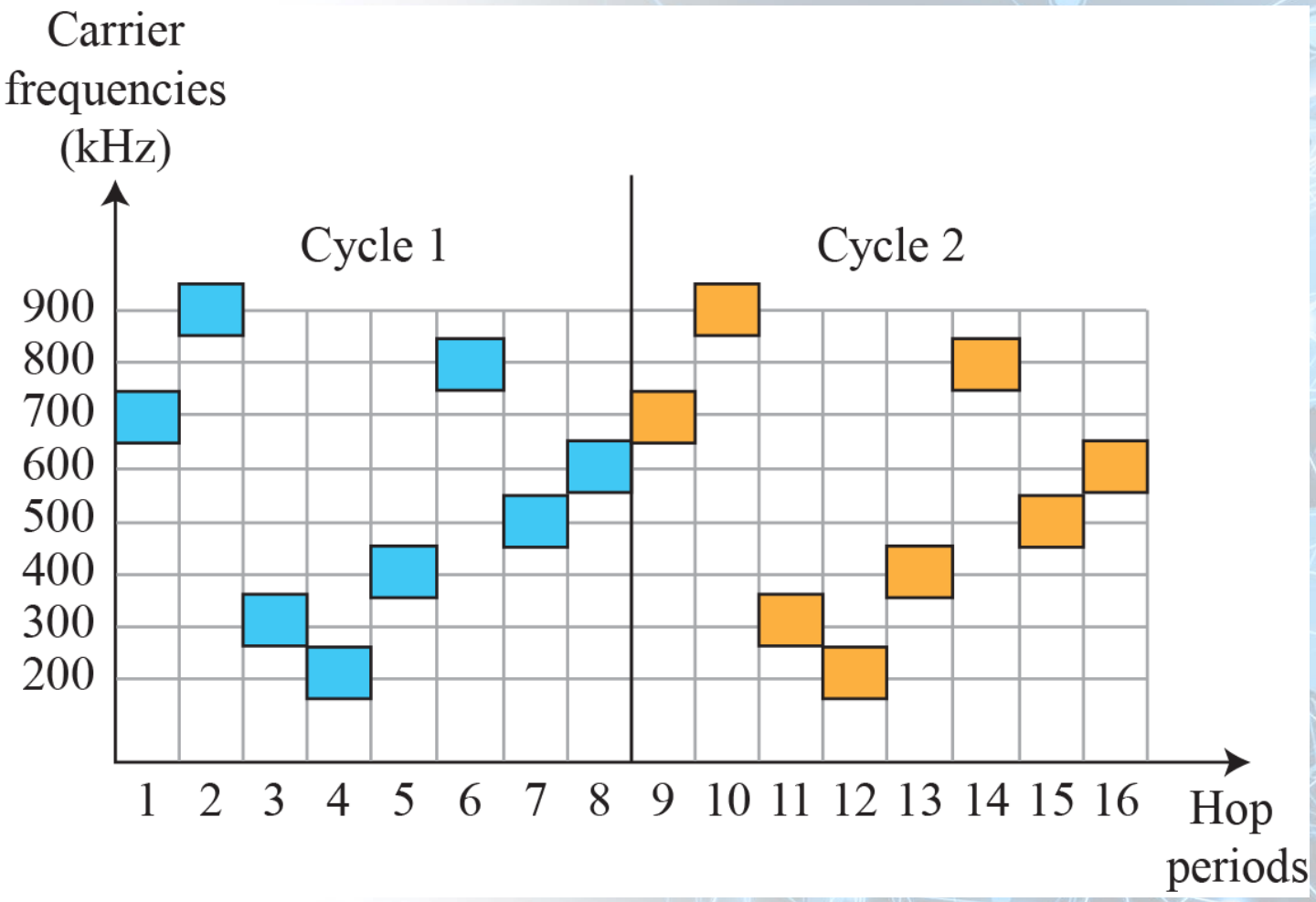
Frequency Hopping Spread Spectrum (FHSS)



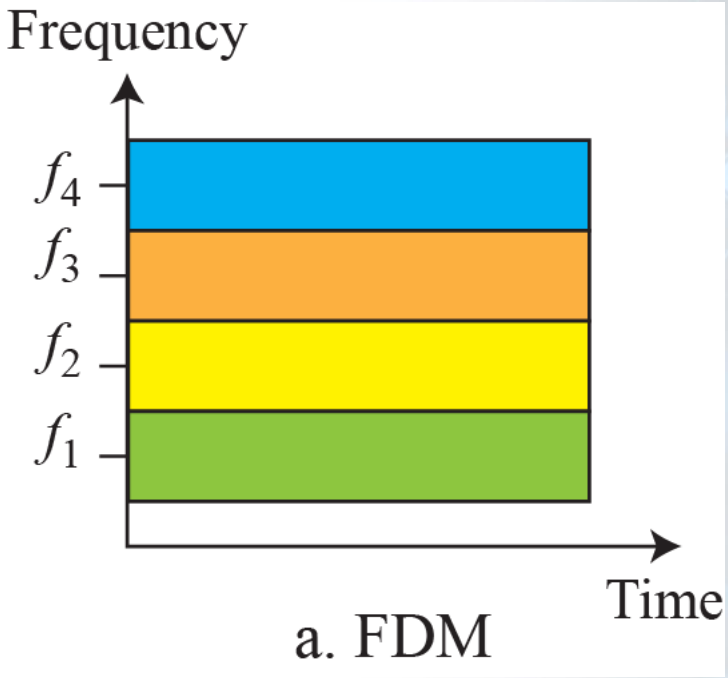
Frequency Selection in FHSS



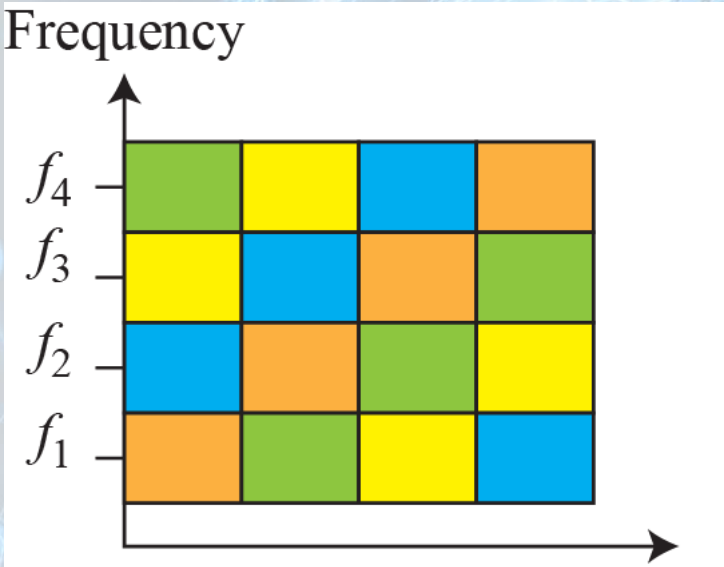
FHSS Cycles


Carrier frequencies (kHz)
Cycle 1
Cycle 2
900
800
700
600
500
400
300
200
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Hop periods

Bandwidth Sharing



a. FDM

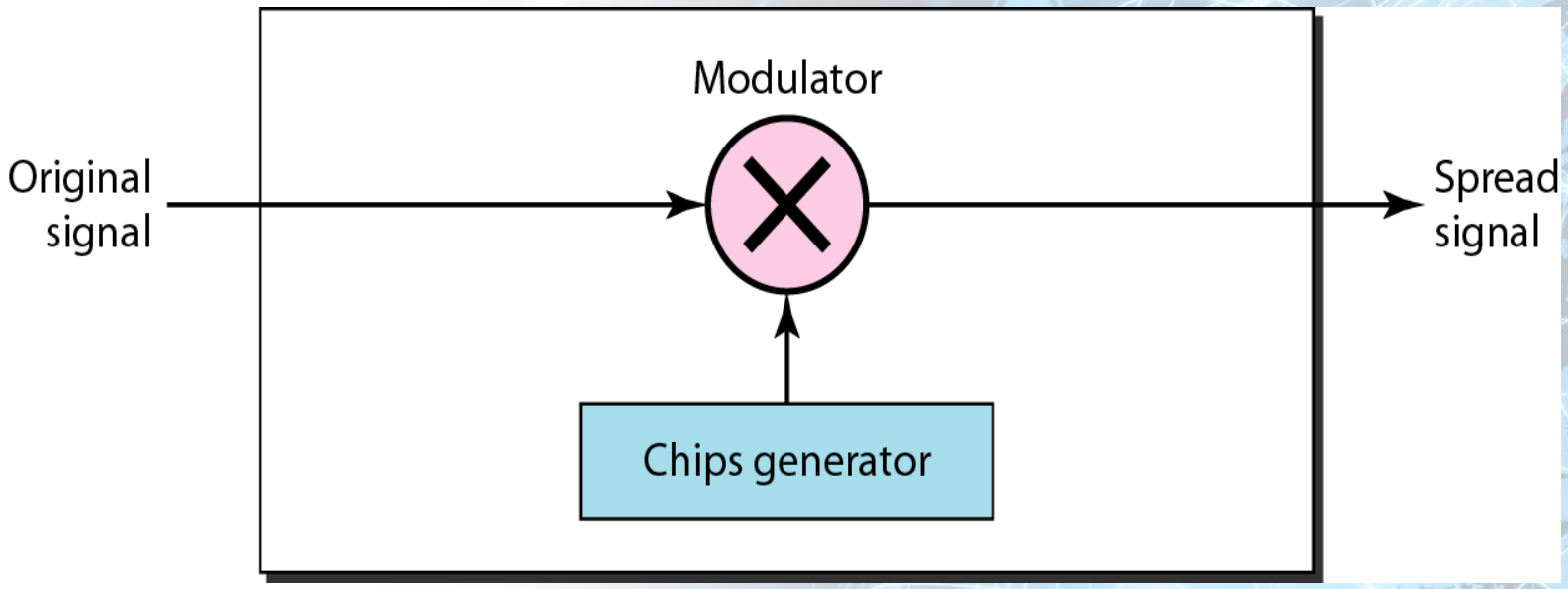


b. FHSS

DSSS

- DSSS also expands the bandwidth of the original signal, but the process is different
- We replace each data bit with ‘n’ bits using a spreading code
- Each bit is assigned a code of ’n’ bits, called chips, where the chip rate is ‘n’ times that of the data bit

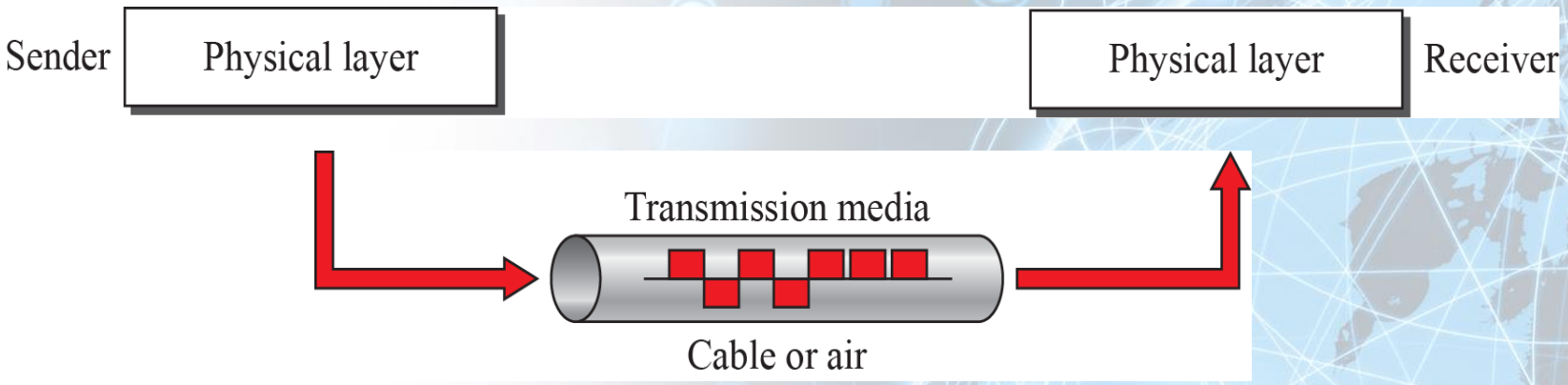
DSSS



Transmission Media

- Located below the physical layer and are directly controlled by the physical layer
- Belong to layer zero
- Metallic Media i.e. Twisted pair and Coaxial Cable
- Optical Fiber Cable
- Free Space i.e. Air, Vaccum

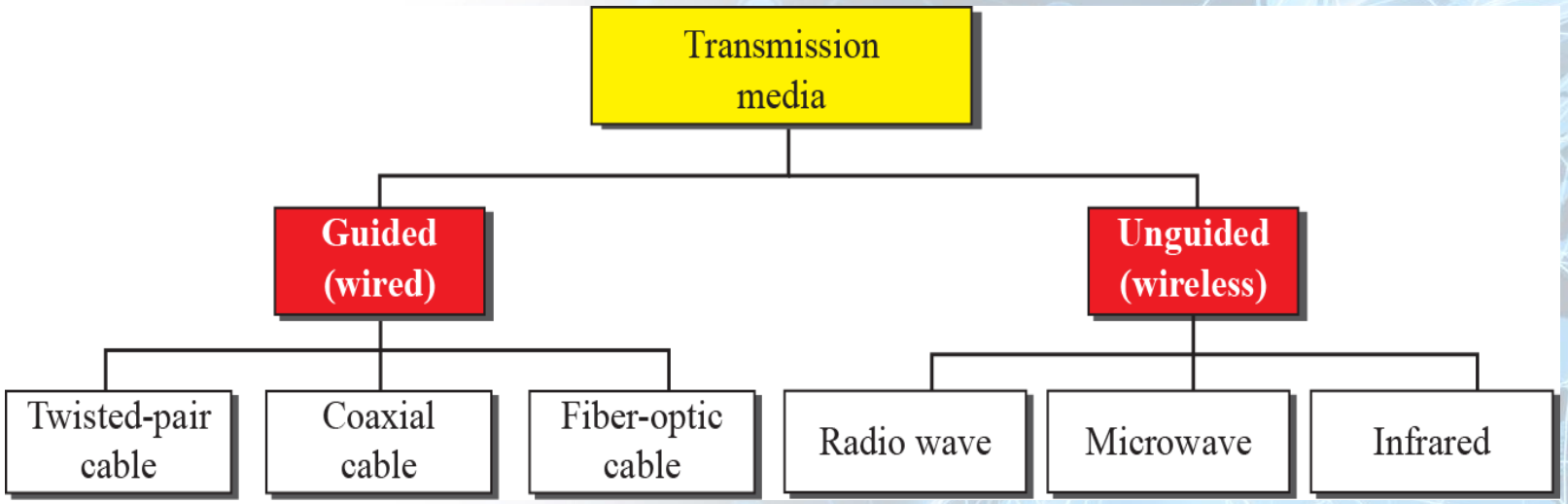
Transmission Media & Physical Payer



Transmission Media

- Located below the physical layer and are directly controlled by the physical layer
- Belong to layer zero
- Metallic Media i.e. Twisted pair and Coaxial Cable
- Optical Fiber Cable
- Free Space i.e. Air, Vaccum

Classes of Transmission Media



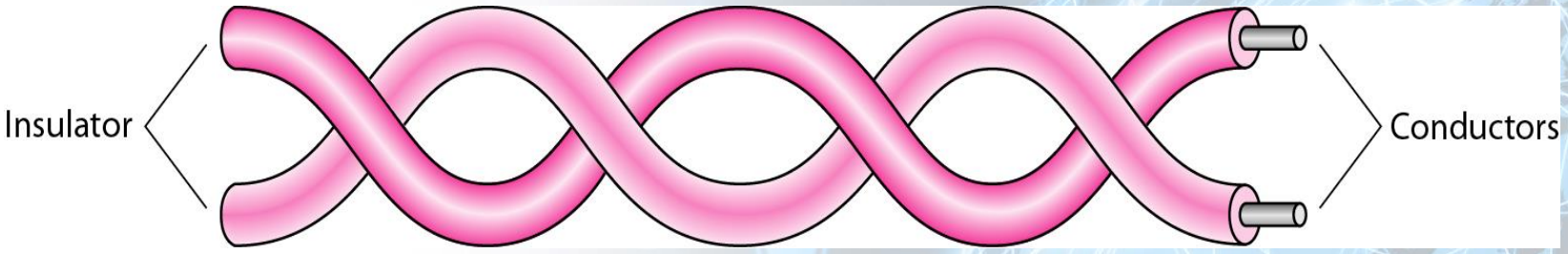
Guided Media

- Media that provides a conduit from one device to another
- Twisted-pair cable, coaxial cable, and fiber-optic cable
- Signal traveling along any of these media is directed and contained by the physical limits of the medium

Twisted-Pair Cable

- Consists of 2 copper conductors, each with its own plastic insulation, twisted together
- One wire carries signals and other is ground reference
- Receiver uses difference between the two
- Interference (Noise) & Crosstalk

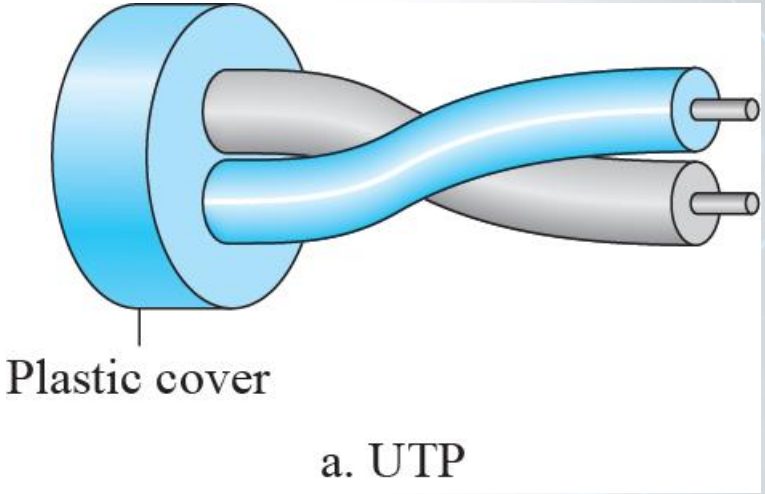
Twisted-Pair Cable

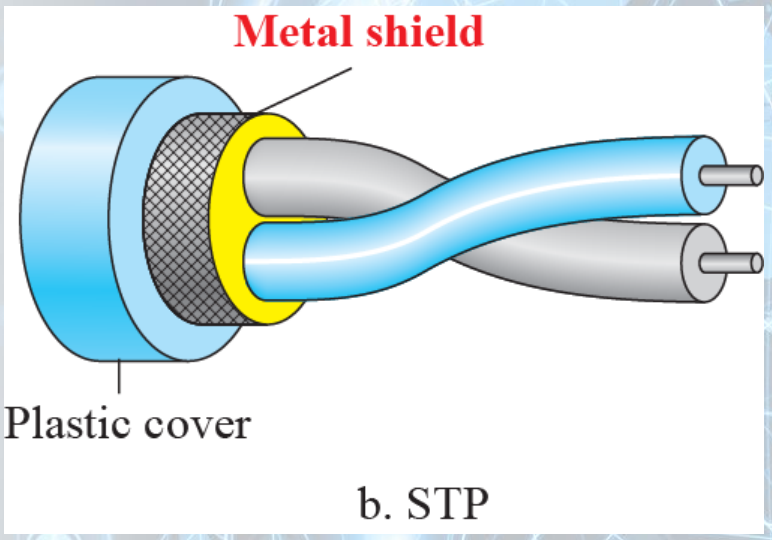


Twisted-Pair Cable

- UTP
- STP

Unshielded vs. Shielded Twisted Pair Cable

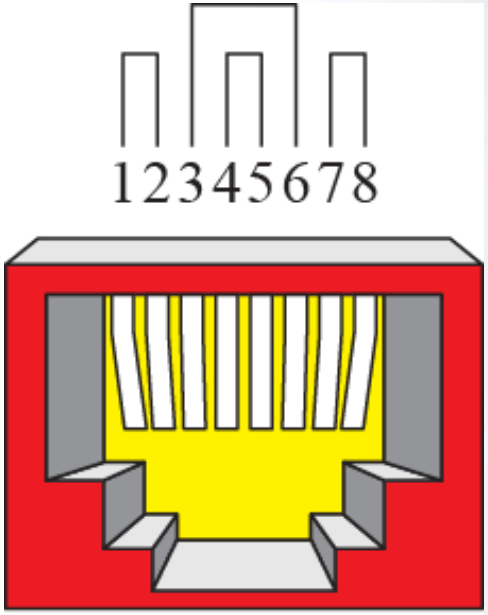




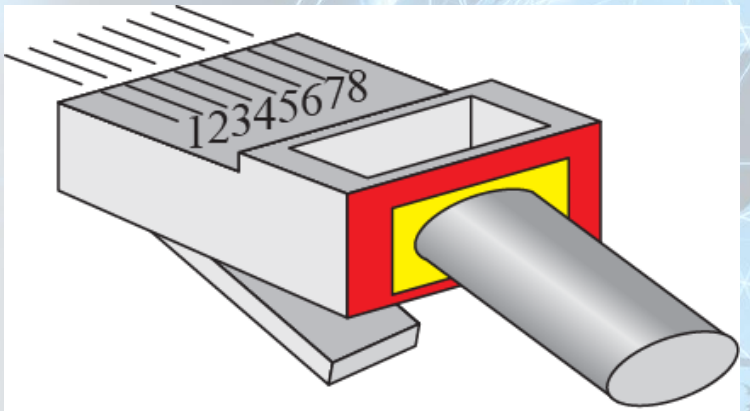
Categories of Unshielded Twisted-Pair Cables

Category	*Specification*	*Data Rate (Mbps)*	*Use*
1	Unshielded twisted-pair used in telephone	< 0.1	Telephone
2	Unshielded twisted-pair originally used in T lines	2	T-1 lines
3	Improved CAT 2 used in LANs	10	LANs
4	Improved CAT 3 used in Token Ring networks	20	LANs
5	Cable wire is normally 24 AWG with a jacket and outside sheath	100	LANs
5E	An extension to category 5 that includes extra features to minimize the crosstalk and electromagnetic interference	125	LANs
6	A new category with matched components coming from the same manufacturer. The cable must be tested at a 200-Mbps data rate.	200	LANs
7	Sometimes called *SSTP (shielded screen twisted-pair)*. Each pair is individually wrapped in a helical metallic foil followed by a metallic foil shield in addition to the outside sheath. The shield decreases the effect of crosstalk and increases the data rate.	600	LANs

UTP Connectors

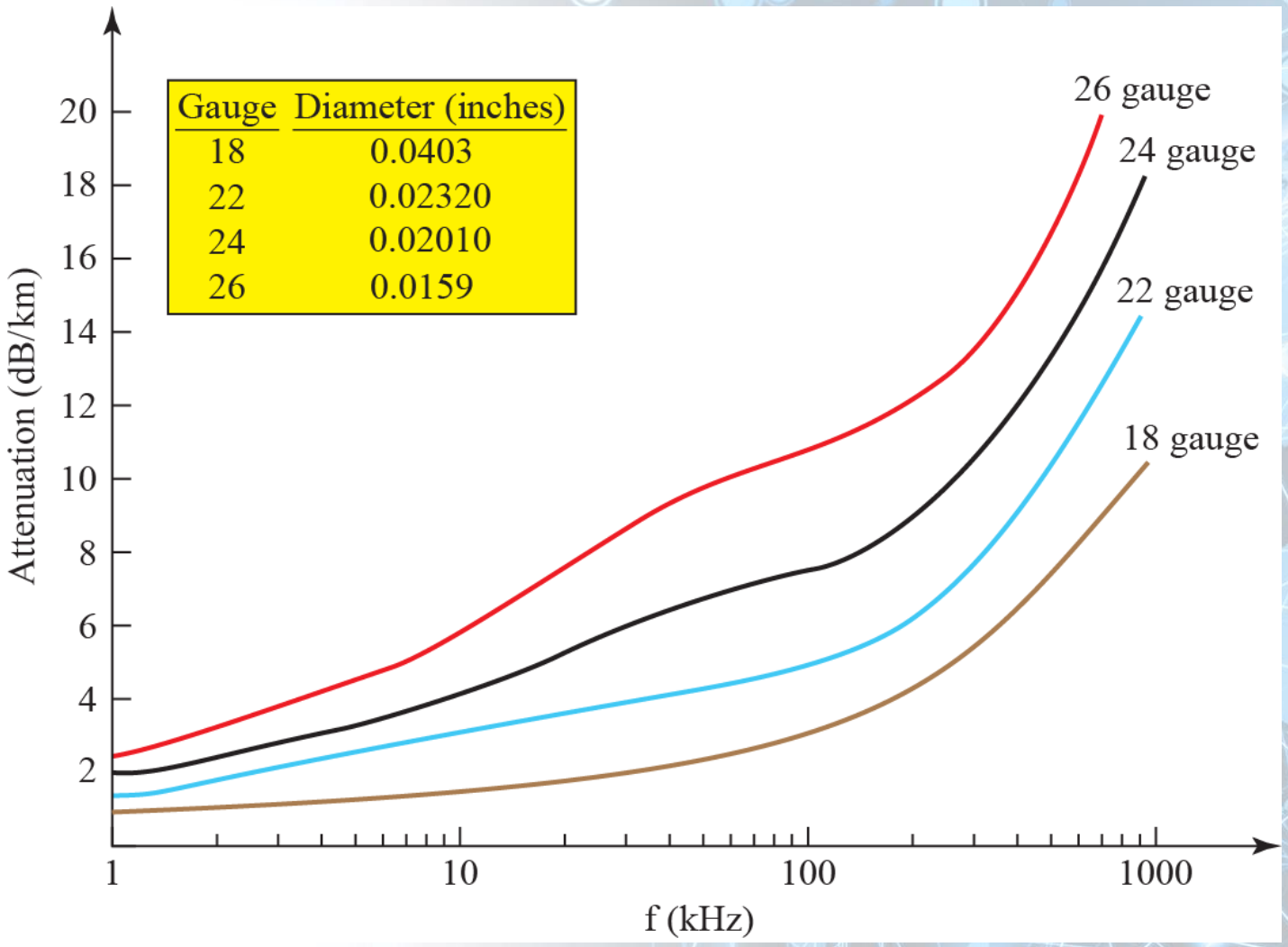


RJ-45 Female



RJ-45 Male

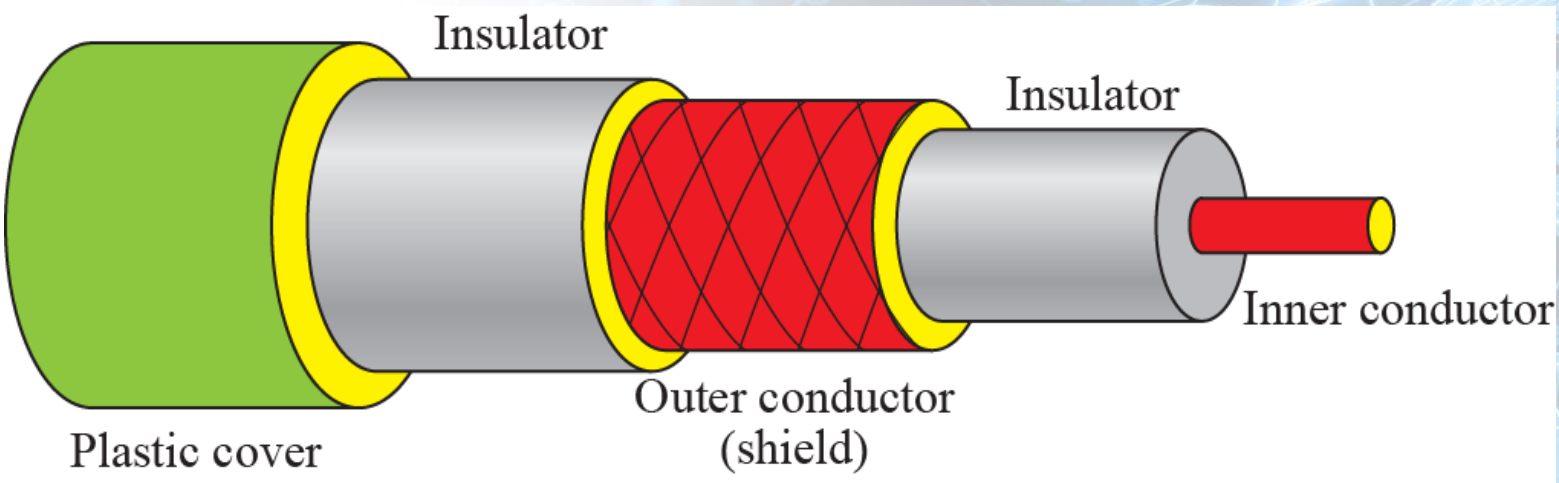
UTP Performance



Coaxial Cable

- Carries signals of higher frequency ranges than those in twisted pair cable

Coaxial Cable



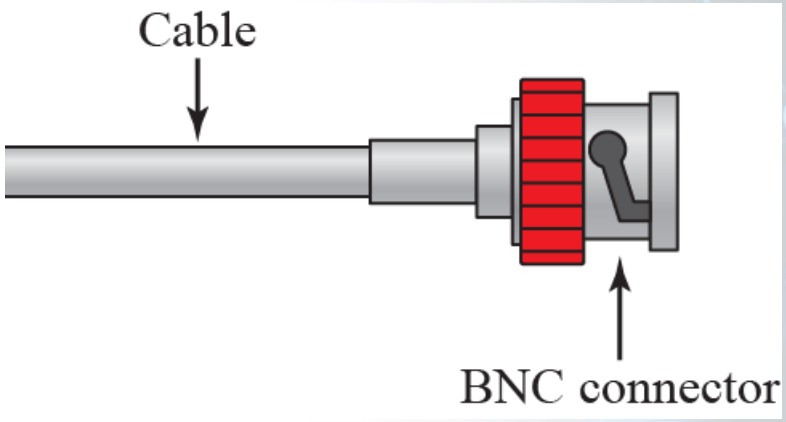
Categories of Coaxial Cables

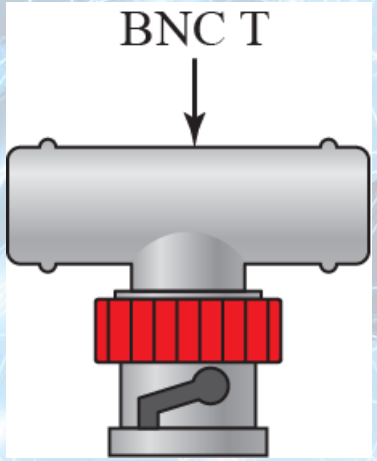
Category	*Impedance*	*Use*
RG-59	75 Ω	Cable TV
RG-58	50 Ω	Thin Ethernet
RG-11	50 Ω	Thick Ethernet

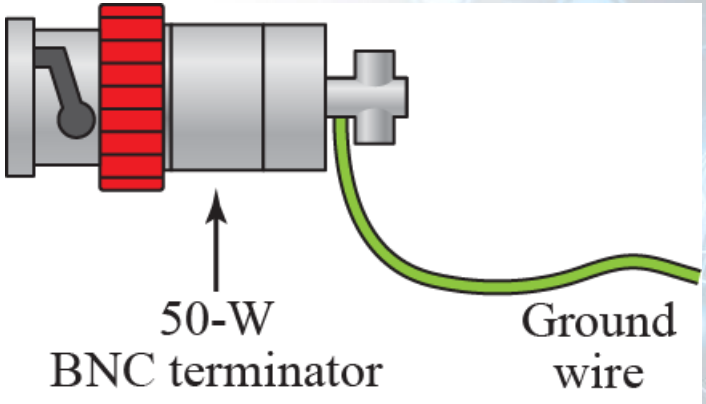
Coaxial Cable

- Carries signals of higher frequency ranges than those in twisted pair cable

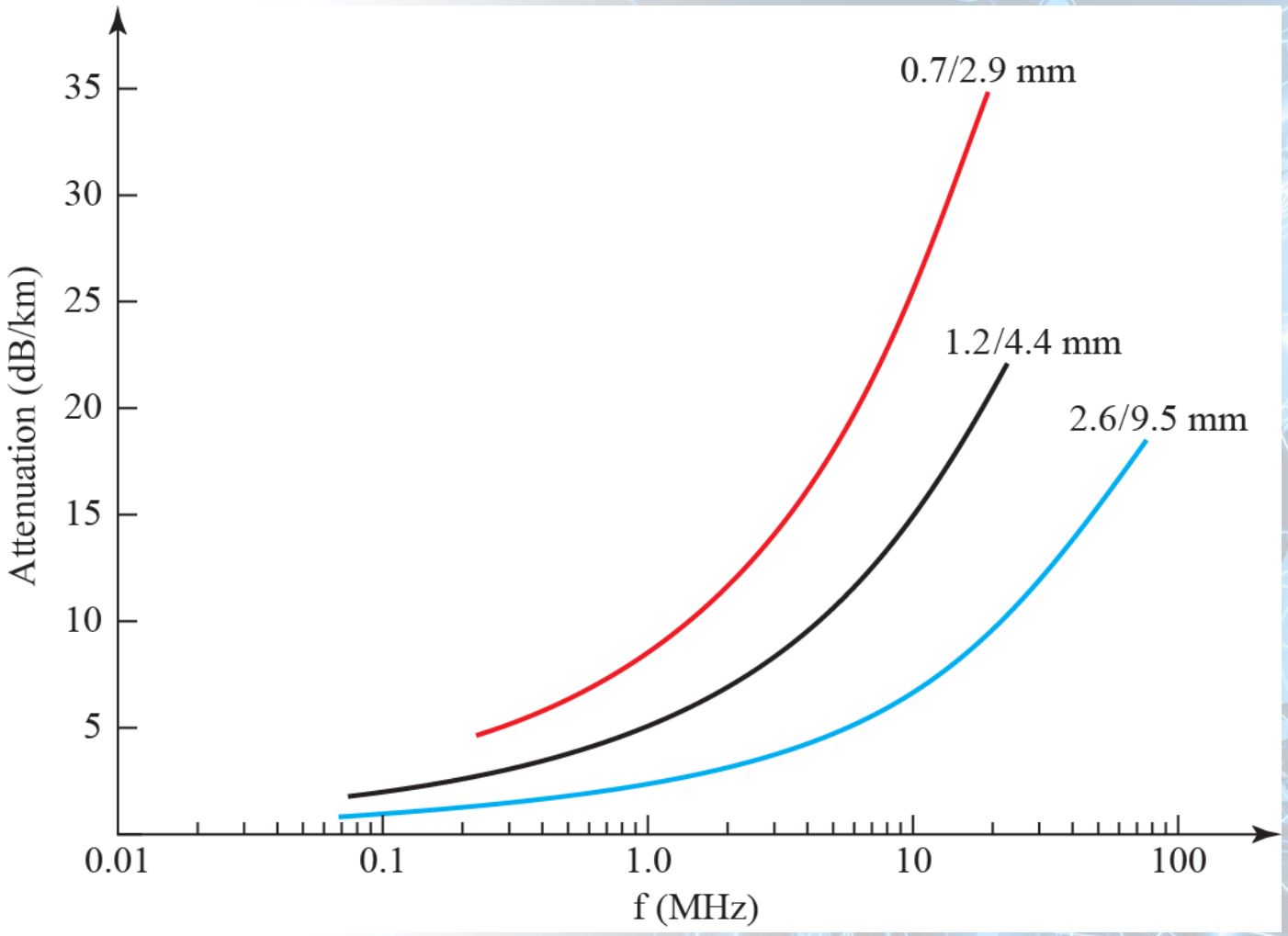
BNC Connectors







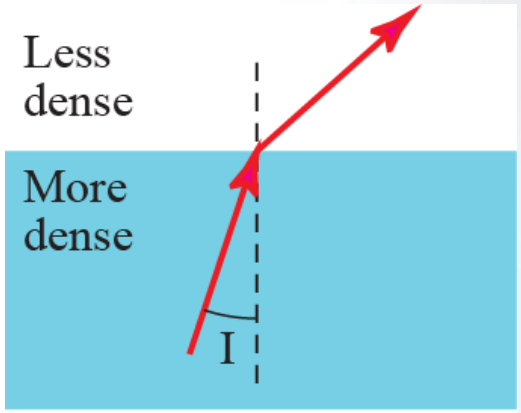
Coaxial Cable Performance



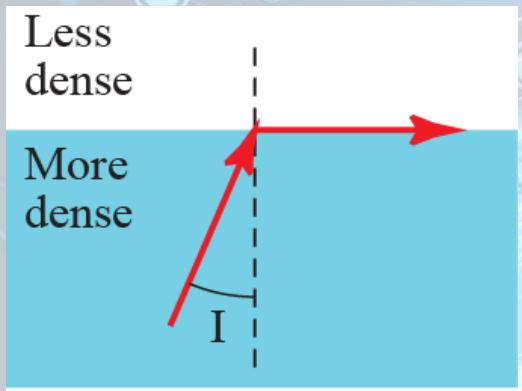
Fiber-Optic Cable

- Made of glass or plastic and transmits signals in the form of light
- Light travels in a straight line as long as it is moving through a single uniform substance
- If a ray of light traveling through one substance suddenly enters another substance (of a different density), the ray changes direction

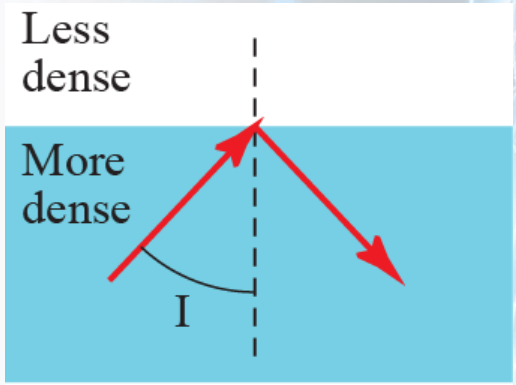
Bending of Light Ray



I < critical angle,
refraction



I = critical angle,
refraction

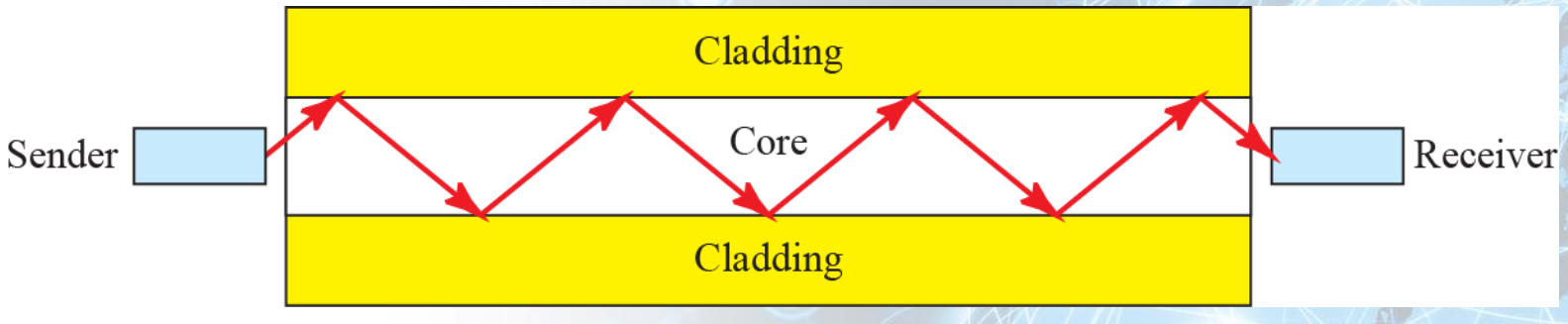


I > critical angle,
reflection

Fiber-Optic Cable

- Made of glass or plastic and transmits signals in the form of light

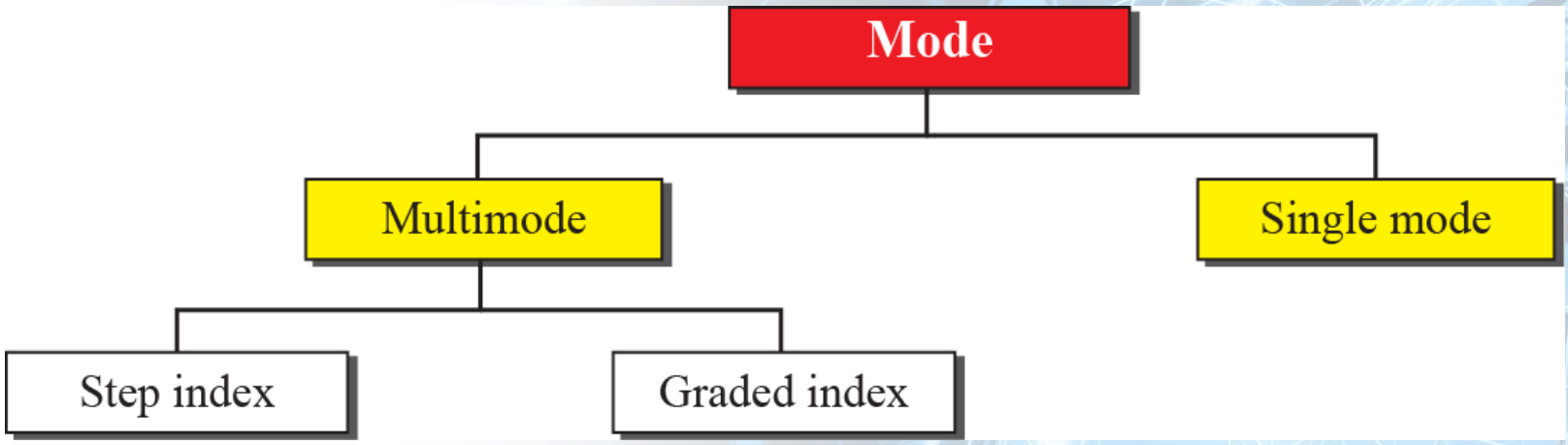
Optical Fiber



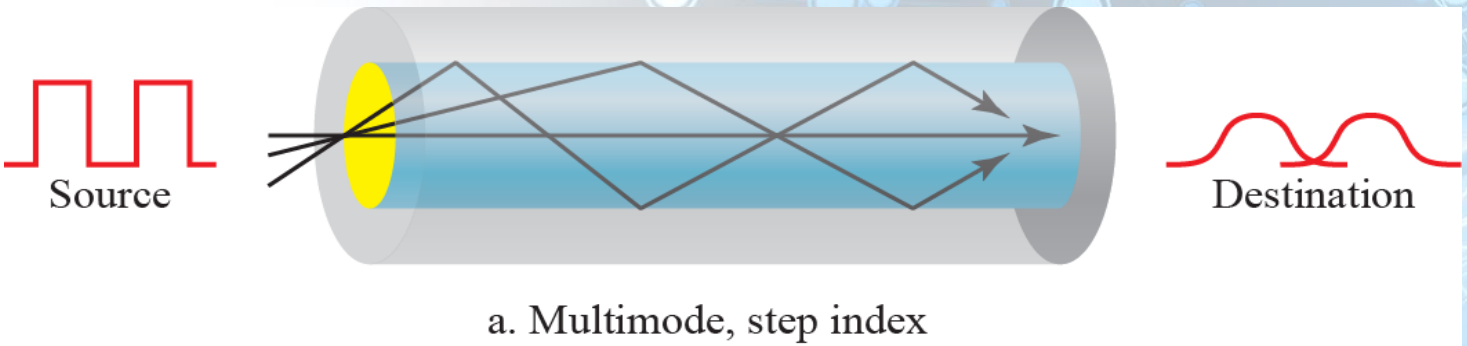
Fiber-Optic Cable

- Made of glass or plastic and transmits signals in the form of light

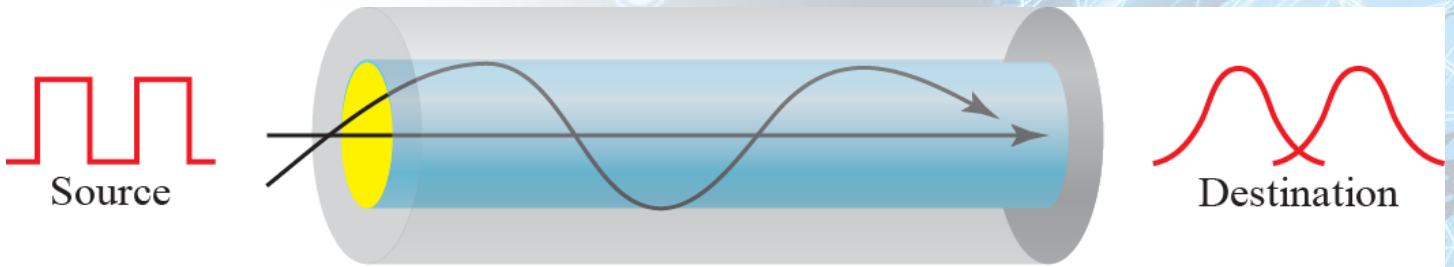
Propagation Modes



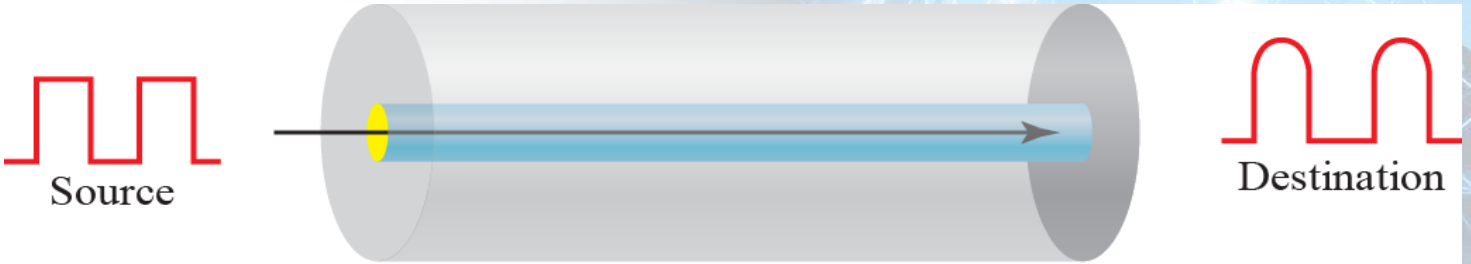
Modes



a. Multimode, step index



b. Multimode, graded index



c. Single mode

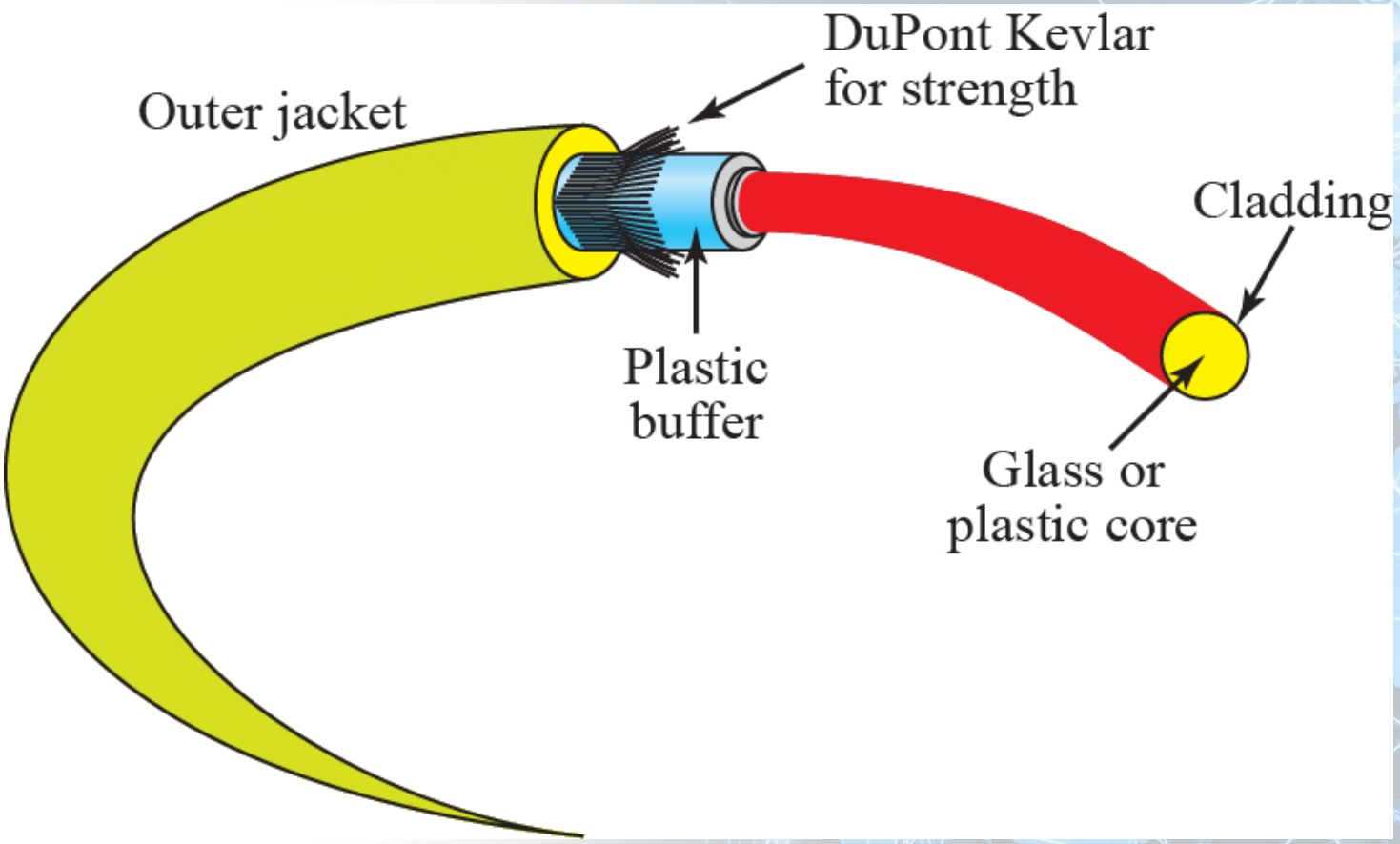
Fiber-Optic Cable

- Made of glass or plastic and transmits signals in the form of light

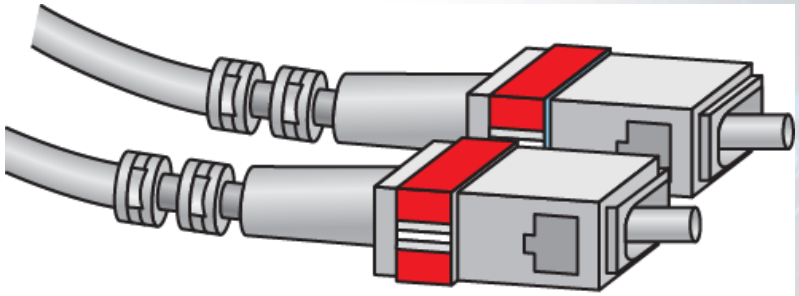
Fiber Types

Type	*Core (μm)*	*Cladding (μm)*	*Mode*
50/125	50.0	125	Multimode, graded index
62.5/125	62.5	125	Multimode, graded index
100/125	100.0	125	Multimode, graded index
7/125	7.0	125	Single mode

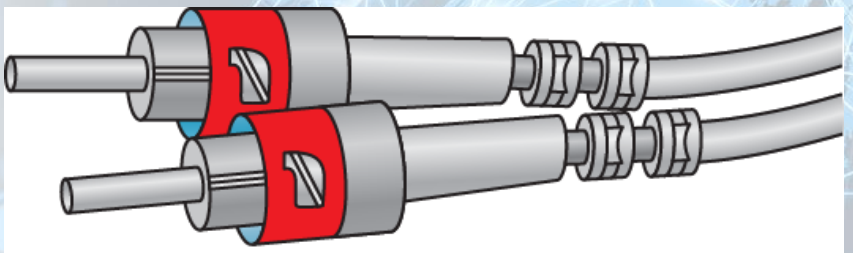
Fiber Composition



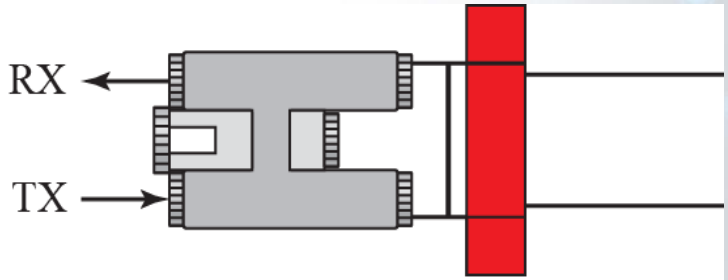
Fiber-Optic Cable Connector



SC connector

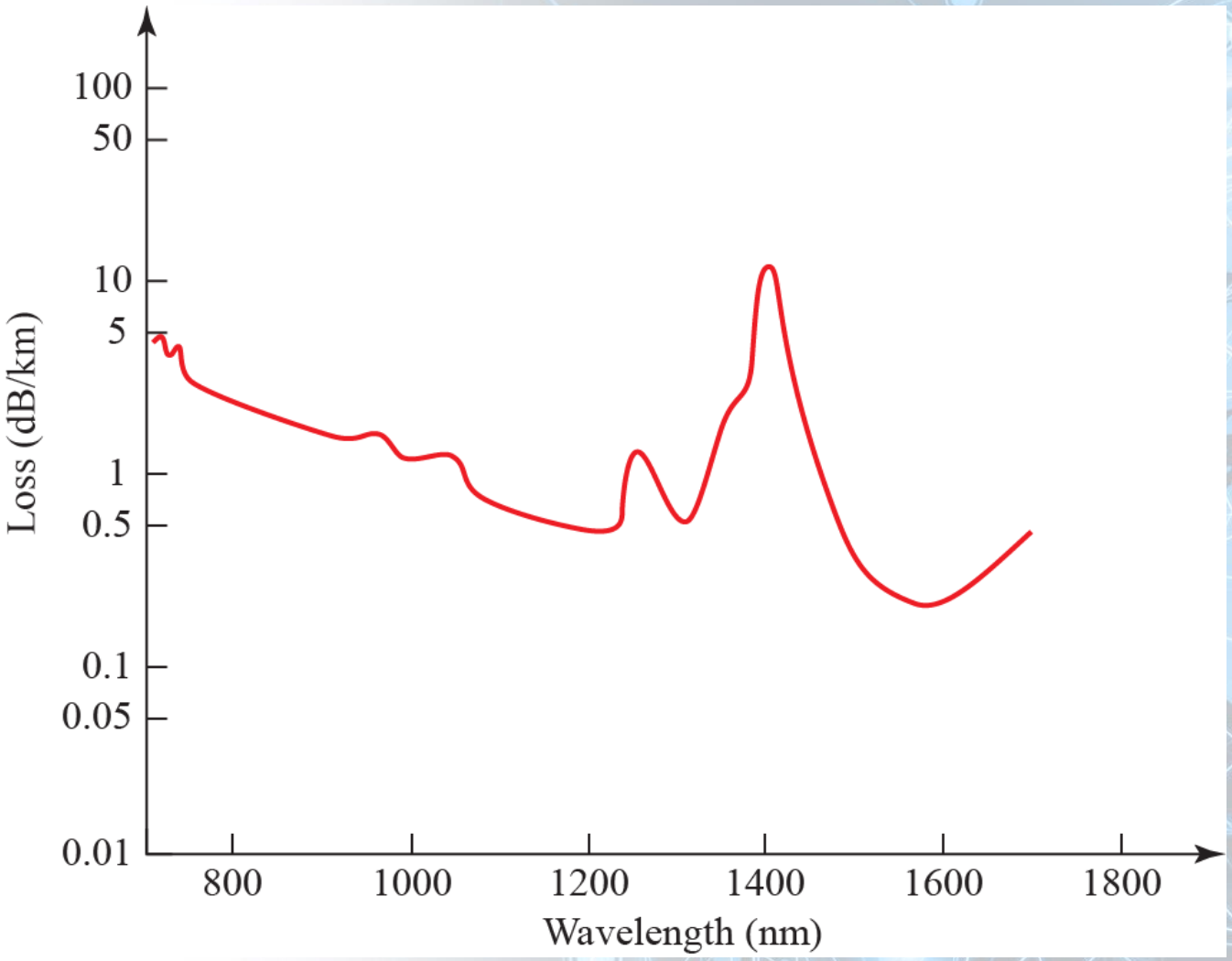


ST connector



MT-RJ connector

Optical Fiber Performance



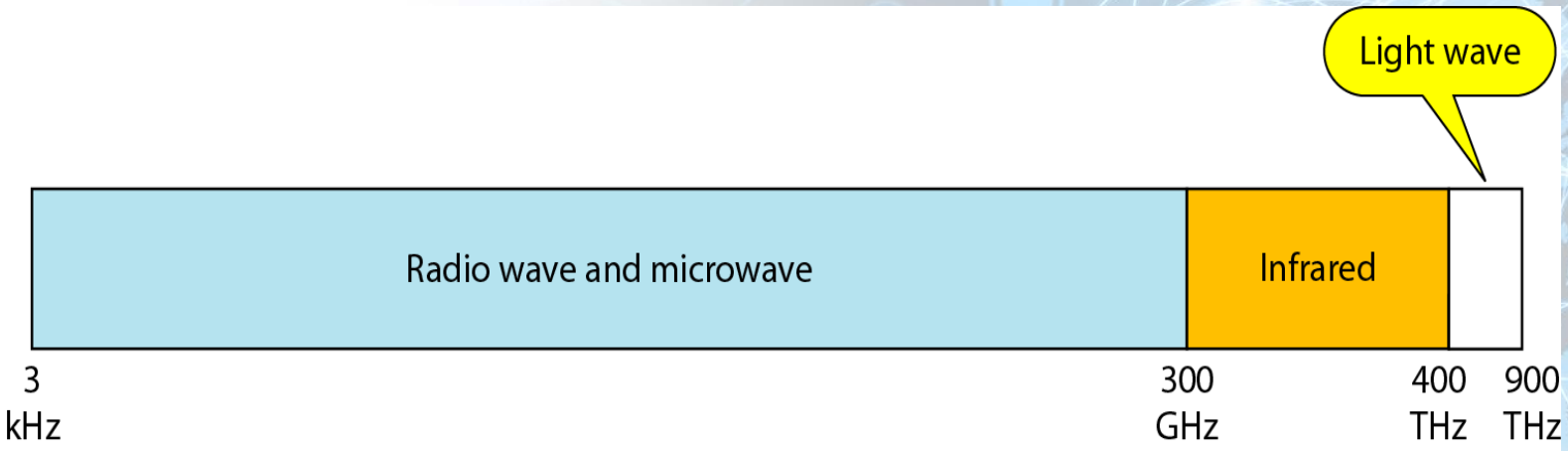
Advantages & Disadvantages

- Higher Bandwidth
- Less Attenuation
- Less EM Interference
- Light Weight
- Less corrosive than copper
- Installation/Maintenance
- Unidirectional
- Cost

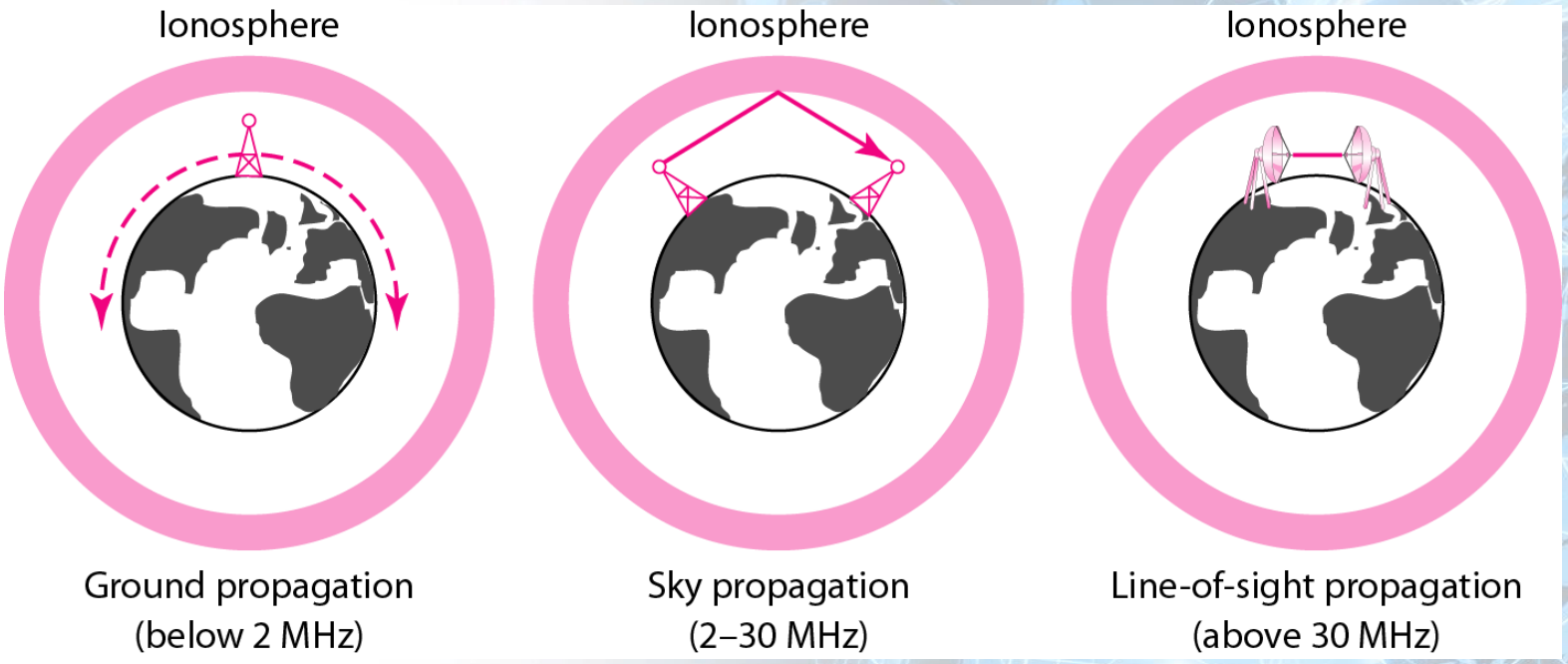
Unguided Media

- Unguided medium transport waves without using a physical conductor
- Often referred to wireless communication
- Signals are normally broadcast through free space and thus are available to anyone who has a device capable of receiving them

Electromagnetic Spectrum



Propagation Methods



Bands

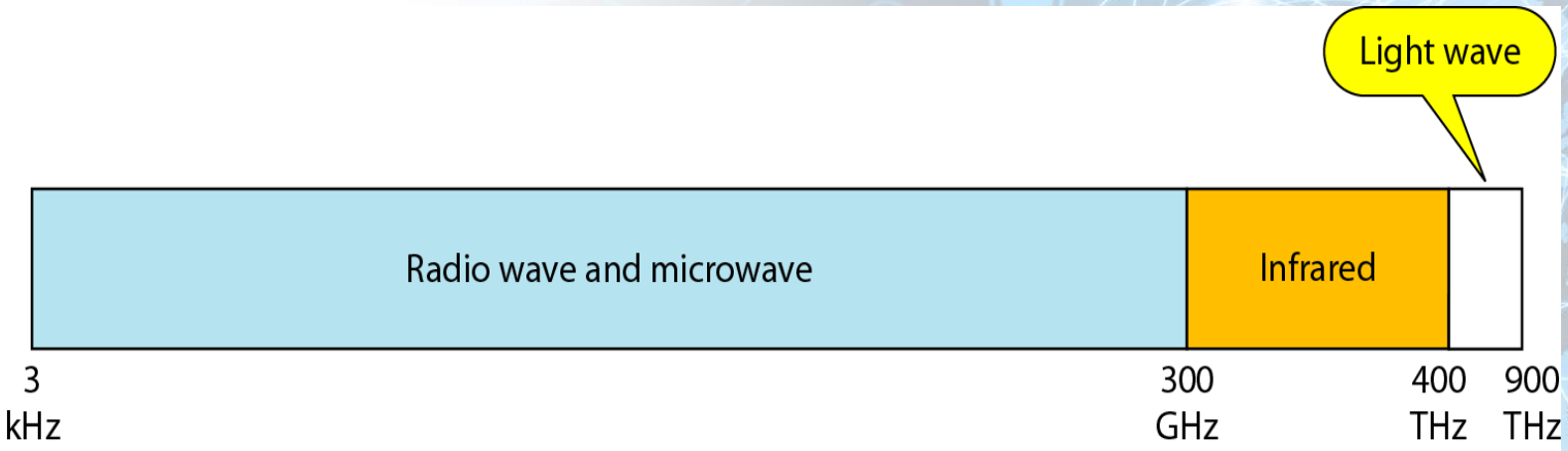
Band	*Range*	*Propagation*	*Application*
very low frequency (VLF)	3–30 kHz	Ground	Long-range radio navigation
low frequency (LF)	30–300 kHz	Ground	Radio beacons and navigational locators
middle frequency (MF)	300 kHz–3 MHz	Sky	AM radio
high frequency (HF)	3–30 MHz	Sky	Citizens band (CB), ship/aircraft
very high frequency (VHF)	30–300 MHz	Sky and line-of-sight	VHF TV, FM radio
ultrahigh frequency (UHF)	300 MHz–3 GHz	Line-of-sight	UHF TV, cellular phones, paging, satellite
superhigh frequency (SF)	3–30 GHz	Line-of-sight	Satellite
extremely high frequency (EHF)	30–300 GHz	Line-of-sight	Radar, satellite

Radio Waves

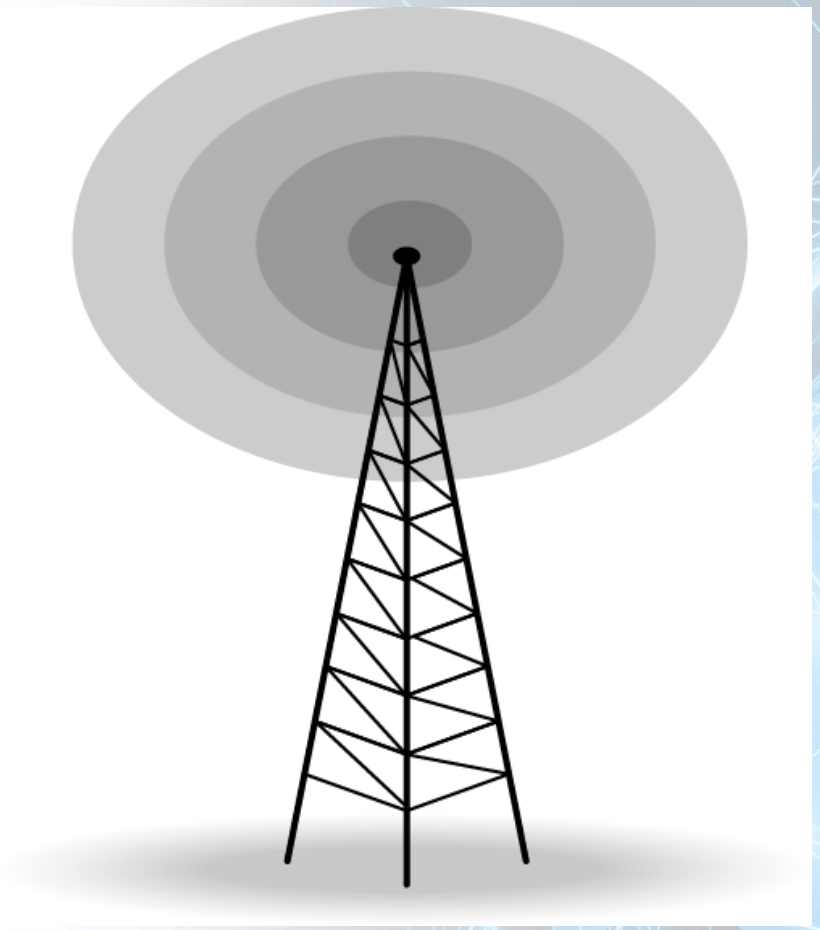
- Electromagnetic waves ranging in frequencies between 3 kHz and 1 GHz are normally called radio waves

- Electromagnetic waves ranging in frequencies between 1 and 300 GHz are called microwaves

Electromagnetic Spectrum



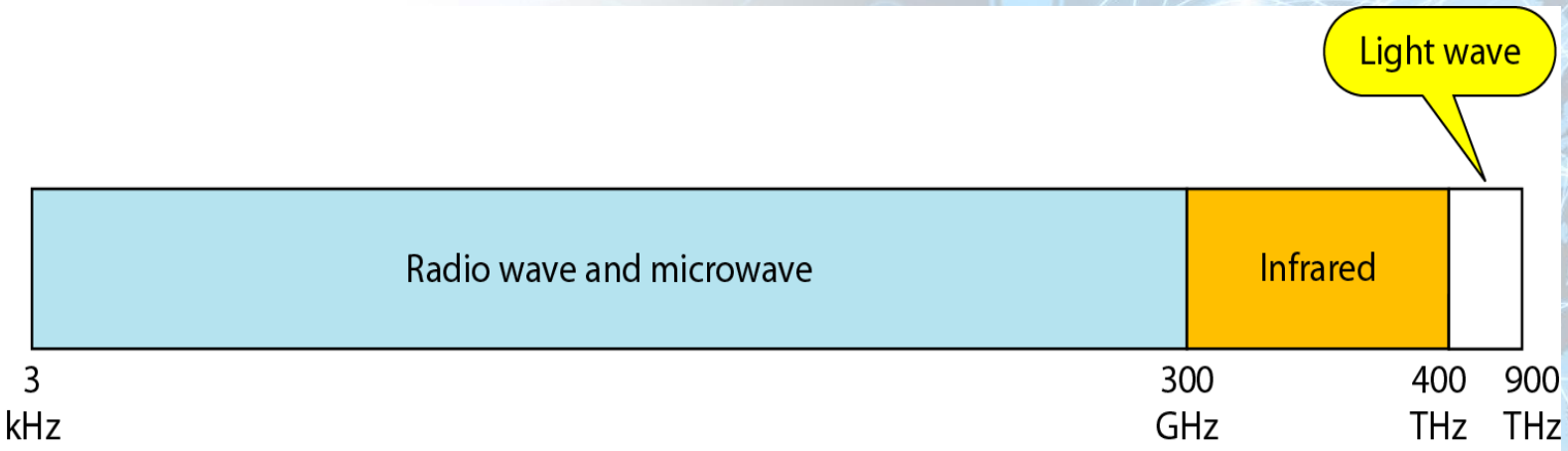
Omnidirectional Antenna



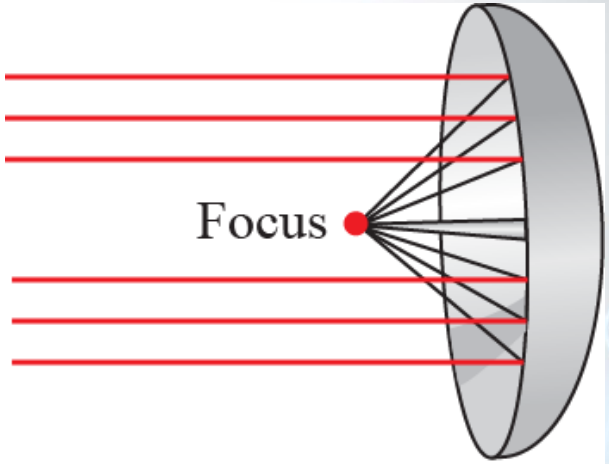
Microwaves

- Electromagnetic waves having frequencies between 1 and 300 GHz are called microwaves
- Microwaves are unidirectional
- When an antenna transmits microwaves, they can be narrowly focused

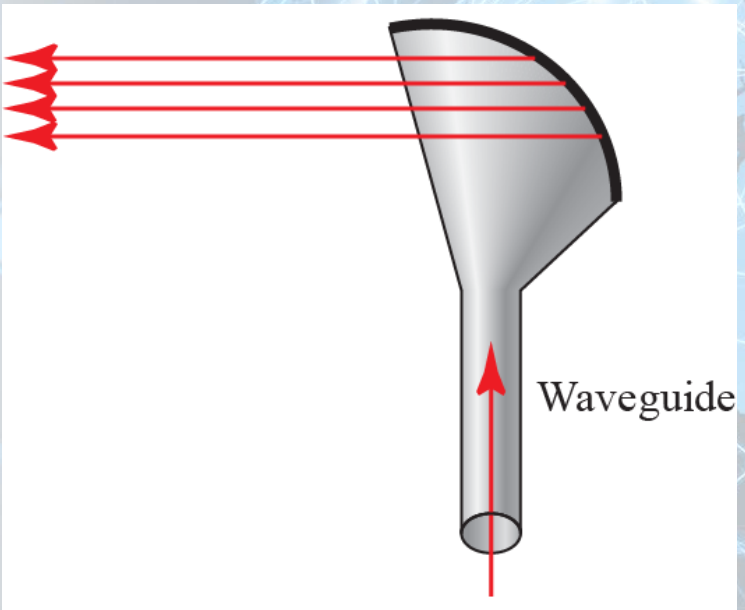
Electromagnetic Spectrum



Unidirectional Antennas



a. Parabolic dish antenna



b. Horn antenna

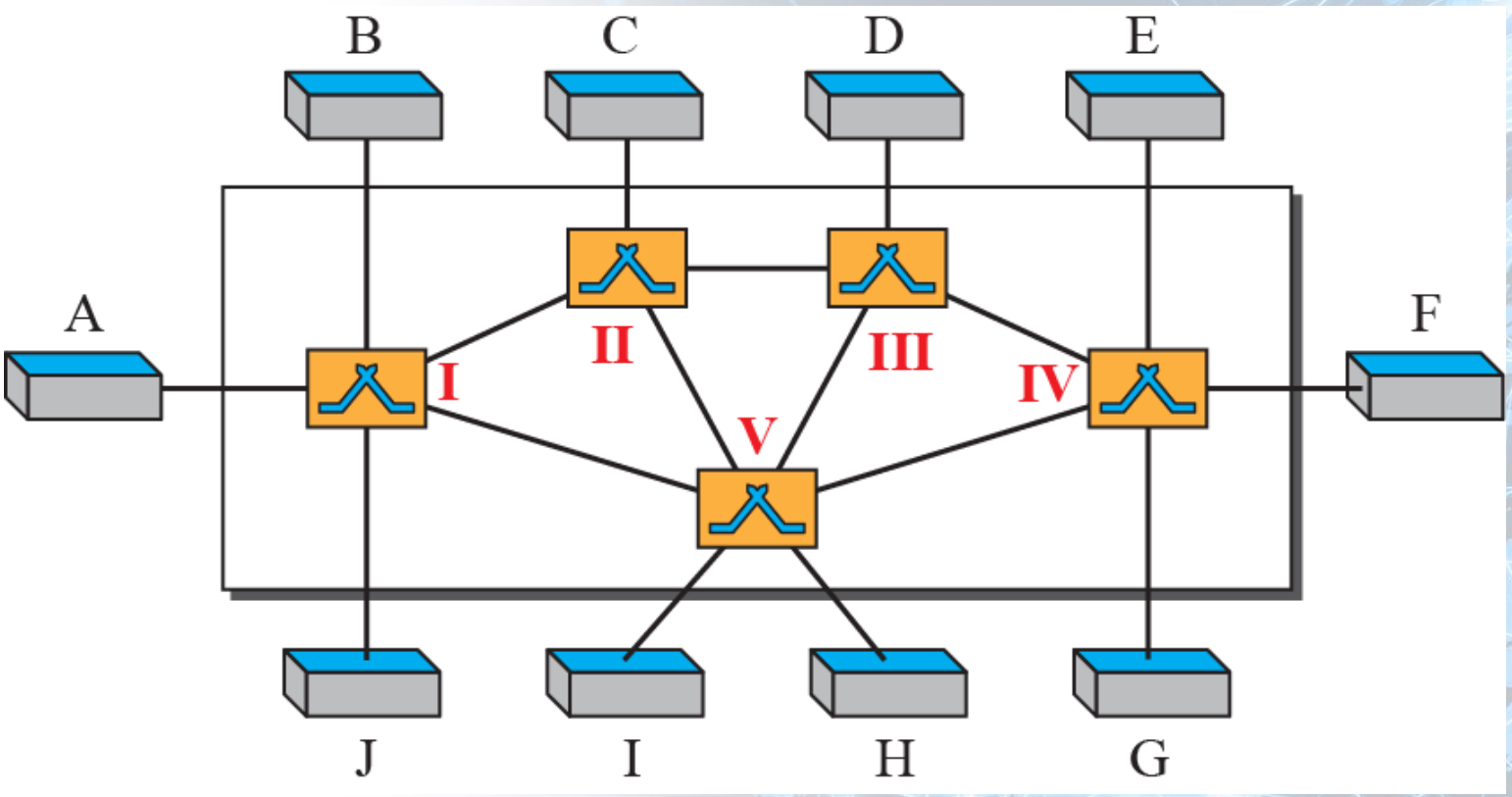
Infrared

- Infrared waves, with frequencies from 300 GHz to 400 THz (wavelengths from 1 mm to 770 nm), can be used for short-range communication
- Infrared waves, having high frequencies, cannot penetrate walls
- Prevents interference between one system and another

Switching

- A network is a set of connected devices
- Problem of how to connect multiple devices to make one-to-one communication possible
- The solution is Switching
- Switched network consists of a series of switches

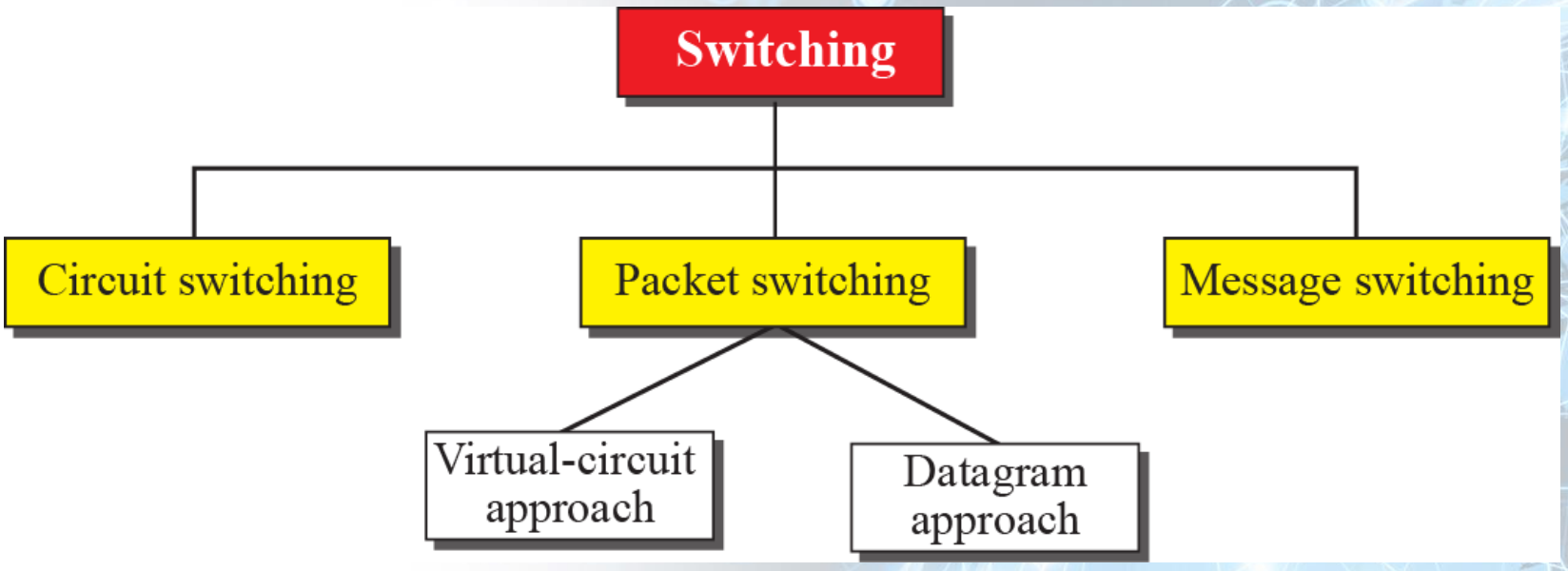
Switched Network



Three Methods of Switching

- Three Methods:
  - ✓ Circuit Switching
  - ✓ Packet Switching
  - ✓ Message switching
- The first two are commonly used today
- The third has been phased out in general communications

Taxonomy of Switched Networks



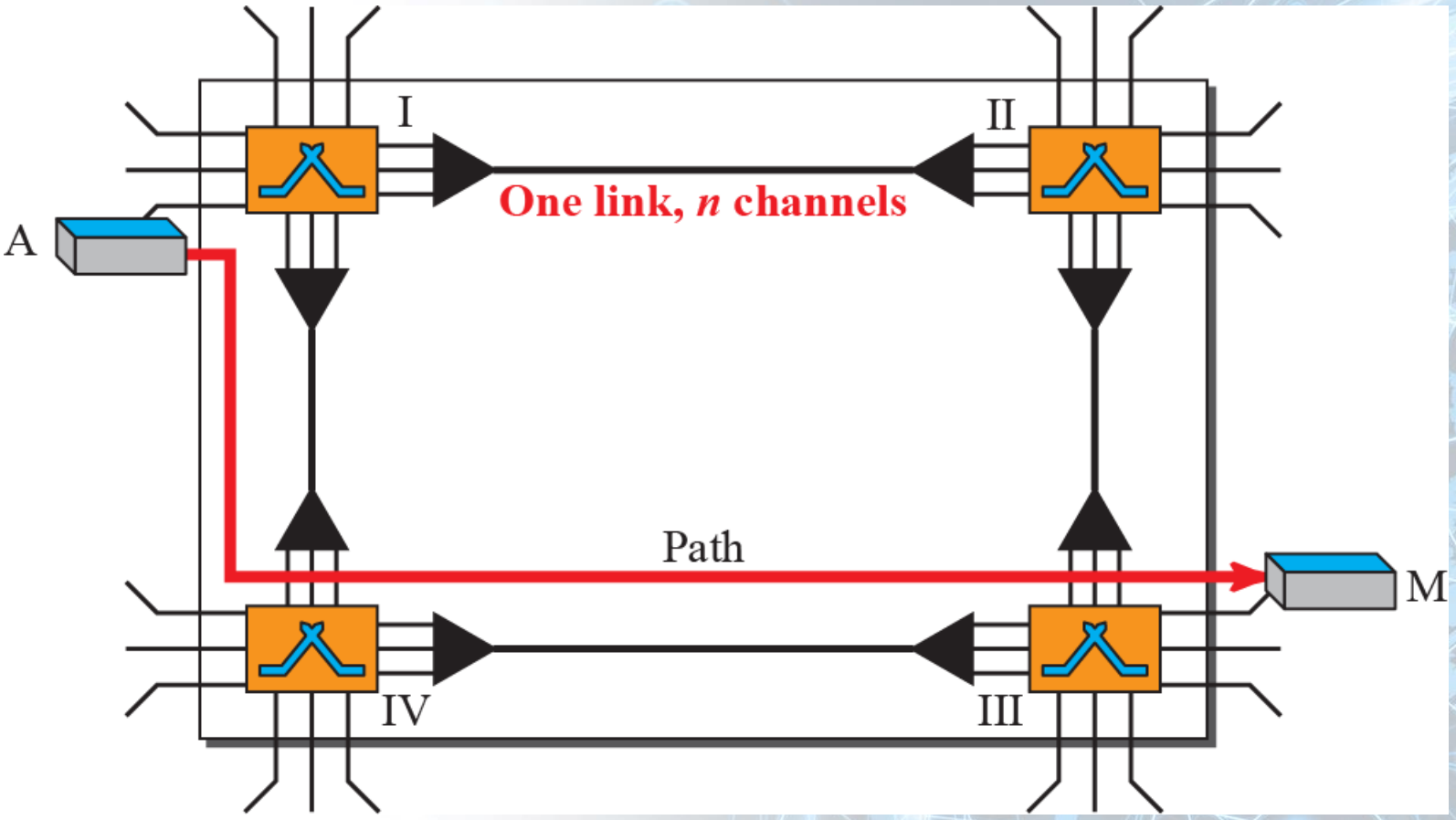
Circuit-switched Networks

- A set of switches connected by physical links
- A connection between two stations is a dedicated path made of one or more links
- Each connection uses only one dedicated channel on each link
- Each link is normally divided into n channels by using FDM or TDM

Circuit-switched Networks

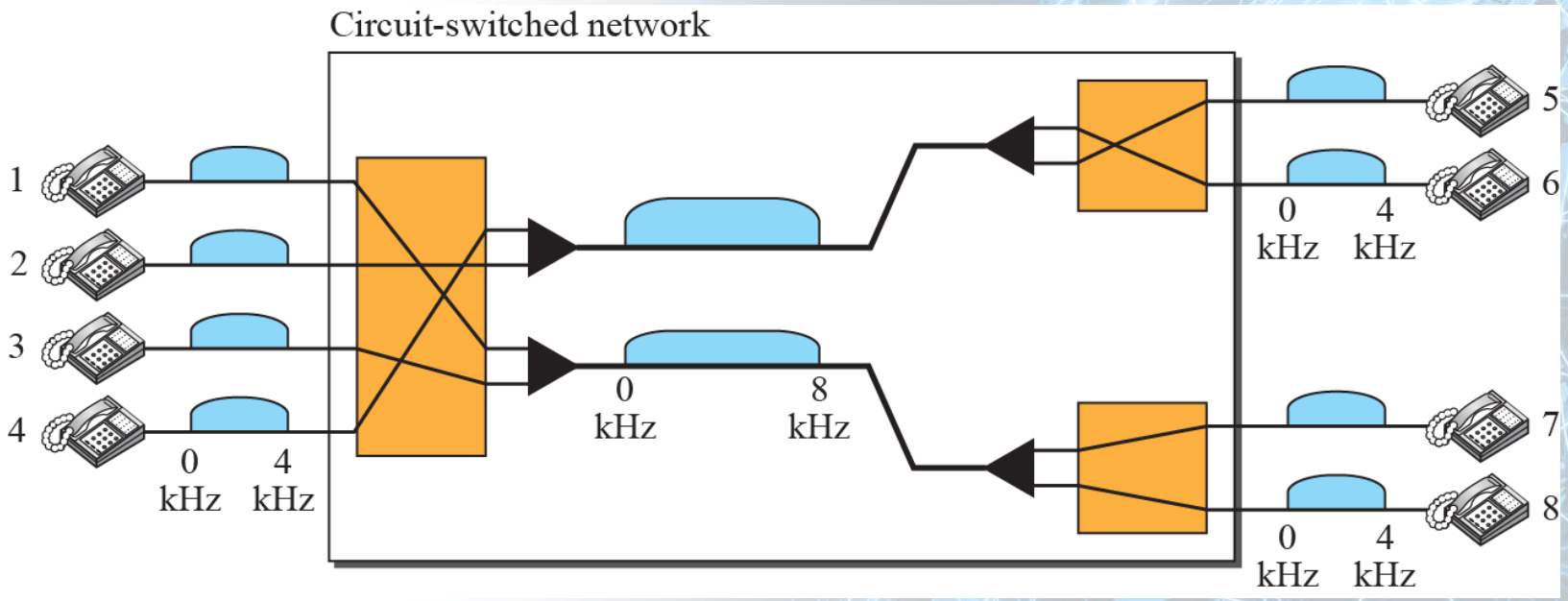
- A set of switches connected by physical links

A Circuit-Switched Network



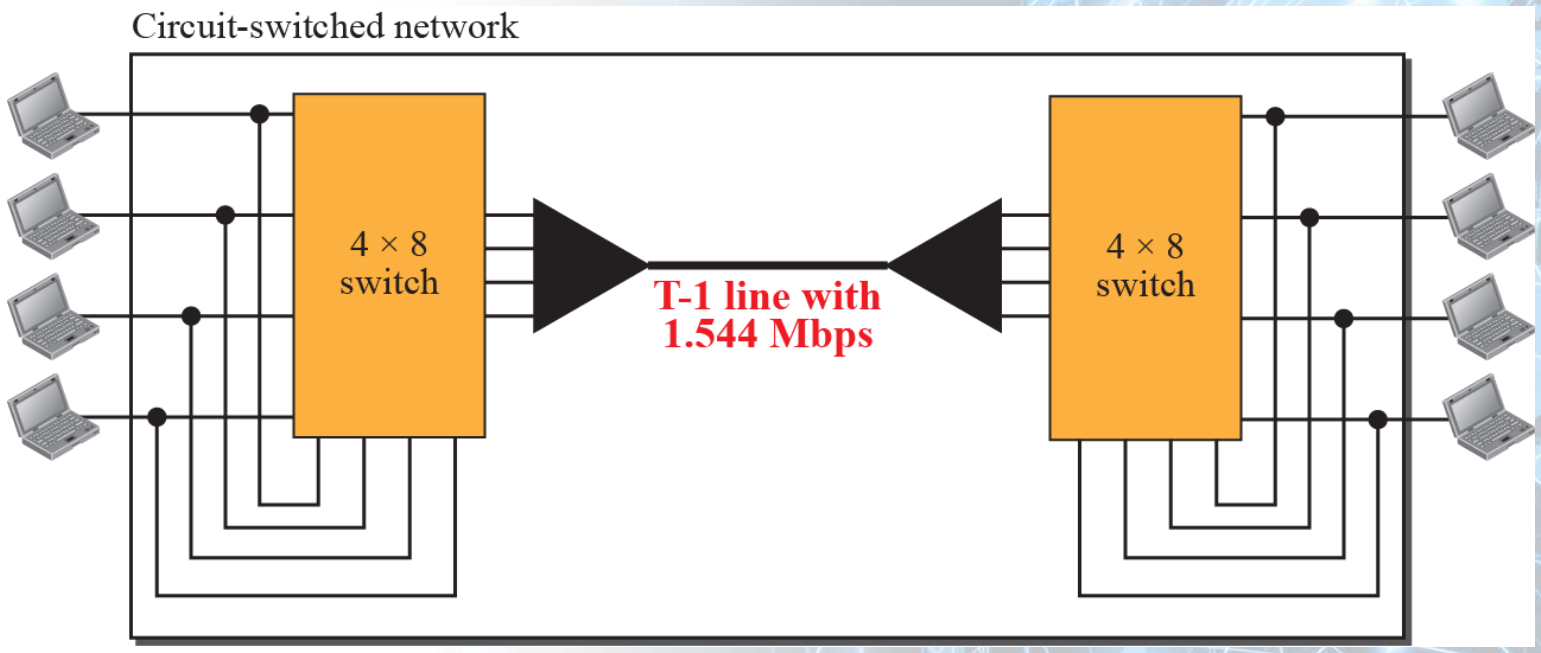
Example

As a trivial example, let us use a circuit-switched network to connect eight telephones in a small area. Communication is through 4-kHz voice channels. We assume that each link uses FDM to connect a maximum of two voice channels. The bandwidth of each link is then 8 kHz.



Example

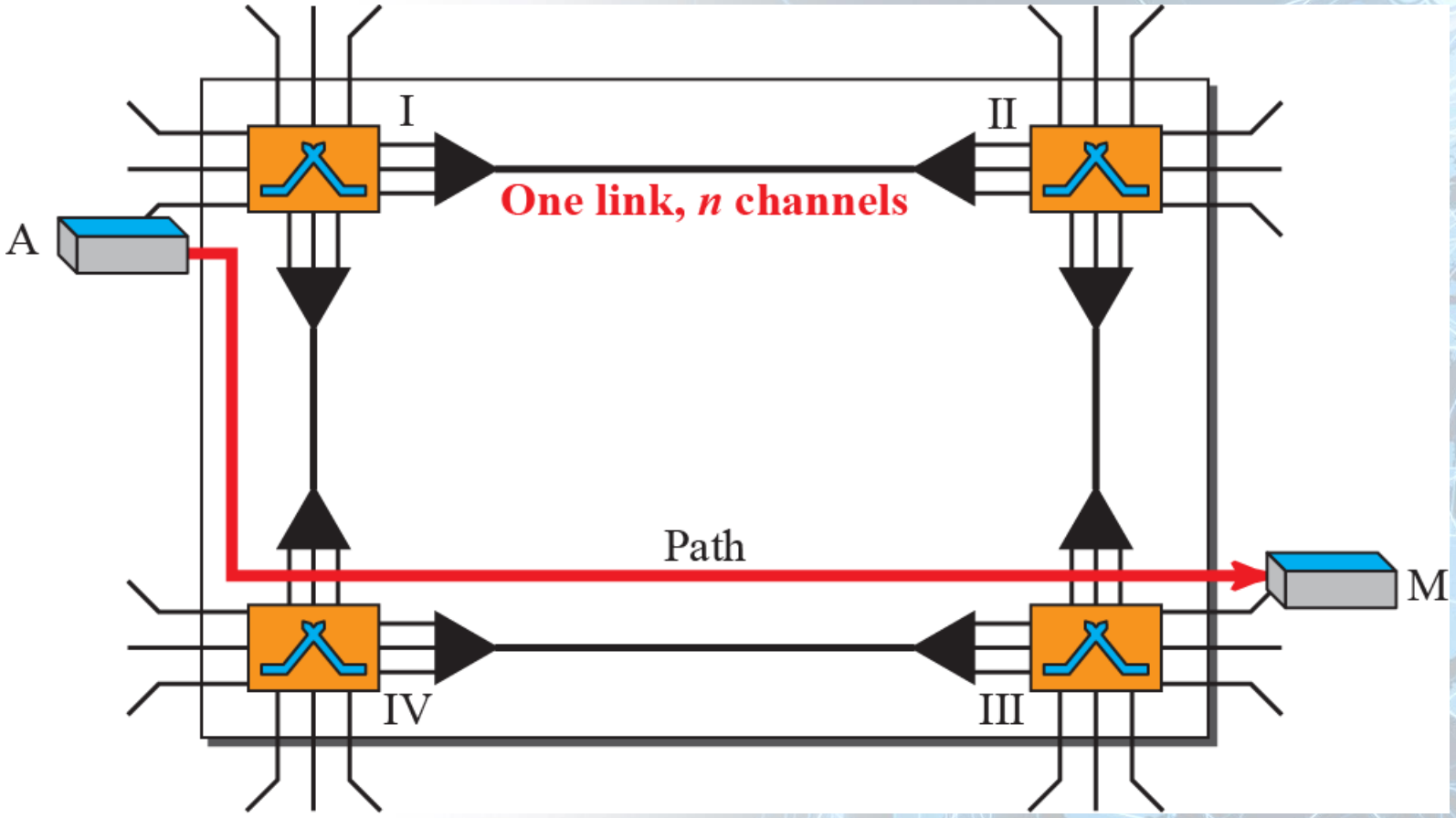
As another example, consider a circuit-switched network that connects computers in two remote offices of a private company. The offices are connected using a T-1 line leased from a communication service provider. There are two 4 × 8 (4 inputs and 8 outputs) switches in this network.



Three Phases in a Circuit Switched Network

- The actual communication in a circuit-switched network requires 3 phases:
  - ✓ Connection Setup
  - ✓ Data Transfer
  - ✓ Connection Teardown

Three Phases in a Circuit Switched Network



Efficiency of a Circuit-Switched Network

- Not as efficient as packet switching because resources are allocated during the entire duration of the connection and these resources are unavailable to other connections

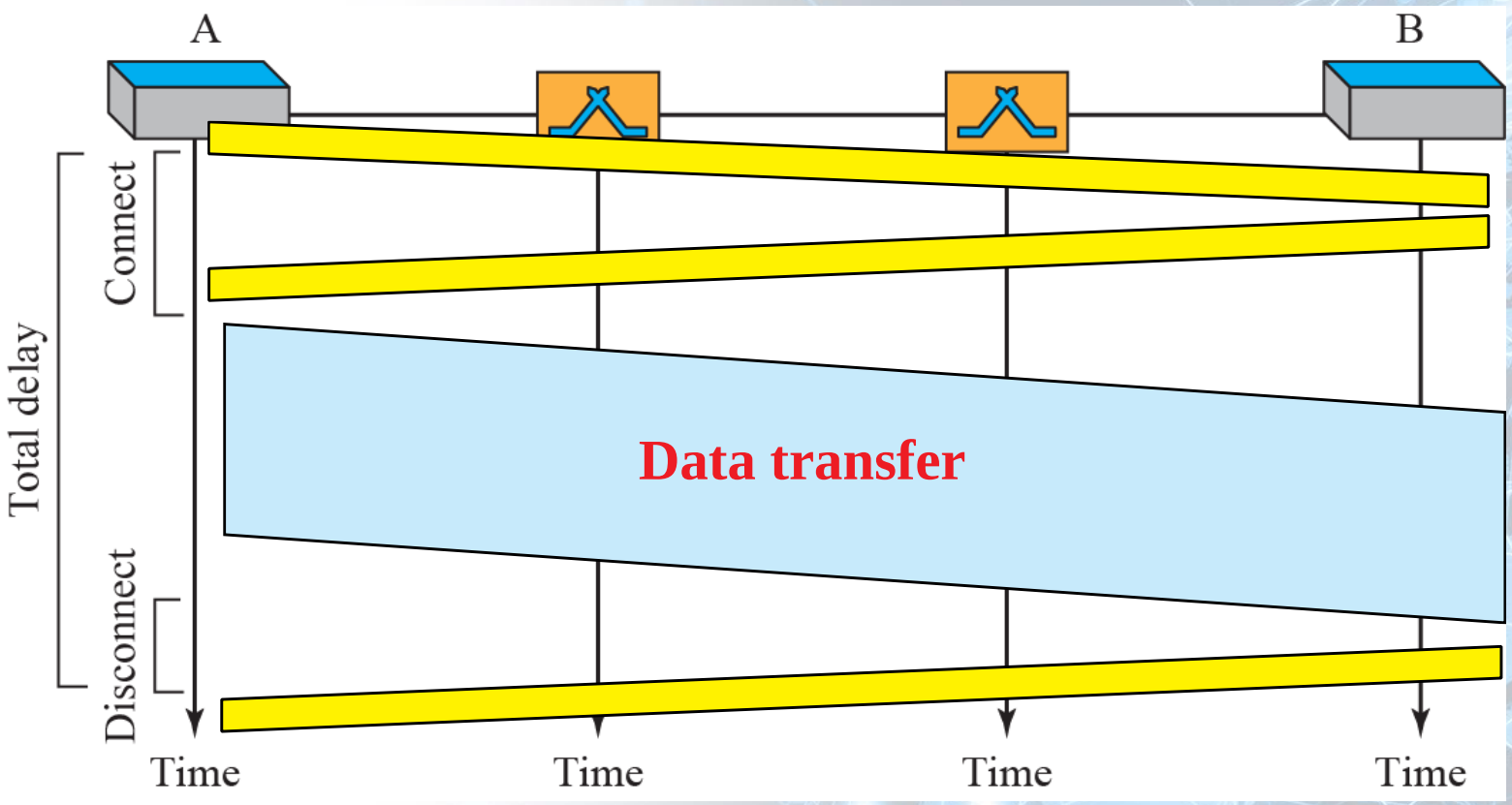
Efficiency of a Circuit-Switched Network

- In a telephone network, people normally terminate the communication when they have finished their conversation
- Data Network is an issue

Delay in a Circuit-Switched Network

- Circuit switched networks have low efficiency but minimal delay
- Data is not delayed at each switch; the resources are allocated for the duration of the connection

Delay in a Circuit-Switched Network



Packet Switching

- If the message is going to pass through a packet-switched network, it needs to be divided into packets of fixed or variable size
- The size of the packet is determined by the network and the governing protocol

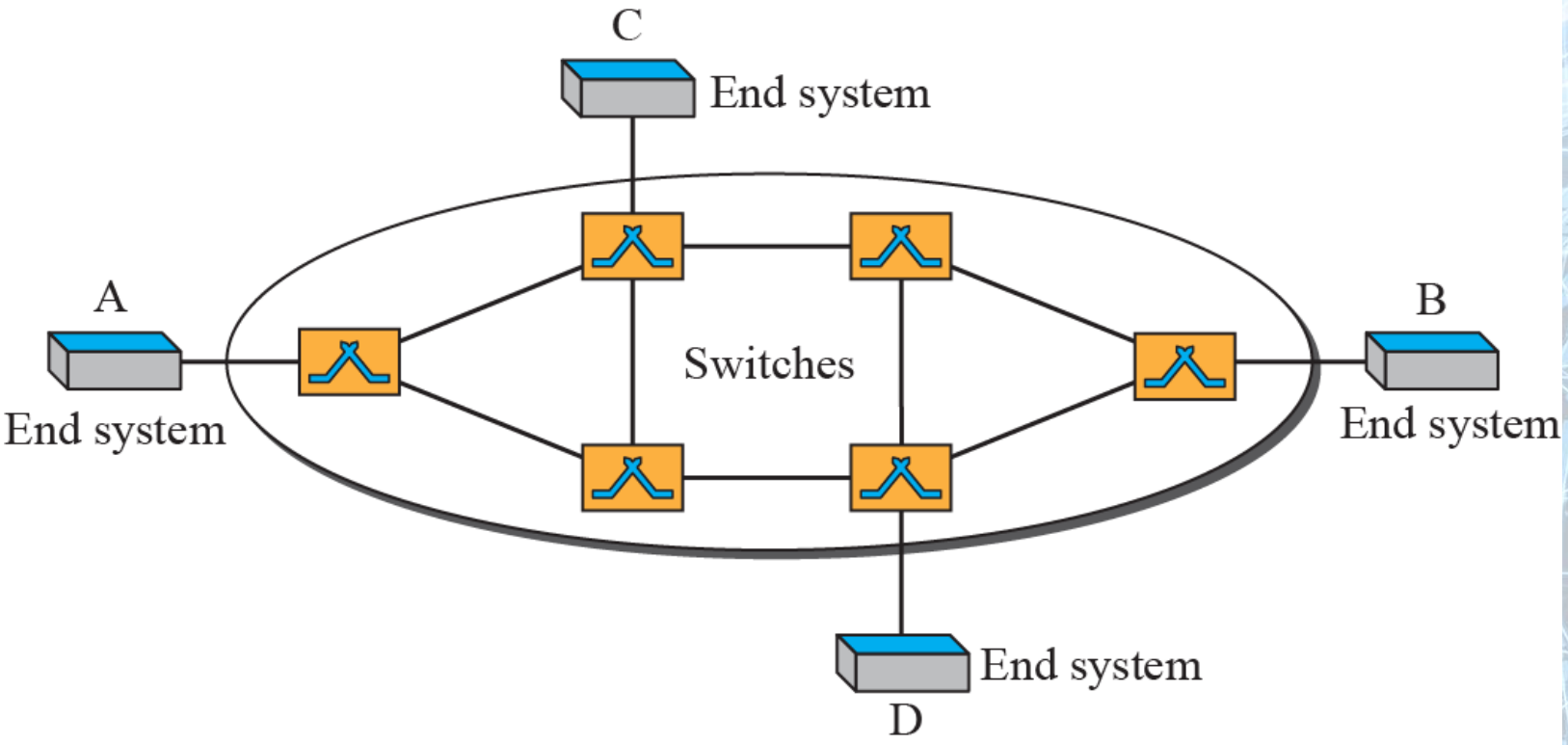
Datagram Networks

- Each packet is treated independently of all others.
- Even if a packet is part of a multi-packet transmission, the network treats it as though it existed alone
- Packets are referred to as datagrams

Virtual-Circuit Networks

- **A virtual-circuit network is a cross between a circuit-switched network and a datagram network**

Virtual-circuit network



Virtual-Circuit Networks

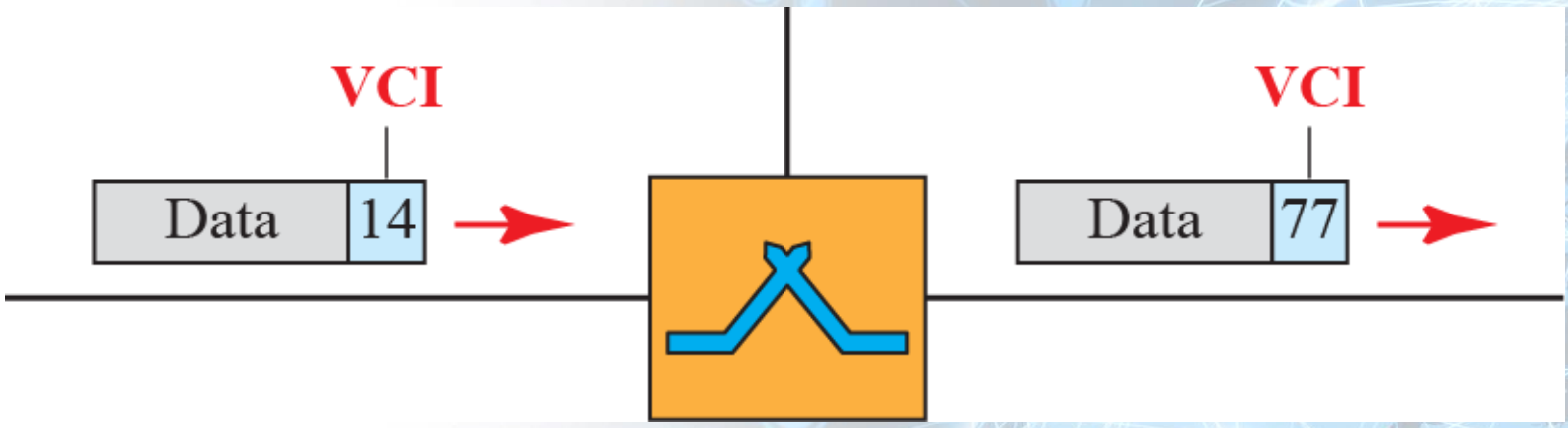
- **A virtual-circuit network is a cross between a circuit-switched network and a datagram network**

Virtual-Circuit Networks

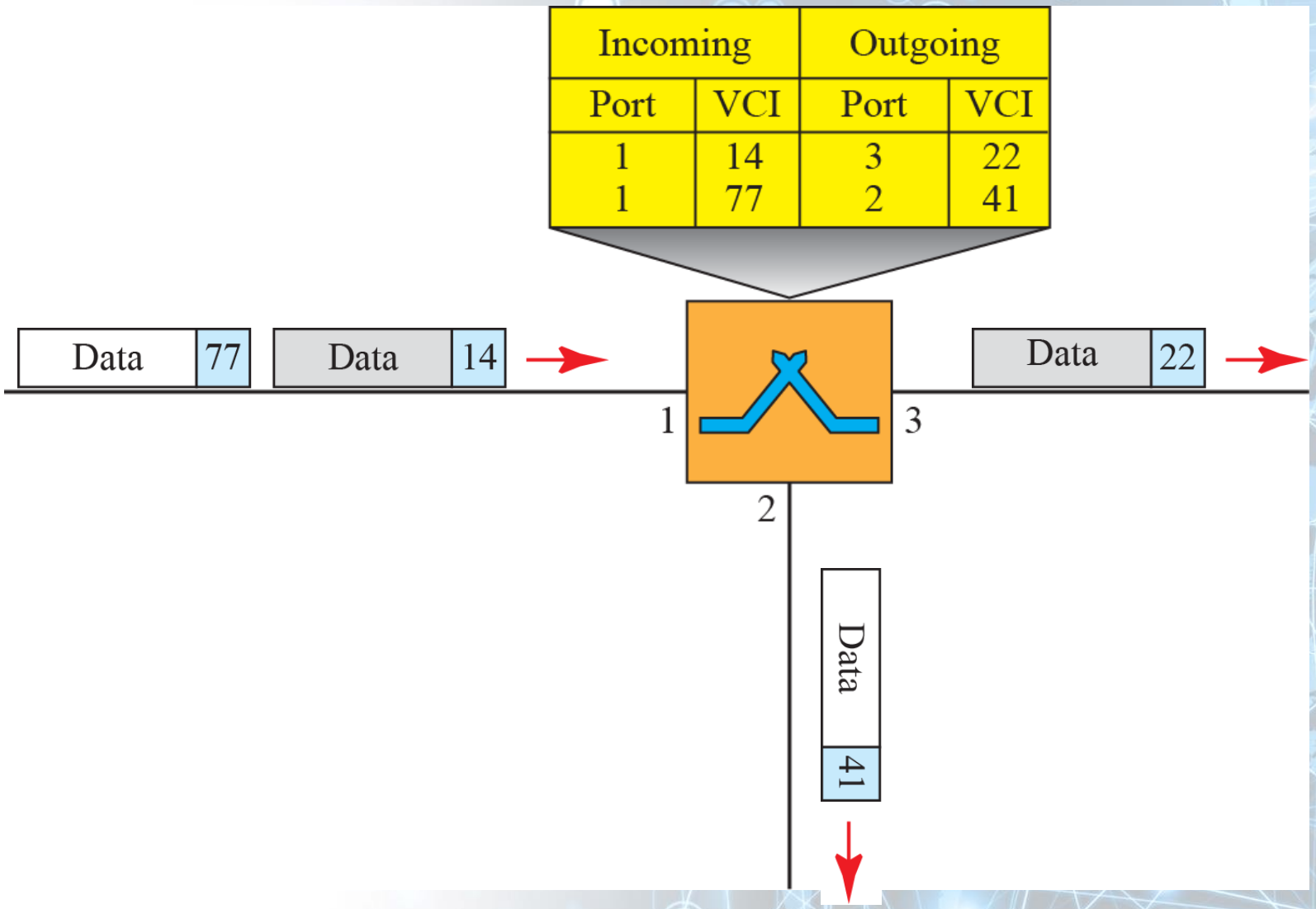
Virtual-Circuit Networks

- **A virtual-circuit network is a cross between a circuit-switched network and a datagram network**

Virtual-Circuit Identifier



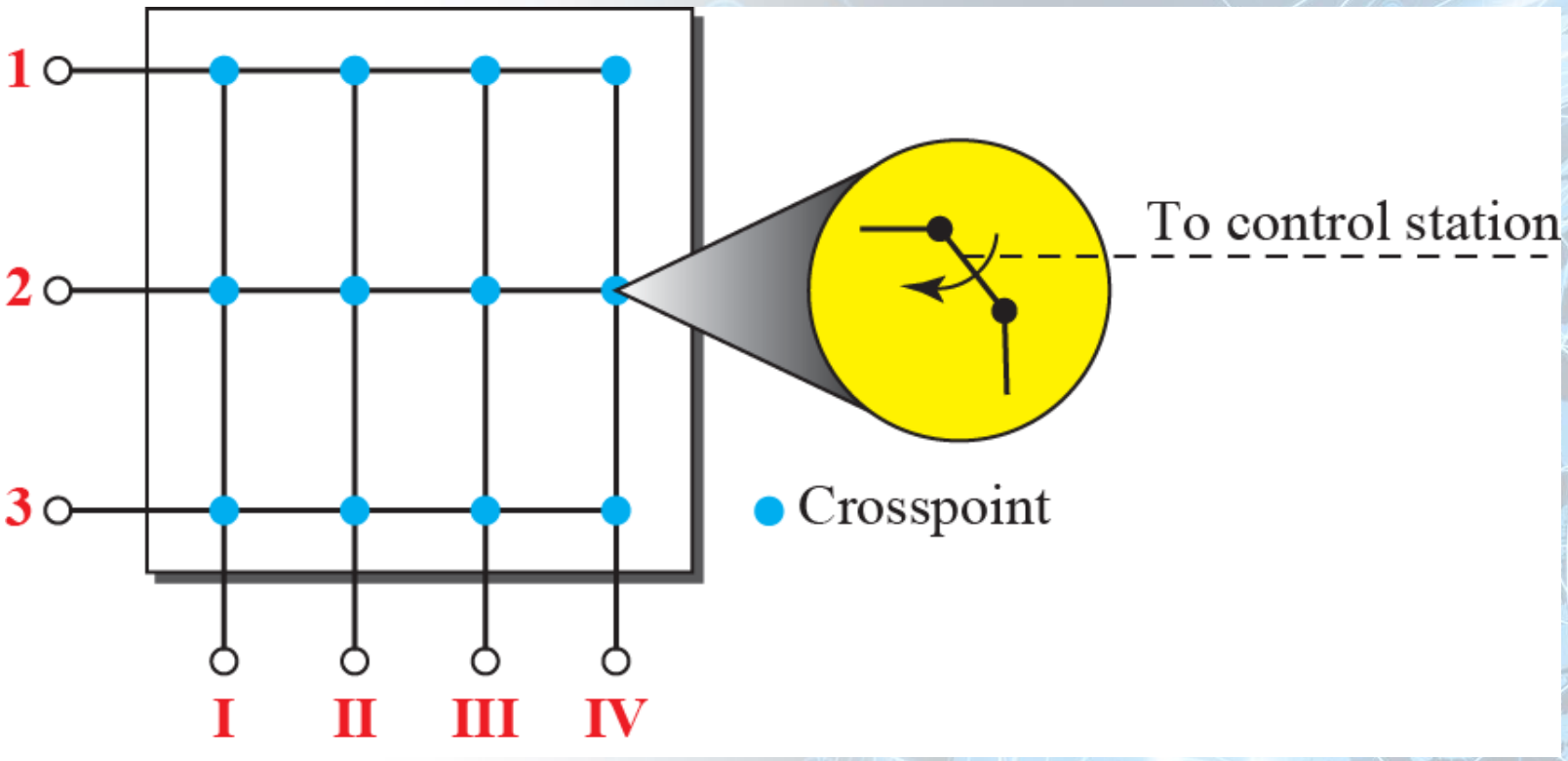
Switch & table for a virtual-circuit network



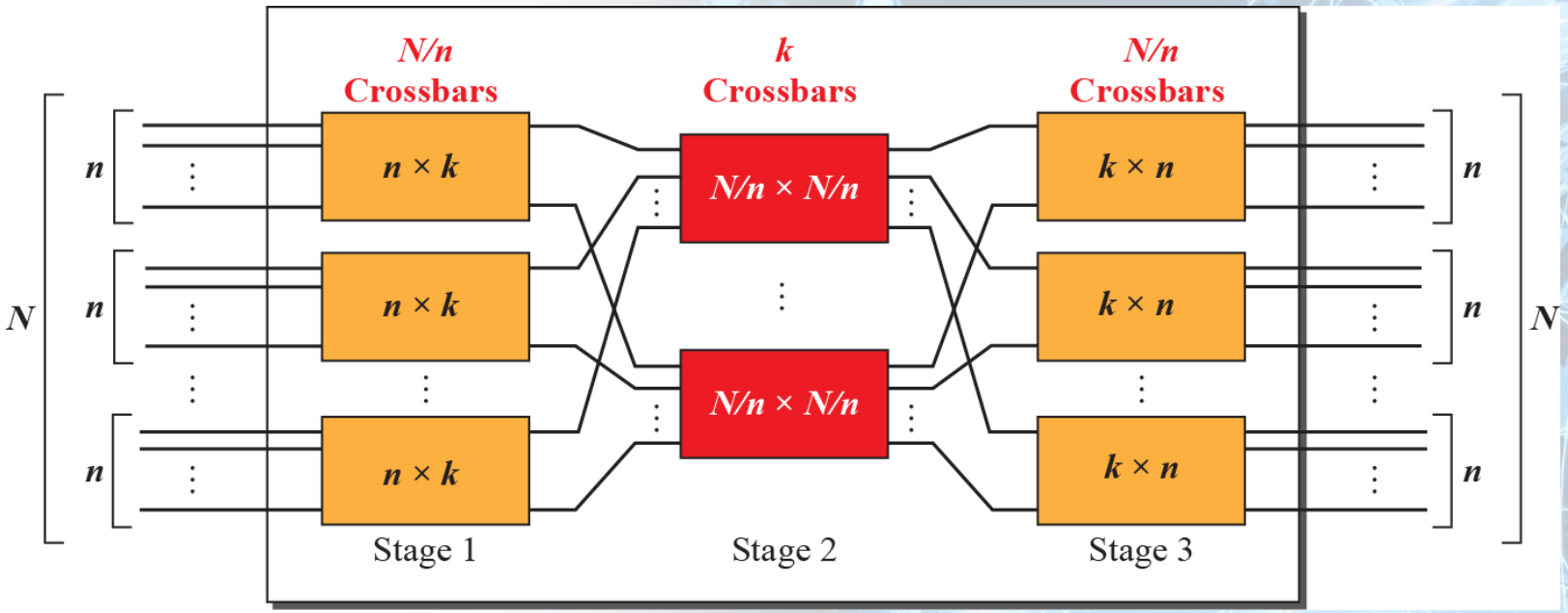
Structure Of A Circuit Switch

- Circuit switching today can use either of two technologies:
  - ✓ The Space-Division switch
  - ✓ The Time-Division switch

Crossbar switch with 3 inputs & 4 outputs



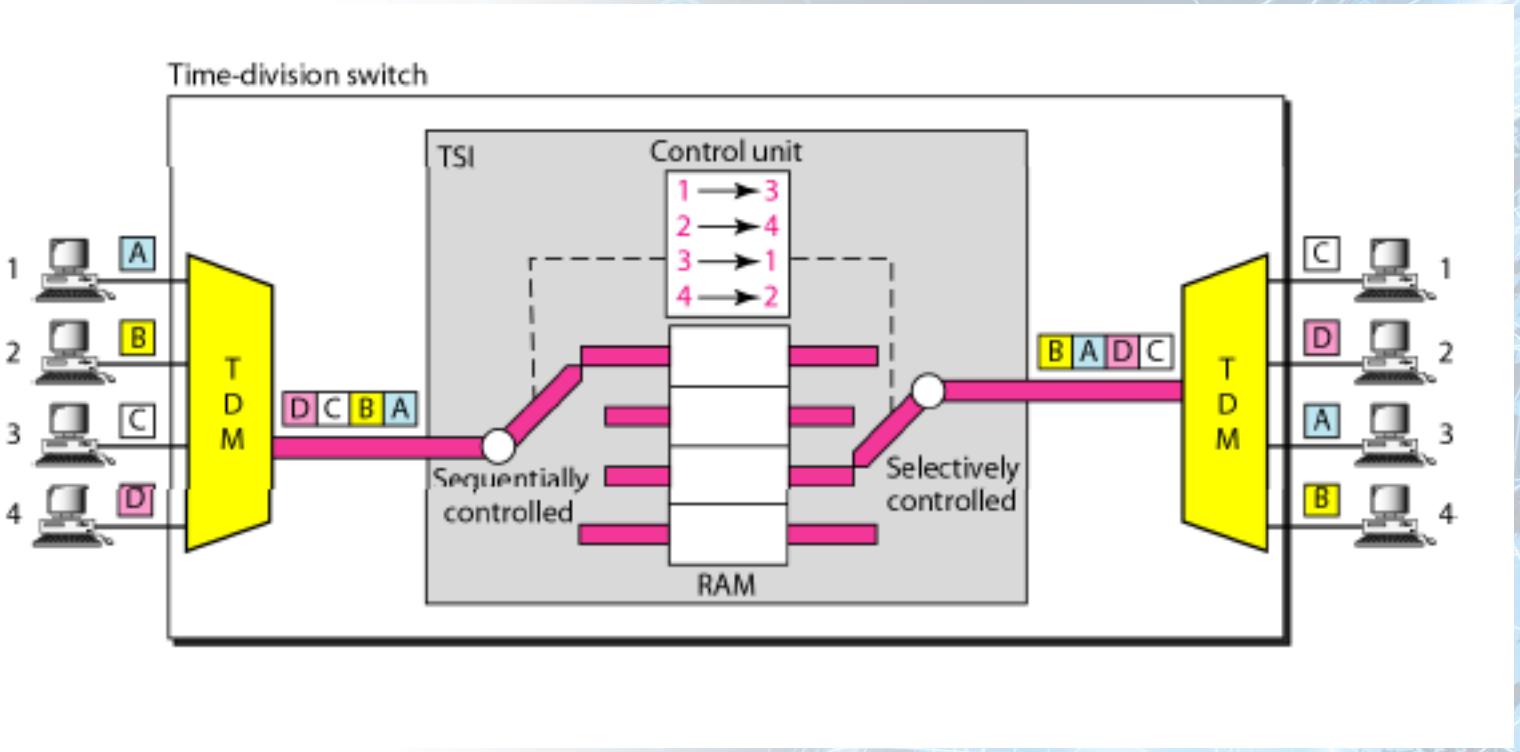
Multistage Switch



Time-Division Switch

- Uses TDM inside a switch
- Most popular technology is Time-Slot Interchange (TSI)

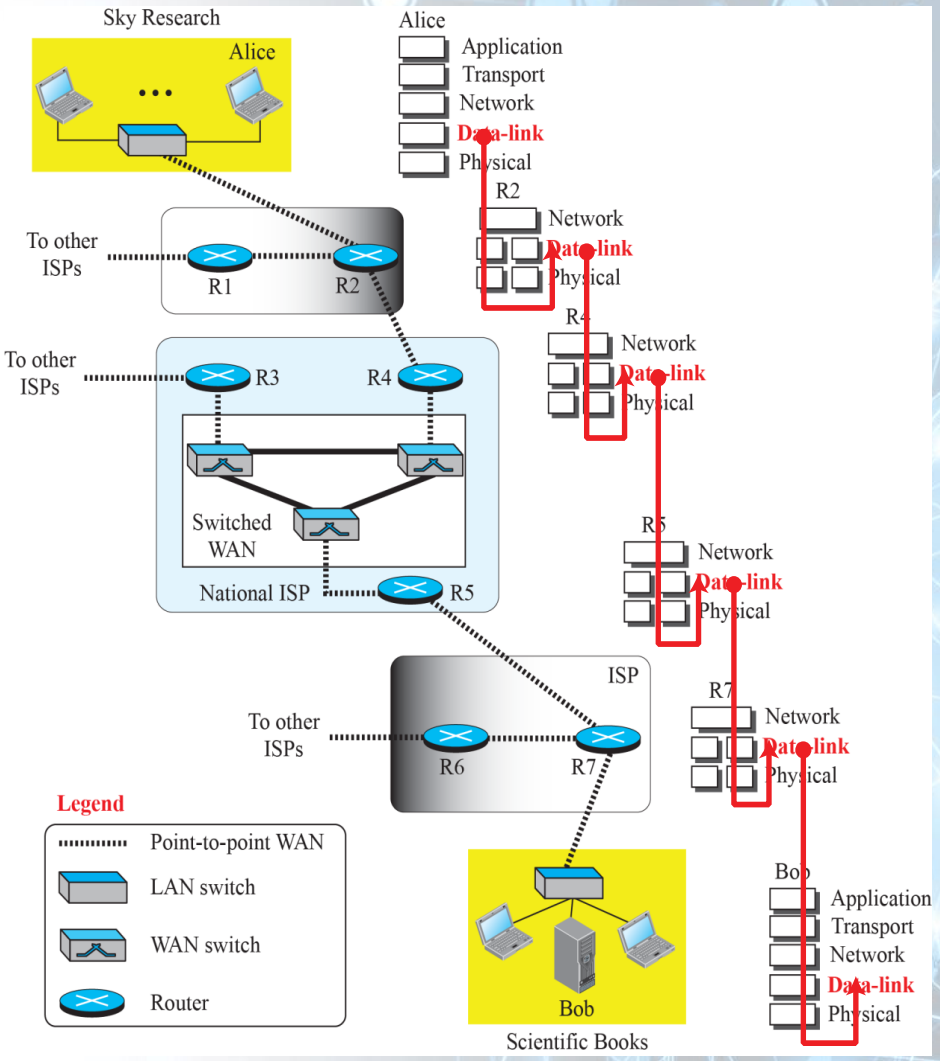
Time-Division Switch



Data-Link Layer

- The Internet is a combination of networks glued together by connecting devices (routers or switches)
- If a packet is to travel from a host to another host, it needs to pass through these networks
- Data Link layer controls node-to-node communication

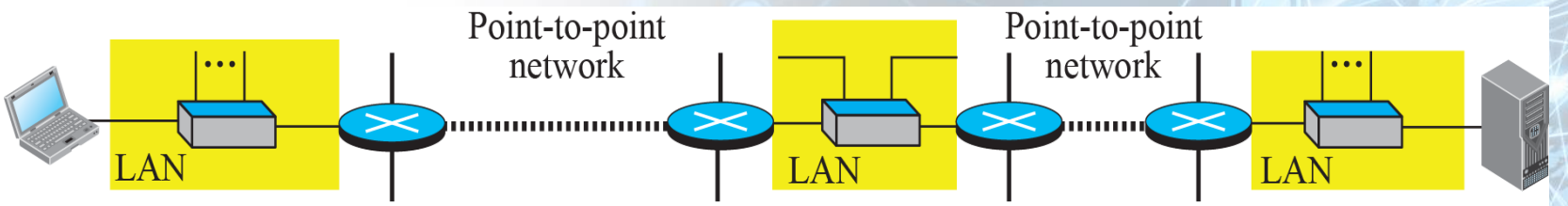
Communication at the Data-Link Layer



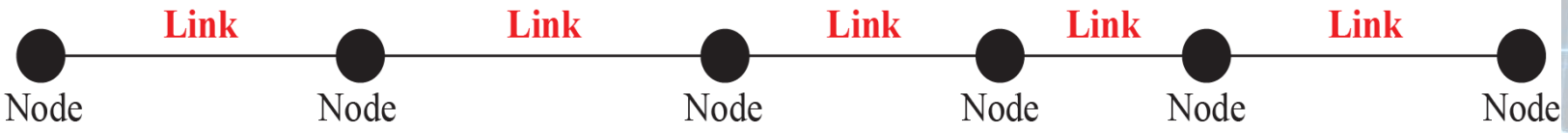
Nodes and Links

- Communication at the data-link layer is node-to-node
- A data unit from one point in the Internet needs to pass through many networks (LANs and WANs) to reach another point
- We refer to the two end hosts and the routers as nodes and the networks in between as links

Nodes and Links



a. A small part of the Internet

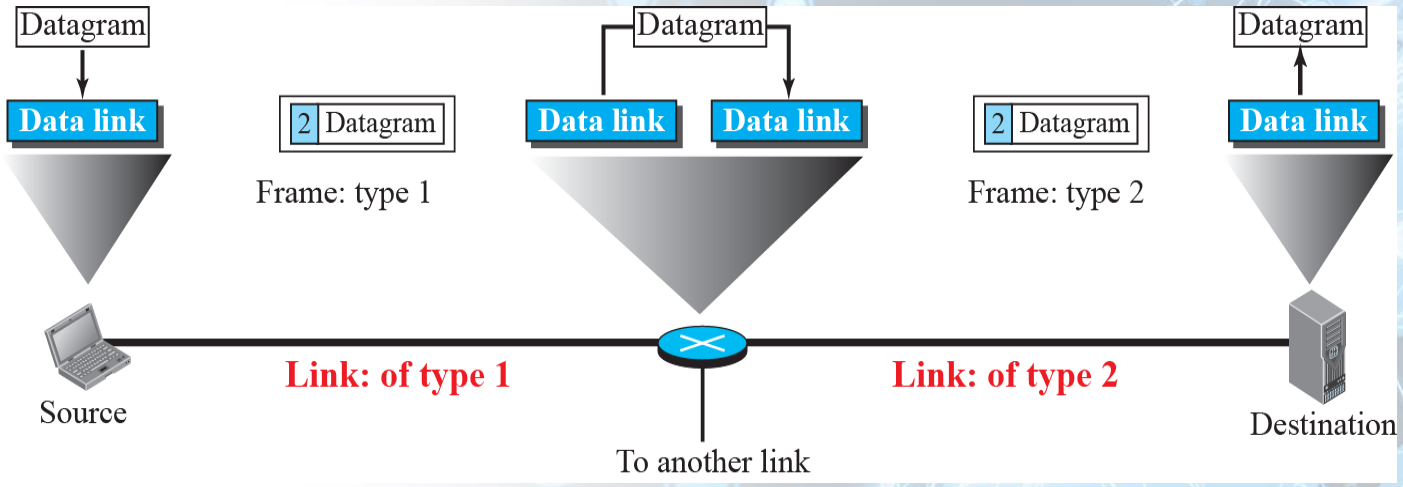


b. Nodes and links

Services provided by Data-Link Layer

- Located between the physical and the network layers
- Provides services to Network Layer and receives services from Physical layer
- Framing
- Flow Control
- Error Control
- Congestion Control

A Communication with only Three Nodes



Services provided by Data-Link Layer

- Data-Link layer provides services to Network Layer and receives services from Physical layer

  - ✓ Framing
  - ✓ Flow Control
  - ✓ Error Control
  - ✓ Congestion Control

Two Categories of Links

- Two nodes are physically connected by a transmission medium such as cable or air
- Data-link layer controls how the medium is used
  - ✓ Data-link layer can use whole capacity
  - ✓ Data-link layer can use only part of the capacity

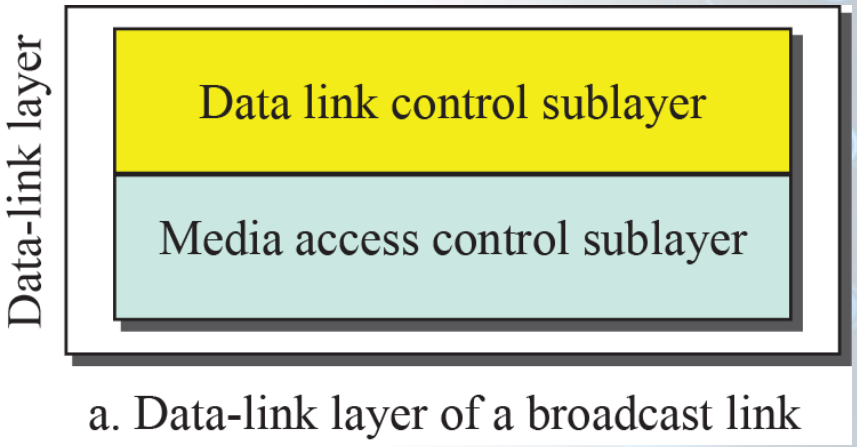
Two Categories of Links

- We can have the following two types of links:
  - ✓ Point-to-point link or a
  - ✓ Broadcast link

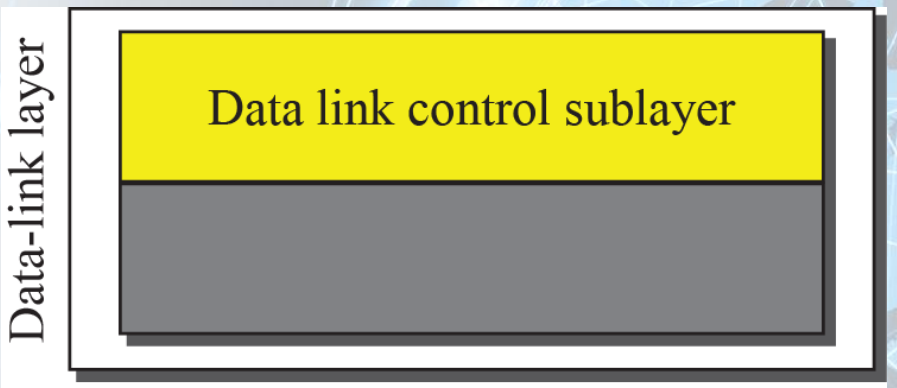
Two Sublayers of Data-Link Layer

- We can divide the data-link layer into two sublayers:
  - Data Link Control (DLC)
  - Media Access Control (MAC)

Dividing the data-link layer into two sublayers



a. Data-link layer of a broadcast link

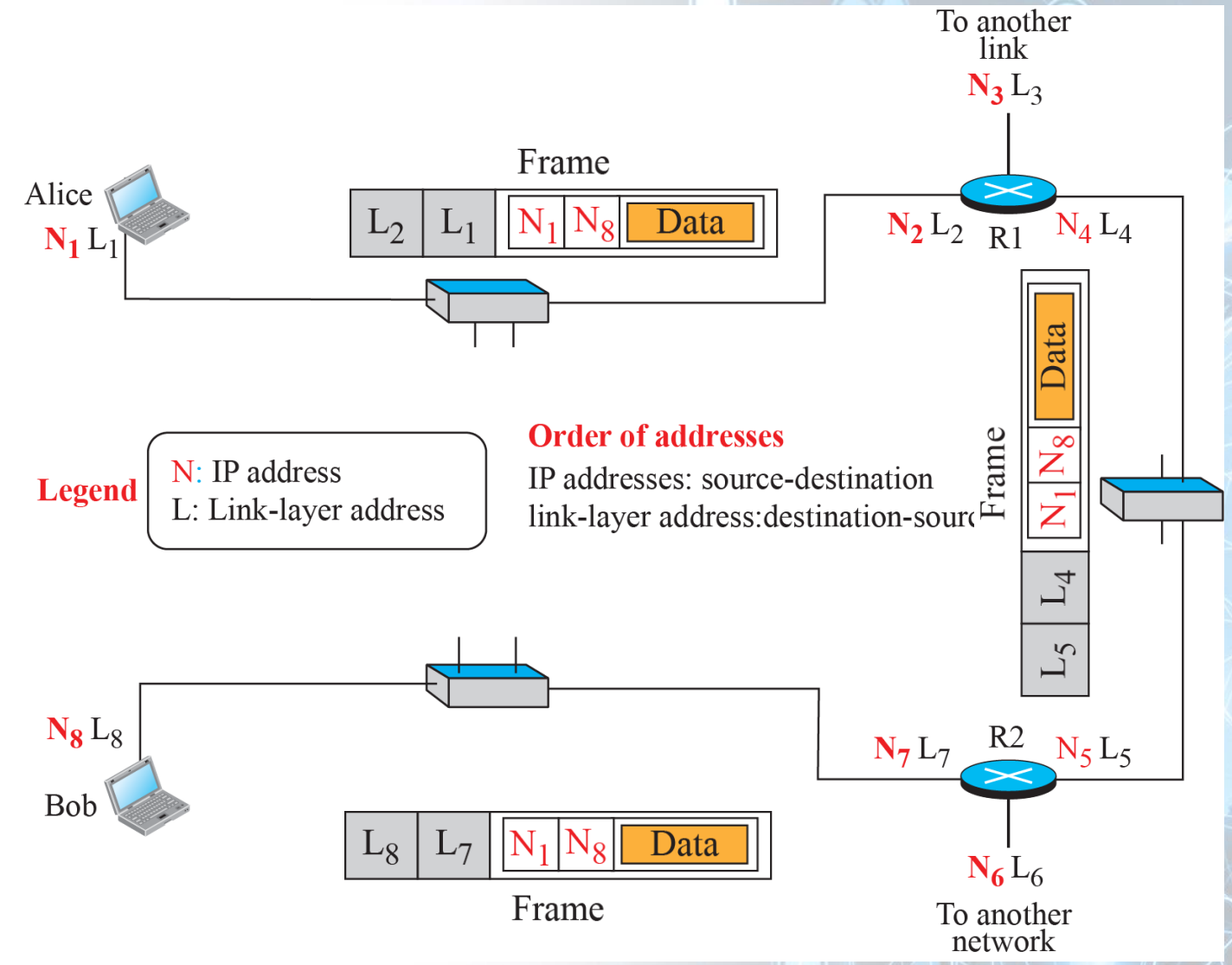


b. Data-link layer of a point-to-point link

Why LINK-LAYER ADDRESSING?

- IP addresses are the identifiers at the network layer
- In Internet we cannot make a packet reach its destination using only IP addresses
- Source and destination IP addresses define the two ends but cannot define which links the packet will take

IP addresses & Link-Layer Addresses



Three Types of addresses

- Some link-layer protocols define three types of addresses:
- Unicast
- Multicast
- Broadcast

Example

The unicast link-layer addresses in the most common LAN, Ethernet, are 48 bits (six bytes) that are presented as 12 hexadecimal digits separated by colons; for example, the following is a link-layer address of a computer. The second digit needs to be an odd number.

A3:34:45:11:92:F1

Example

The multicast link-layer addresses in the most common LAN, Ethernet, are 48 bits (six bytes) that are presented as 12 hexadecimal digits separated by colons. The second digit, however, needs to be an even number in hexadecimal. The following shows a multicast address:

A2:34:45:11:92:F1

Example

The broadcast link-layer addresses in the most common LAN, Ethernet, are 48 bits, all 1s, that are presented as 12 hexadecimal digits separated by colons. The following shows a broadcast address:

FF:FF:FF:FF:FF:FF

Address Resolution Protocol (ARP)

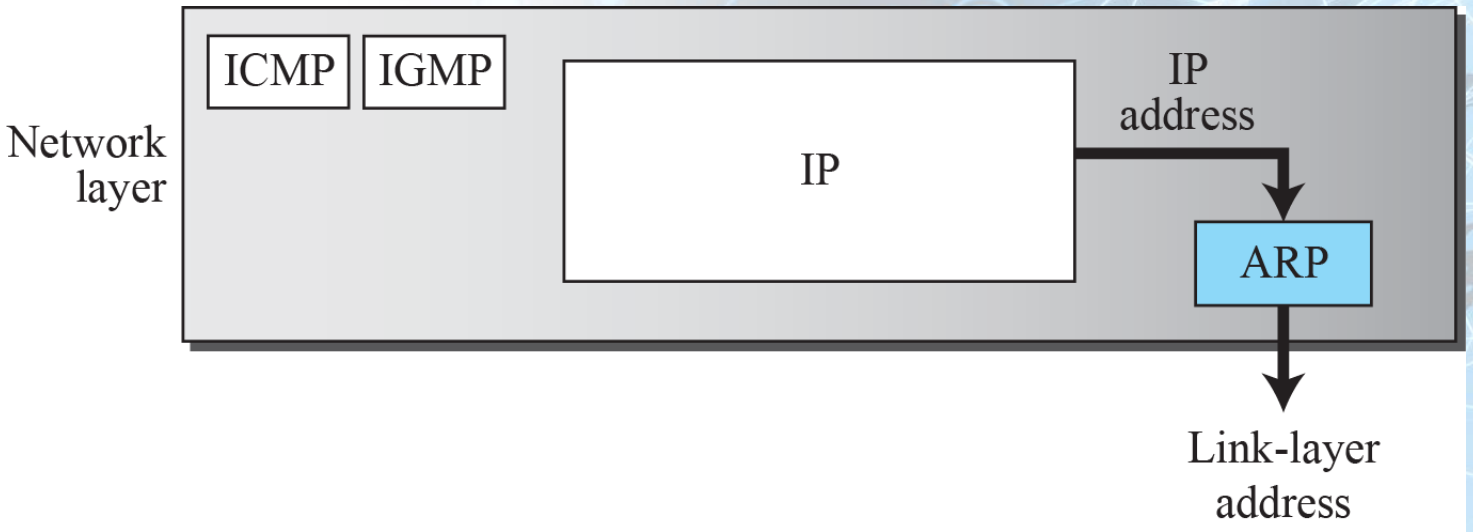
- Anytime a node has an IP packet to send to another node in a link, it has the IP address of the receiving node

- IP address of the next node is not helpful in moving a frame through a link; we need the link-layer address of the next node

Address Resolution Protocol (ARP)

- We need Address Resolution Protocol (ARP)

Position of ARP in TCP/IP protocol suite

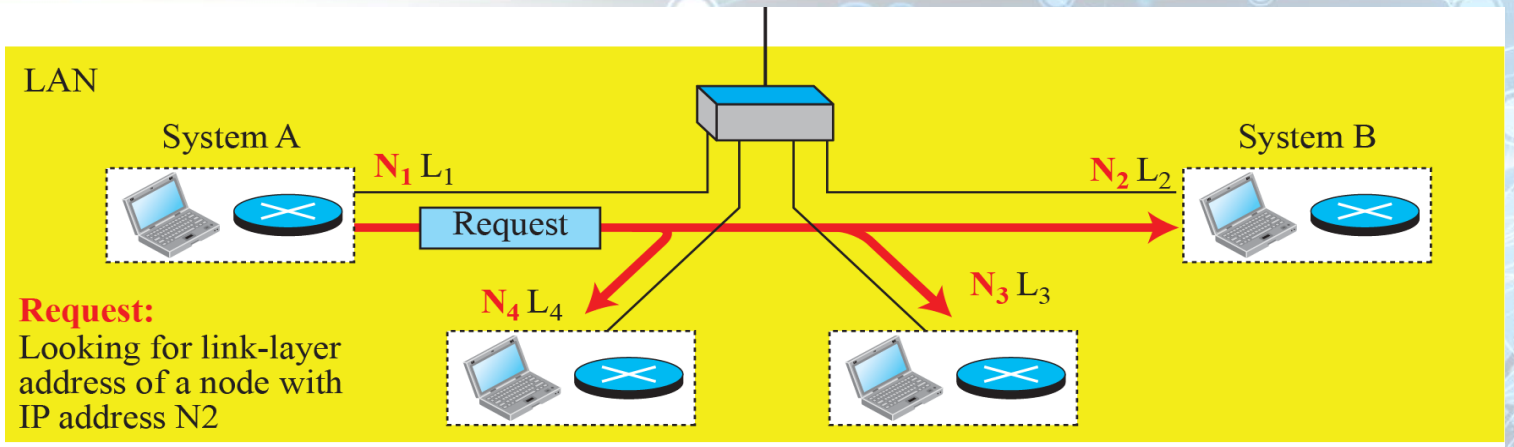


Address Resolution Protocol (ARP)

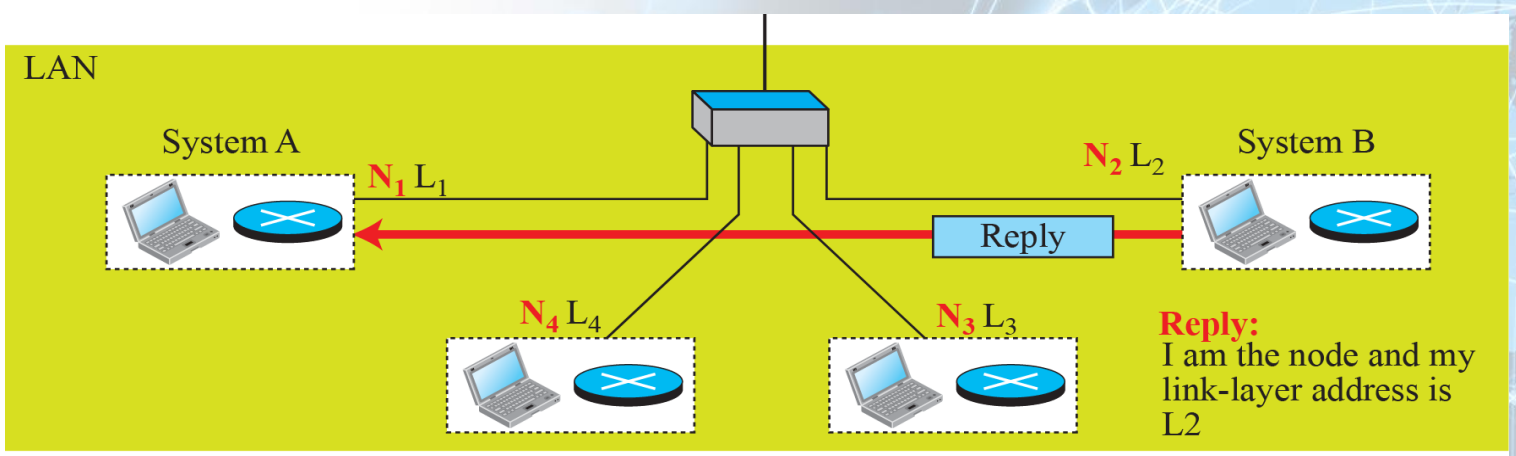
- Anytime a node has an IP packet to send to another node in a link, it has the IP address of the receiving node

- IP address of the next node is not helpful in moving a frame through a link; we need the link-layer address of the next node

ARP Operation



a. ARP request is broadcast



b. ARP reply is unicast

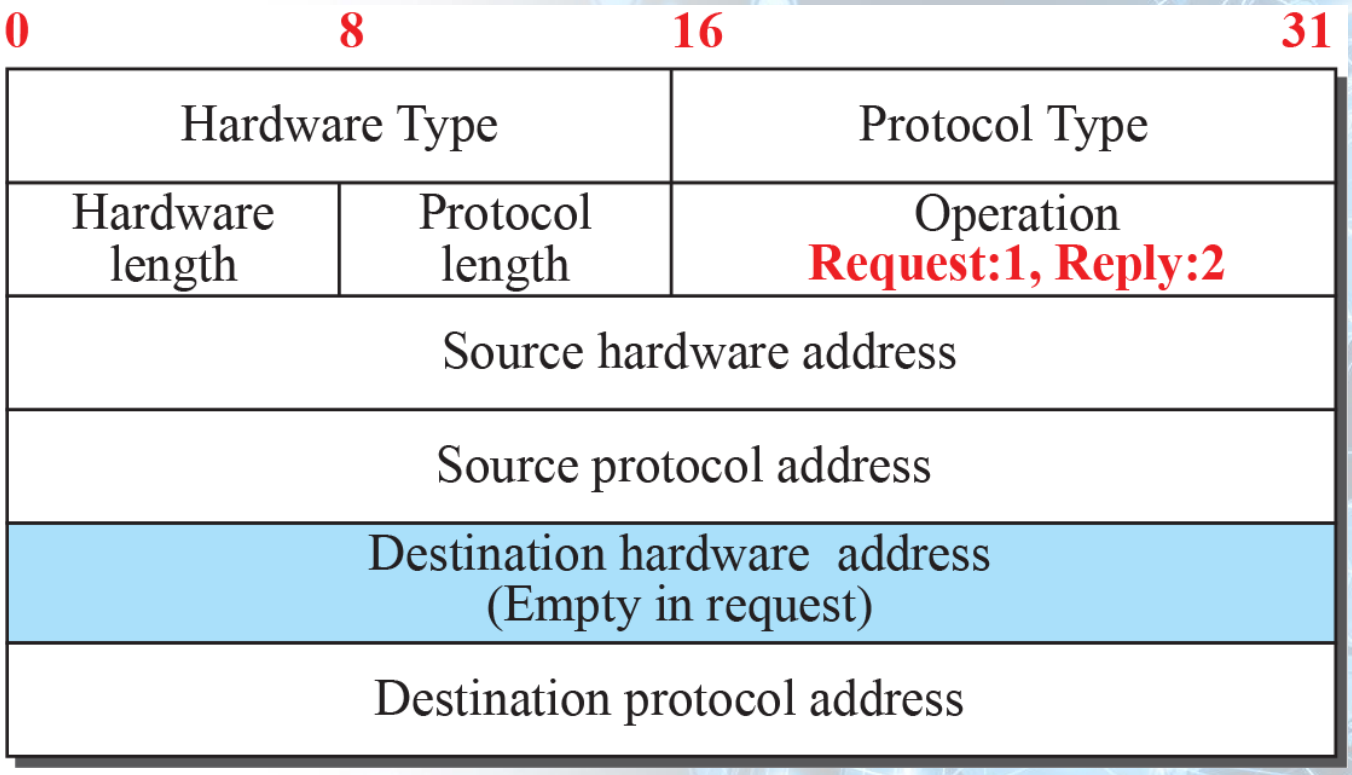
Address Resolution Protocol (ARP)

- Anytime a node has an IP packet to send to another node in a link, it has the IP address of the receiving node

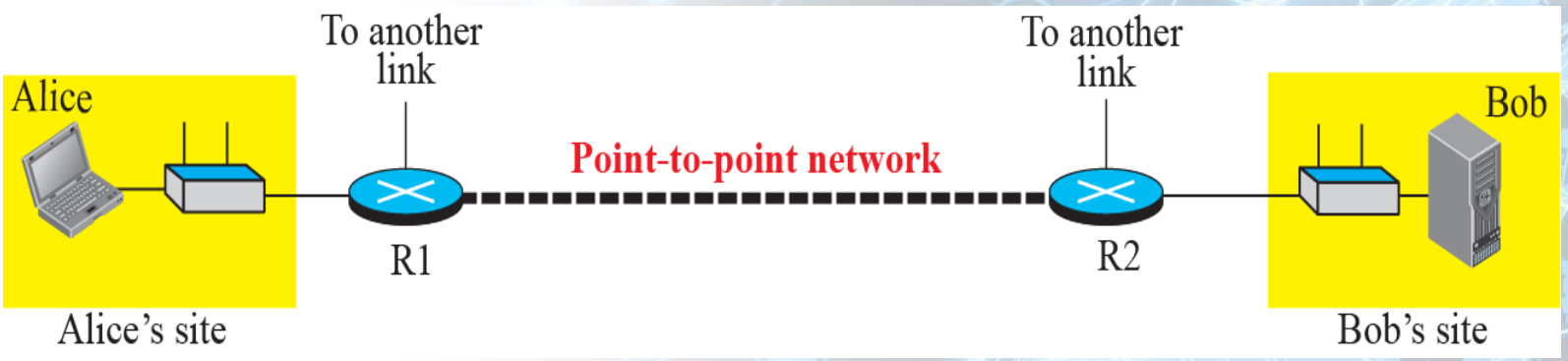
- IP address of the next node is not helpful in moving a frame through a link; we need the link-layer address of the next node

ARP Packet

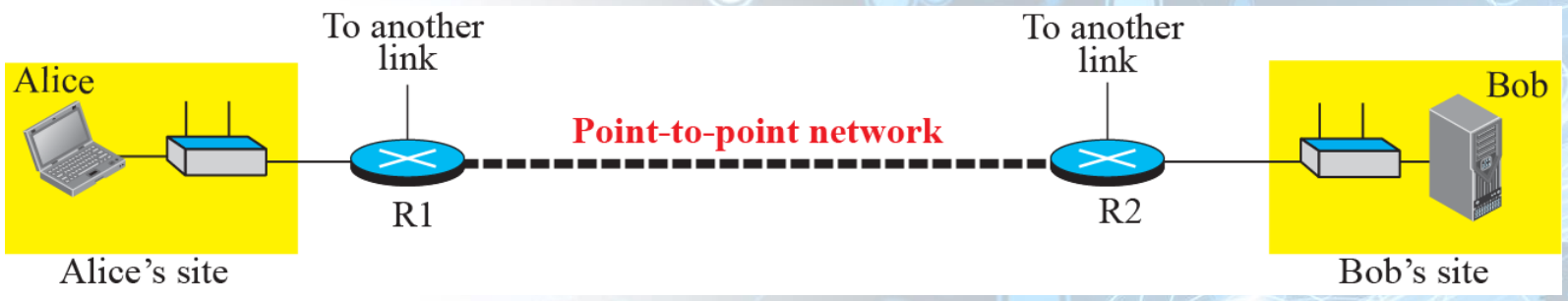
Hardware: LAN or WAN protocol
Protocol: Network-layer protocol

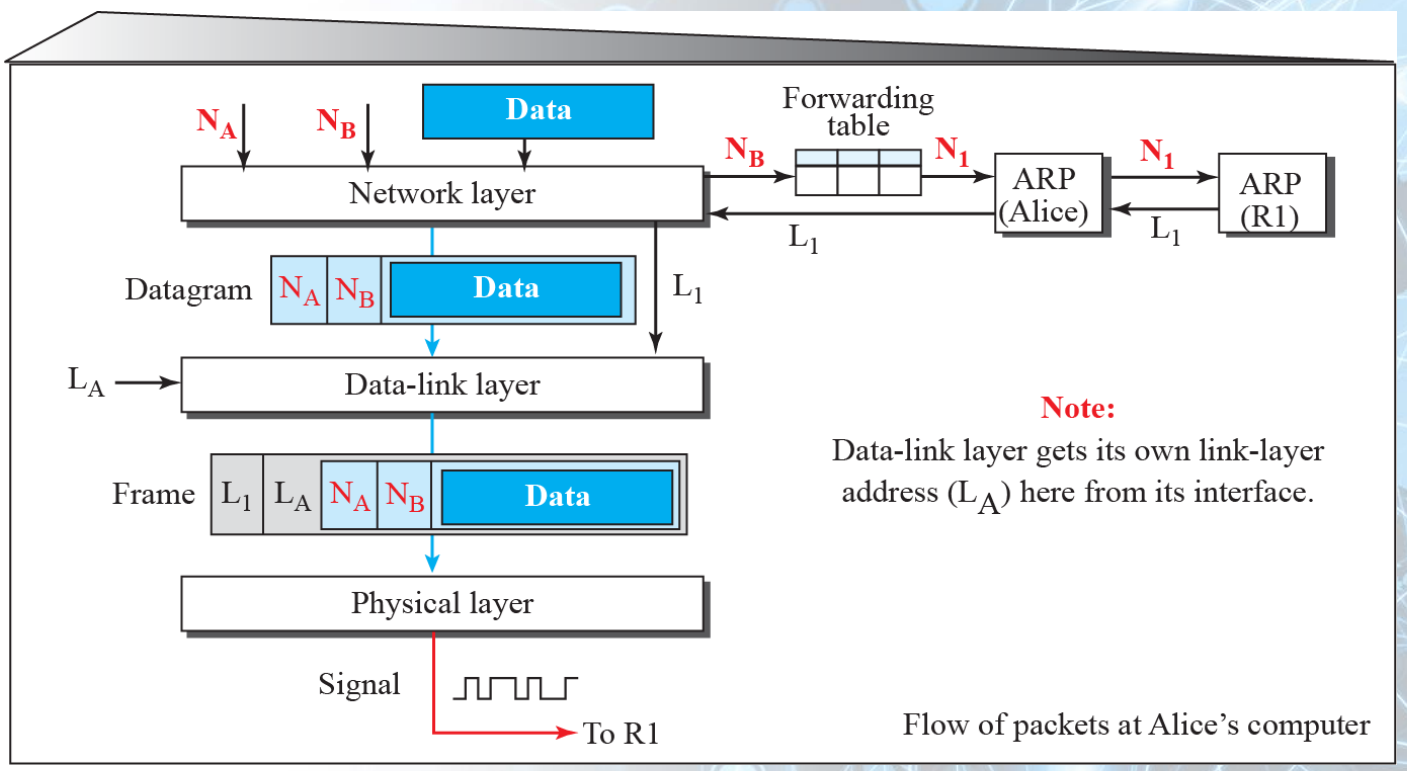


The internet for our example

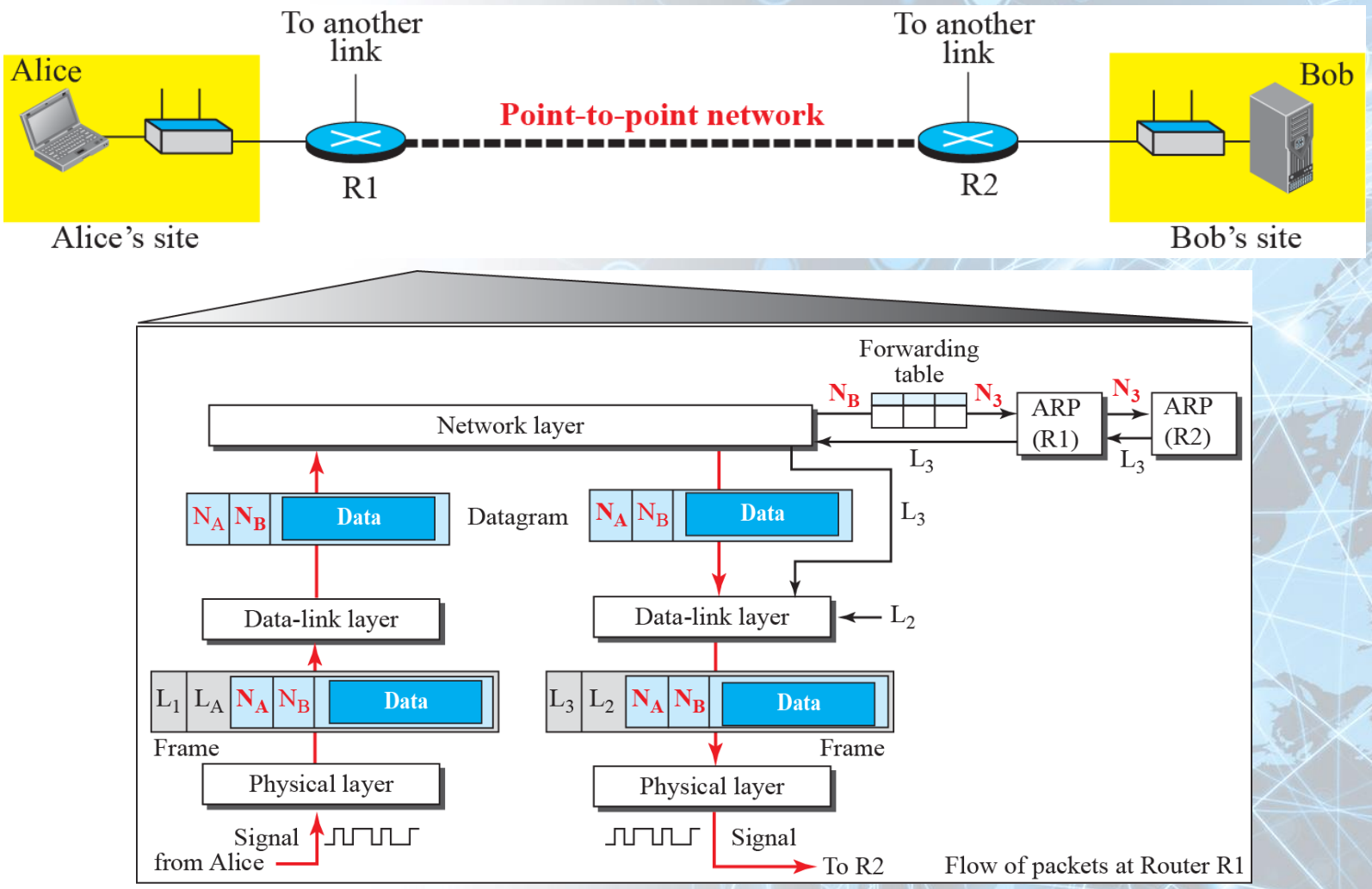


Flow of packets at Alice site

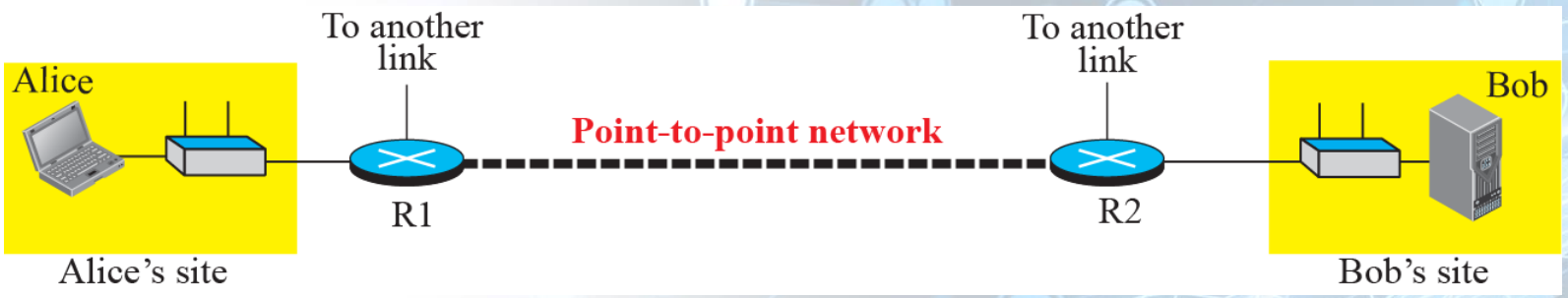


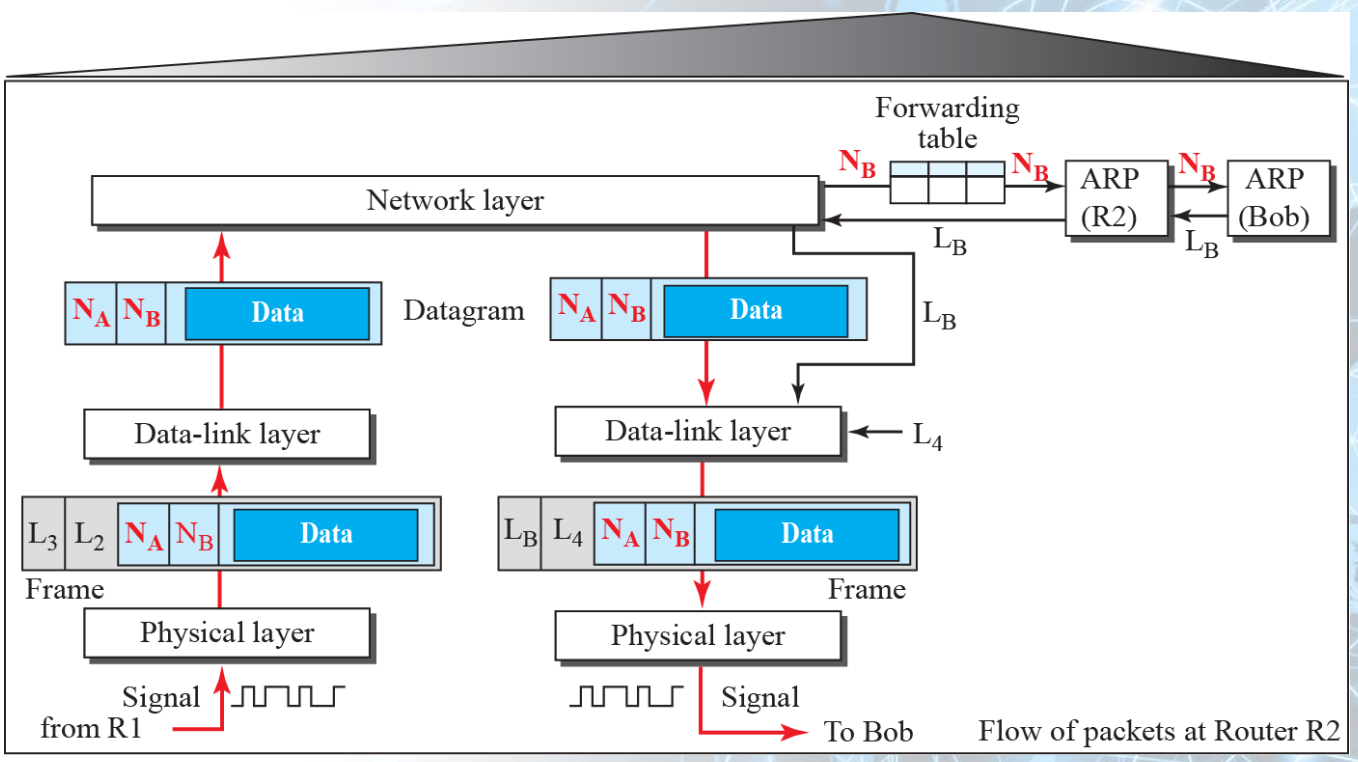


Flow of activities at router R1

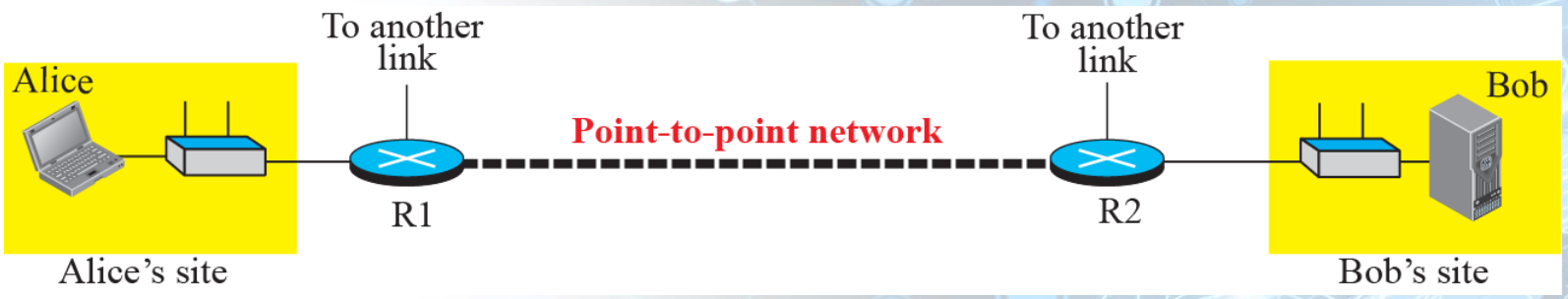


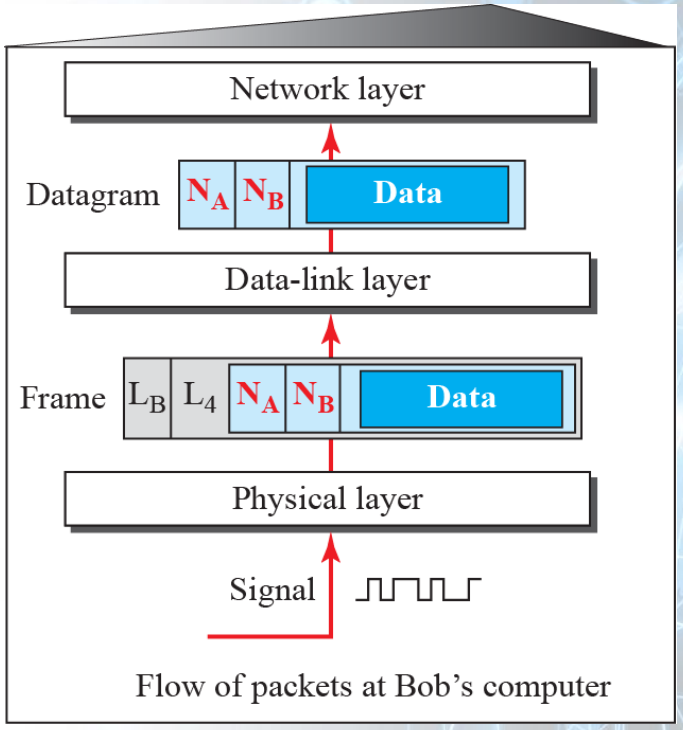
Flow of activities at router R2





Activities at Bob's site





Types of Errors

- Data transmission suffers unpredictable changes because of interference
- The interference can change the shape of the signal
  - ✓ **Single-bit error** means that only 1 bit of a given data unit (such as a byte, character, or packet) is changed from 1 to 0 or from 0 to 1

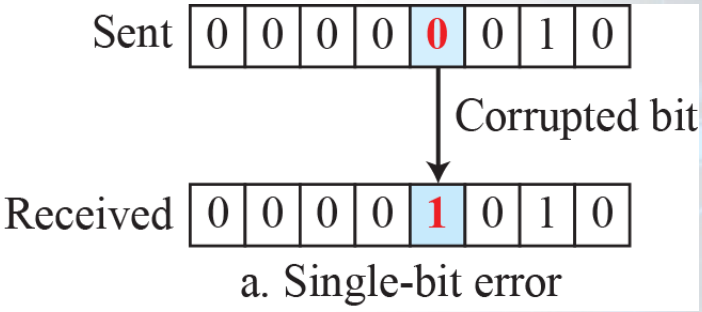
Types of Errors

- ✓ **Burst Error means that 2 or more bits in the data unit have changed from 1 to 0 or from 0 to 1**

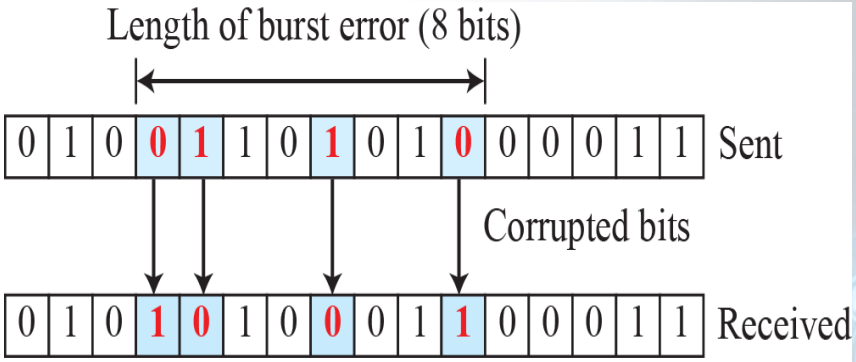
Types of Errors

- ✓ **Single-bit error** means that only 1 bit of a given data unit (such as a byte, character, or packet) is changed from 1 to 0 or from 0 to 1
- ✓ **Burst Error** means that 2 or more bits in the data unit have changed from 1 to 0 or from 0 to 1

Single-Bit and Burst Error



a. Single-bit error



b. Burst error

Redundancy

- Central concept in detecting or correcting errors is Redundancy
- To be able to detect or correct errors, we send some extra bits with our data
- The presence of these redundant bits allows the receiver to detect or correct corrupted bits

Detection versus Correction

- Correction is more difficult than the detection
- In error detection, we are only looking to see if any error has occurred (Yes or No)
- We are not interested in the number of corrupted bits in Detection
- Single-bit error is same as a Burst error

Detection versus Correction

- In Error Correction, we need to know:
  - ✓ The exact number of bits that are corrupted and,
  - ✓ Their location in the message

Coding

- Redundancy is achieved through various coding schemes
- Sender adds redundant bits through a process that creates a relationship between redundant bits and the actual data bits
- The receiver checks the relationships between the two sets of bits to detect errors

Coding

- The ratio of redundant bits to data bits and the robustness of the process are important factors in any coding scheme

Types of Coding Schemes

- **Coding schemes can be divided into 2 broad categories:**
  - ✓ **Block Coding**
  - ✓ **Convolution Coding**

Block Coding

- We divide our message into blocks, each of ‘k’ bits, called datawords
- We add ‘r’ redundant bits to each block to make the length ‘n = k + r’
- The resulting ‘n-bit’ blocks are called codewords

BLOCK CODING in Error Detection

- If the following two conditions are met, the receiver can detect a change in the original codeword:
  - ✓ The receiver has (or can find) a list of valid codewords
  - ✓ The original codeword has changed to an invalid one

Process of Error Detection in Block Coding

Block Coding

- We divide our message into blocks, each of ‘k’ bits, called datawords
- We add ‘r’ redundant bits to each block to make the length ‘n = k + r’
- The resulting ‘n-bit’ blocks are called codewords

Example

Let us assume that k = 2 and n = 3. Table below shows the list of datawords and codewords. Later, we will see how to derive a cod word from a dataword.

Datawords	*Codewords*	*Datawords*	*Codewords*
00	000	10	101
01	011	11	110

Hamming Distance

- Hamming Distance between two words of the same size is the number of differences between the corresponding bits
- Hamming Distance between two words x and y is $d(x,y)$
- Hamming distance between received codeword and sent codeword is number of bits corrupted

Example

Let us find the Hamming distance between two pairs of words.

1. **d(000, 011)**
2. **d(10101, 11110)**

Minimum Hamming Distance

- **Minimum Hamming Distance is smallest hamming distance between all possible pairs of codewords**

- **$d_{min} = s+1$**
  where,
  s → no. of detectable errors
  d_{min} → minimum hamming distance

Example

A code scheme has a Hamming distance $d_{min} = 4$. This code guarantees the detection of up to how many errors?

Linear Block Codes

- **Subset of Block Codes in which the exclusive OR of two valid codewords creates another valid codeword**

Example

The code below is a linear block code because the result of XORing any codeword with any other codeword is a valid codeword. For example, the XORing of the second and third codewords creates the fourth one.

Datawords	*Codewords*	*Datawords*	*Codewords*
00	000	10	101
01	011	11	110

The numbers of 1s in the nonzero codewords are 2, 2, and 2. So the minimum Hamming distance is $d_{min} = 2$.

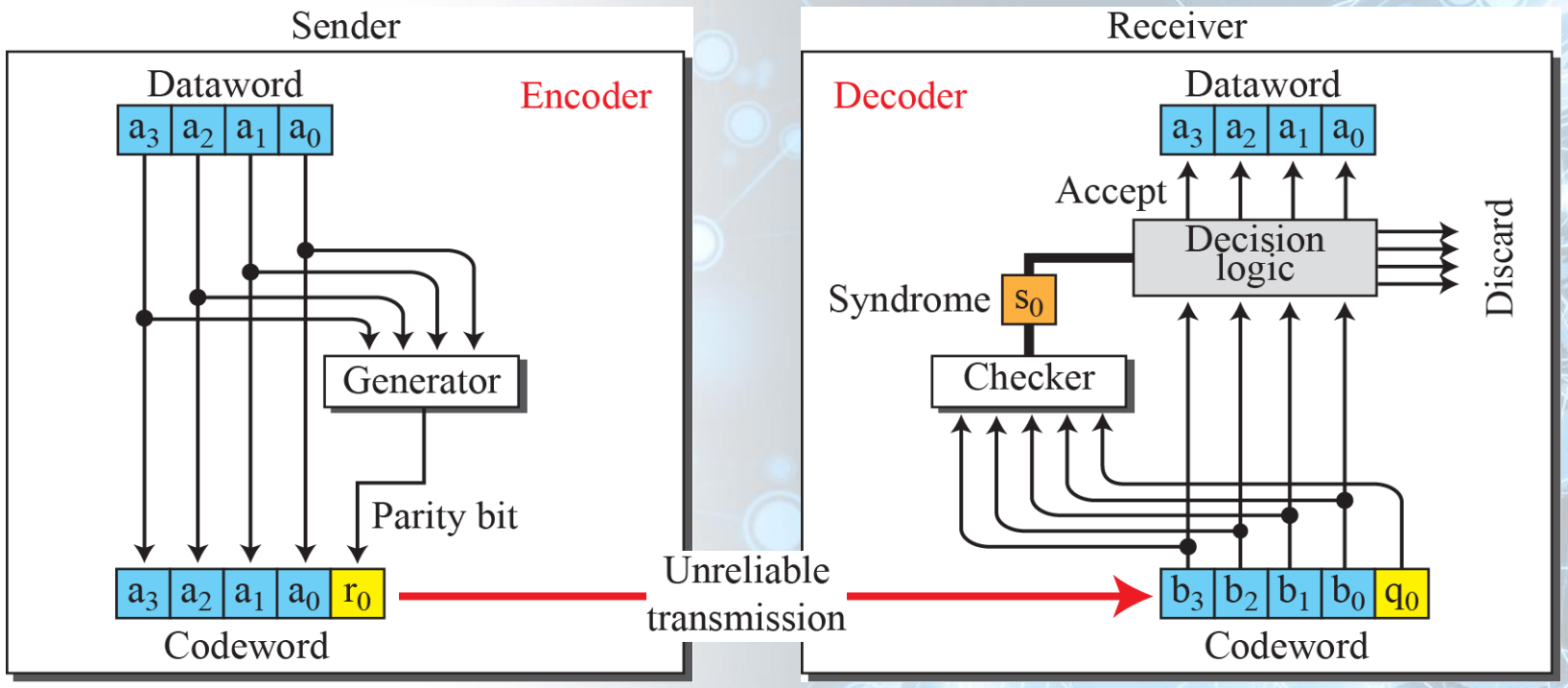
Parity-Check Code

- Most common error-detecting code
- Linear block code (n=k+1)
- The extra parity bit is selected to make total number of 1s in codeword even

Simple parity-check code C(5, 4)

Datawords	Codewords	*Datawords*	Codewords
0000	00000	1000	10001
0001	00011	1001	10010
0010	00101	1010	10100
0011	00110	1011	10111
0100	01001	1100	11000
0101	01010	1101	11011
0110	01100	1110	11101
0111	01111	1111	11110

Encoder & decoder for simple parity-check code



CYCLIC CODES

- Special linear block codes with one extra property
- If a codeword is cyclically shifted (rotated), the result is another codeword
- If 1011000 is a codeword and we cyclically left-shift, then 0110001 is also a codeword

Cyclic Redundancy Check (CRC)

- **Subset of Cyclic Codes**
- **Cyclic redundancy check (CRC) is used in networks such as LANs and WANs**

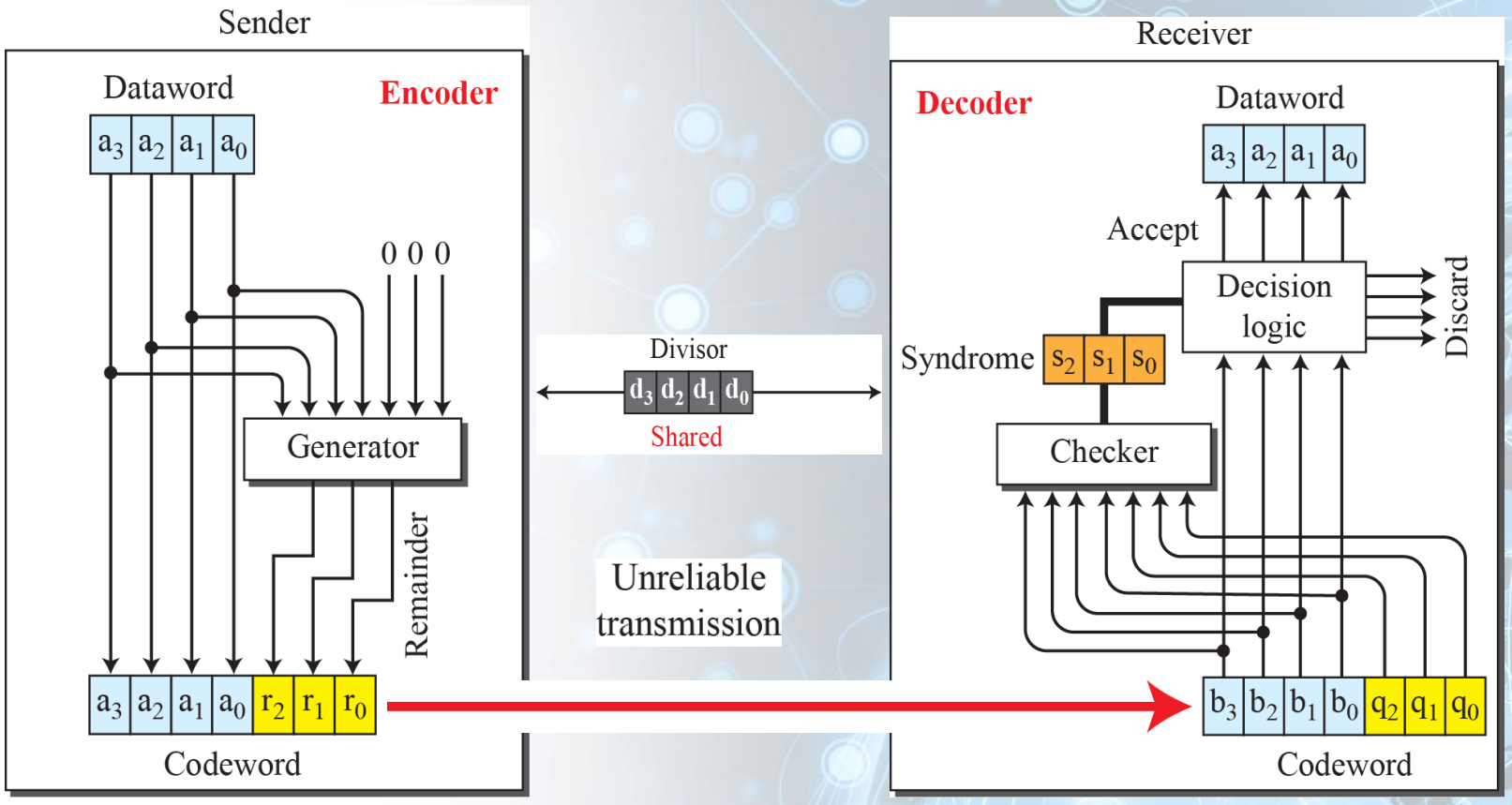
A CRC code with C(7, 4)

Dataword	*Codeword*	*Dataword*	*Codeword*
0000	0000000	1000	1000101
0001	0001011	1001	1001110
0010	0010110	1010	1010011
0011	0011101	1011	1011000
0100	0100111	1100	1100010
0101	0101100	1101	1101001
0110	0110001	1110	1110100
0111	0111010	1111	1111111

Cyclic Redundancy Check (CRC)

- **Subset of Cyclic Codes**
- **Cyclic redundancy check (CRC) is used in networks such as LANs and WANs**

CRC Encoder and Decoder



Cyclic Code Analysis using Polynomials

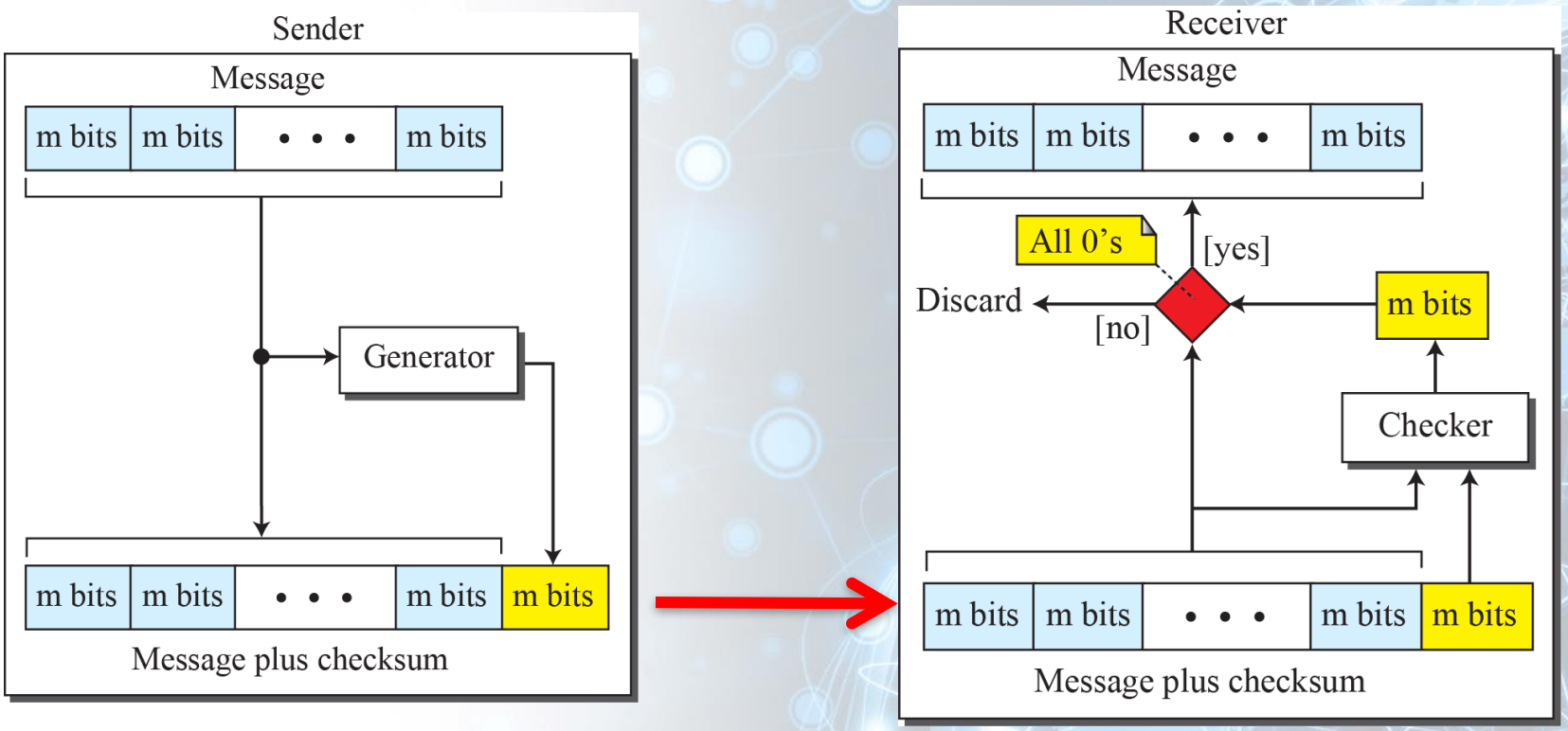
Advantages of Cyclic Codes

- Good performance in detection:
  - Single-bit errors
  - Double errors
  - Odd number of errors
  - Burst errors
- Easy Implementation
- Fast Implementation

CHECKSUM

- Error-detection technique that can be applied to a message of any length
- Checksum mostly used at the network and transport layer rather than the data-link layer

Checksum


Sender
Message
m bits
m bits
m bits
Generator
m bits
m bits
m bits
m bits
Message plus checksum
Receiver
Message
m bits
m bits
m bits
All 0's
[yes]
Discard
[no]
m bits
Checker
m bits
m bits
m bits
m bits
Message plus checksum

Concept behind Checksum

- **The idea of the traditional checksum is simple. We show this using a simple example**

Example

Suppose the message is a list of five 4-bit numbers that we want to send to a destination. In addition to sending these numbers, we send the sum of the numbers.
Set of numbers is (7, 11, 12, 0, 6)

Example

In the previous example, the decimal number 36 in binary is $(100100)_2$. To change it to a 4-bit number we add the extra leftmost bit to the right four bits as shown below

$$(10)_2 + (0100)_2 = (0110)_2$$

$$\longrightarrow (6)_{10}$$

Forward Error Correction

- Retransmission of corrupted and lost packets is not useful for real-time multimedia transmission
- We need to correct the error or reproduce the packet immediately
- Several techniques developed and are commonly called Forward Error Correction techniques

Using Hamming Distance

- For error detection, we definitely need more distance
- It can be shown that to correct ‘t’ errors, we need to have:

$$d_{min} = 2t + 1$$

- If we want to correct 10 bits in a packet, we need to make the minimum hamming distance 21 bits
- A lot of redundant bits need to be sent with the data

Using Hamming Distance

If we want to correct 10 bits in a packet, we need to make the minimum hamming distance 21 bits

Using XOR

Another recommendation is to use the property of the exclusive OR operation as shown below.

$$R = P_1 \oplus P_2 \oplus \ldots \oplus P_i \oplus \ldots \oplus P_N$$

This means:

$$P_i = P_1 \oplus P_2 \oplus \ldots \oplus R \oplus \ldots \oplus P_N$$

Using XOR

Another recommendation is to use the property of the exclusive OR operation as shown below.

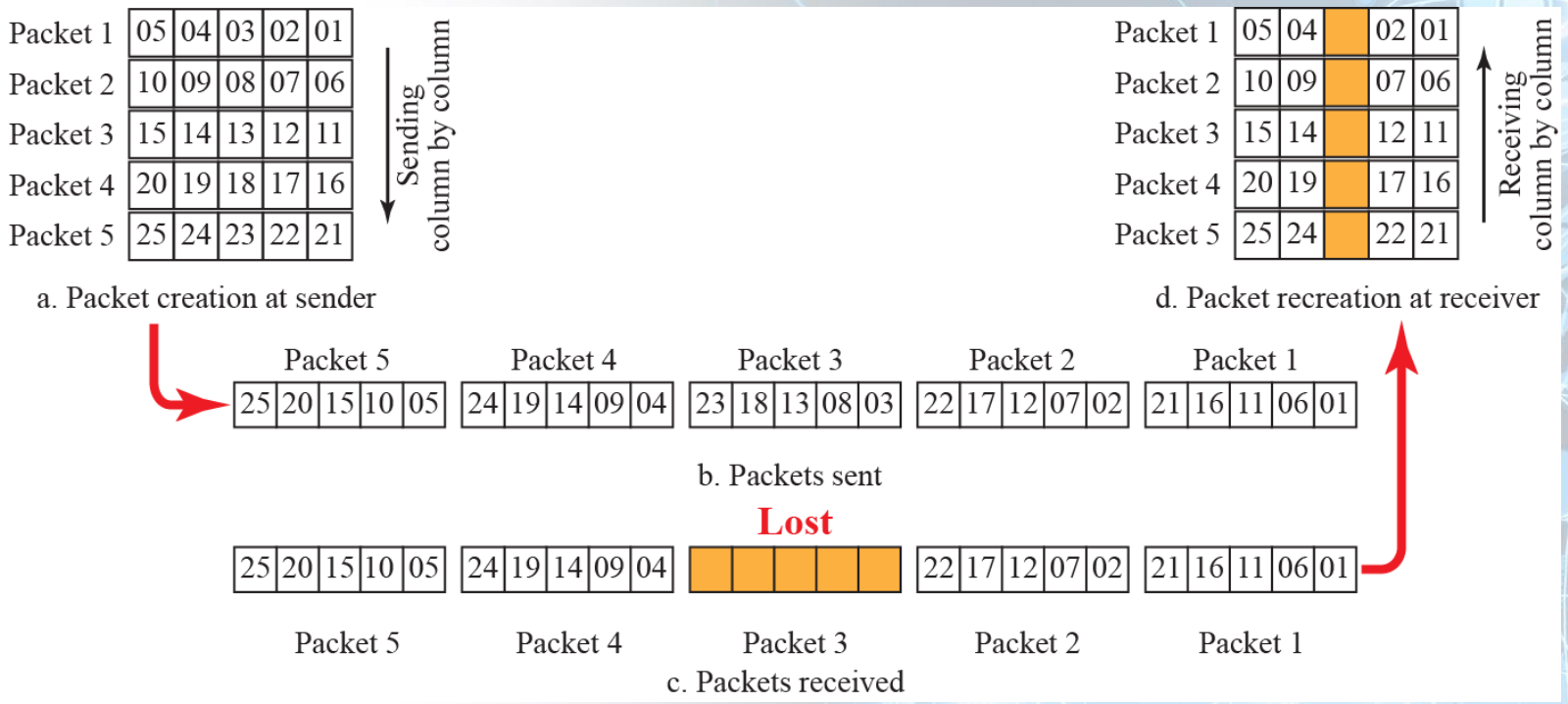
$$R = P_1 \oplus P_2 \oplus .. \oplus P_i \oplus ... \oplus P_N$$

Chunk Interleaving

- Another way to achieve FEC in multimedia is to allow some small chunks to be missing at the receiver

- We cannot afford to let all the chunks belonging to the same packet be missing; however, we can afford to let one chunk be missing in each packet

Interleaving



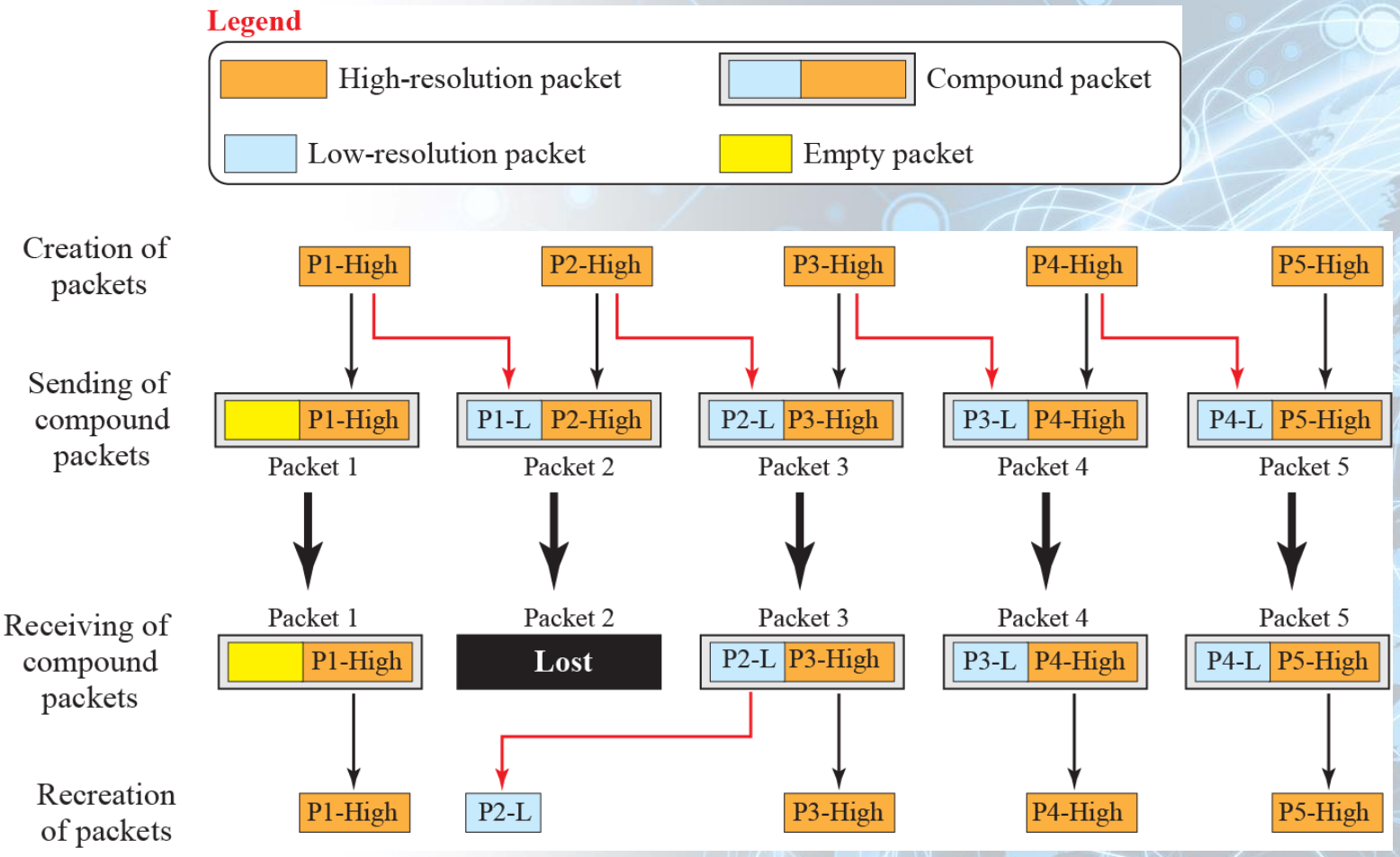
Combining Hamming Distance & Interleaving

- Hamming distance and interleaving can be combined
- We can first create n-bit packets that can correct t-bit errors
- Then we interleave m rows and send the bits column by column
- Possible to correct burst errors up to m × t bits of errors

Compounding High & Low Resolution Packets

- Creation of a duplicate of each packet with a low-resolution redundancy and combine the redundant version with the next packet
- For example, we can create four low-resolution packets out of five high-resolution packets and send them

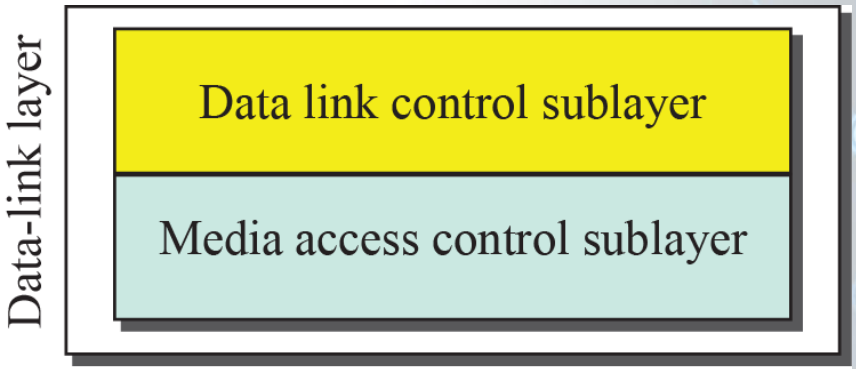
Compounding High-and-Low resolution Packets



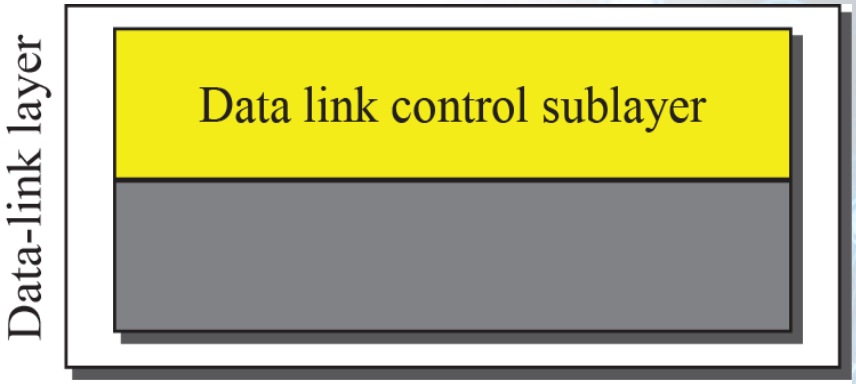
Data Link Control (DLC) Services

- The data link control (DLC) deals with procedures for communication between two adjacent nodes no matter whether the link is dedicated or broadcast
- Data link control functions include framing, flow control and error control

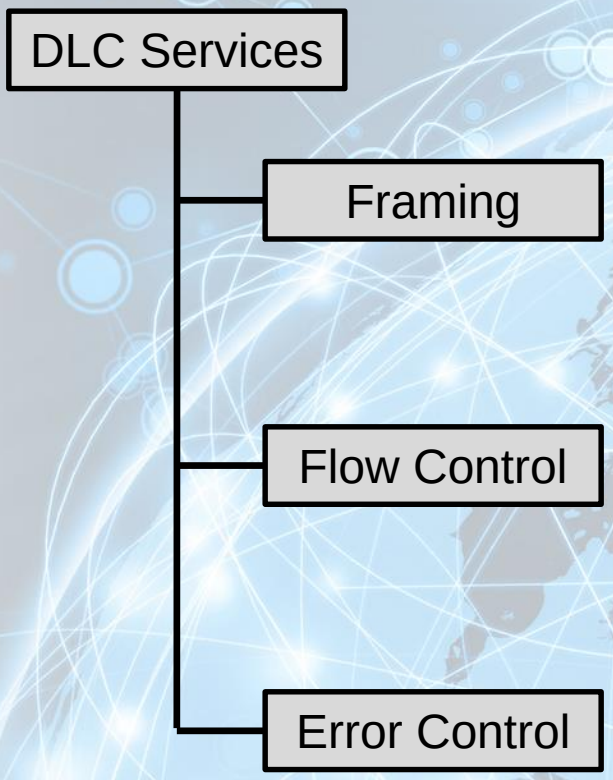
DLC Services



a. Data-link layer of a broadcast link



b. Data-link layer of a point-to-point link



Framing

- Data-Link layer needs to pack bits into frames, so that each frame is distinguishable from another
- Our postal system practices a type of framing
- Framing separates a message by adding a sender address and a destination address

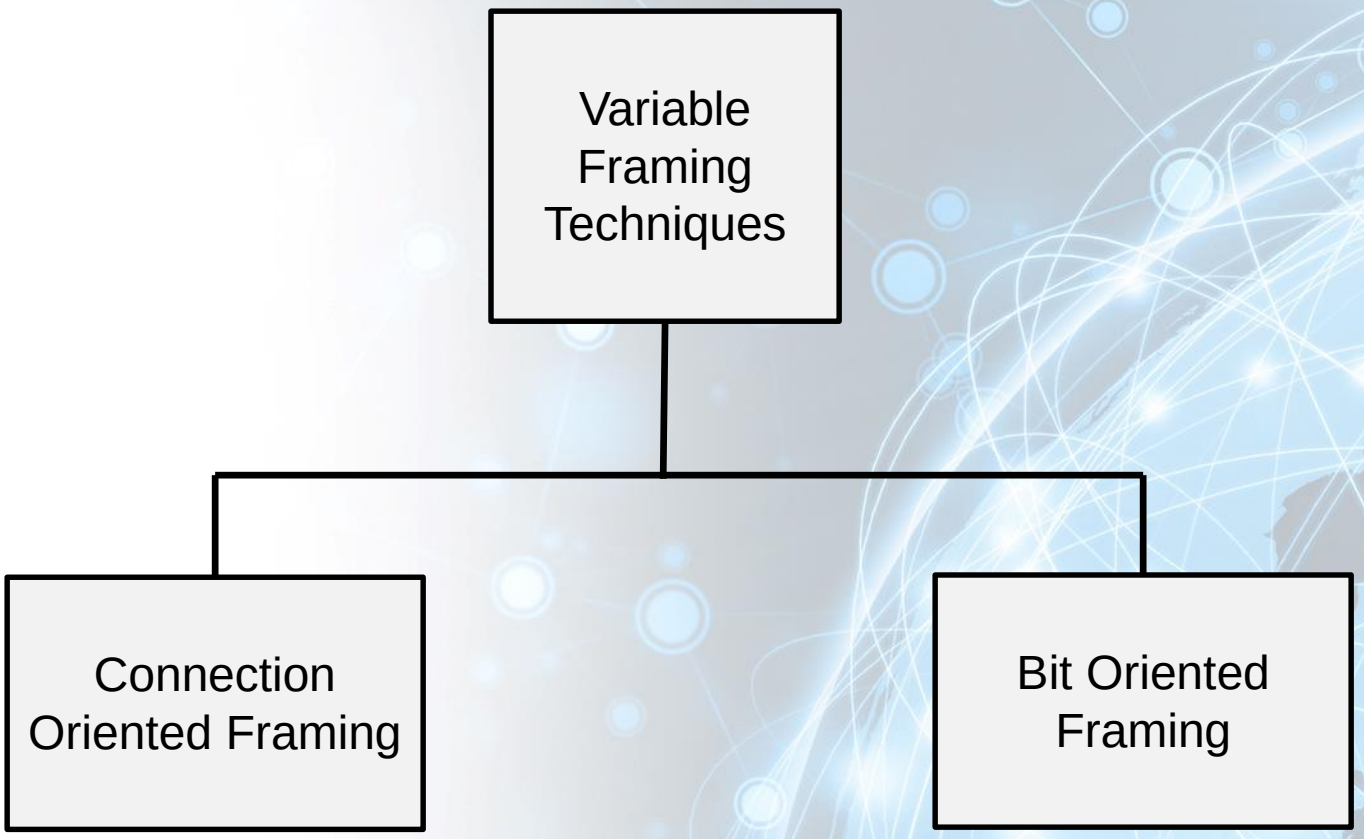
Framing

- The destination address defines where the packet is to go; the sender address helps the recipient acknowledge the receipt

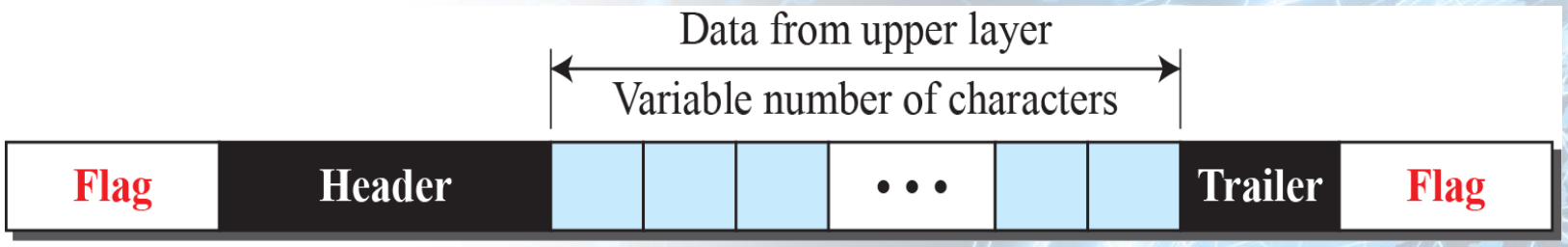
Frame Size

- Why not one BIG Frame?
- Frames can be of:
  - ✓ Fixed Size
    - ➢ Size acts as a boundary/delimiter
  - ✓ Variable Size
    - ➢ How to define Beginning and End of a Frame?

Variable Framing Techniques



A Frame in a Character-Oriented Protocol



Connection Oriented Framing

- **Data to be carried are 8-bit characters**

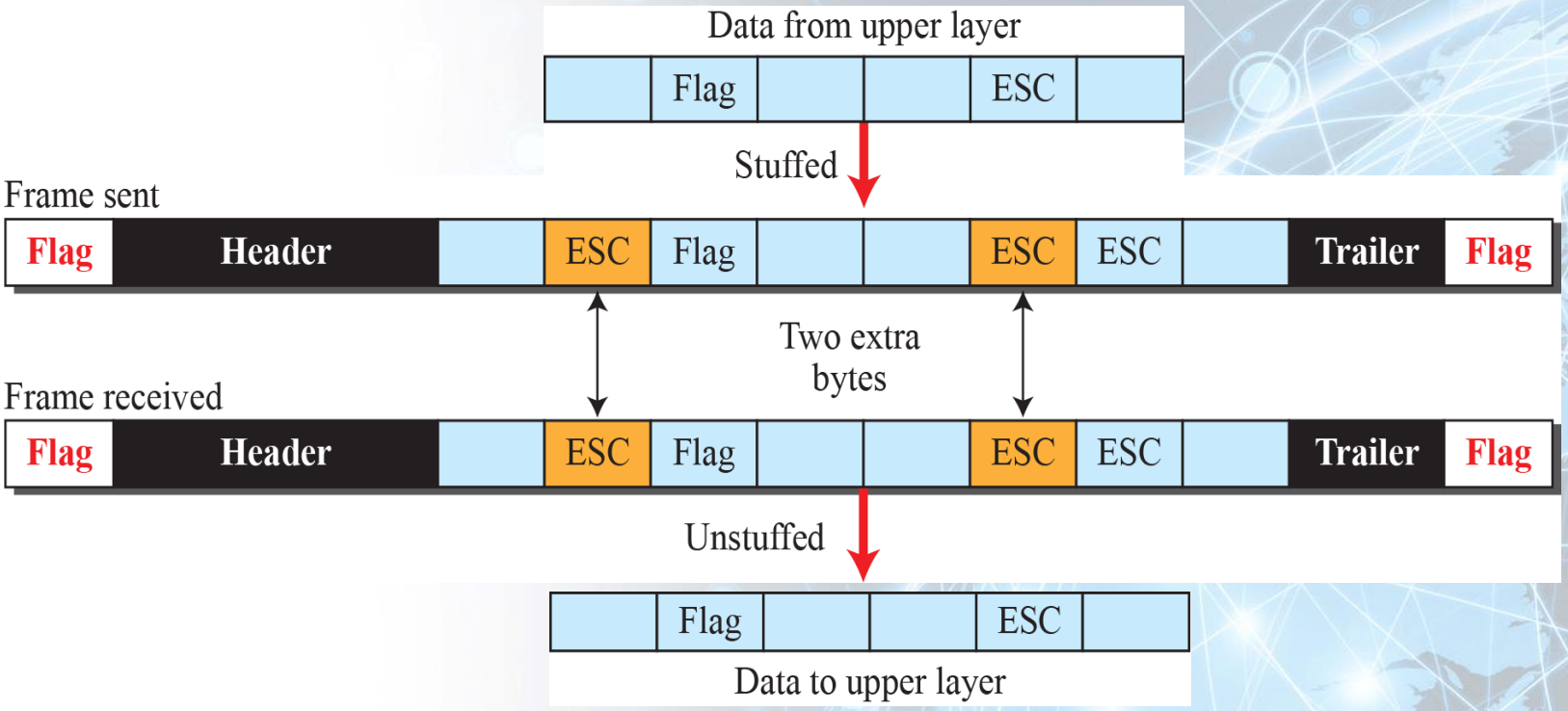
Byte Stuffing in Connection-Oriented Framing

- Connection-oriented Framing used text characters as flags
- Nowadays any character used for flag can also be a part of the data
- In order to avoid confusing the receiver, we use Byte Stuffing

Byte Stuffing in Connection-Oriented Framing

- Several Issues:
  - ✓ One or more escape characters followed by a byte with same pattern as a flag?
  - ✓ Unicode (16/32 bit) vs. 8-bit characters
- Data is stuffed with a pre-defined Escape Character (byte) when there is a character with same pattern as a flag

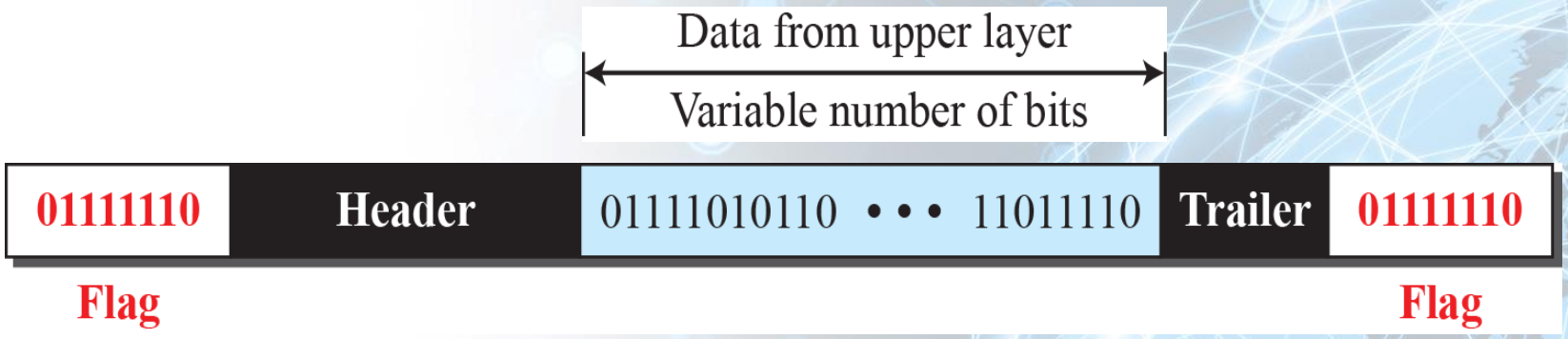
Byte Stuffing and Unstuffing



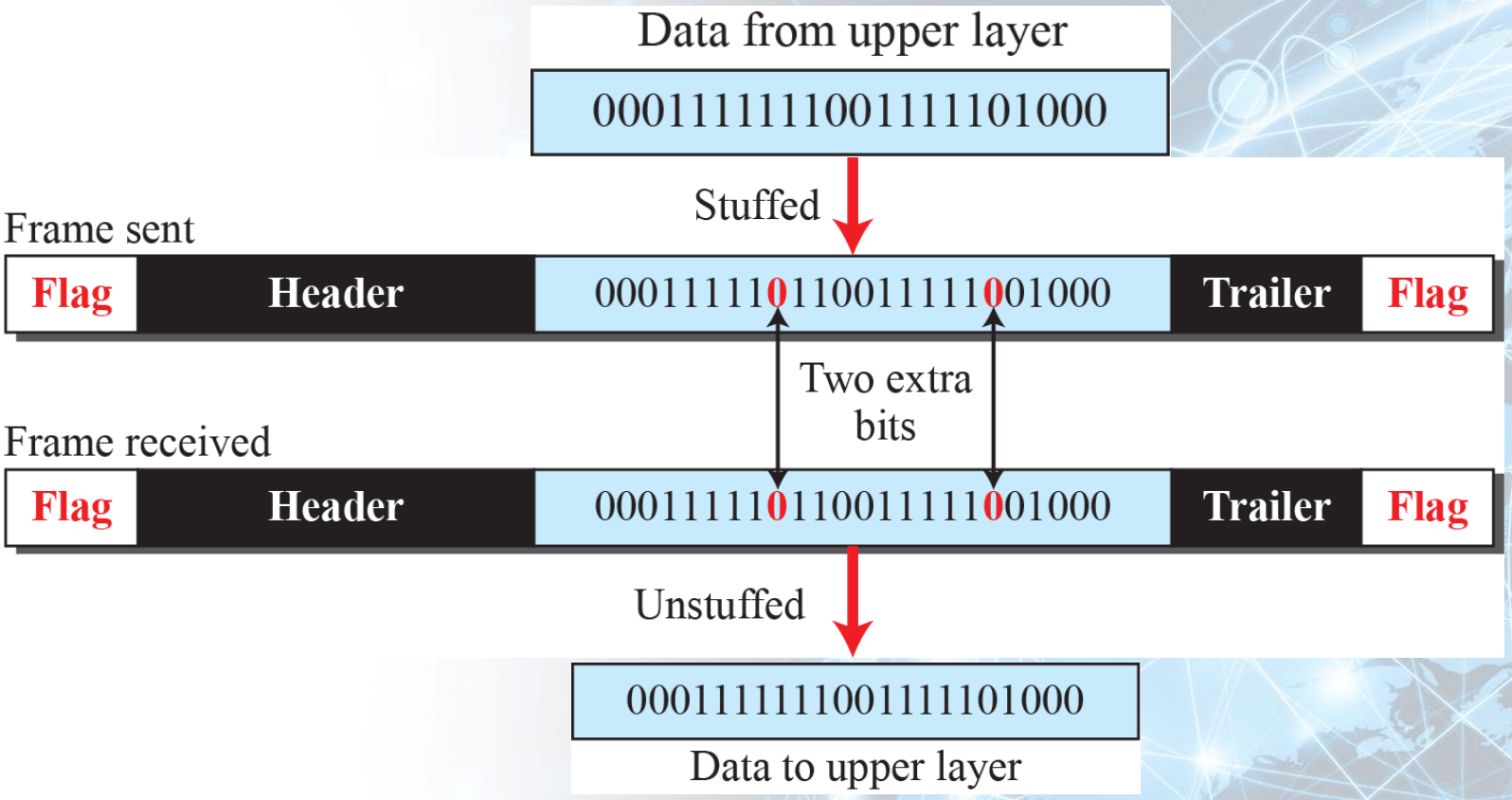
Bit-Oriented Framing

- Data section of frame is a sequence of bits
- We need a delimiter to separate one frame from the other
- A special 8-bit pattern (01111110) to define beginning and end of a frame
- Same issue as Connection-oriented Framing

A Frame in a Bit-Oriented Protocol



Bit Stuffing and Unstuffing



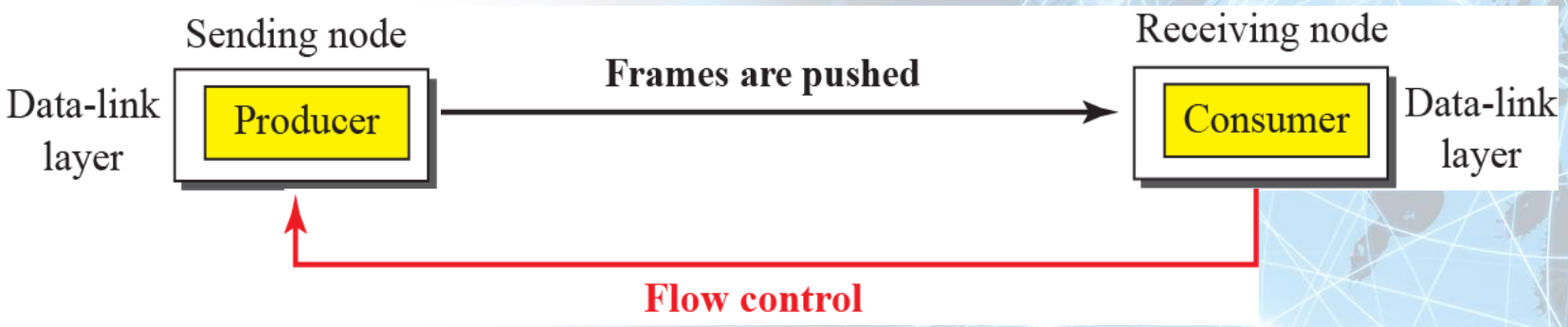
Flow and Error Control

- One of the responsibilities of the data-link control sublayer is flow and error control at the data-link layer

Flow Control

- Balance between production and consumption rates
- If frames are produced faster than they are consumed at the receiving data link layer, the frames will be discarded
- Use of buffers; one at sending end and other at receiving end

Flow Control at the Data Link Layer



Example

- Consumers need to communicate with the producers on two occasions:
  - ✓ When the buffer is full; &
  - ✓ When there are vacancies

- ✓ If the two parties use a buffer with only one slot, the communication can be easier

Error Control

- **Error Control at Data Link layer uses CRC in one of the two ways:**
  - ✓ **If a frame is corrupted, it is silently discarded and if it is good, it is delivered to network layer**
  - ✓ **If frame is corrupted, it is silently discarded and if it is good, an acknowledgement is sent to sender**

Connectionless and Connection-Oriented

- A DLC protocol can be either connectionless or connection-oriented
- Connectionless: No relationship between the frames
- Connection-Oriented: Frames are numbered and sent in order

DATA-LINK LAYER PROTOCOLS

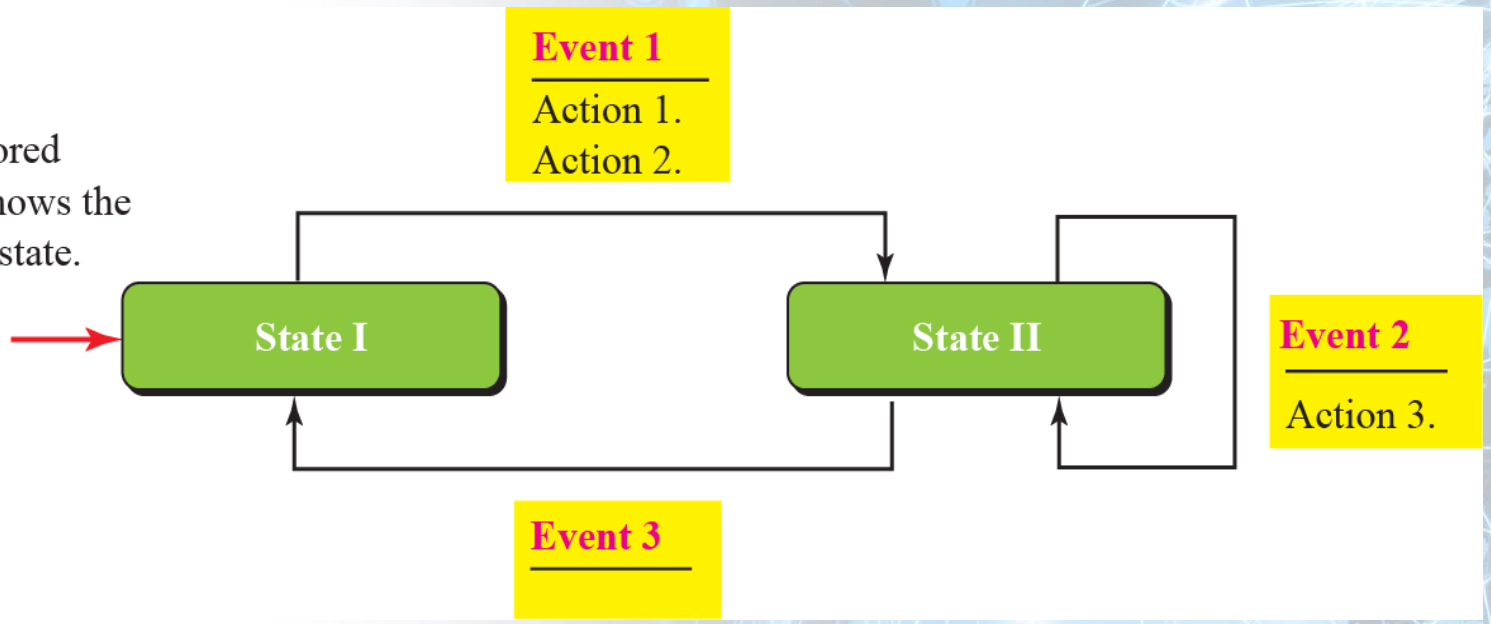
- Traditionally four protocols have been defined for the data-link layer to deal with flow and error control:
  - ✓ Simple Protocol
  - ✓ Stop-and-Wait Protocol
  - ✓ Go-Back-N Protocol
  - ✓ Selective-Repeat Protocol
- Last two protocols have almost disappeared completely

Finite State Machine (FSM)

- A machine with a finite number of states
- Machines stays in one of the states until an event occurs
- Each event is associated with 2 reactions:
  - ✓ List of actions to be performed
  - ✓ Determining the next state

Finite State Machine (FSM)

Note:
The colored arrow shows the starting state.



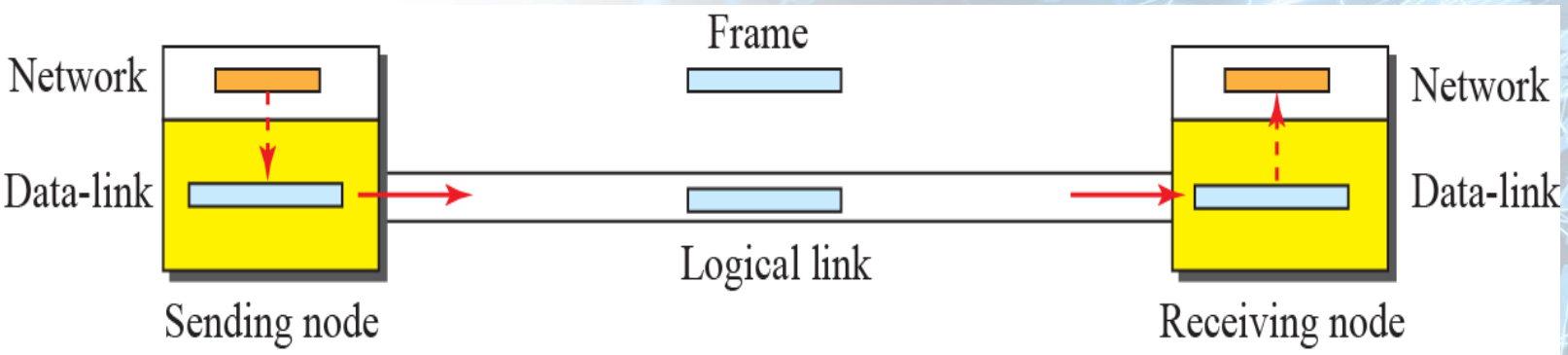
DATA-LINK LAYER PROTOCOLS

- Traditionally four protocols have been defined for the data-link layer to deal with flow and error control:
  - ✓ Simple Protocol
  - ✓ Stop-and-Wait Protocol
  - ✓ Go-Back-N Protocol
  - ✓ Selective-Repeat Protocol

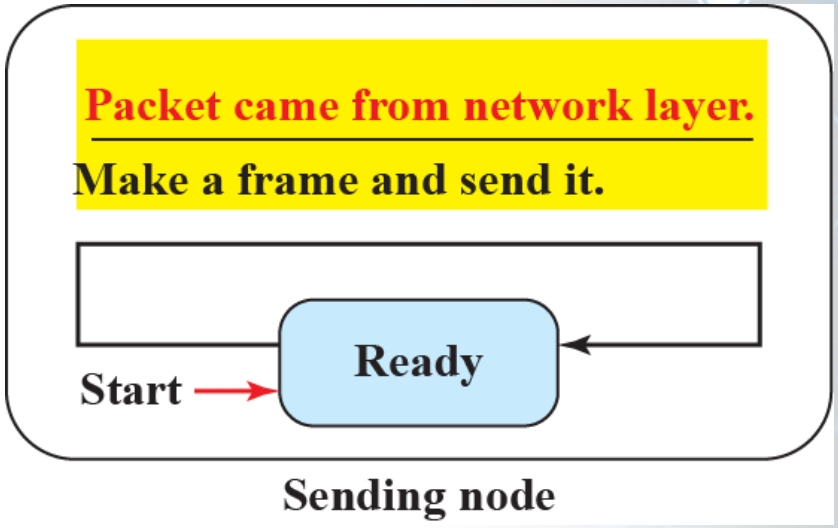
Simple Protocol

- Simple protocol has neither flow nor error control
- Assumption: The receiver can immediately handle any frame it receives
- The receiver can never be overwhelmed with incoming frames

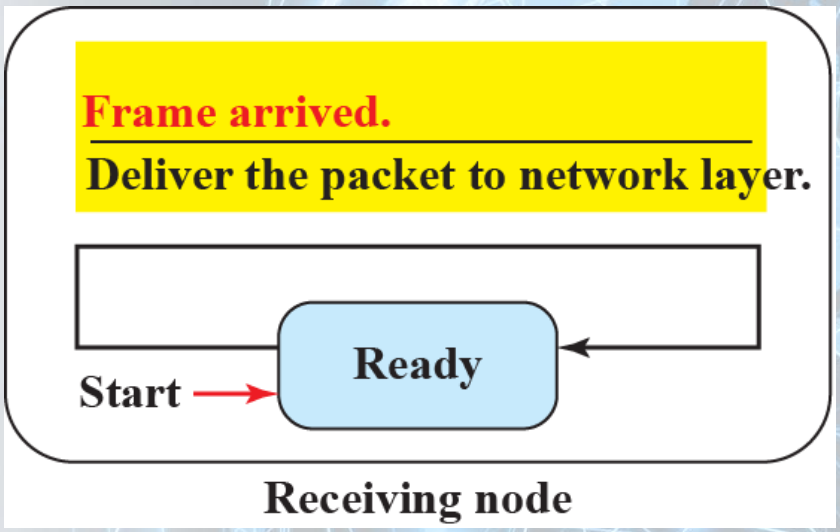
Simple Protocol



FSM for Simple Protocol



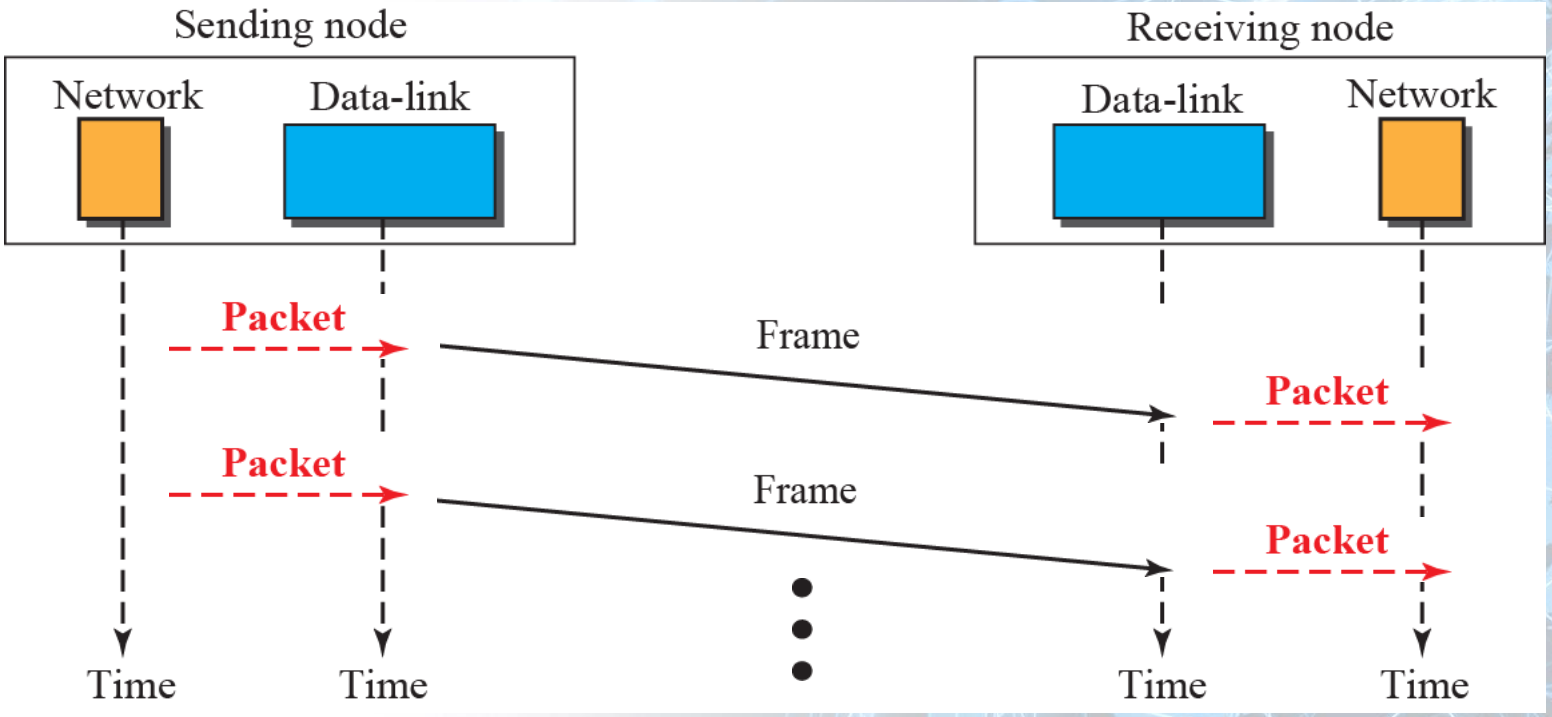
Sending node



Receiving node

Example

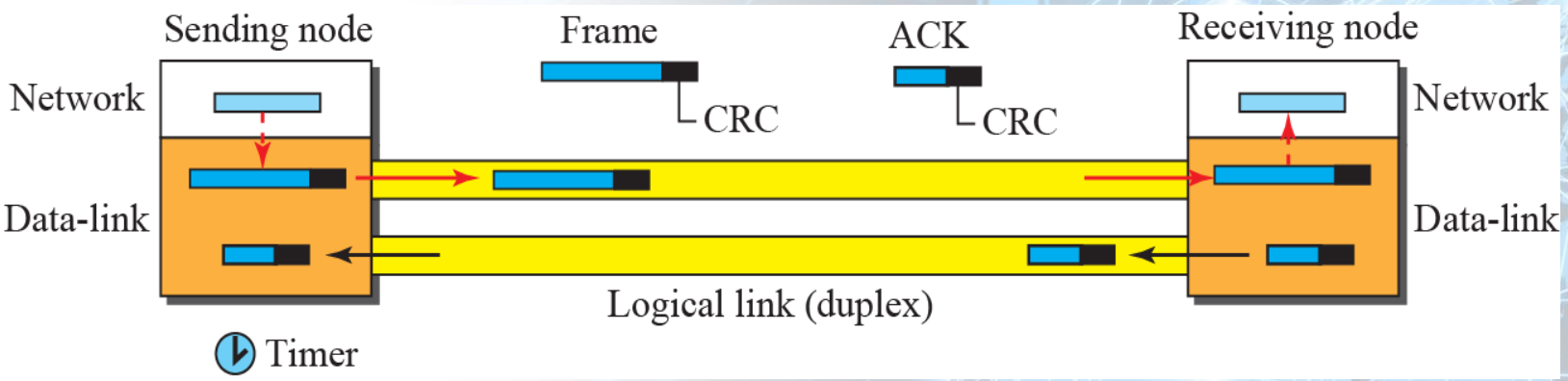
Here is an example of communication using this protocol. It is very simple. The sender sends frames one after another without even thinking about the receiver.



Stop-and-Wait Protocol

- Stop-and-Wait protocol uses both flow and error control
- The sender sends one frame at a time and waits for an acknowledgment before sending the next one
- To detect corrupted frames, we add a CRC code

Stop-and-Wait Protocol



Stop-and-Wait Protocol

- Stop-and-Wait protocol uses both flow and error control
- The sender sends one frame at a time and waits for an acknowledgment before sending the next one
- To detect corrupted frames, we add a CRC code

Example

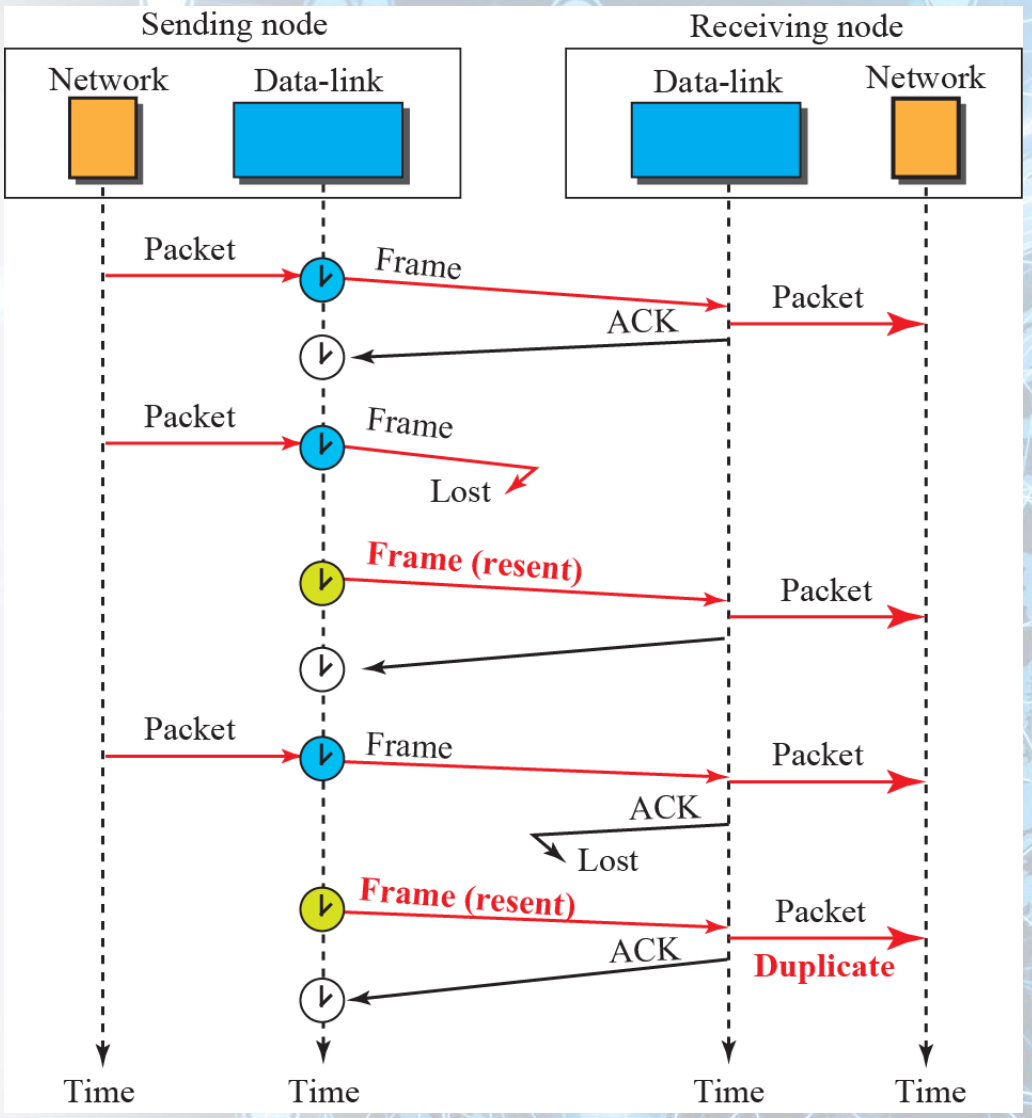
Legend

- Start the timer.
- Stop the timer.
- Restart a time-out timer.

Notes:

A lost frame means either lost or corrupted.

A lost ACK means either lost or corrupted.



Example

Legend

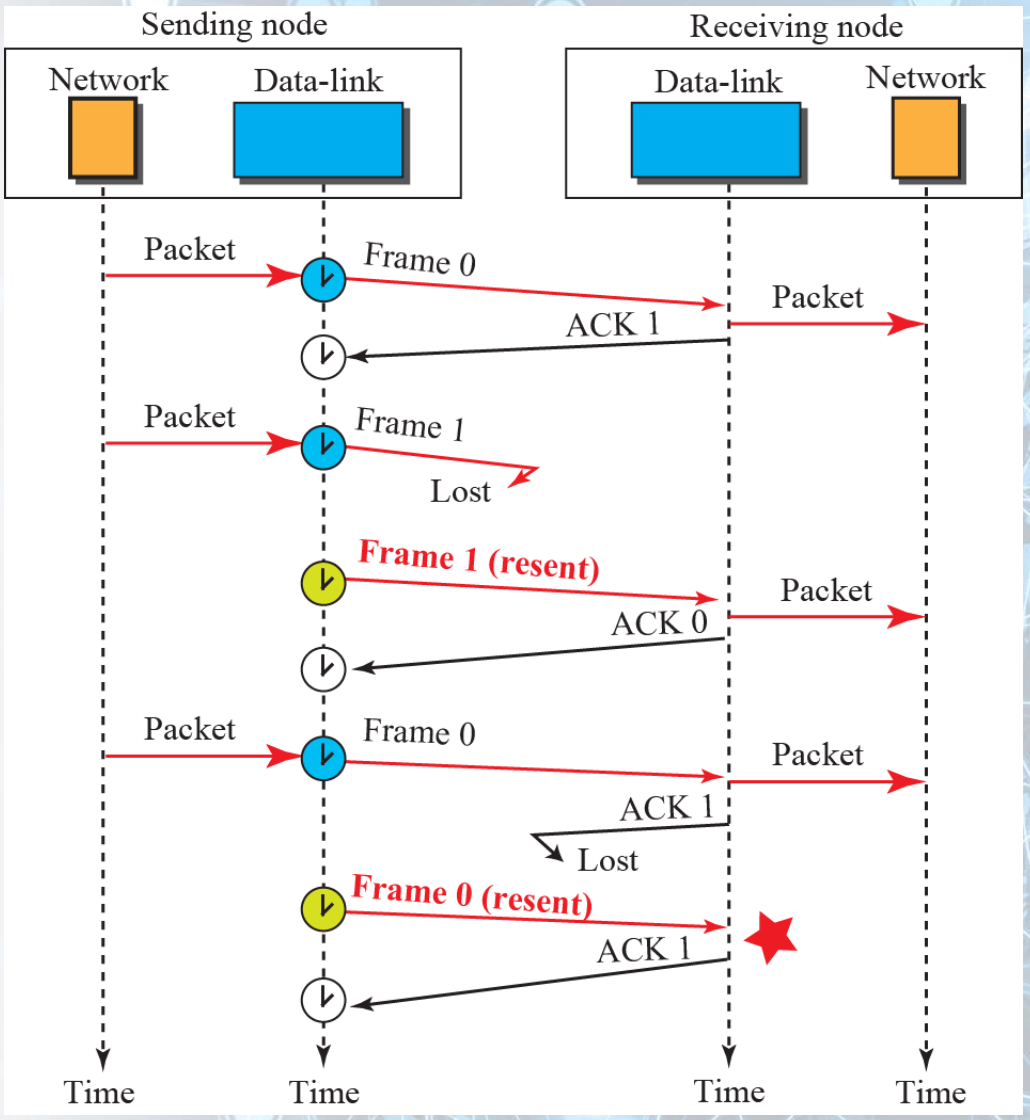
- Start the timer.
- Stop the timer.
- Restart a time-out timer.

Notes:

A lost frame means either lost or corrupted.

A lost ACK means either lost or corrupted.

Frame 0 is discarded because the receiver expects frame 1.



Piggybacking

- Both Simple and Stop-and-wait protocols are designed for unidirectional communication
- Data flows in one direction and ACK travels in the other
- To make the system efficient, the data in one direction is piggybacked with the acknowledgment in the other direction

High-level Data Link Control (HDLC)

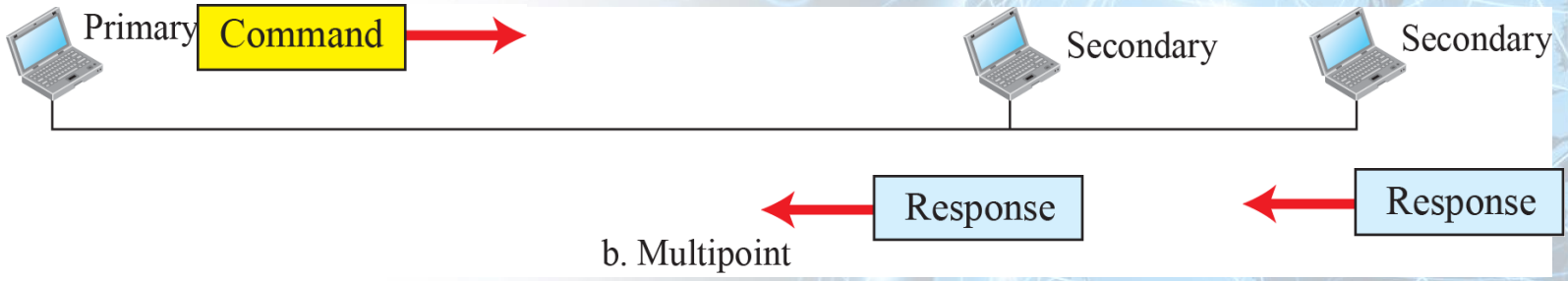
- Bit -oriented protocol for communication over point-to-point and multipoint links
- It implements Stop-and-Wait protocol
- Most of the concepts defined in this protocol is the basis for other protocols such as PPP, Ethernet, or wireless LANs

Configurations & Transfer Modes in HDLC

- HDLC provides two common transfer modes that can be used in different configurations:
  - ✓ Normal Response Mode (NRM) &
  - ✓ Asynchronous Balanced Mode (ABM)

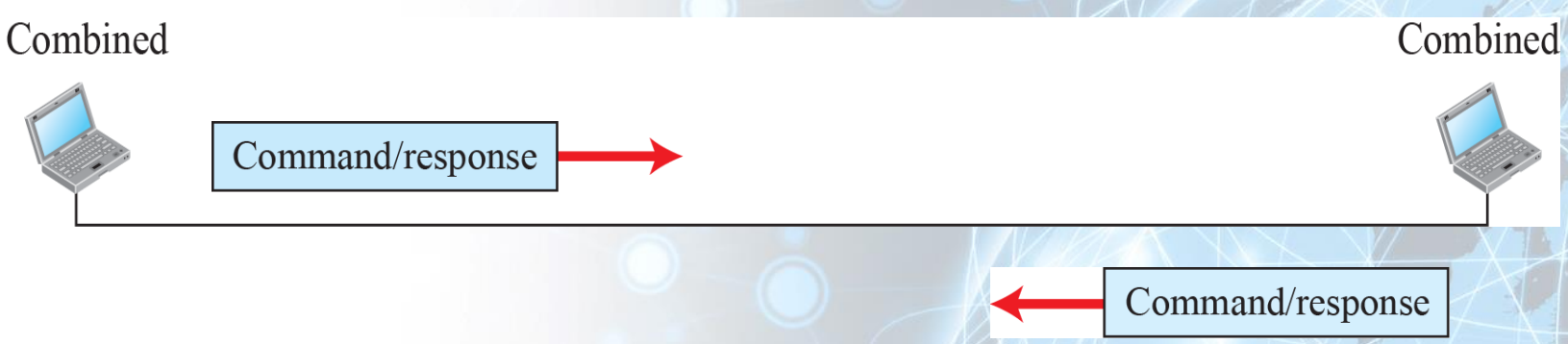
Normal Response Mode

a. Point-to-point



b. Multipoint

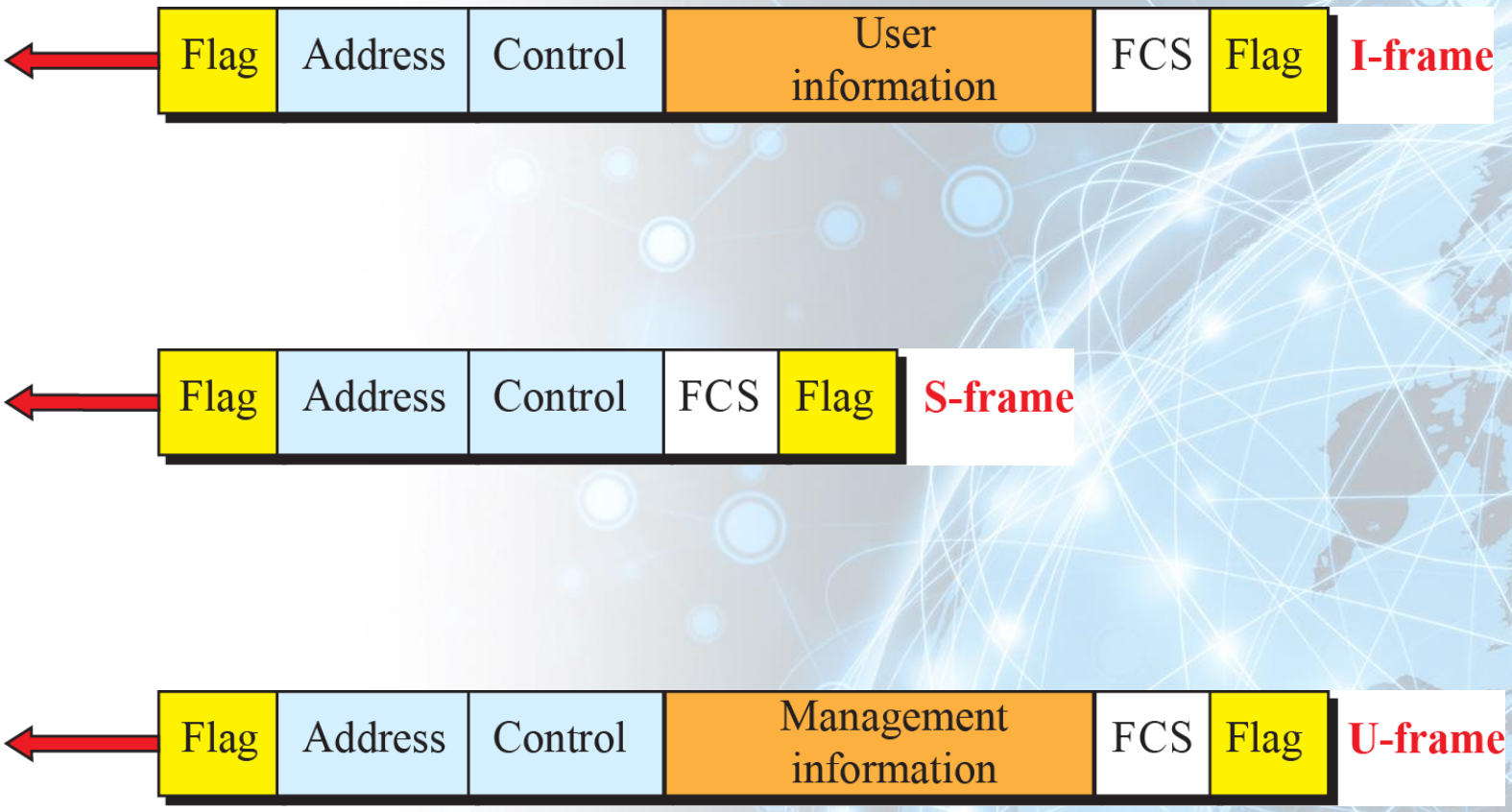
Asynchronous Balanced Mode



Framing

- **HDLC defines three types of frames:**
  - ✓ **information frames (I-frames)**
  - ✓ **Supervisory frames (S-frames)**
  - ✓ **Unnumbered frames (U-frames)**

HDLC Frames


Flag
Address
Control
User information
FCS
Flag
I-frame
Flag
Address
Control
FCS
Flag
S-frame
Flag
Address
Control
Management information
FCS
Flag
U-frame

Point-to-Point Protocol (PPP)

- Most common protocol for point-to-point access
- Millions of Internet users who need to connect their home computers to the server of an Internet service provider use PPP
- To control and manage the transfer of data, there is a need for a PPP at the data-link layer

Services provided by PPP

The designers of PPP have included several services to make it suitable for a point-to-point protocol, but have ignored some traditional services to make it simple

Services Included	Services Not Included
Framing	Flow Control
Link Establishment and Data Exchange	Error Correction (PPP has CRC detection only)
Authentication	No Sequence Numbering
Multilink PPP Address configuration	Absence of sophisticated Addressing Mechanism
Network Address configuration	

Point-to-Point Protocol (PPP)

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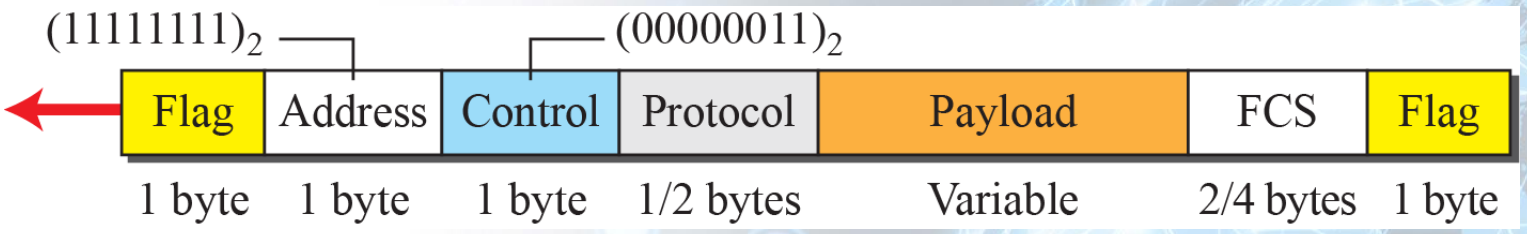
- Millions of Internet users who need to connect their home computers to the server of an Internet service provider use PPP
- To control and manage the transfer of data, there is a need for a PPP at the data-link layer

PPP Frame Format

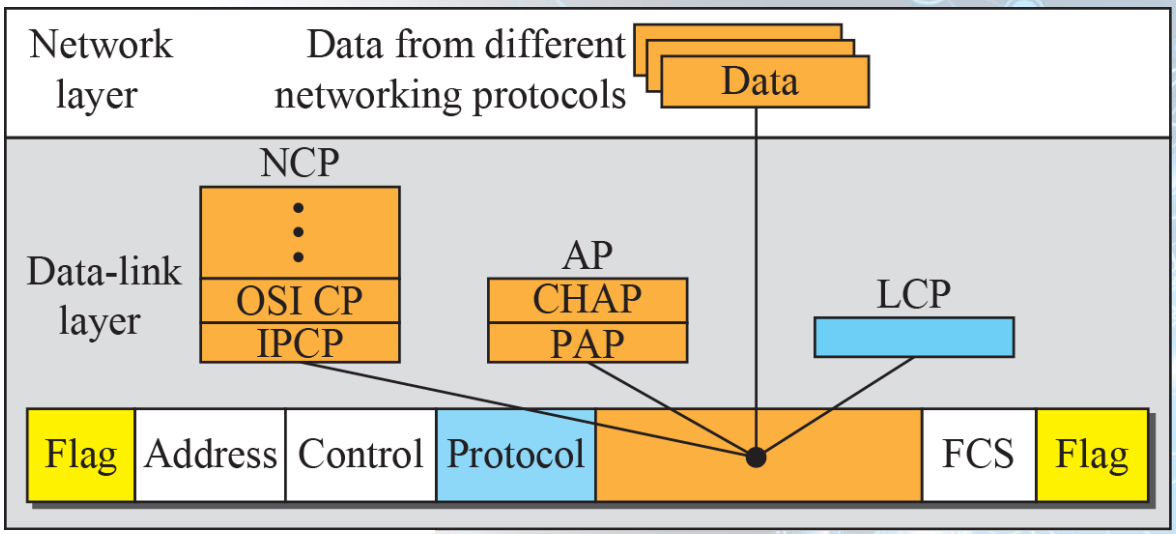
PPP uses a character-oriented (or byte-oriented) frame



Multiplexing in PPP

- Although PPP is a link-layer protocol, it uses another set of protocols to establish the link, authenticate and carry the network-layer data
- Three sets of protocols are:
  - Link Control Protocol (LCP)
  - Two Authentication Protocols (APs)
  - Several Network Control Protocols (NCPs)

Multiplexing in PPP



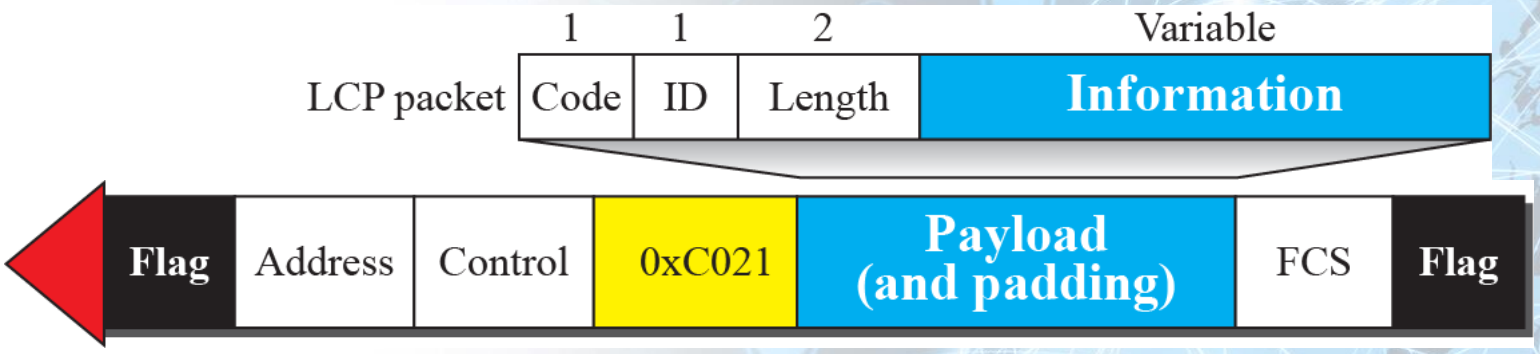
Legend

LCP : Link control protocol
AP : Authentication protocol
NCP: Network control protocol

Protocol values:

LCP : 0xC021
AP : 0xC023 and 0xC223
NCP: 0x8021 and ....
Data: 0x0021 and ....

LCP Packet encapsulated in a Frame



LCP Packets

Code	Packet Type	Description
0x01	Configure-request	Contains the list of proposed options and their values
0x02	Configure-ack	Accepts all options proposed
0x03	Configure-nak	Announces that some options are not acceptable
0x04	Configure-reject	Announces that some options are not recognized
0x05	Terminate-request	Request to shut down the line
0x06	Terminate-ack	Accept the shutdown request
0x07	Code-reject	Announces an unknown code
0x08	Protocol-reject	Announces an unknown protocol
0x09	Echo-request	A type of hello message to check if the other end is alive
0x0A	Echo-reply	The response to the echo-request message
0x0B	Discard-request	A request to discard the packet

Multiplexing in PPP

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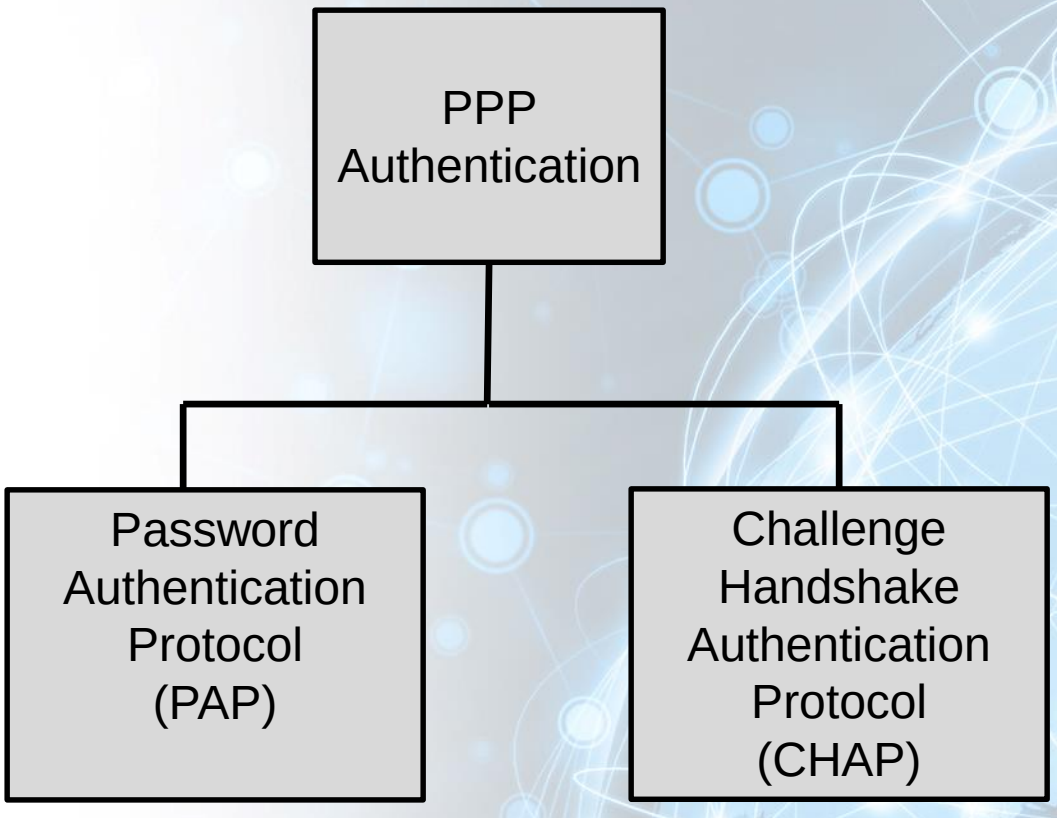
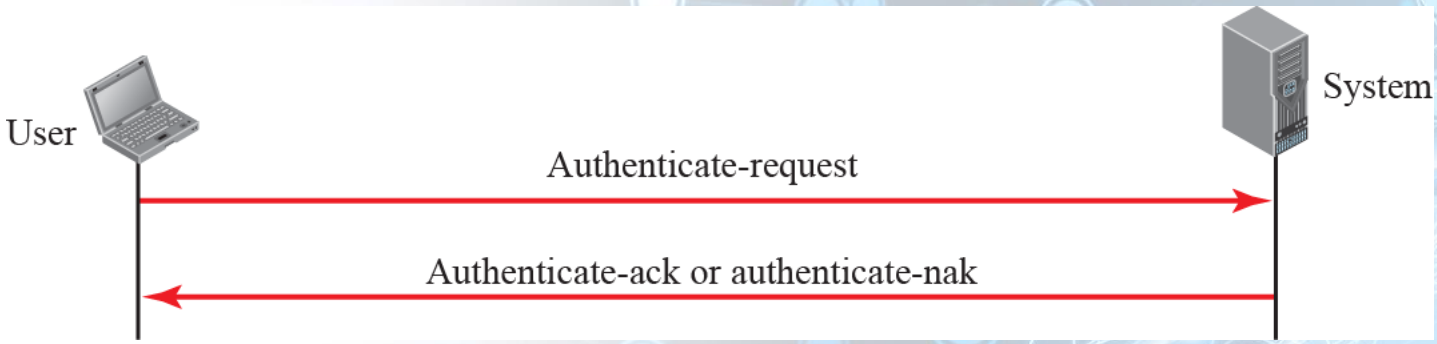
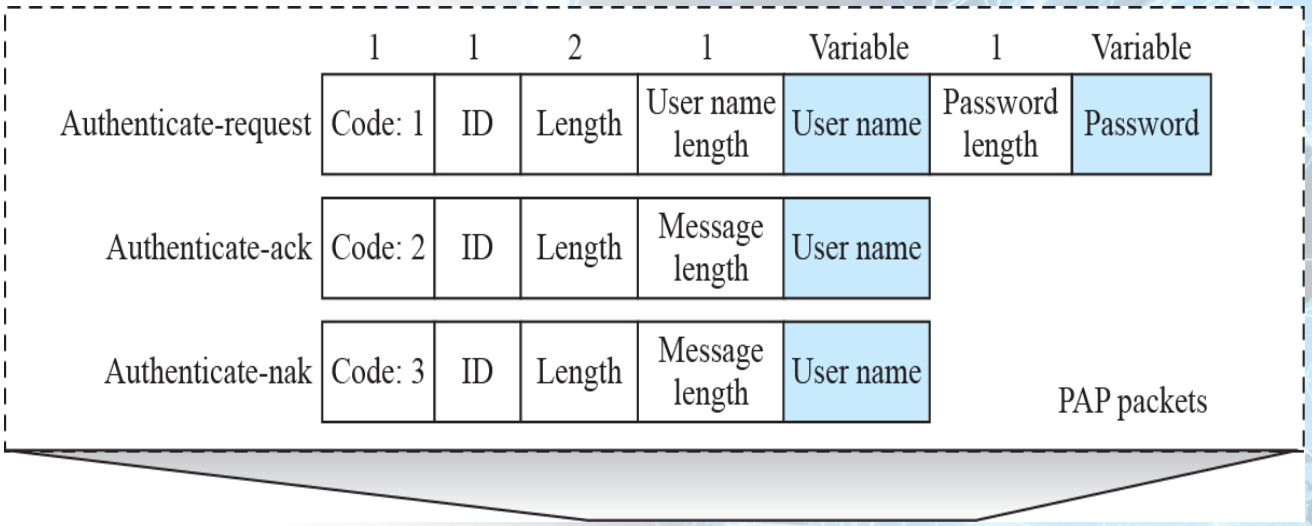
Authentication Protocols in PPP

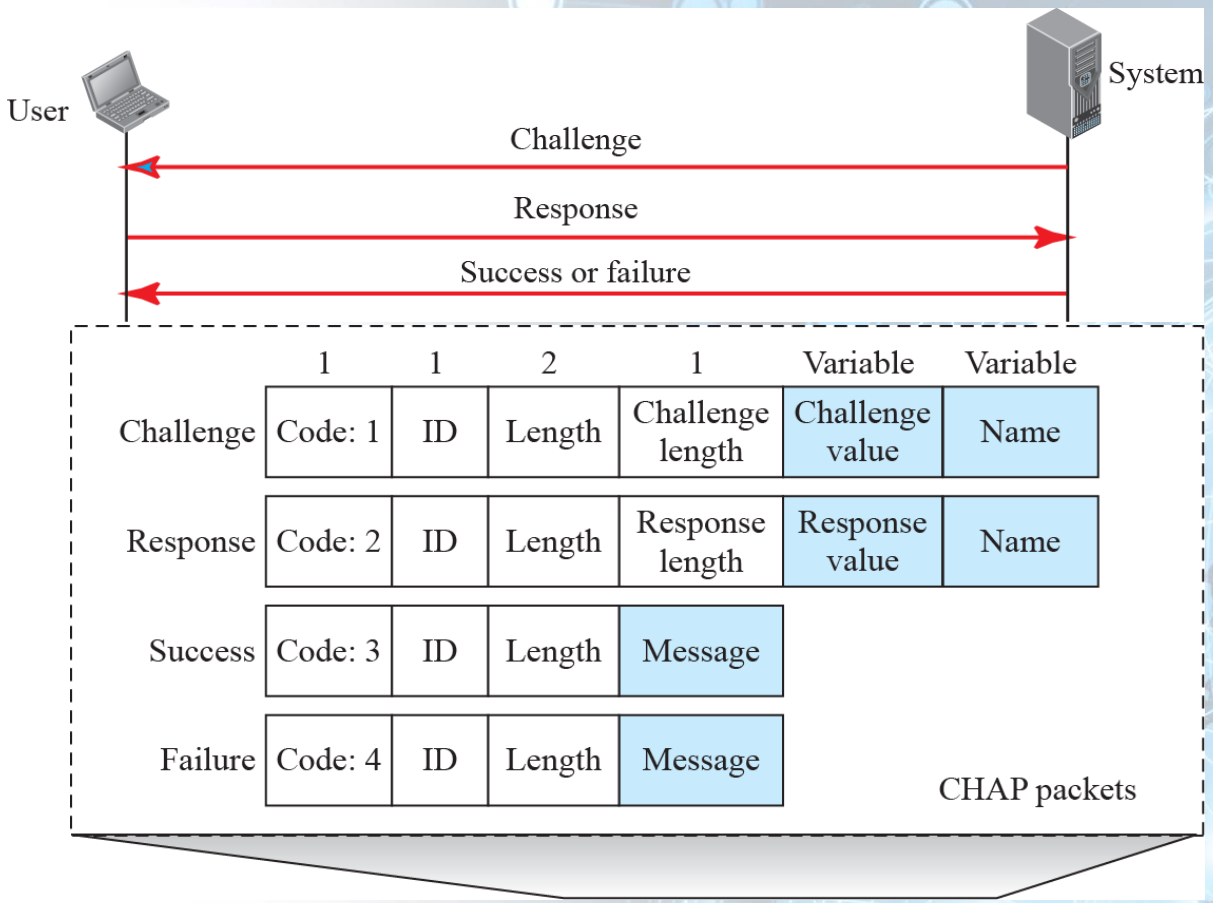


PAP packets encapsulated in a PPP frame

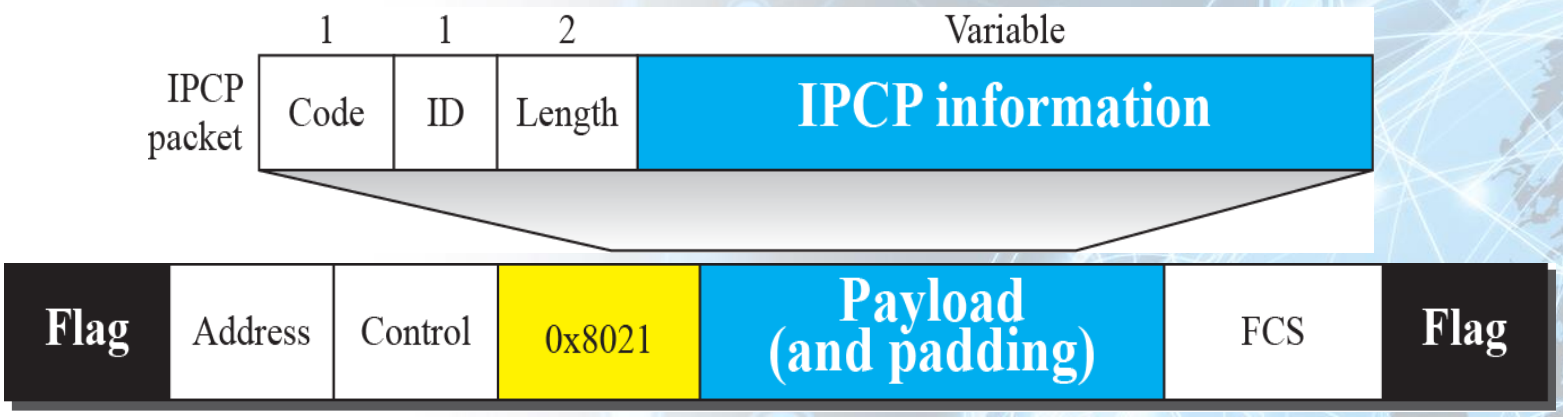




CHAP Packets encapsulated in a PPP frame



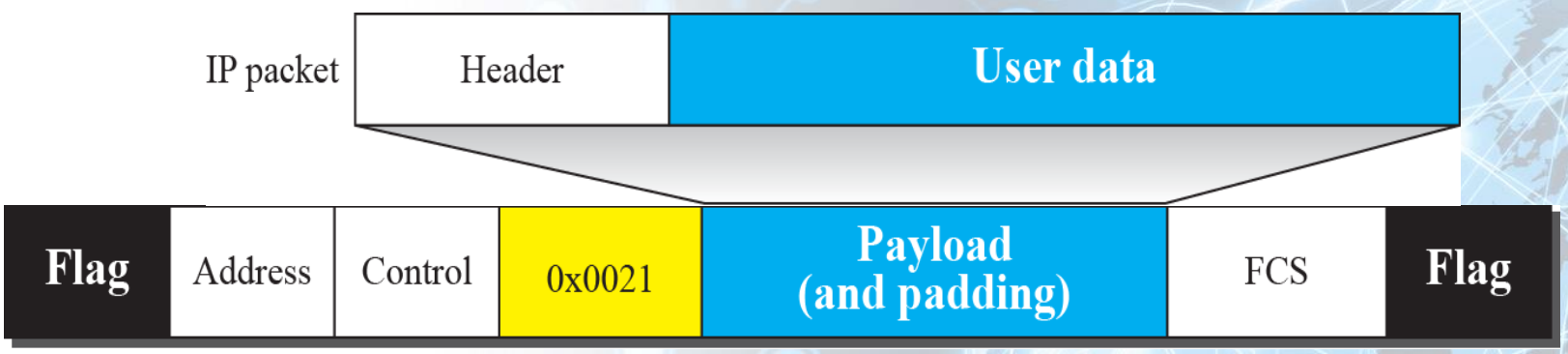
Internet Protocol Control Protocol (IPCP)



Code values for IPCP Packets

Code	*IPCP Packet*
0x01	Configure-request
0x02	Configure-ack
0x03	Configure-nak
0x04	Configure-reject
0x05	Terminate-request
0x06	Terminate-ack
0x07	Code-reject

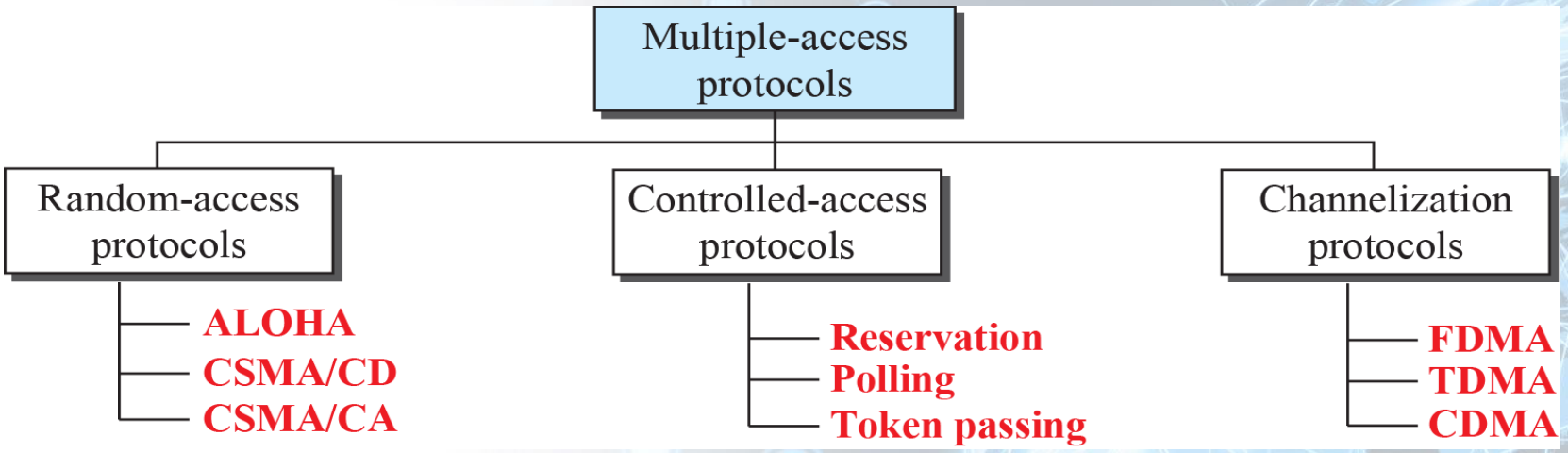
IP datagram encapsulated in a PPP frame



Media Access Control (MAC) Sub-Layer

- When nodes use a multipoint or broadcast link, we need a multiple-access protocol to coordinate access to the link
- Many protocols have been devised to handle access to a shared link
- All of these protocols belong to Media Access Control (MAC) sub-layer

Taxonomy of Multiple-Access Protocols



Random Access

- In random-access or contention no station is superior to the other and none is assigned control over the other
- Station that has data to send uses a procedure defined by the protocol to make a decision on whether or not to send
- This decision depends on the state of the medium (idle or busy)

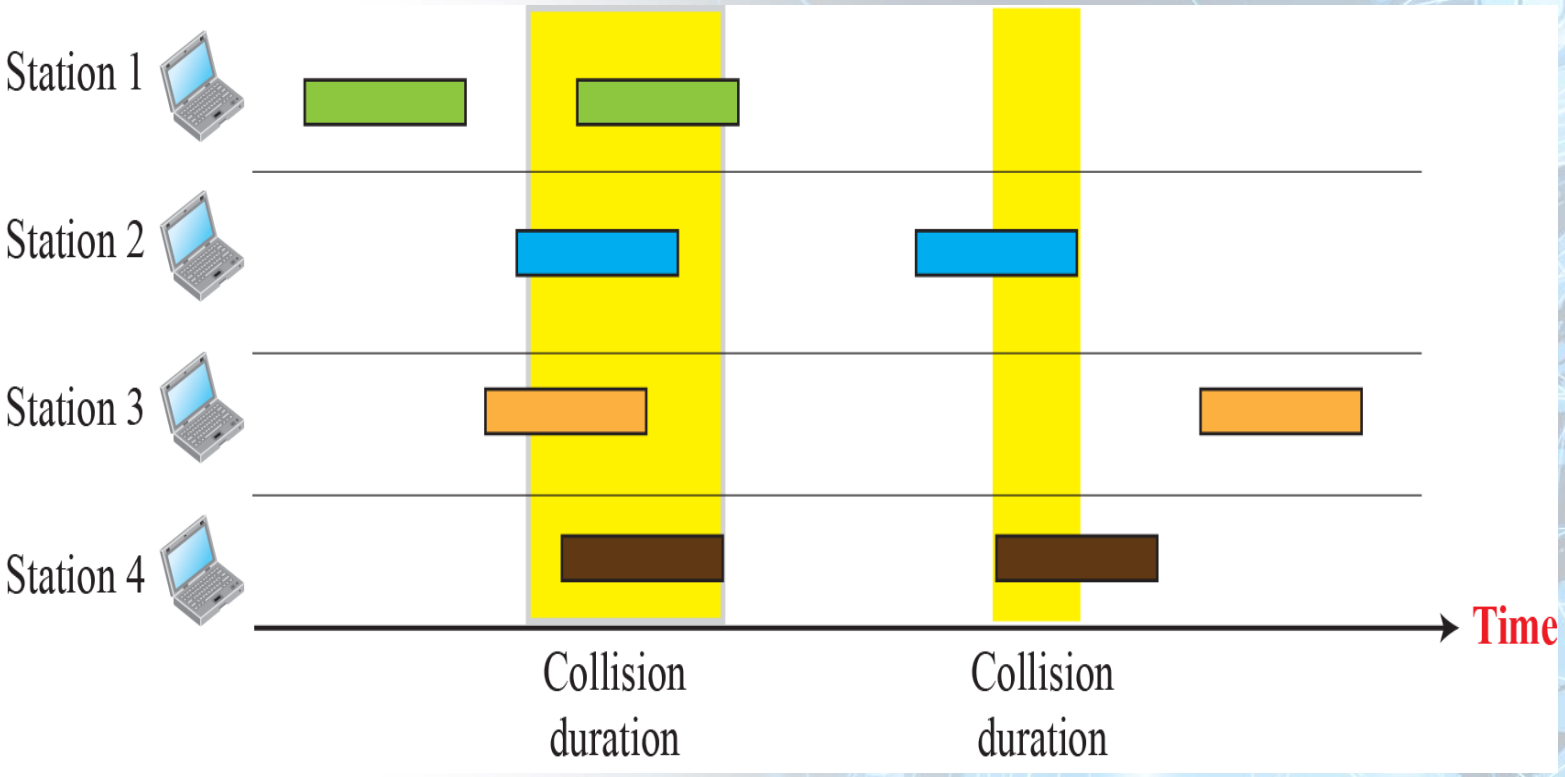
ALOHA

- ALOHA, the earliest random access method, was developed in early 1970s
- Designed for a radio (wireless) LAN, but it can be used on any shared medium
- Potential collisions in this arrangement as the medium is shared between the stations

ALOHA

- When a station sends data, another station may attempt to do so at the same time
- The data from the two stations collide and become garbled

Frames in a pure ALOHA network



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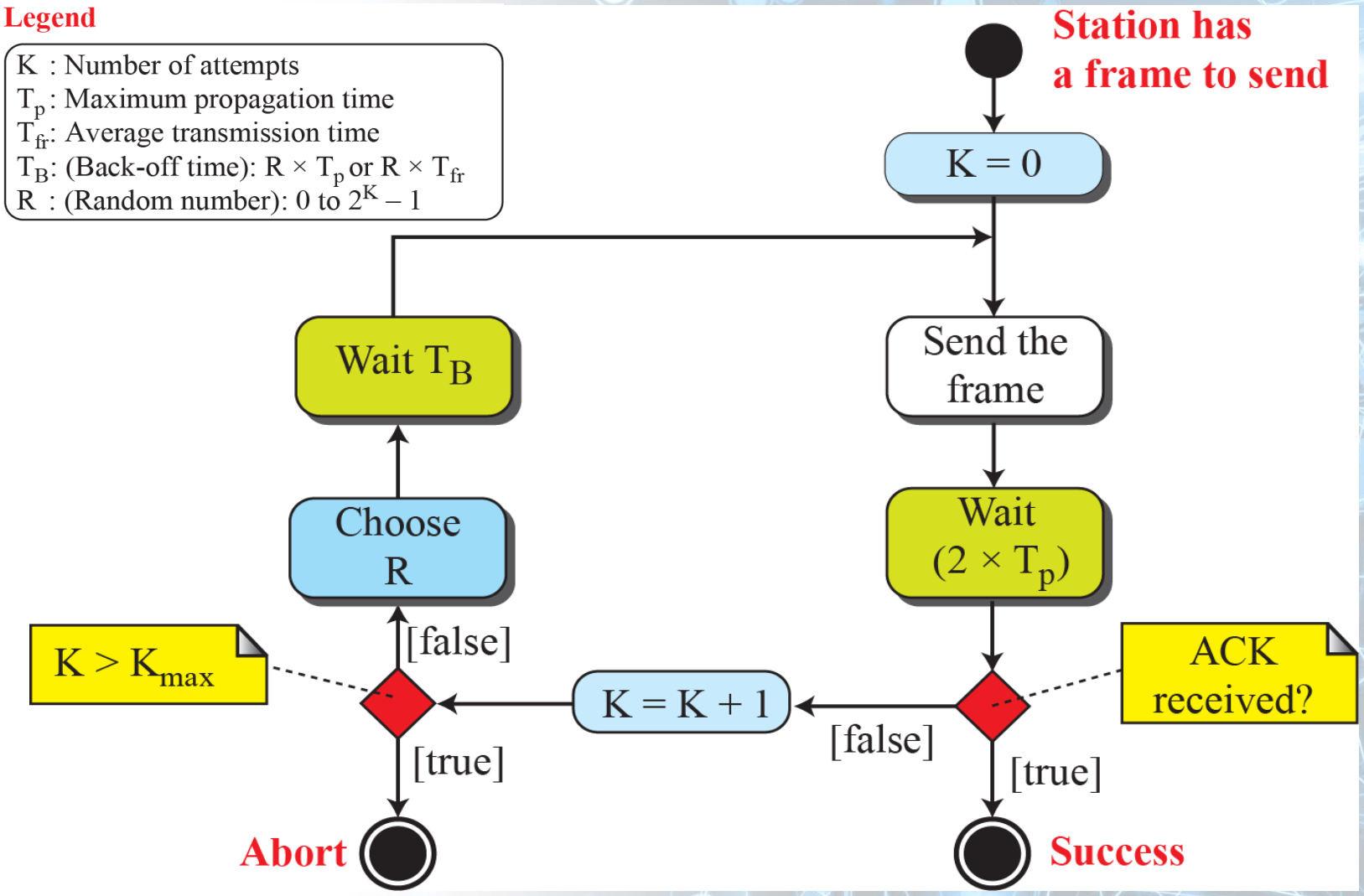
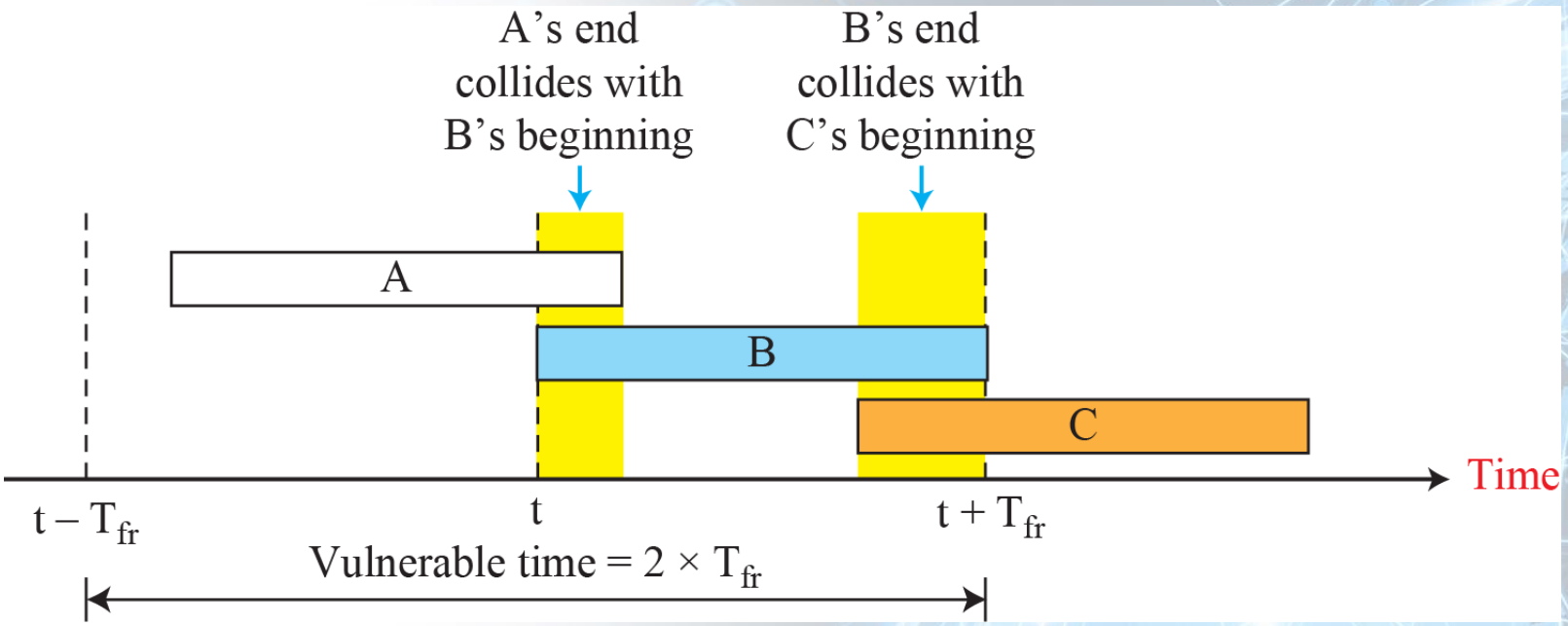
Procedure for pure ALOHA protocol



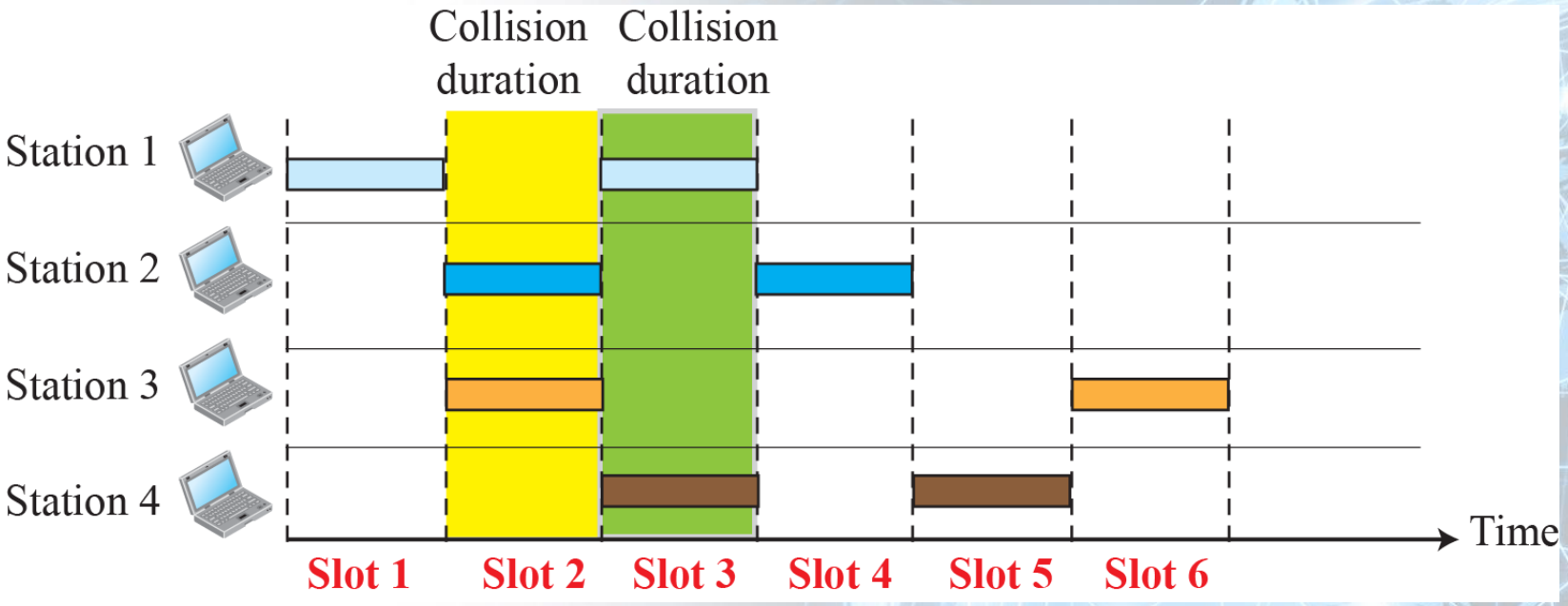
Vulnerable Time for pure ALOHA protocol



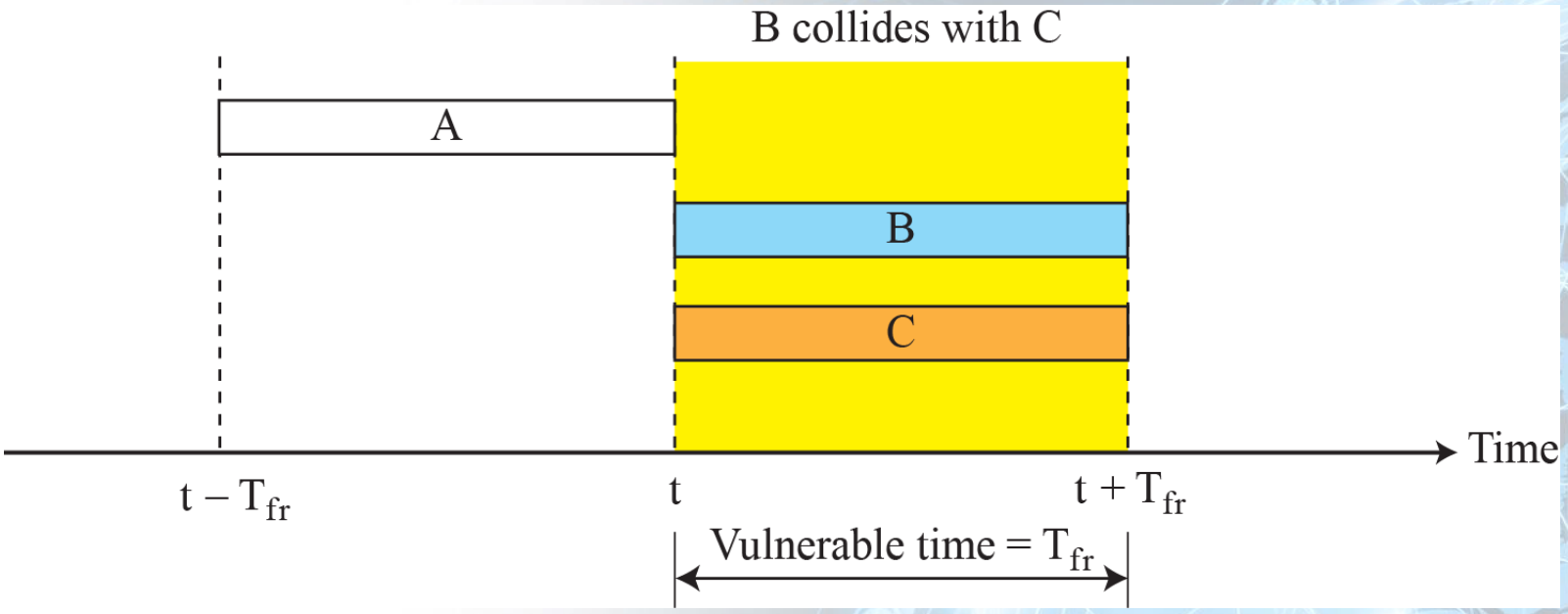
Slotted ALOHA

- We divide time into slots of T_{fr} sec and force the station to send only at the beginning of the slot
- Invented to improve the efficiency of pure ALOHA
- If a station misses the time slot, it must wait until beginning of next time slot reducing vulnerable time to T_{fr} (vs. 2 x T_{fr} for pure ALOHA)

Frames in a Slotted ALOHA Network



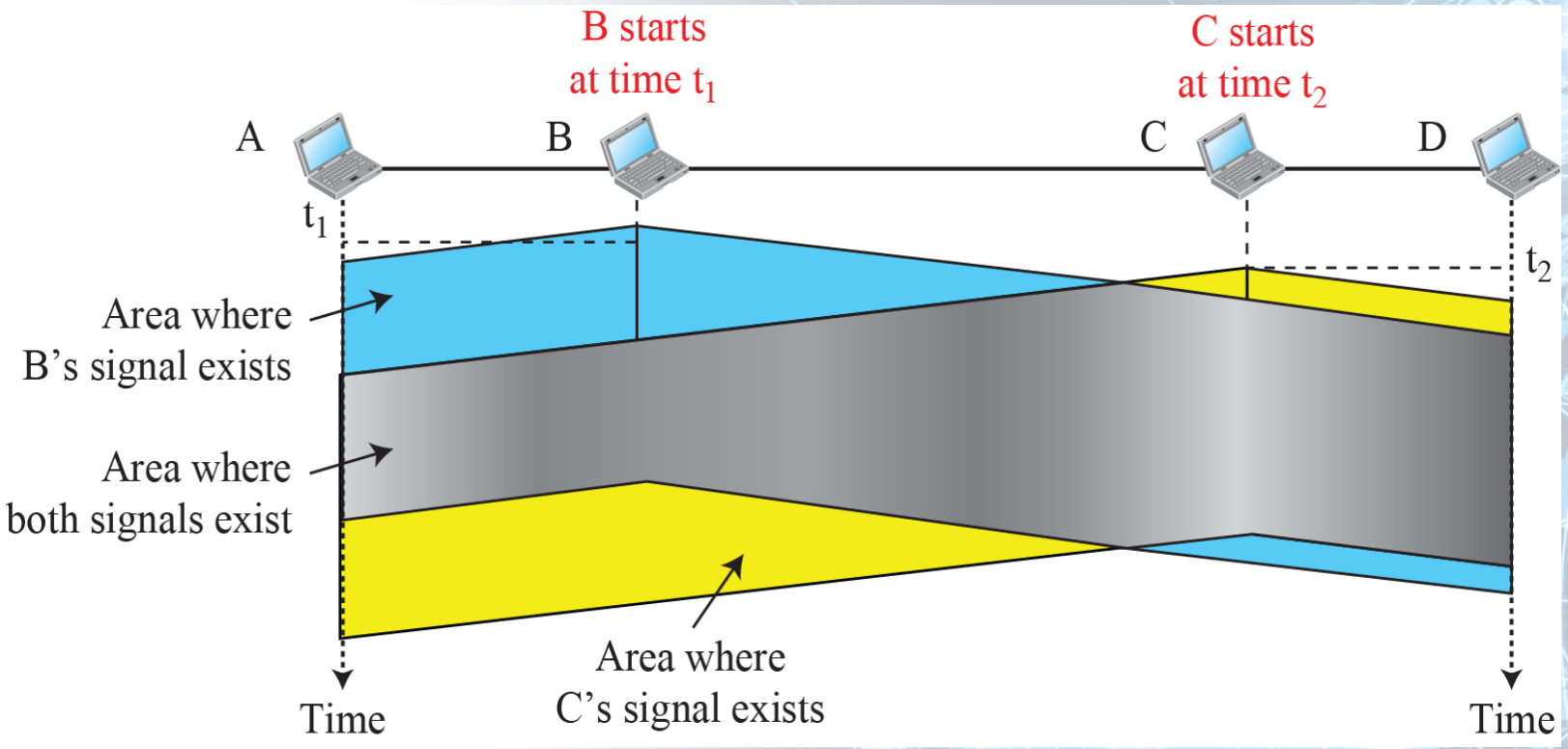
Vulnerable Time for Slotted ALOHA



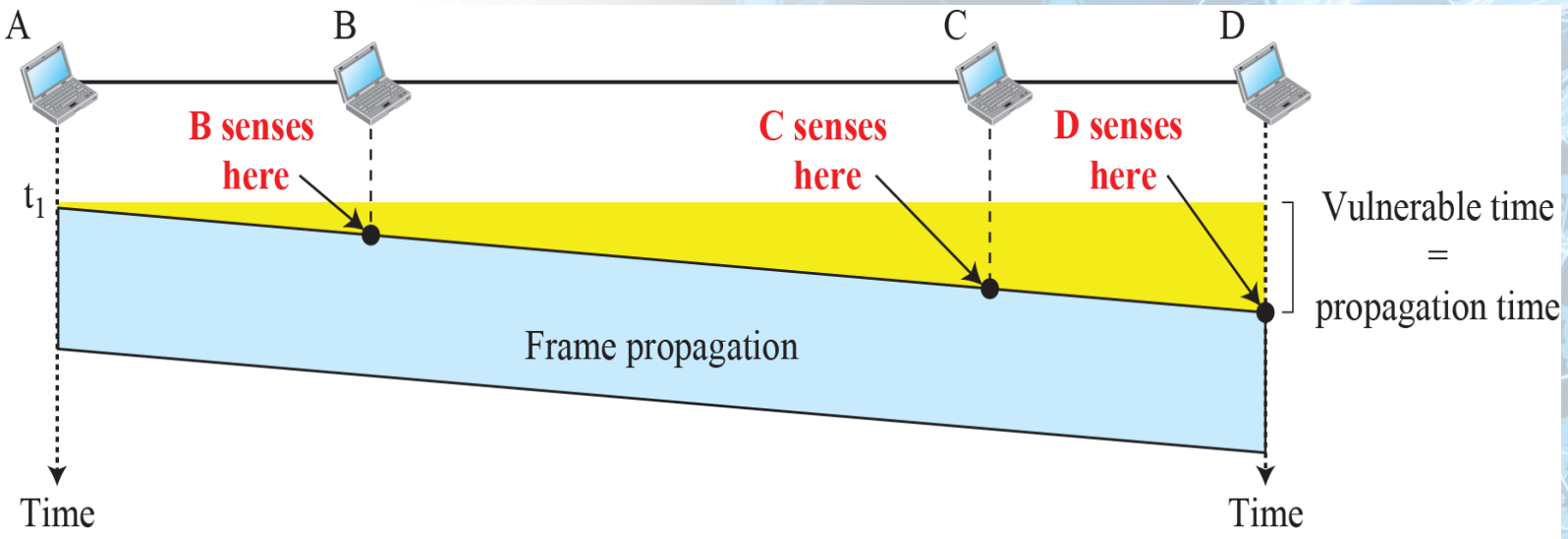
Carrier Sense Multiple Access (CSMA)

- To minimize the chance of collision and, therefore, increase the performance, CSMA was developed
- The chance of collision is reduced as the station is required to sense/listen to the medium before sending data
- ‘sense before transmit’ or ‘listen before talk’

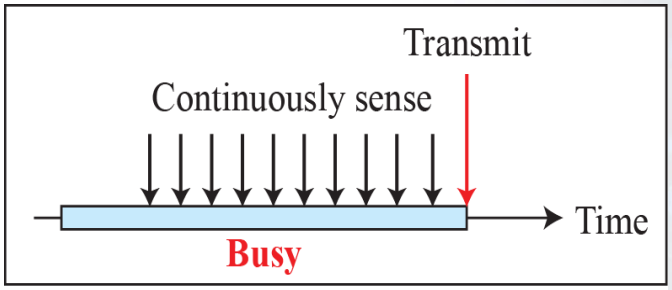
Space/Time Model of a Collision in CSMA



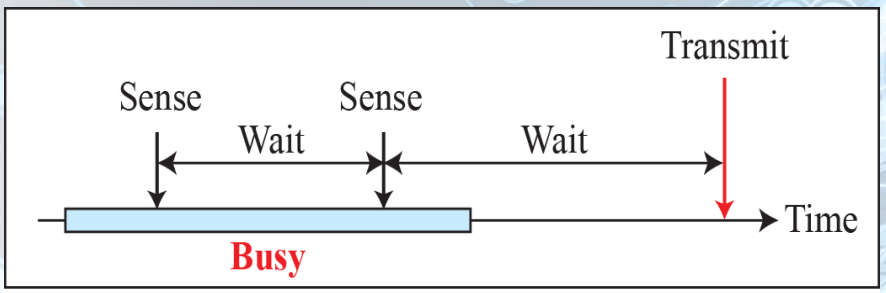
Vulnerable Time in CSMA



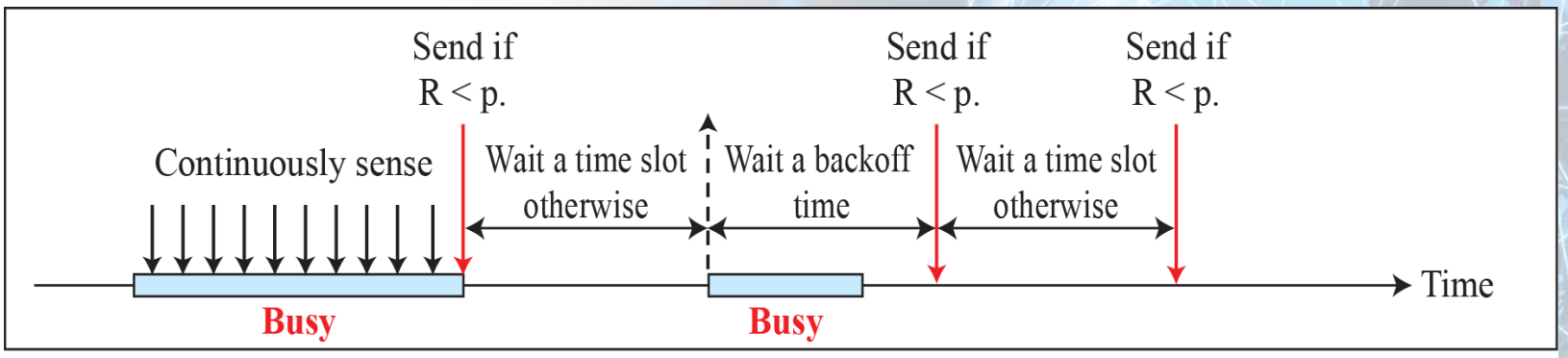
Behavior of Three Persistence Methods



a. 1-persistent



b. Nonpersistent

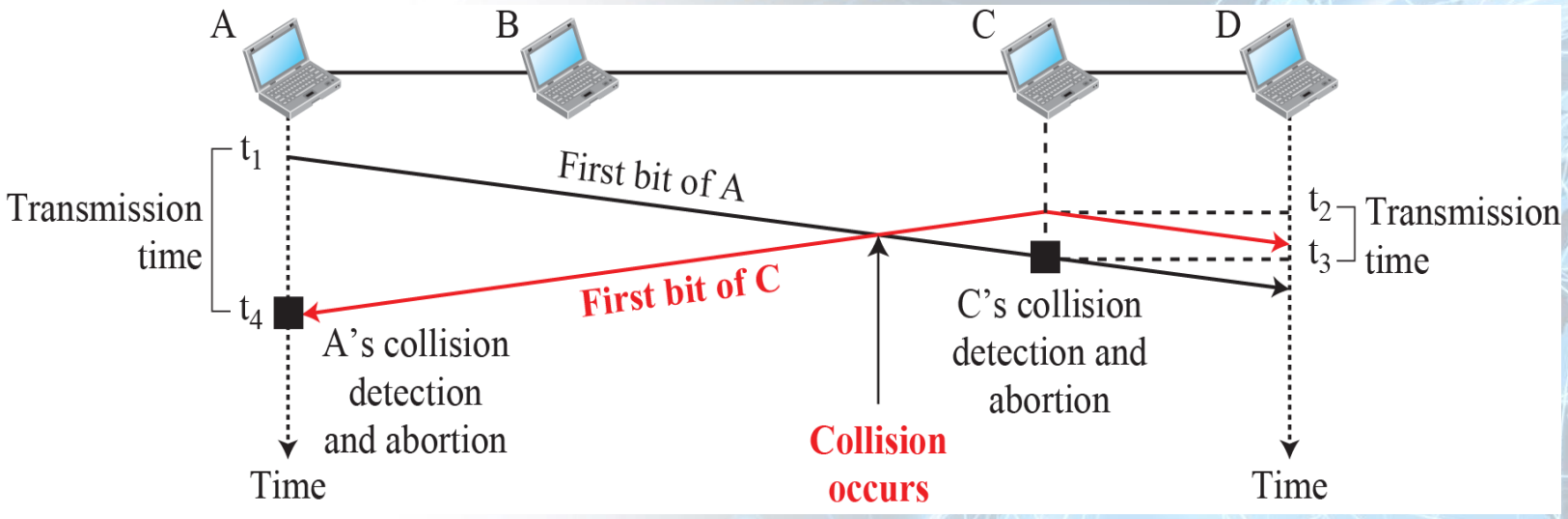


c. *p*-persistent

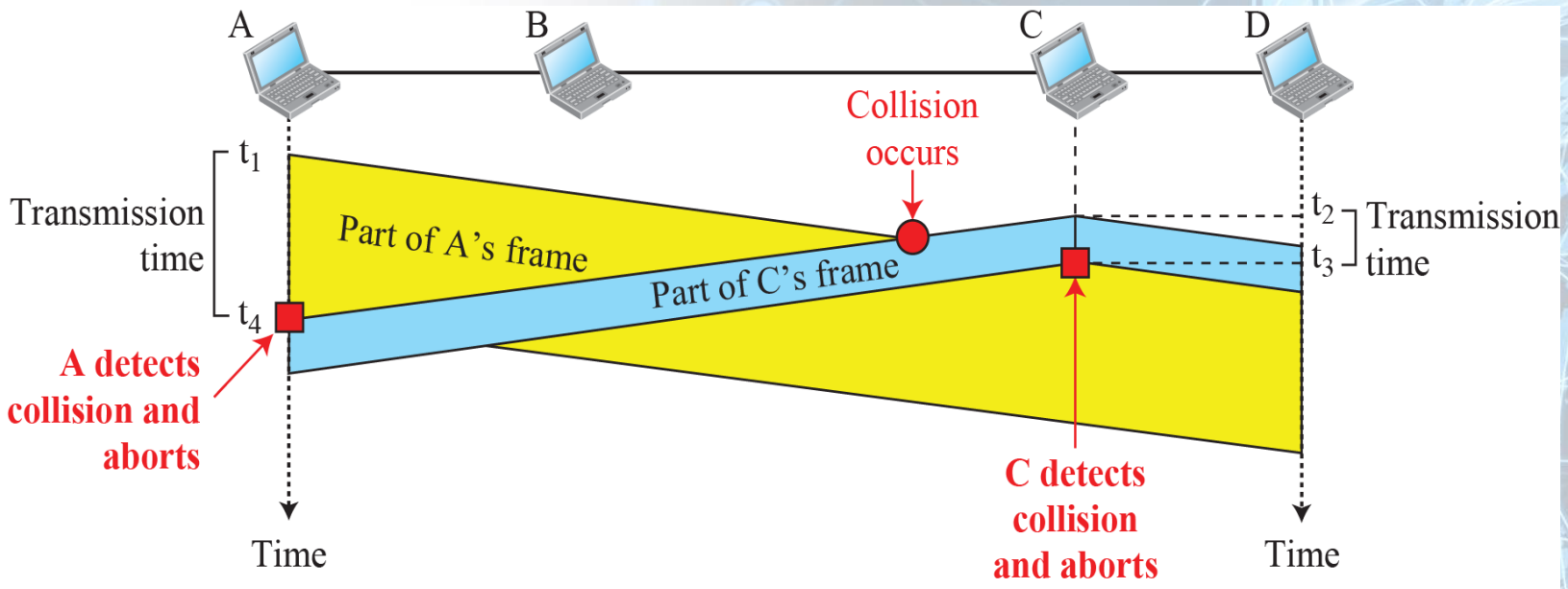
Carrier Sense Multiple Access/Collision Detection

- CSMA method does not specify the procedure following a collision
- CSMA/CD augments the algorithm to handle the collision
- The station monitors the medium after it sends a frame to see if the transmission was successful. If there is a collision, the frame is sent again

Collision of the First Bits in CSMA/CD



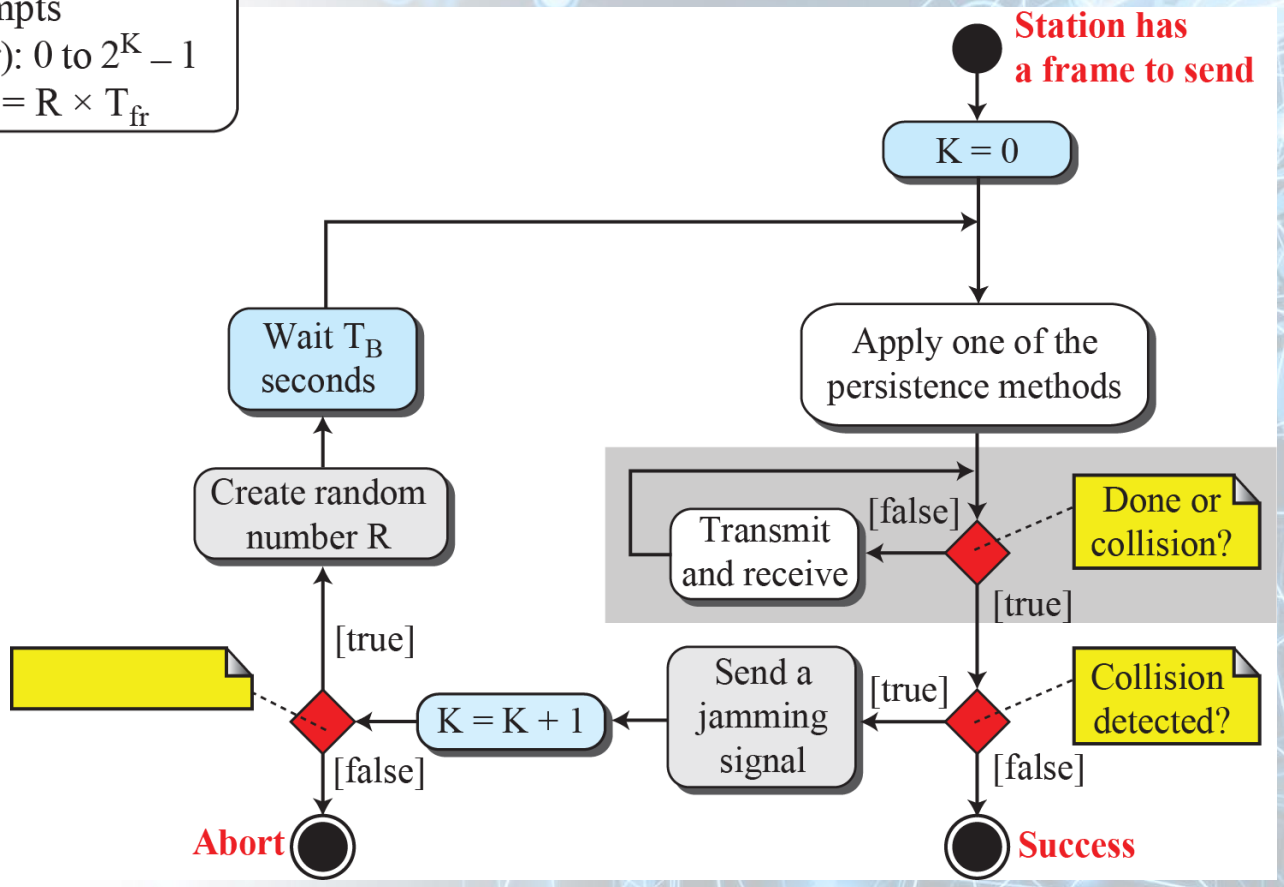
Collision and Abortion in CSMA/CD



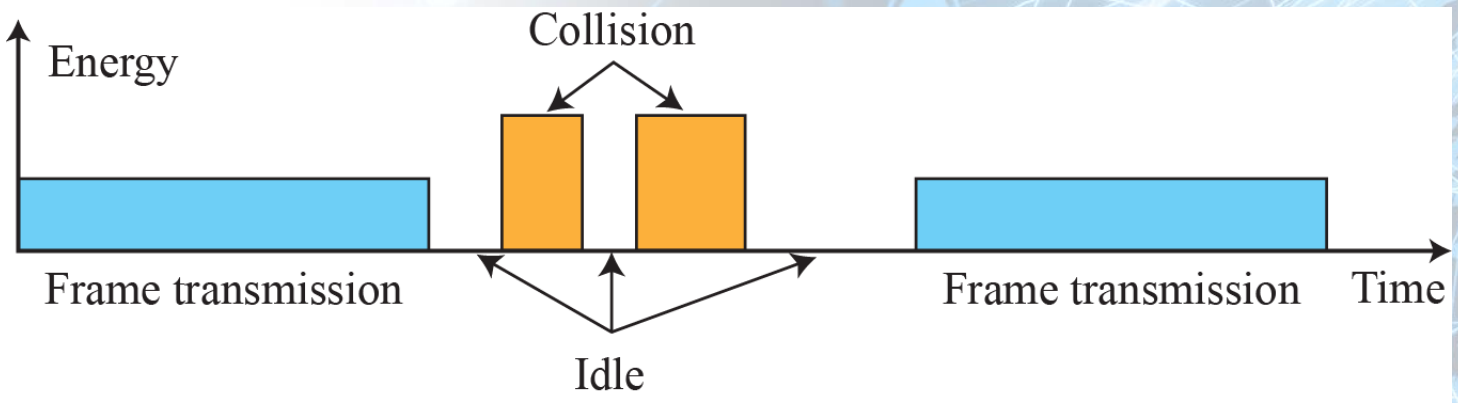
Flow Diagram for the CSMA/CD

Legend

T_{fr}: Frame average transmission time
K : Number of attempts
R : (random number): 0 to $2^K - 1$
T_B: (Back-off time) = R × T_{fr}



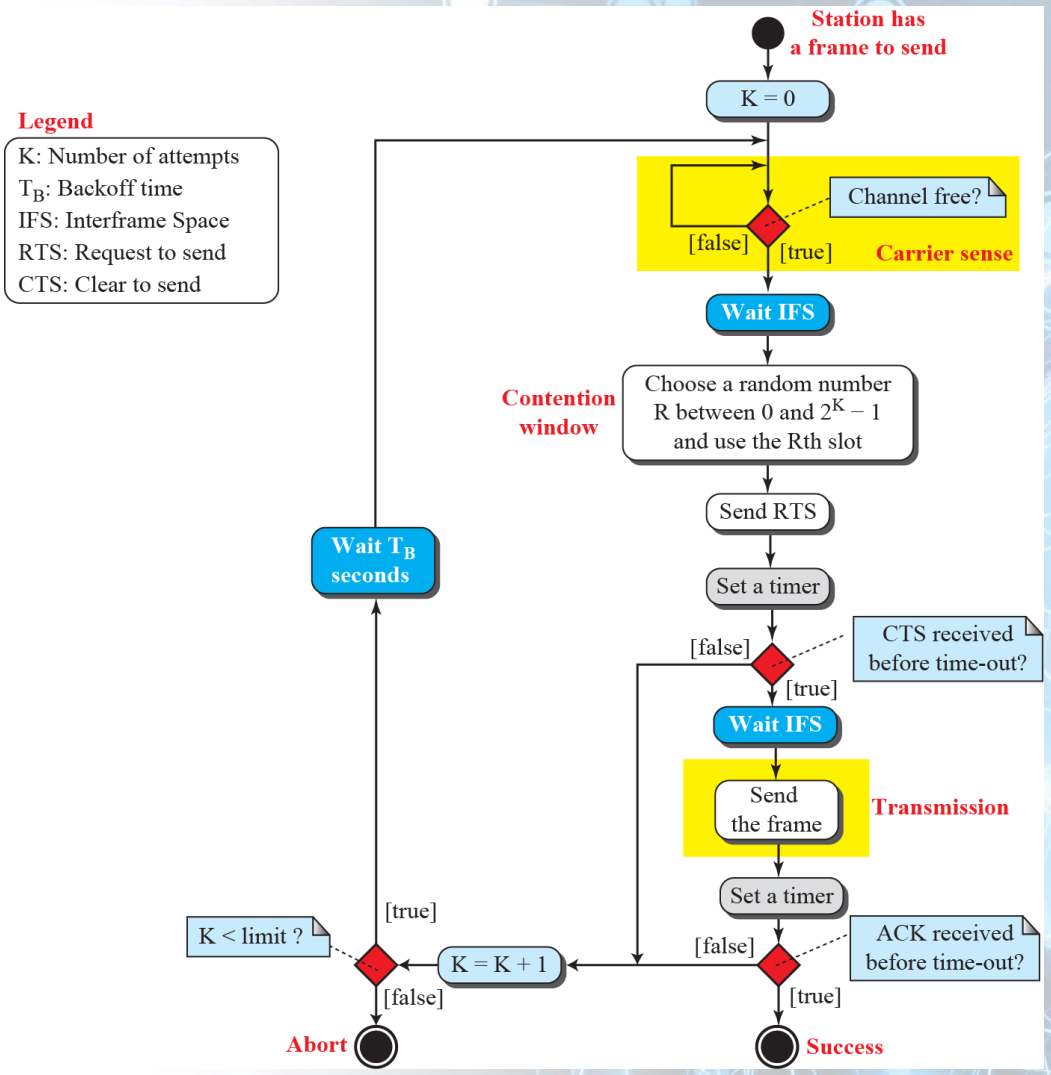
Energy Level During Transmission, Idleness and Collision



Carrier Sense Multiple Access/Collision Avoidance

- CSMA/CA was invented for Wireless Networks
- Collisions are avoided through the use of three strategies:
  - ✓ The Interfame Space
  - ✓ The Contention Window
  - ✓ Acknowledgements

Flow Diagram for CSMA/CA



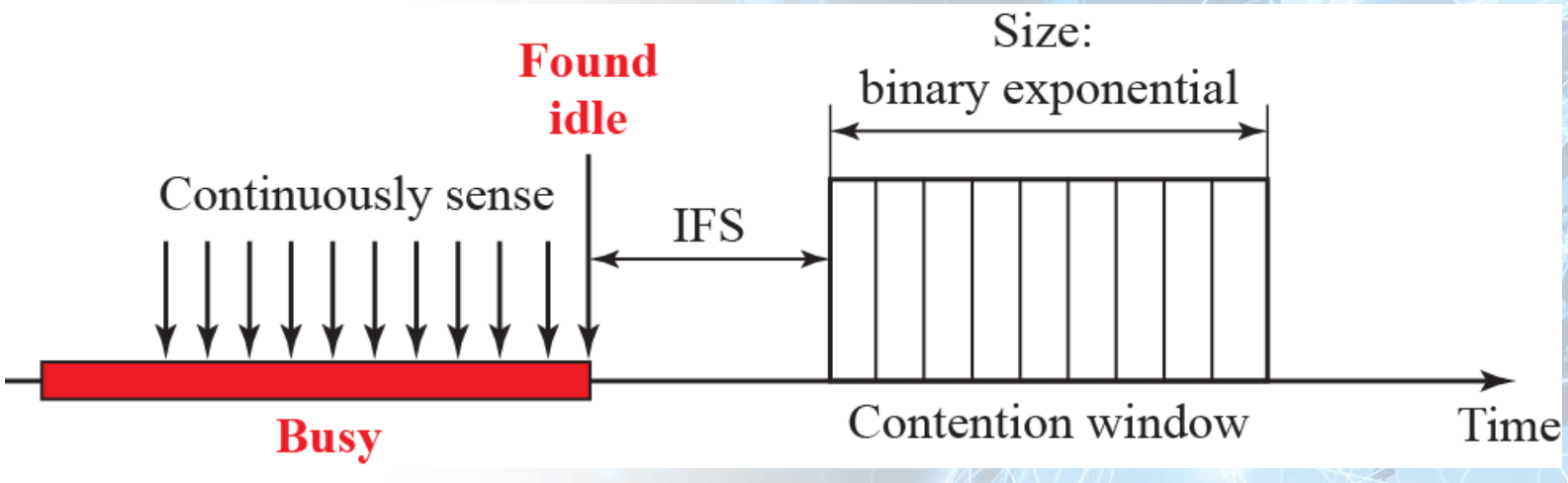
Carrier Sense Multiple Access/Collision Avoidance

- CSMA/CA was invented for Wireless Networks
- Collisions are avoided through the use of three strategies:
  - ✓ The Interfame Space
  - ✓ The Contention Window
  - ✓ Acknowledgements

CSMA/CA

- **Interframe Space (IFS): Collisions are avoided by deferring transmission even if the channel is idle**
- **Contention Window: Amount of time divided into slots. Station chooses a random number of slots as its wait time (one slot first time and double each time system cannot detect an idle channel)**

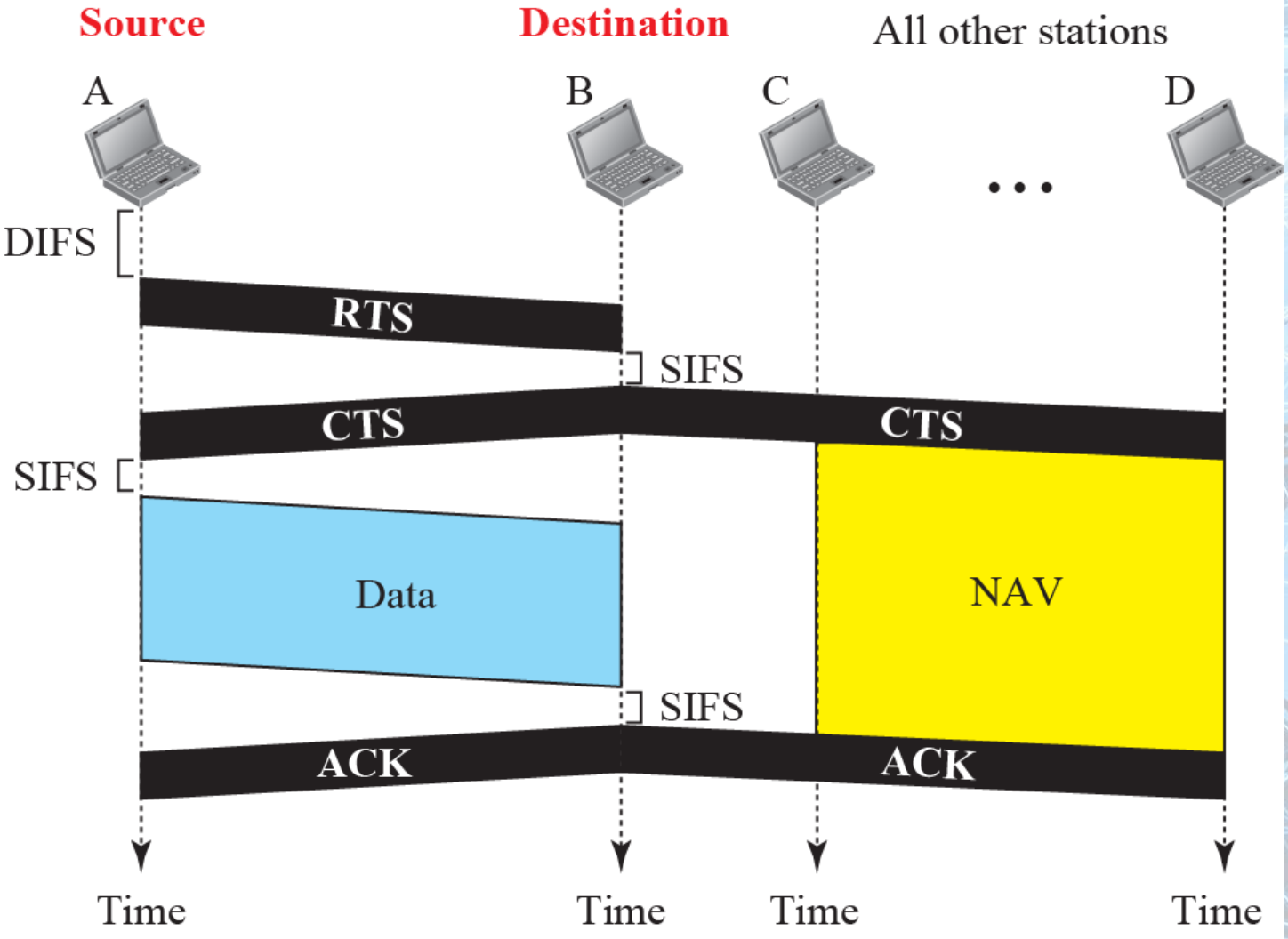
Contention Window



CSMA/CA

- **Acknowledgement: Positive acknowledgement and time-out timer can help guarantee that the receiver has received the frame**

CSMA/CA and Network Allocation Vector (NAV)



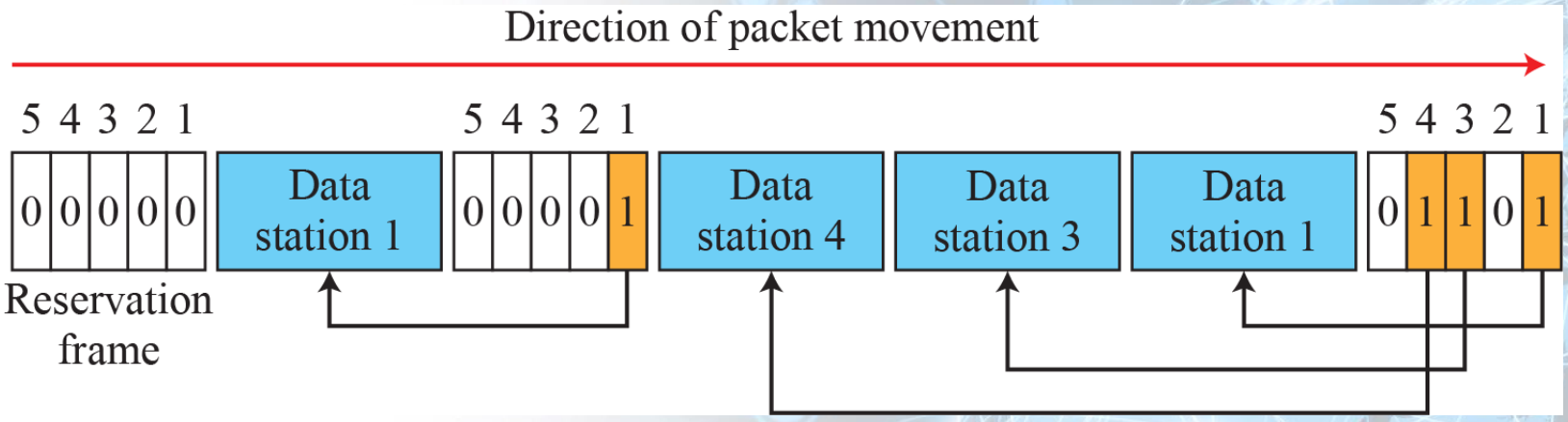
CONTROLLED ACCESS

- The stations consult one another to find which station has the right to send
- A station cannot send unless authorized by other stations
- We discuss three controlled-access methods:
  - ✓ Reservation
  - ✓ Polling
  - ✓ Token Passing

Reservation

- In the reservation method, a station needs to make a reservation before sending data
- Time is divided into intervals
- In each interval, a reservation frame precedes the data frames sent in that interval

Reservation Access Method



Polling

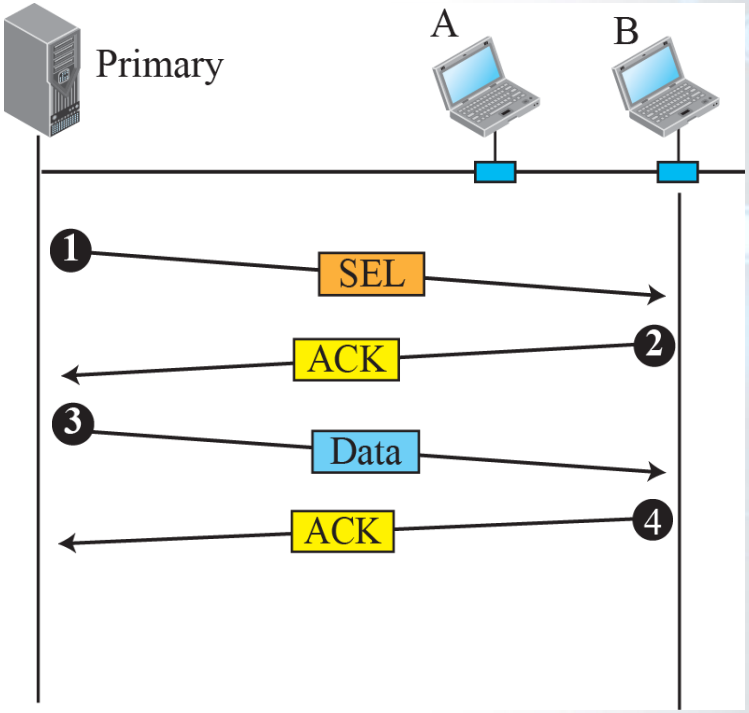
- Polling works with topologies in which one device is designated as a primary station and the other devices are secondary stations
- All data exchanges must be made through primary device even when the ultimate destination is a secondary device

Polling

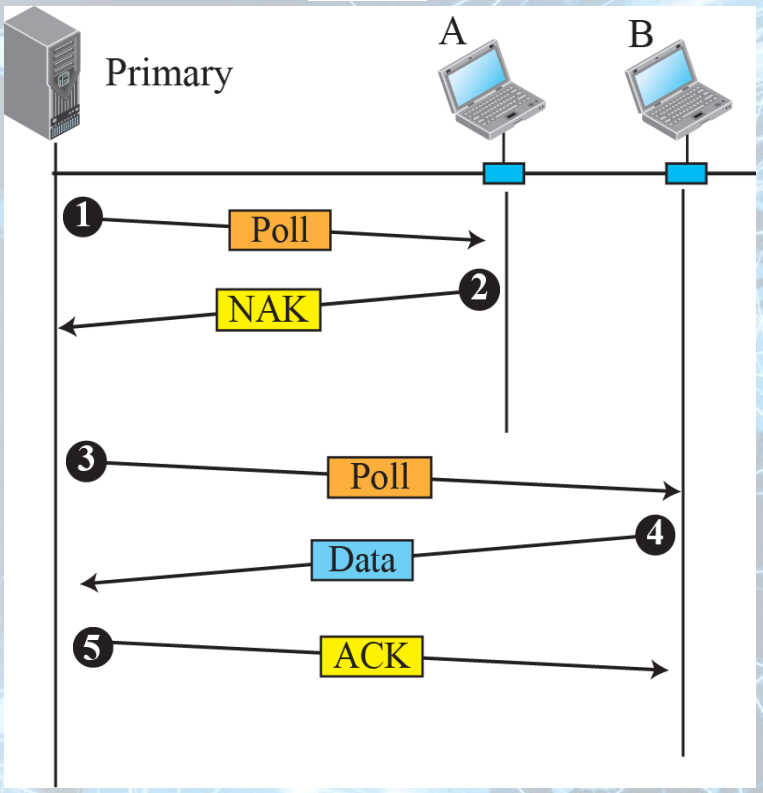
- The primary device controls the link; the secondary devices follow its instructions

Select and Poll Functions in Polling-Access Method

Select



Poll



CONTROLLED ACCESS

- **Three controlled-access methods:**
  - ✓ **Reservation**
  - ✓ **Polling**
  - ✓ **Token Passing**

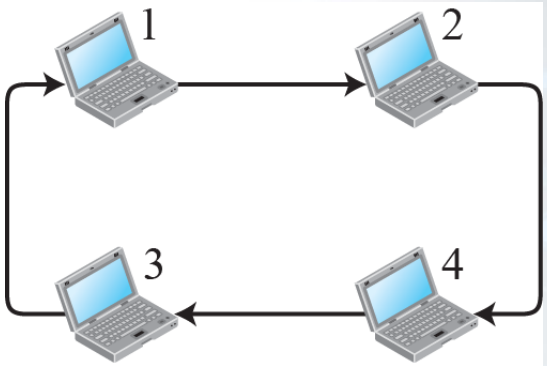
Token Passing

- In the token-passing method, the stations in a network are organized in a logical ring
- For each station, there is a predecessor and a successor
- The predecessor is the station which is logically before the station in the ring; the successor is the station which is after the station in the ring

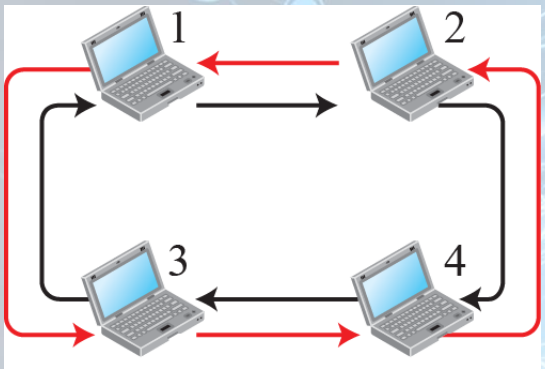
Token Passing

- Special packet called TOKEN circulates through the ring
- Possession of TOKEN gives the station the right to send the data
- TOKEN Management is required to manage possession time, Token monitoring, priority assignment etc.

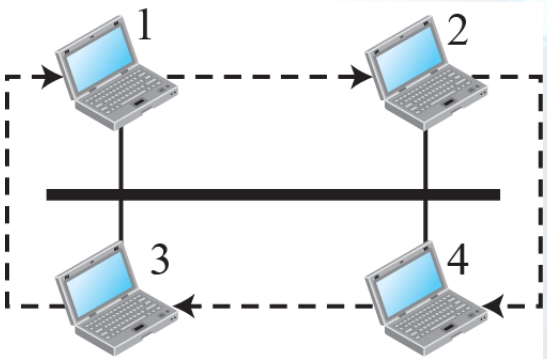
Logical Ring & Physical Topology in Token-Passing Method



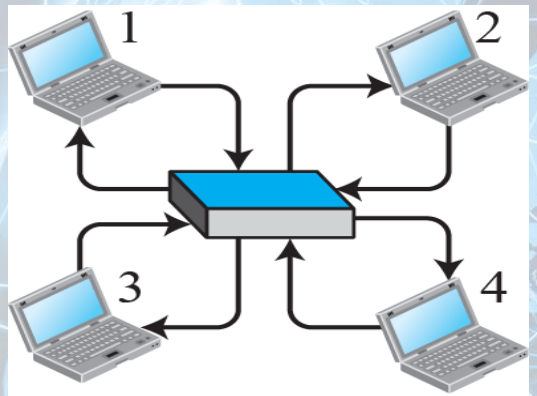
a. Physical ring



b. Dual ring



c. Bus ring



d. Star ring

CHANNELIZATION (Channel Partition)

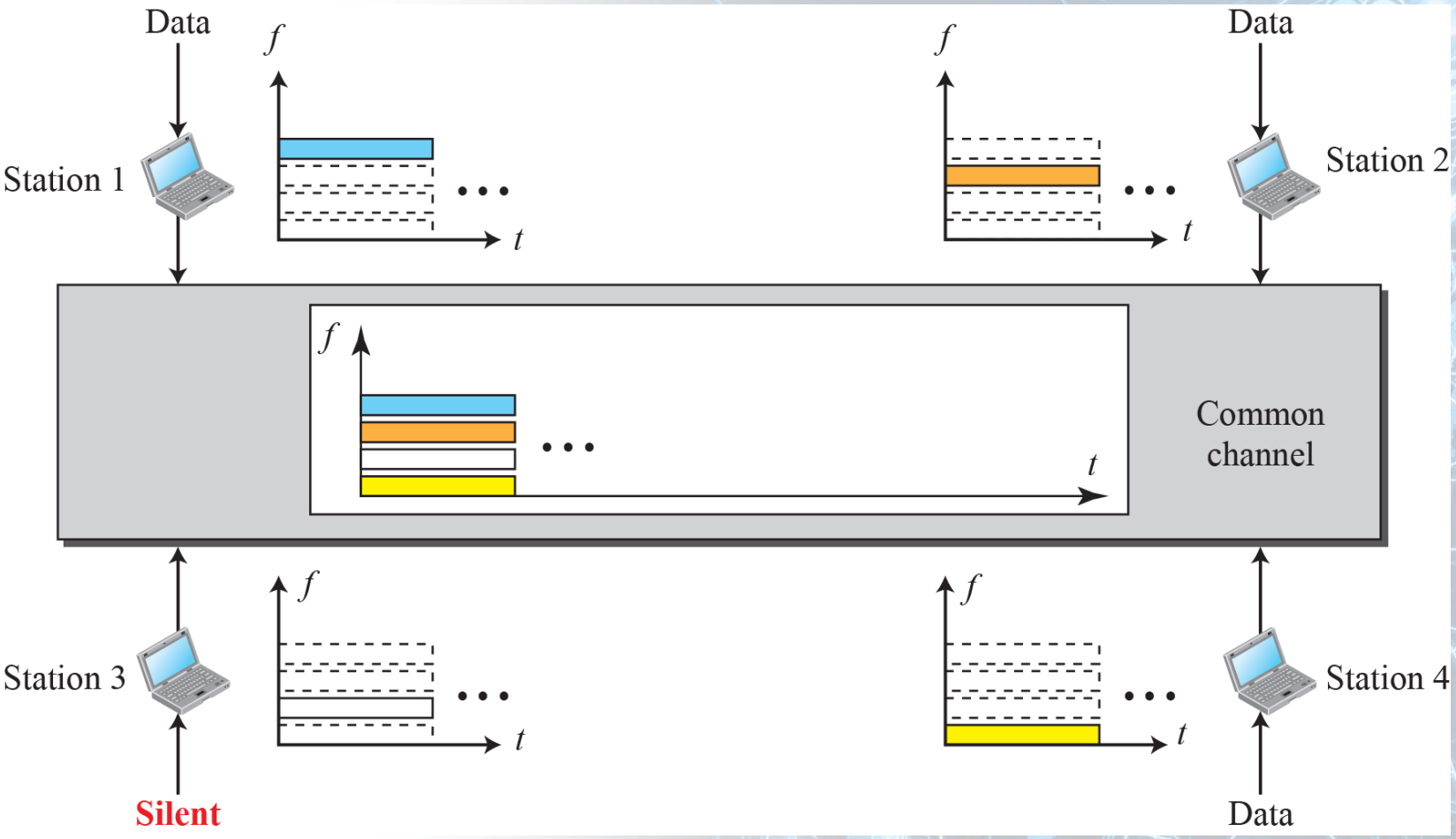
- The available bandwidth of a link is shared in time, frequency, or through code, among different stations

- We discuss three protocols:
  - ✓ Frequency Division Multiple Access (FDMA)
  - ✓ Time Division multiple Access (TDMA)
  - ✓ Code Division Multiple Access (CDMA)

Frequency-Division Multiple Access (FDMA)

- In FDMA, the available bandwidth is divided into frequency bands
- Each station is allocated a band to send its data i.e. each band is reserved for a specific station, and it belongs to the station all the time
- Each station also uses a bandpass filter to confine the transmitter frequencies

Frequency-Division Multiple Access (FDMA)



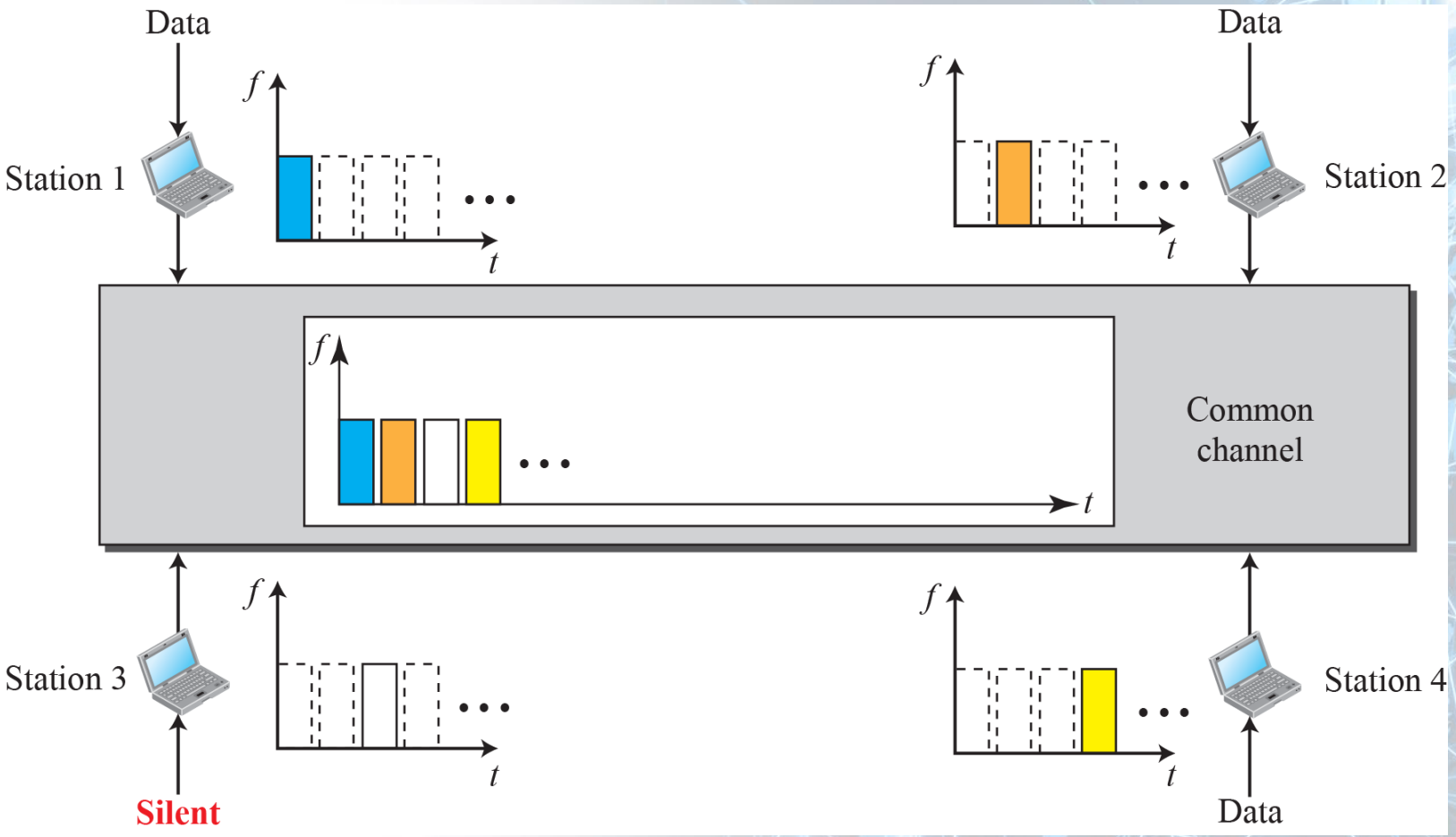
CHANNELIZATION (Channel Partition)

- **Three protocols:**
  - ✓ **Frequency Division Multiple Access (FDMA)**
  - ✓ **Time Division Multiple Access (TDMA)**
  - ✓ **Code Division Multiple Access (CDMA)**

TDMA

- Stations share the bandwidth of the channel in time
- Each station is allocated a time slot during which it can send data
- Each station transmits its data in its assigned time slot

Time-Division Multiple Access (TDMA)



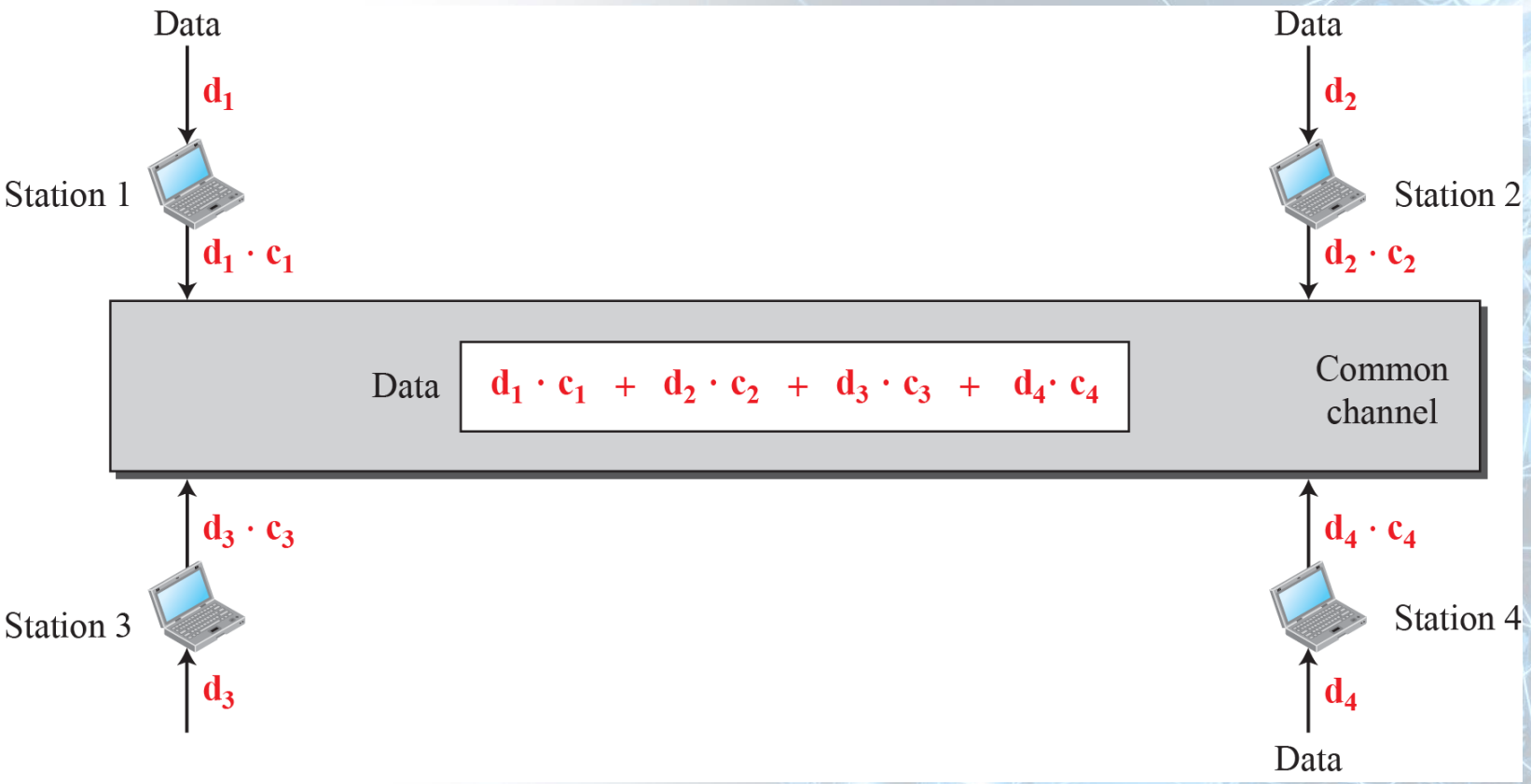
CHANNELIZATION (Channel Partition)

- **Three protocols:**
  - ✓ **Frequency Division Multiple Access (FDMA)**
  - ✓ **Time Division Multiple Access (TDMA)**
  - ✓ **Code Division Multiple Access (CDMA)**

Code Division Multiple Access (CDMA)

- CDMA differs from FDMA in that only one channel occupies the entire bandwidth of the link
- CDMA differs from TDMA in that all stations can send data simultaneously; there is no timesharing

Simple idea of Communication with Code



Data Representation in CDMA

Ethernet Protocol

- Data-link layer and the physical layer are the territory of the local and wide area networks
- We can have wired or wireless networks

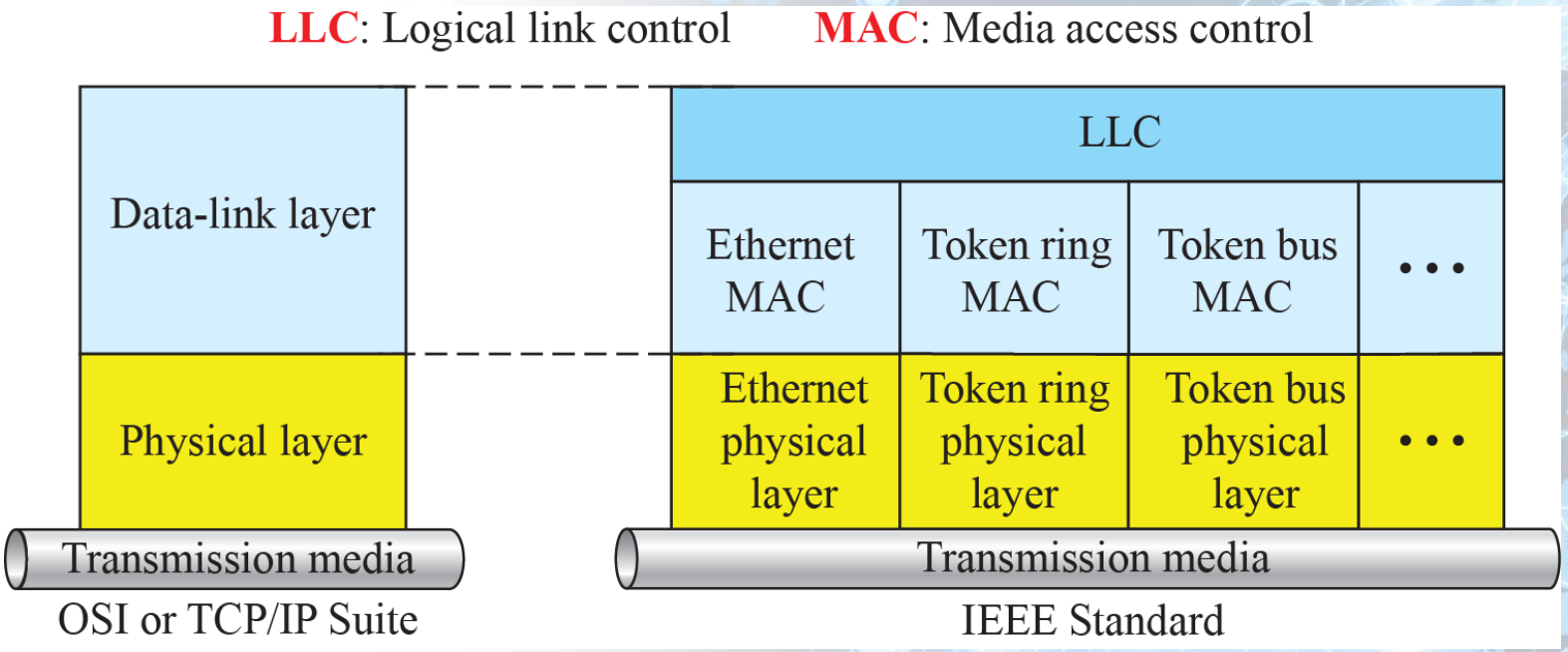
IEEE Project 802

- In 1985, the Computer Society of the IEEE started a project, called Project 802, to set standards to enable inter-communication among equipment from a variety of manufacturers
- Project 802 did not seek to replace any part of the OSI model or TCP/IP protocol suite

IEEE Project 802

- A way of specifying functions of the physical layer and the data-link layer of major LAN protocols

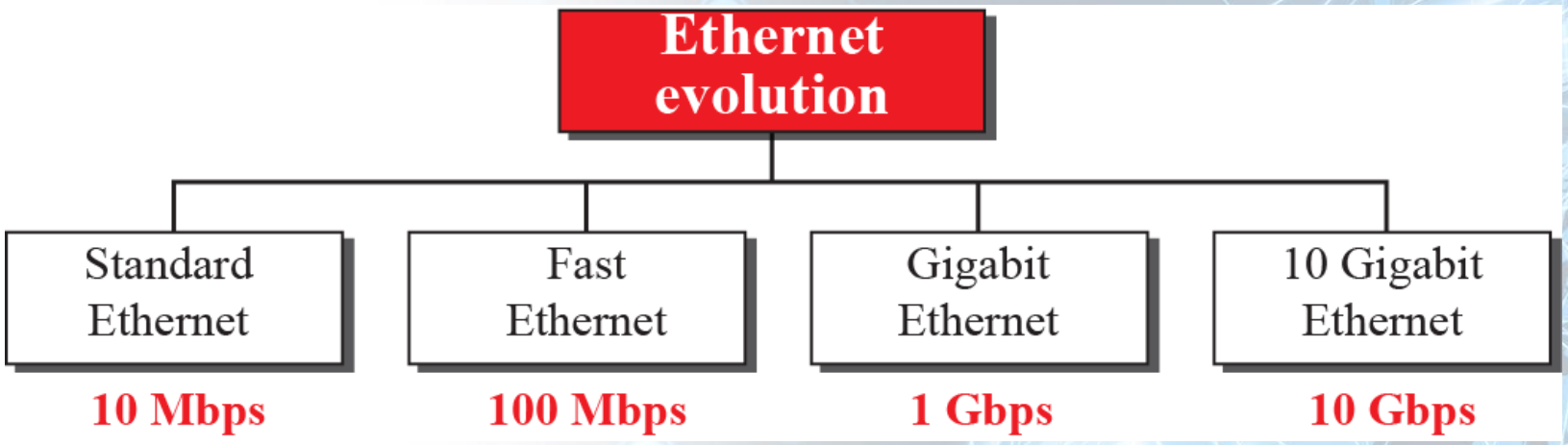
IEEE Standard for LANs



Ethernet Evolution

- The Ethernet LAN was developed in the 1970s
- Since then, it has gone through four generations:
  - ✓ Standard Ethernet (10 Mbps)
  - ✓ Fast Ethernet (100 Mbps)
  - ✓ Gigabit Ethernet (1 Gbps)
  - ✓ 10 Gigabit Ethernet (10 Gbps)

Ethernet Evolution



Standard Ethernet

- The original Ethernet technology with the data rate of 10 Mbps is called Standard Ethernet
- Most implementations have moved to later evolutions
- Still some features of the Standard Ethernet that have not changed during the evolution

Connectionless & Unreliable Service

- Each frame is independent of other
- No connection establishment or tear down process
- The sender may overwhelm receiver with frames and frames are dropped
- If frame drops, sender will not know about it unless we are using TCP (Transport)

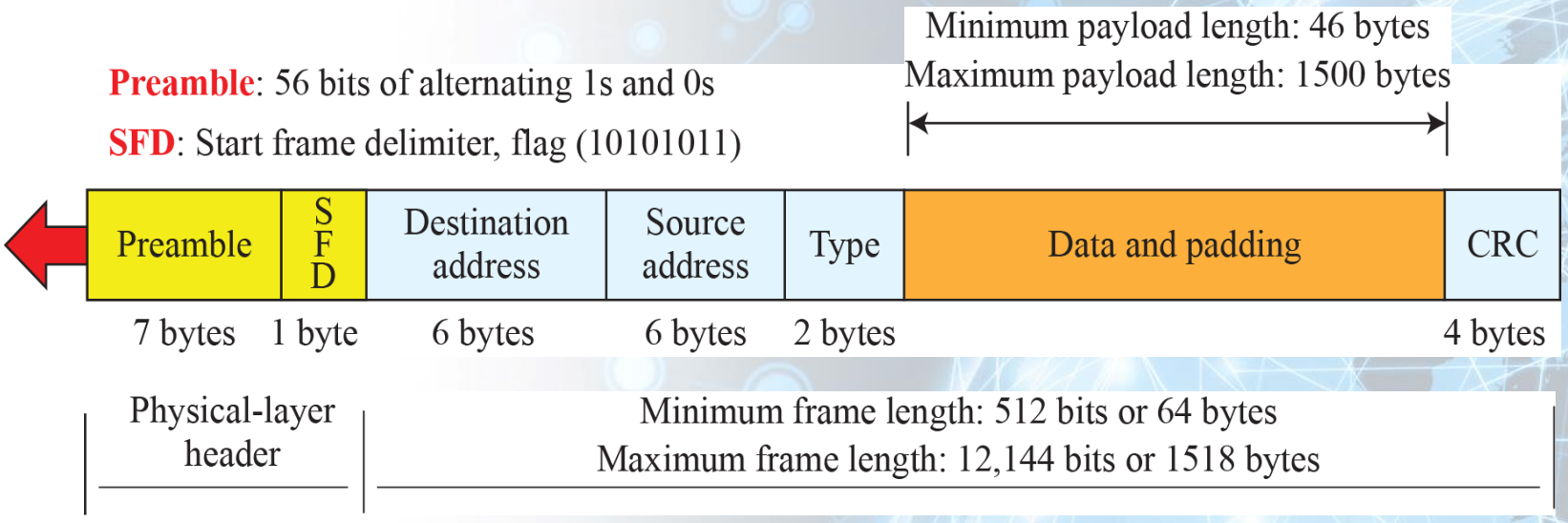
Connectionless & Unreliable Service

- Ethernet is unreliable like IP and UDP
- If a frame is corrupted, receiver silently drops it
- Left to high level protocols to find out abut it

Standard Ethernet

- **The original Ethernet technology with the data rate of 10 Mbps is called Standard Ethernet**

Ethernet Frame Format



Addressing in Standard Ethernet

- Each station on Ethernet has its own network interface card (NIC)
- The NIC fits inside the station and provides the station with a link-layer/physical address
- The Ethernet address is 6 bytes (48 bits), normally written in hexadecimal notation, with a colon between the bytes

Addressing

- For example, the following shows an Ethernet MAC address:

  4A:30:10:21:10:1A

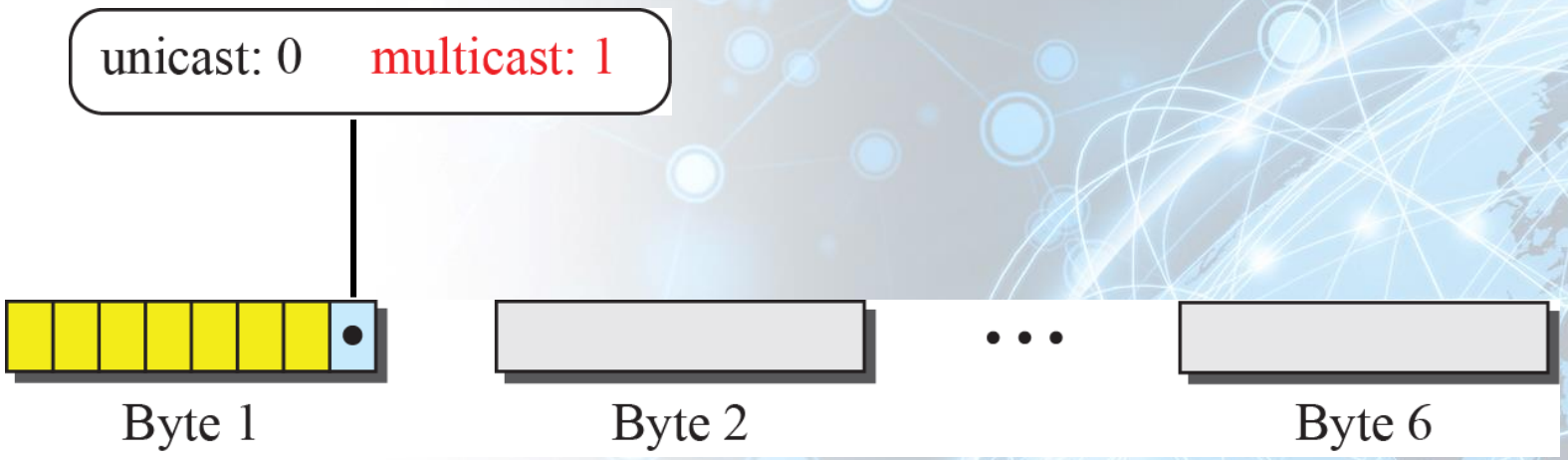
Transmission of Address Bits

How the address 47:20:1B:2E:08:EE is sent out online.

The address is sent left to right, byte by byte; for each byte, it is sent right to left, bit by bit, as shown below:

Hexadecimal	47	20	1B	2E	08	EE
Binarys	01000111	00100000	00011011	00101110	00001000	11101110
Transmitted ←	11100010	00000100	11011000	01110100	00010000	01110111

Unicast and Multicast Addresses



Example 13.2

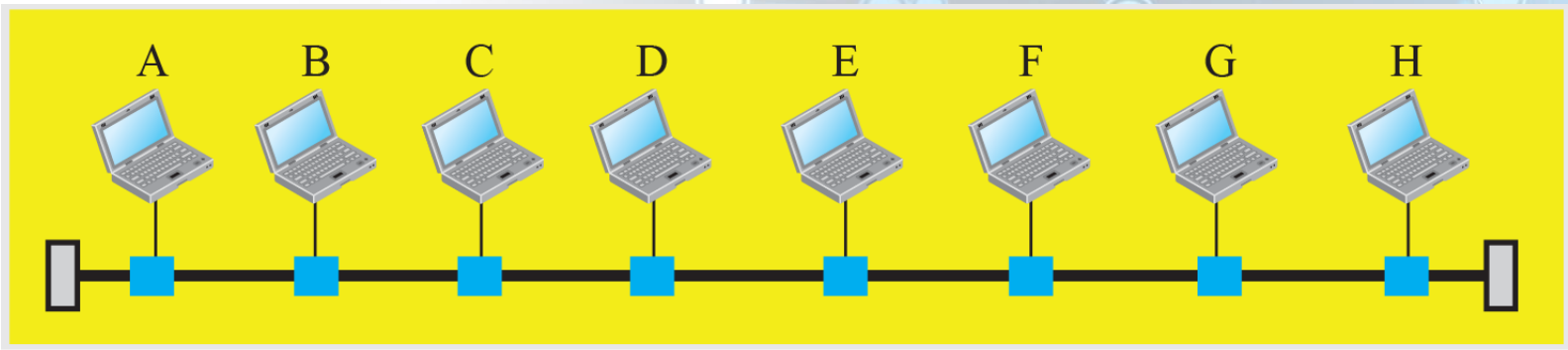
Define the type of the following destination addresses:

a. **4A:30:10:21:10:1A**
b. **47:20:1B:2E:08:EE**
c. **FF:FF:FF:FF:FF:FF**

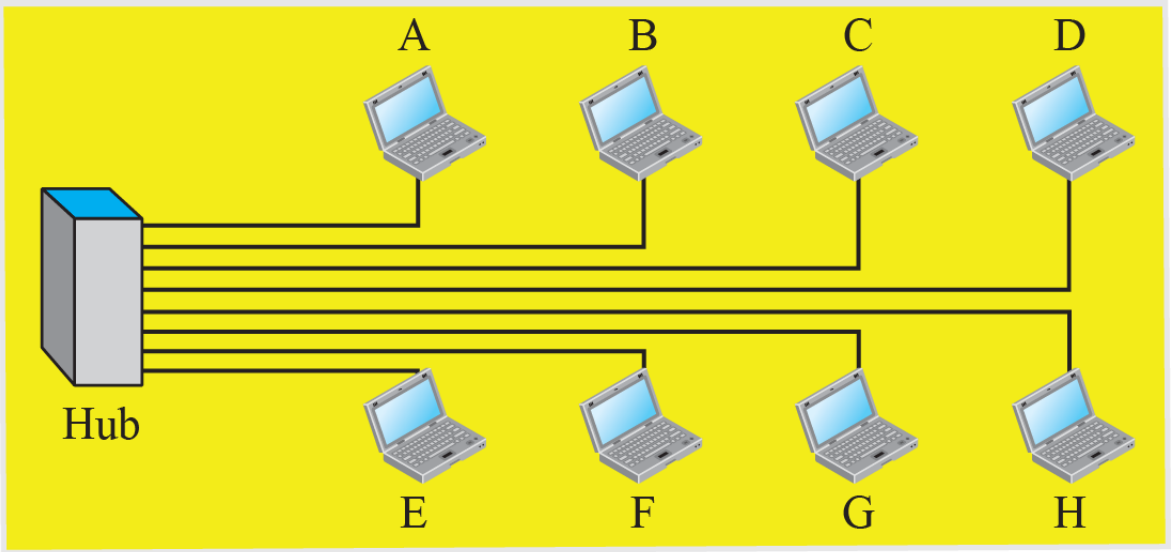
To find the type of the address, we need to look at the second hexadecimal digit from the left. If it is even, the address is unicast. If it is odd, the address is multicast. If all digits are Fs, the address is broadcast. Therefore, we have the following:

a. **This is a unicast address because A in binary is 1010 (even).**
b. **This is a multicast address because 7 in binary is 0111 (odd).**
c. **This is a broadcast address because all digits are Fs in hexadecimal.**

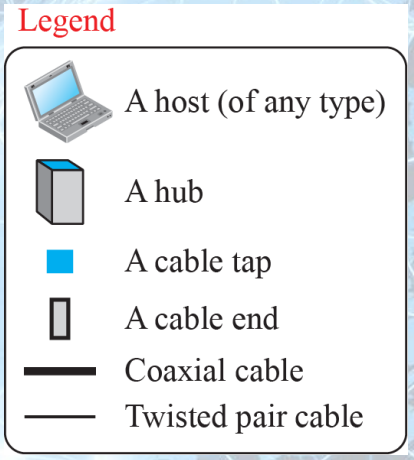
Implementation of Standard Ethernet



a. A LAN with a bus topology using a coaxial cable



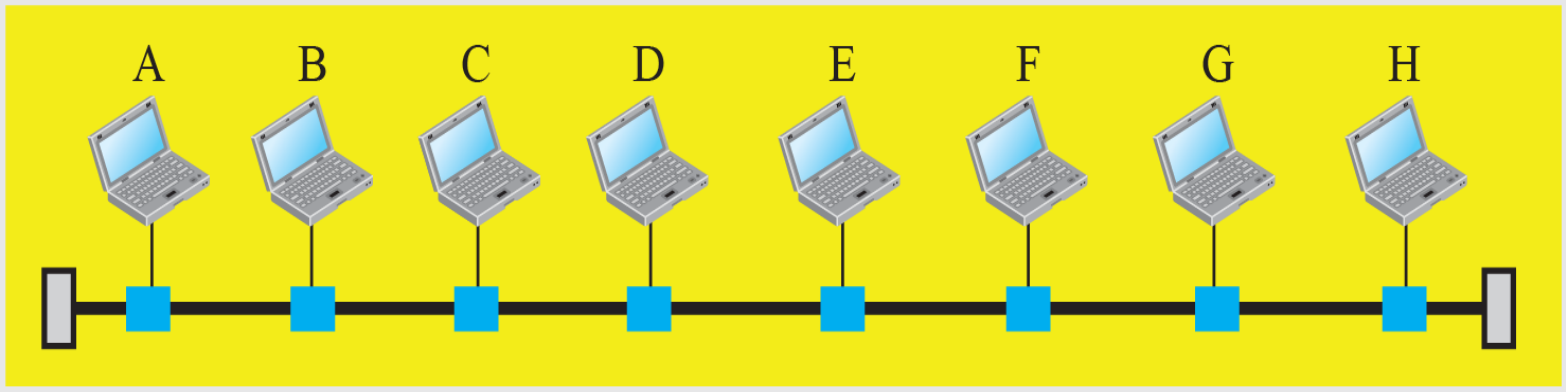
b. A LAN with a star topology using a hub



Access Method in Standard Ethernet

- Since the network that uses the standard Ethernet protocol is a broadcast network, we need to use an access method to control access to the sharing medium
- The standard Ethernet chose CSMA/CD with 1-Persistent Method

Access Method in Standard Ethernet



a. A LAN with a bus topology using a coaxial cable

Efficiency of Standard Ethernet

- The ratio of the time used by a station to send data to the time the medium is occupied by this station

- The practical efficiency of standard Ethernet has been measured to be:

$$\text{Efficiency} = 1/(1+ 6.4 \times a)$$

where a = number of frames that can fit on a medium

Example

In the Standard Ethernet with the transmission rate of 10 Mbps, we assume that the length of the medium is 2500 m and the size of the frame is 512 bits. The propagation speed of a signal in a cable is normally 2×10^{8} m/s.

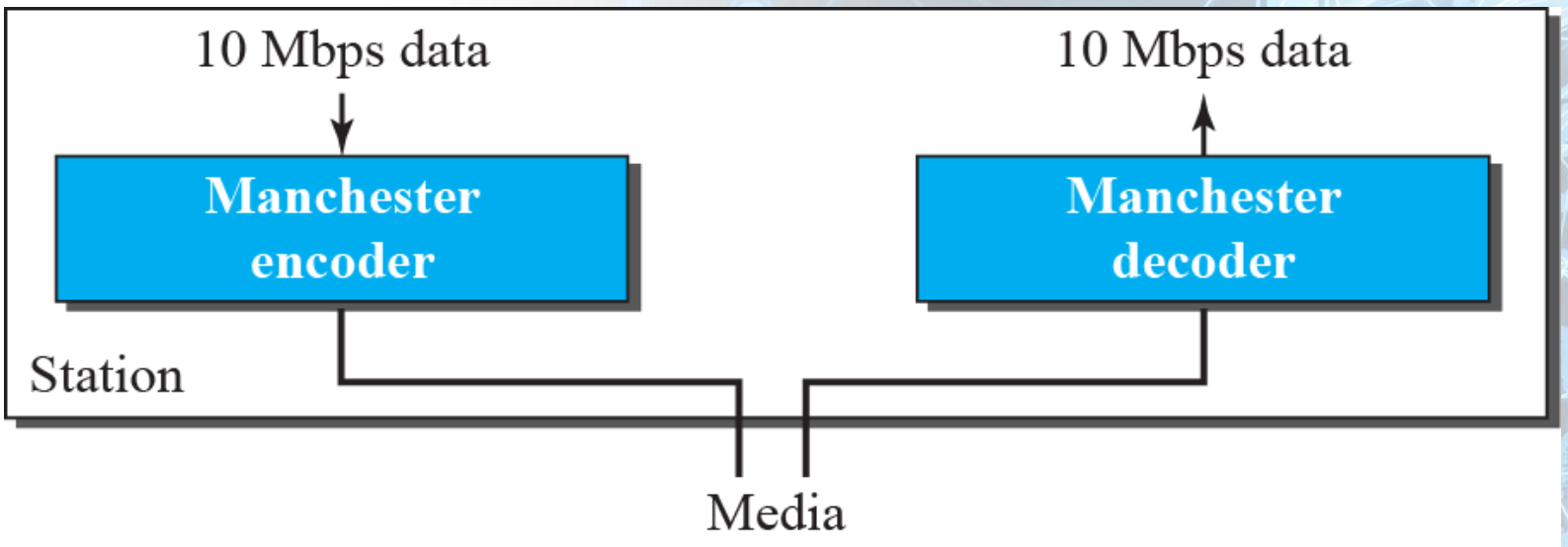
Implementation of Standard Ethernet

- **The Standard Ethernet defined several implementations, but only four of them became popular during the 1980s**

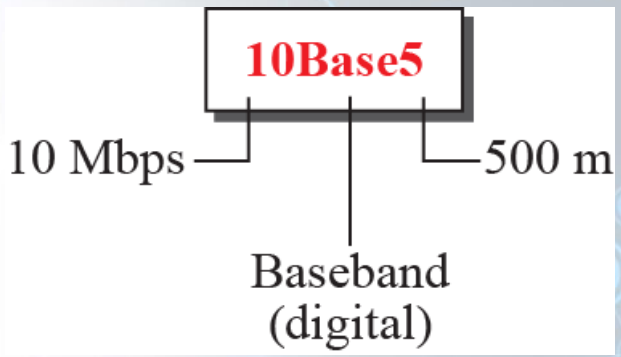
Summary of Standard Ethernet implementations

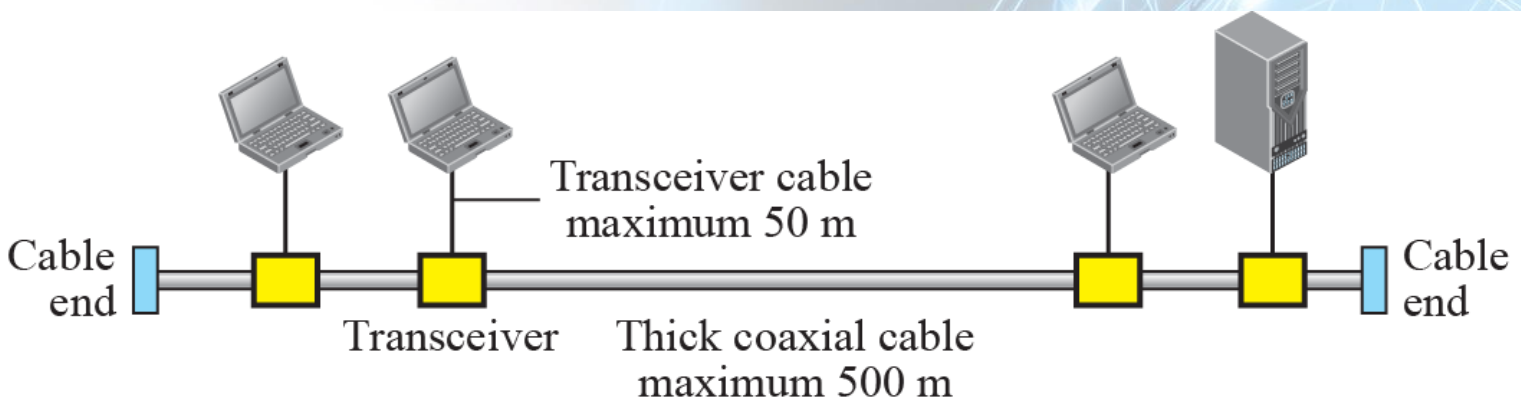
Implementation	*Medium*	*Medium Length*	*Encoding*
10Base5	Thick coax	500 m	Manchester
10Base2	Thin coax	185 m	Manchester
10Base-T	2 UTP	100 m	Manchester
10Base-F	2 Fiber	2000	Manchester

Encoding in Standard Ethernet

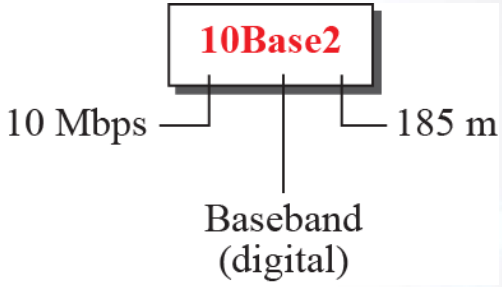


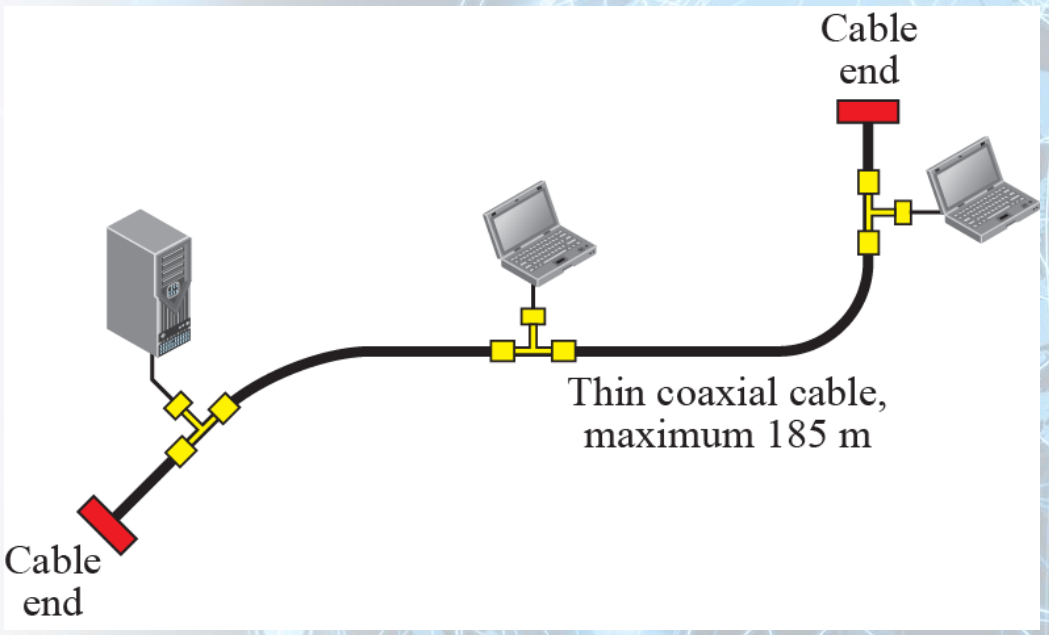
10Base5 implementation



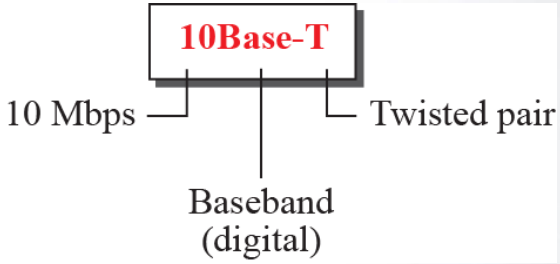


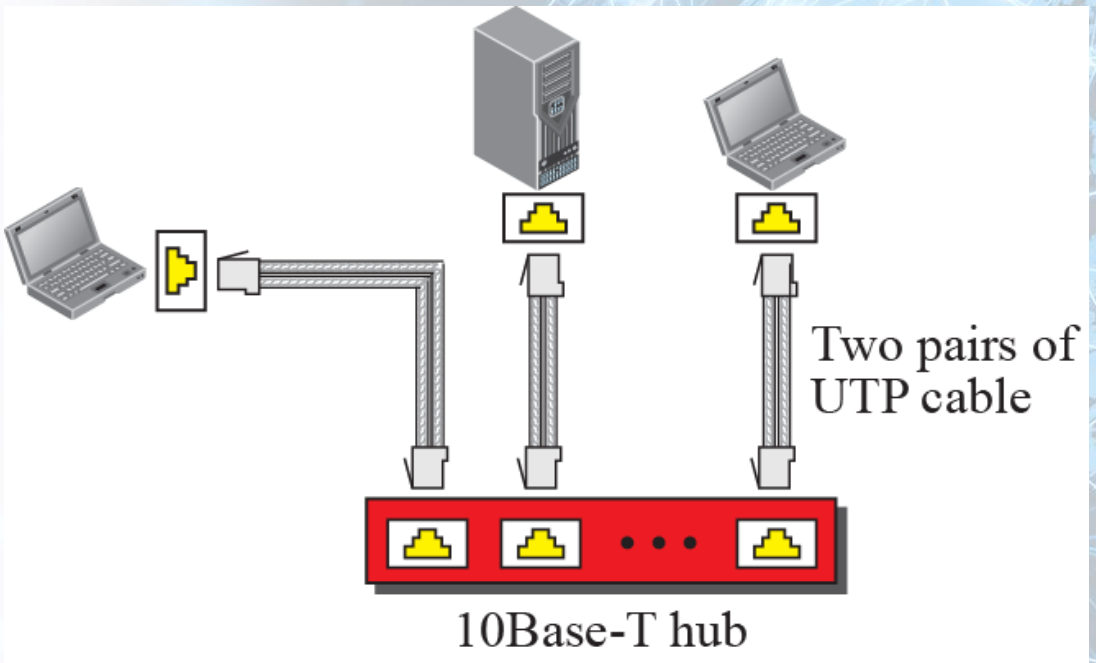
10Base2 implementation



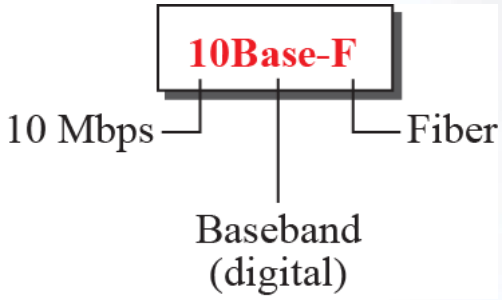


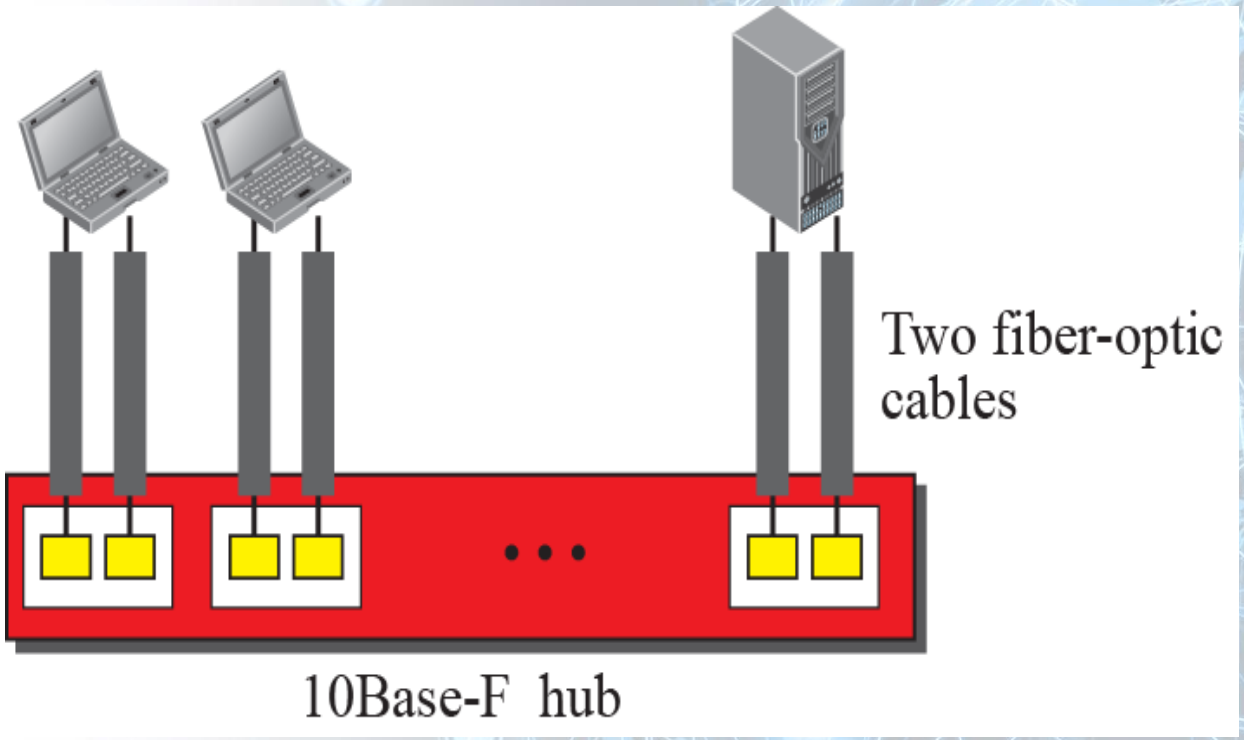
10Base-T implementation





10Base-F implementation



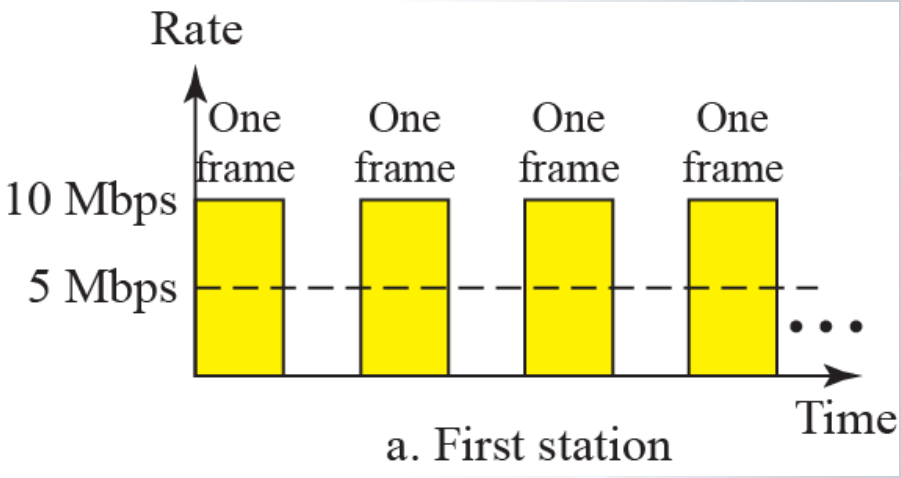


Changes in the Standard

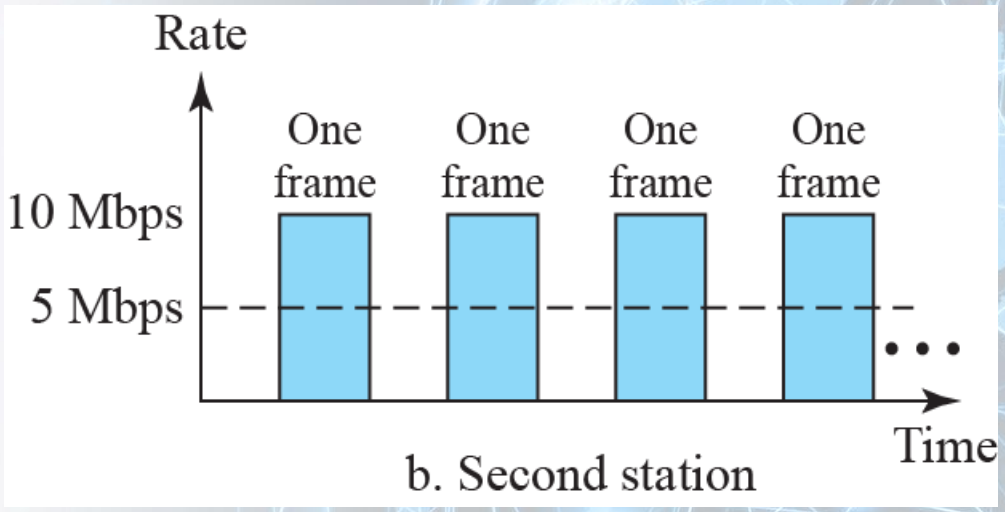
- The changes that occurred to the 10-Mbps Standard Ethernet opened the road to the evolution of the Ethernet to become compatible with other high-data-rate LANs

  - ✓ Bridged Ethernet
  - ✓ Switched Ethernet
  - ✓ Full-Duplex Ethernet

Bridged Ethernet- Sharing Bandwidth

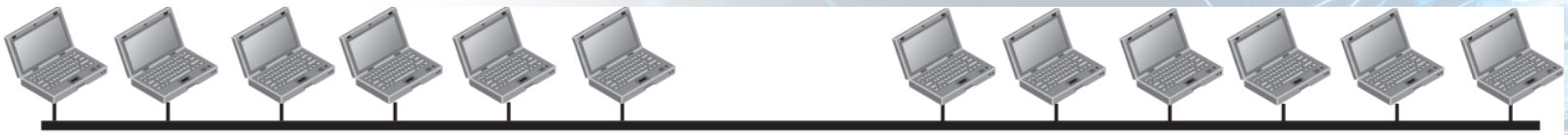


a. First station



b. Second station

A Network with and without Bridging



a. Without bridging

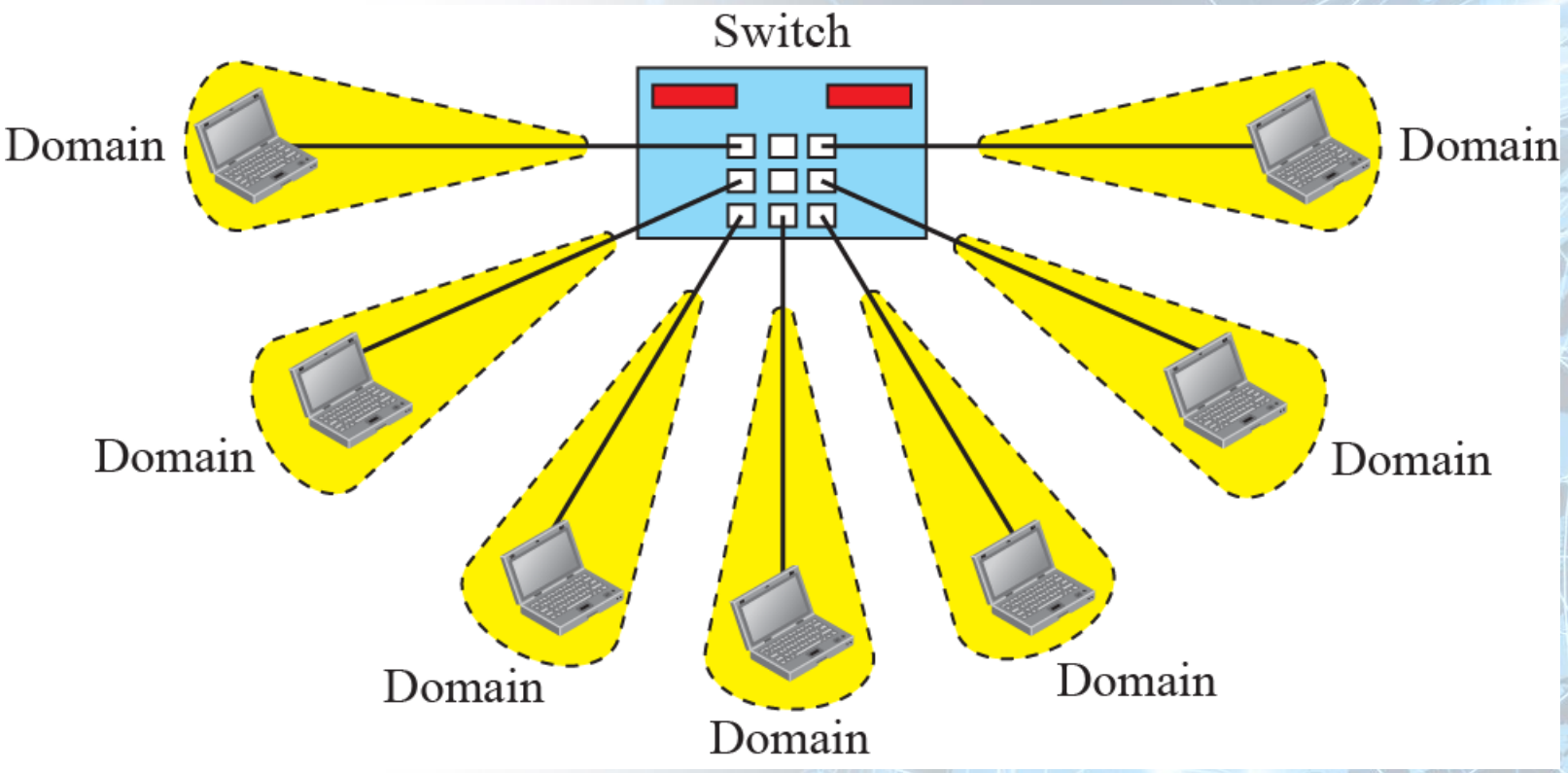
b. With bridging

Changes in the Standard

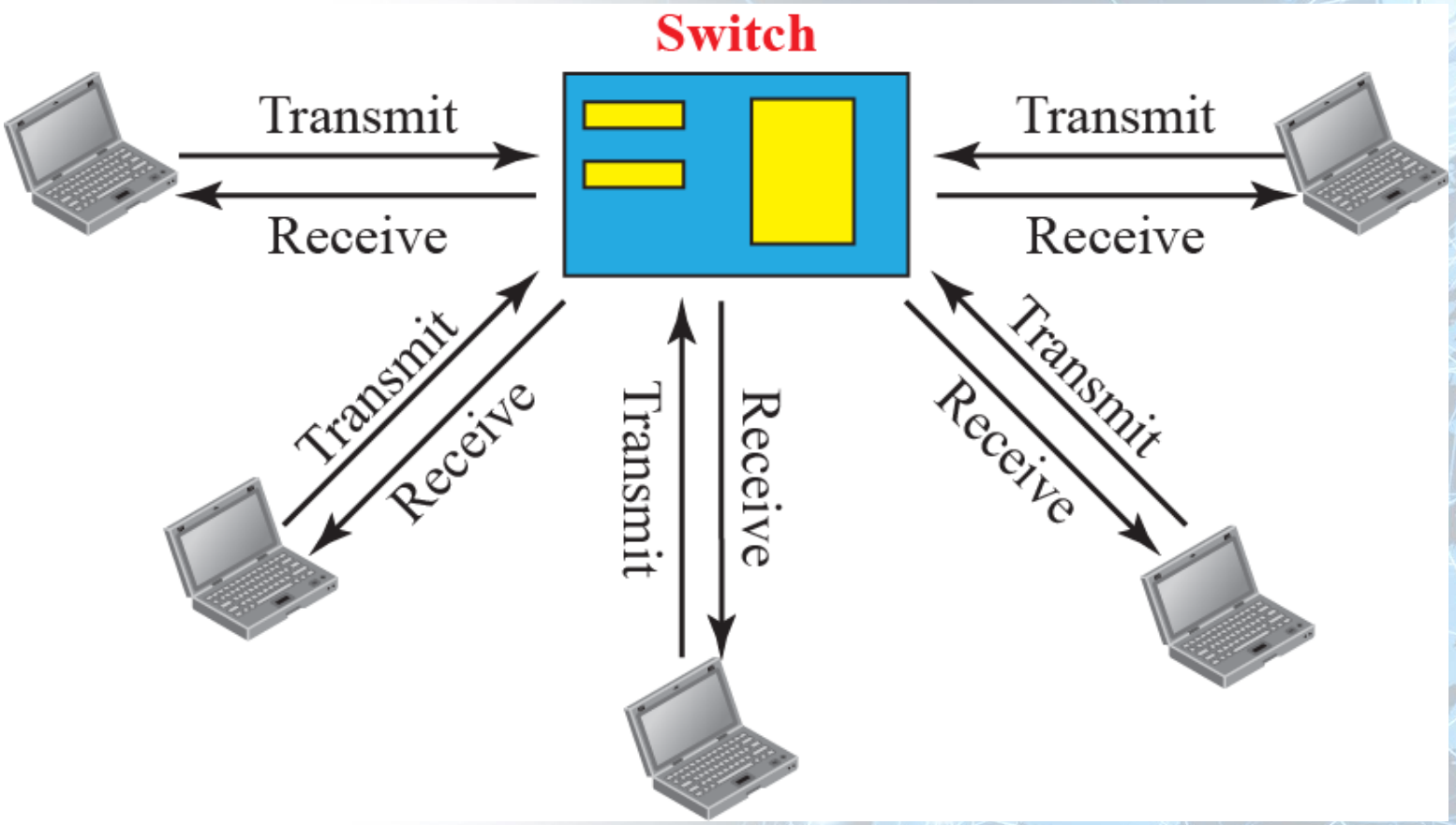
- The changes that occurred to the 10-Mbps Standard Ethernet opened the road to the evolution of the Ethernet to become compatible with other high-data-rate LANs

  - ✓ Bridged Ethernet
  - ✓ Switched Ethernet
  - ✓ Full-Duplex Ethernet

Switched Ethernet



Full – Duplex Switched Ethernet



Fast Ethernet

- In the 1990s, Ethernet made a big jump by increasing the transmission rate to 100 Mbps, and the new generation was called the Fast Ethernet
- To make it compatible with the Standard Ethernet, the MAC sublayer was left unchanged

Fast Ethernet

- But the features of the Standard Ethernet that depend on the transmission rate, had to be changed

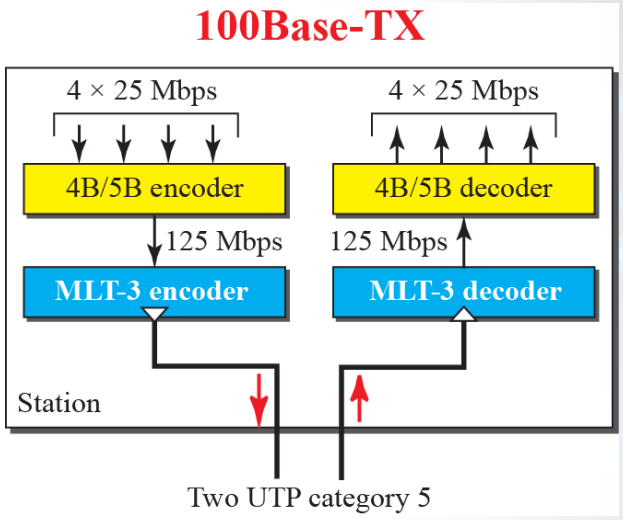
- Goals of Fast Ethernet:

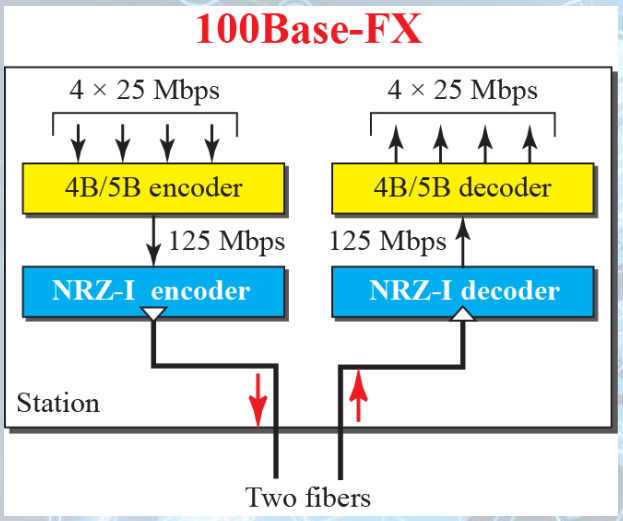
  - ✓ Upgrade data rate to 100Mbps
  - ✓ Make it compatible with Standard Ethernet
  - ✓ Keep same 48-bit address
  - ✓ Keep same frame format

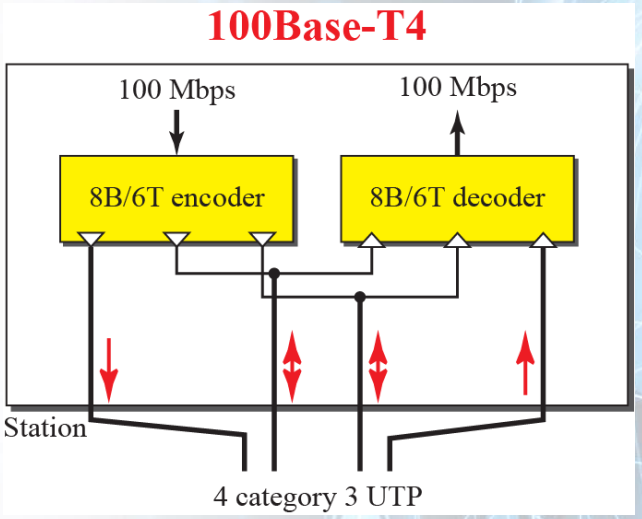
Physical Layer

- To be able to handle a 100 Mbps data rate, several changes need to be made at the physical layer

Encoding for Fast Ethernet







Implementation of Fast Ethernet implementations

Implementation	*Medium*	*Medium Length*	*Wires*	*Encoding*
100Base-TX	STP	100 m	2	4B5B + MLT-3
100Base-FX	Fiber	185 m	2	4B5B + NRZ-I
100Base-T4	UTP	100 m	4	Two 8B/6T

Gigabit Ethernet

- Need for an even higher data rate resulted in the design of IEEE Standard 802.3z Gigabit Ethernet Protocol (1000 Mbps)

Gigabit Ethernet

- The goals of the Gigabit Ethernet were:
  - ✓ Upgrade the data rate to 1 Gbps
  - ✓ Make it compatible with standard or Fast Ethernet
  - ✓ Use same 48 bit address
  - ✓ Use the same frame format
  - ✓ Keep same minimum and maximum frame lengths

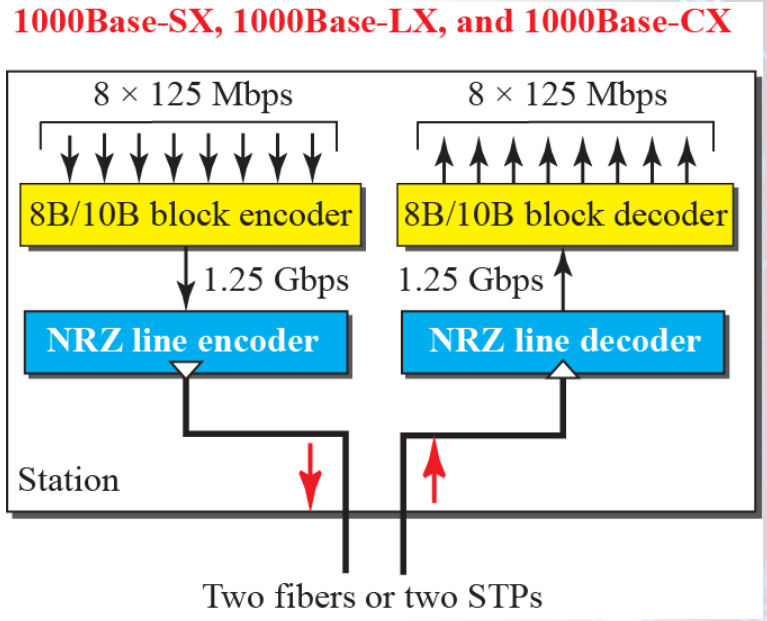
MAC Sub-layer

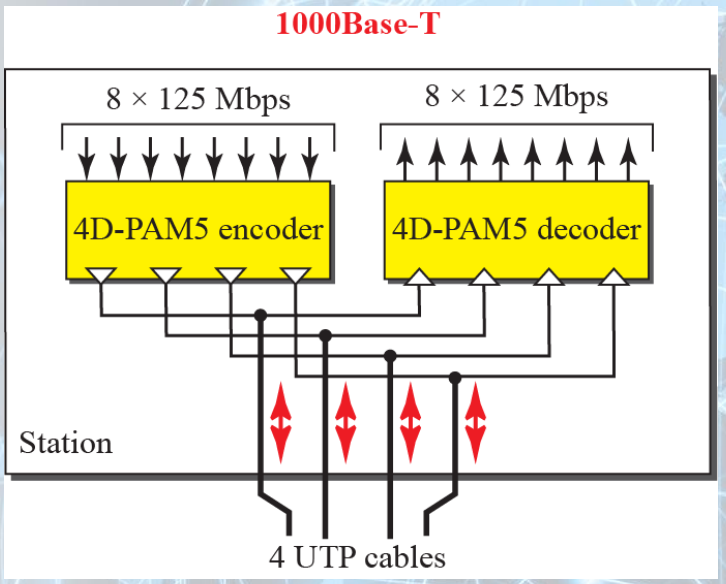
- A main consideration in the evolution of Ethernet was to keep the MAC sublayer untouched
- To achieve a data rate of 1 Gbps, this was no longer possible
- Gigabit Ethernet has two distinctive approaches for medium access:
  - ✓ Half-duplex
  - ✓ Full-duplex

Physical Layer

- The physical layer in Gigabit Ethernet is more complicated than that in Standard or Fast Ethernet
- We briefly discuss some features of this layer:

Encoding in Gigabit Ethernet





Summary of Gigabit Ethernet Implementations

Implementation	*Medium*	*Medium Length*	*Wires*	*Encoding*
1000Base-SX	Fiber S-W	550 m	2	8B/10B + NRZ
1000Base-LX	Fiber L-W	5000 m	2	8B/10B + NRZ
1000Base-CX	STP	25 m	2	8B/10B + NRZ
1000Base-T4	UTP	100 m	4	4D-PAM5

10-gigabit Ehternet

- The idea is to extend the technology, the data rate, and the coverage distance so that the Ethernet can be used in LANs and MANs (metropolitan area network)
- The IEEE committee created 10 Gigabit Ethernet and called it Standard 802.3ae

Implementation

- 10 Gigabit Ethernet operates only in full-duplex mode, which means there is no need for contention; CSMA/CD is not used in 10 Gigabit Ethernet
- Four implementations are most common:

Implementation

Implementation	*Medium*	*Medium Length*	*Number of wires*	*Encoding*
10GBase-SR	Fiber 850 nm	300 m	2	64B66B
10GBase-LR	Fiber 1310 nm	10 Km	2	64B66B
10GBase-EW	Fiber 1350 nm	40 Km	2	SONET
10GBase-X4	Fiber 1310 nm	300 m to 10 Km	2	8B10B

Other Wired Networks

- Access Networks
  - ✓ Networks that connect a small LAN to an ISP
- Wide Area Networks
  - ✓ Wired networks used to transfer data over long distances

Telephone Network

- The telephone network had its beginnings in the late 1800s
- Plain Old Telephone System (POTS) was originally an analog system using analog signals to transmit voice
- With the advent of the computer era, the network, in the 1980s, began to carry data in addition to voice

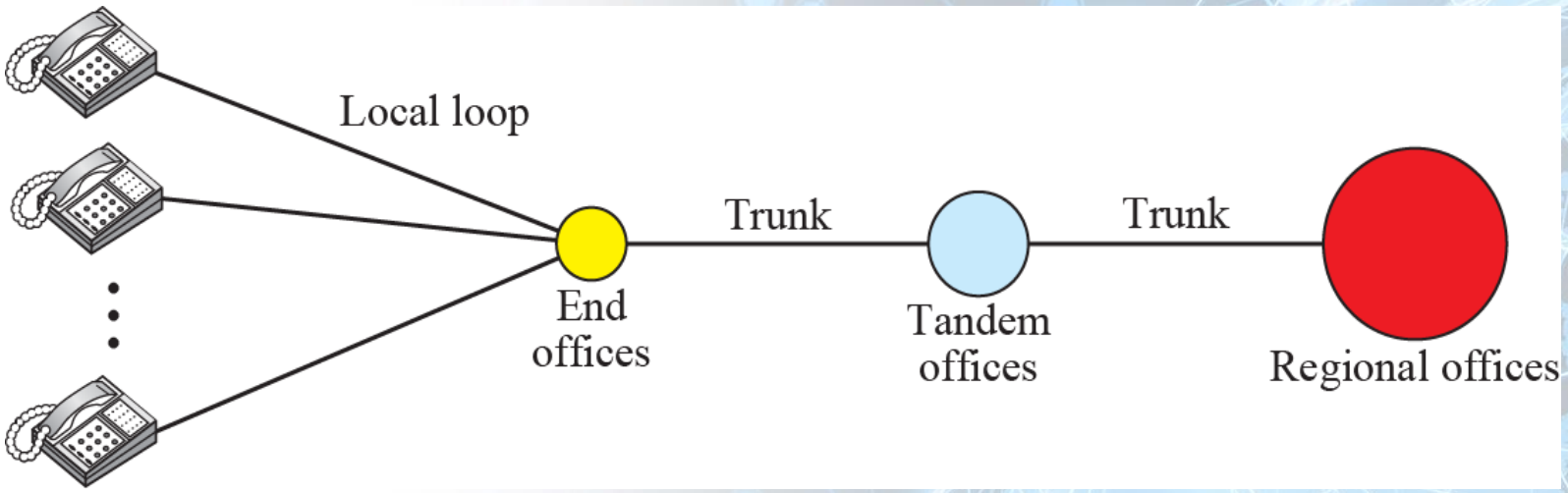
Telephone Network

- During the last decade, the telephone network has undergone many technical changes and the network is now Digital as well as Analog

Major Components

- The telephone network is made of three major components:
  - ✓ Local Loops
  - ✓ Trunks
  - ✓ Switching offices
- The telephone network has several levels of switching offices:
  - ✓ End offices
  - ✓ Tandem offices
  - ✓ Regional offices

A Telephone System



Local-Access Transport Areas (LATAs)

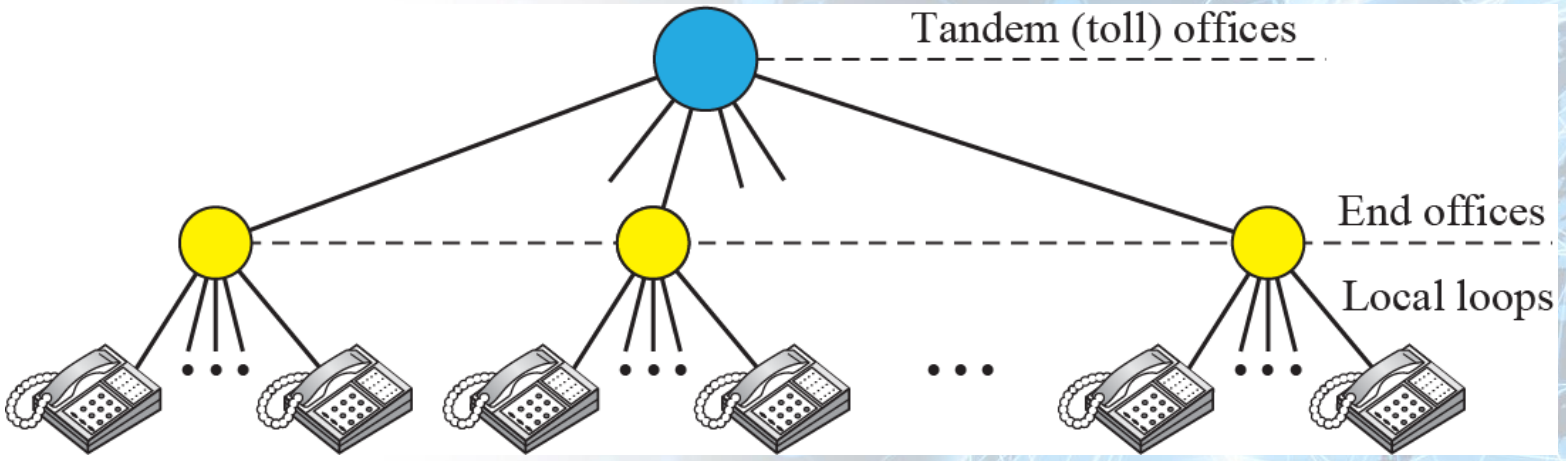
- A LATA can be a small or large metropolitan area
- A small state may have a single LATA; a large state may have several LATAs
- A LATA boundary may overlap with state boundary; part of a LATA can be in one state, part in another state

Intra-LATA and Inter-LATA Services

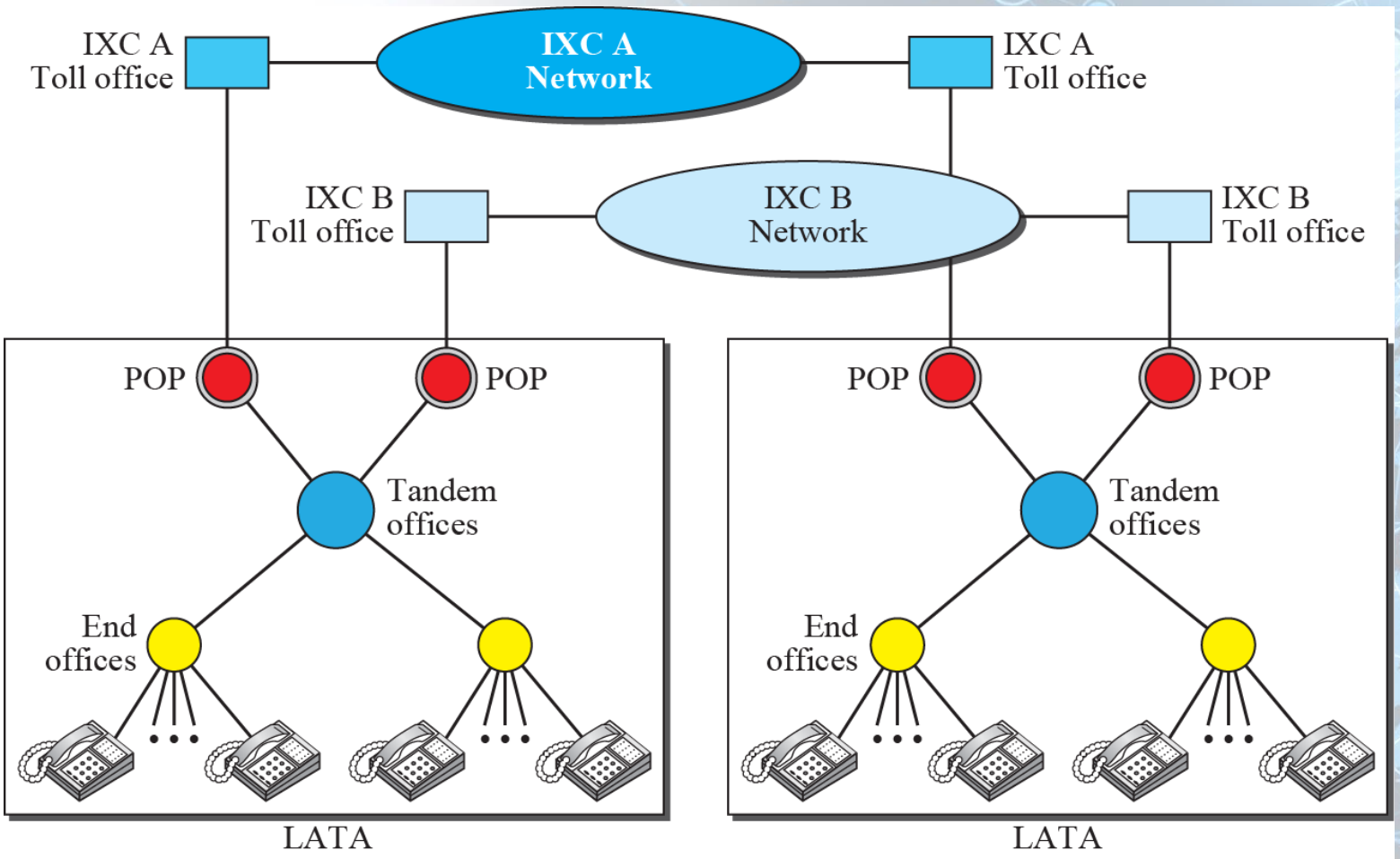
- Services offered by Telephone companies inside a LATA are called Intra-LATA services and between LATAs are called Inter-LATA services

- Carrier that handles Intra-LATA are called a Local Exchange Carrier (LEC) and the ones that handle Inter-LATA are called Interexchange Carriers (IXCs)

Switching Offices in a LATA



Points of Presence (POPs)



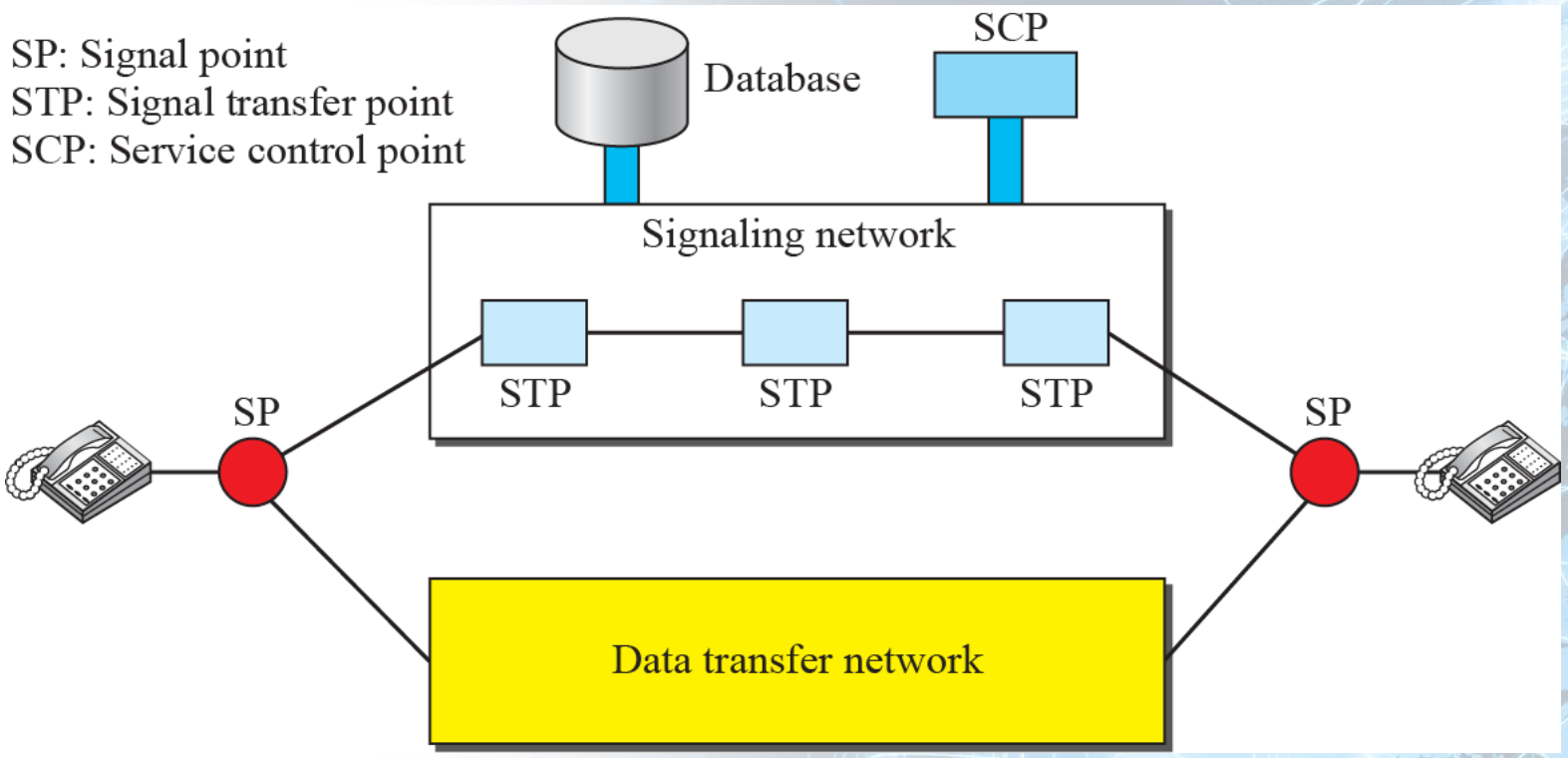
Signaling

- The telephone network in the beginning, used a circuit-switched network with dedicated links to transfer voice communication
- The operator connected the two parties by using a wire with two plugs inserted into the corresponding two jacks
- Later, the signaling system became automatic

Signaling

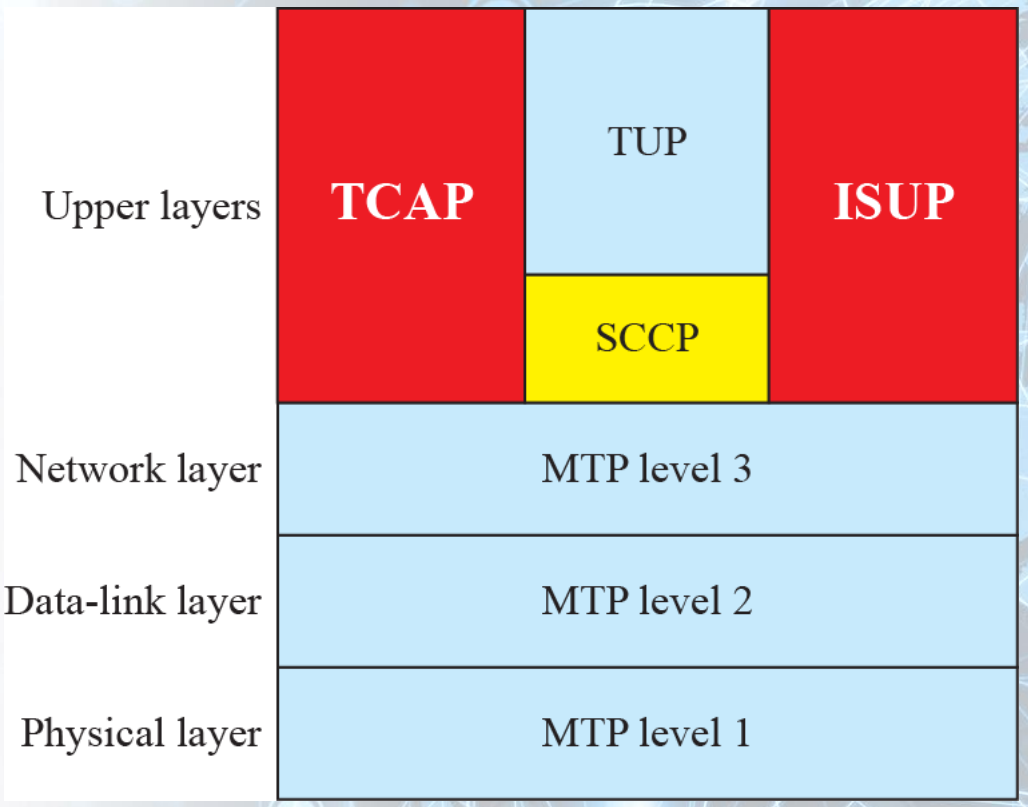
- Rotary telephones were invented that sent a digital signal defining each digit in a multi-digit telephone number
- As telephone networks evolved into a complex network, the functionality of the signaling system increased

Data Transfer and Signaling Network



Layers in SS7

MTP: Message transfer part
SCCP: Signaling connection control point
TCAP: Transaction capabilities application port
TUP: Telephone user port
ISUP: ISDN user port



Services

- **Telephone companies provide two types of services:**
  - ✓ **Analog Services**
    - ➢ **Analog Switched Services**
    - ➢ **Analog Leased Services**
  - ✓ **Digital Services**
    - ➢ **Switched /56 Service**
    - ➢ **Digital Data Service**

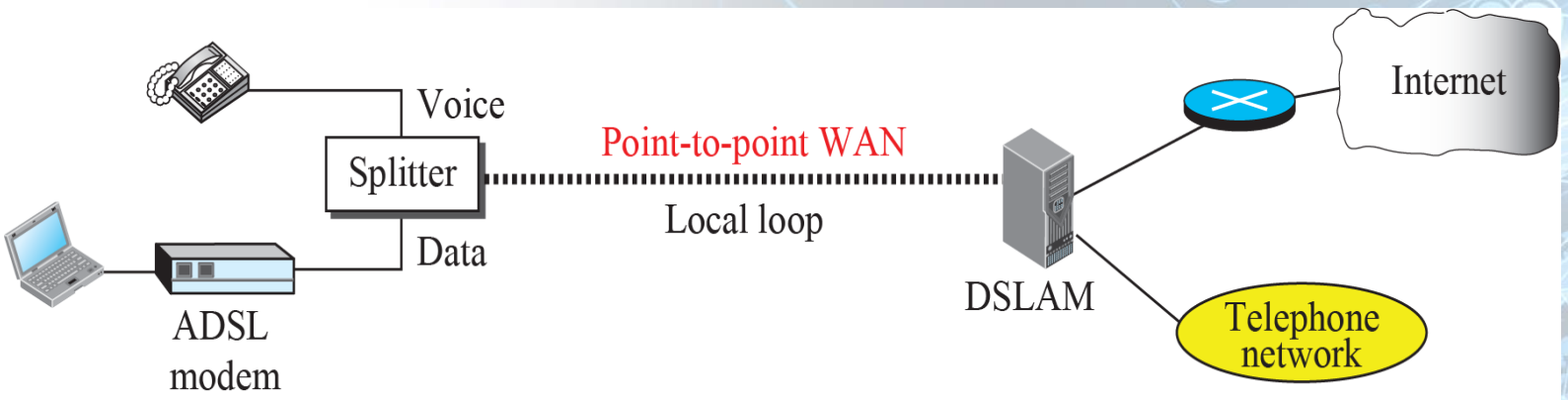
Digital Subscriber Line (DSL)

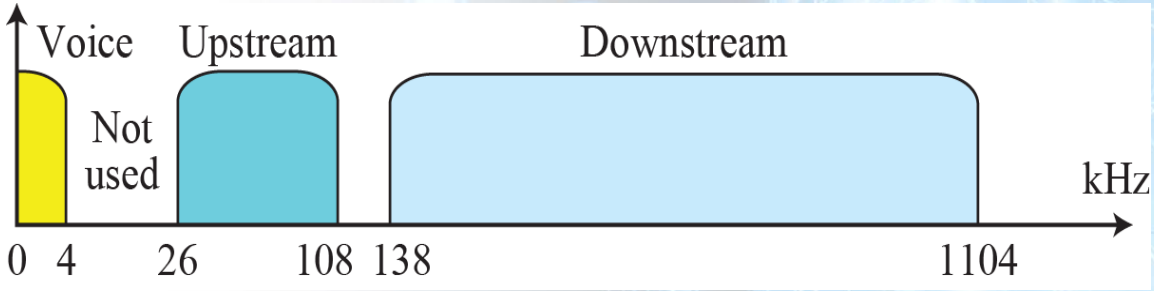
- After traditional dial-up modems reached their peak data rate, telephone companies developed another technology, DSL, to provide higher-speed access to the Internet
- DSL supports high-speed digital communication over the existing telephone

Digital Subscriber Line (DSL)

- DSL technology is a set of technologies, each differing in the first letter (ADSL, VDSL, HDSL, and SDSL)

ADSL Point-to-Point Network





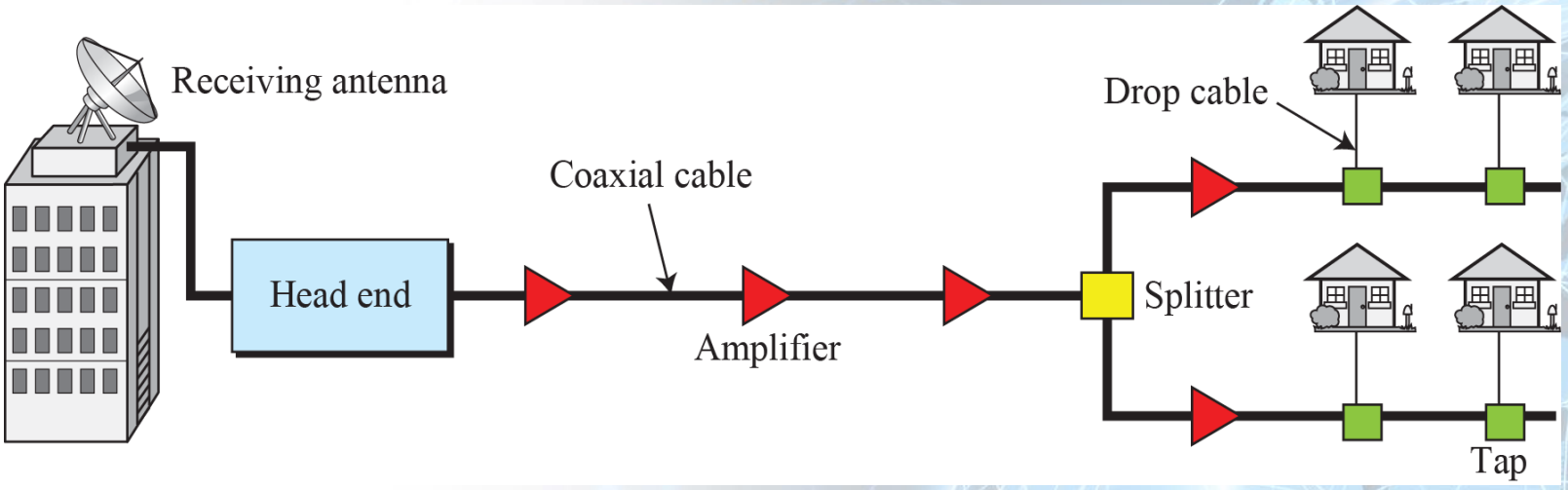
Cable Network

- The Cable TV networks were initially created to provide remote subscribers access to TV programs
- Cable networks enabled access to remote broadcasting stations via microwave connections
- Cable TV also found a good ISP market by using some of the channels originally designed for video

Traditional Cable Networks

- Cable TV started to distribute broadcast video signals to locations with poor or no reception in the late 1940s
- It was called community antenna television (CATV) because an antenna at the top of a tall hill or building received the signals from the TV stations

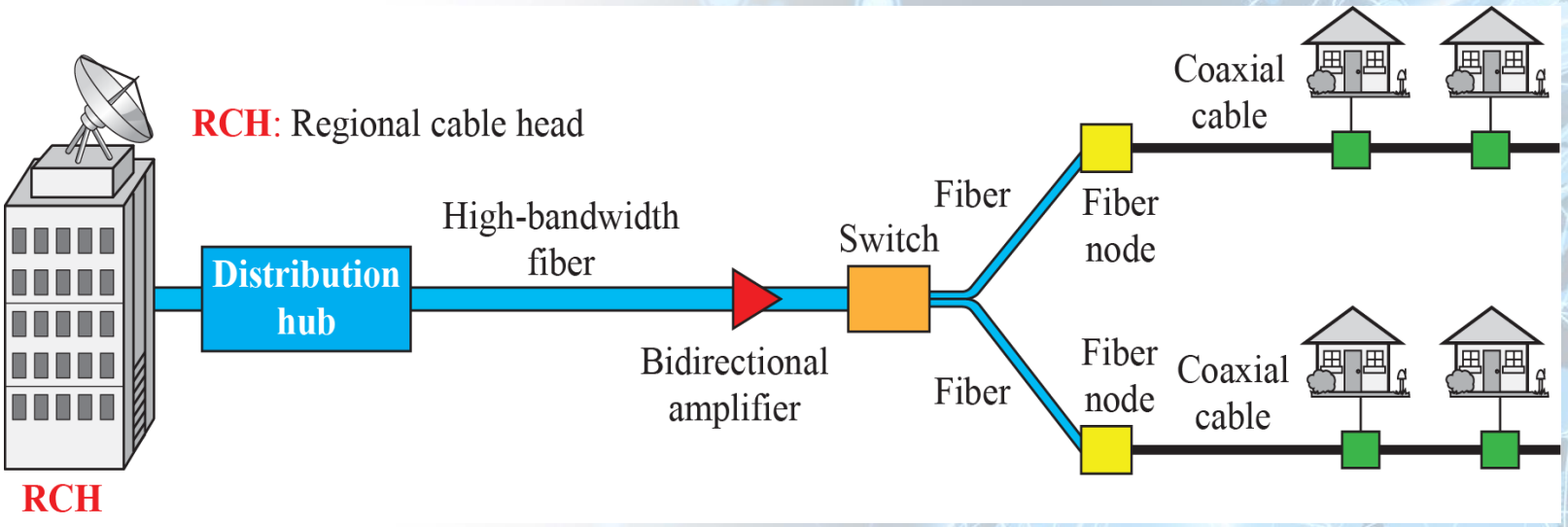
Traditional Cable TV Network



Hybrid Fiber Coaxial (HFC) Network

- Second generation of cable network is called a Hybrid Fiber-Coaxial (HFC) network
- The network uses a combination of fiber-optic and coaxial cable

Hybrid Fiber-Coaxial (HFC) Network



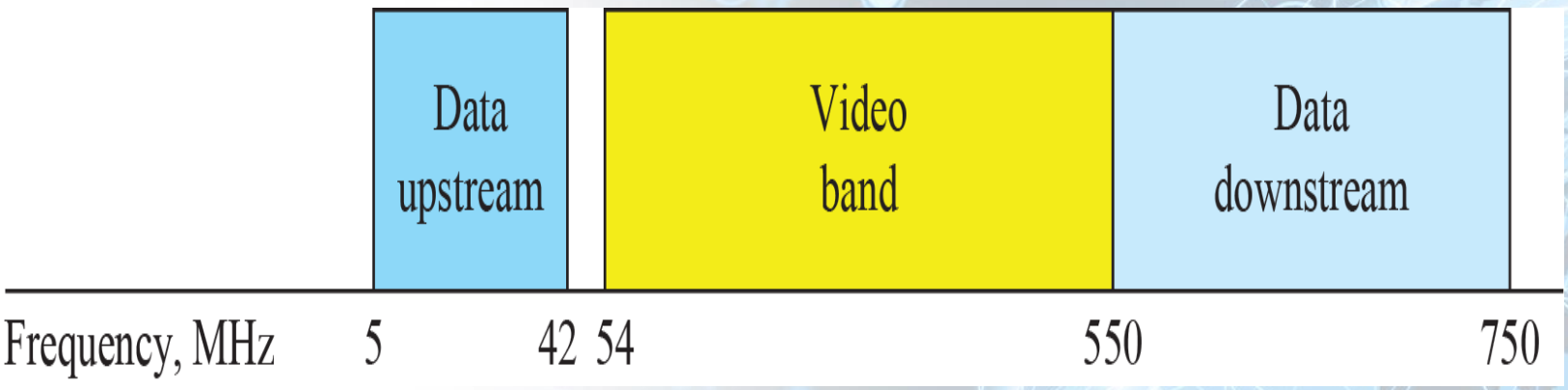
Cable TV for Data Transfer

- Cable companies are now competing with telephone companies for the residential customer who wants high-speed data transfer
- DSL technology provides high-data-rate connections for residential subscribers over the local loop BUT UTP is susceptible to Interfence

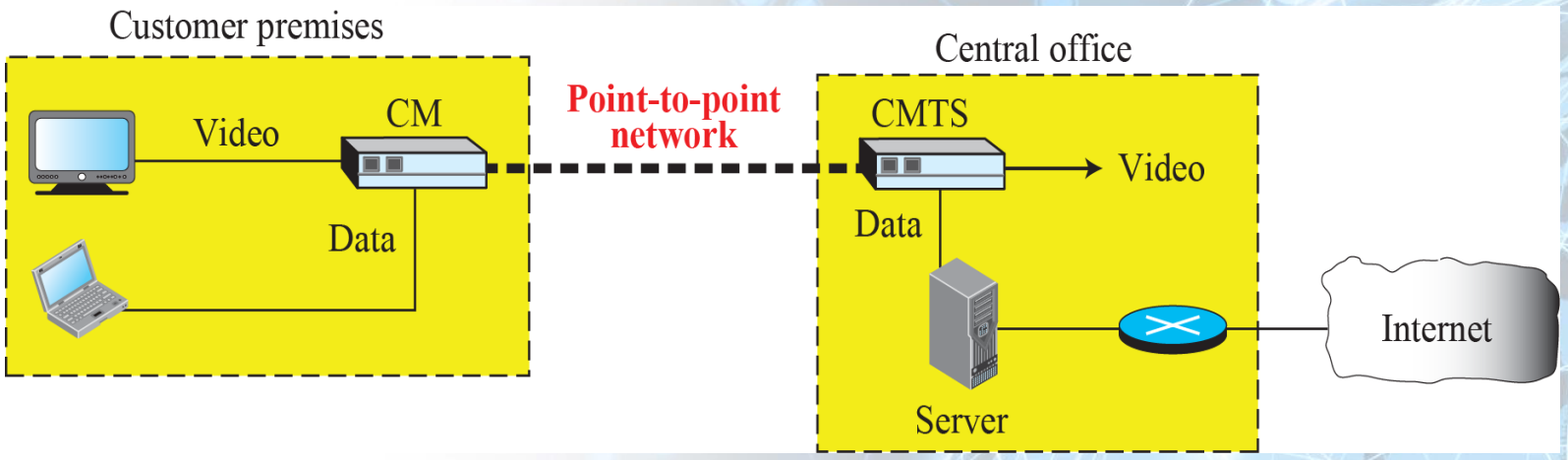
Cable TV for Data Transfer

- This imposes an upper limit on the data rate. A solution is the use of the cable TV network

Division of Coaxial Cable Band by CATV



Cable Modem Transmission System (CMTS)



Synchronous Optical Network (SONET)

- A wide area network (WAN) that is used as a transport network to carry loads from other WANs
- ITU–T standard called Synchronous Digital Hierarchy (SDH)
- Architecture of a SONET system consists of signals, devices, and connections

SONET Architecture

- **Signals**
  - ✓ Synchronous Transport Signals (STS)
  - ✓ Optical Carriers (OCs)
  - ✓ Synchronous Transport Module (STM)
- **SONET Devcies**
  - ✓ STS Mux/Demux
  - ✓ Regenerators
  - ✓ Add-Drop Multiplexer and Terminals
- **Connections**
  - ✓ Section
  - ✓ Line
  - ✓ Path

SONET Signals

STS	*OC*	*Rate (Mbps)*	*STM*
STS-1	OC-1	51.840	
STS-3	OC-3	155.520	**STM-1**
STS-9	OC-9	466.560	**STM-3**
STS-12	OC-12	622.080	**STM-4**
STS-18	OC-18	933.120	**STM-6**
STS-24	OC-24	1244.160	**STM-8**
STS-36	OC-36	1866.230	**STM-12**
STS-48	OC-48	2488.320	**STM-16**
STS-96	OC-96	4976.640	**STM-32**
STS-192	OC-192	9953.280	**STM-64**

SONET Architecture

- **Signals**
  - ✓ Synchronous Transport Signals (STS)
  - ✓ Optical Carriers (OCs)
  - ✓ Synchronous Transport Module (STM)
- **SONET Devcies**
  - ✓ STS Mux/Demux
  - ✓ Regenerators
  - ✓ Add-Drop Multiplexer and Terminals
- **Connections**
  - ✓ Section
  - ✓ Line
  - ✓ Path

SONET Devices

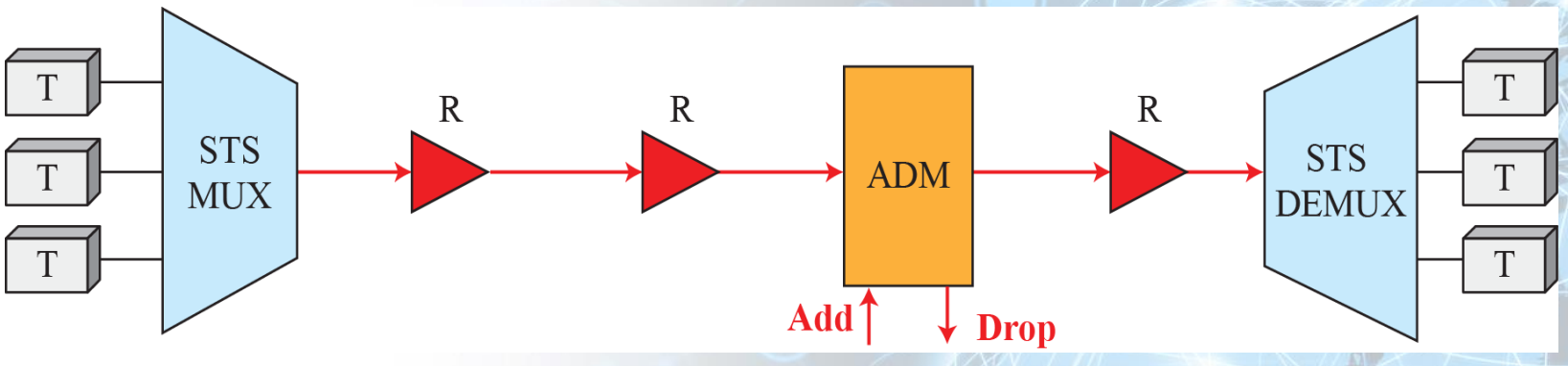
ADM: Add/drop multiplexer

STS MUX: Synchronous transport signal multiplexer

STS DEMUX: Synchronous transport signal demultiplexer

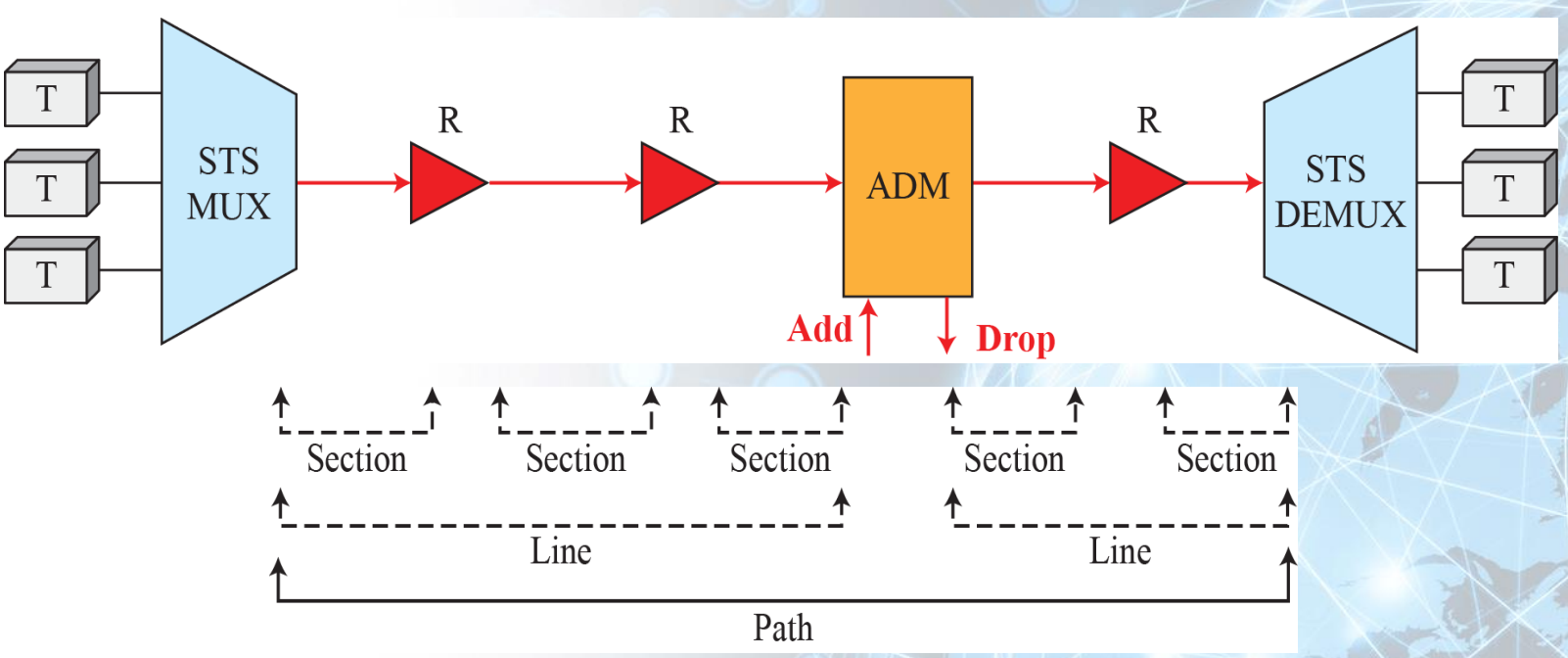
R: Regenerator

T: Terminal



SONET Connections

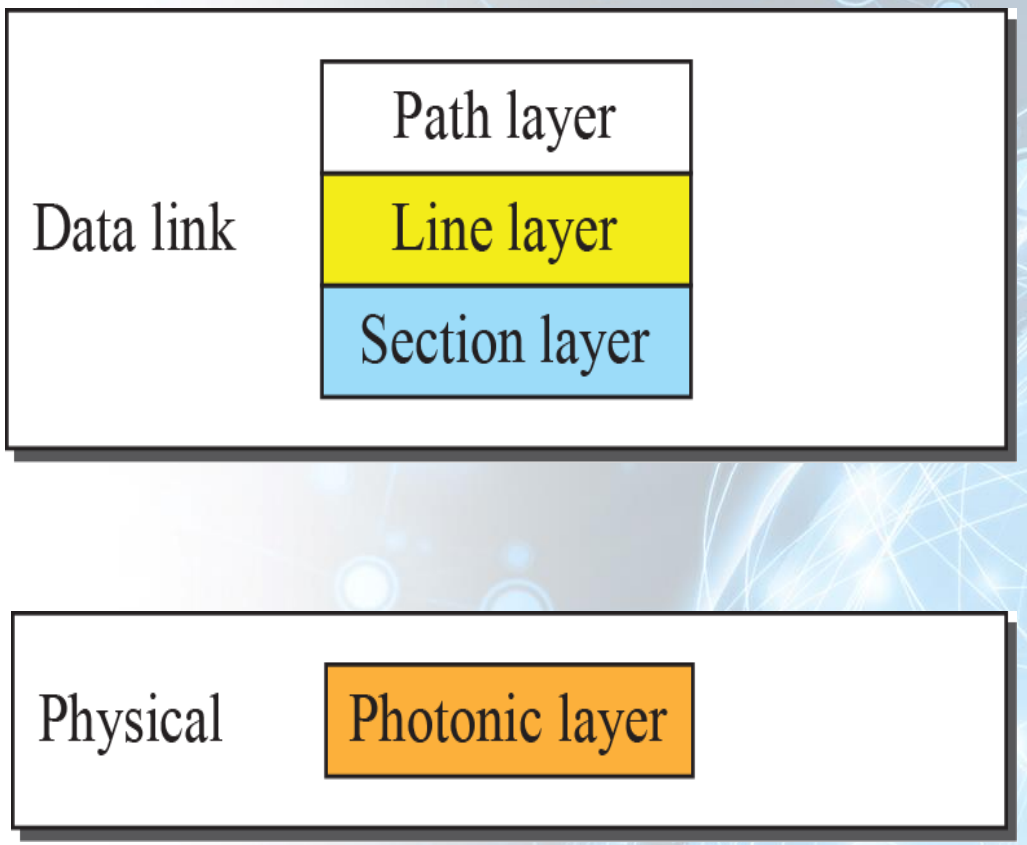
ADM: Add/drop multiplexer
STS MUX: Synchronous transport signal multiplexer
STS DEMUX: Synchronous transport signal demultiplexer
R: Regenerator
T: Terminal



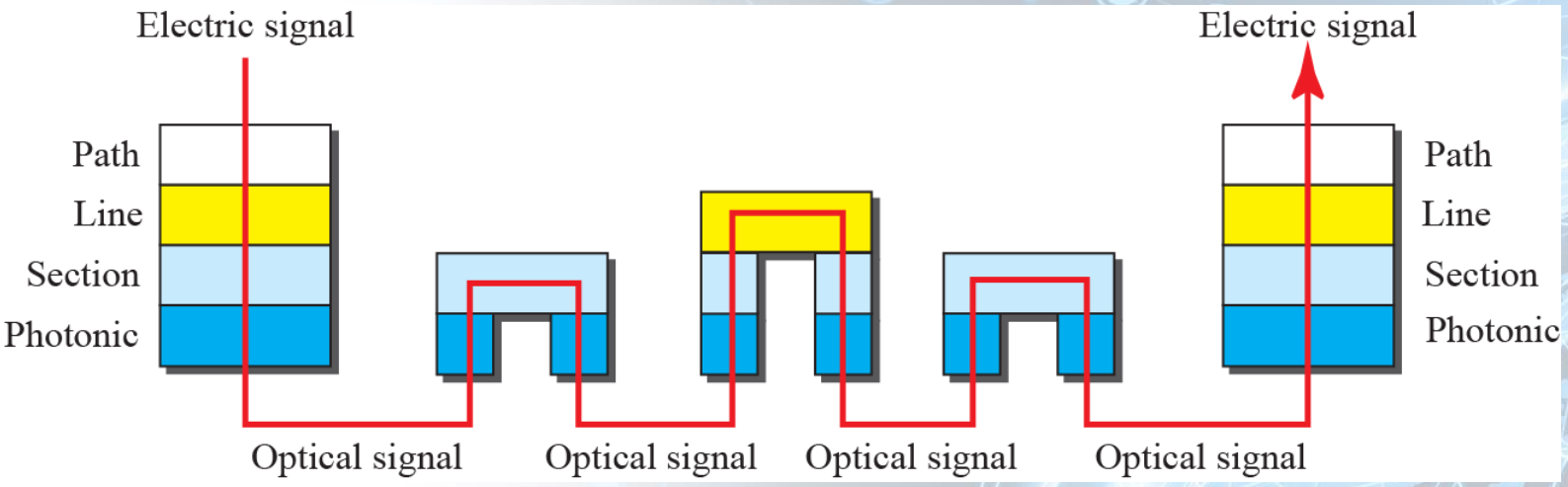
SONET Layers

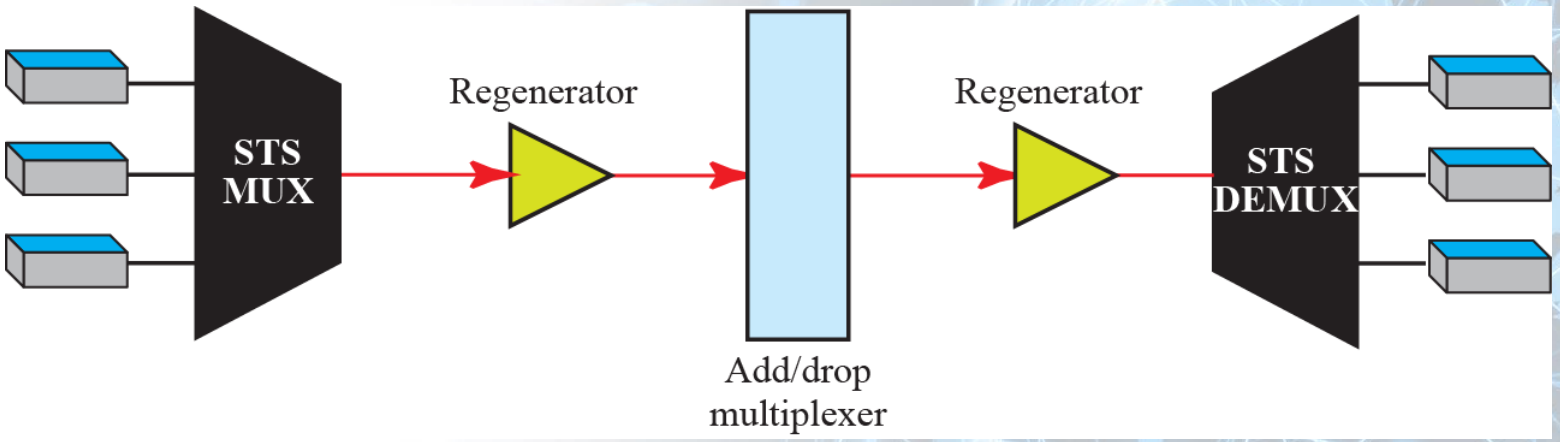
- The SONET standard includes four functional layers:
  - ✓ The Path Layer
  - ✓ The Line Layer
  - ✓ The Section Layer
  - ✓ The Photonic Layer
- The layers correspond to both the physical and the data-link layers

SONET Layers



Device-Layer Relationship in SONET

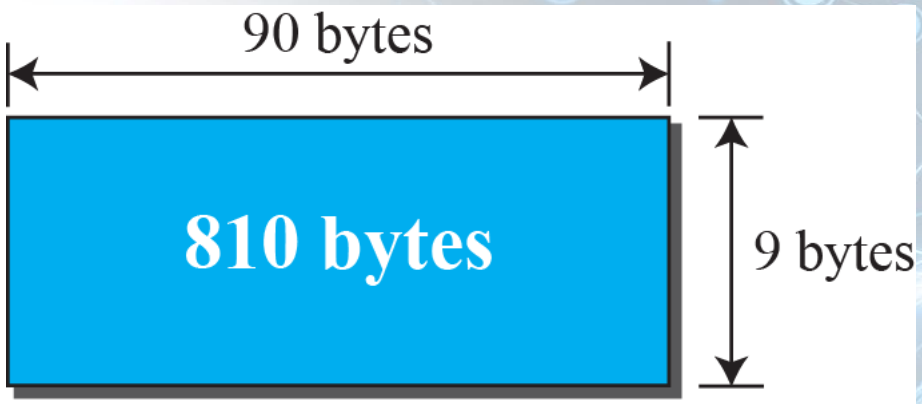




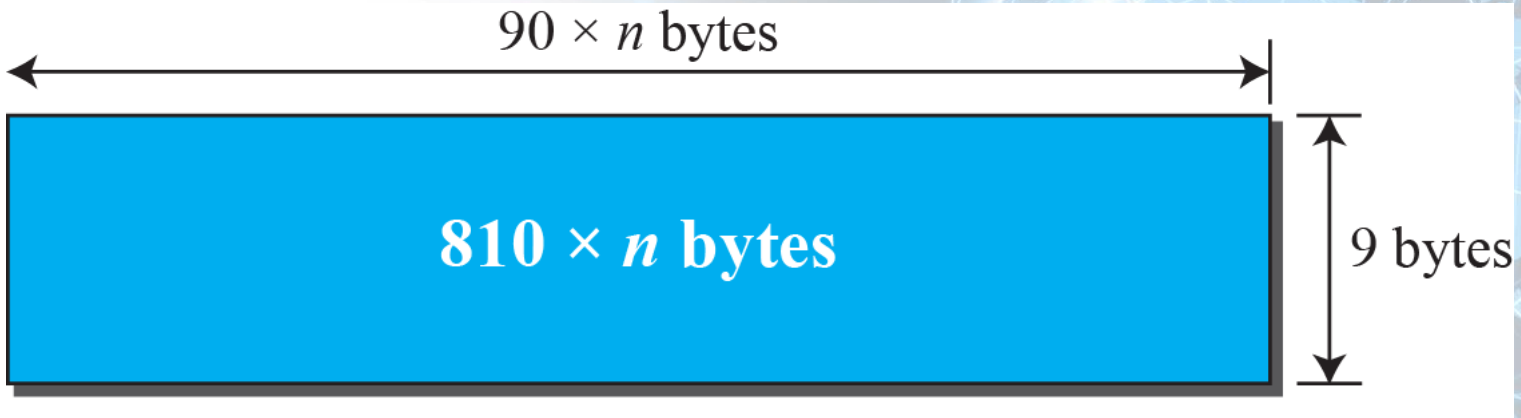
SONET Frames

- Each synchronous transport signal STS-n is composed of 8000 frames
- Each frame is a two-dimensional matrix of bytes with 9 rows by 90×n columns
- STS-1 frame is 9 rows by 90 columns (810 bytes), and an STS-3 is 9 rows by 270 columns (2430 bytes)

An STS-1 and an STS-n Frame

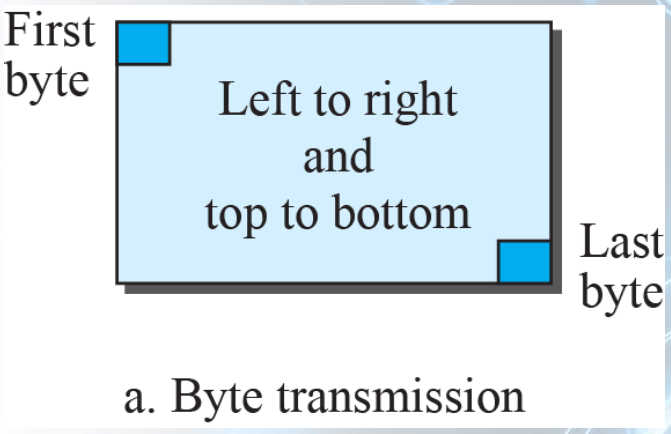


a. STS-1 frame

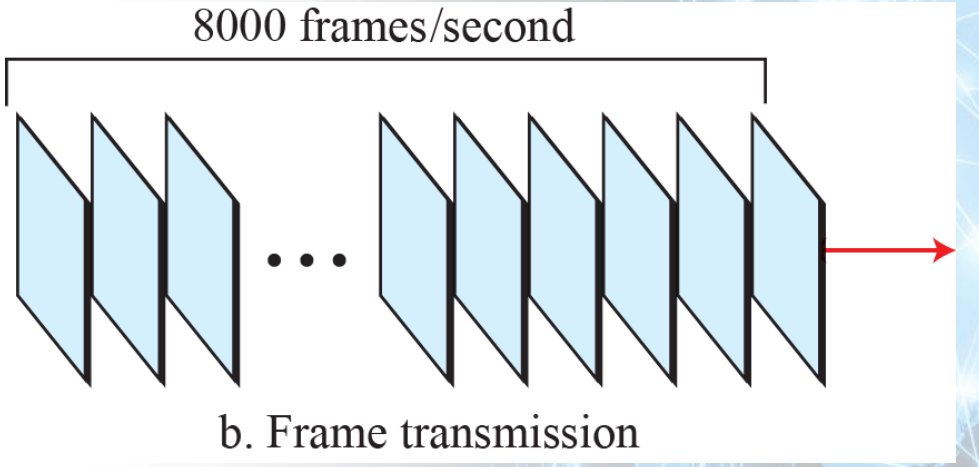


b. STS-*n* frame

STS-1 Frames in Transition



a. Byte transmission



b. Frame transmission

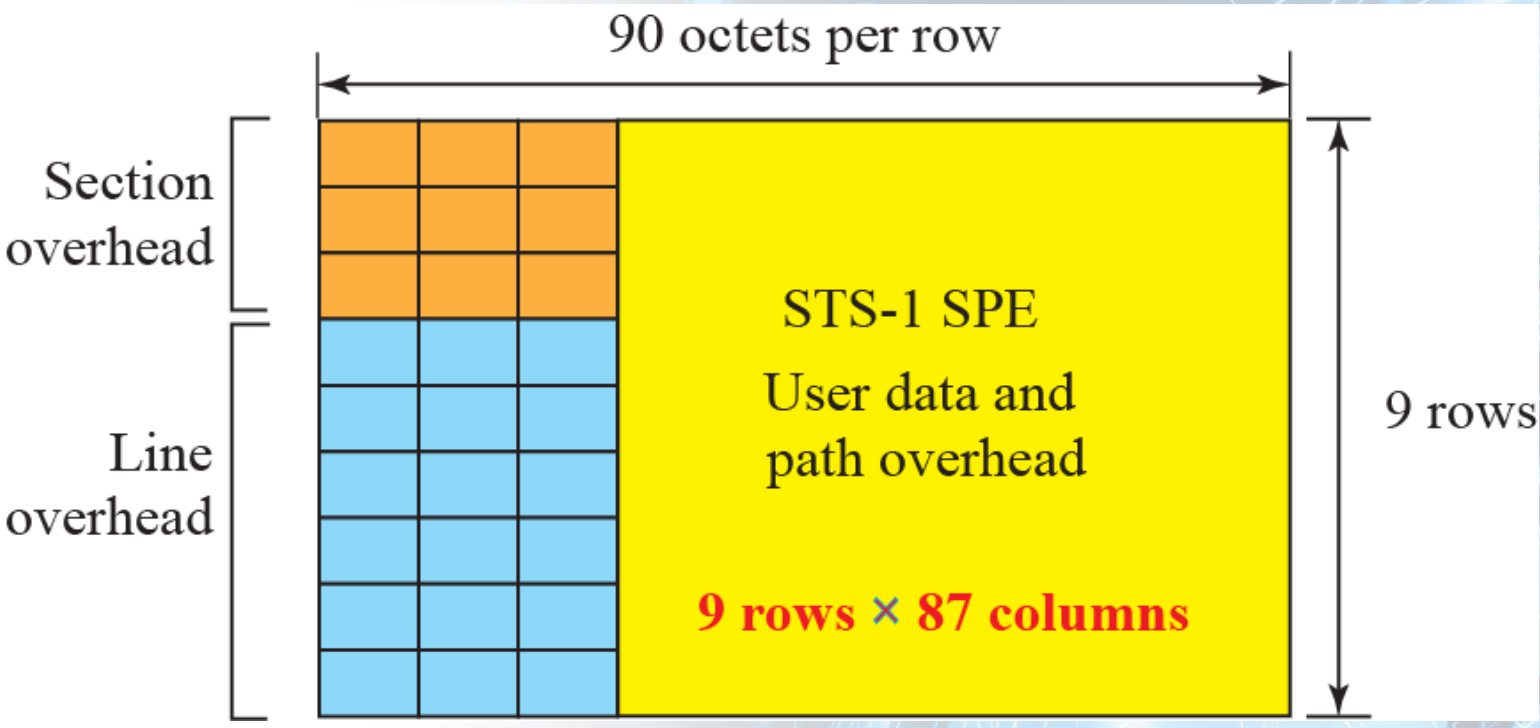
Example

Find the data rate of an STS-1 signal

Example

Find the data rate of an STS-3 signal

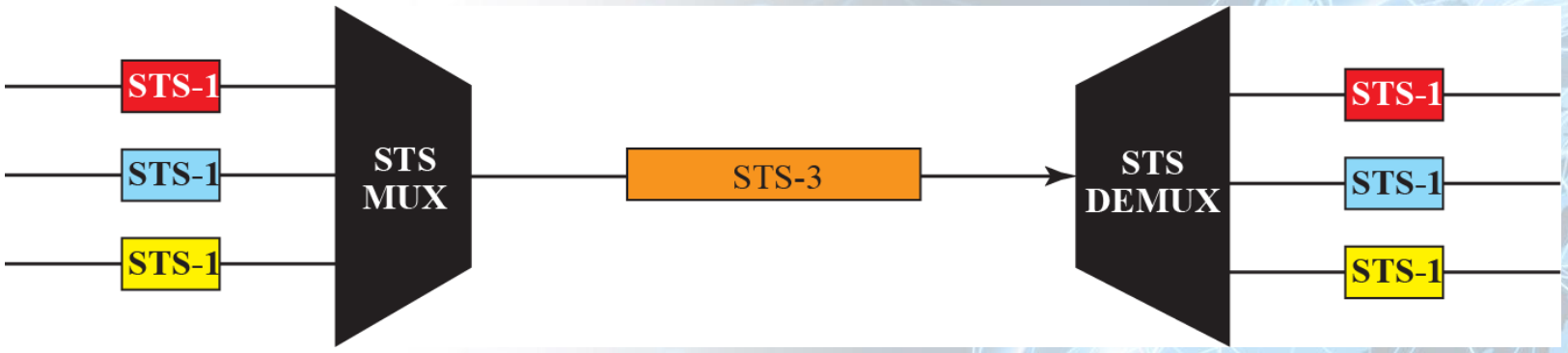
STS-1 Frame Format



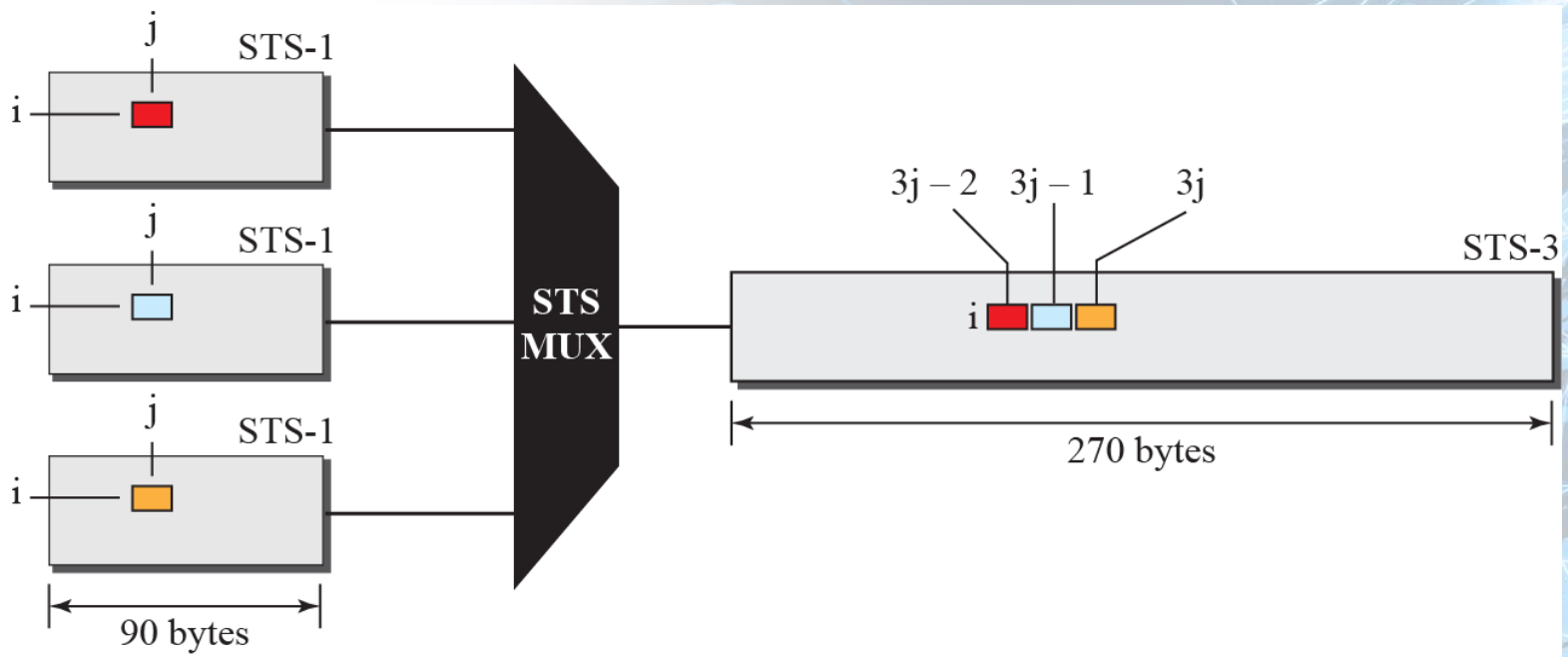
STS Multiplexing

- In SONET, frames of lower rate can be synchronously time-division multiplexed into a higher-rate frame
- For example, three STS-1 signals (channels) can be combined into one STS-3 signal (channel), four STS-3s can be multiplexed into one STS-12, and so on

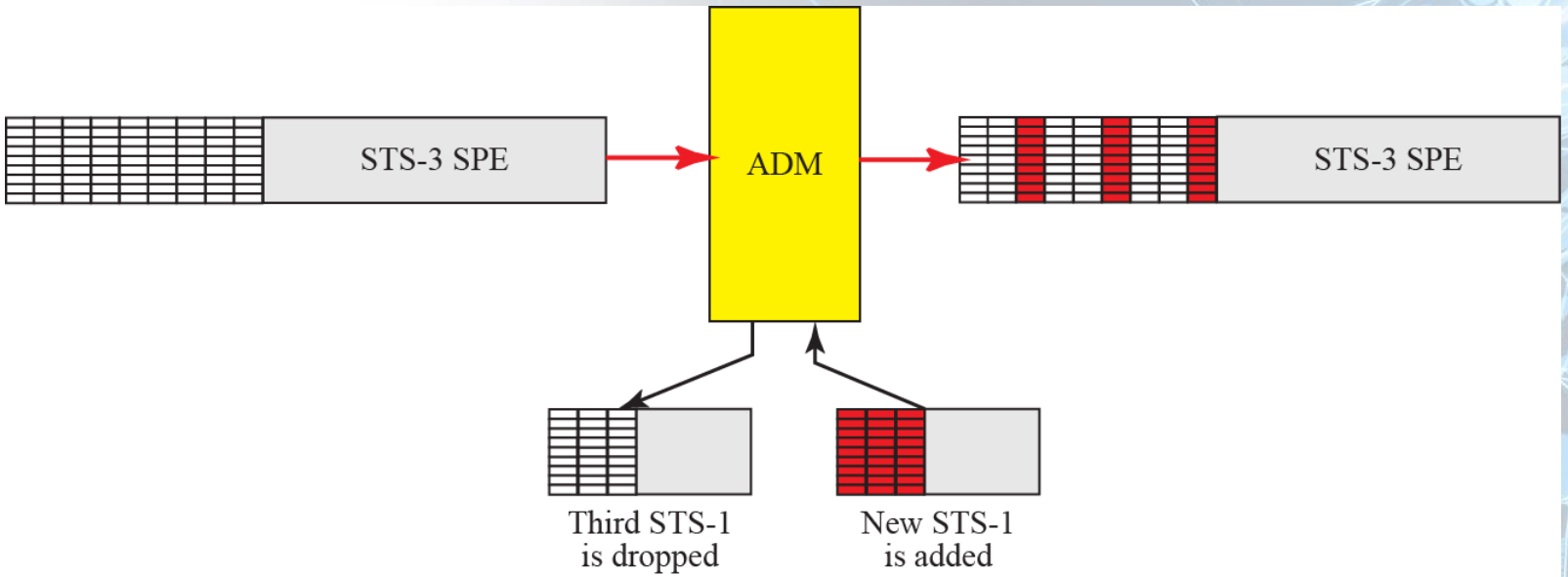
STS Multiplexing/Demultiplexing



Byte Interleaving



Add/Drop Multiplexer



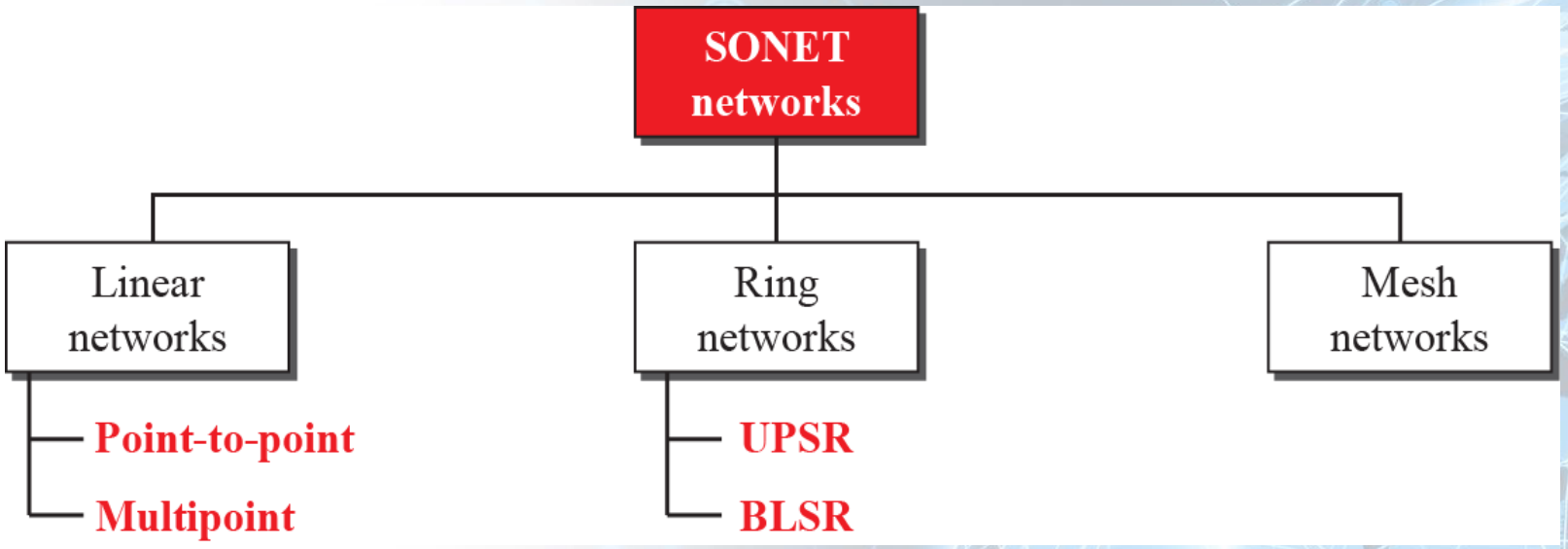
SONET Networks

- SONET network can be used as a high-speed backbone carrying loads from other networks such as ATM or IP

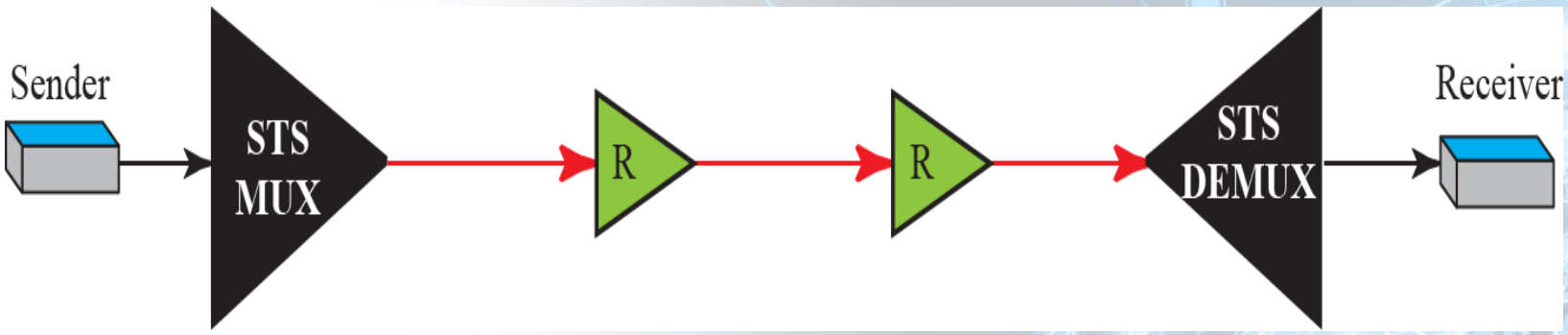
- We can roughly divide SONET networks into three categories:

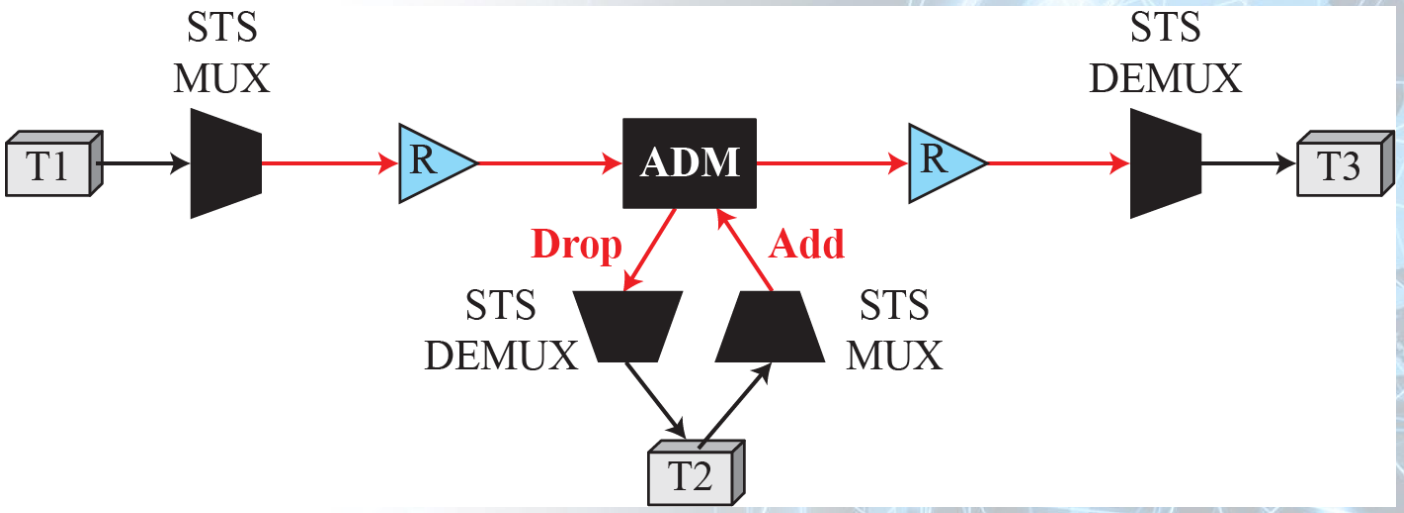
  - ✓ Linear Networks
  - ✓ Ring Networks
  - ✓ Mesh networks

Taxonomy of SONET Networks

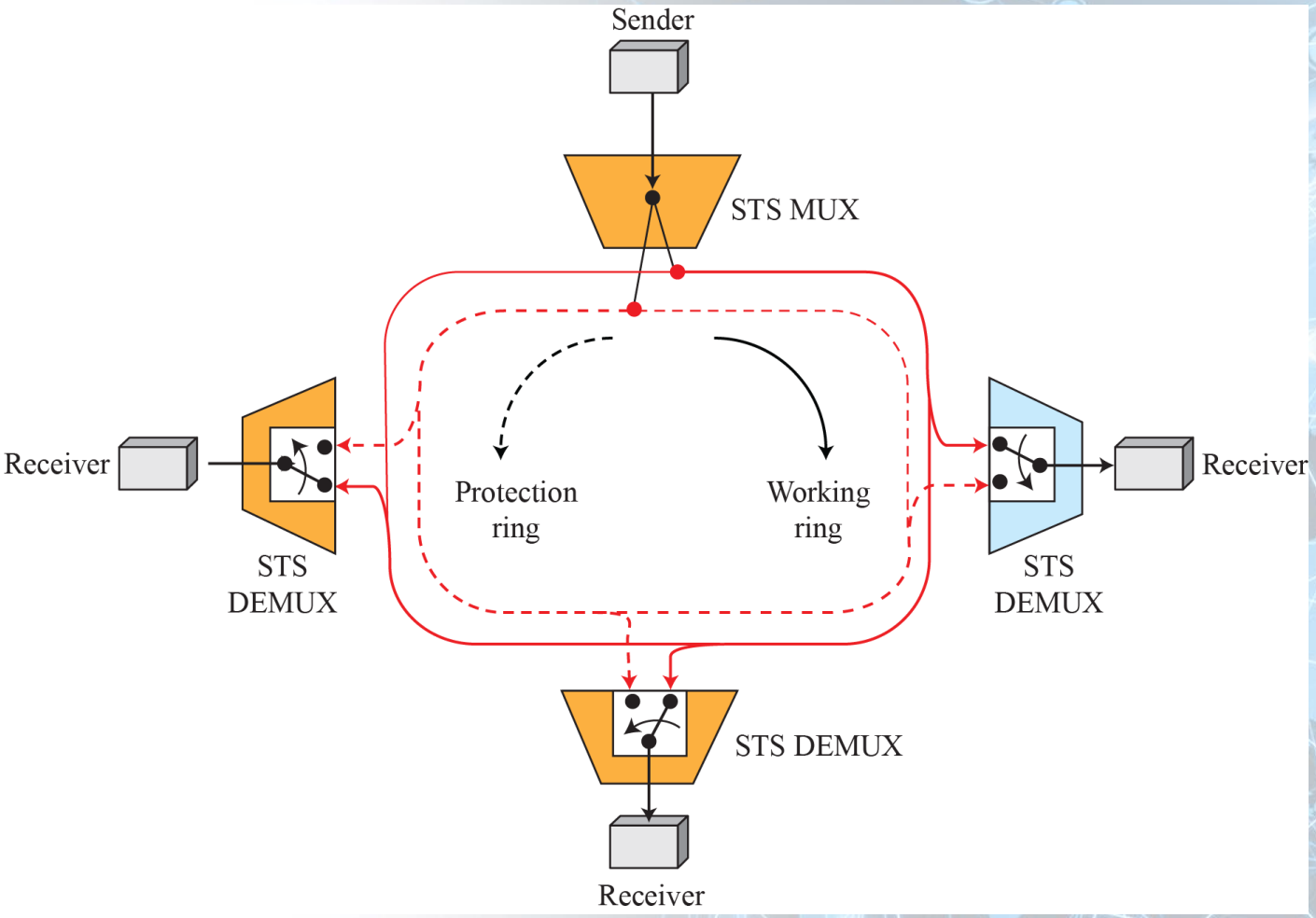


SONET Networks – Linear Networks

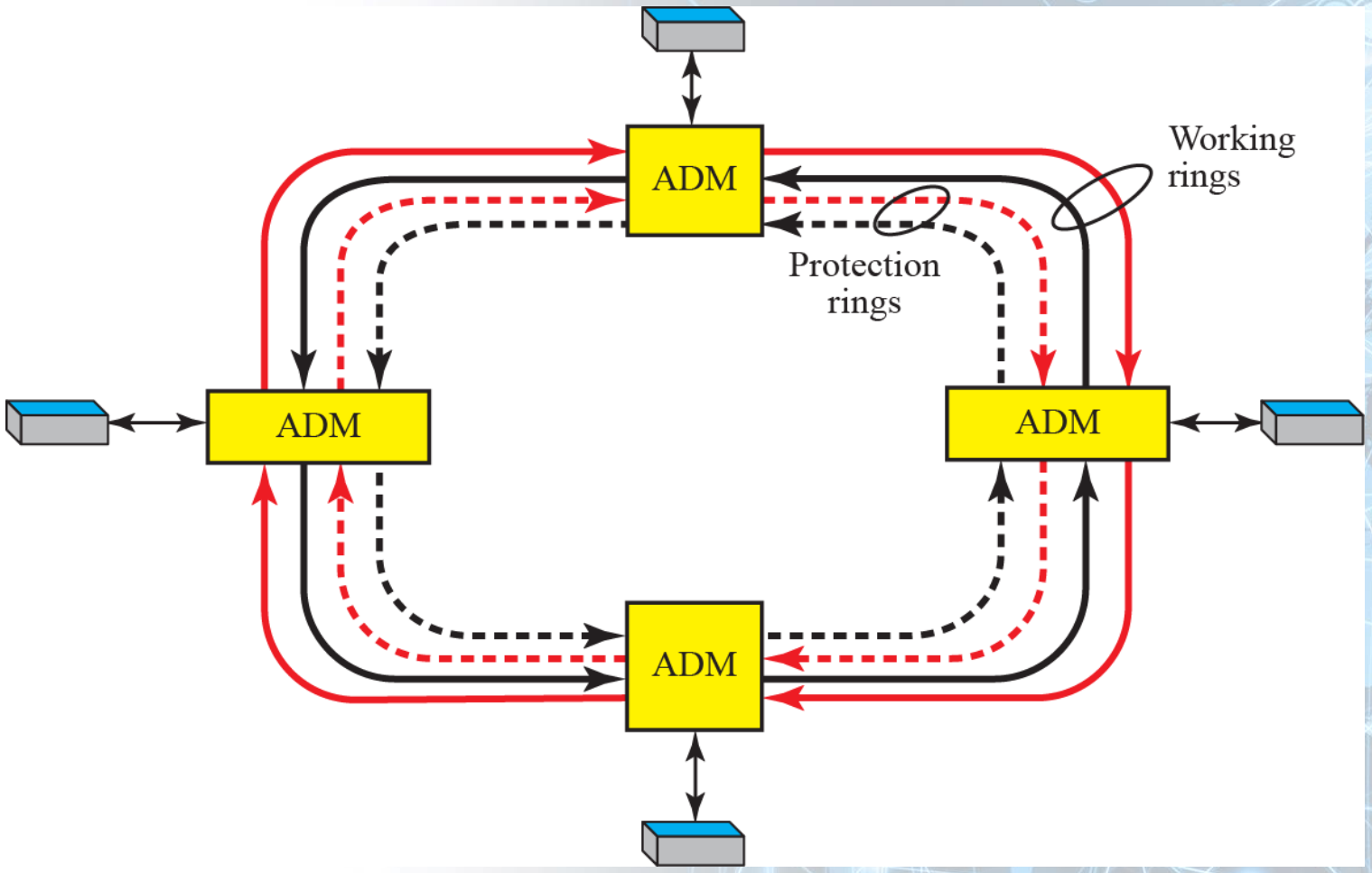




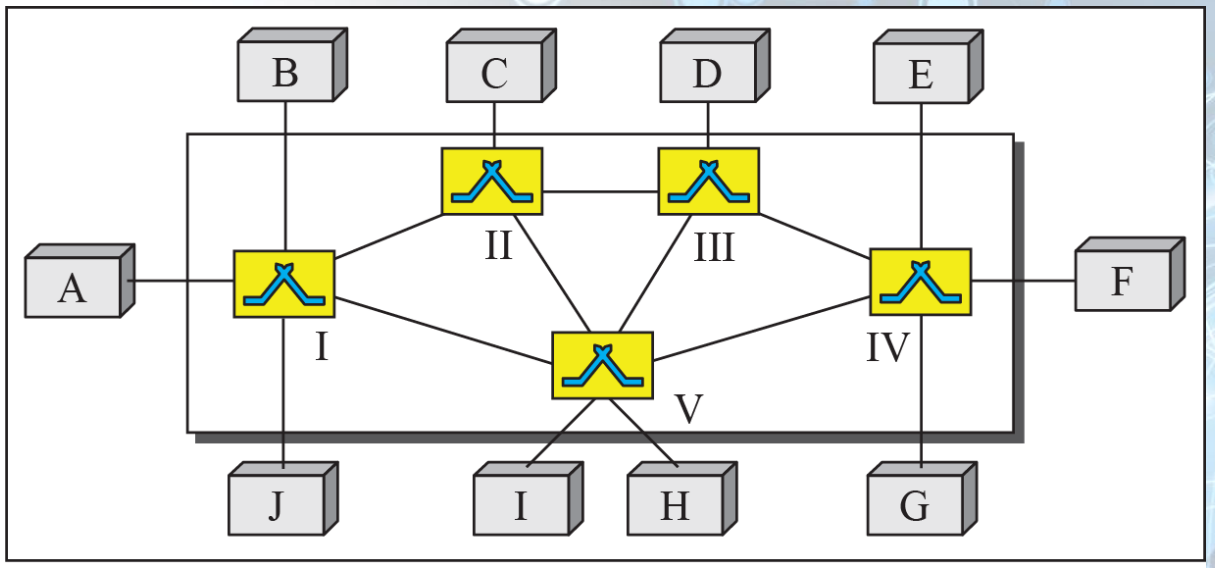
SONET Networks – Ring Networks



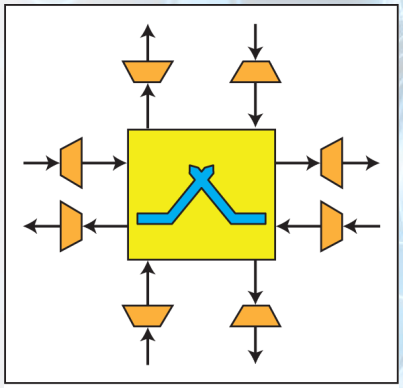
SONET Networks – Ring Networks



SONET Networks – Mesh Networks



a. SONET mesh network



b. Cross-connect switch

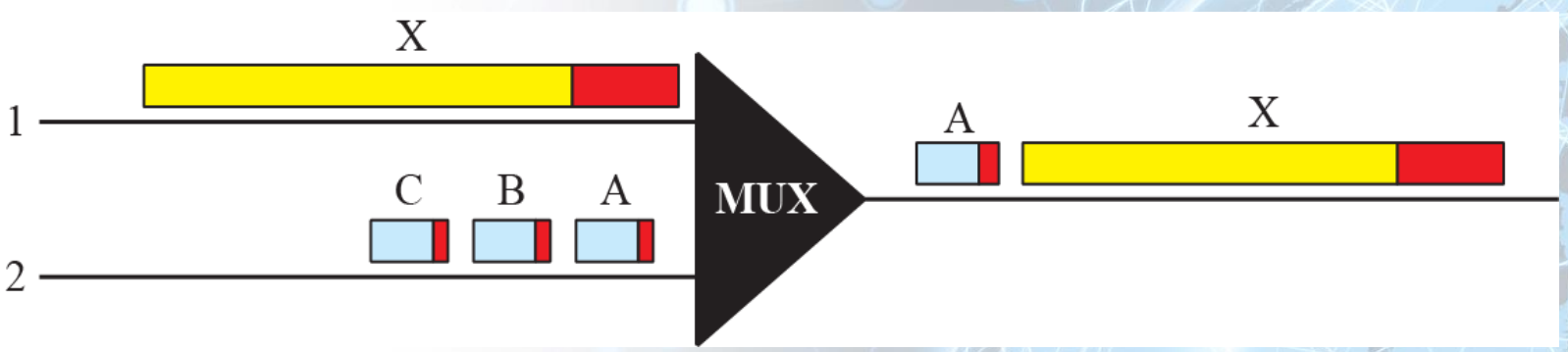
ATM

- Asynchronous Transfer Mode (ATM) is a switched wide area network based on the cell relay protocol designed by the ATM forum
- The combination of ATM and SONET will allow high-speed interconnection of networks

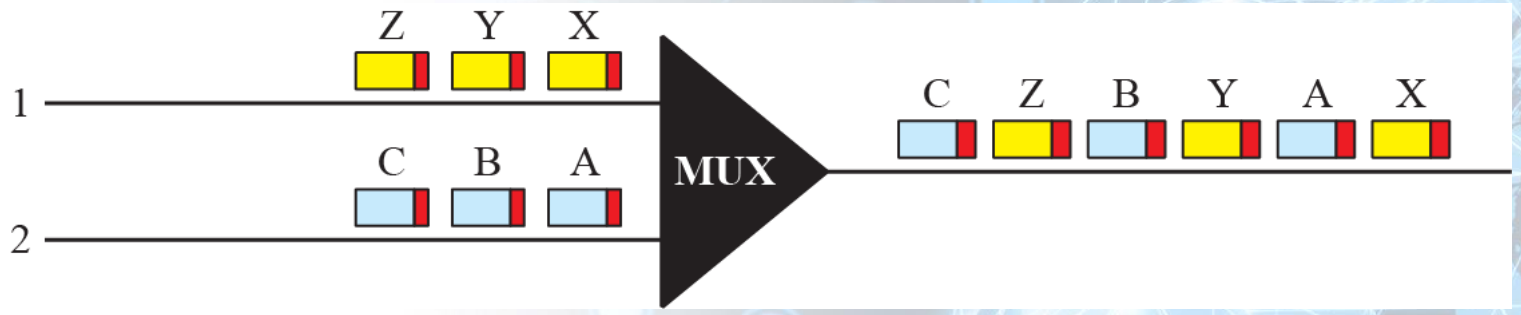
Problems

- Some of the problems associated with existing systems are:
  - ✓ Frame Networks
  - ✓ Mixed Network Traffic
- Solution
  - ✓ Cell Networks
  - ✓ Asynchronous TDM

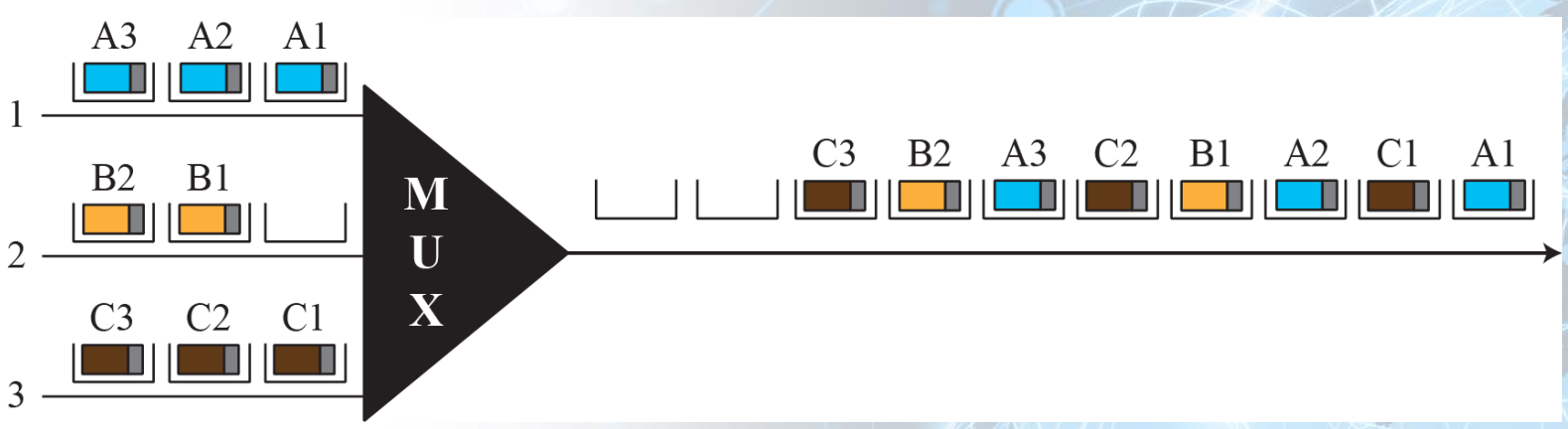
Multiplexing using Different Frame Size



Multiplexing using Cells



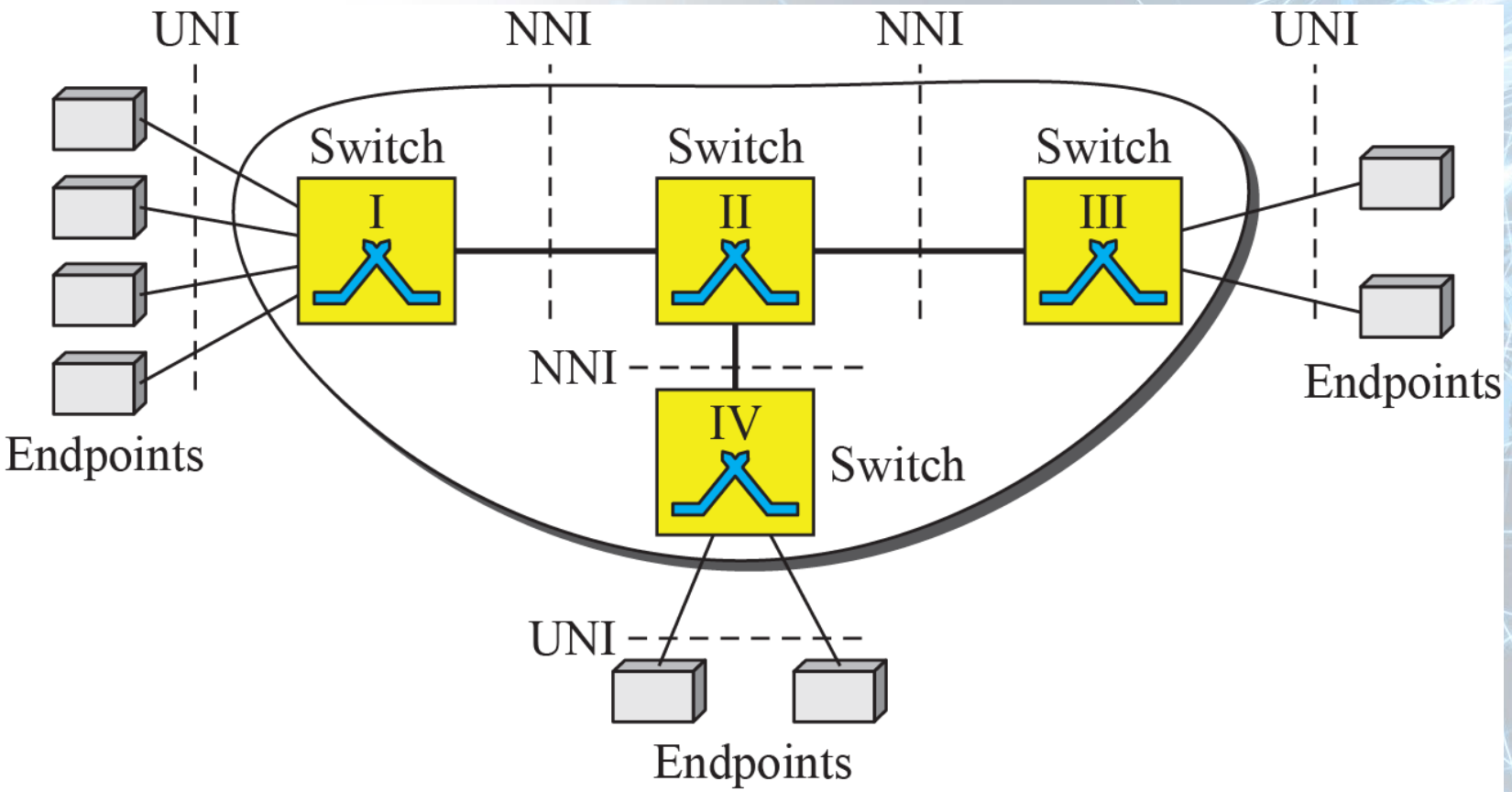
ATM Multiplexing



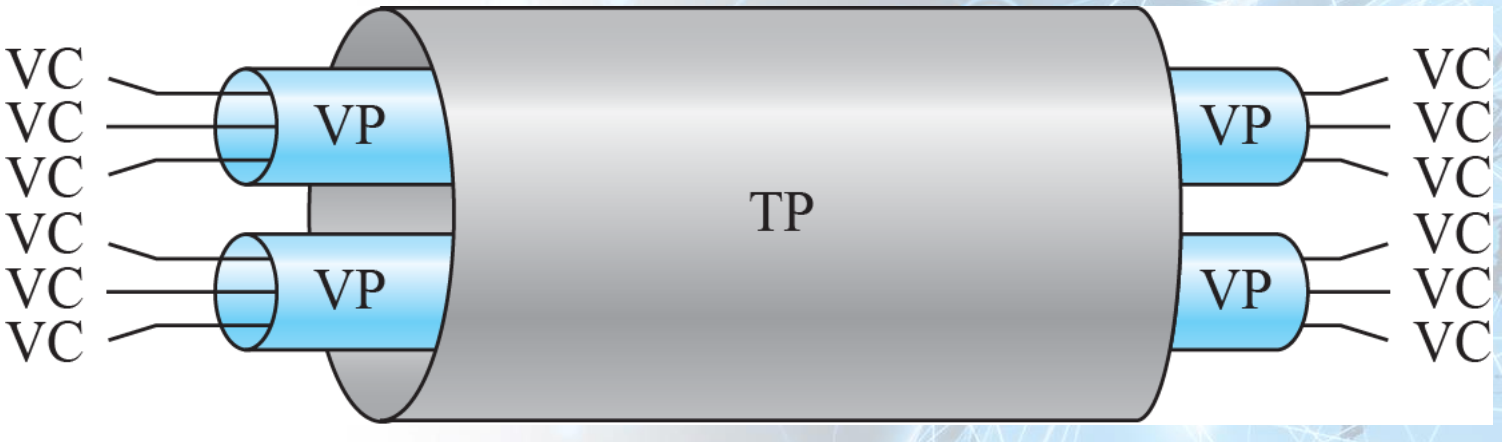
Architecture

- ATM is a cell-switched network
- The user access devices, called the endpoints, are connected through a user-to-network interface (UNI) to the switches inside the network
- The switches are connected through network-to-network interfaces (NNIs)

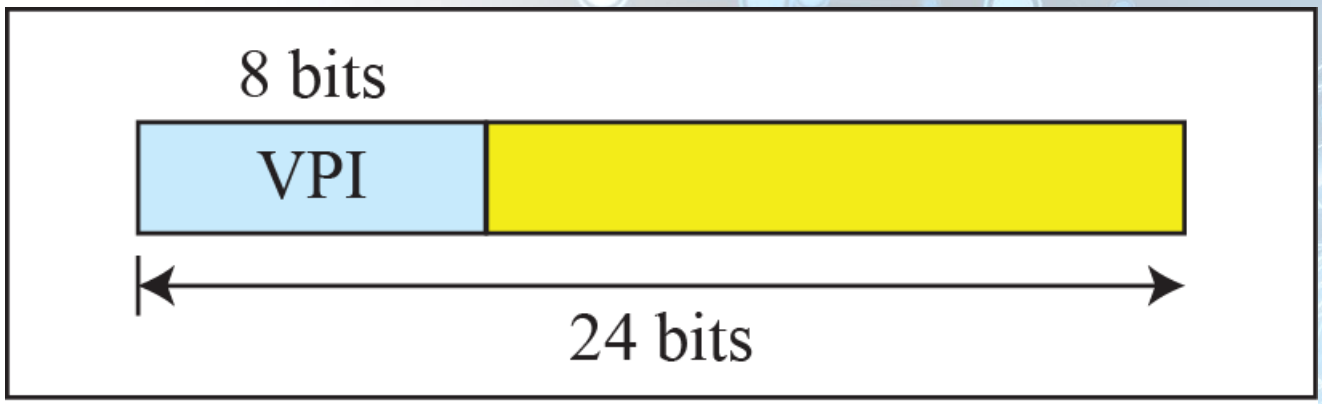
Architecture of an ATM Network



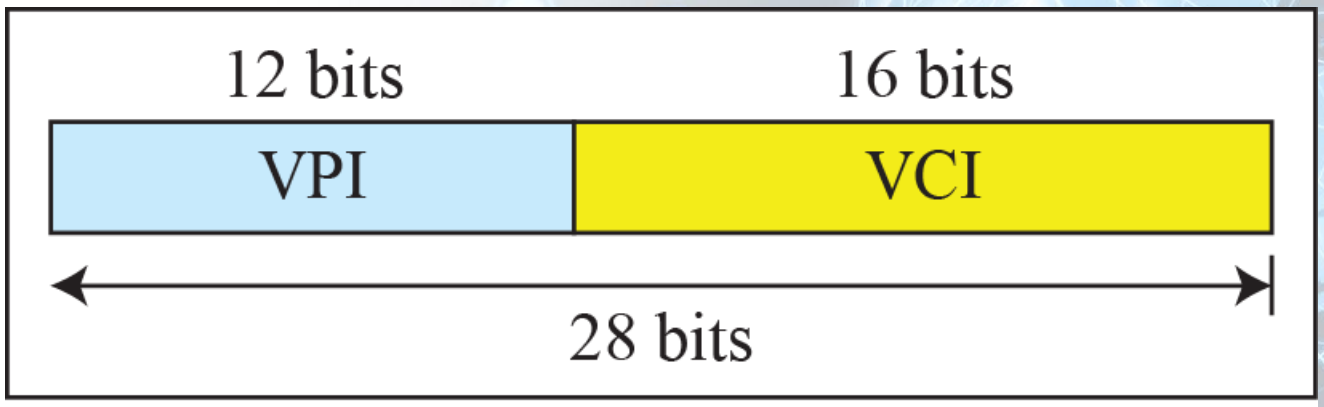
TP, VPs, and VCs



Virtual connection identifiers in UNIs & NNIs

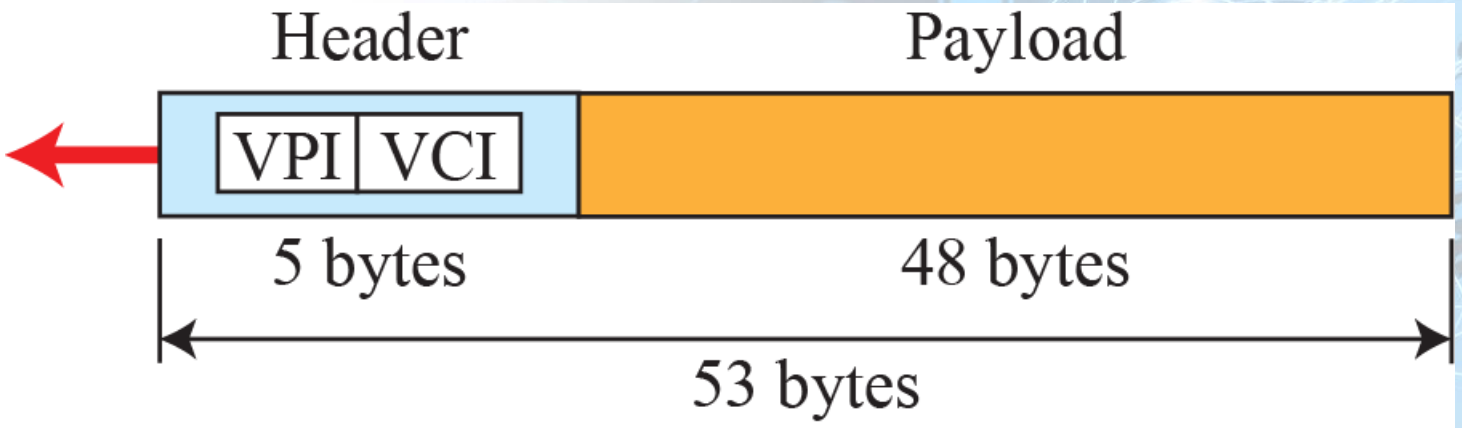


a. VPI and VCI in a UNI

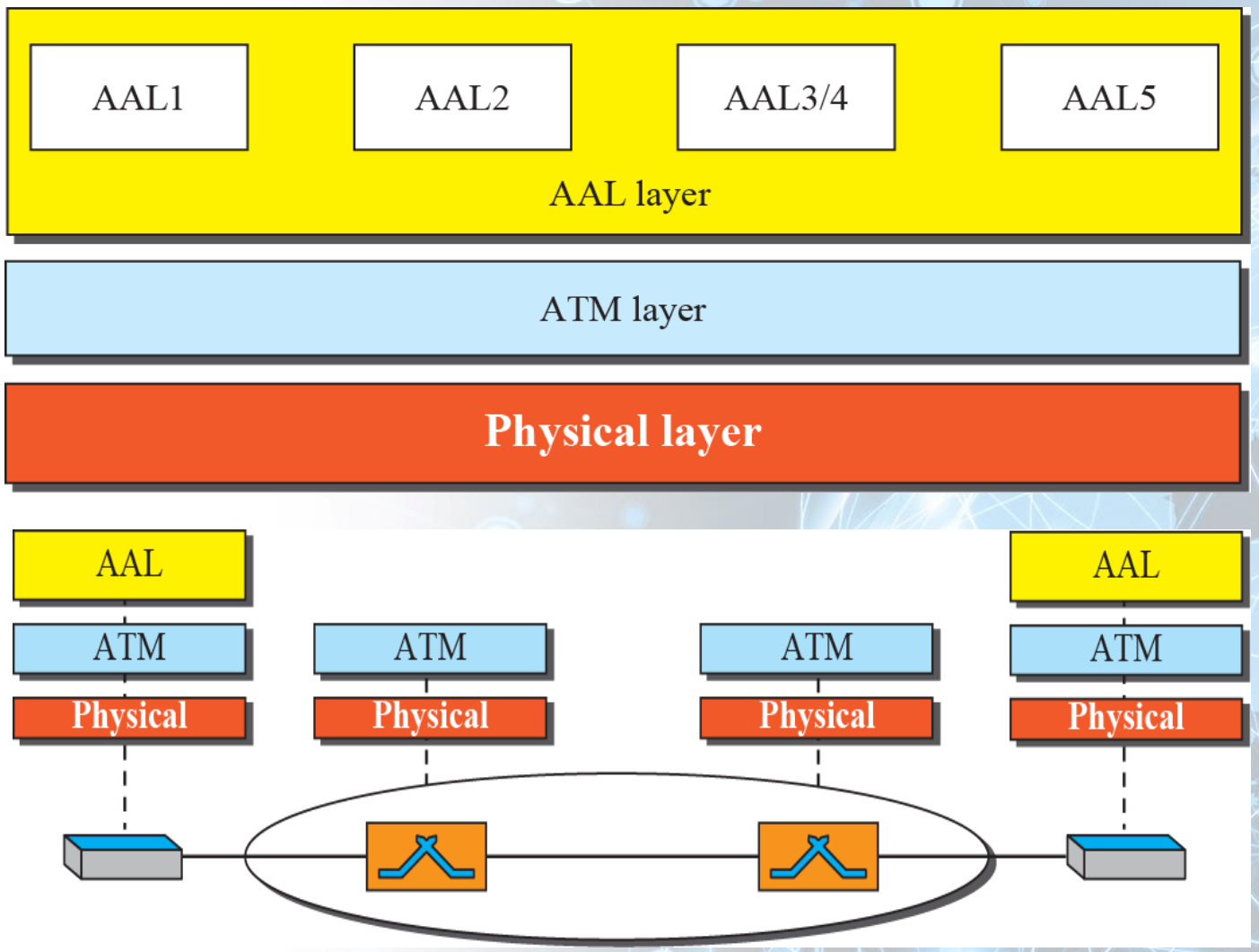


b. VPI and VCI in an NNI

An ATM Cell



ATM Layers


AAL1
AAL2
AAL3/4
AAL5
AAL layer
ATM layer
Physical layer
AAL
ATM
Physical
AAL
ATM
Physical
ATM
Physical
ATM
Physical

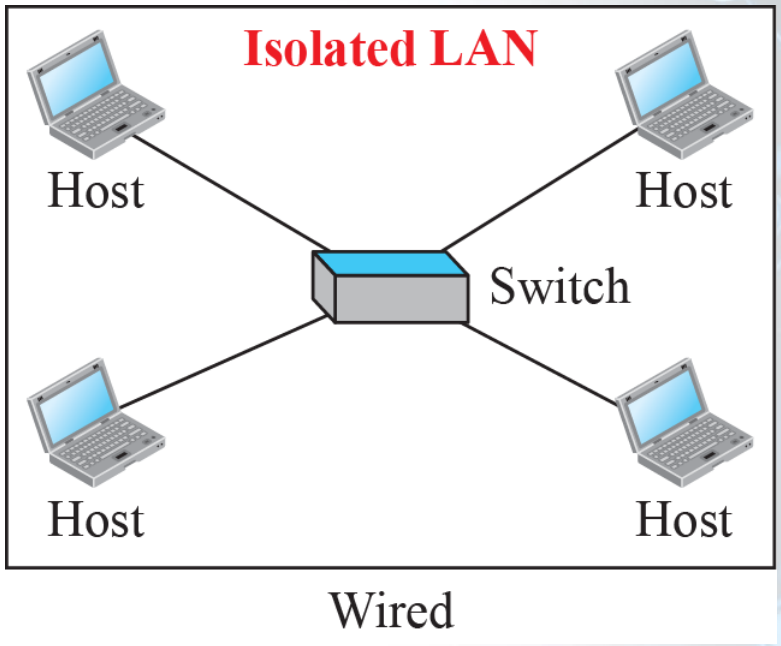
Introduction

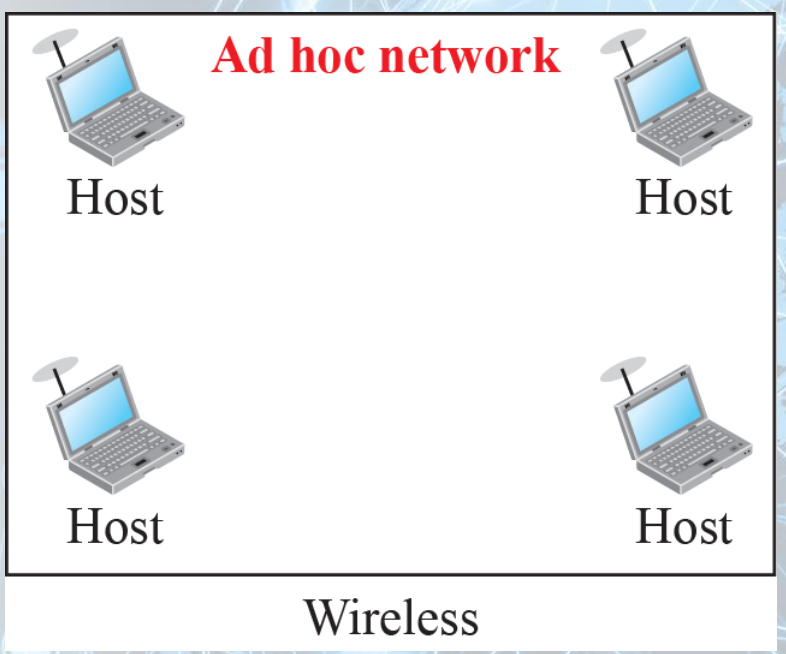
- Wireless communication is one of the fastest-growing technologies
- The demand for connecting devices without the use of cables is increasing everywhere
- Wireless LANs can be found on college campuses, in office buildings, and in many public areas

Architectural Comparison

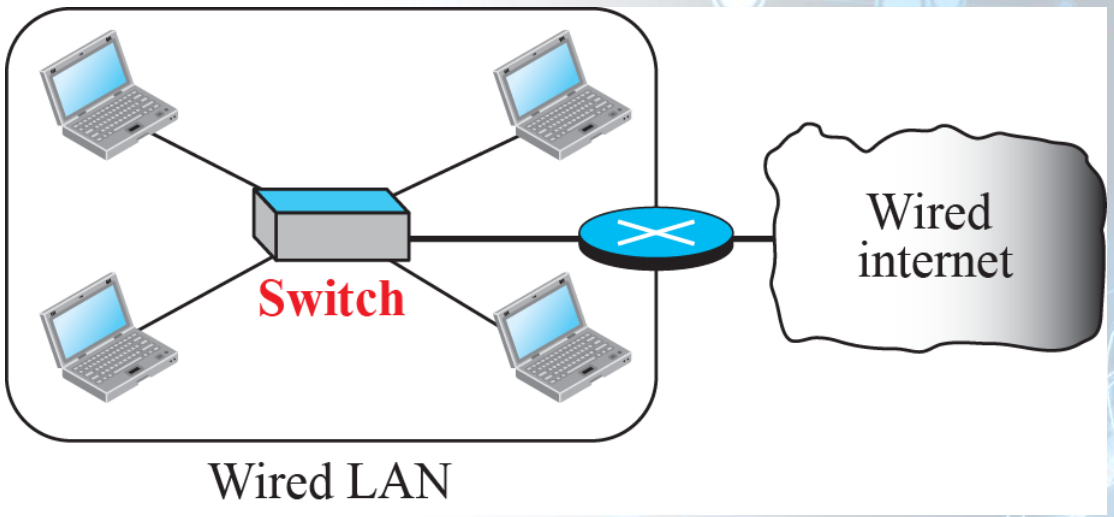
- Architecture comparison of wired and wireless LANs
  - ✓ Medium
  - ✓ Hosts
  - ✓ Isolated LANs
  - ✓ Connection to other Networks
  - ✓ Moving between Environments

Isolated LANs: Wired versus Wireless

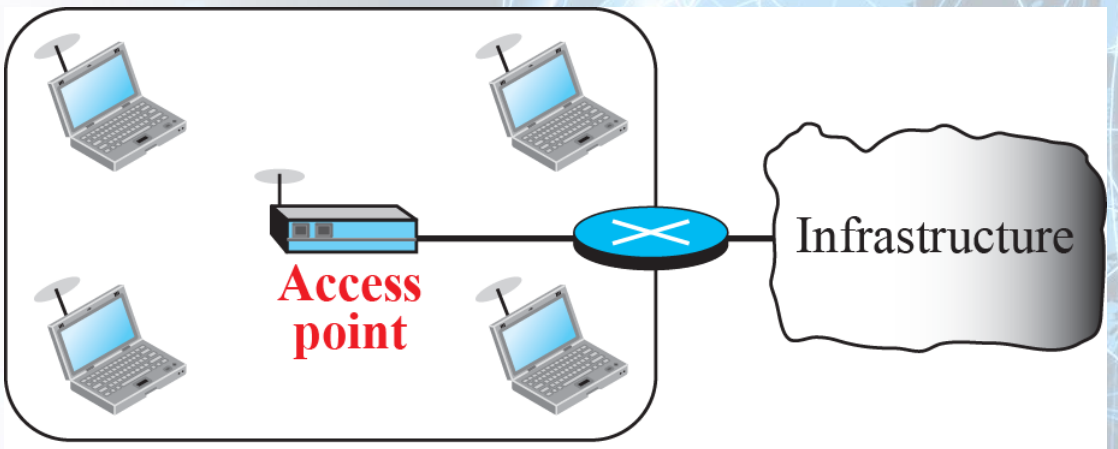




Connection of a Wired/Wireless LAN to other networks



Wired LAN



Infrastructure network

Characteristics of a Wireless LAN

- Several characteristics of wireless LANs either do not apply to wired LANs or the existence of these is negligible and can be ignored
  - ✓ Attenuation
  - ✓ Interference
  - ✓ Multipath Propagation
  - ✓ Error

Access Control

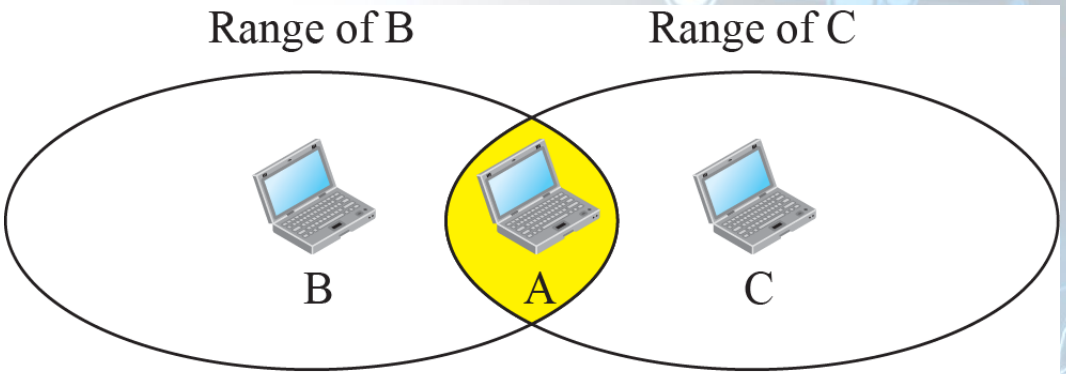
- Most important issue in a wireless LAN is how a wireless host can get access to the shared medium (air)
- CSMA/CD does not work in wireless LANs for three reasons:
  1. Wireless hosts don't have power to send and receive at the same time

Access Control

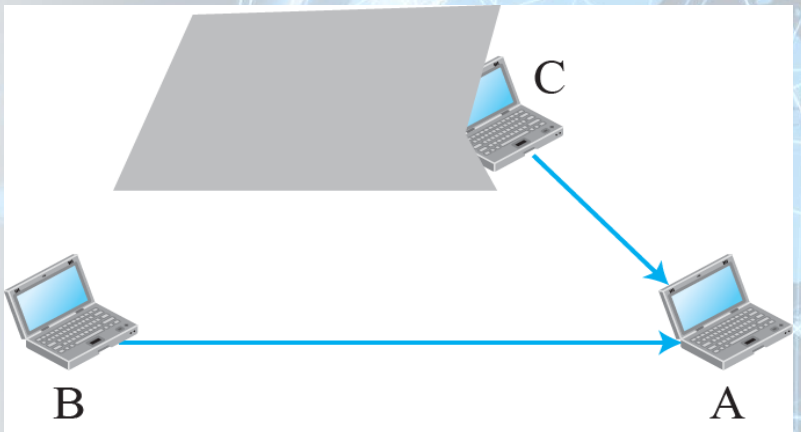
2. The hidden station problem prevents collision detection

3. The distance between stations can be large

Hidden Station Problem



a. Stations B and C are not in each other's range.



b. Stations B and C are hidden from each other.

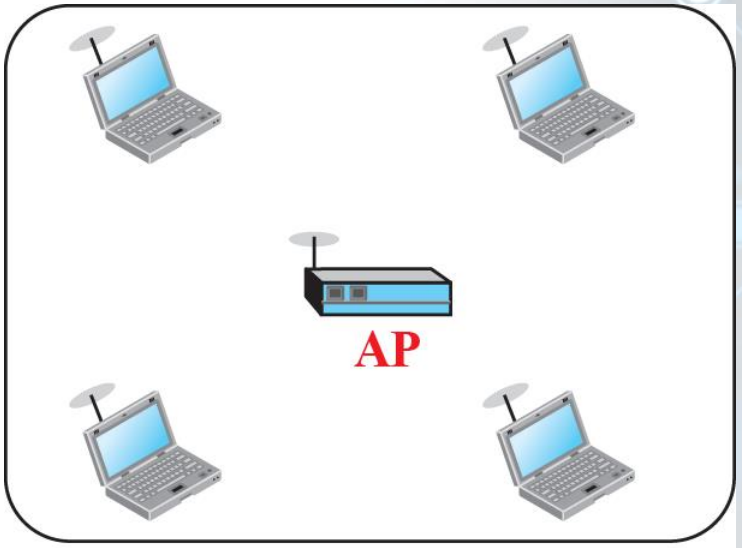
IEEE 802.11 PROJECT

- IEEE has defined the specifications for a wireless LAN, called IEEE 802.11, which covers the physical and data-link layers
- It is sometimes called Wireless Ethernet
- The term WiFi (short for wireless fidelity) as a synonym for wireless LAN (certified by WiFi alliance)

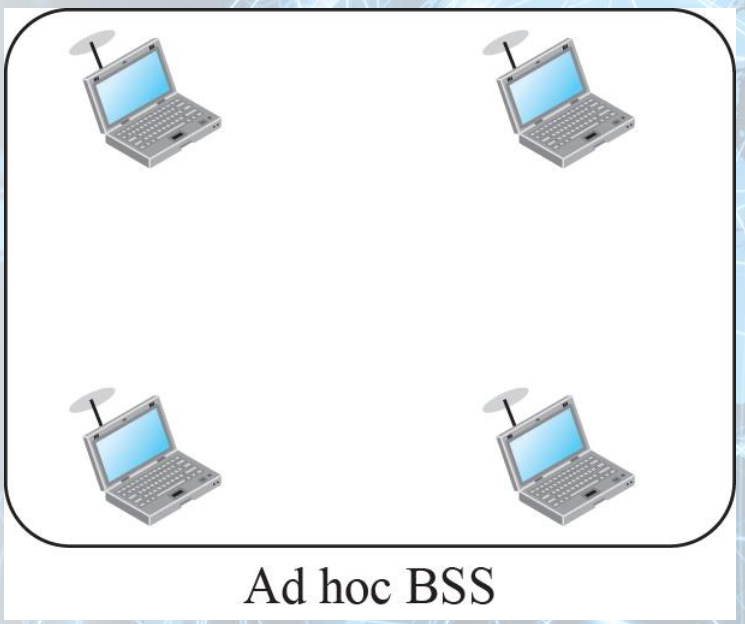
Architecture

- The standard defines two kinds of services:
  - ✓ The basic service set (BSS); and
  - ✓ The Extended service set (ESS)

Basic Service Sets (BSSs)

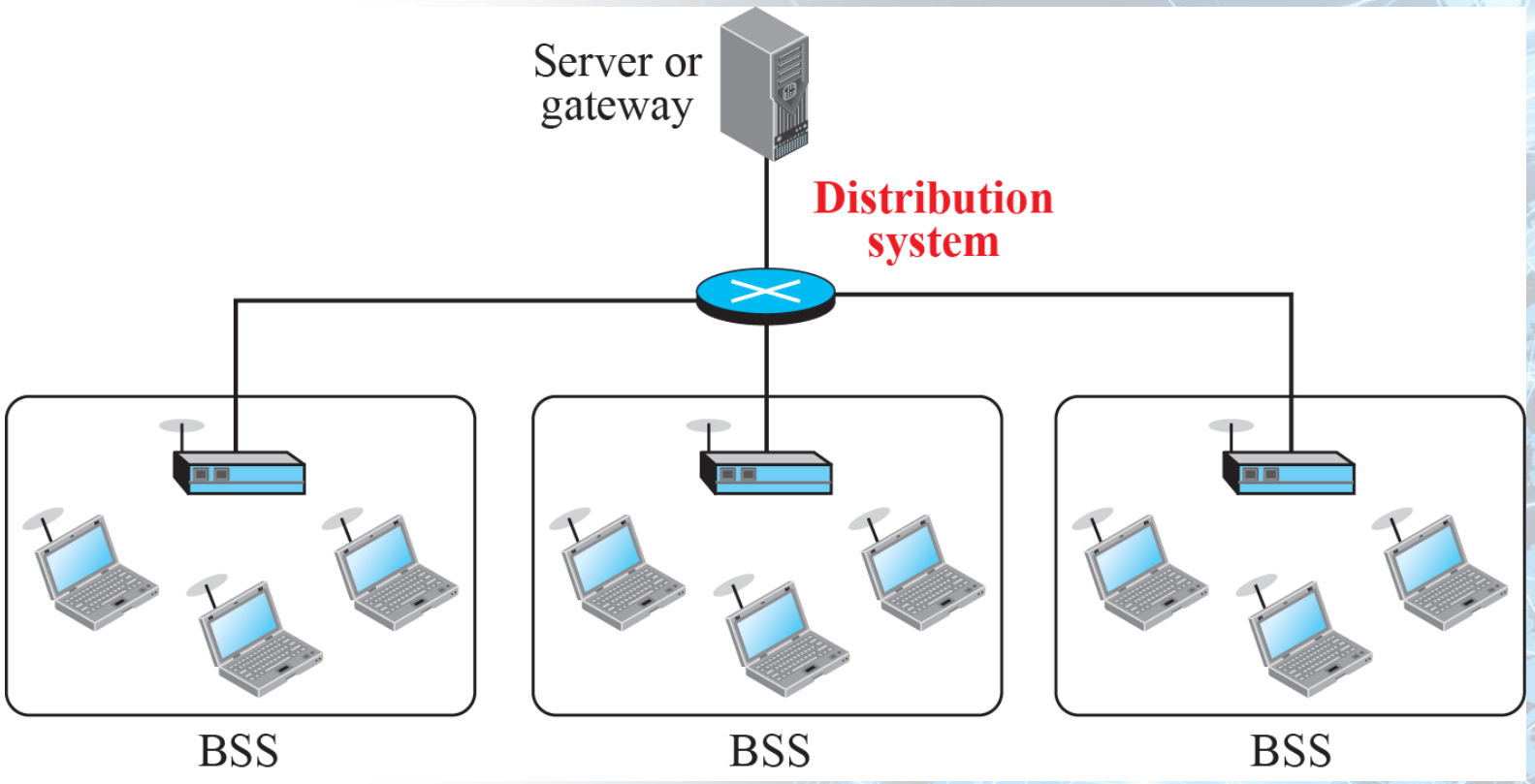


Infrastructure BSS



Ad hoc BSS

Extended Service Set (ESS)



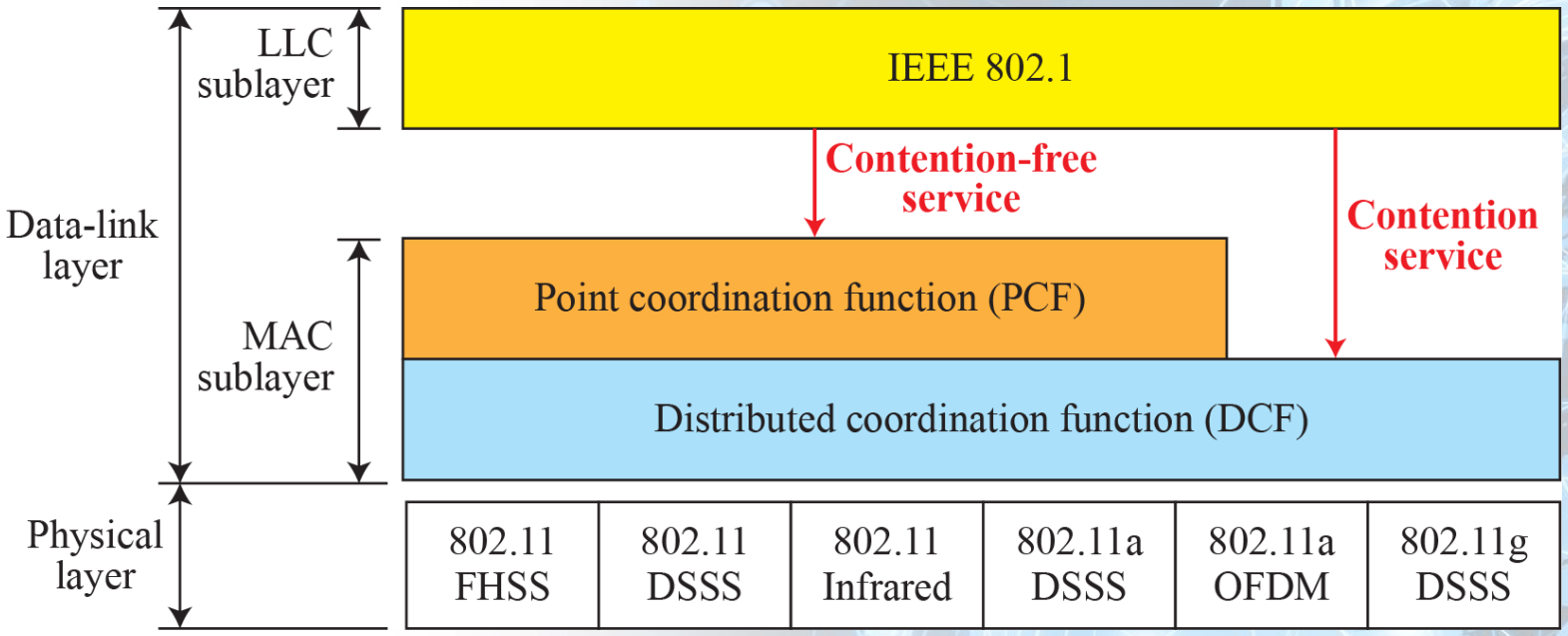
Types of Stations

- No-Transition Mobility
- BSS-Transition Mobility
- ESS-Transition Mobility

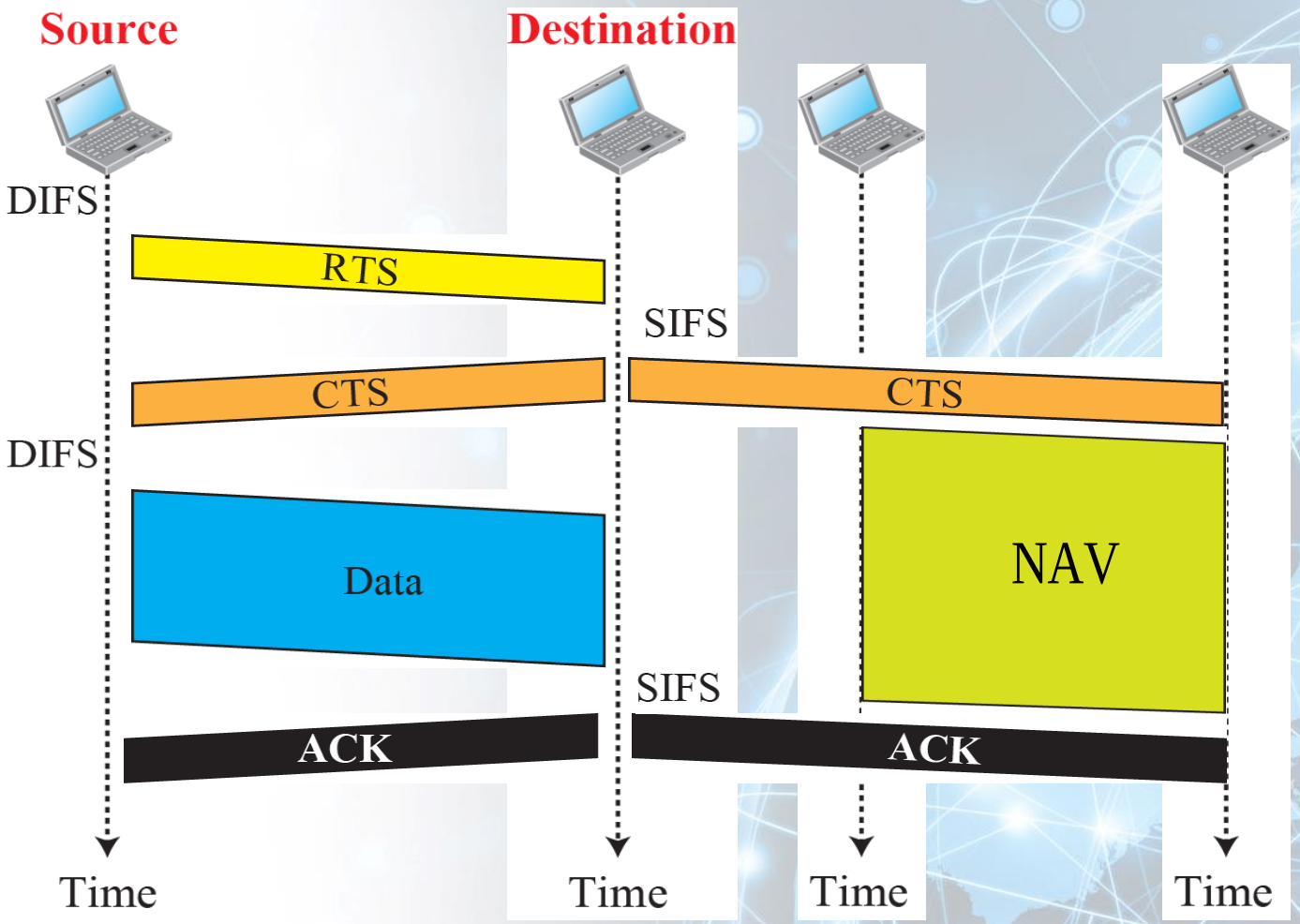
MAC Sub-layer

- **IEEE 802.11 defines two MAC sub-layers:**
  - ✓ **The Distributed Coordination Function (DCF) ; and**
  - ✓ **The Point Coordination Function (PCF)**

MAC Layers in IEEE 802.11 Standard



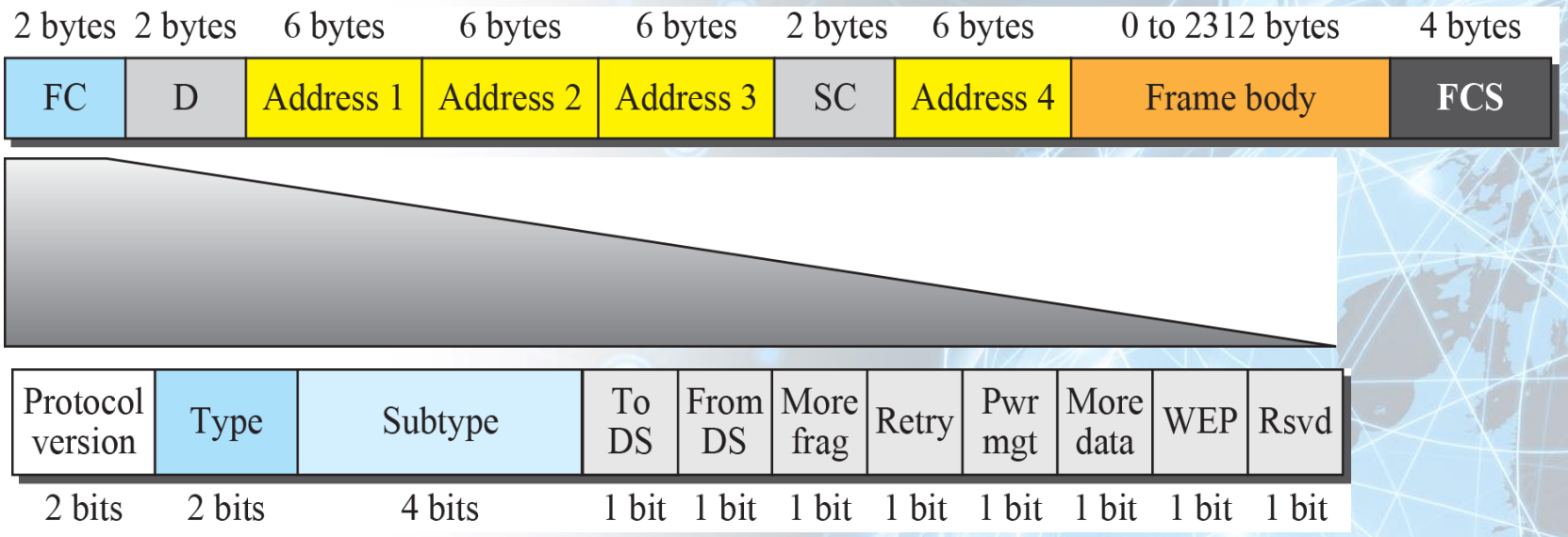
CSMA/CA and NAV



MAC Sub-layer

- **IEEE 802.11 defines two MAC sub-layers:**
  - ✓ **The Distributed Coordination Function (DCF) ; and**
  - ✓ **The Point Coordination Function (PCF)**

Frame Format



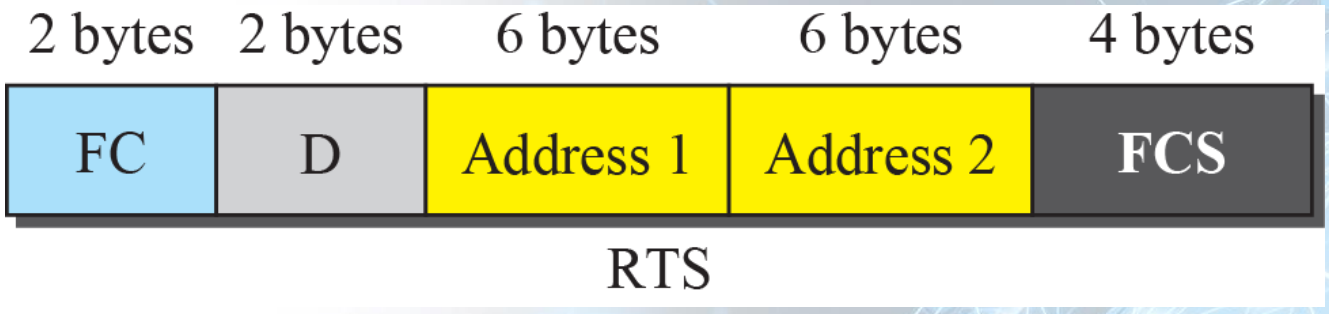
Subfields in FC field

Field	*Explanation*
Version	Current version is 0
Type	Type of information: management (00), control (01), or data (10)
Subtype	Subtype of each type (see Table 6.2)
To DS	Defined later
From DS	Defined later
More flag	When set to 1, means more fragments
Retry	When set to 1, means retransmitted frame
Pwr mgt	When set to 1, means station is in power management mode
More data	When set to 1, means station has more data to send
WEP	Wired equivalent privacy (encryption implemented)
Rsvd	Reserved

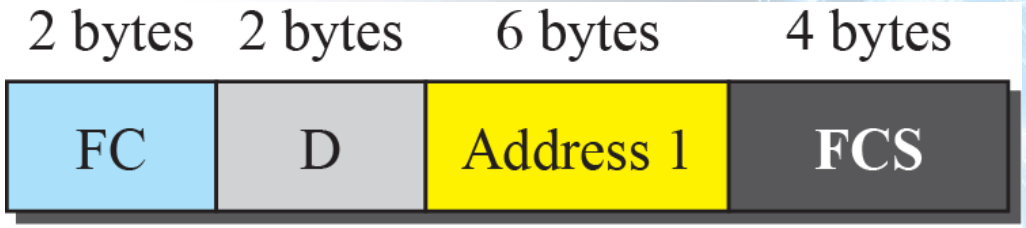
Frame Types

- Management Frames
- Control Frames
- Data Frames

Control Frames



RTS



CTS or ACK

Values of Subfields in Control Frames

Subtype	*Meaning*
1011	Request to send (RTS)
1100	Clear to send (CTS)
1101	Acknowledgment (ACK)

Physical Layer

- All physical implementations, except the infrared, operate in the industrial, scientific, and medical (ISM) band, which defines 3 unlicensed bands in 3 ranges:

  - ✓ 902–928 MHz
  - ✓ 2.400–4.835 GHz
  - ✓ 5.725–5.850 GHz

Specifications

IEEE	*Technique*	*Band*	*Modulation*	*Rate (Mbps)*
802.11	FHSS	2.400–4.835 GHz	FSK	1 and 2
	DSSS	2.400–4.835 GHz	PSK	1 and 2
	None	Infrared	PPM	1 and 2
802.11a	OFDM	5.725–5.850 GHz	PSK or QAM	6 to 54
802.11b	DSSS	2.400–4.835 GHz	PSK	5.5 and 11
802.11g	OFDM	2.400–4.835 GHz	Different	22 and 54
802.11n	OFDM	5.725–5.850 GHz	Different	600

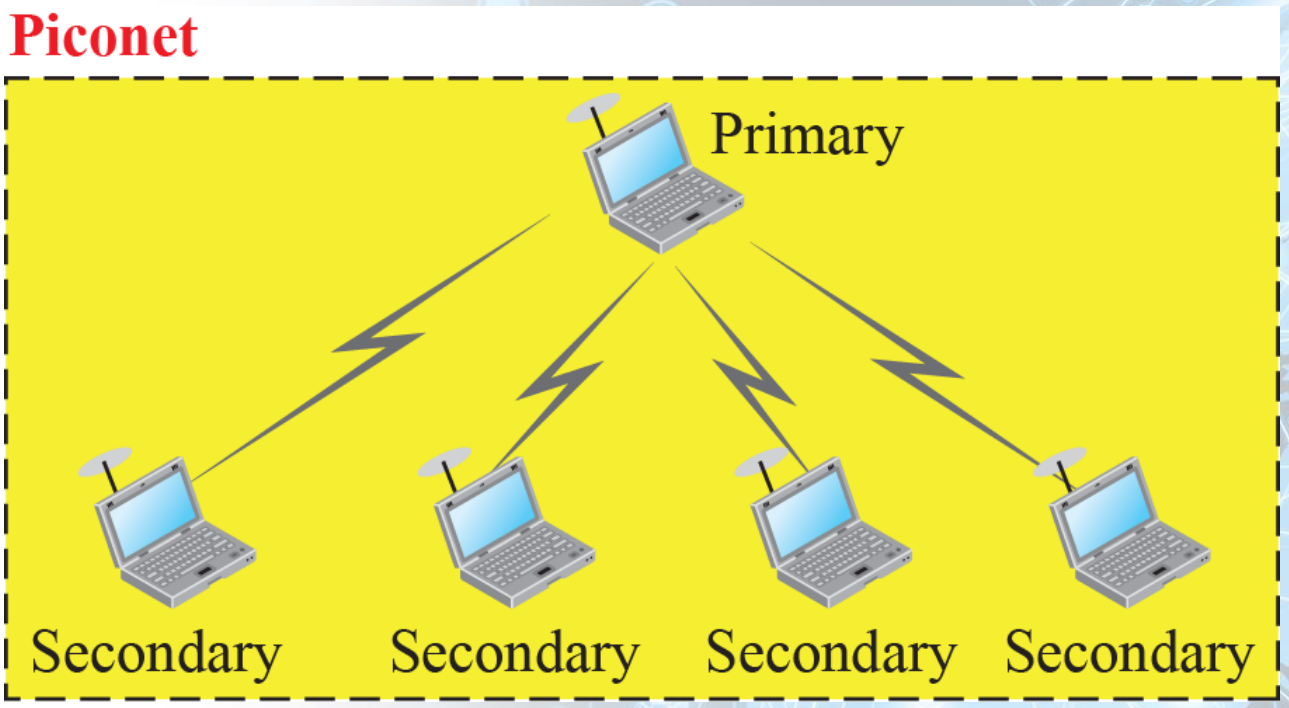
BLUETOOTH

- Bluetooth is a wireless LAN technology designed to connect devices of different functions when they are at a short distance from each other
- A Bluetooth LAN is an ad hoc network
- The devices, sometimes called gadgets, find each other and make a network called a Piconet

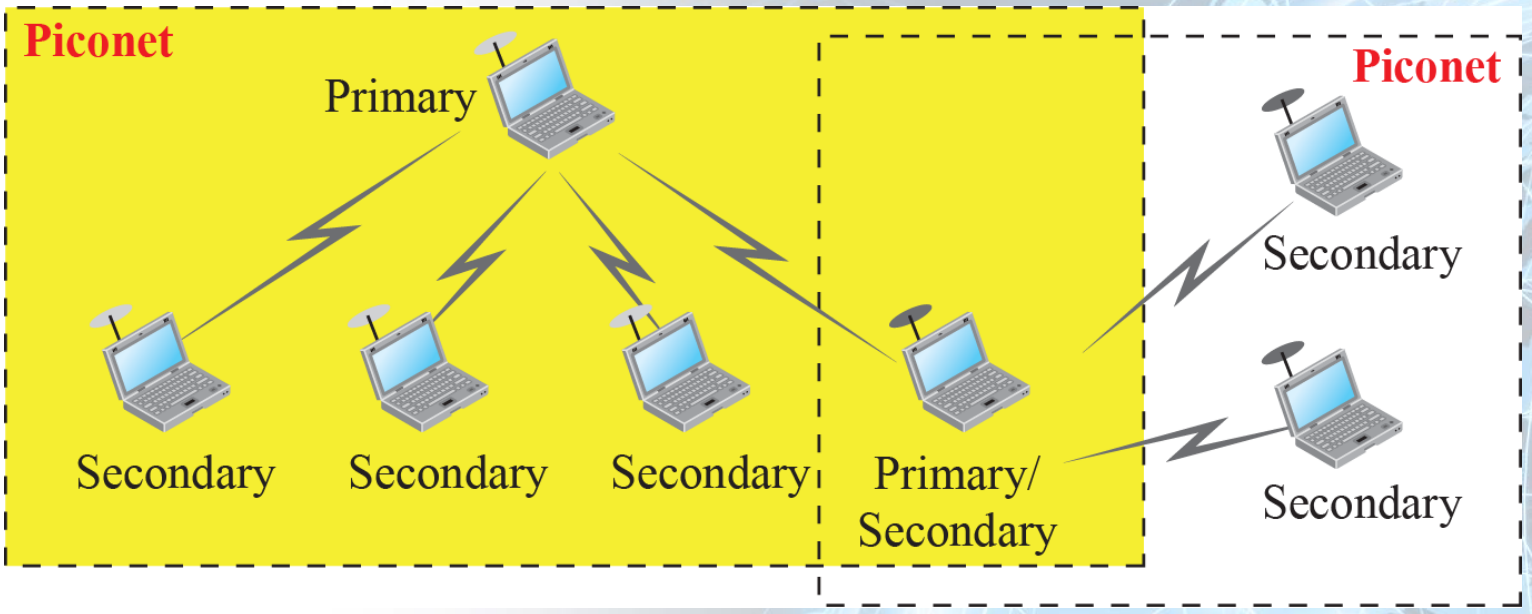
Architecture

- **Bluetooth defines two types of networks:**
  - ✓ **Piconet**
  - ✓ **Scatternet**

Piconet


Piconet
Primary
Secondary
Secondary
Secondary
Secondary

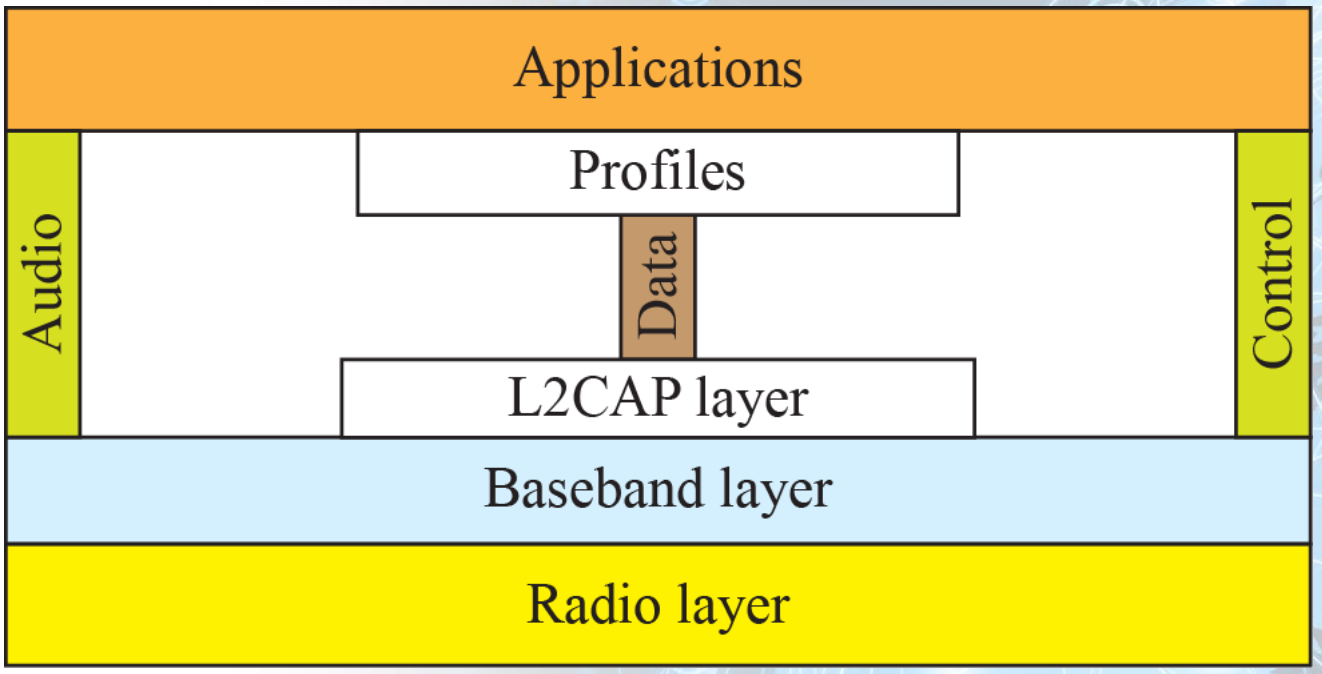
Scatternet


Piconet
Primary
Secondary
Secondary
Secondary
Primary/
Secondary
Piconet
Secondary
Secondary

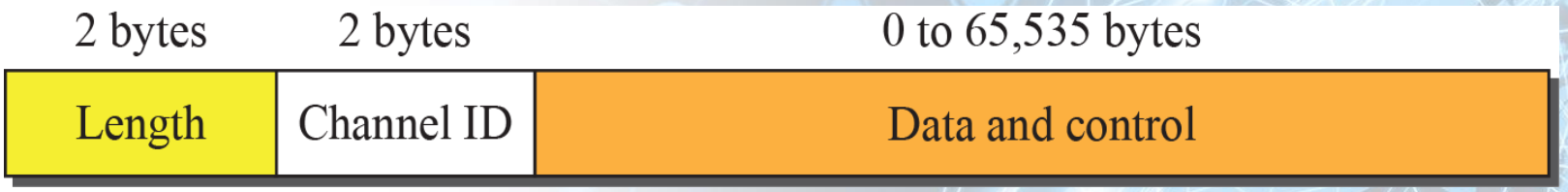
Bluetooth Layers

- Bluetooth uses several layers that do not exactly match those of the Internet model we have defined in this book

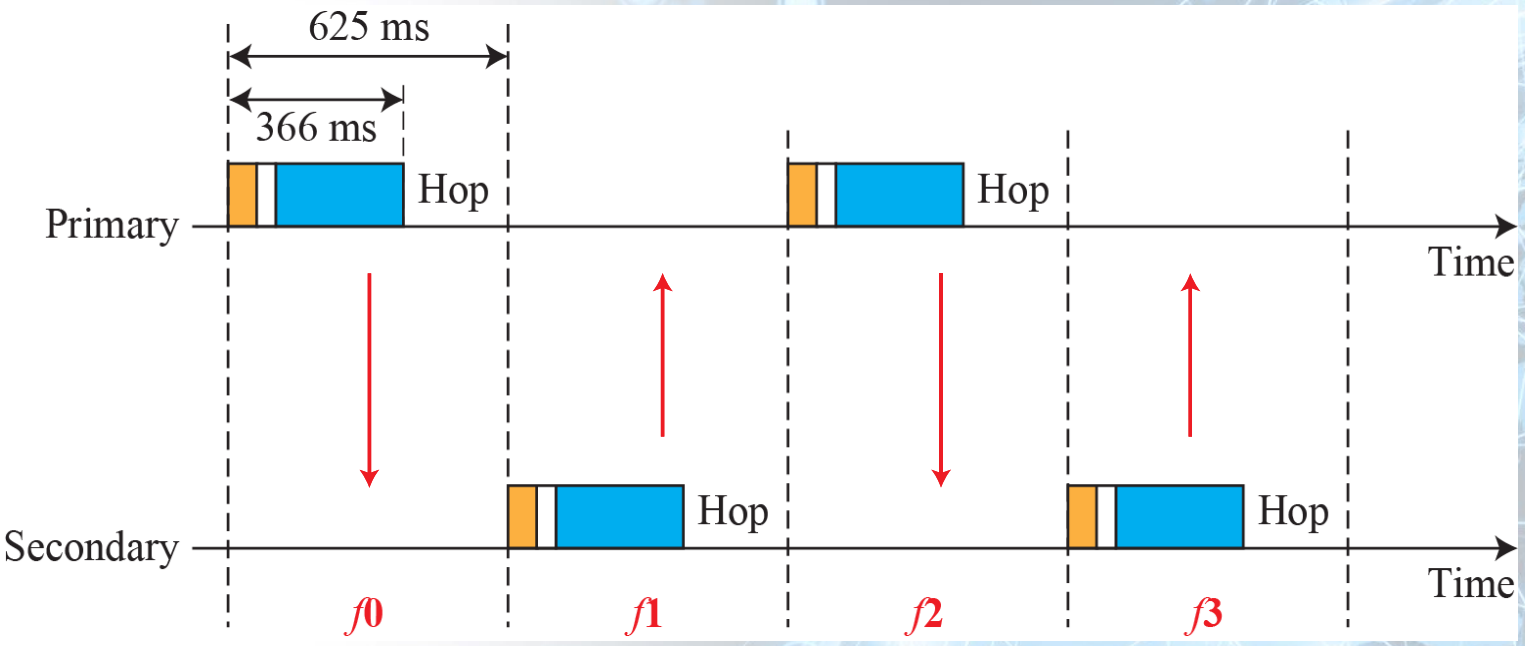
Bluetooth Layers



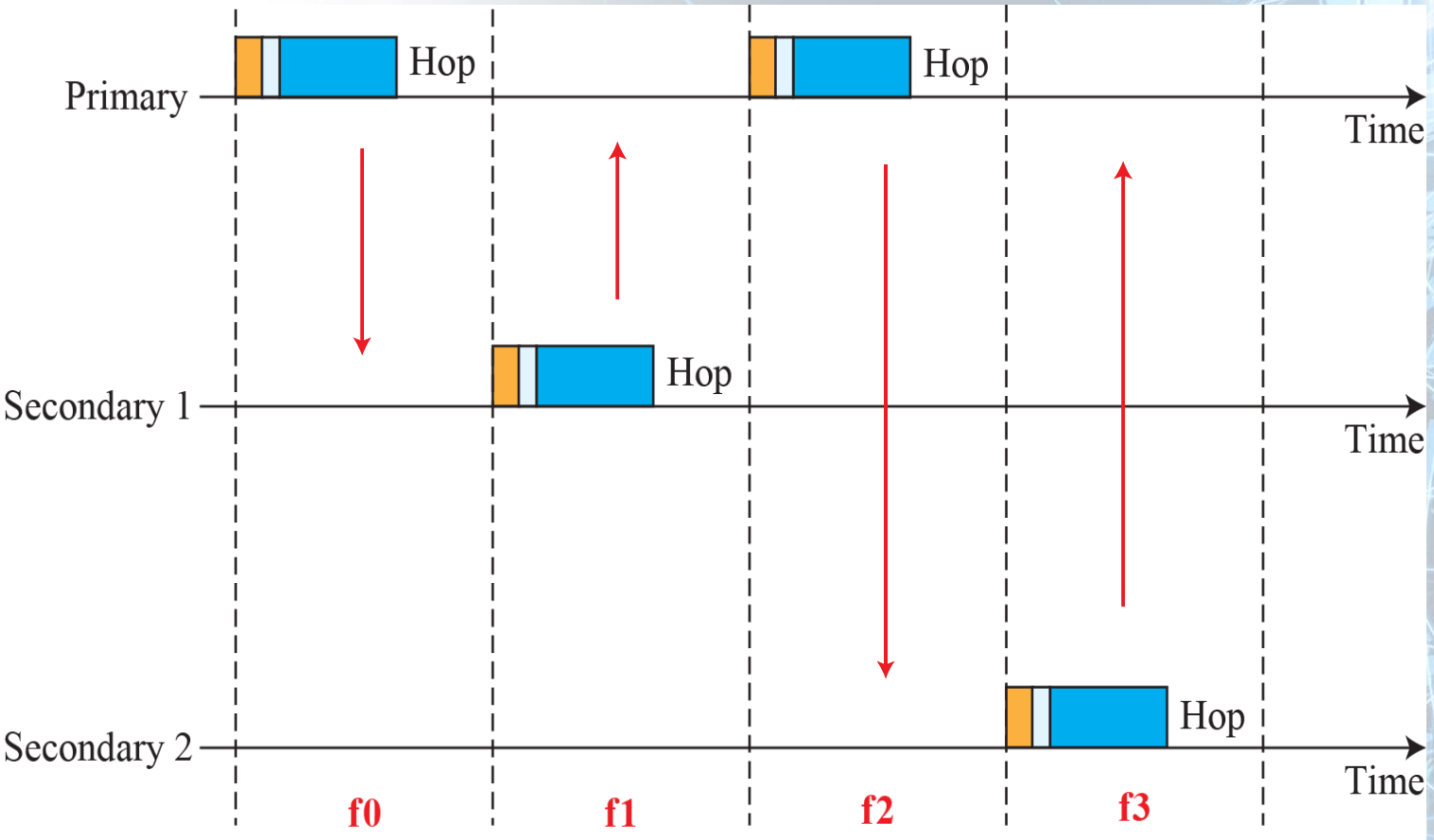
L2CAP Data Packet Format



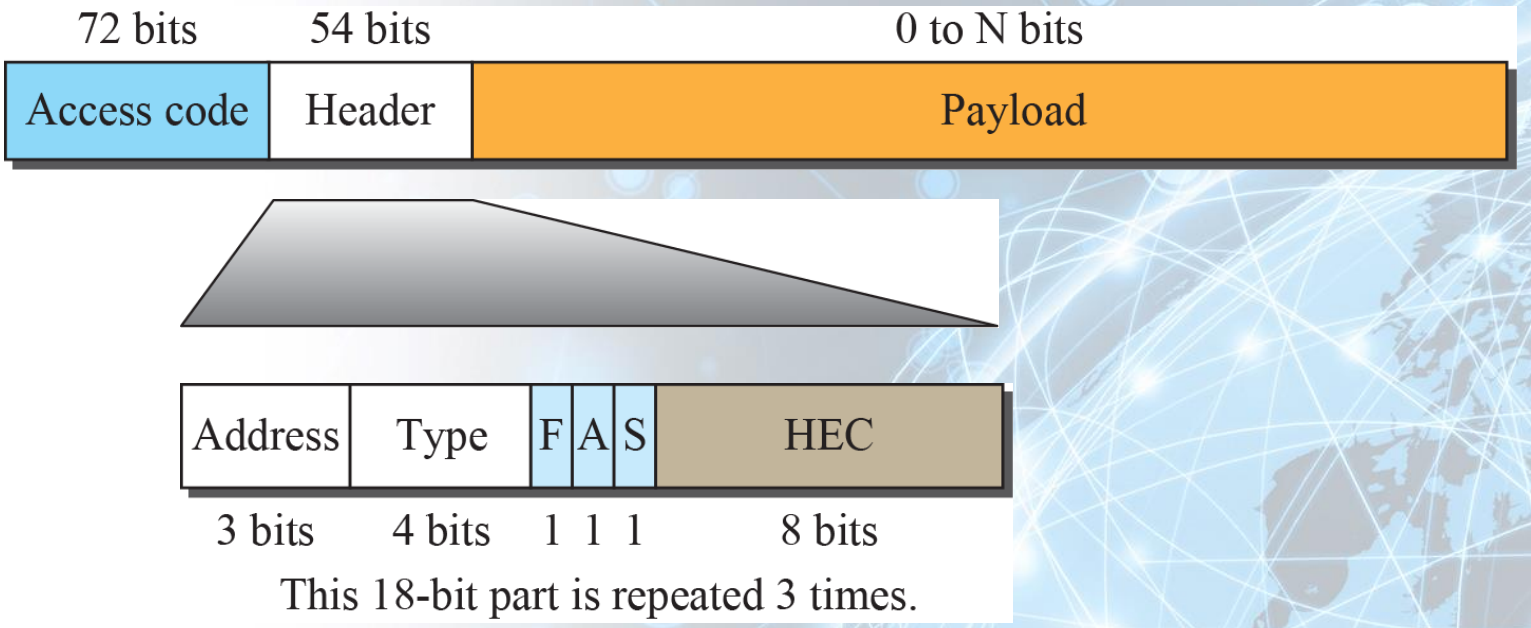
Single-Secondary Communication



Multiple-Secondary Communication



Frame Format Types



N = 240 for 1-slot frame

N = 1490 for 3-slot frame

N = 2740 for 5-slot frame

Bluetooth

- Bluetooth is a wireless LAN technology designed to connect devices of different functions when they are at a short distance from each other
- A Bluetooth LAN is an ad hoc network
- The devices, sometimes called gadgets, find each other and make a network called a Piconet

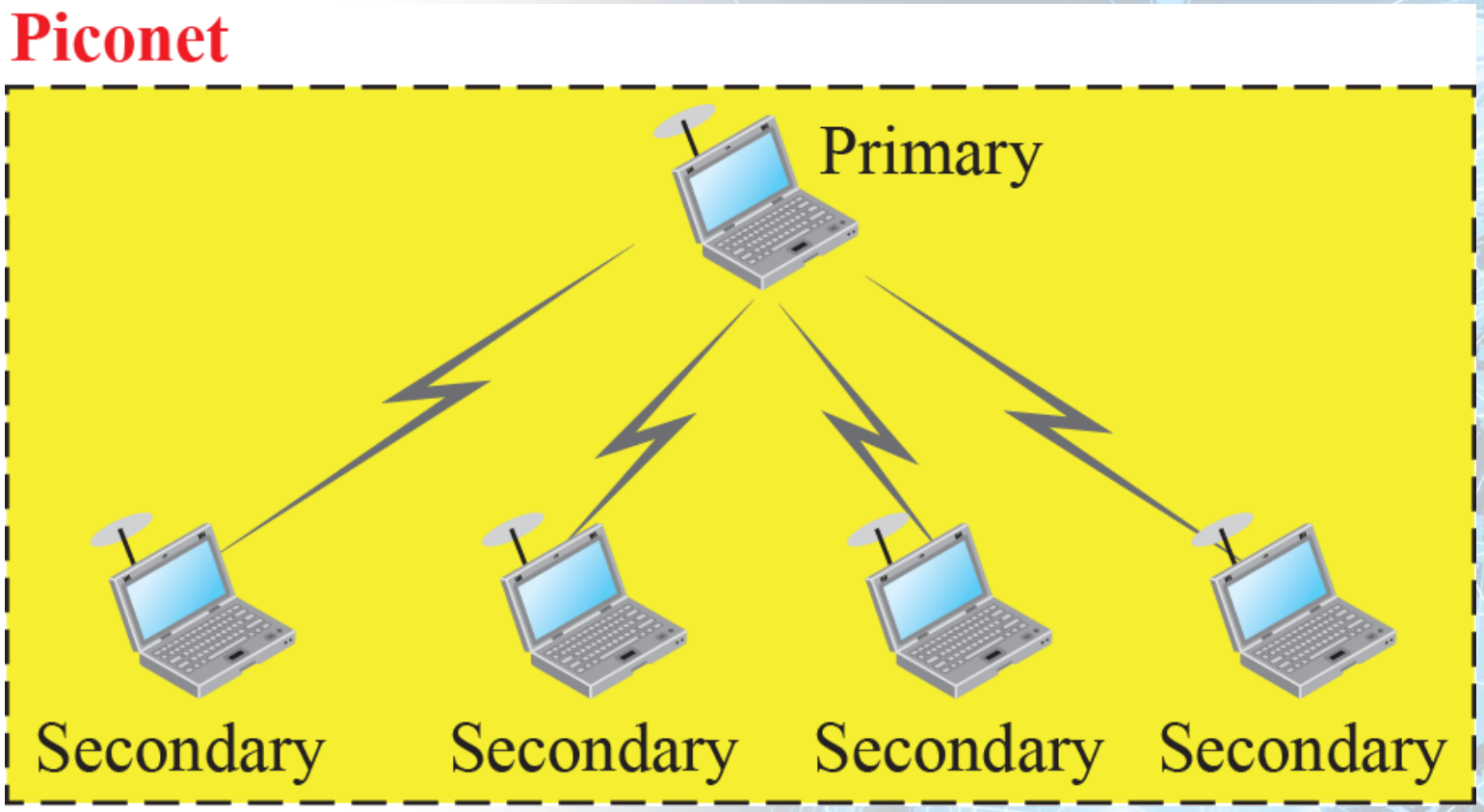
Bluetooth

- Bluetooth technology is the implementation of a protocol defined by the IEEE 802.15 standard
- The standard defines a wireless Personal-Area Network (PAN) operable in an area the size of a room or a hall

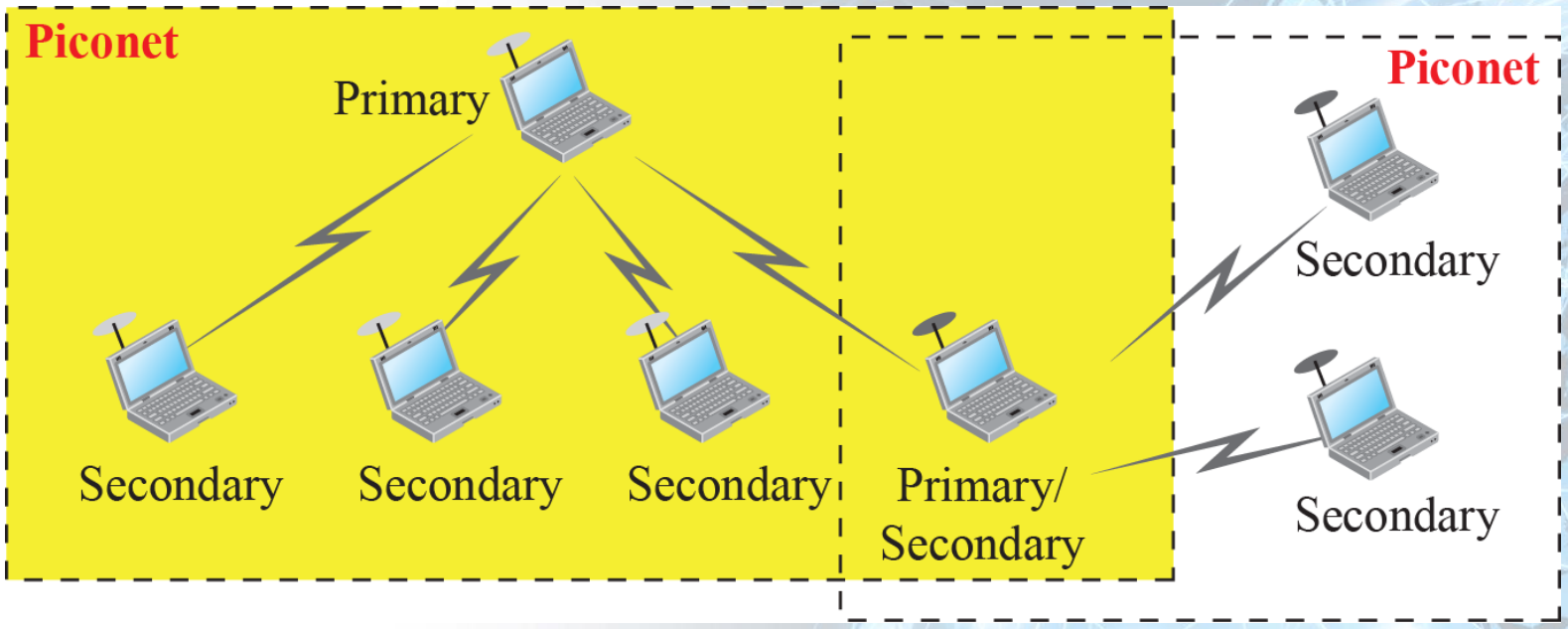
Architecture

- **Bluetooth defines two types of networks:**
  - ✓ **Piconet**
  - ✓ **Scatternet**

Piconet


Piconet
Primary
Secondary
Secondary
Secondary
Secondary

Scatternet


Piconet
Primary
Secondary
Secondary
Secondary
Primary/
Secondary
Piconet
Secondary
Secondary

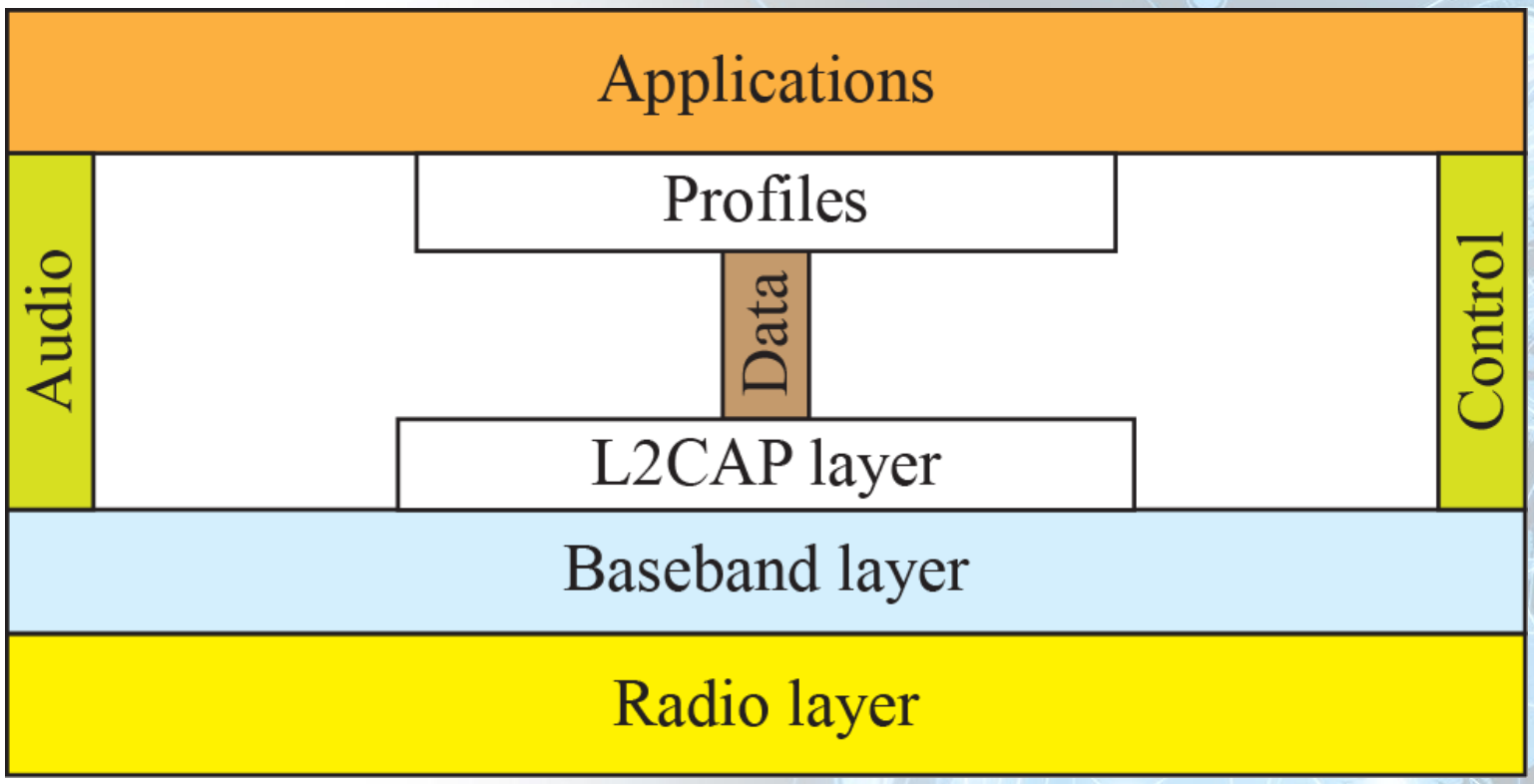
Bluetooth Devices

- A Bluetooth device has a built-in short-range radio transmitter
- The current data rate is 1 Mbps with a 2.4-GHz bandwidth
- This means that there is a possibility of interference between the IEEE 802.11b wireless LANs and Bluetooth LANs

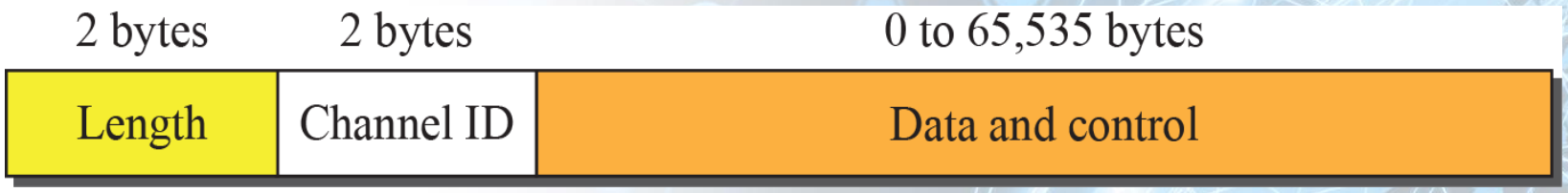
Bluetooth Layers

- Bluetooth uses several layers that do not exactly match those of the Internet model we have defined already

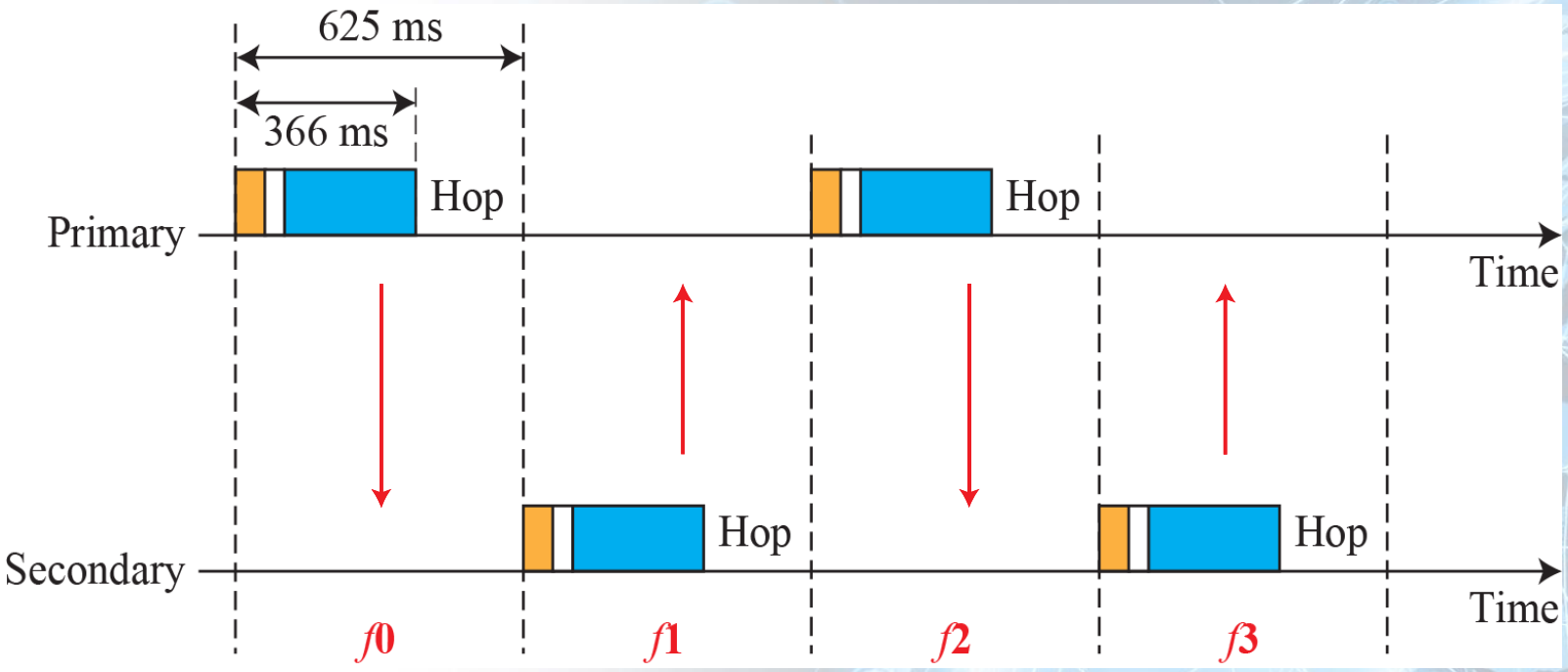
Bluetooth Layers



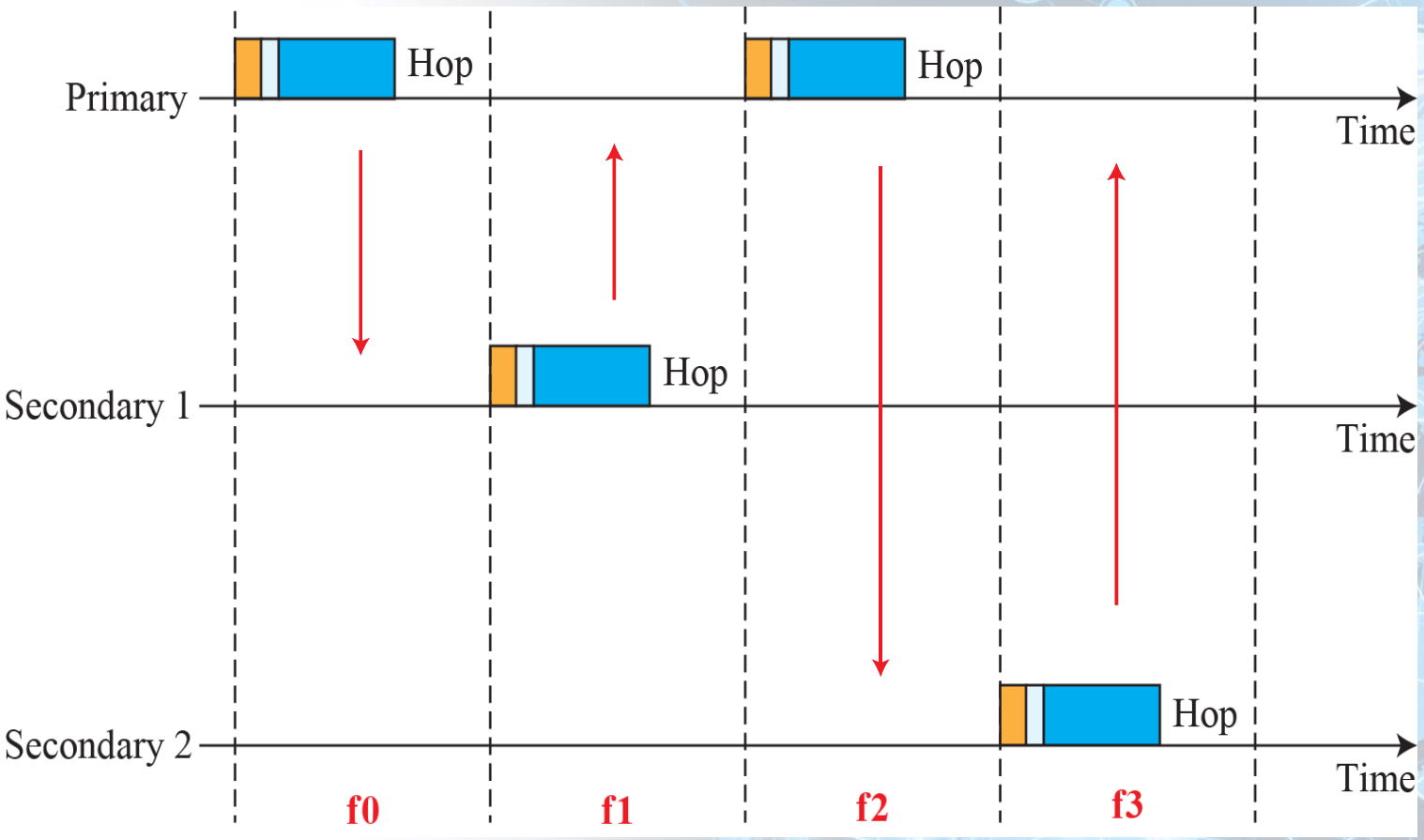
L2CAP Data Packet Format



Single-Secondary Communication



Multiple-Secondary Communication



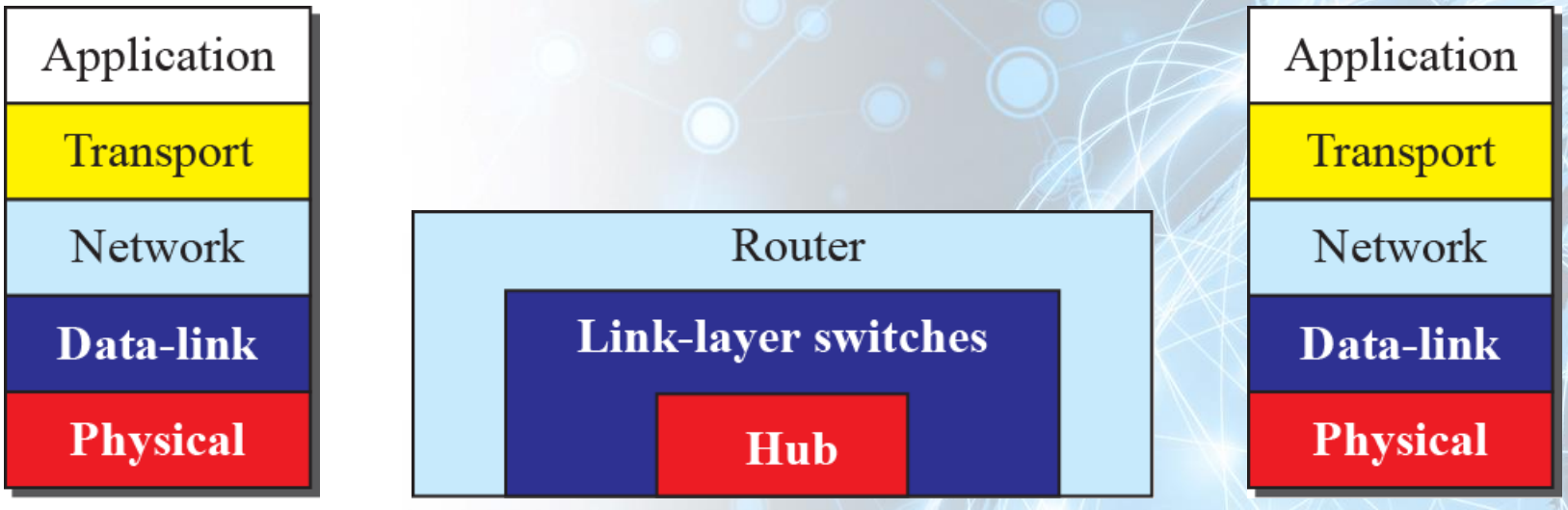
Connecting Devices

- Hosts and networks do not normally operate in isolation
- Connecting devices connect hosts together to make a network or connect networks together to make an internet
- Connecting devices can operate in different layers of the Internet model

Connecting Devices

- Three kinds of connecting devices:
  - ✓ Hubs
  - ✓ Link-layer switches
  - ✓ Routers

Three Categories of Connecting Devices



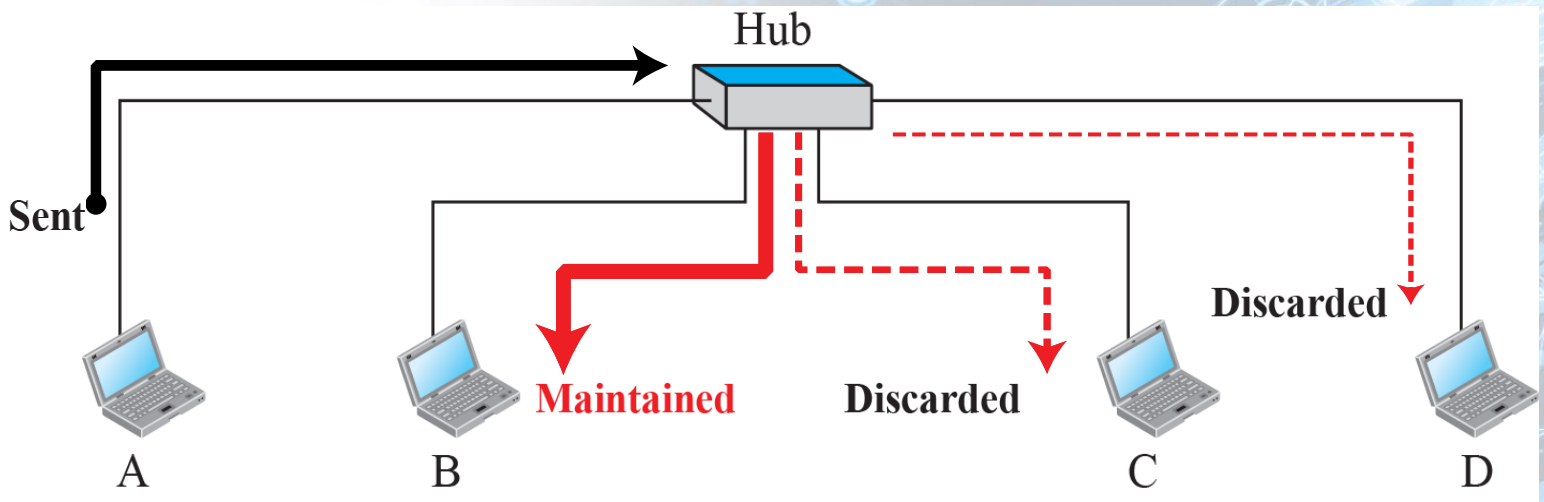
Hubs

- Hub is a device that operates only in the physical layer
- Signals that carry information within a network can travel a fixed distance before attenuation impacts the data
- A hub (repeater) receives a signal and, before it becomes too weak or corrupted, regenerates it

Hubs

- Hub is a device that operates only in the physical layer

Hub



Link-Layer Switches

- A link-layer switch (or switch) operates in both the physical and the data-link layers
- As a physical-layer device, it regenerates the signal it receives
- As a link-layer device, the link-layer switch can check the MAC addresses (source and destination) contained in the frame

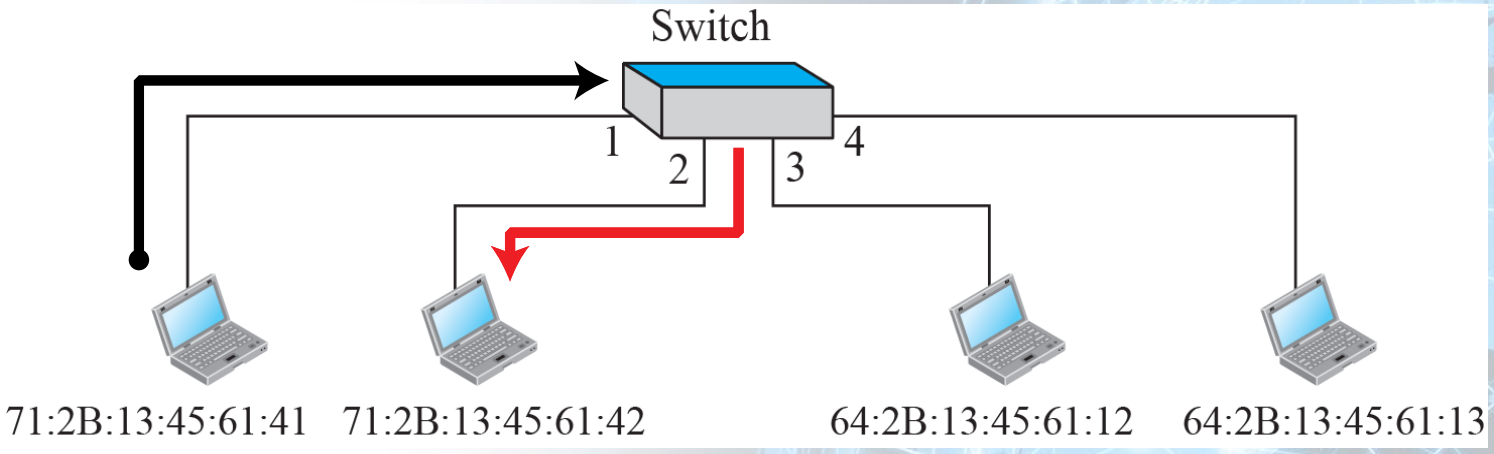
Switch versus Hub

- Switch has the ‘Filtering’ capability
- Unlike hub, a switch can check the destination address of a frame and decide on outgoing port
- Switch eliminates collisions and does not require carrier sensing
- Switches connect heterogeneous devices

Link-Layer Switch

Switching table

Address	Port
71:2B:13:45:61:41	1
71:2B:13:45:61:42	2
64:2B:13:45:61:12	3
64:2B:13:45:61:13	4



Link-Layer Switches

- A link-layer switch (or switch) operates in both the physical and the data-link layers

Learning Switch

Address	Port

a. Original

Address	Port
71:2B:13:45:61:41	1

b. After A sends a frame to D

Address	Port
71:2B:13:45:61:41	1
64:2B:13:45:61:13	4

c. After D sends a frame to B

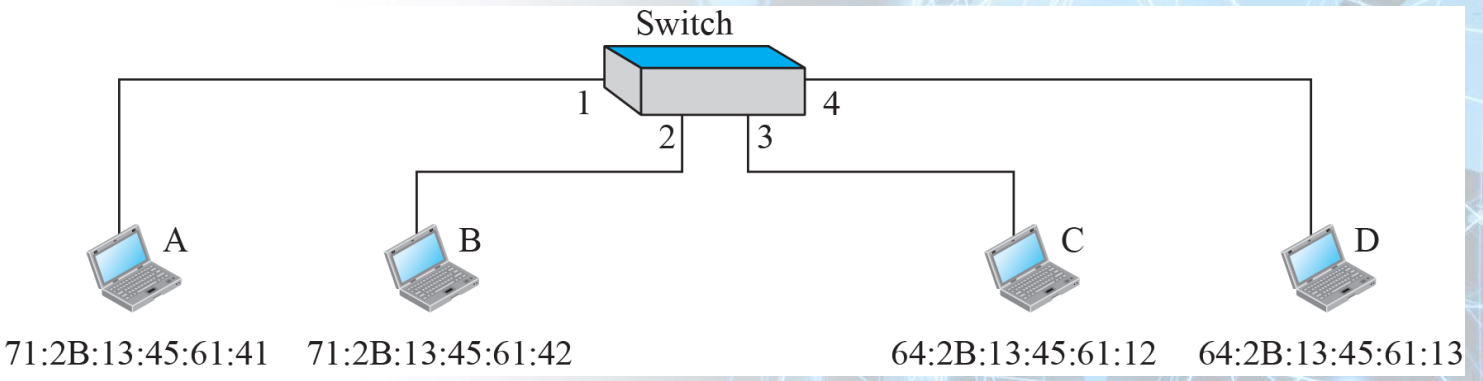
Address	Port
71:2B:13:45:61:41	1
64:2B:13:45:61:13	4
71:2B:13:45:61:42	2

d. After B sends a frame to A

Address	Port
71:2B:13:45:61:41	1
64:2B:13:45:61:13	4
71:2B:13:45:61:42	2
64:2B:13:45:61:12	3

e. After C sends a frame to D

Gradual building of Table

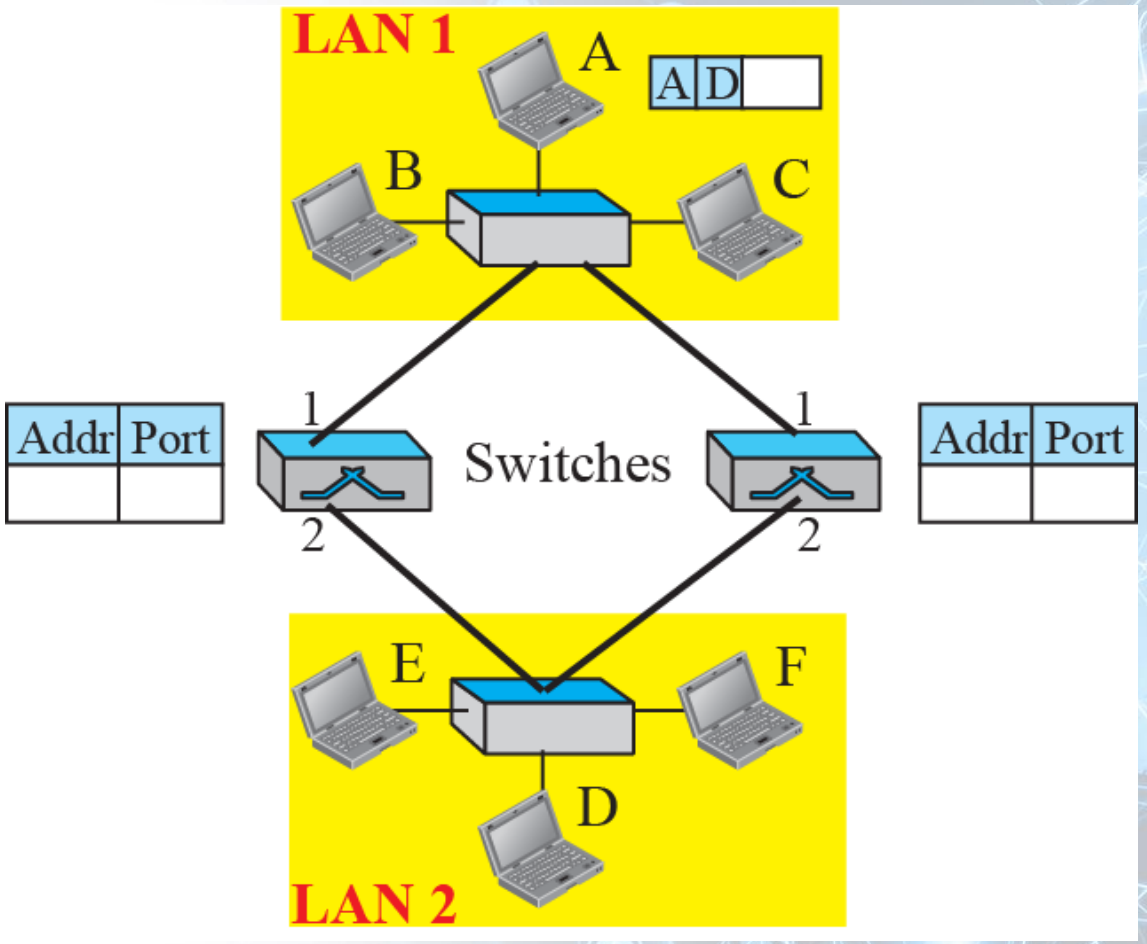


Loop Problem in a Switch

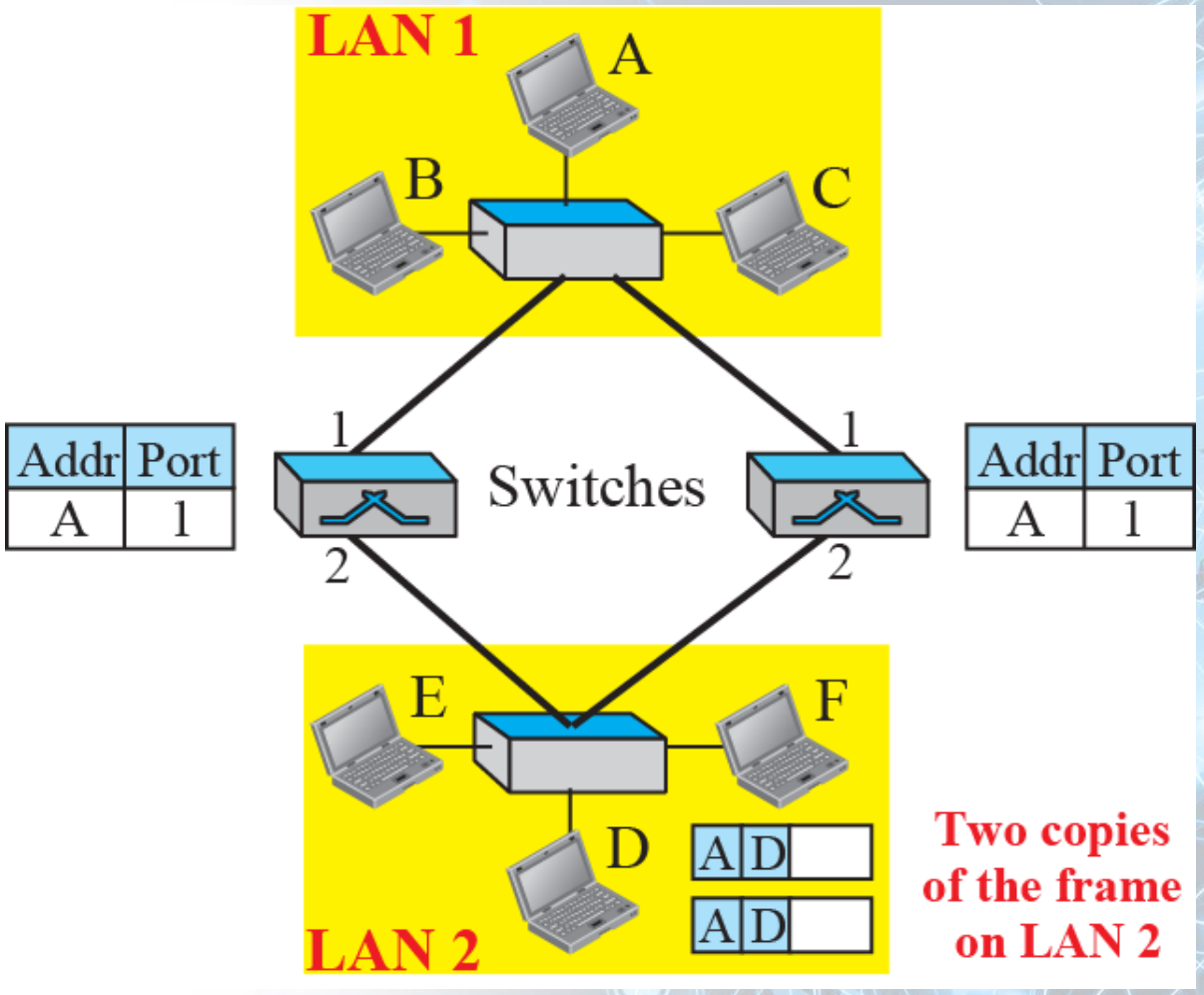
- Redundant switches create Loops in the system
- Created when two or more broadcasting LANs are connected by more than one switch

Loop Problem in a Learning Switch (Part a)

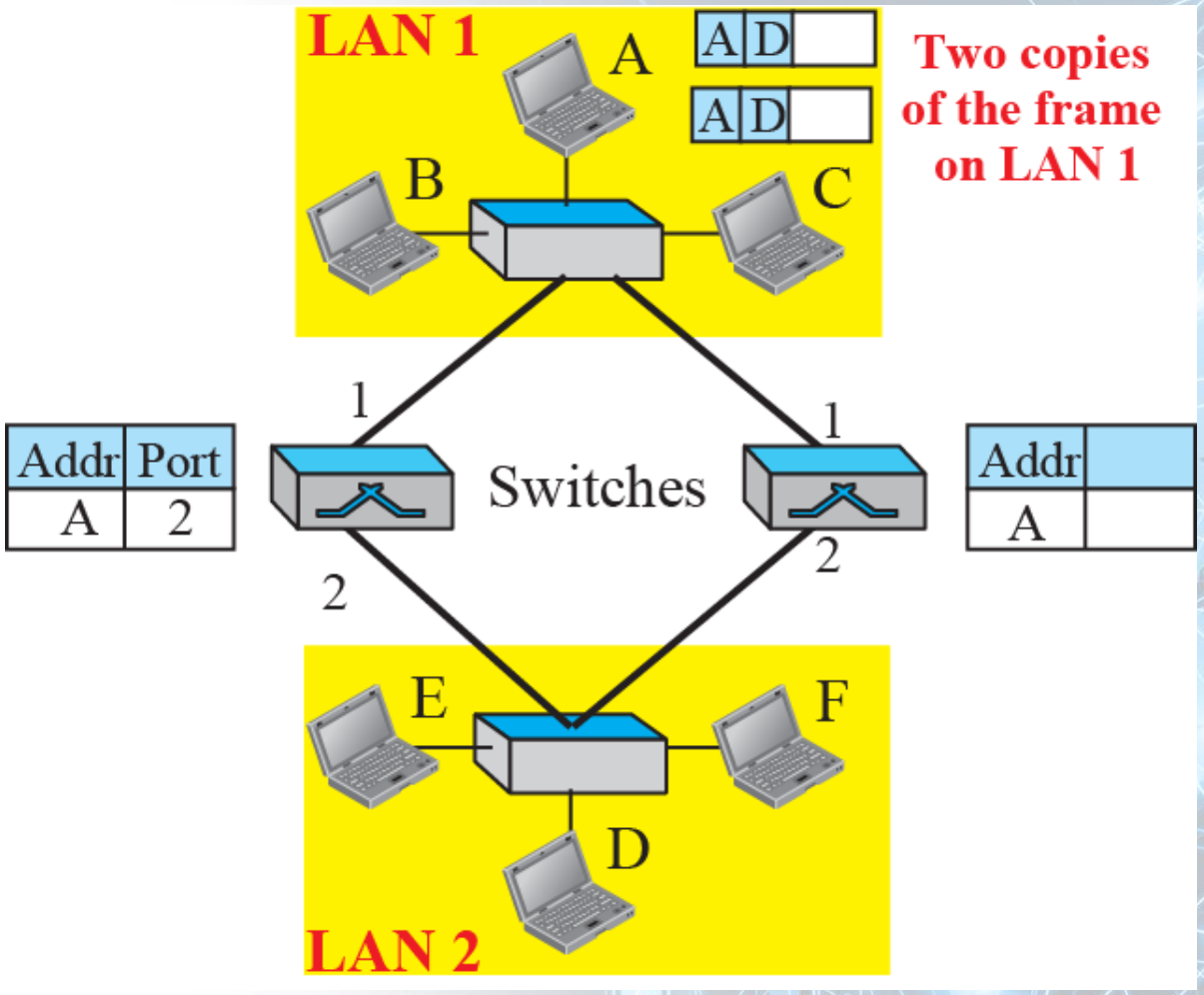
a. Station A sends a frame to station D



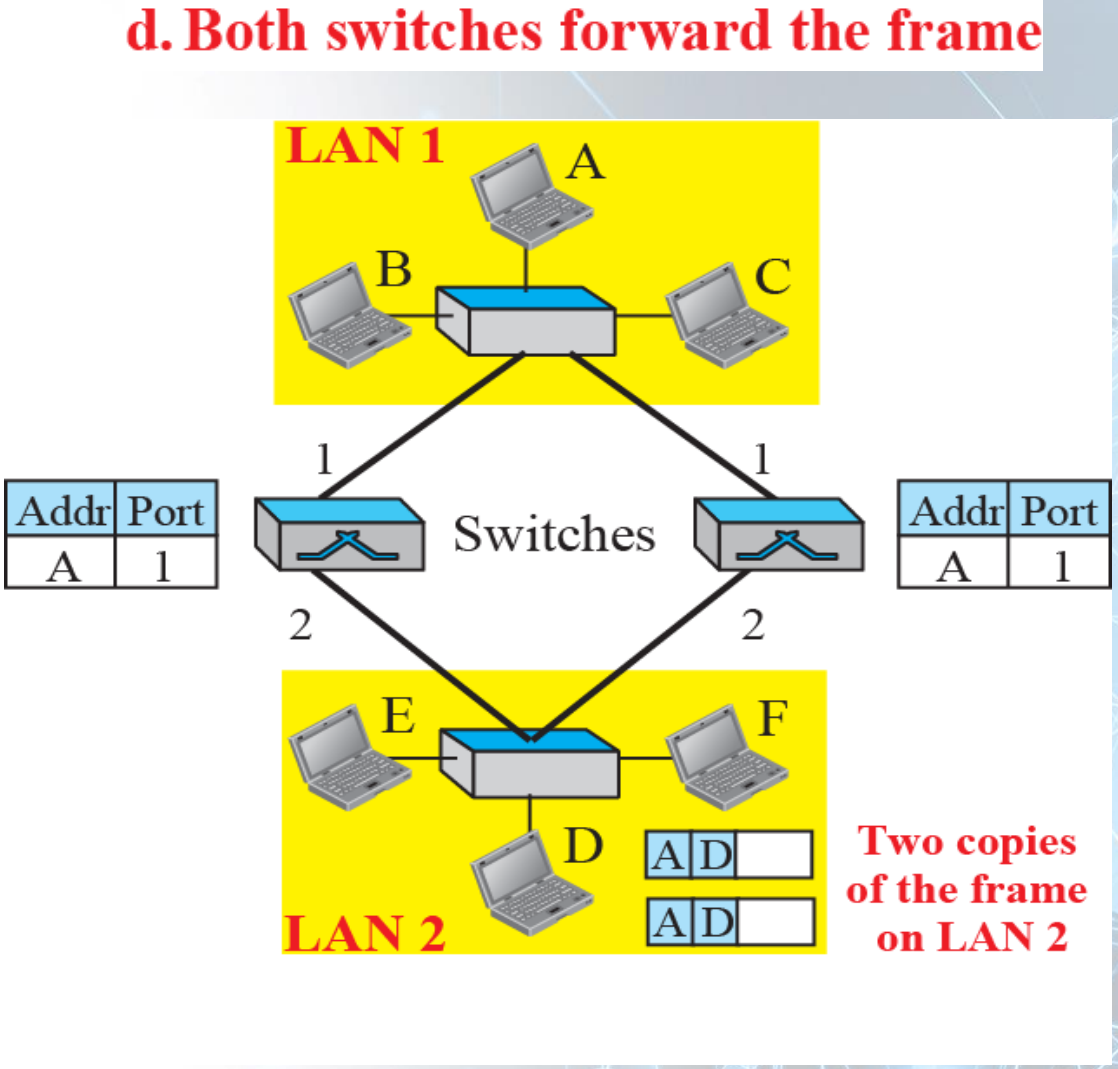
Loop Problem in a Learning Switch (Part b)



Loop Problem in a Learning Switch (Part c)



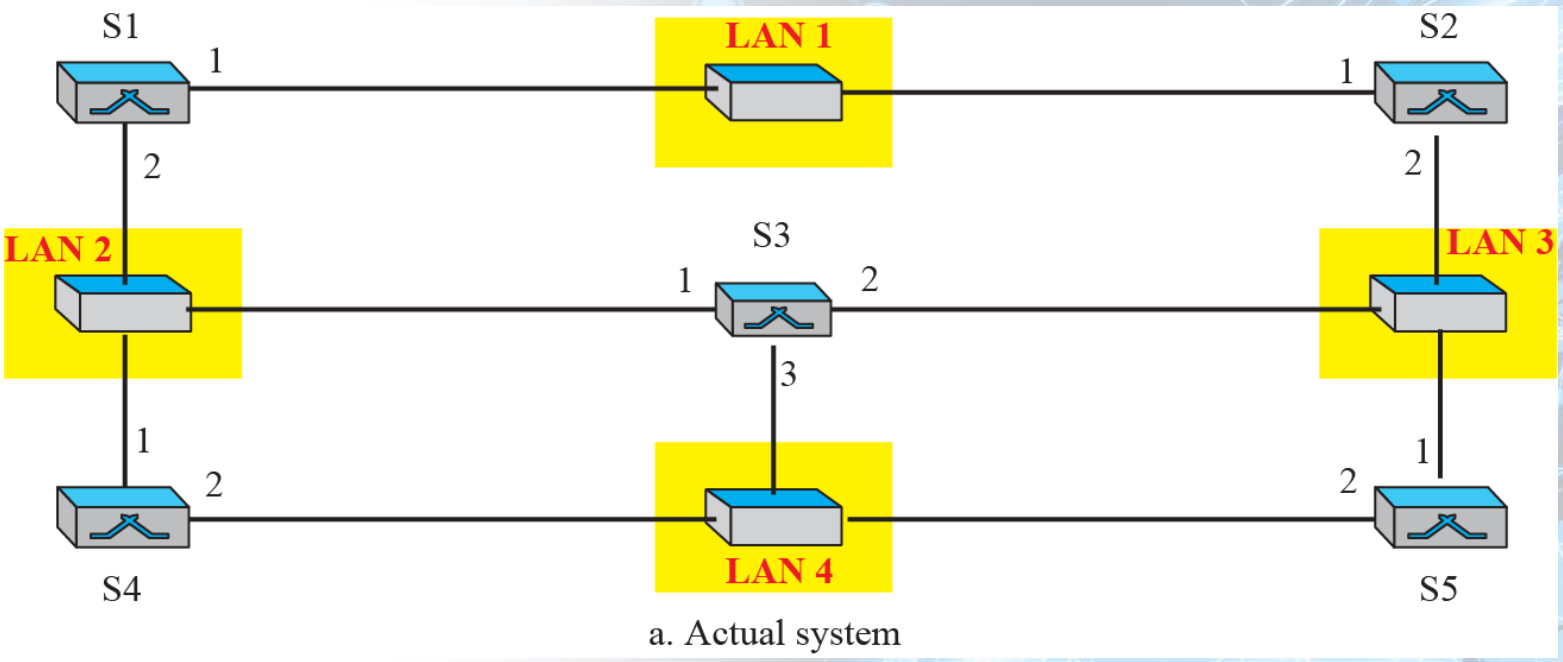
Loop Problem in a Learning Switch (part d)



Spanning Tree Algorithm

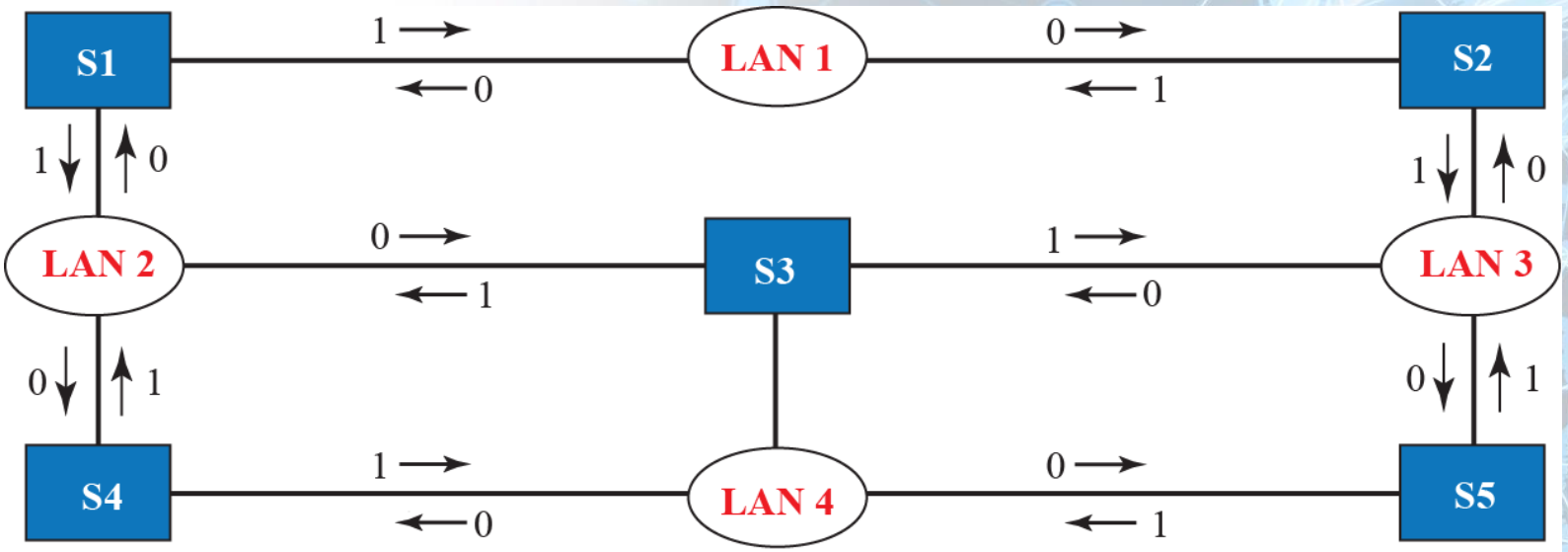
- In graph theory, Spanning Tree is a graph in which there is no loop
- In a switched LAN, this means creating a topology in which each LAN can be reached from any other LAN through one path only (no loop)
- To find the spanning tree, we assign a cost (metric) to each LAN link

A system of Connected LANs and its Graph (Part a)



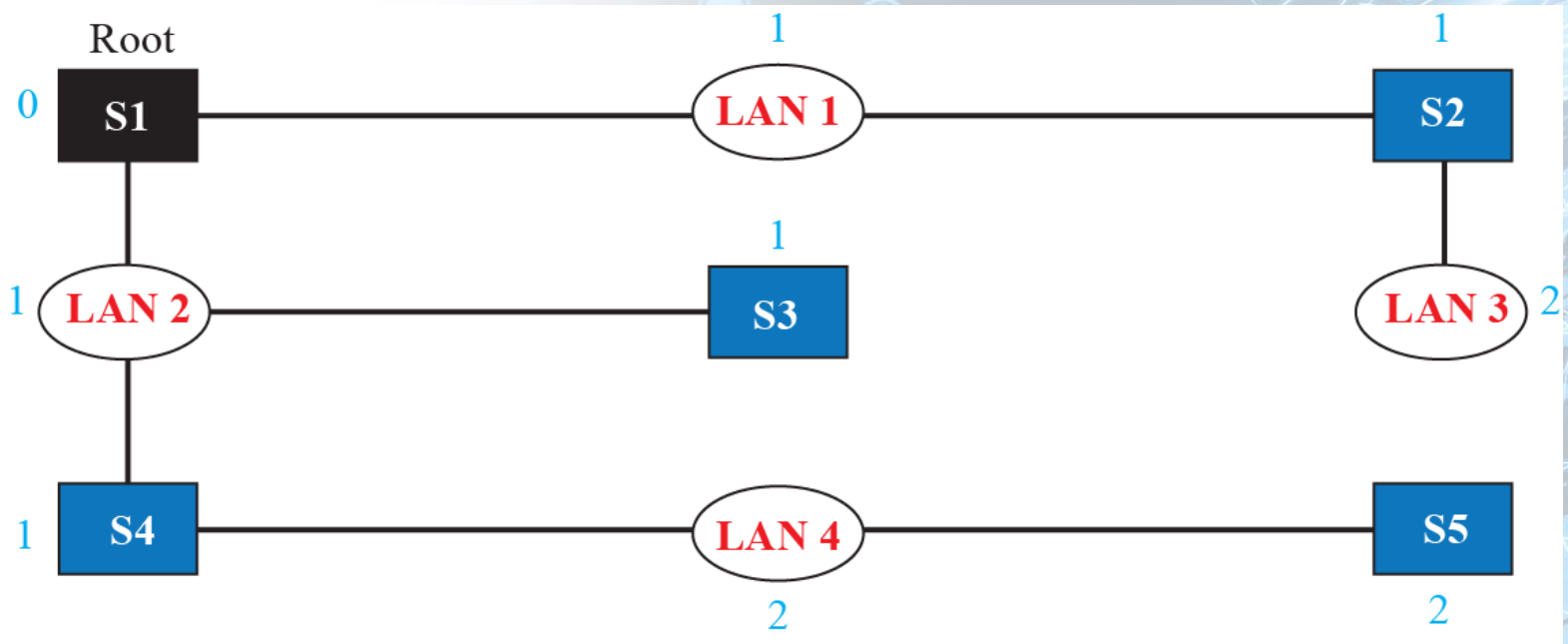
a. Actual system

A System of Connected LANs and its Graph (Part b)



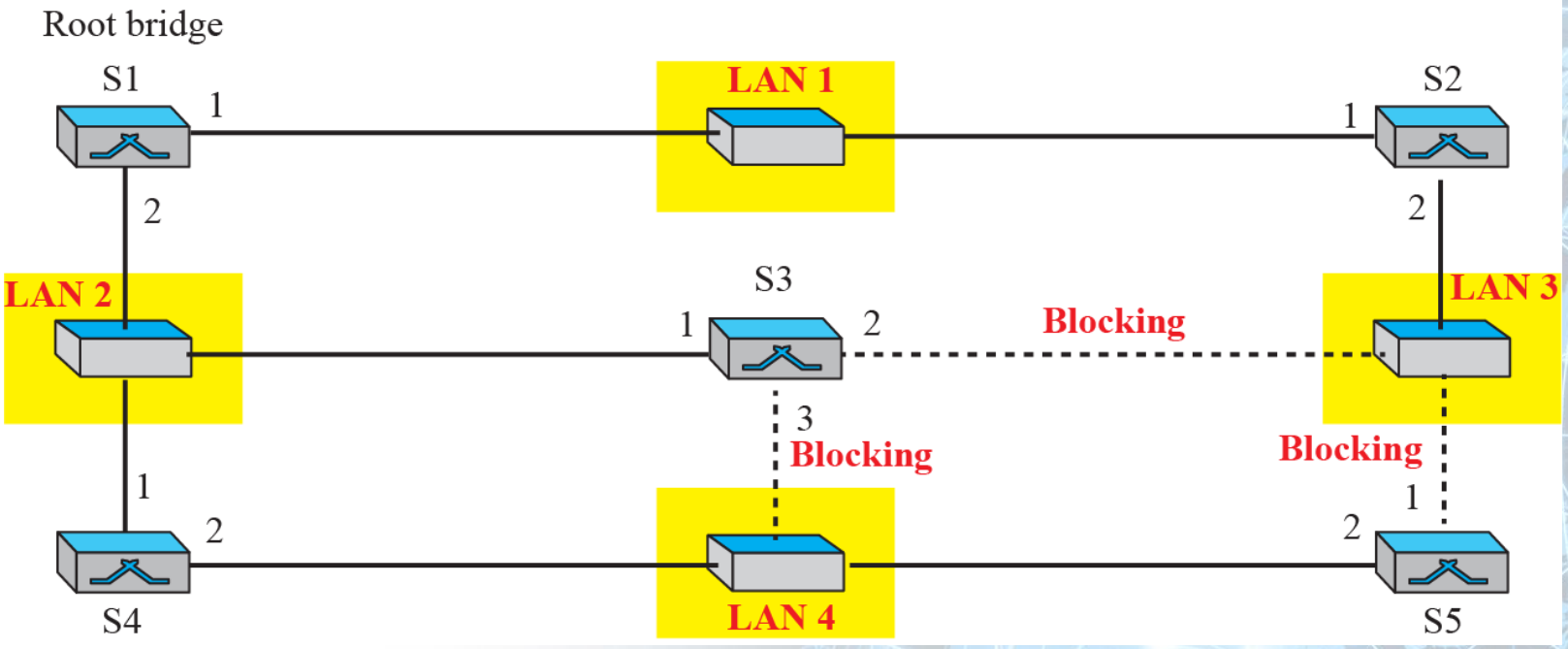
b. Graph representation with cost assigned to each arc

Finding Shortest Path/Spanning Tree for a Switch



Forwarding & Blocking Ports after using Spanning Tree

Ports 2 and 3 of bridge S3 are blocking ports (no frame is sent out of these ports).
Port 1 of bridge S5 is also a blocking port (no frame is sent out of this port).



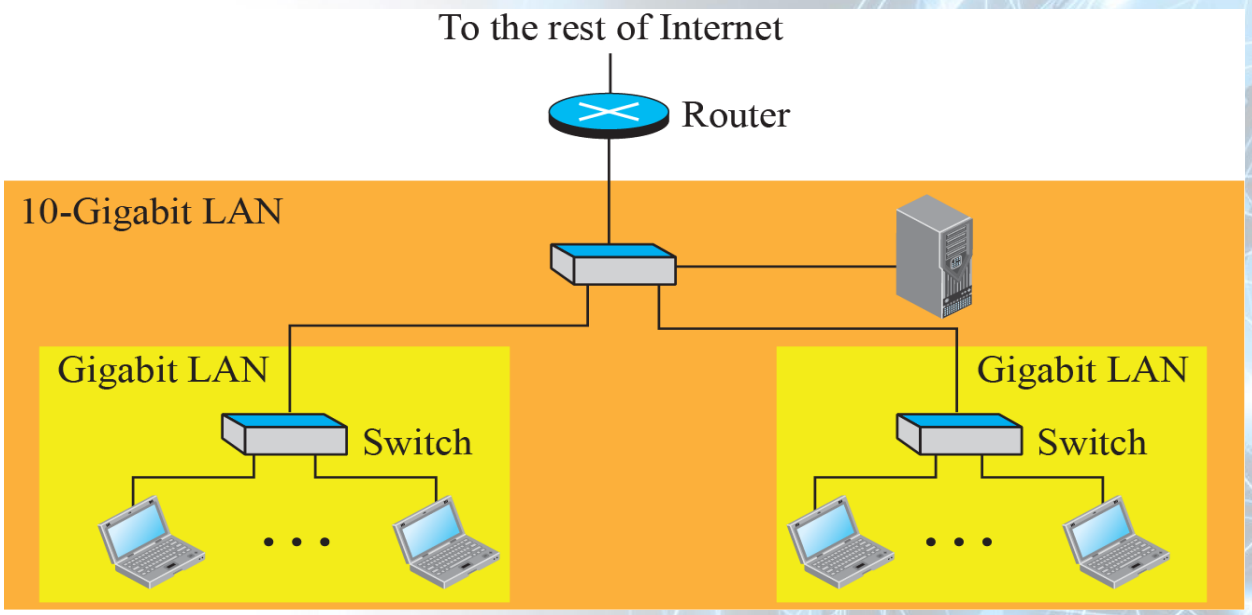
Routers

- We compare routers to two-layer switch and a hub
- A router is a three-layer device; it operates in the physical, data-link, and network layers

Router vs. Switch

Three differences between a router and a repeater or a switch:

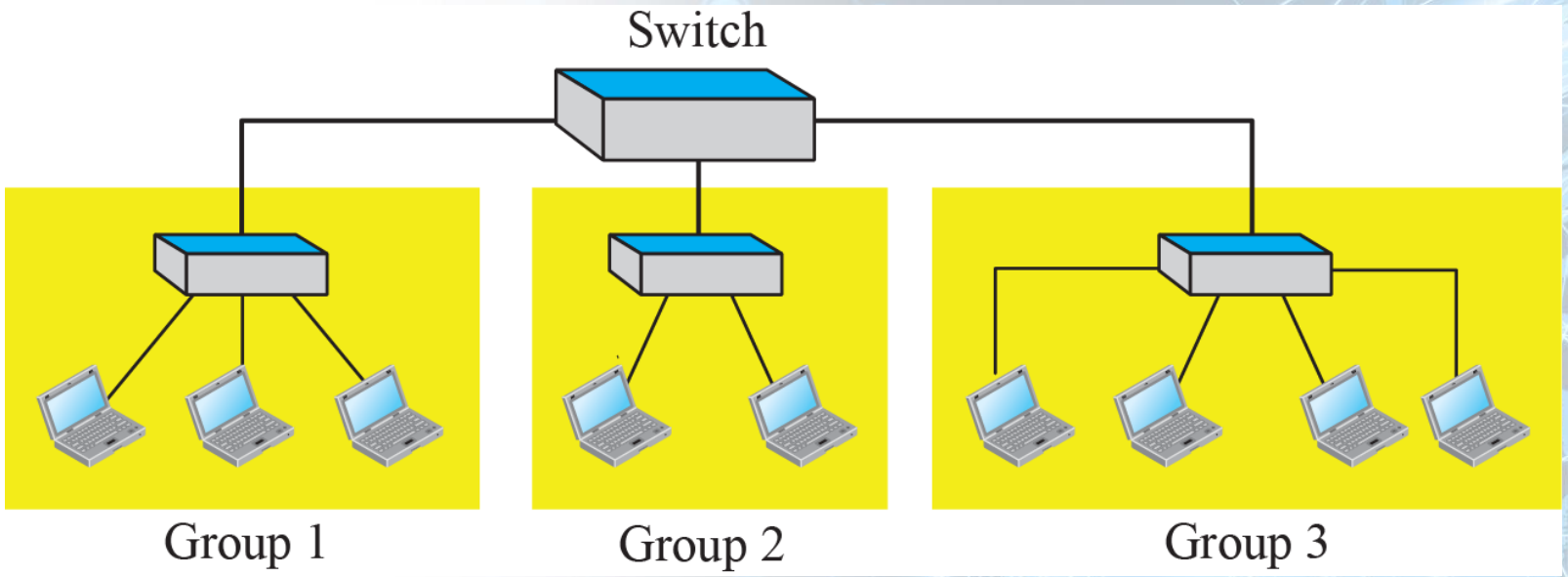
1. A router has a physical and logical (IP) address for each of its interfaces.
2. A router acts only on those packets in which the link-layer destination address matches the address of the interface at which the packet arrives.
3. A router changes the link-layer address of the packet (both source and destination) when it forwards the packet.



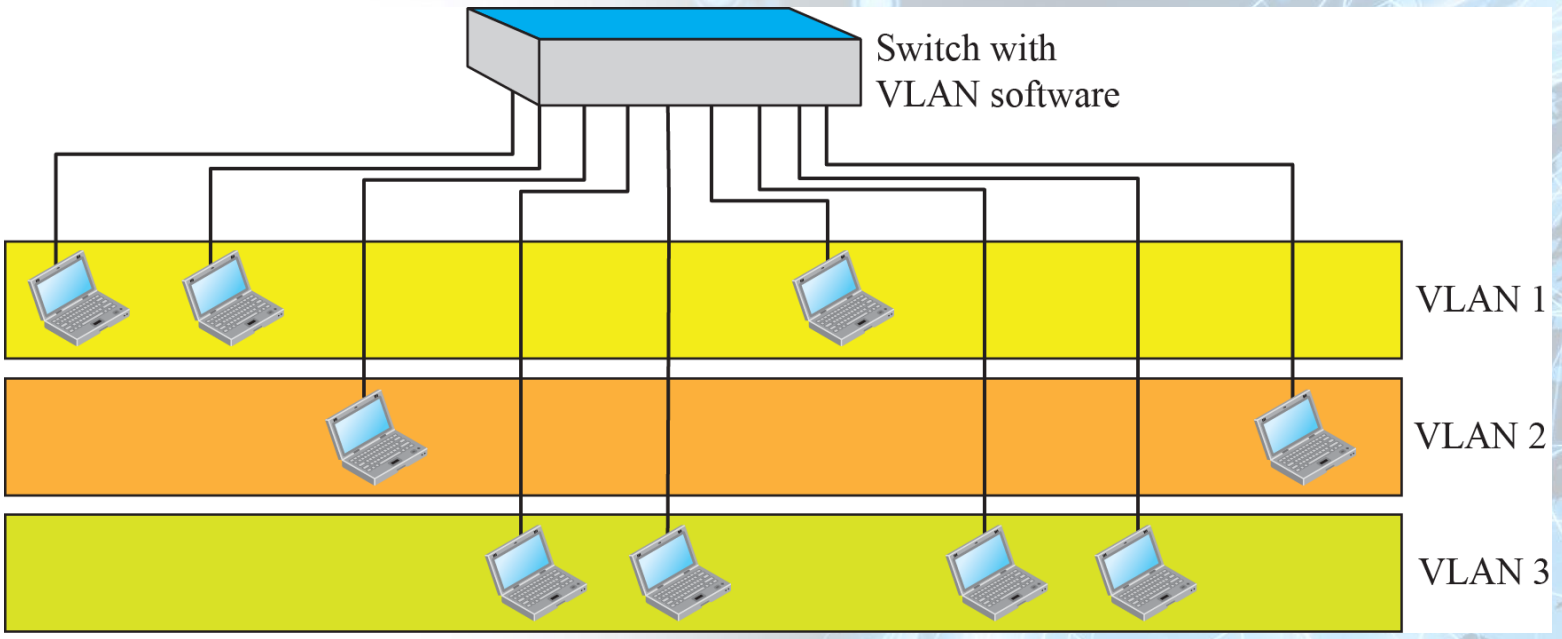
VIRTUAL LANS (VLAN)

- A VLAN is a LAN configured by software, not by physical wiring
- A station is considered part of a LAN if it physically belongs to that LAN i.e. The criterion of membership is geographic
- Provides a virtual connection between two stations belonging to two different physical LANs

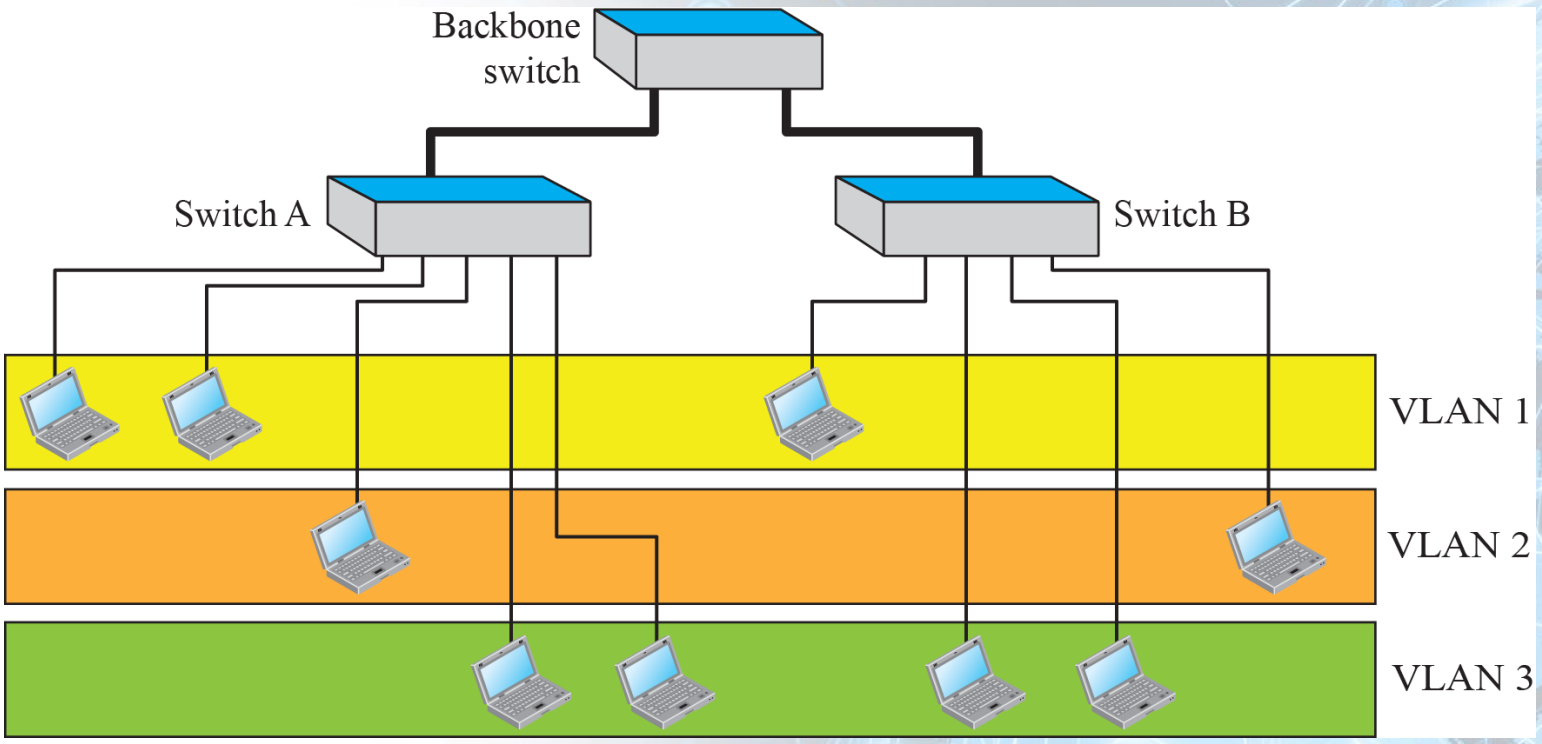
A Switch Connecting three LANs



A Switch using VLAN Software



Two Switches in a Backbone using VLAN Software



Membership of a VLAN

- What characteristic can be used to group stations in a VLAN?
- Vendors use different characteristics such as interface numbers, port numbers, MAC addresses, IP addresses, IP multicast addresses, or a combination of two or more of these

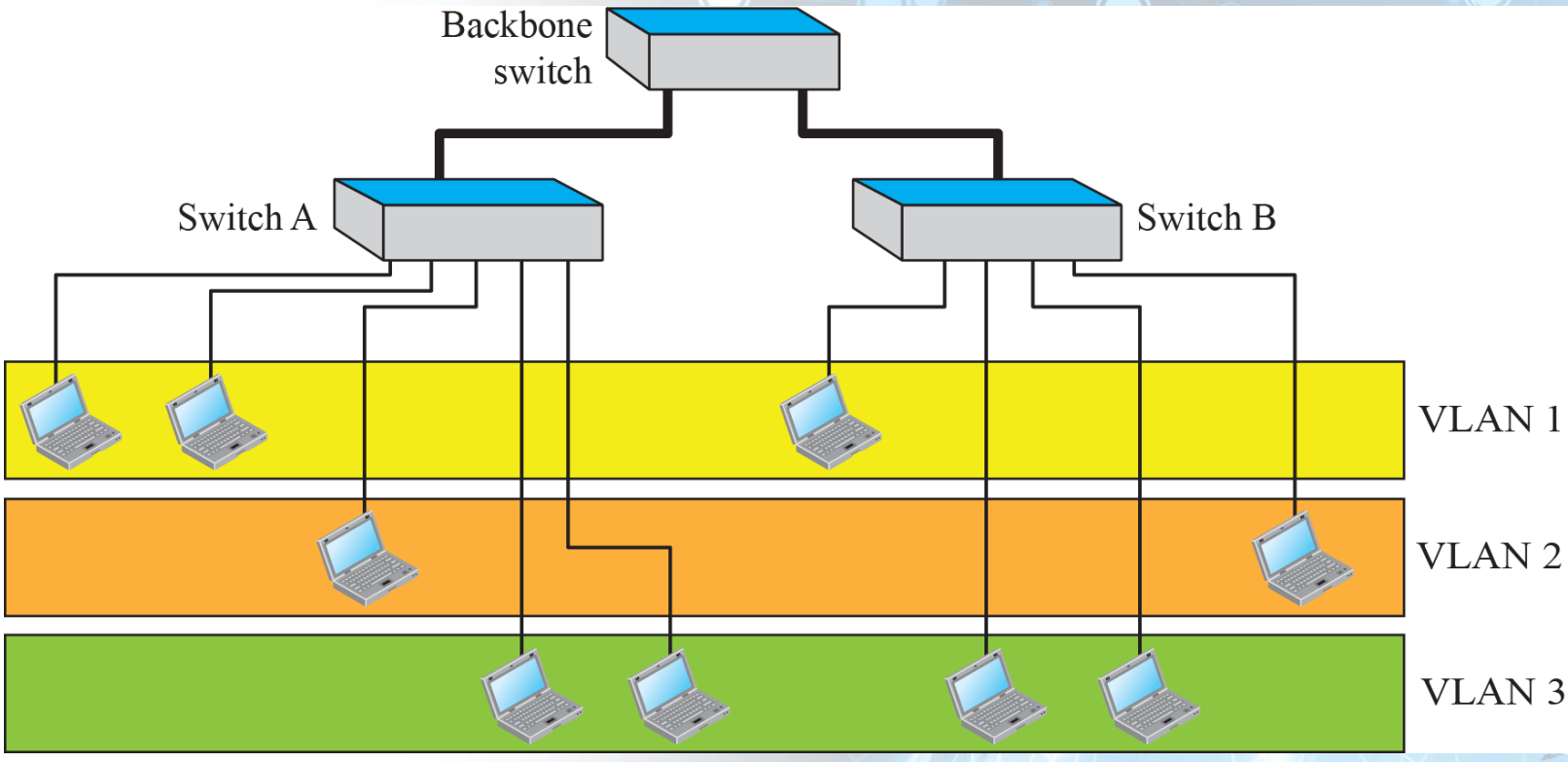
Configuration of a VLAN

- How are the stations grouped into different VLANs?
- Stations are configured in one of three ways:
  - ✓ Manually
  - ✓ Semi-Automatically
  - ✓ Automatically

Communication between Switches

- In a multi-switched backbone, each switch must know:
  - ✓ Which station belongs to which VLAN; and
  - ✓ The membership of stations connected to other switches

Communication between Switches



Switch A must know the membership status of stations connected to switch B, and switch B must know the same about switch A. Three methods have been devised for this purpose: table maintenance, frame tagging, and time-division multiplexing.

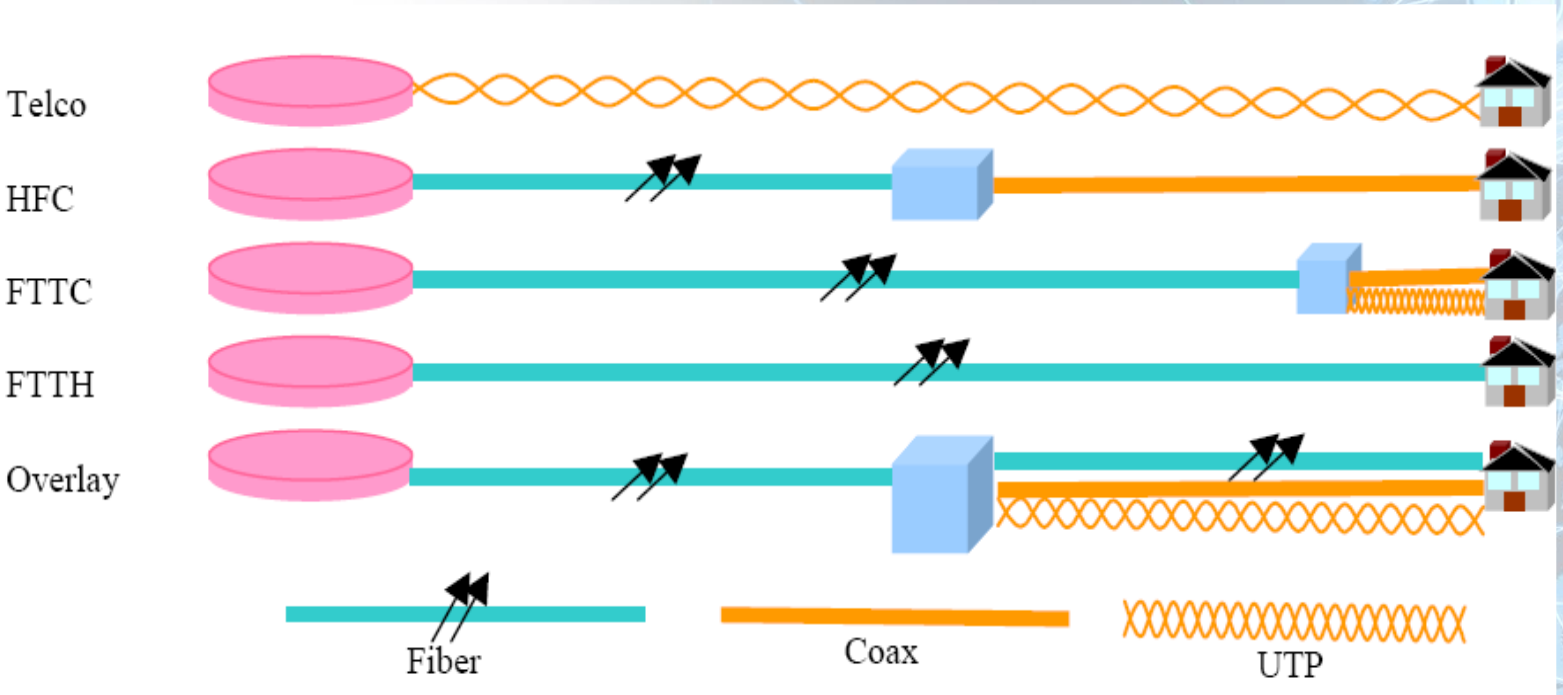
Advantages of using VLANs

- **Cost and Time Reduction**
- **Creating virtual Workgroups**
- **Security**

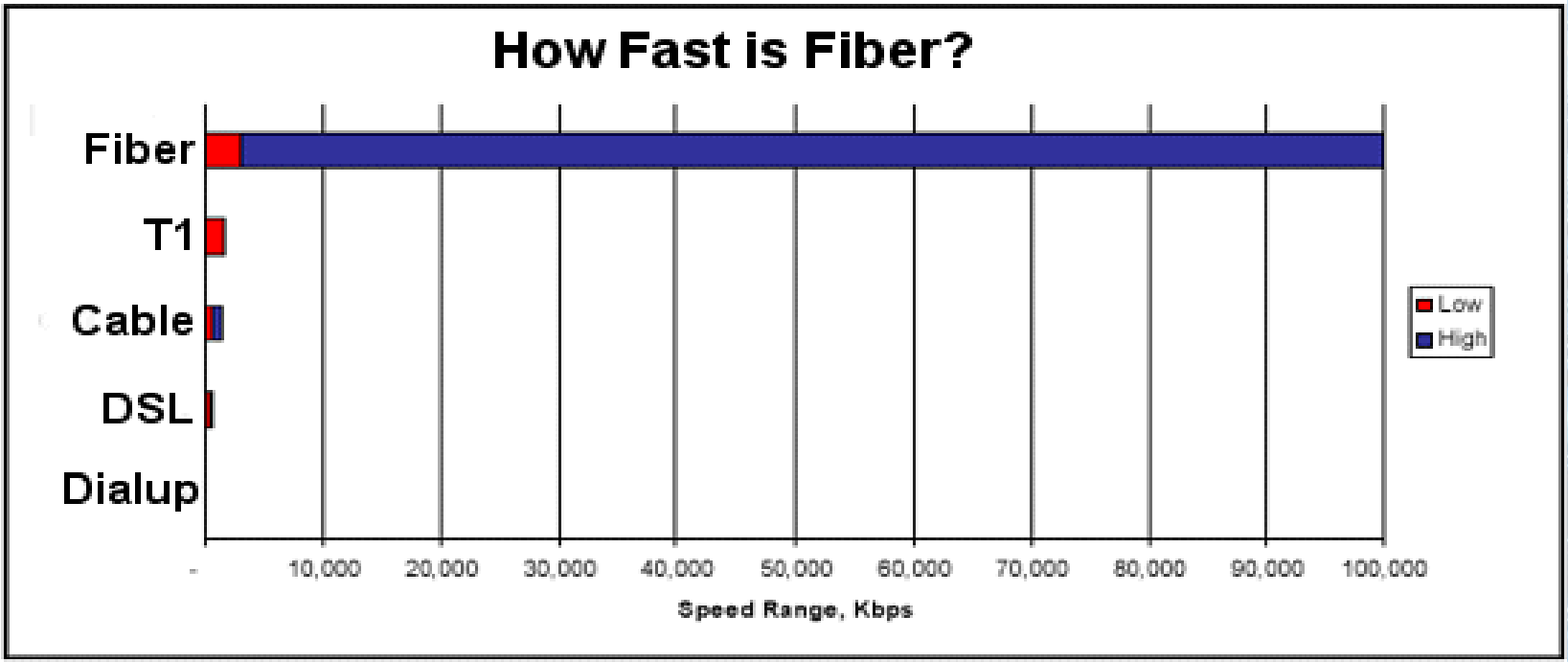
Comparison of Modern Access Technologies

- Telco
- HFC
- FTTx

Comparison of Modern Access Technologies



Fiber – The Medium of the Future!



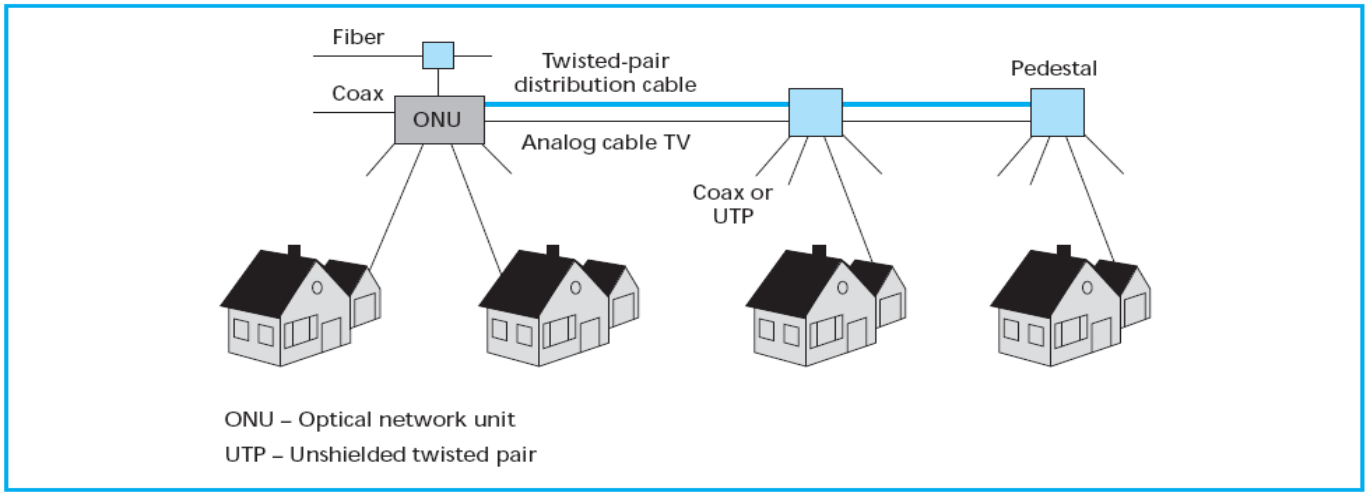
Fiber To The Curb (FTTC)

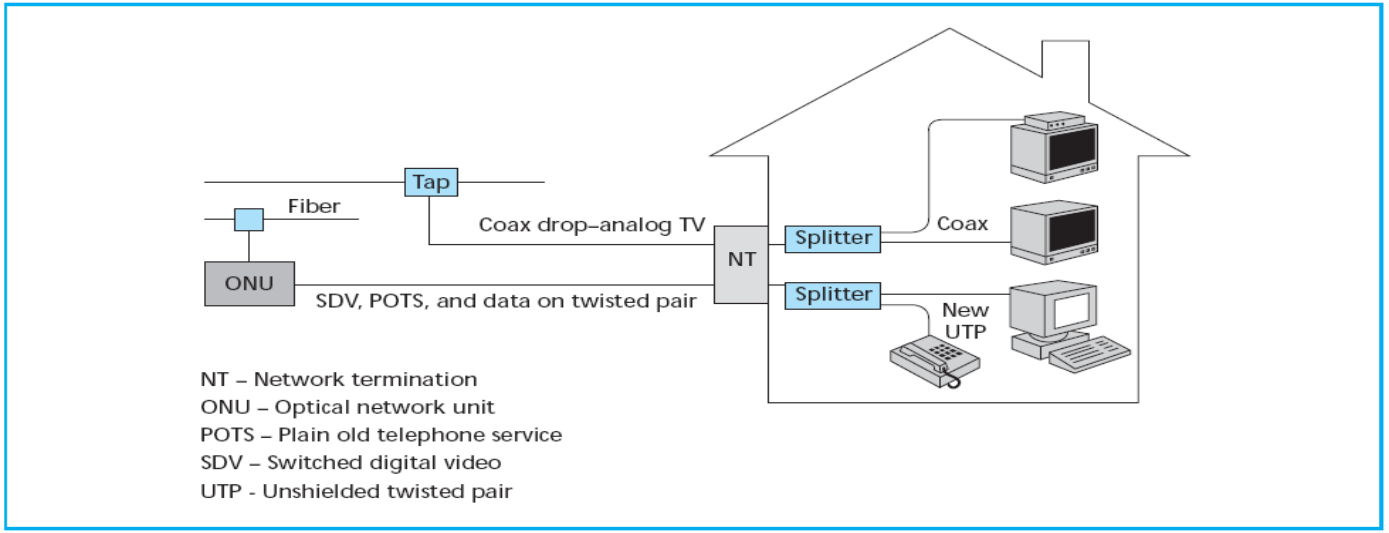
- An access network in which fiber is used for part, but not the entire link from the provider to the end-user
- An optical to electrical (O/E) conversion takes place somewhere near the end-user
- The terminal network segment of a FTTC network is usually twisted pair or coaxial cable

Fiber To The Curb (FTTC)

- The final optical receiver in a FTTC network typically serves several customers

Fiber To The Curb (FTTC)

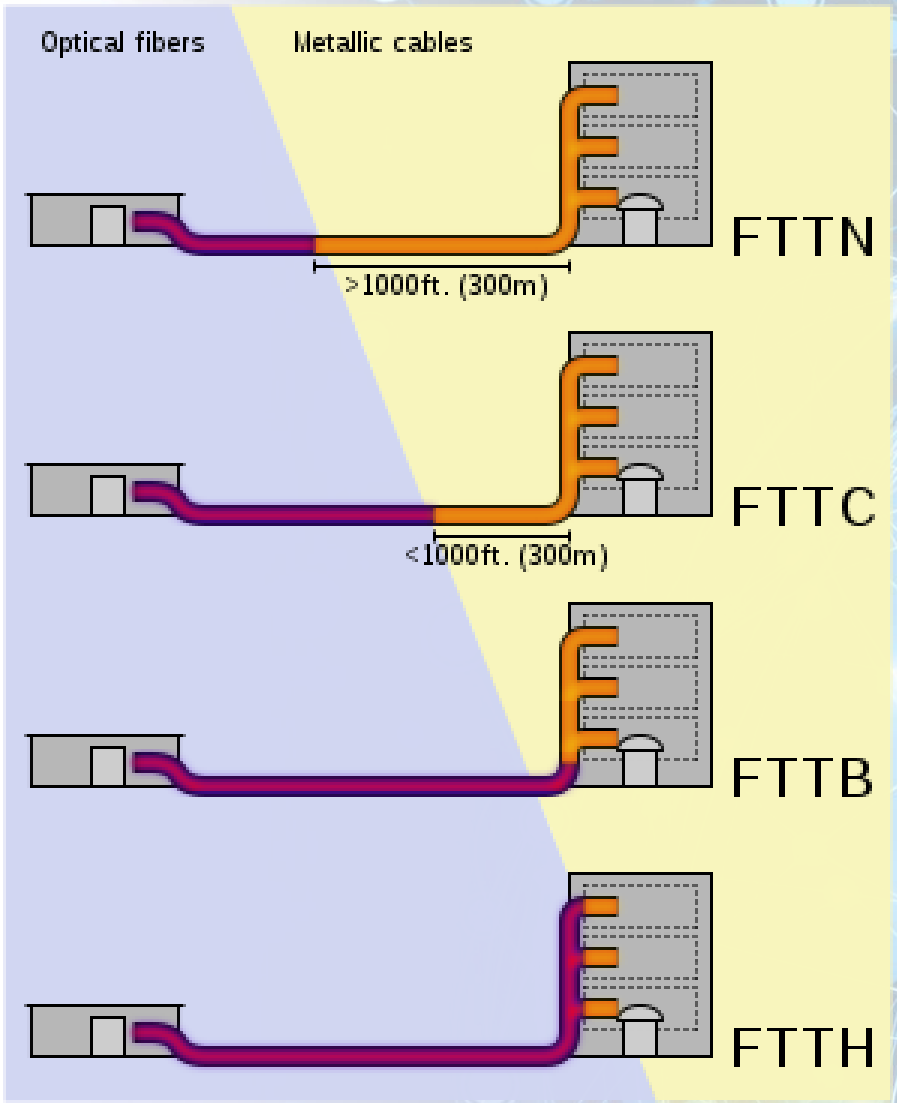




Fiber To The Home (FTTH)

- **Need: High-speed data, reliable voice and high-quality video**
- **Problems:**
  - ✓ **How to get high speed lines out to each customer?**
  - ✓ **How to future-proof the architecture?**
- **Solution: FTTH**

Fiber To The Home (FTTH)

- Fiber-to-the-home (FTTH) is the installation of optical fiber from a telephone switch directly into the subscriber's home
- It is one of the latest access technologies
- FTTH is also referred to as Fiber-to-the-Building (FTTB)

Fiber To The Home (FTTH)