NETWORK MODELS

PROTOCOL LAYERING

- A protocol defines the rules that both the sender and receiver and all intermediate devices need to follow to be able to communicate effectively.
- When communication is simple, we may need only one simple protocol.
  When communication is complex, we need to divide the task b/w different layers. We need a protocol at each layer, or protocol layering.

First Scenario

- In the first scenario, communication is so simple that it can occur in only one layer (Figure 2.1).
- Assume Maria and Ann are neighbors with a lot of common ideas.
- Communication between Maria and Ann takes place in one layer, face to face, in the same language

Figure 2.1 *A single-layer protocol*

Second Scenario

- Maria and Ann communicate using regular mail through the post office (Figure 2.2).
- However, they do not want their ideas to be revealed by other people if the letters are intercepted.
- They agree on an encryption/decryption technique.
- The sender of the letter encrypts it to make it unreadable by an intruder; the receiver of the letter

decrypts it to get the original letter.

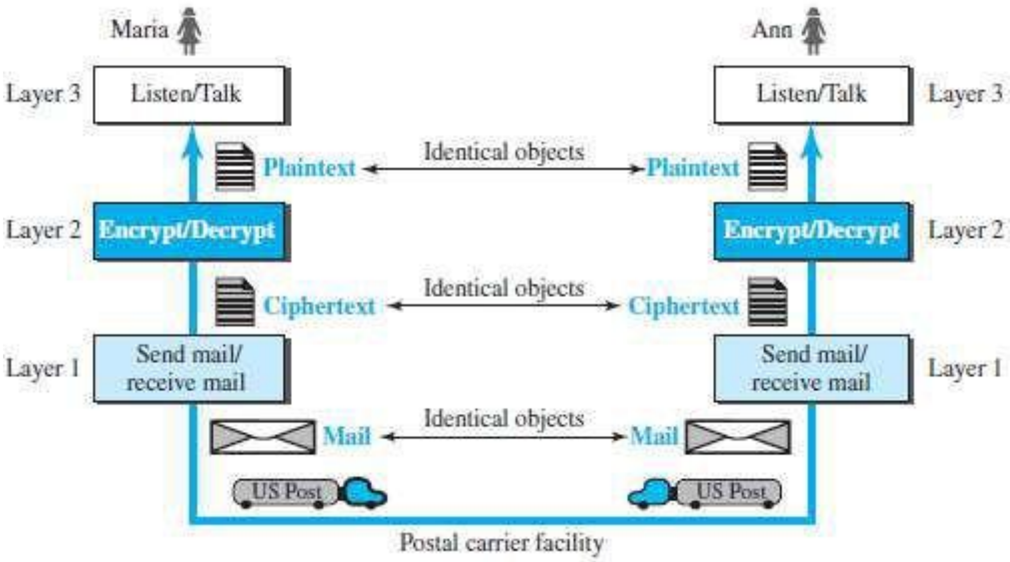

Figure 2.2 *A three-layer protocol*

Protocol Layering

- Protocol layering enables us to divide a complex task into several smaller and simpler tasks.
- Modularity means independent layers.

• A layer (module) can be defined as a black box with inputs and outputs, without concern about how inputs are changed to outputs.
• If two machines provide the same outputs when given the same inputs, they can replace each other.
• Advantages:
1) It allows us to separate the services from the implementation.
2) There are intermediate systems that need only some layers, but not all layers.
• Disadvantage:
1) Having a single layer makes the job easier. There is no need for each layer to provide a service to the upper layer and give service to the lower layer.

Principles of Protocol Layering

1) First Principle

• If we want bidirectional communication, we need to make each layer able to perform 2 opposite tasks, one in each direction.
• For example, the third layer task is to listen (in one direction) and talk (in the other direction).

2) Second Principle

• The two objects under each layer at both sites should be identical.
• For example, the object under layer 3 at both sites should be a plaintext letter.

Logical Connections

• We have layer-to-layer communication (Figure 2.3).
• There is a logical connection at each layer through which 2 end systems can send the object created from that layer.

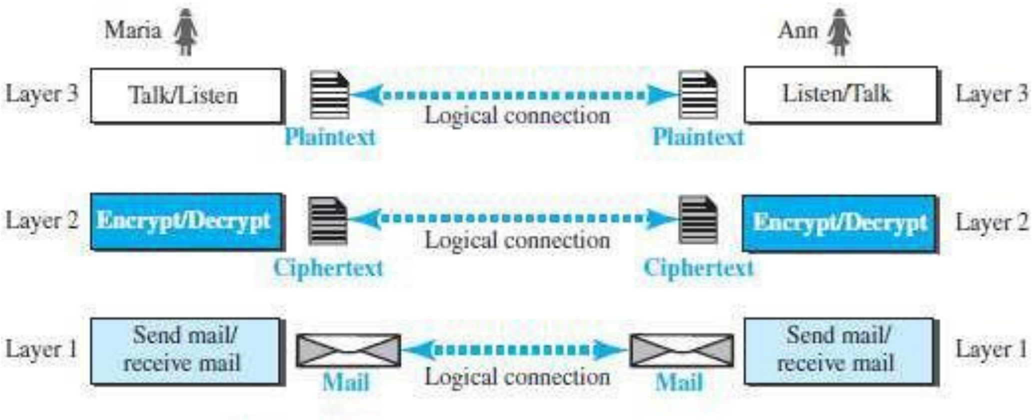

Figure 2.3 *Logical connection between peer layers*

TCP/IP PROTOCOL SUITE

• TCP/IP is a protocol-suite used in the Internet today.
• Protocol-suite refers a set of protocols organized in different layers.
• It is a hierarchical protocol made up of interactive modules, each of which provides a specific functionality.
• The term hierarchical means that each upper level protocol is supported by the services provided by one or more lower level protocols.

Layered Architecture

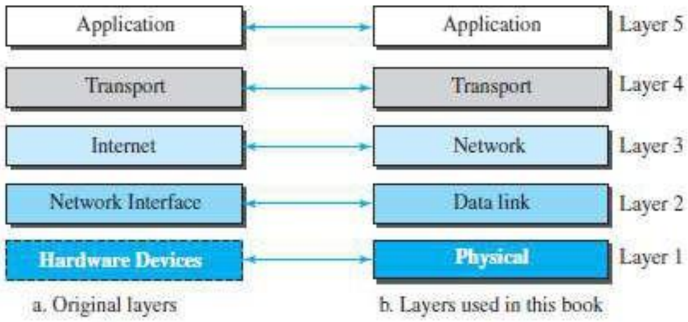

Figure 2.4 *Layers in the TCP/IP protocol suite*

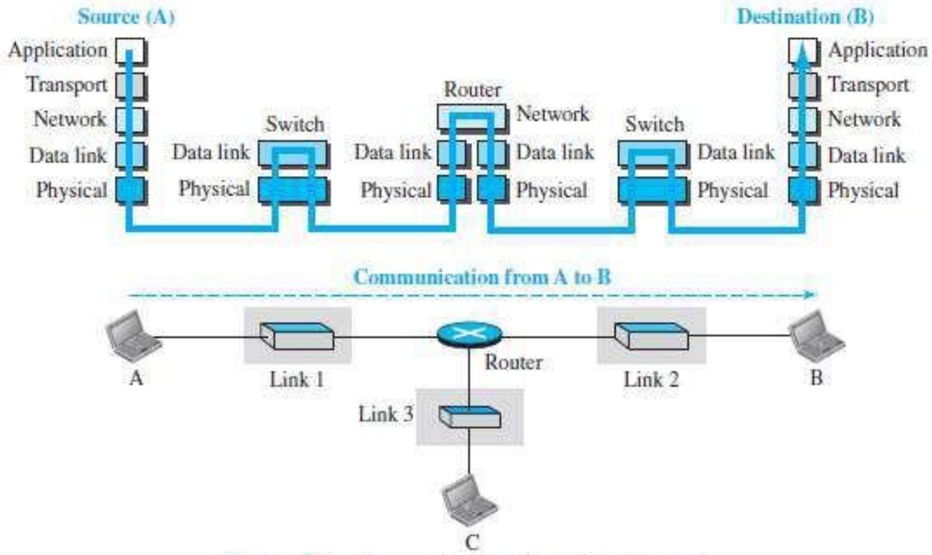

Figure 2.5 *Communication through an internet*

- Let us assume that computer A communicates with computer B (Figure 2.4).
- As the Figure 2.5 shows, we have five communicating devices:
  1) Source host (computer A) 2) Link-layer switch in link 1
  3) Router 4) Link-layer switch in link 2
  5) Destination host (computer B).
- Each device is involved with a set of layers depending on the role of the device in the internet.
- The two hosts are involved in all five layers.
- The source host
  → creates a message in the application layer and
  → sends the message down the layers so that it is physically sent to the destination host.
- The destination host
  → receives the message at the physical layer and
  → then deliver the message through the other layers to the application layer.
- The router is involved in only three layers; there is no transport or application layer.
- A router is involved in n combinations of link and physical layers.
  where n = number of links the router is connected to.
- The reason is that each link may use its own data-link or physical protocol.
- A link-layer switch is involved only in two layers: i) data-link and ii) physical

Layers in the TCP/IP Protocol Suite

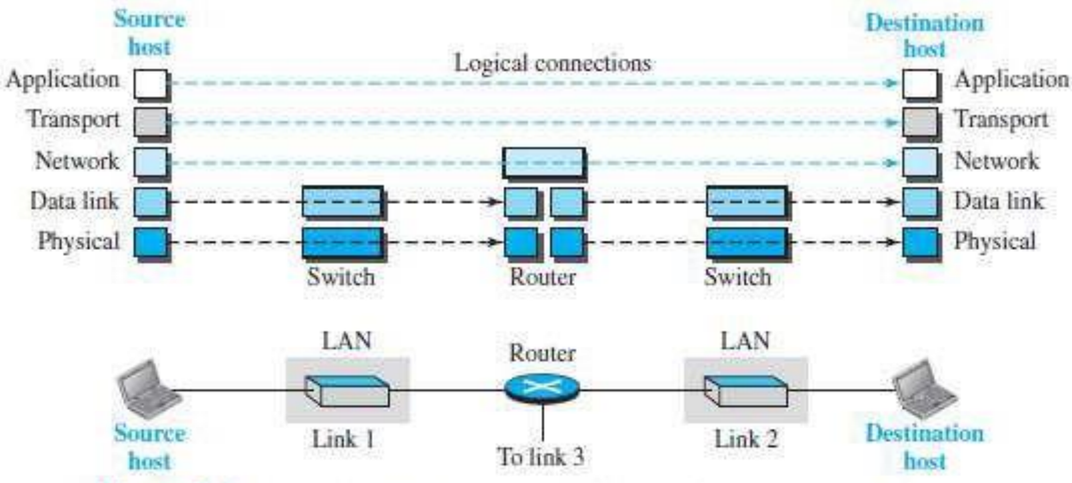

Figure 2.6 *Logical connections between layers of the TCP/IP protocol suite*

- As shown in the figure 2.6, the duty of the application, transport, and network layers is end-to-end.
- However, the duty of the data-link and physical layers is hop-to-hop. A hop is a host or router.
- The domain of duty of the top three layers is the internet. The domain of duty of the two lower layers is the link.
- In top 3 layers, the data unit should not be changed by any router or link-layer switch. In bottom 2 layers, the data unit is changed only by the routers, not by the link-layer switches.

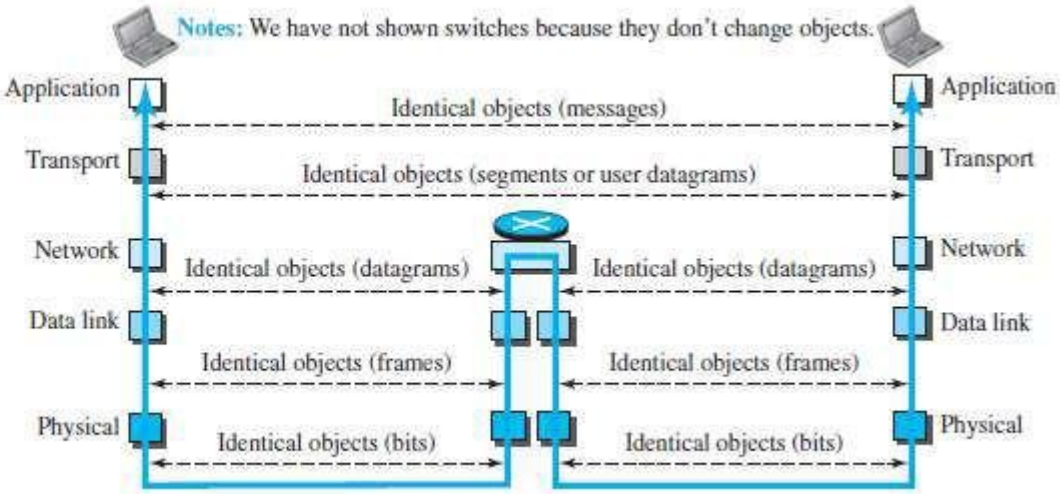

Figure 2.7 *Identical objects in the TCP/IP protocol suite*

- Identical objects exist between two hops. Because router may fragment the packet at the network layer and send more packets than received (Figure 2.7).
- The link between two hops does not change the object.

Description of Each Layer

Physical Layer

- The physical layer is responsible for movements of individual bits from one node to another node.
- Transmission media is another hidden layer under the physical layer.
- Two devices are connected by a transmission medium (cable or air).
- The transmission medium does not carry bits; it carries electrical or optical signals.
- The physical layer
  → receives bits from the data-link layer &
  → sends through the transmission media.

Data Link Layer

- Data-link-layer (DLL) is responsible for moving frames from one node to another node over a link.
- The link can be wired LAN/WAN or wireless LAN/WAN.
- The data-link layer
  → gets the datagram from network layer
  → encapsulates the datagram in a packet called a frame.
  → sends the frame to physical layer.
- TCP/IP model does not define any specific protocol.
- DLL supports all the standard and proprietary protocols.
- Each protocol may provide a different service.
- Some protocols provide complete error detection and correction; some protocols provide only error correction.

Network Layer

- The network layer is responsible for source-to-destination transmission of data.
- The network layer is also responsible for routing the packet.
- The routers choose the best route for each packet.
- we need the separate network layer for
  The separation of different tasks between different layers.
  The routers do not need the application and transport layers.
- TCP/IP model defines 5 protocols:
  1) IP (Internetworking Protocol) 2) ARP (Address Resolution Protocol)
  3) ICMP (Internet Control Message Protocol) 4) IGMP (Internet Group Message Protocol)

Transport Layer

- TL protocols are responsible for delivery of a message from a process to another process.
- The transport layer
  → gets the message from the application layer
  → encapsulates the message in a packet called a segment and
  → sends the segment to network layer.
- TCP/IP model defines 3 protocols:1) TCP (Transmission Control Protocol)
  2) UDP (User Datagram Protocol) &
  3) SCTP (Stream Control Transmission Protocol)

Application Layer

- The two application layers' exchange messages between each other.
- Communication at the application layer is between two processes (two programs running at this layer).
- To communicate, a process sends a request to the other process and receives a response.
- Process-to-process communication is the duty of the application layer.
- TCP/IP model defines following protocols:
  1) SMTP is used to transport email between a source and destination.

2) TELNET is used for accessing a site remotely.
3) FTP is used for transferring files from one host to another.
4) DNS is used to find the IP address of a computer.
5) SNMP is used to manage the Internet at global and local levels.

HTTP is used for accessing the World Wide Web (WWW).

Encapsulation and Decapsulation

A) Encapsulation at the Source Host

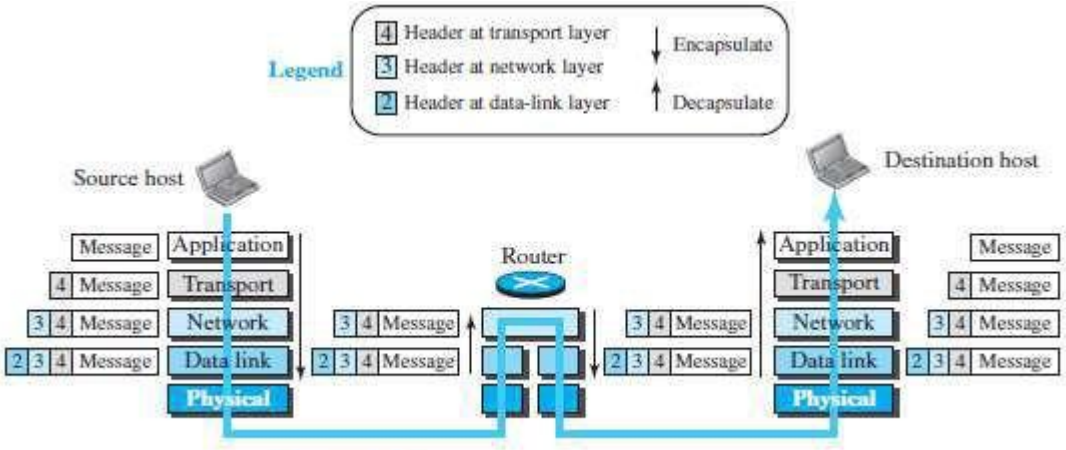

Figure 2.8 *Encapsulation/Decapsulation*

- At the source, we have only encapsulation (Figure 2.8).

1) At the application layer, the data to be exchanged is referred to as a message.
- ➢ A message normally does not contain any header or trailer.
- ➢ The message is passed to the transport layer.

2) The transport layer takes the message as the payload.
- ➢ TL adds its own header to the payload.
- ➢ The header contains
  - → identifiers of the source and destination application programs
  - → information needed for flow, error control, or congestion control.
- ➢ The transport-layer packet is called the segment (in TCP) and the user datagram (in UDP).
- ➢ The segment is passed to the network layer.

3) The network layer takes the transport-layer packet as payload.
- ➢ NL adds its own header to the payload.
- ➢ The header contains
  - → addresses of the source and destination hosts
  - → some information used for error checking of the header &
  - → fragmentation information.
- ➢ The network-layer packet is called a datagram.
- ➢ The datagram is passed to the data-link layer.

4) The data-link layer takes the network-layer packet as payload.
- ➢ DLL adds its own header to the payload.
- ➢ The header contains the physical addresses of the host or the next hop (the router).
- ➢ The link-layer packet is called a frame.
- ➢ The frame is passed to the physical layer for transmission

B) Decapsulation and Encapsulation at the Router

- At the router, we have both encapsulation & encapsulation and because the router is connected to two or more links.

1) Data-link layer
  - → receives frame from physical layer

→ decapsulates the datagram from the frame and
→ passes the datagram to the network layer.

2) The network layer
→ inspects the source and destination addresses in the datagram header and
→ consults forwarding table to find next hop to which the datagram is to be delivered.

➢ The datagram is then passed to the data-link layer of the next link.

3) The data-link layer of the next link
→ encapsulates the datagram in a frame and
→ passes the frame to the physical layer for transmission.

C) Decapsulation at the Destination Host

• At the destination host, each layer
→ decapsulates the packet received from lower layer
→ removes the payload and
→ delivers the payload to the next-higher layer

Addressing

• We have logical communication between pairs of layers.
• Any communication that involves 2 parties needs 2 addresses: source address and destination address.
• We need 4 pairs of addresses (Figure 2.9):

2) At the application layer, we normally use names to define
→ site that provides services
→ e-mail address

3) At the transport layer, addresses are called port numbers.
➢ Port numbers define the application-layer programs at the source and destination.
➢ Port numbers are local addresses that distinguish between several programs running at the same time.

4) At the network-layer, addresses are called IP addresses.
➢ IP address uniquely defines the connection of a device to the Internet.
➢ The IP addresses are global, with the whole Internet as the scope.

5) At the data link-layer, addresses are called MAC addresses
➢ The MAC addresses defines a specific host or router in a network (LAN or WAN).
➢ The MAC addresses are locally defined addresses.

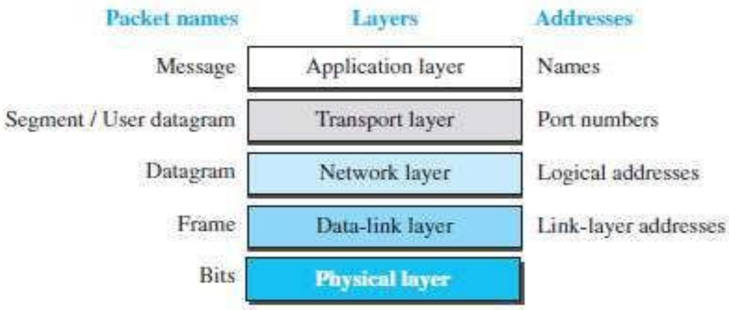

Figure 2.9 *Addressing in the TCP/IP protocol suite*

Multiplexing and Demultiplexing

• Multiplexing means a protocol at a layer can encapsulate a packet from several next-higher layer protocols (one at a time) (Figure 2.10).
• Demultiplexing means a protocol can decapsulate and deliver a packet to several next-higher layer protocols (one at a time).

6) At transport layer, either UDP or TCP can accept a message from several application-layer protocols.

7) At network layer, IP can accept
→ a segment from TCP or a user datagram from UDP.
→ a packet from ICMP or IGMP.

8) At data-link layer, a frame may carry the payload coming from IP or ARP.

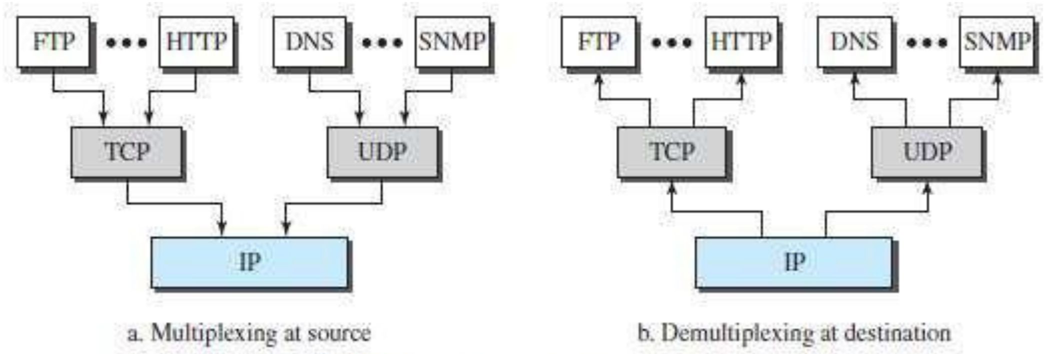

Figure 2.10 *Multiplexing and demultiplexing*

OSI MODEL

- OSI model was developed by ISO.
- ISO is the organization, OSI is the model.
- Purpose: OSI was developed to allow systems with diff. platforms to communicate with each other.
- Platform means hardware, software or operating system.
- OSI is a network-model that defines the protocols for network communications.
- OSI has 7 layers as follows
  1) Application Layer
  2) Presentation Layer
  3) Session Layer
  4) Transport Layer
  5) Network Layer
  6) Data Link Layer
  7) Physical Layer

OSI vs. TCP/IP

The four bottommost layers in the OSI model & the TCP/IP model are same (Figure 2.12). However, the Application-layer of TCP/IP model corresponds to the Session, Presentation & Application Layer of OSI model.

Two reasons for this are:

1) TCP/IP has more than one transport-layer protocol.
2) Many applications can be developed at Application layer

The OSI model specifies which functions belong to each of its layers.

In TCP/IP model, the layers contain relatively independent protocols that can be mixed and matched depending on the needs of the system.

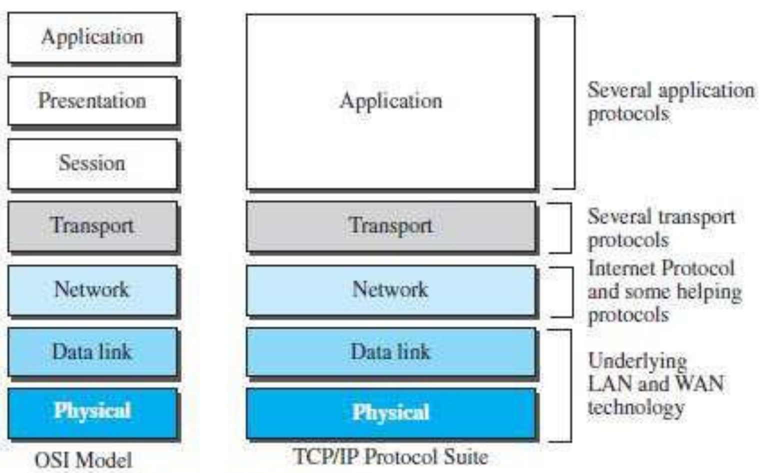

Figure 2.12 *TCP/IP and OSI model*

Lack of OSI Model's Success

• OSI was completed when TCP/IP was fully in place and a lot of time and money had been spent on the suite; changing it would cost a lot.
• Some layers in the OSI model were never fully defined.
• When OSI was implemented by an organization in a different application, it did not show a high
enough level of performance

DATA AND SIGNALS

Analog & Digital Data

• To be transmitted, data must be transformed to electromagnetic-signals.
• Data can be either analog or digital.

1) Analog Data refers to information that is continuous.
➢ For example:
The sounds made by a human voice.

2) Digital Data refers to information that has discrete states.
➢ For example:
Data are stored in computer-memory in the form of 0s and 1s.

Analog & Digital Signals

• Signals can be either analog or digital (Figure 3.2).
Analog Signal has infinitely many levels of intensity over a period of time.
Digital Signal can have only a limited number of defined values.

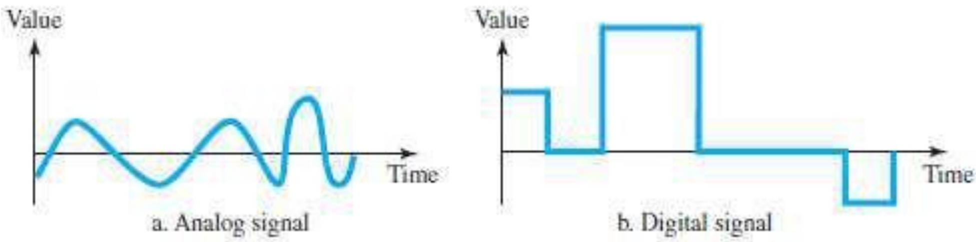

Figure 3.2 *Comparison of analog and digital signals*

Periodic & Non-Periodic Signals

• The signals can take one of 2 forms: periodic or non-periodic.

3) Periodic Signal
➢ Signals which repeat itself after a fixed time period are called Periodic Signals.
➢ The completion of one full pattern is called a cycle.

4) Non-Periodic Signal
➢ Signals which do not repeat itself after a fixed time period are called Non-Periodic Signals.

DIGITAL SIGNALS

• Information can be represented by a digital signal.
• For example:
1) 1 can be encoded as a positive voltage.
0 can be encoded as a zero voltage (Figure 3.17a).

2) A digital signal can have more than 2 levels (Figure 3.17b).

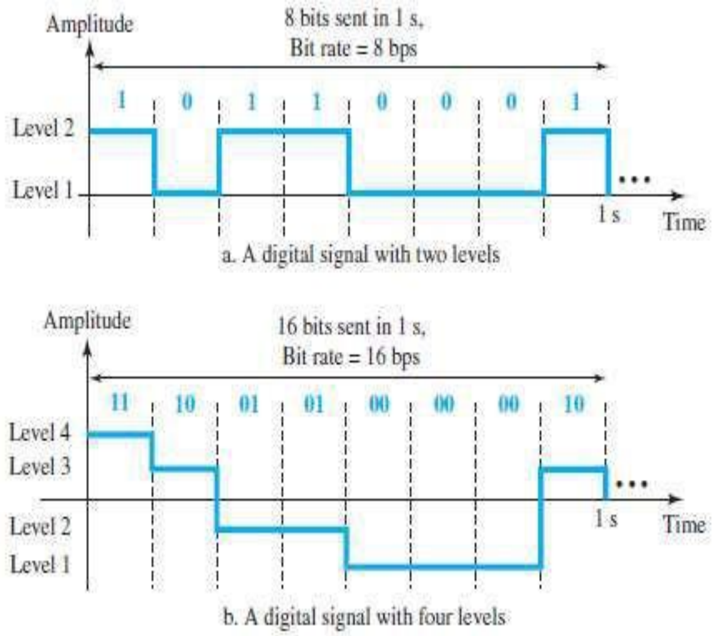

Figure 3.17 *Two digital signals: one with two signal levels and the other with four signal levels*

Digital Signal as a Composite Analog Signal

- A digital signal is a composite analog signal.
- A digital signal, in the time domain, comprises connected vertical and horizontal line segments.
  1) A vertical line in the time domain means a frequency of infinity (sudden change in time);
  2) A horizontal line in the time domain means a frequency of zero (no change in time).
- Fourier analysis can be used to decompose a digital signal.
  1) If the digital signal is periodic, the decomposed signal has a frequency domain representation with an infinite bandwidth and discrete frequencies (Figure 3.18a).
  2) If the digital signal is non-periodic, the decomposed signal has a frequency domain representation with an infinite bandwidth and continuous frequencies (Figure 3.18b).

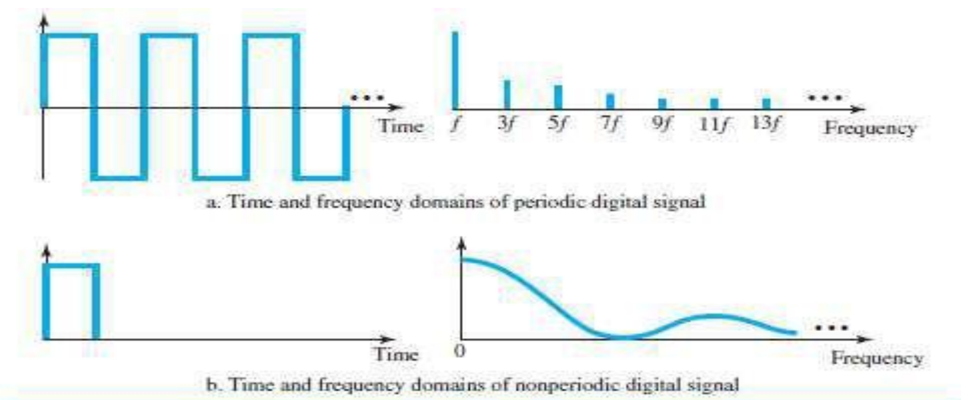

Figure 3.18 *The time and frequency domains of periodic and nonperiodic digital signals*

Transmission of Digital Signals

• Two methods for transmitting a digital signal:
3) Baseband transmission 2) Broadband transmission (using modulation).

Baseband Transmission

• Baseband transmission means sending a digital signal over a channel without changing the digital signal to an analog signal (Figure 3.19).

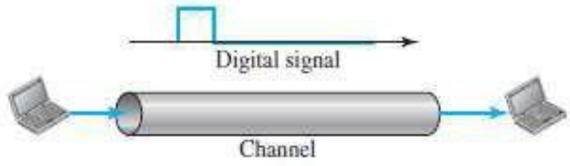

Figure 3.19 *Baseband transmission*

• Baseband transmission requires that we have a low-pass channel.
• Low-pass channel means a channel with a bandwidth that starts from zero.
• For example, we can have a dedicated medium with a bandwidth constituting only one channel.

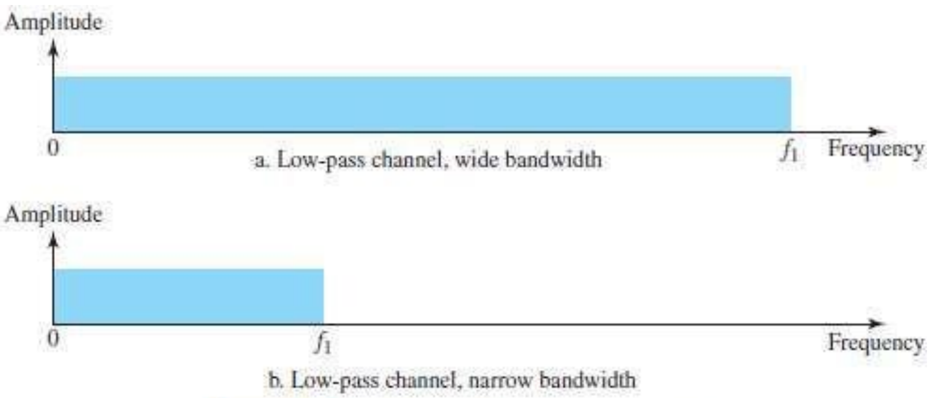

Figure 3.20 *Bandwidths of two low-pass channels*

• Two cases of a baseband communication:
Case 1: Low-pass channel with a wide bandwidth (Figure 3.20a)
Case 2: Low-pass channel with a limited bandwidth (Figure 3.20b)

-**Broadband Transmission (Using Modulation)**

• Broadband transmission or modulation means changing the digital signal to an analog signal for transmission.
• Modulation allows us to use a bandpass channel (Figure 3.24).
• Bandpass channel means a channel with a bandwidth that does not start from zero.
• This type of channel is more available than a low-pass channel.

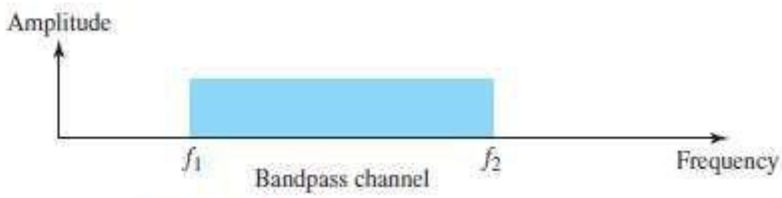

Figure 3.24 *Bandwidth of a bandpass channel*

• If the available channel is a bandpass channel,
We cannot send the digital signal directly to the channel;

We need to convert the digital signal to an analog signal before transmission (Figure 3.25).

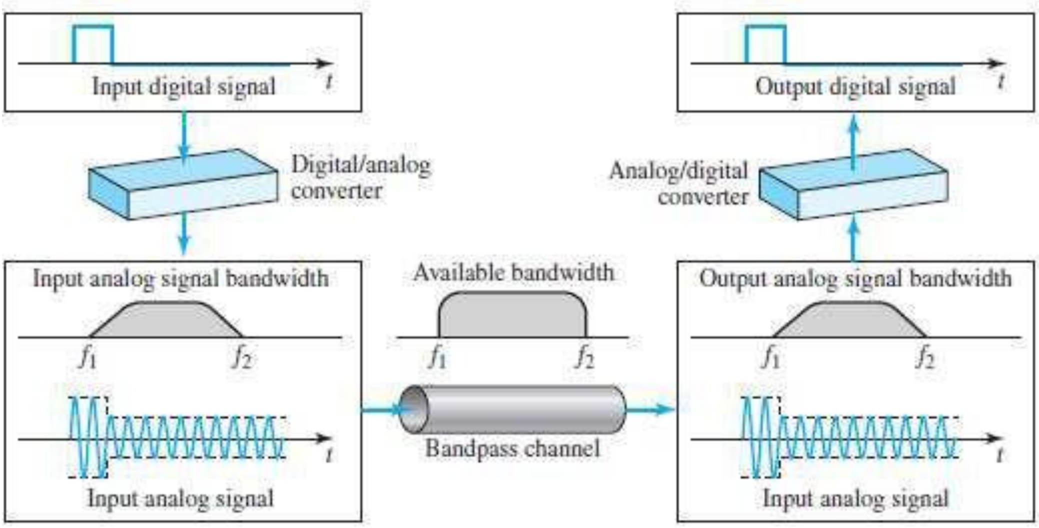

Figure 3.25 *Modulation of a digital signal for transmission on a bandpass channel*

TRANSMISSION IMPAIRMENT

- Signals travel through transmission media, which are not perfect.
- The imperfection causes signal-impairment.
- This means that signal at beginning of the medium is not the same as the signal at end of medium.
- What is sent is not what is received.
- Three causes of impairment are (Figure 3.26):
  1) Attenuation
  2) Distortion &
  3) Noise.

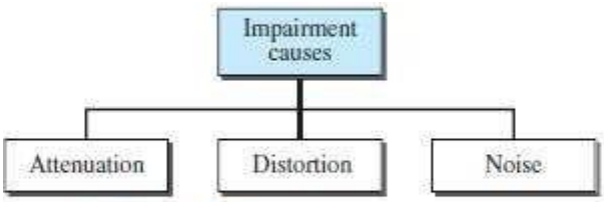

Figure 3.26 *Causes of impairment*

Attenuation

- As signal travels through the medium, its strength decreases as distance increases. This is called attenuation (Figure 3.27).
- As the distance increases, attenuation also increases.
- For example:

  Voice-data becomes weak over the distance & loses its contents beyond a certain distance.
- To compensate for this loss, amplifiers are used to amplify the signal.

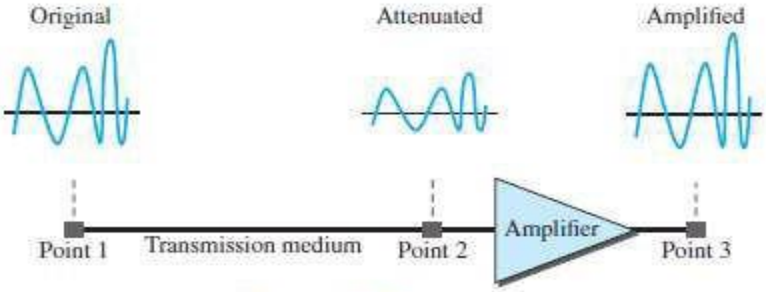

Figure 3.27 *Attenuation*

Distortion

- Distortion means that the signal changes its form or shape (Figure 3.29).
- Distortion can occur in a composite signal made of different frequencies.
- Different signal-components
  → have different propagation speed through a medium.
  → have different delays in arriving at the final destination.
- Differences in delay create a difference in phase if delay is not same as the period-duration.
- Signal-components at the receiver have phases different from what they had at the sender.
- The shape of the composite signal is therefore not the same.

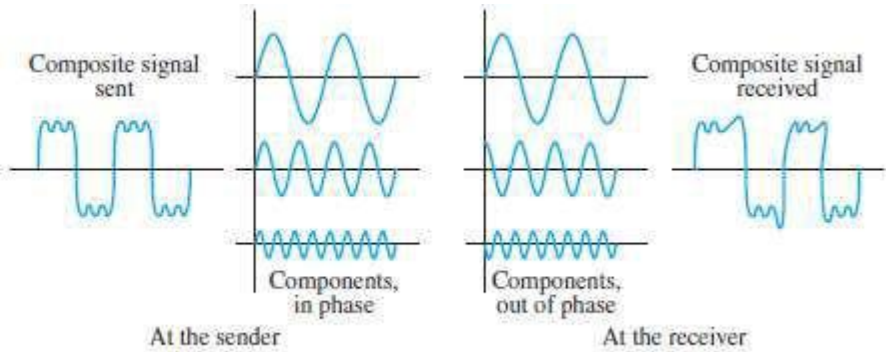

Figure 3.29 *Distortion*

Noise

- Noise is defined as an unwanted data (Figure 3.30).
- In other words, noise is the external energy that corrupts a signal.
- Due to noise, it is difficult to retrieve the original data/information.
- Four types of noise:

i) Thermal Noise

➢ It is random motion of electrons in wire which creates extra signal not originally sent by transmitter.

ii) Induced Noise

➢ Induced noise comes from sources such as motors & appliances.

➢ These devices act as a sending-antenna.
The transmission-medium acts as the receiving-antenna.

iii) Crosstalk

➢ Crosstalk is the effect of one wire on the other.

➢ One wire acts as a sending-antenna and the other as the receiving-antenna.

iv) Impulse Noise

➢ Impulse Noise is a spike that comes from power-lines, lightning, and so on. (spike → a signal with high energy in a very short time)

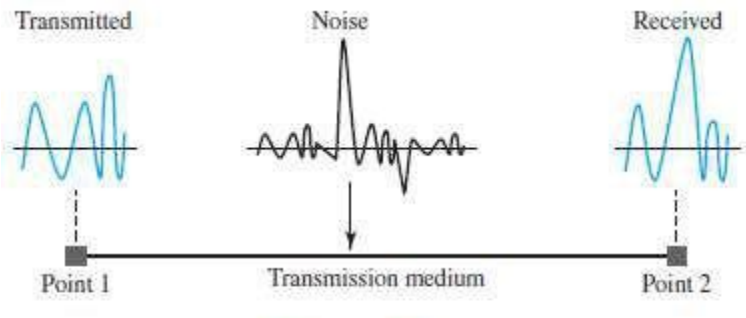

Figure 3.30 *Noise*

DATA RATE LIMITS

- Data-rate depends on 3 factors:
  1) Bandwidth available
  2) Level of the signals
  3) Quality of channel (the level of noise)
- Two theoretical formulas can be used to calculate the data-rate:
  1) Nyquist for a noiseless channel and
  2) Shannon for a noisy channel.

Noiseless Channel: Nyquist Bit Rate

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

$$\text{Bitrate} = 2 \times \text{Bandwidth} \times \log_2 L$$

maximum bit-rate

where bandwidth = bandwidth of the channel
L = number of signal-levels used
to represent data BitRate =
bitrate of channel in bps

➢ According to the formula,
¤ By increasing number of signal-levels, we can increase the bit-rate.
¤ Although the idea is theoretically correct, practically there is a limit.
¤ When we increase the number of signal-levels, we impose a burden on the receiver.
¤ If no. of levels in a signal is 2, the receiver can easily distinguish b/w 0 and 1.
¤ If no. of levels is 64, the receiver must be very sophisticated to distinguish b/w 64 different levels.
¤ In other words, increasing the levels of a signal reduces the reliability of the system.

Noisy Channel: Shannon Capacity

➢ In reality, we cannot have a noiseless channel; the channel is always noisy.
➢ For a noisy channel, the Shannon capacity formula defines the theoretical

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

maximum bit-rate.

where bandwidth = bandwidth of channel in bps.
SNR = signal-to-noise ratio and Capacity =
capacity of channel in bps.

➢ This formula does not consider the no. of levels of signals being transmitted (as done in the Nyquist bit rate).
This means that no matter how many levels we have, we cannot achieve a data-rate higher than the capacity of the channel.
➢ In other words, the formula defines a characteristic of the channel, not the method of transmission.

Study the problems from class Notes

PERFORMANCE

Bandwidth

• One characteristic that measures network-performance is bandwidth.

• Bandwidth of analog and digital signals is calculated in separate ways:

(1) Bandwidth of an Analog Signal (in hz)

➢ Bandwidth of an analog signal is expressed in terms of its frequencies.

➢ Bandwidth is defined as the range of frequencies that the channel can carry.

➢ It is calculated by the difference b/w the maximum frequency and the minimum frequency.

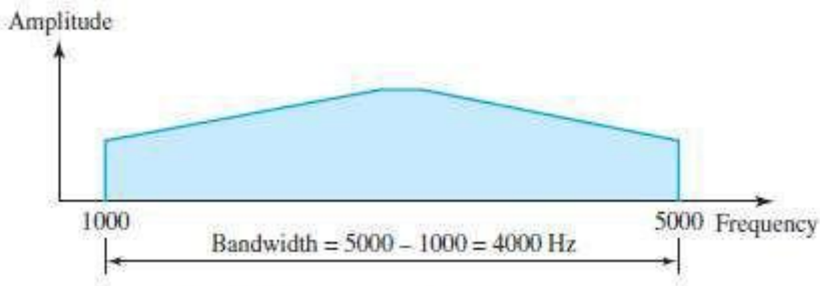

Figure 3.13 *The bandwidth of signals*

In figure 3.13, the signal has a minimum frequency of F1 = 1000Hz and maximum frequency of F2 = 5000Hz.

Hence, the bandwidth is given by F2 – F1= 5000 - 1000 = 4000 Hz

(2) Bandwidth of a Digital Signal (in bps)

➢ Bandwidth refers to the number of bits transmitted in one second in a channel (or link).

➢ For example:

The bandwidth of a Fast Ethernet is a maximum of 100 Mbps. (This means that this network can send 100 Mbps).

Relationship between (1) and (2)

• There is an explicit relationship between the bandwidth in hertz and bandwidth in bits per seconds.

• Basically, an increase in bandwidth in hertz means an increase in bandwidth in bits per second.

• The relationship depends on

→ baseband transmission or

→ transmission with modulation.

Throughput

• The throughput is a measure of how fast we can actually send data through a network.

• Although, bandwidth in bits per second and throughput seem the same, they are actually 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.

• In other words,

1) The bandwidth is a potential measurement of a link.

2) The throughput is an actual measurement of how fast we can send data. For example:

¤ We may have a link with a bandwidth of 1 Mbps, but the devices connected to the end of the link may handle only 200 kbps.

¤ This means that we cannot send more than 200 kbps through this link.

Latency (Delay)

- The latency 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.

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

1) Propagation Time

➢ Propagation time is defined as the time required for a bit to travel from source to destination.

➢ Propagation time is given by

Propagation time = Distance / (Propagation Speed)

➢ Propagation speed of electromagnetic signals depends on

→ medium and

→ frequency of the signal.

2) Transmission Time

➢ The time required for transmission of a message depends on

→ size of the message and

→ bandwidth of the channel.

➢ The transmission time is given by

Transmission time = (Message size) / Bandwidth

3) Queuing Time

➢ Queuing-time is the time needed for each intermediate-device to hold the message before it can be processed.

(Intermediate device may be a router or a switch)

➢ The queuing-time is not a fixed factor. This is because

i) Queuing-time changes with the load imposed on the network.

ii) When there is heavy traffic on the network, the queuing-time increases.

➢ An intermediate-device

→ queues the arrived messages and

→ processes the messages one by one.

➢ If there are many messages, each message will have to wait.

4) Processing Delay

➢ Processing delay is the time taken by the routers to process the packet header.

Bandwidth Delay Product

- Two performance-metrics of a link are 1) Bandwidth and 2) Delay
- The bandwidth-delay product is very important in data-communications.
- Let us elaborate on this issue, using 2 hypothetical cases as examples.

Case 1: The following figure shows case 1 (Figure 3.32).

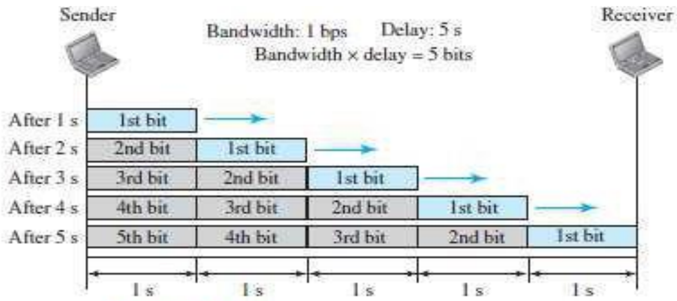

Figure 3.32 *Filling the link with bits for case 1*

➢ Let us assume,

Bandwidth of the link = 1 bps   Delay of the link = 5s.

➢ From the figure 3.32, bandwidth-delay product is 1 x 5 = 5. Thus, there can be maximum 5 bits on the line.

➢ There can be no more than 5 bits at any time on the link.

Case 2: The following figure shows case 2 (Figure 3.33).

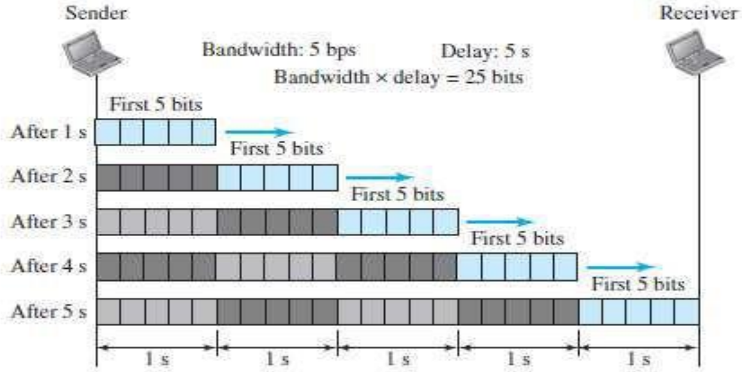

Figure 3.33 *Filling the link with bits in case 2*

- ➢ Let us assume,
  Bandwidth of the link = 5 bps Delay of the link = 5s.
- ➢ From the figure 3.33, bandwidth-delay product is 5 x 5 = 25. Thus, there can be maximum 25 bits on the line.
- ➢ At each second, there are 5 bits on the line, thus the duration of each bit is 0.20s.

- The above 2 cases show that the (bandwidth X delay) is the number of bits that can fill the link.
- This measurement is important if we need to
  → send data in bursts and
  → wait for the acknowledgment of each burst.
- To use the maximum capability of the link
  → We need to make the burst-size as (2 x bandwidth x delay).
  → We need to fill up the full-duplex channel (two directions).
- Amount (2x bandwidth x delay) is the number of bits that can be in transition at any time (Fig 3.34).

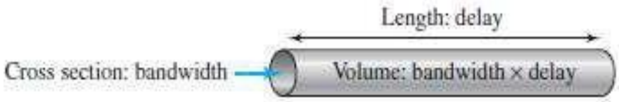

Figure 3.34 *Concept of bandwidth-delay product*

Jitter

- Another performance issue that is related to delay is jitter.
- We can say that jitter is a problem
  → if different packets of data encounter different delays and
  → if the application using the data at the receiver site is time-sensitive (for ex: audio/video).