# Chapter 1

# Introduction

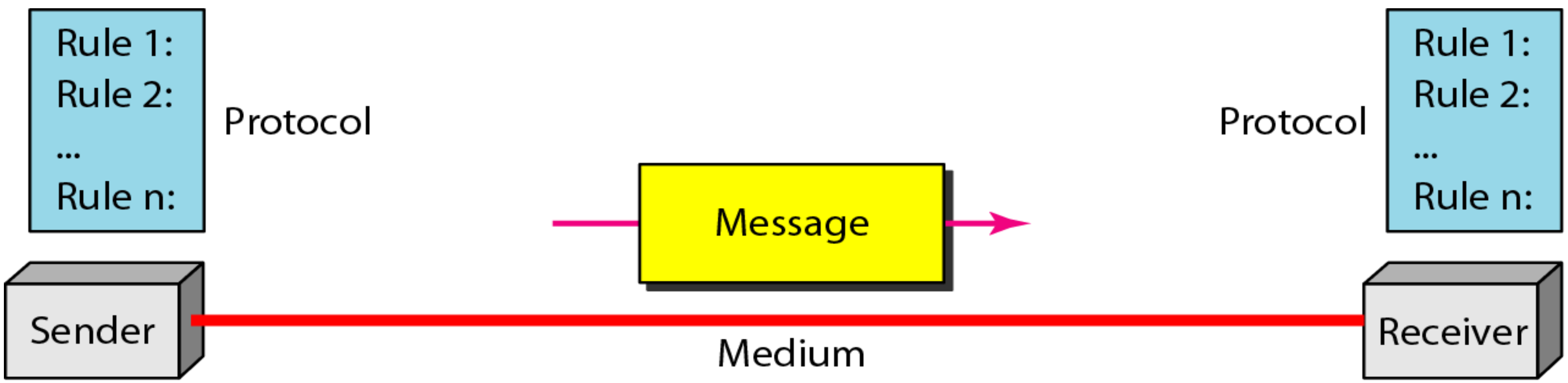
# 1-1 DATA COMMUNICATIONS

***The term telecommunication means communication at a distance. The word data refers to information presented in whatever form is agreed upon by the parties creating and using the data. Data communications are the exchange of data between two devices via some form of transmission medium such as a wire cable.***

***Topics discussed in this section:***

**Components**
**Data Representation**
**Data Flow**

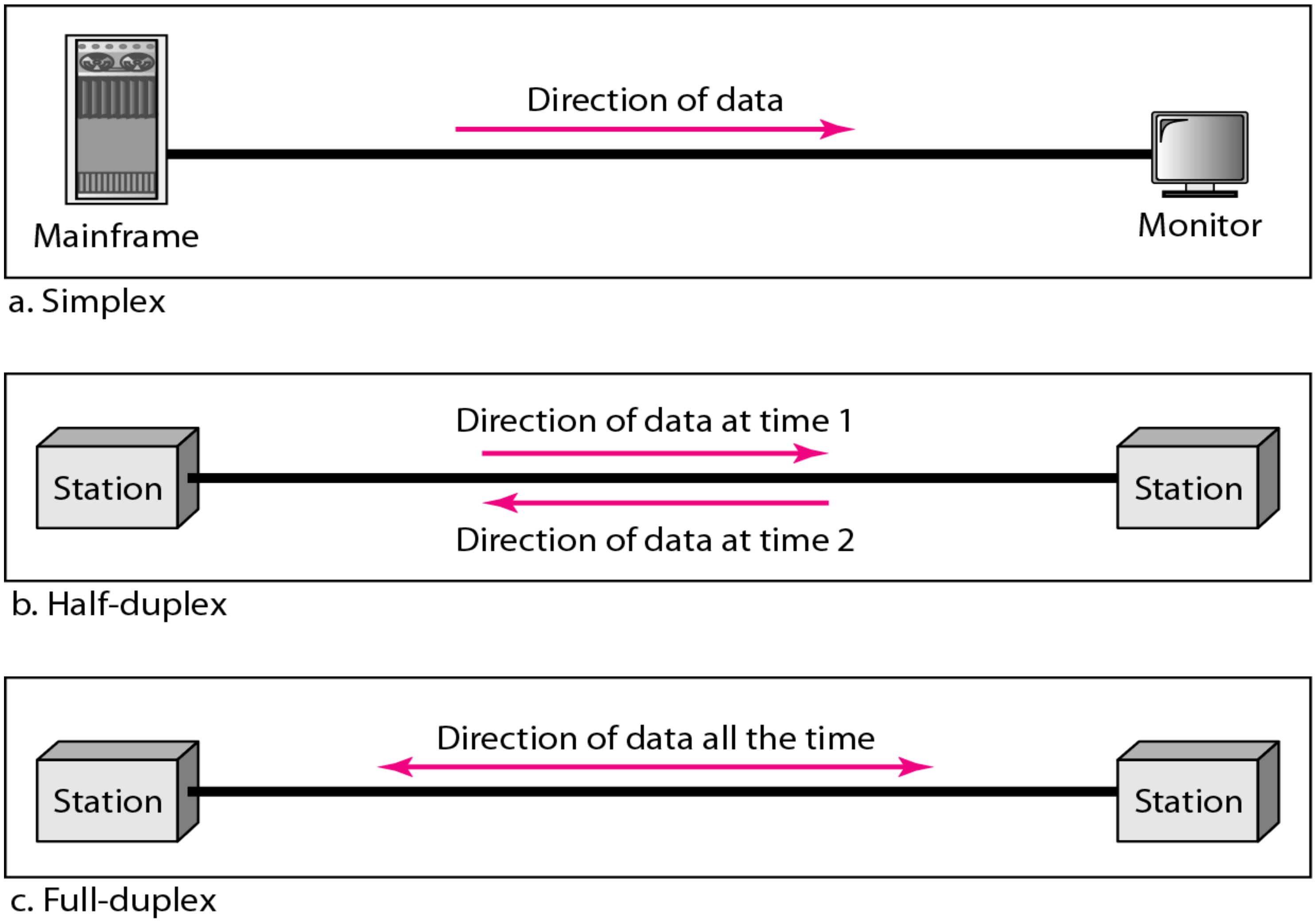
## Figure 1.1 *Five components of data communication*



# Data Representation

- TEXT – unicode (32 bits to represent character)- ASCII
- NUMBERS
- IMAGES-composed of a matrix of pixel
- AUDIO- recording or broadcasting of sound or music.
- VIDEO- recording or broadcasting of a picture or movie

## Figure 1.2 *Data flow (simplex, half-duplex, and full-duplex)*



# 1-2 NETWORKS

*A **network** is a set of devices (often referred to as **nodes**) connected by communication **links**. A node can be a computer, printer, or any other device capable of sending and/or receiving data generated by other nodes on the network.*

***Topics discussed in this section:***

**Distributed Processing**
**Network Criteria**
**Physical Structures**
**Network Models**
**Categories of Networks**
**Interconnection of Networks: Internetwork**

# NETWORKS

Set of nodes connected via physical links

- 1) Distributing Processing
- 2) Sharing Data and centralization
- 3) Security and robustness

# Network Criteria

- 1) Performance : Transmission and response times - throughput and delay.

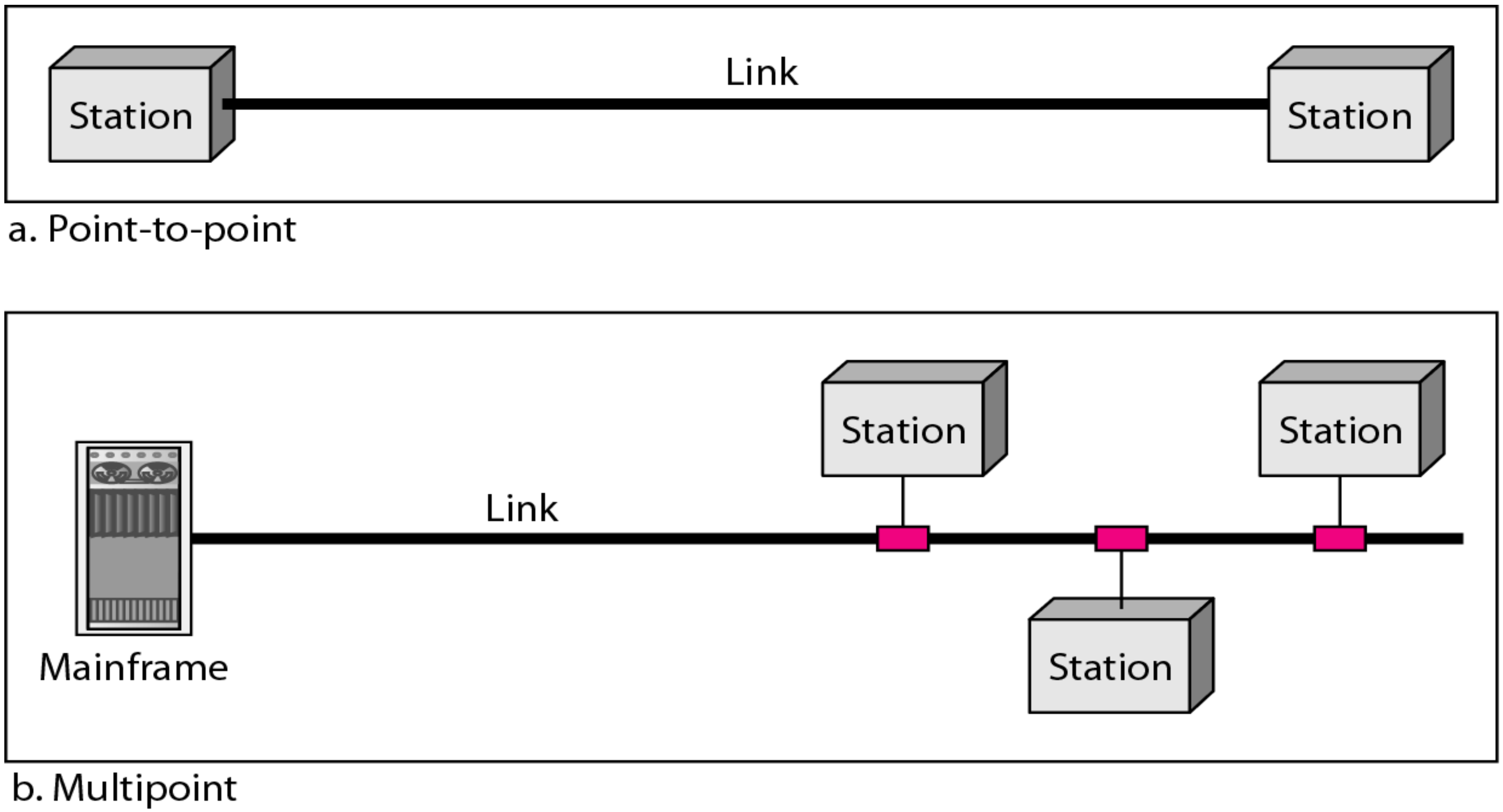
  2) Reliability: How often the networks fail

  3) Security: Privacy and integrity of communication Data; recovery from breaches and data loss.

# Physical Structures:

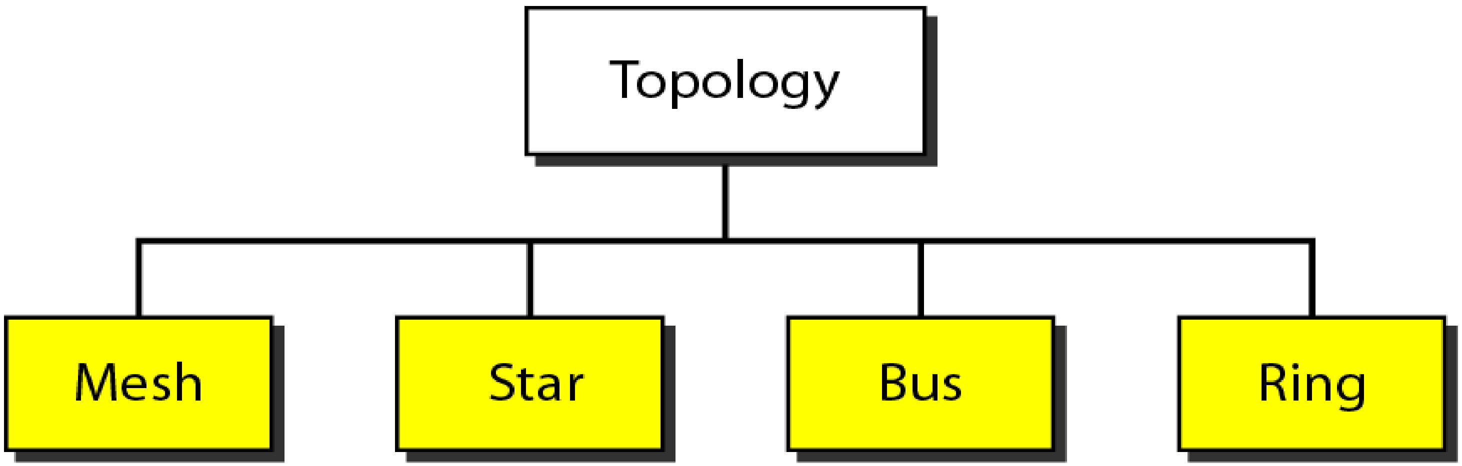
- Types of connections:
- 1) Point to Point: (P to P) Dedicated link to be utilized only by end devices.
- 2) Multipoint (Multidrop): Many end devices share the link capacity.

## Figure 1.3 *Types of connections: point-to-point and multipoint*



# Physical Topology

## **Figure 1.4** *Categories of topology*

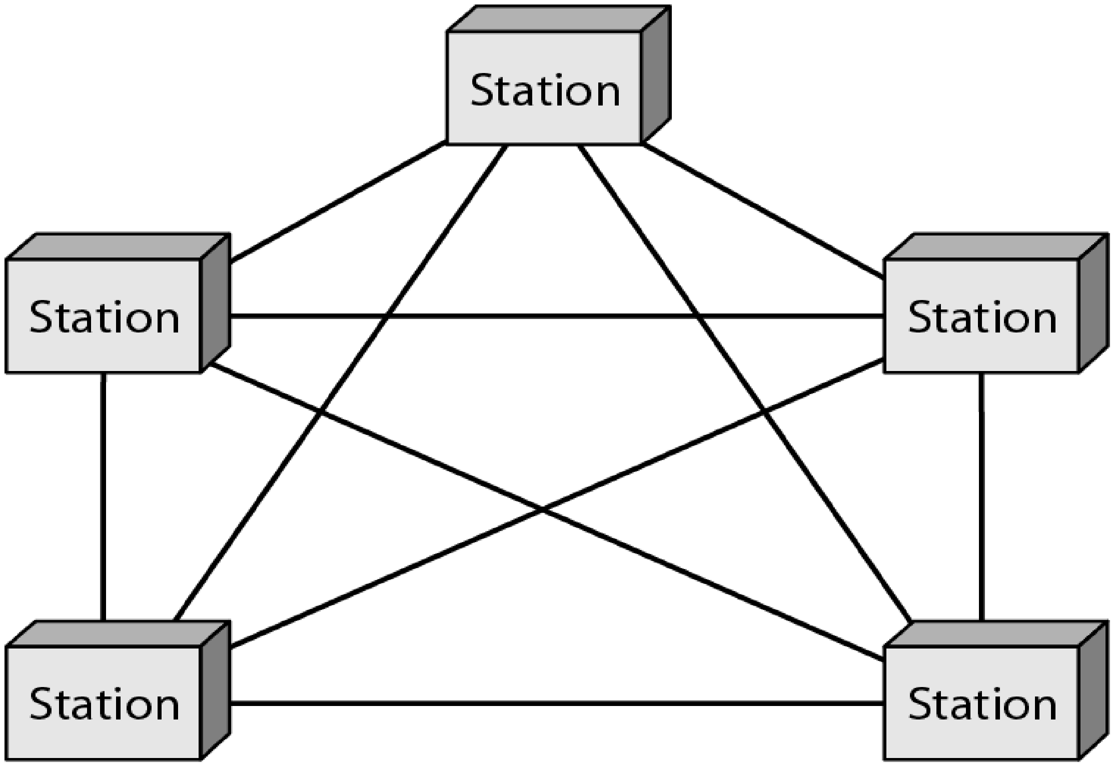


# Physical Topology

- A) Mesh:

- Each device has dedicated point-to-point link to other devices. Fully connected mesh will have n( n-1)/ 2  F.D. links
  - Where n = number of nodes
- Advantages: Fast communication, Robust and Privacy (Security)
- Disadvantages: Cabling Space and cost

## Figure 1.5 *A fully connected mesh topology (five devices)*

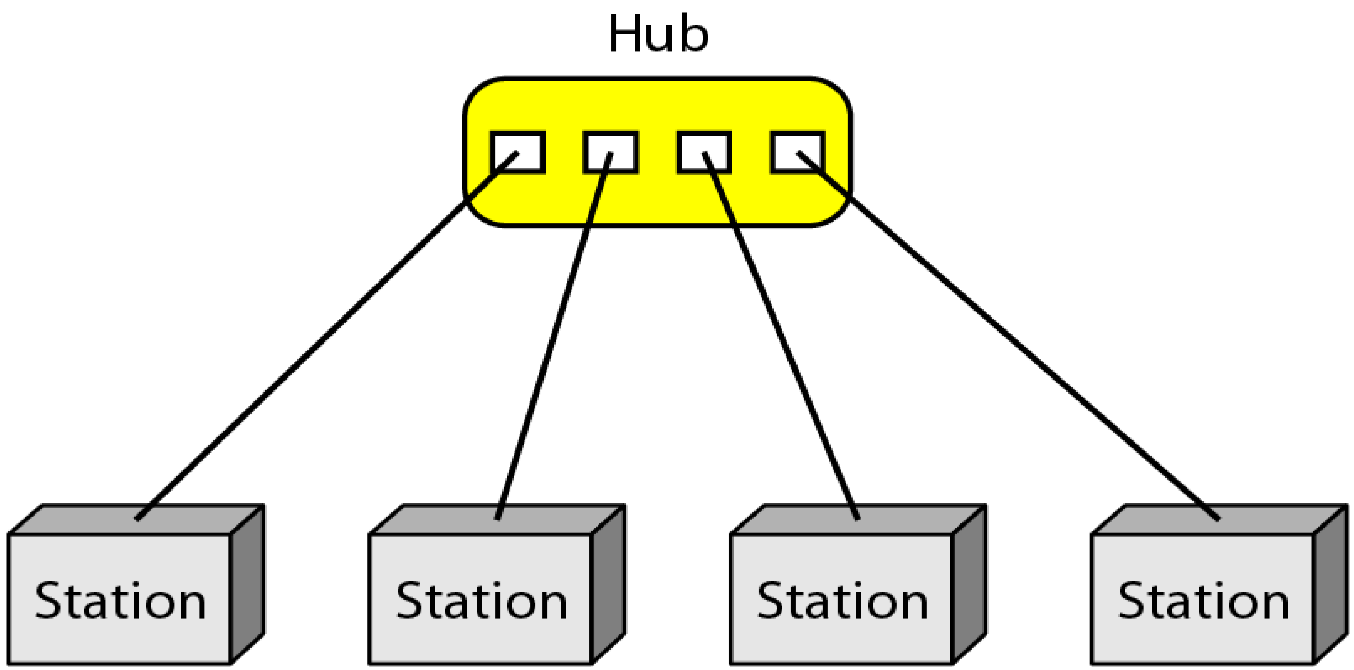


# Physical Topology (cont..)

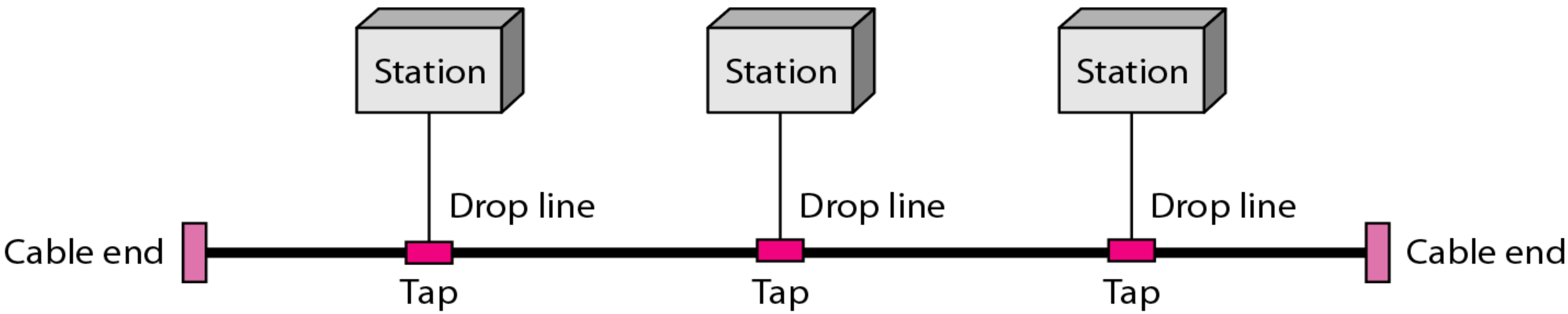
- B) Star:

- Devices are connected Point to Point to a central “Hub” (Controller Exchanger)
- Advantages: Less cabling and H/W ports, two hops only.
- Disadvantage: Not robust

## Figure 1.6 *A star topology connecting four stations*



## **Figure 1.7** *A bus topology connecting three stations*



– C) Bus:

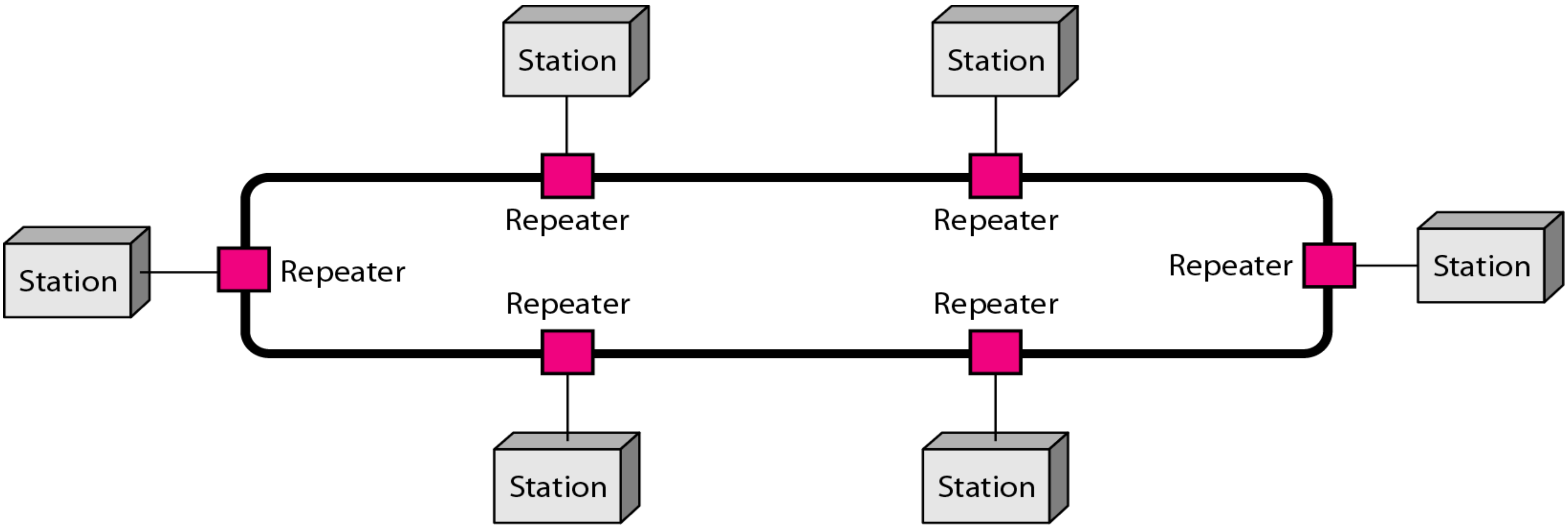
- Multipoint link as “backbone” for a network where devices have drop line to tap into the bus

Advantage: Less Cabling

- Disadvantages: Topology dependent, limit number of nodes on the bus due to signal

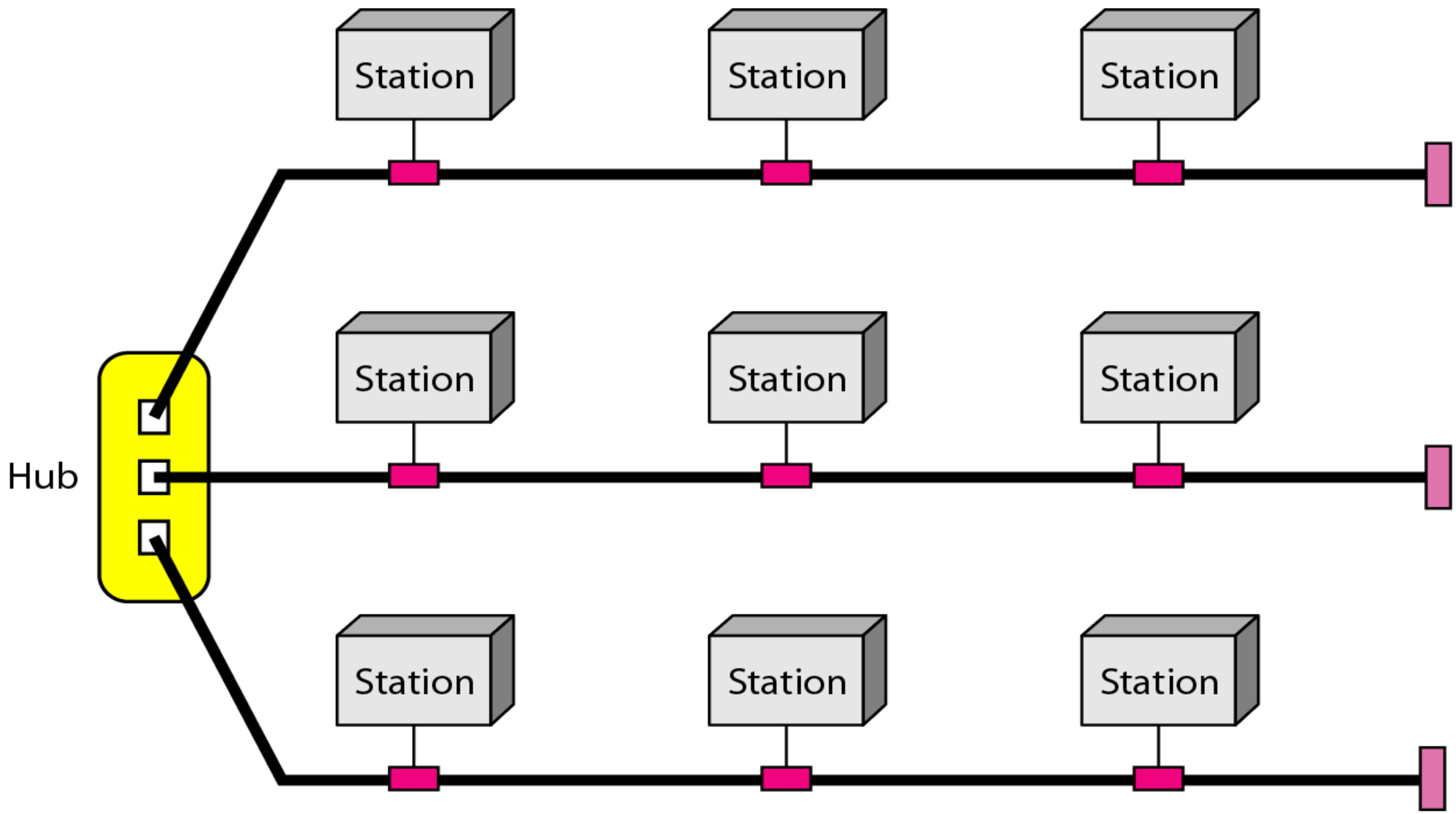
  power loss with distance, not so robust

## Figure 1.8 *A ring topology connecting six stations*



- C) Ring: Each device connects Point to Point with only two other devices in a left and right neighbors arrangement via a repeater.
- Advantages : easy installation, better fault isolation and robustness.
- Disadvantages: N/2 hops communication

## Figure 1.9 *A hybrid topology: a star backbone with three bus networks*

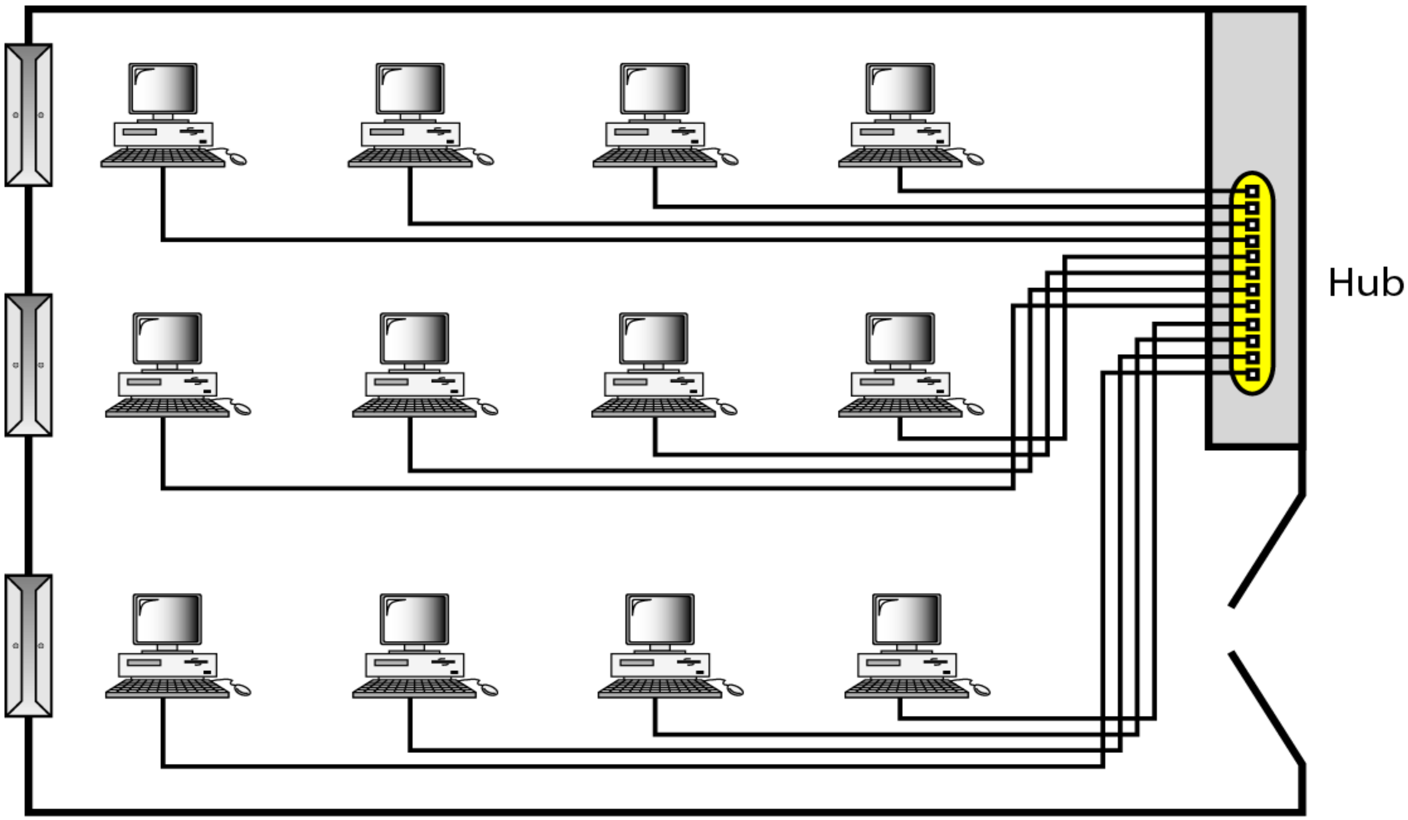


- D) Hybrid: • Pizza “star” inside a “ ring”
- Pros: Better robustness, still low cost, Delay is 1 hop (until the star is not with a ring cut, max 2. • Star of busses

# Categories of Networks:

- Local Area Networks (LAN): Few Kilometers Connects devices (PCs, printers, servers.) within the same room, building, company, and campus.
- Topologies most used are bus, ring and star.

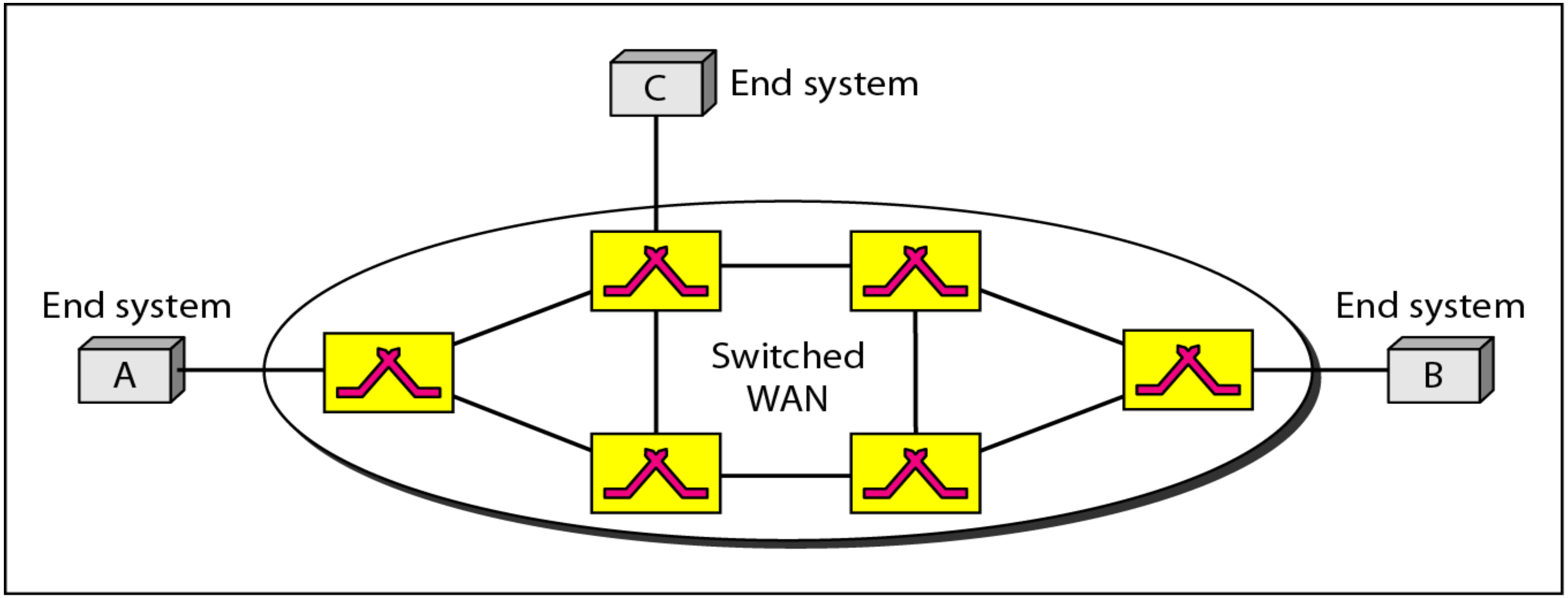
## Figure 1.10 *An isolated LAN connecting 12 computers to a hub in a closet*



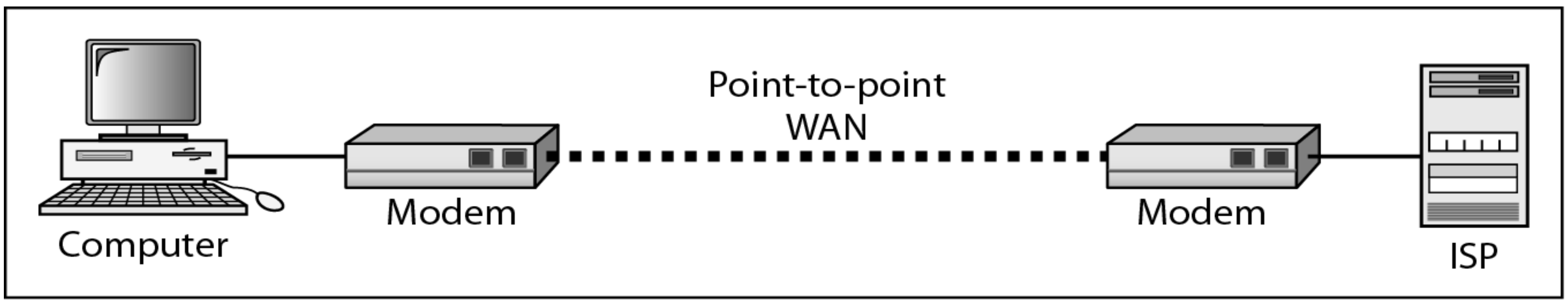
# Categories of Networks(cont..)

- Wide Area Networks (WAN):
- span a large geographical area about 100’s – 1000’s of Km
- 1) Switched: End users connected via a cloud of switches (subnet).
- 2) Point-to Point: Line leased from telephone company/ TV connecting users to the ISP for Internet access.

## Figure 1.11 *WANs: a switched WAN and a point-to-point WAN*

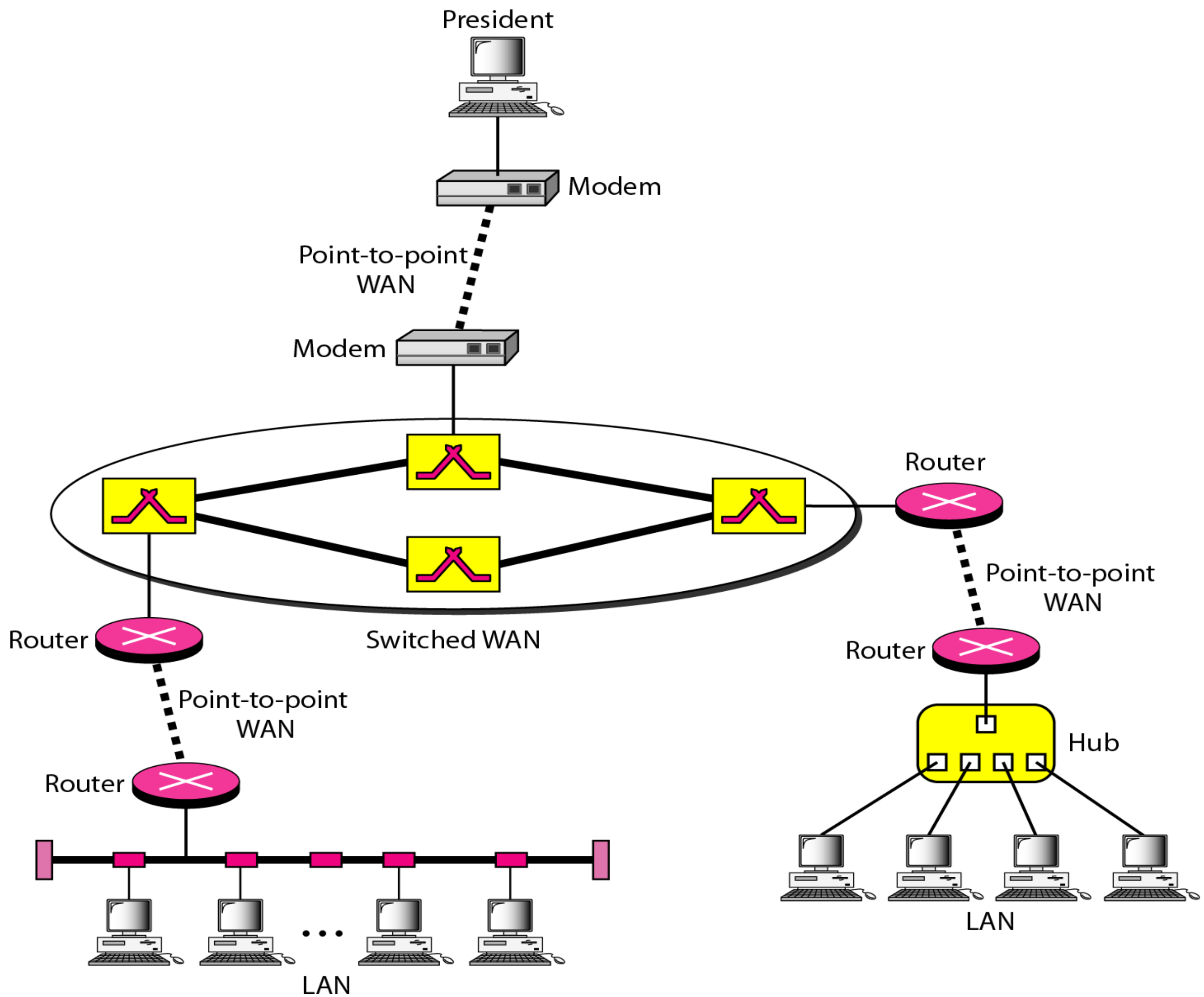



a. Switched WAN




b. Point-to-point WAN

## Figure 1.12 *A heterogeneous network made of four WANs and two LANs*



# Categories of Networks(cont..)

- Metropolitan Area Networks:
- MAN town/city
- High-speed backbone linking multiple LAN's, DSL, TV cables.

# 1-3 THE INTERNET

***The Internet has revolutionized many aspects of our daily lives. It has affected the way we do business as well as the way we spend our leisure time. The Internet is a communication system that has brought a wealth of information to our fingertips and organized it for our use.***

***Topics discussed in this section:***

**A Brief History**

**The Internet Today (ISPs)**

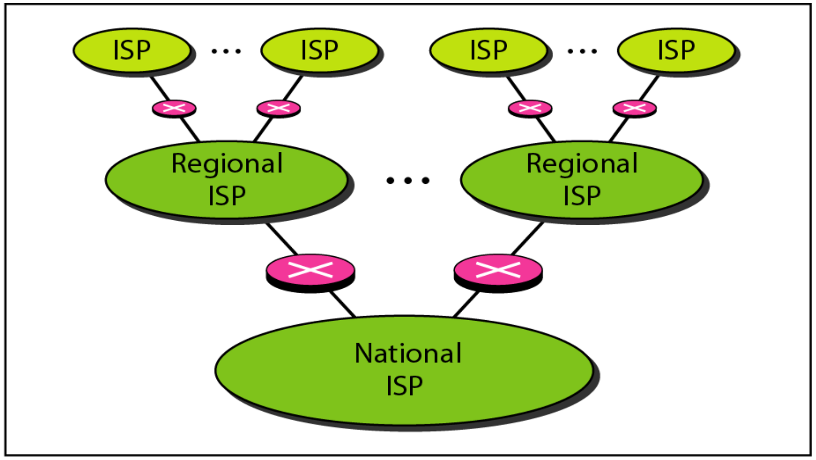
# The Internet

- Internet evolved from ARPANET
  - first operational packet network
  - applied to tactical radio & satellite nets also
  - had a need for interoperability
  - lead to standardized TCP/IP protocols

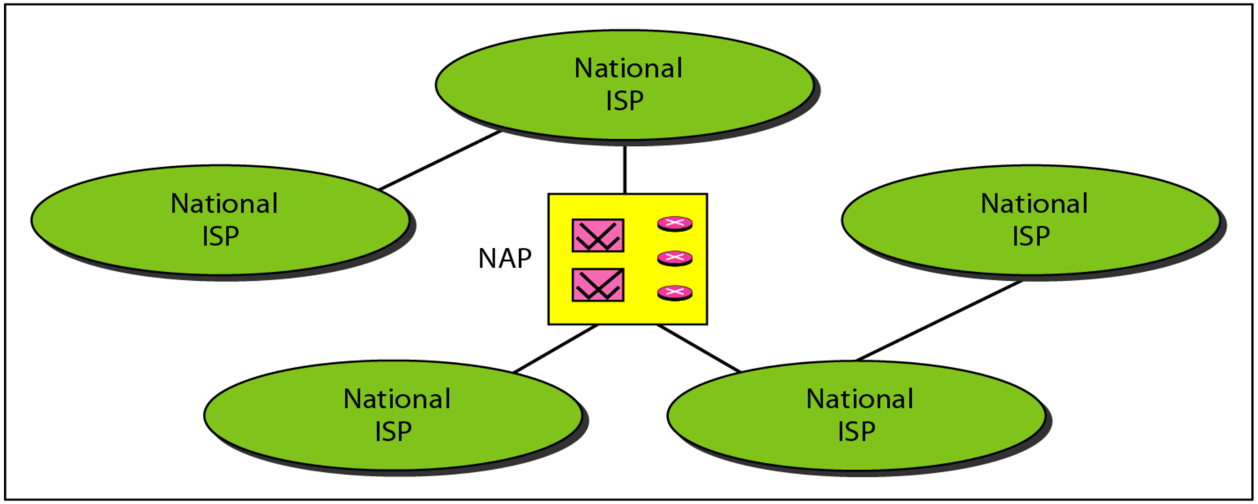
# The Internet:

- Huge number of interconnected Networks (100000’s) private organized, e.g.’ government, schools, research facilities, in many countries
- Collection of LAN’S, MAN’S and WAN’s.
  - The internet protocol stack is the TCP/IP
  - End users use the internet via Internet Service providers (ISPs) which are of the following hierarchies:

# Figure 1.13 *Hierarchical organization of the Internet*

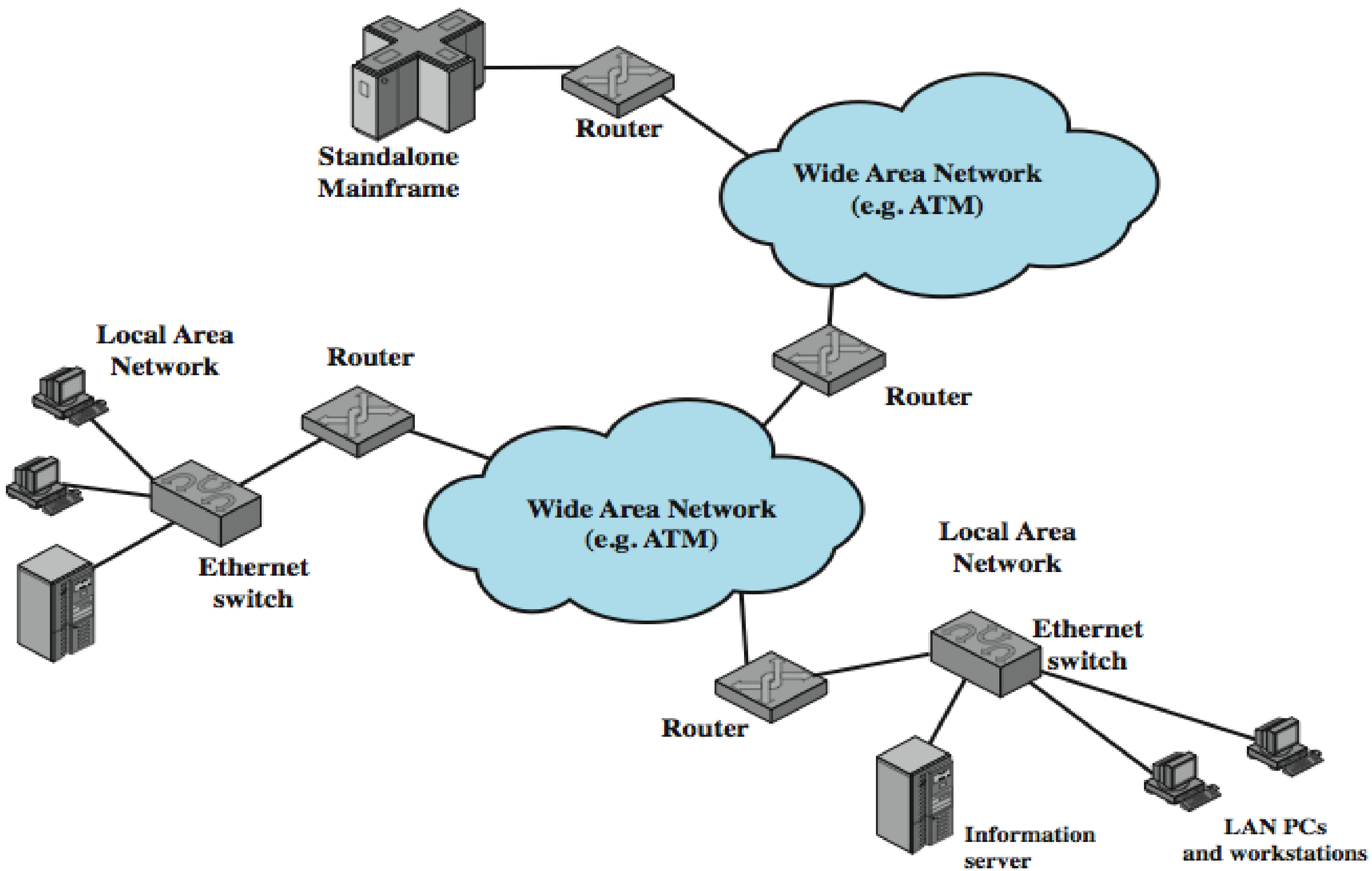



a. Structure of a national ISP

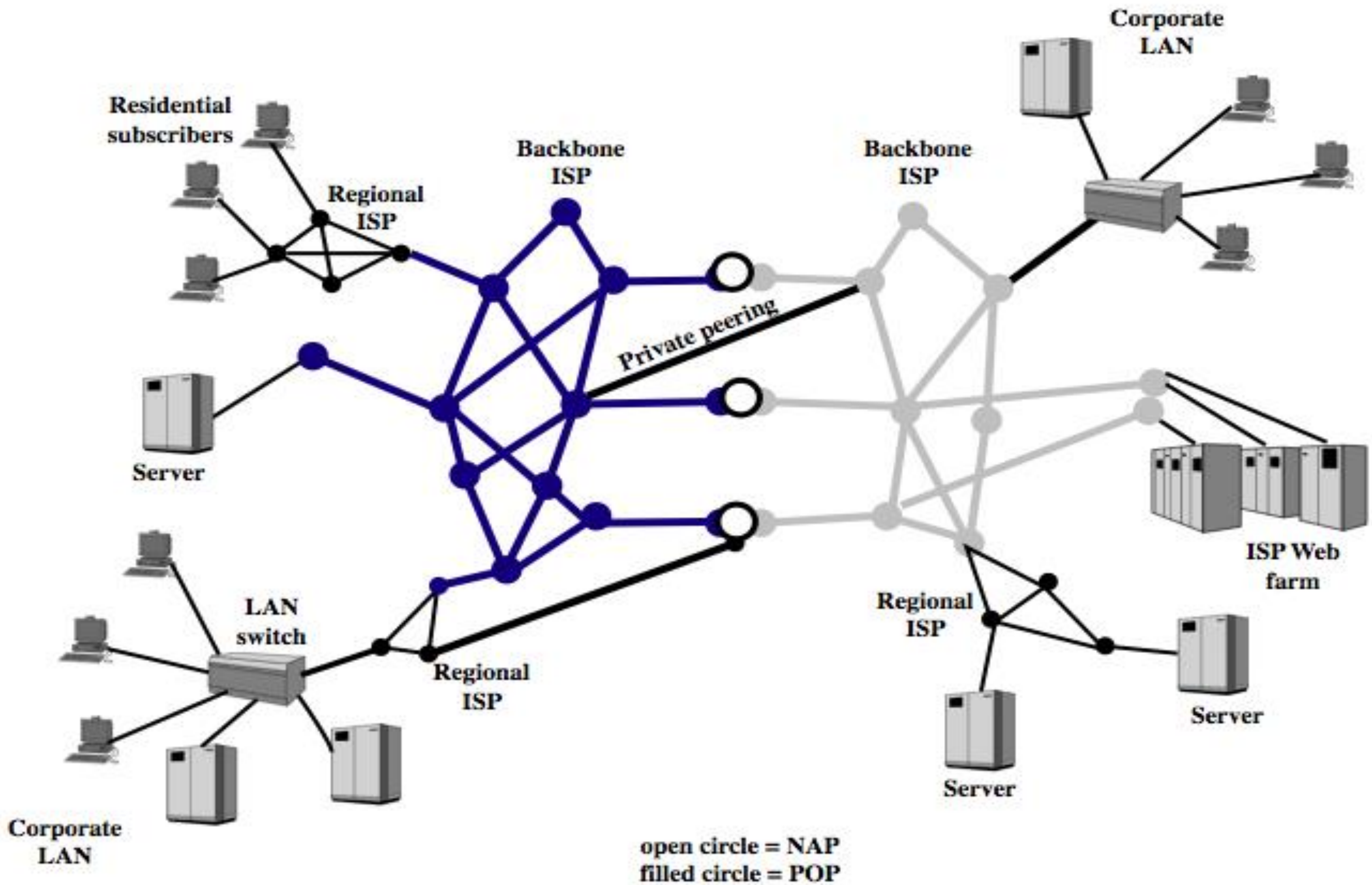



b. Interconnection of national ISPs

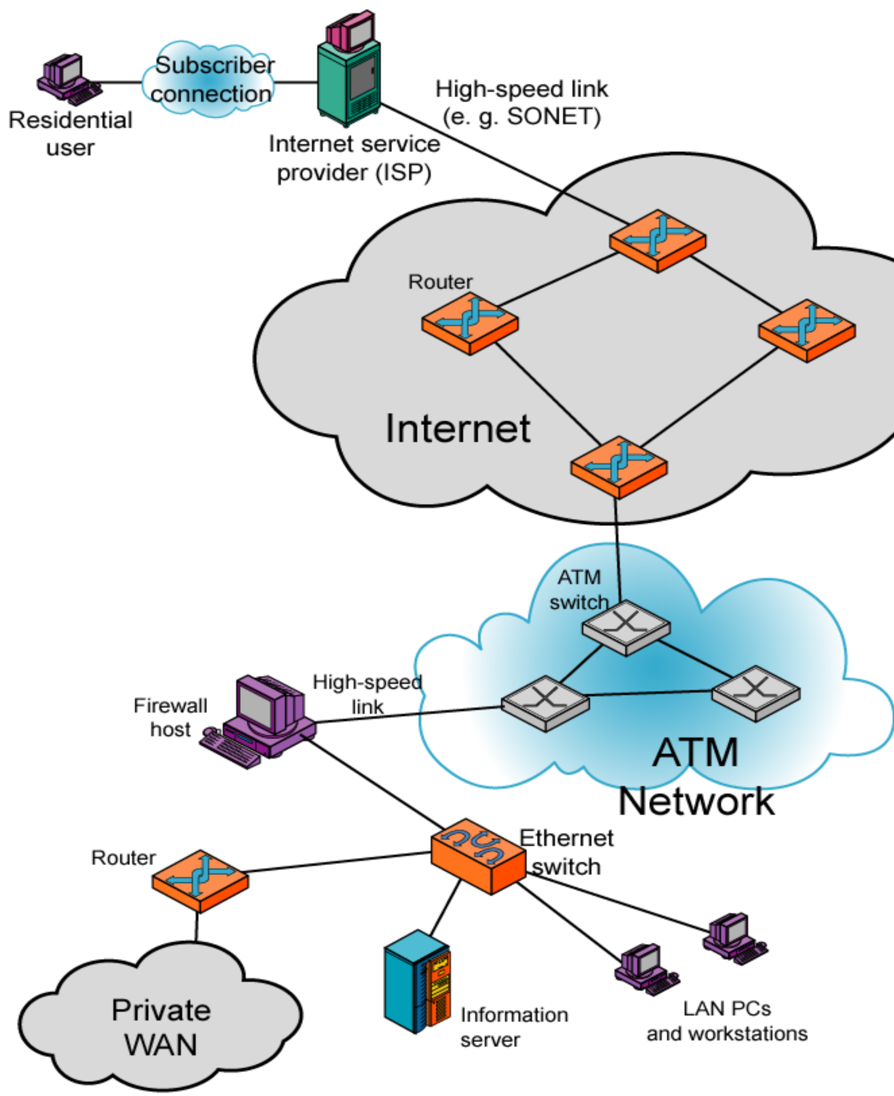
# Internet Elements



# Internet Architecture



# Example Configuration



# 1-4 PROTOCOLS AND STANDARDS

***In this section, we define two widely used terms: protocols and standards. First, we define protocol, which is synonymous with rule. Then we discuss standards, which are agreed-upon rules.***

***Topics discussed in this section:***

**Protocols**
**Standards**
**Standards Organizations**
**Internet Standards**

# What is a protocol?

- Communications between computers requires very specific unambiguous rules
- A protocol is a set of rules that governs how two or more communicating parties are to interact

Examples

- Internet Protocol (IP)
- Transmission Control Protocol (TCP)
- HyperText Transfer Protocol (HTTP)
- Simple Mail Transfer Protocol (SMTP)

- Elements:

  1) Syntax: PDU(Protocol Data Unit) format

  2) Semantics: The meaning of each PDU’s field

  3) Timing: Synchronization of communication when PDU is to be transferred and its data rate.

# What is a standard?

– • A “ standard is set of guidelines” to users and manufactures to ensure interconnectivity.

– 1) “Defacto” not approved but widely used (TCP/IP)

– 2) “Dejure”: approved by recognized body (IEEE 802.X).

# Summary

- introduced data communications needs
- communications model
- defined data communications
- overview of networks
- introduce Internet

- Alternative Switching technologies used include:
  - circuit switching
  - packet switching
  - frame relay
  - Asynchronous Transfer Mode (ATM)

# Circuit Switching

- Uses a dedicated communications path established for duration of conversation
- comprising a sequence of physical links
- with a dedicated logical channel
- eg. telephone network

# Packet Switching

- data sent out of sequence
- small chunks (packets) of data at a time
- packets passed from node to node between source and destination
- used for terminal to computer and computer to computer communications

# Frame Relay

- packet switching systems have large overheads to compensate for errors
- modern systems are more reliable
- errors can be caught in end system
- Frame Relay provides higher speeds
- with most error control overhead removed

# Asynchronous Transfer Mode (ATM)

- evolution of frame relay
- fixed packet (called cell) length
- with little overhead for error control
- anything from 10Mbps to Gbps
- constant data rate using packet switching technique with multiple virtual circuits


# Chapter 2

# Network Models

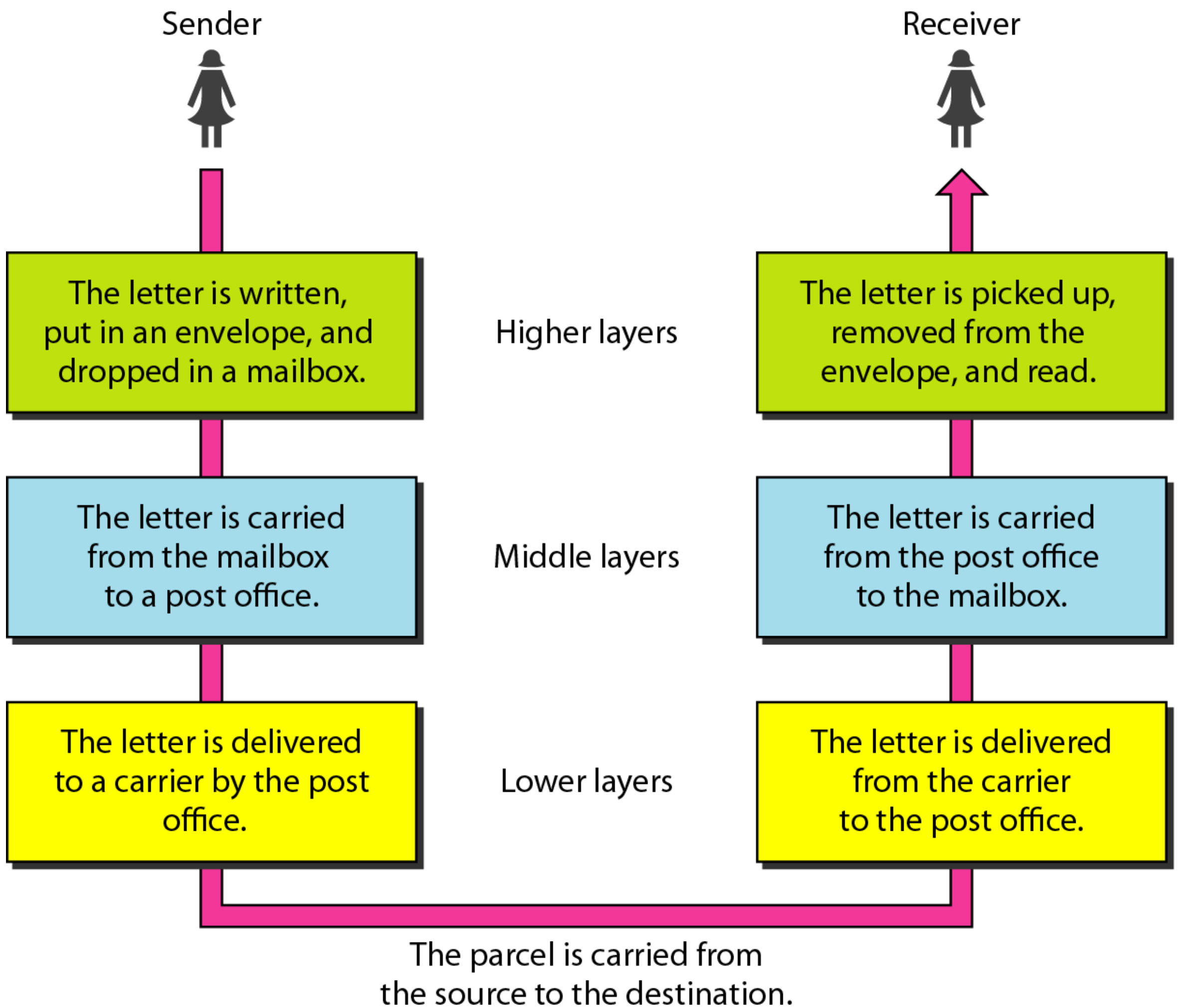
# 2-1 LAYERED TASKS

***We use the concept of layers in our daily life. As an example, let us consider two friends who communicate through postal mail. The process of sending a letter to a friend would be complex if there were no services available from the post office.***

***Topics discussed in this section:***

**Sender, Receiver, and Carrier**
**Hierarchy**

## Figure 2.1 Tasks involved in sending a letter



# 2-2 THE OSI MODEL

***Established in 1947, the International Standards Organization (ISO) is a multinational body dedicated to worldwide agreement on international standards. An ISO standard that covers all aspects of network communications is the Open Systems Interconnection (OSI) model. It was first introduced in the late 1970s.***

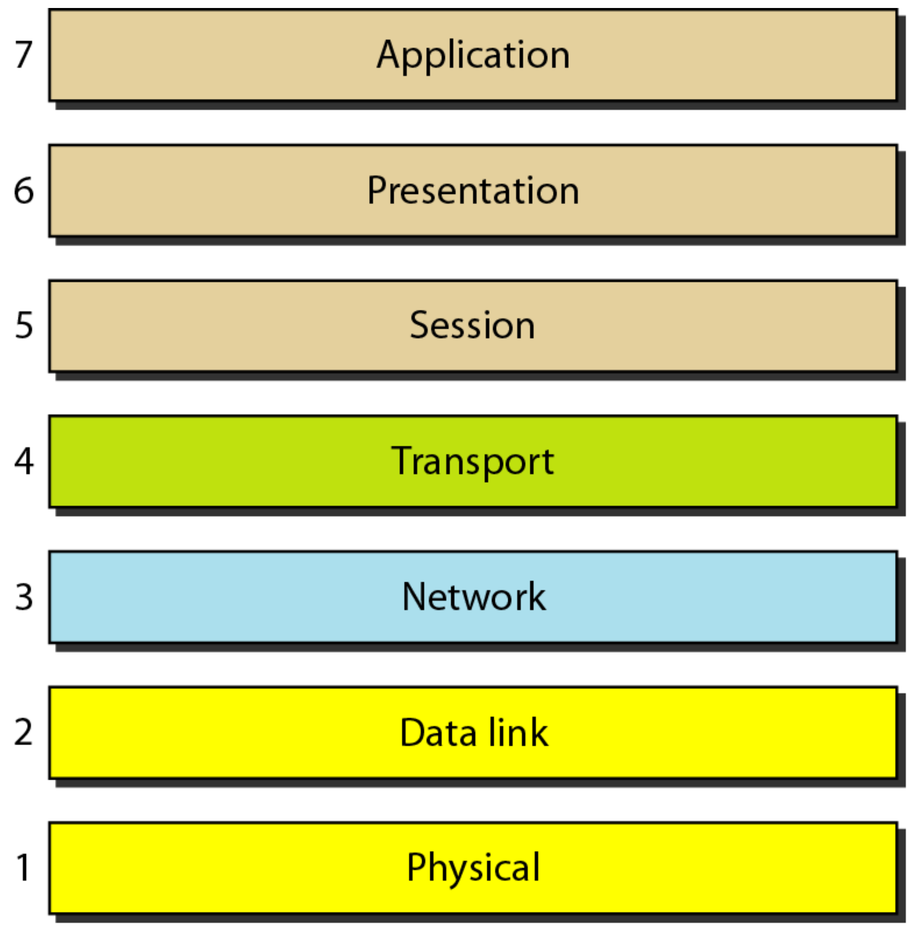
***Topics discussed in this section:***

**Layered Architecture**
**Peer-to-Peer Processes**
**Encapsulation**

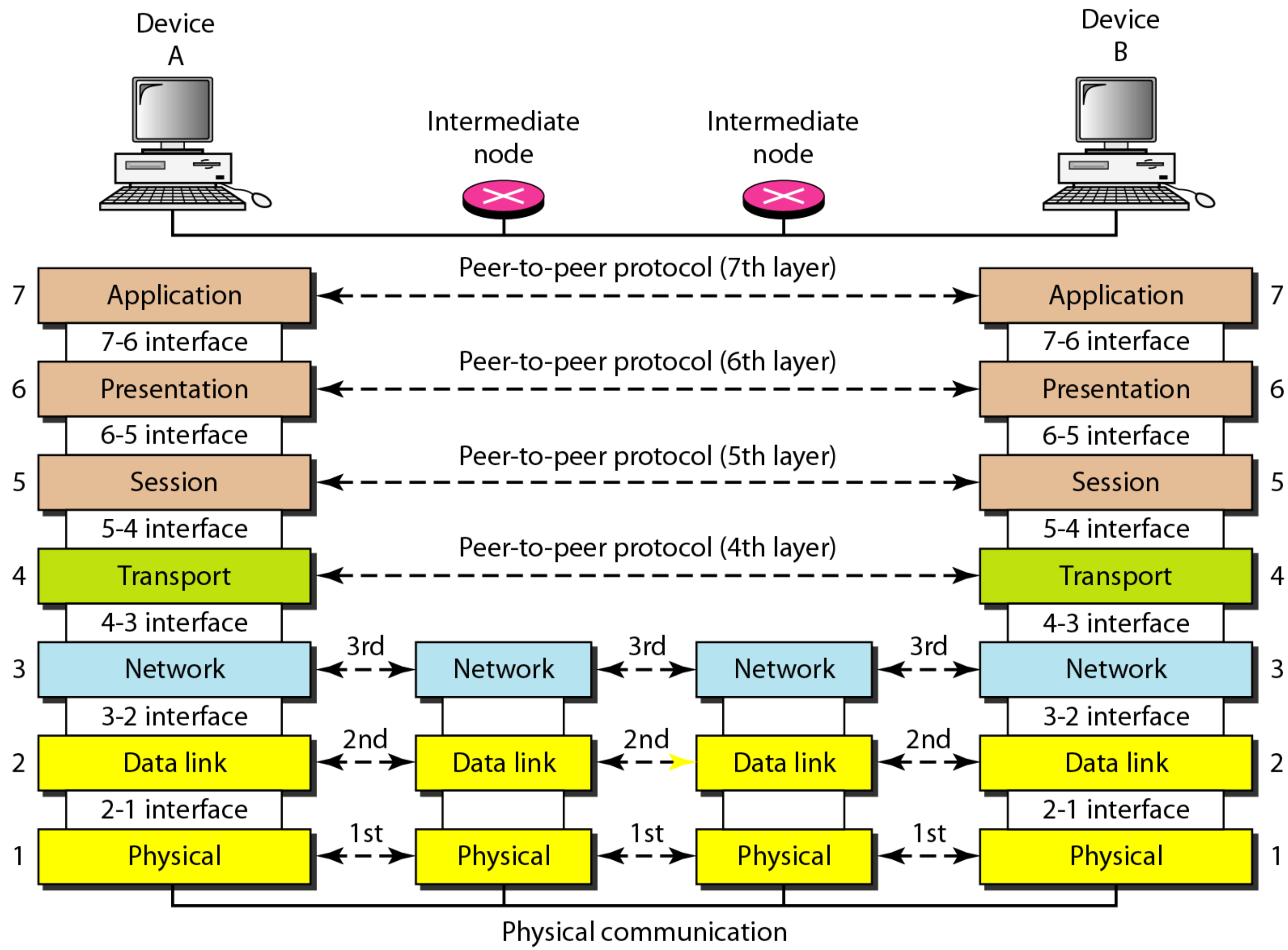
*Note*

**ISO is the organization.**
**OSI is the model.**

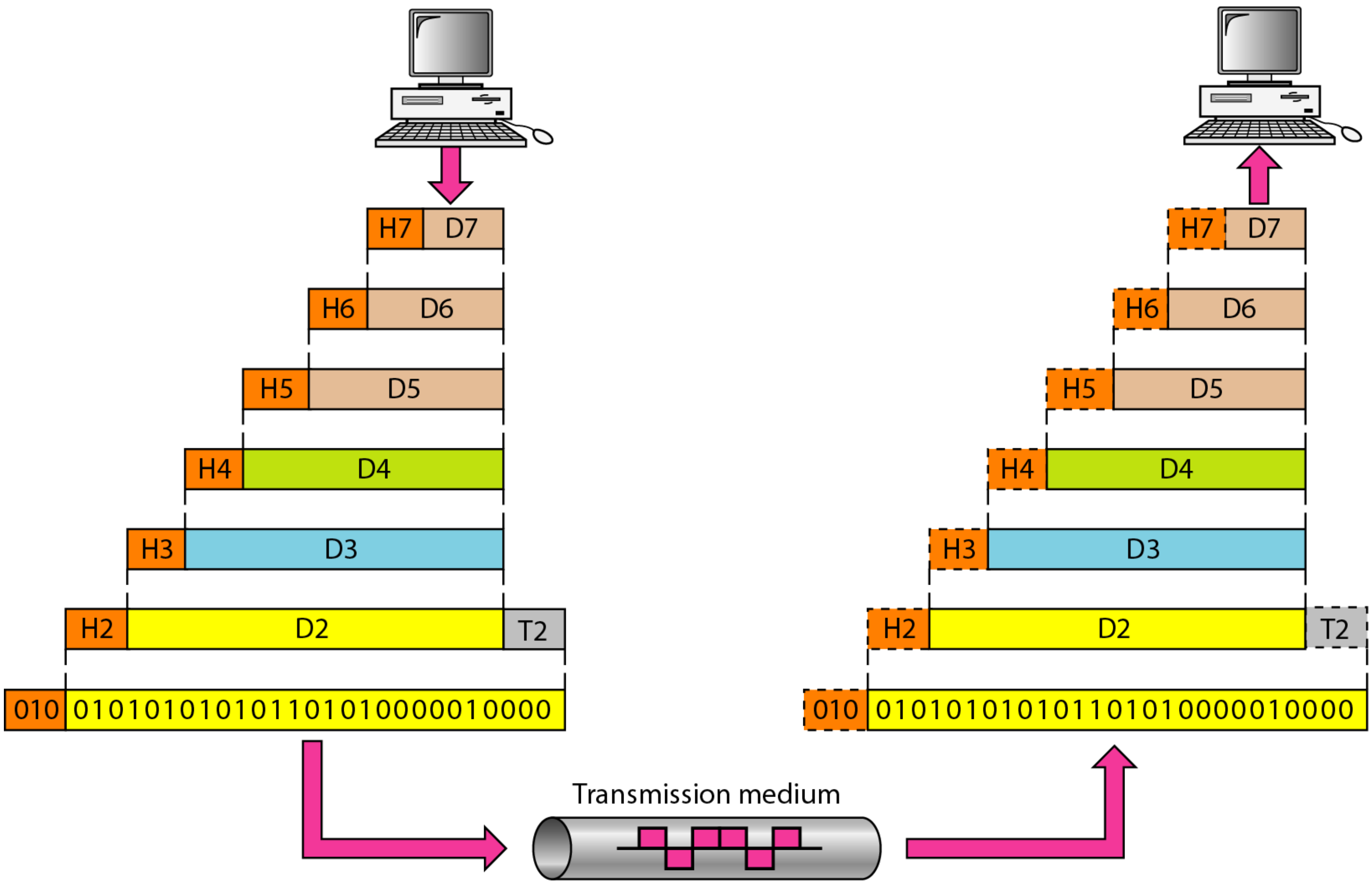
## Figure 2.2 *Seven layers of the OSI model*



## Figure 2.3 *The interaction between layers in the OSI model*



## **Figure 2.4** *An exchange using the OSI model*



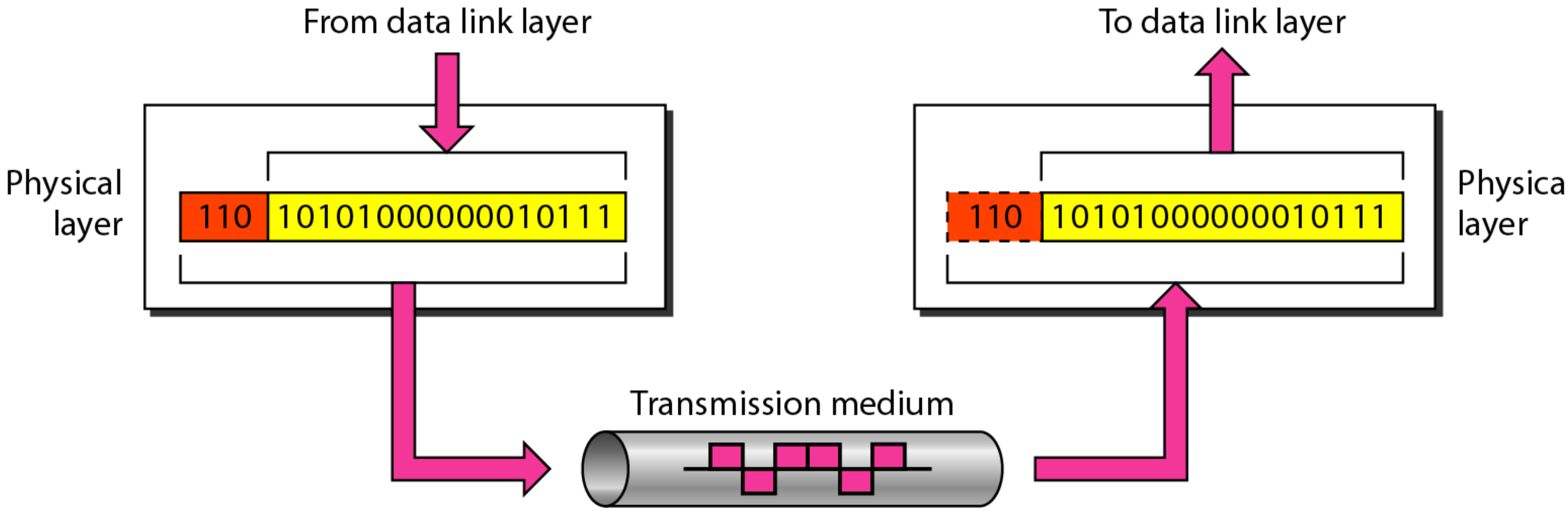
# 2-3 LAYERS IN THE OSI MODEL

***In this section we briefly describe the functions of each layer in the OSI model.***

***Topics discussed in this section:***

**Physical Layer**
**Data Link Layer**
**Network Layer**
**Transport Layer**
**Session Layer**
**Presentation Layer**
**Application Layer**

## Figure 2.5 *Physical layer*



***Note***

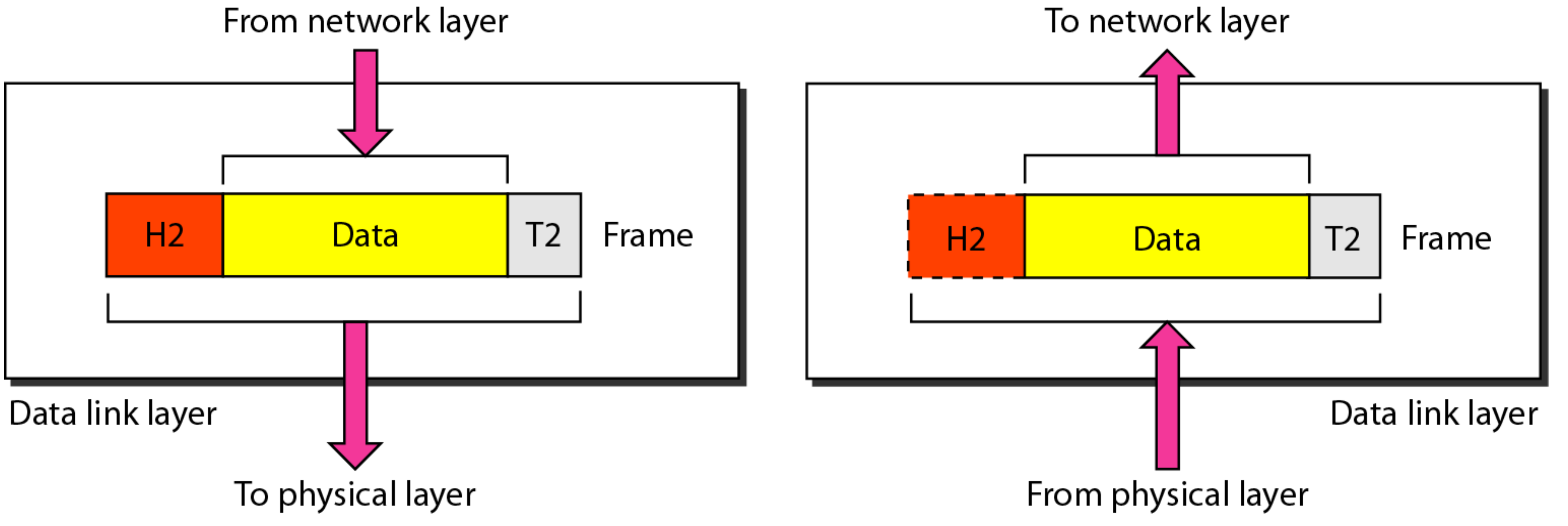
**The physical layer is responsible for movements of individual bits from one hop (node) to the next.**

## *Physical layer*

***Physical layer concerns with:***

- **Physical characteristics of Interfaces & medium, Type of transmission medium**
- **Representation of bits**
- **Data rate**
- **Synchronization of bits**
- **Line configuration**
- **Physical topology**
- **Transmission mode**

## Figure 2.6 *Data link layer*



***Note***

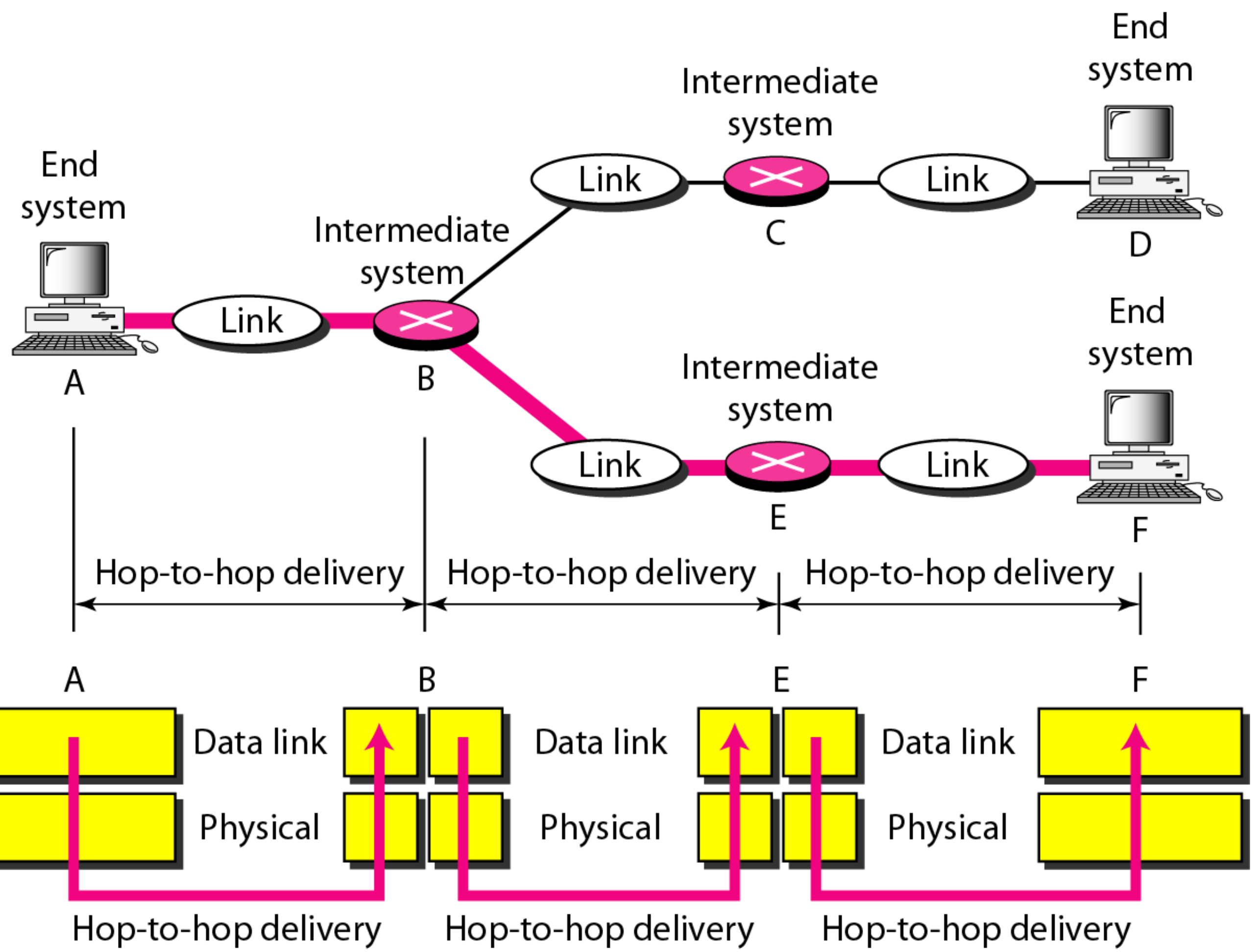
**The data link layer is responsible for moving frames from one hop (node) to the next.**

**Data link layer makes the physical layer appear error-free to the network layer**

***Data link layer concerns with:***

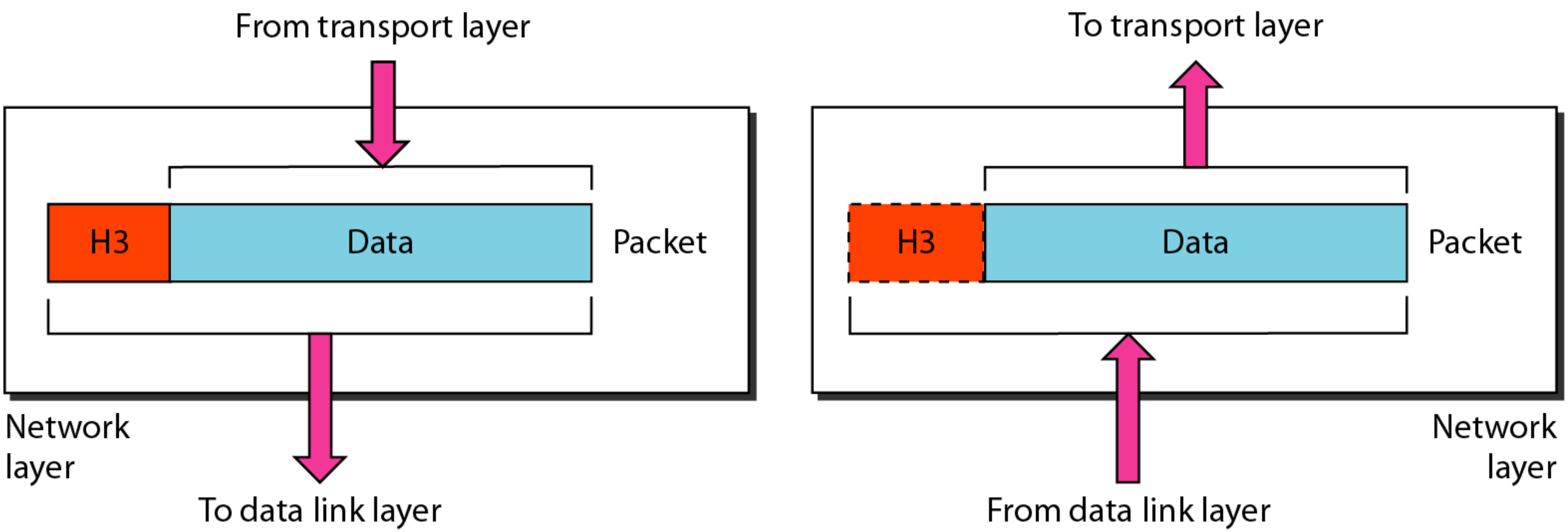
- **Framing**
- **Physical addressing**
- **Flow control**
- **Error control- adds reliability**
- **Access control**

# Figure 2.7 *Hop-to-hop delivery*



## Figure 2.8 *Network layer*

***Network layer is responsible for source to destination delivery of a packet possibly across multiple networks.***



***Note***

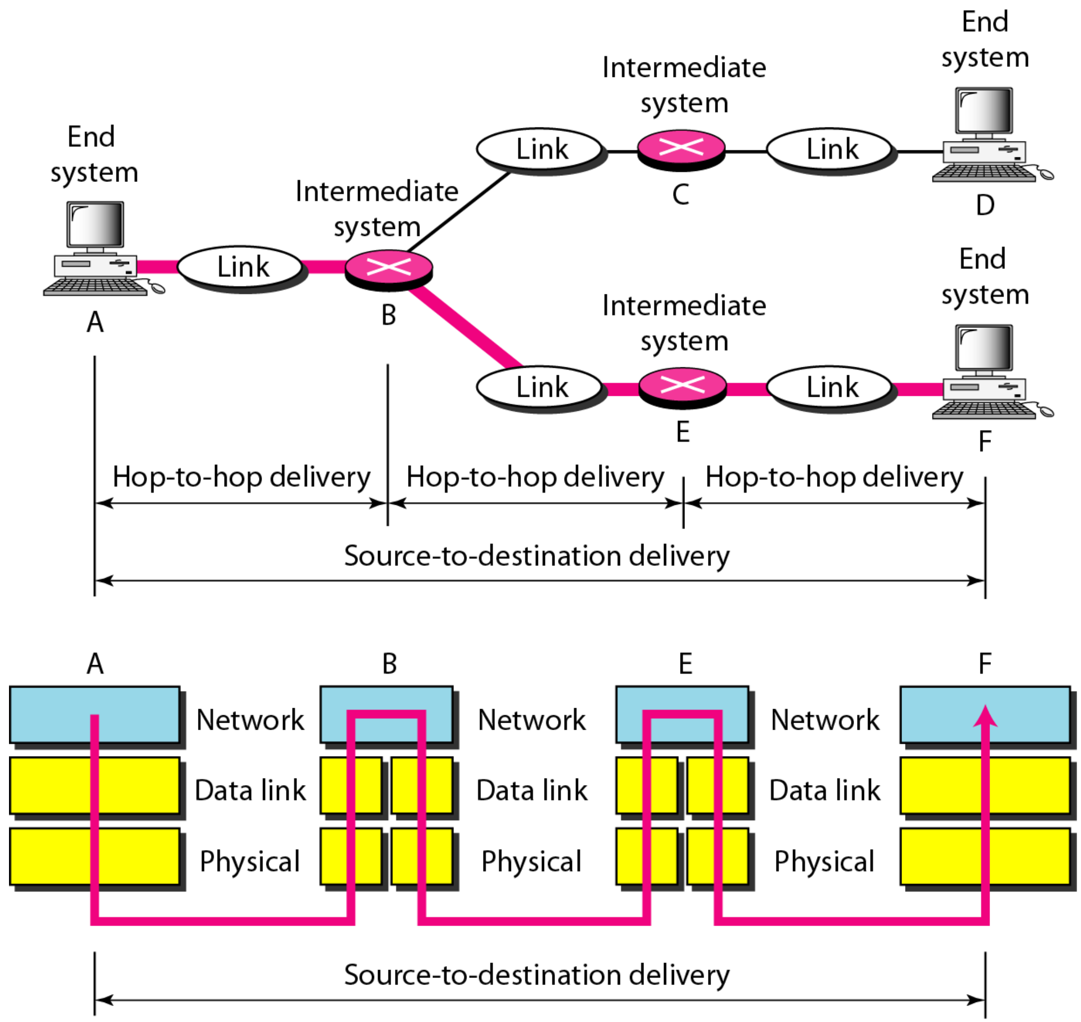
**The network layer is responsible for the delivery of individual packets from the source host to the destination host.**

## *Network layer*

***Network layer is also responsible for :***

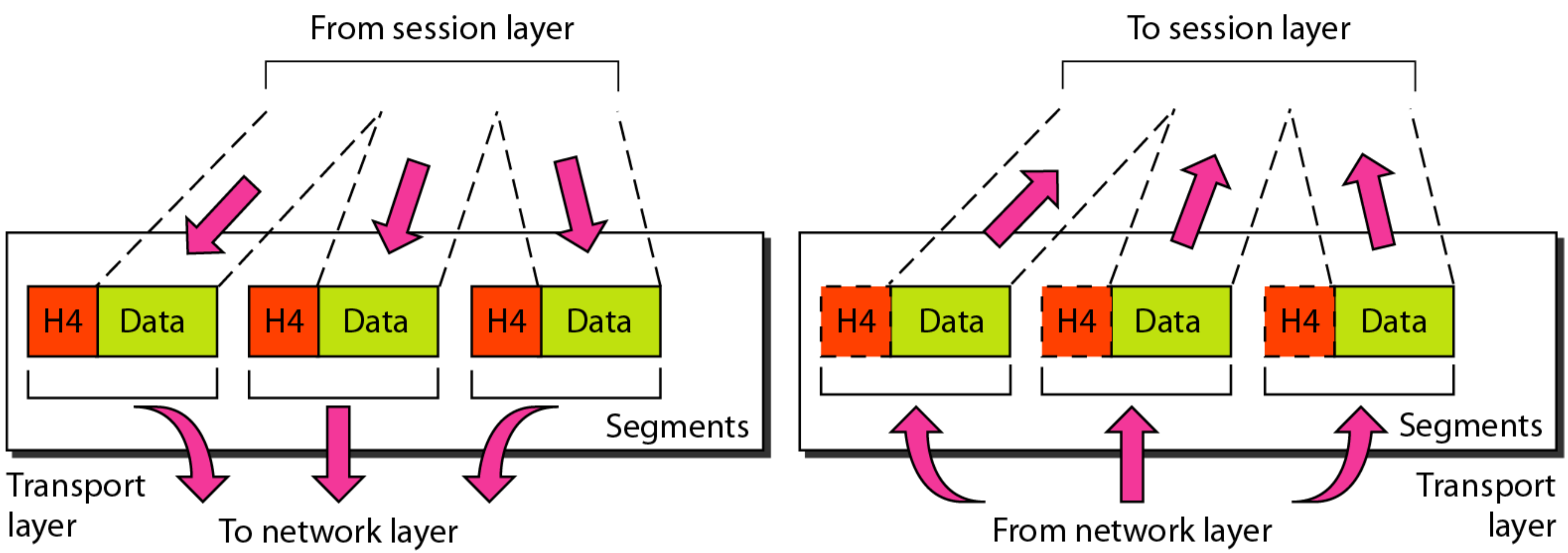
- **Logical addressing**
- **Routing**

# Figure 2.9 *Source-to-destination delivery*



# Figure 2.10 *Transport layer*

***Transport layer is responsible for process to process delivery of the entire message.***



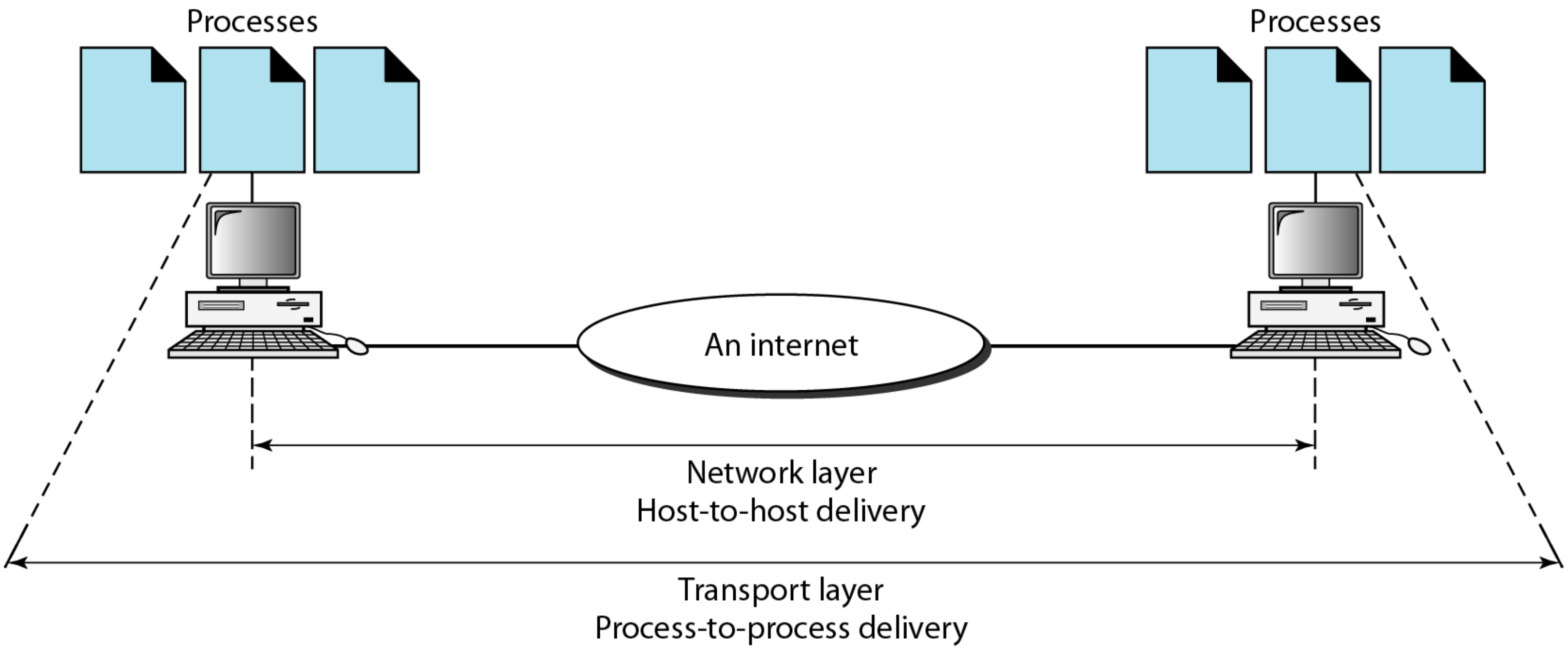
***Note***

**The transport layer is responsible for the delivery of a message from one process to another.**

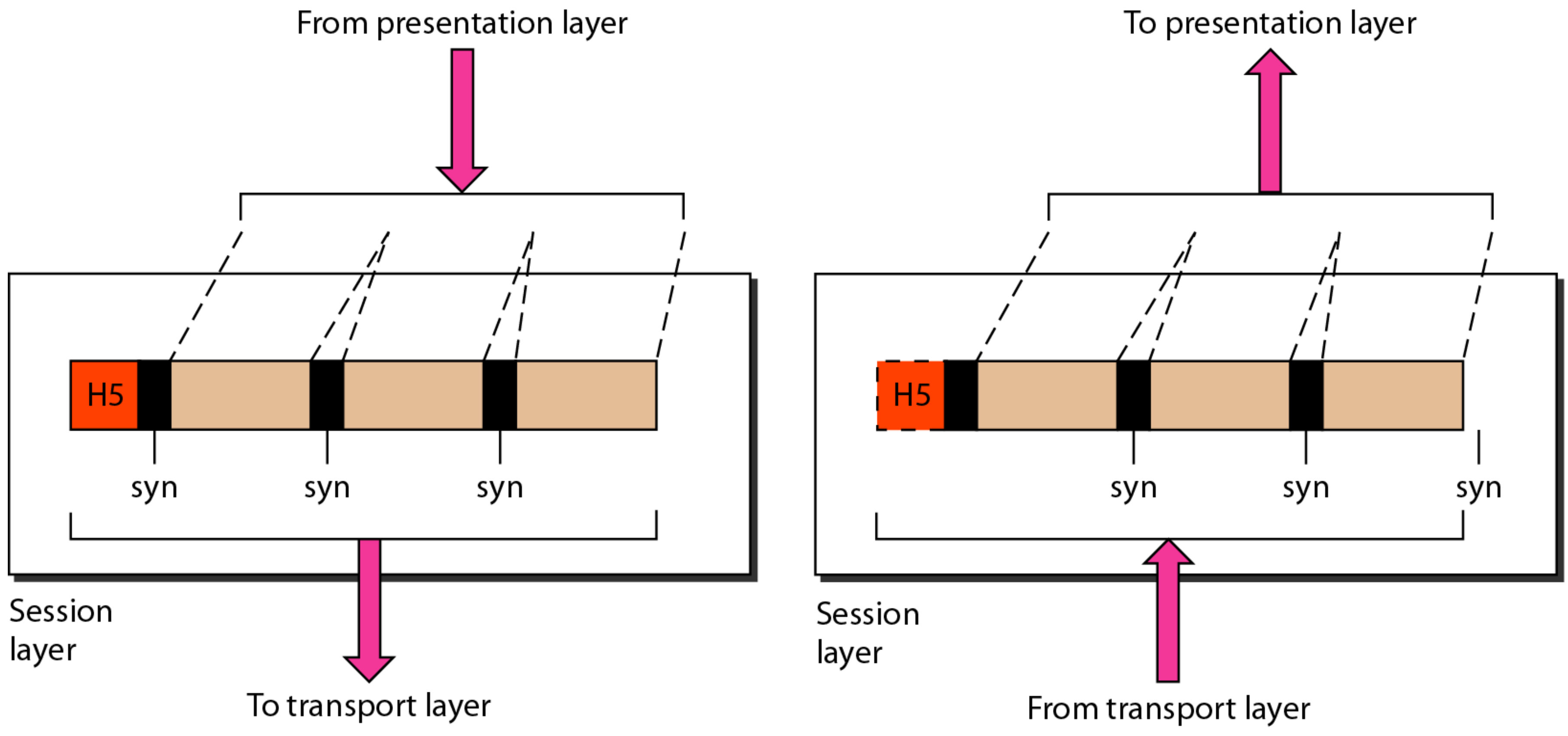
***Transport layer is also responsible for:***

- **Service point addressing**
- **Segmentation and reassembly**
- **connection control**
- **Flow control – end to end**
- **Error control – process to process**

## **Figure 2.11** *Reliable process-to-process delivery of a message*



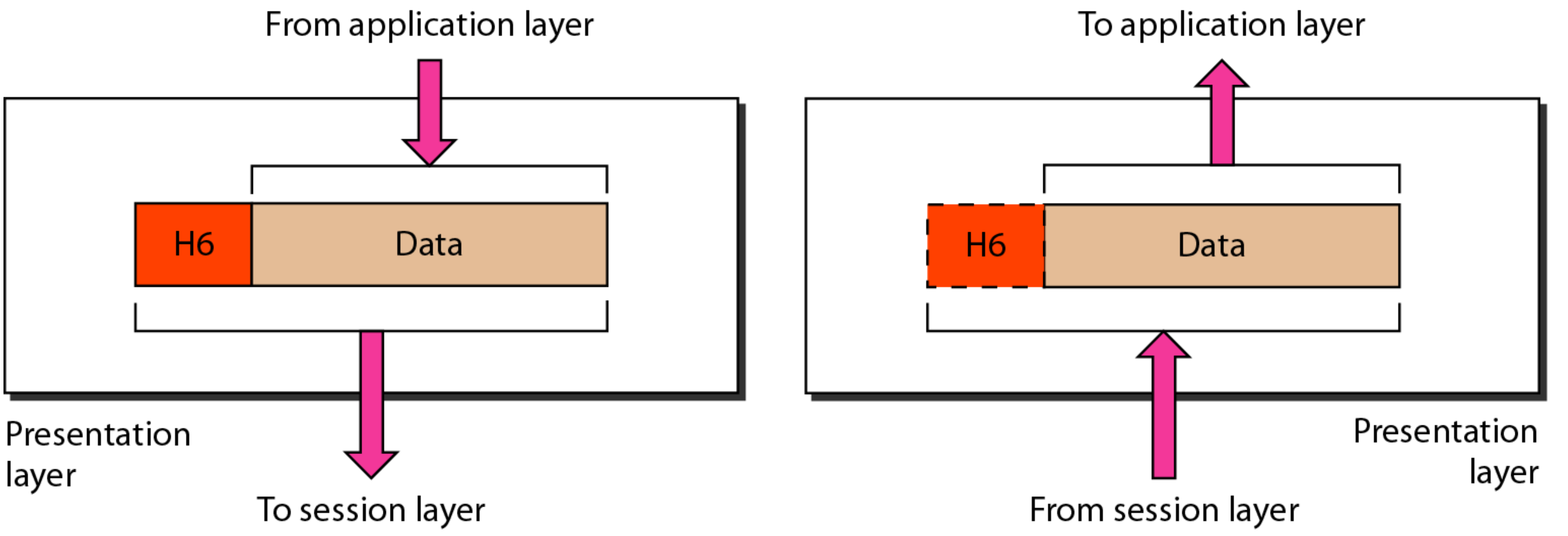
## Figure 2.12 *Session layer*



***Note***

**The session layer is responsible for dialog control and synchronization.**

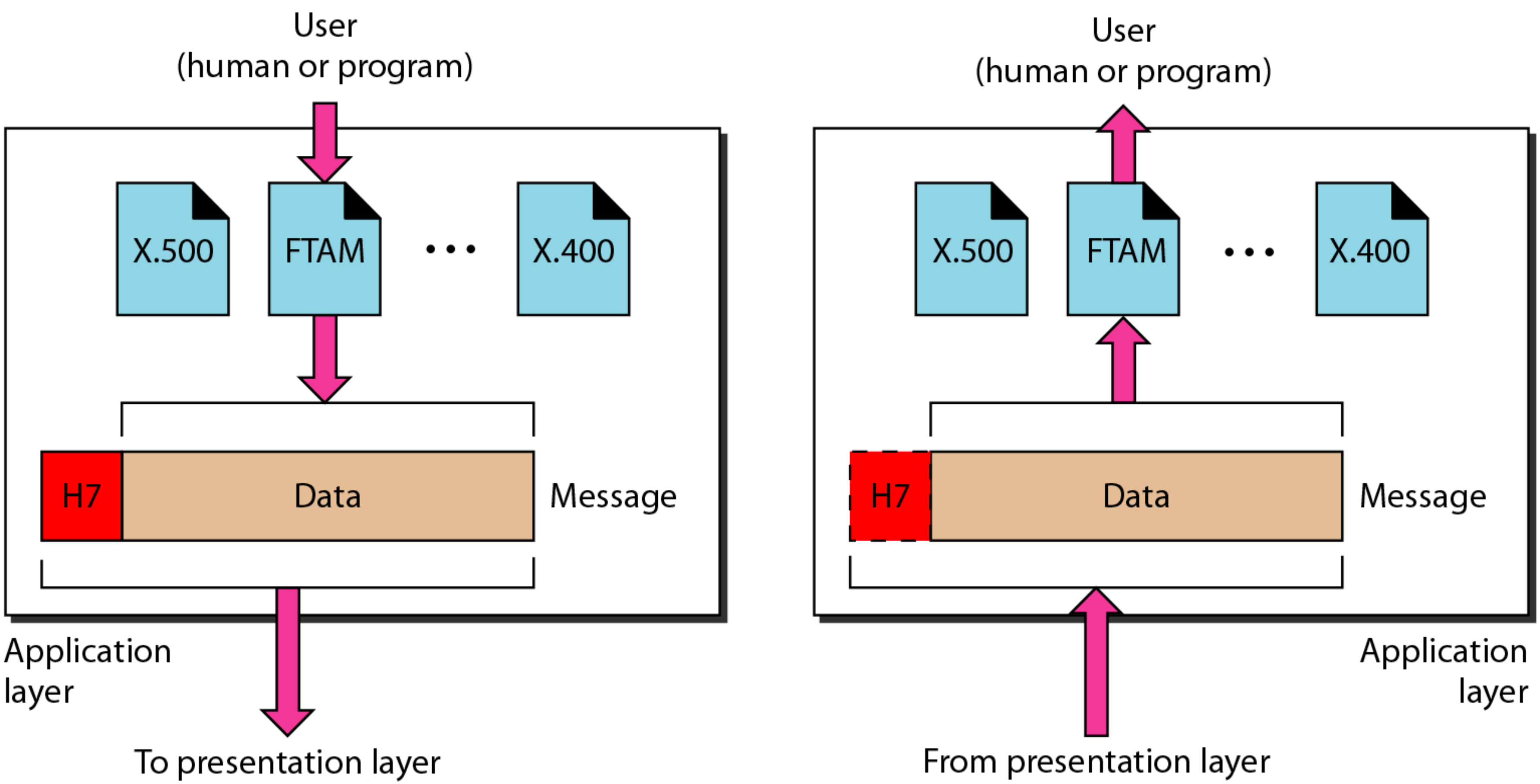
## Figure 2.13 *Presentation layer*



***Note***

**The presentation layer is responsible for translation, compression, and encryption.**

## Figure 2.14 *Application layer*



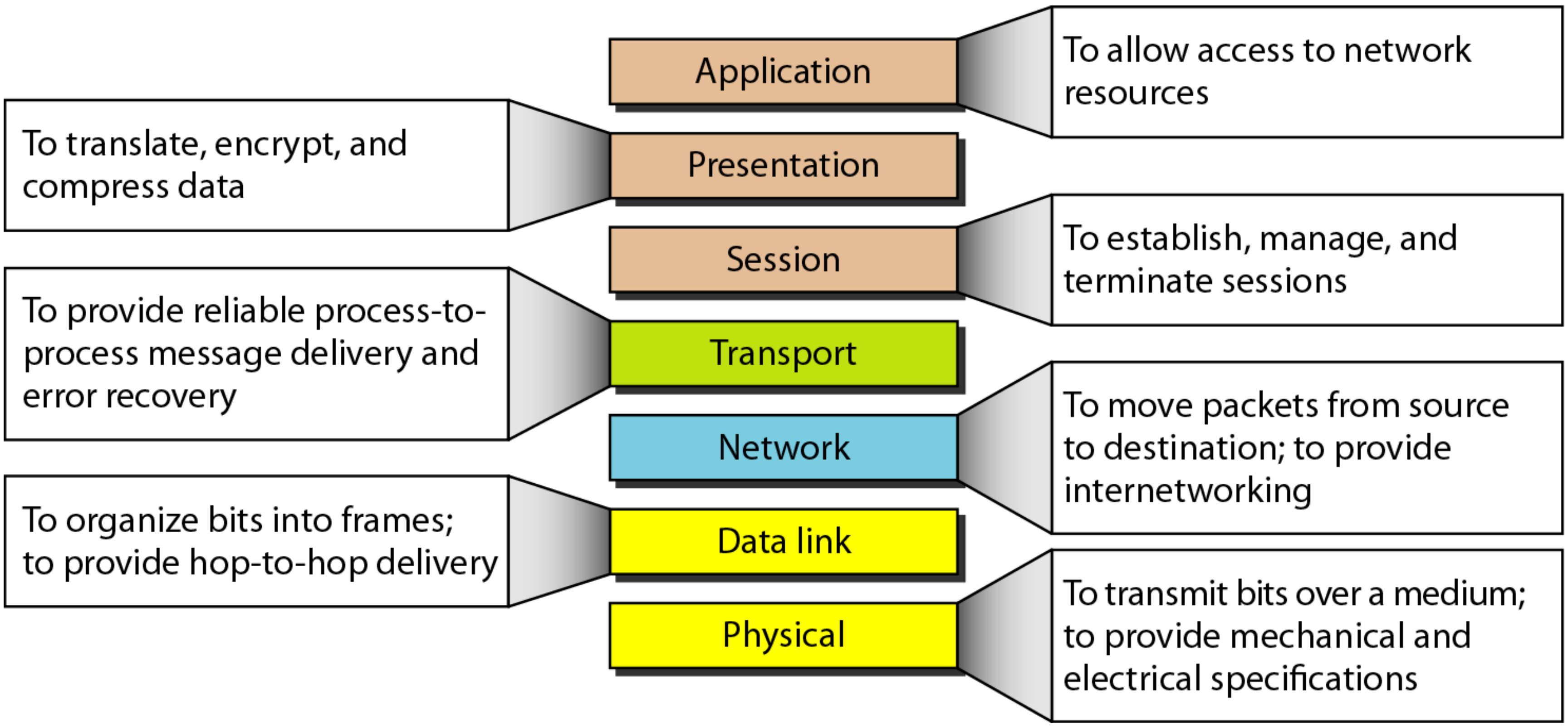
***Note***

**The application layer is responsible for providing services to the user.**

***Specific services provided by the Application layer :***

- **Network virtual terminal (Remote access)**
- **File Transfer, Access and Management**
- **Mail services**
- **Directory services**

## Figure 2.15 *Summary of layers*



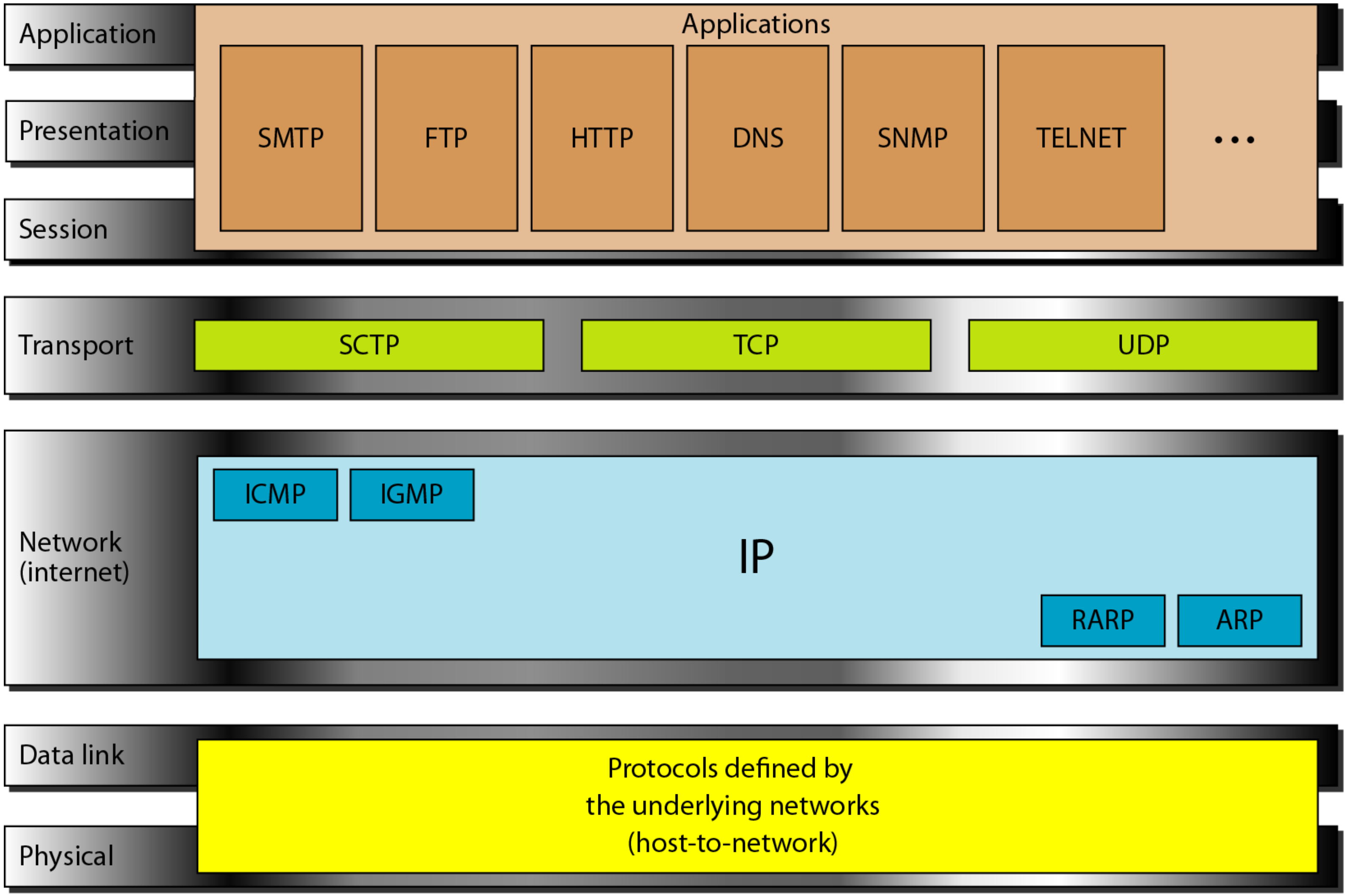
# 2-4 TCP/IP PROTOCOL SUITE

***The layers in the TCP/IP protocol suite do not exactly match those in the OSI model. The original TCP/IP protocol suite was defined as having four layers: host-to-network, internet, transport, and application. However, when TCP/IP is compared to OSI, we can say that the TCP/IP protocol suite is made of five layers: physical, data link, network, transport, and application.***

***Topics discussed in this section:***

**Physical and Data Link Layers**
**Network Layer**
**Transport Layer**
**Application Layer**

# Figure 2.16 *TCP/IP and OSI model*



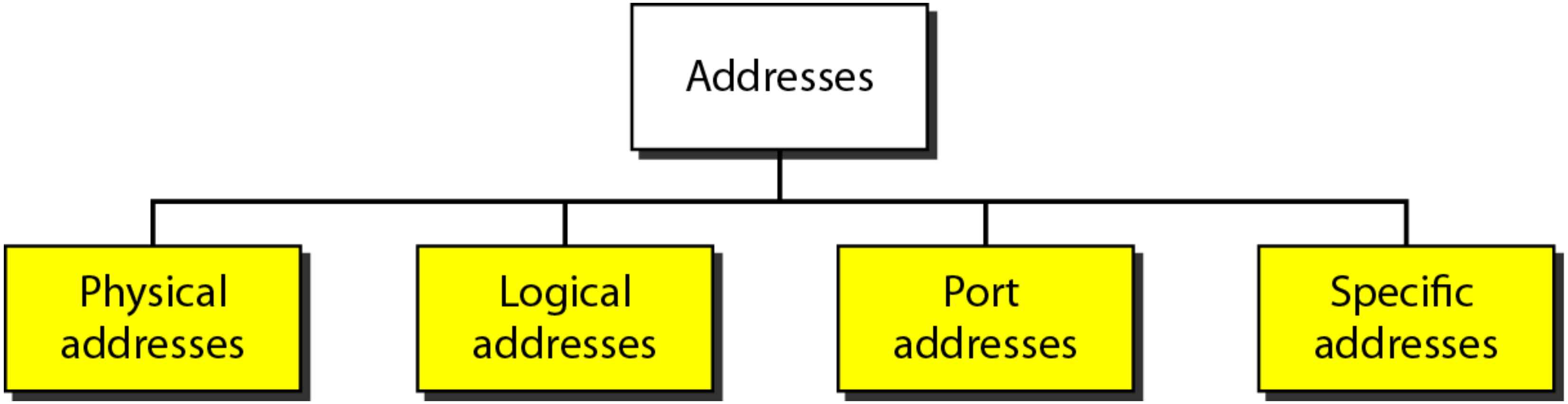
# 2-5 ADDRESSING

***Four levels of addresses are used in an internet employing the TCP/IP protocols: physical, logical, port, and specific.***

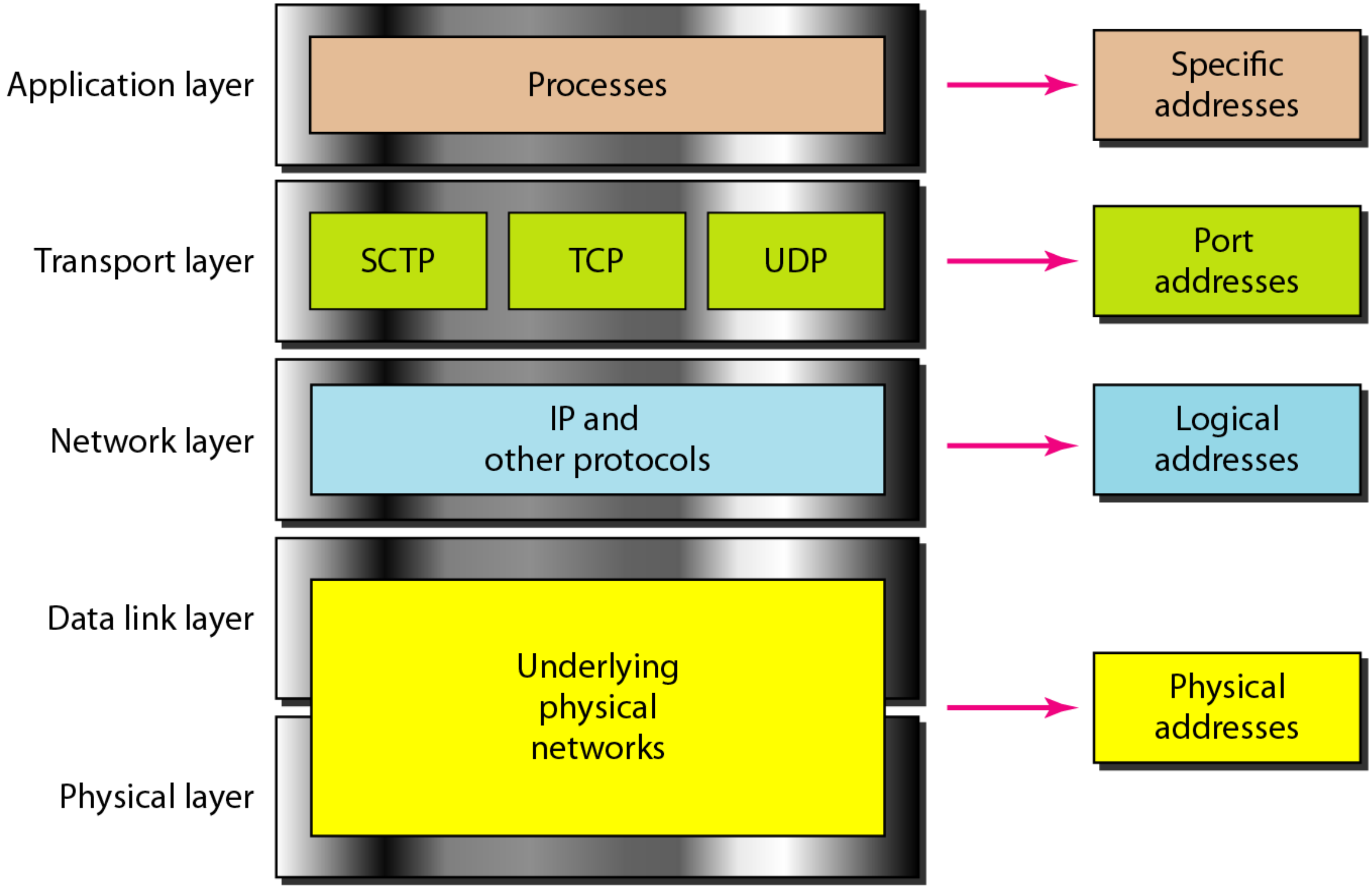
***Topics discussed in this section:***

**Physical Addresses**
**Logical Addresses**
**Port Addresses**
**Specific Addresses**

## Figure 2.17 *Addresses in TCP/IP*



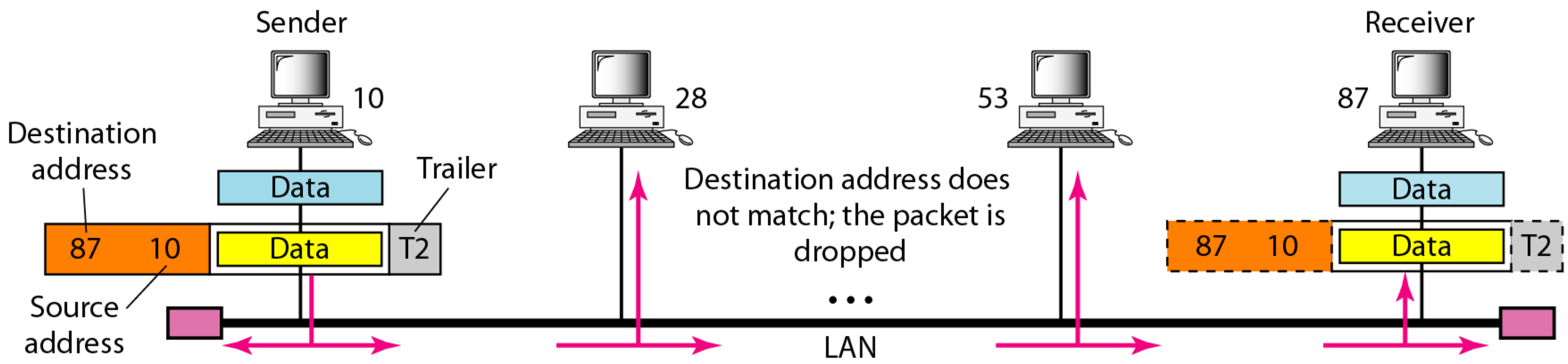
## Figure 2.18 *Relationship of layers and addresses in TCP/IP*



# *Example 2.1*

***In Figure 2.19 a node with physical address 10 sends a frame to a node with physical address 87. The two nodes are connected by a link (bus topology LAN). As the figure shows, the computer with physical address 10 is the sender, and the computer with physical address 87 is the receiver.***

## Figure 2.19 *Physical addresses*



# *Example 2.2*

***As we will see in Chapter 13, most local-area networks use a 48-bit (6-byte) physical address written as 12 hexadecimal digits; every byte (2 hexadecimal digits) is separated by a colon, as shown below:***

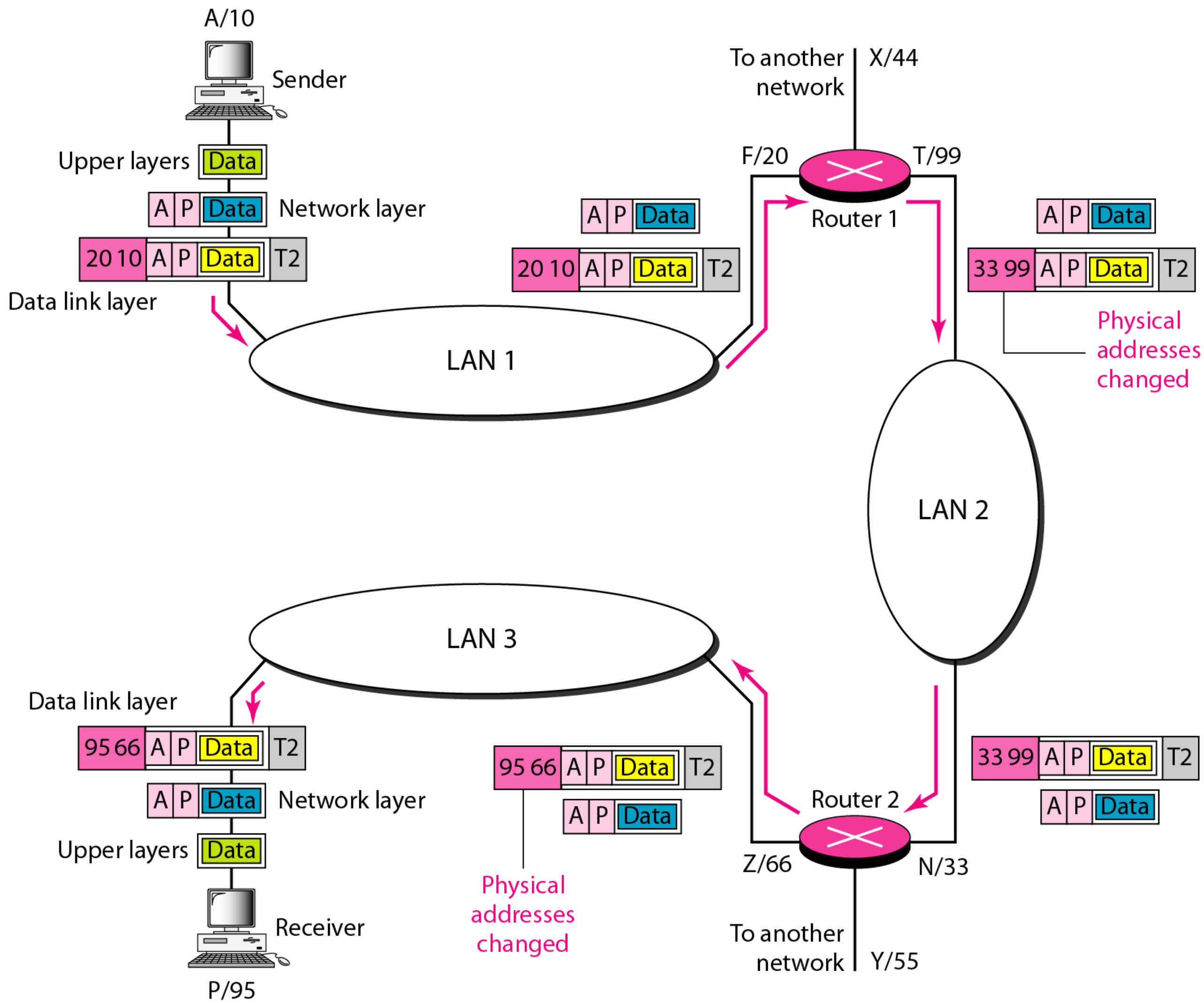
**07:01:02:01:2C:4B**

**A 6-byte (12 hexadecimal digits) physical address.**

# Example 2.3

***Figure 2.20 shows a part of an internet with two routers connecting three LANs. Each device (computer or router) has a pair of addresses (logical and physical) for each connection. In this case, each computer is connected to only one link and therefore has only one pair of addresses. Each router, however, is connected to three networks (only two are shown in the figure). So each router has three pairs of addresses, one for each connection.***

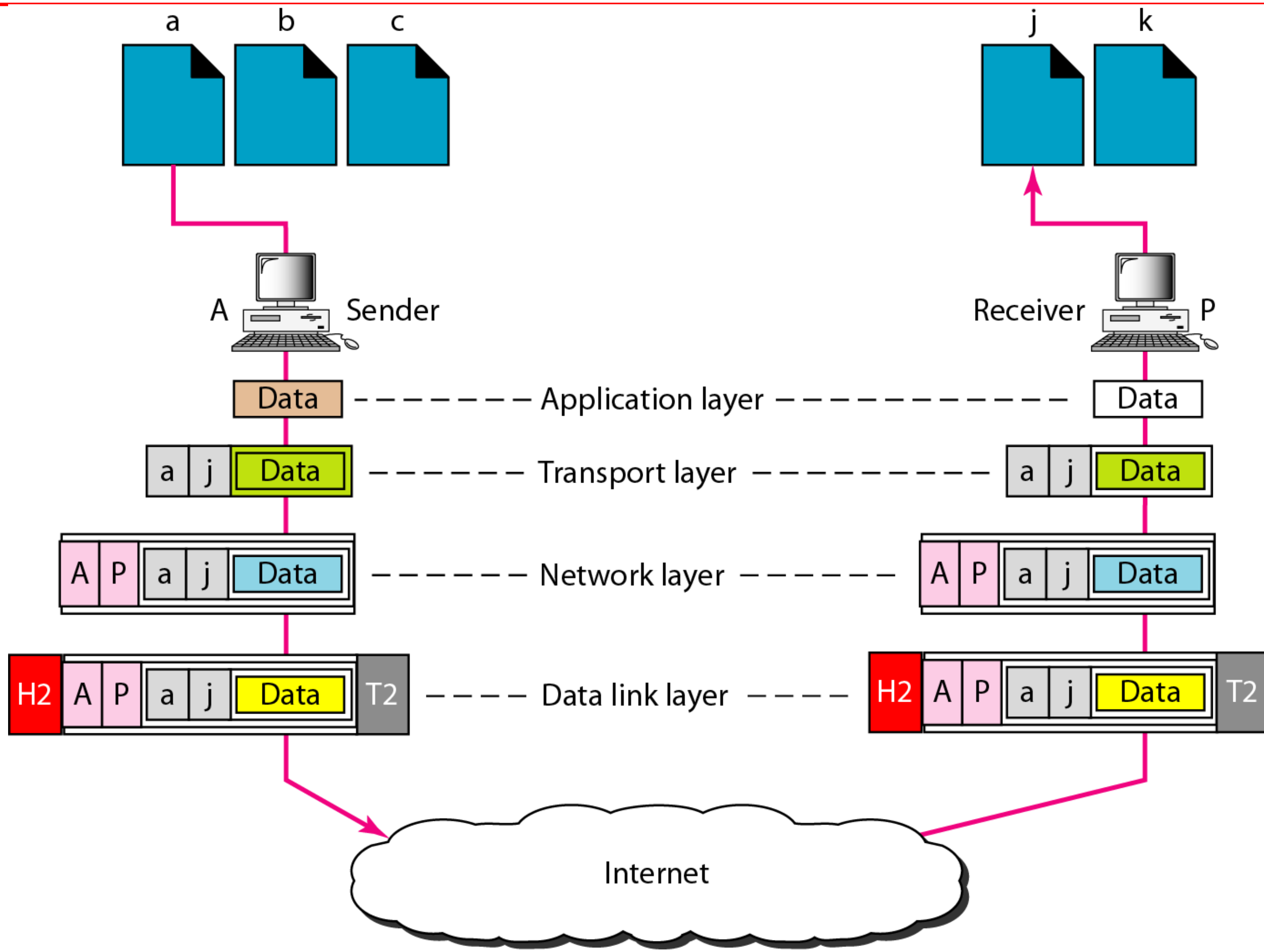
# **Figure 2.20** *IP addresses*



# *Example 2.4*

***Figure 2.21 shows two computers communicating via the Internet. The sending computer is running three processes at this time with port addresses a, b, and c. The receiving computer is running two processes at this time with port addresses j and k. Process a in the sending computer needs to communicate with process j in the receiving computer. Note that although physical addresses change from hop to hop, logical and port addresses remain the same from the source to destination.***

# Figure 2.21 *Port addresses*



***Note***

**The physical addresses will change from hop to hop, but the logical addresses usually remain the same.**

# *Example 2.5*

***As we will see in Chapter 23, a port address is a 16-bit address represented by one decimal number as shown.***

**753**

**A 16-bit port address represented as one single number.**

***Note***

**The physical addresses change from hop to hop,**
**but the logical and port addresses usually remain the same.**



# Chapter 6

# Bandwidth Utilization: Multiplexing

***Note***

**Bandwidth utilization is the wise use of available bandwidth to achieve specific goals.**

**Efficiency can be achieved by multiplexing; privacy and anti-jamming can be achieved by spreading.**

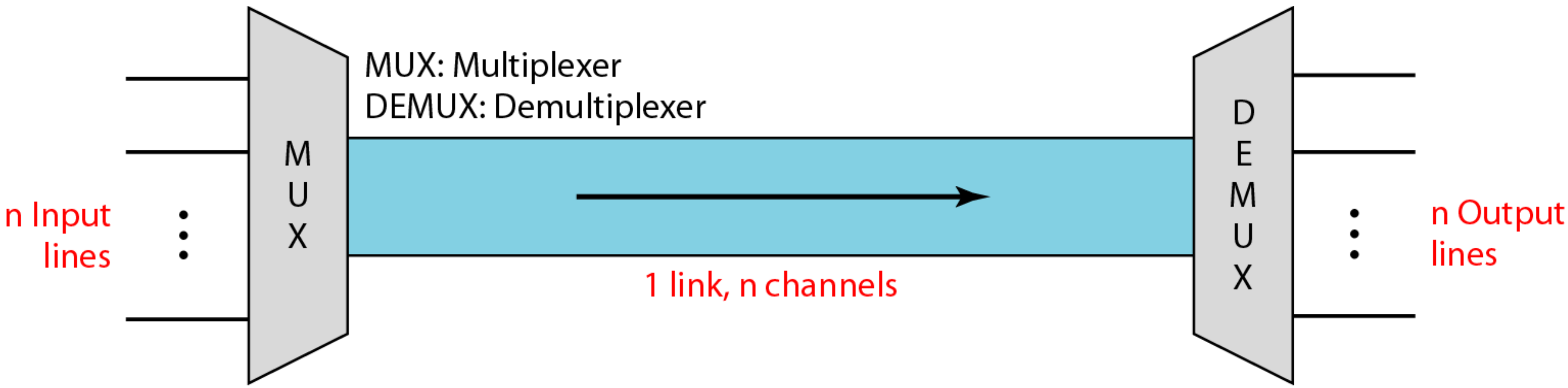
# 6-1 MULTIPLEXING

***Whenever the bandwidth of a medium linking two devices is greater than the bandwidth needs of the devices, the link can be shared. Multiplexing is the set of techniques that allows the simultaneous transmission of multiple signals across a single data link. As data and telecommunications use increases, so does traffic.***

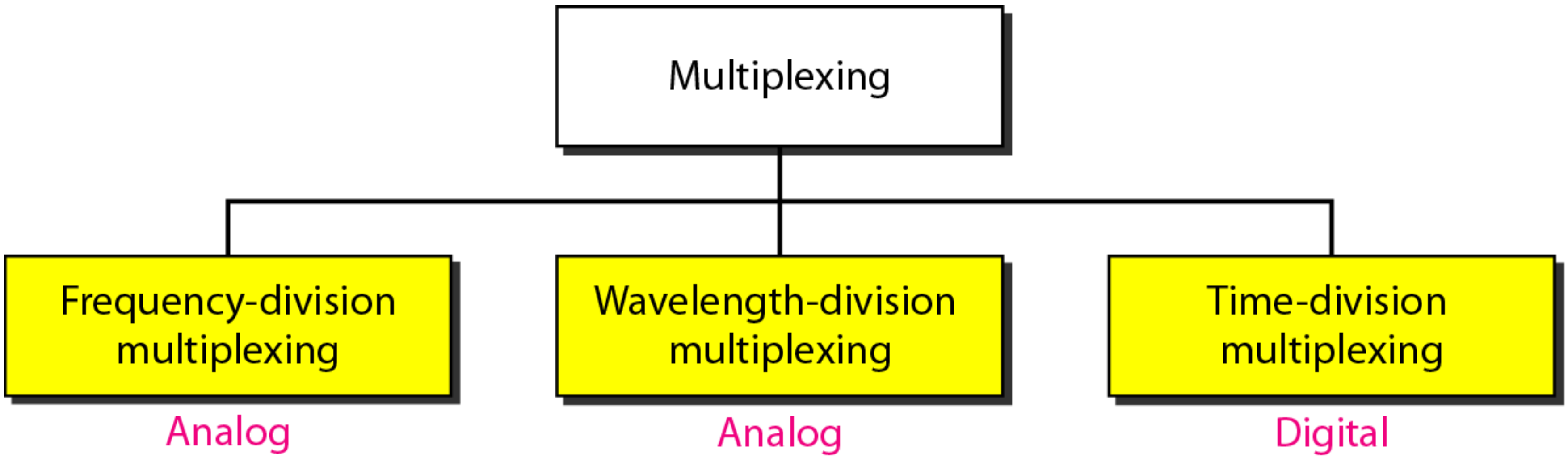
***Topics discussed in this section:***

**Frequency-Division Multiplexing**
**Wavelength-Division Multiplexing**
**Synchronous Time-Division Multiplexing**
**Statistical Time-Division Multiplexing**

## Figure 6.1 *Dividing a link into channels*



## Figure 6.2 *Categories of multiplexing*

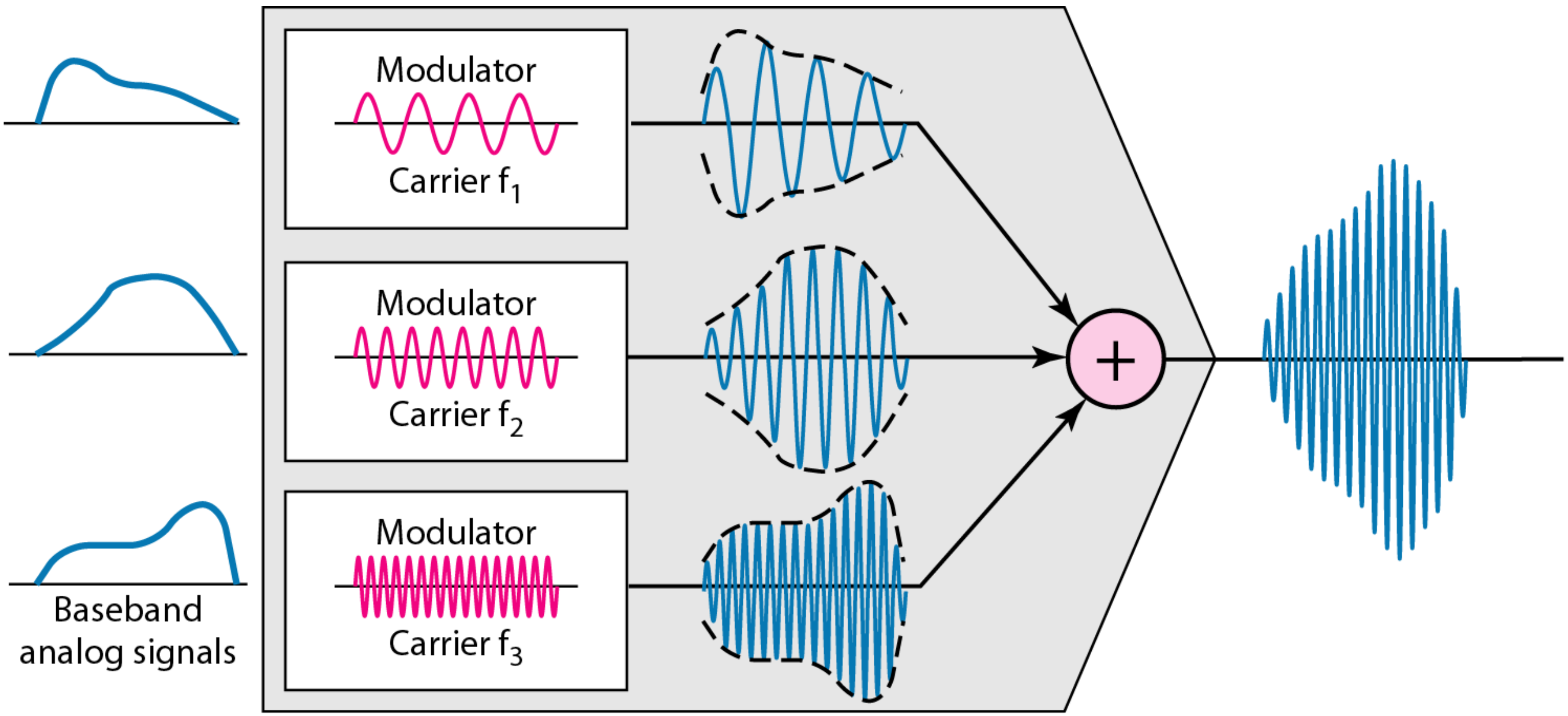


## Figure 6.3 *Frequency-division multiplexing*

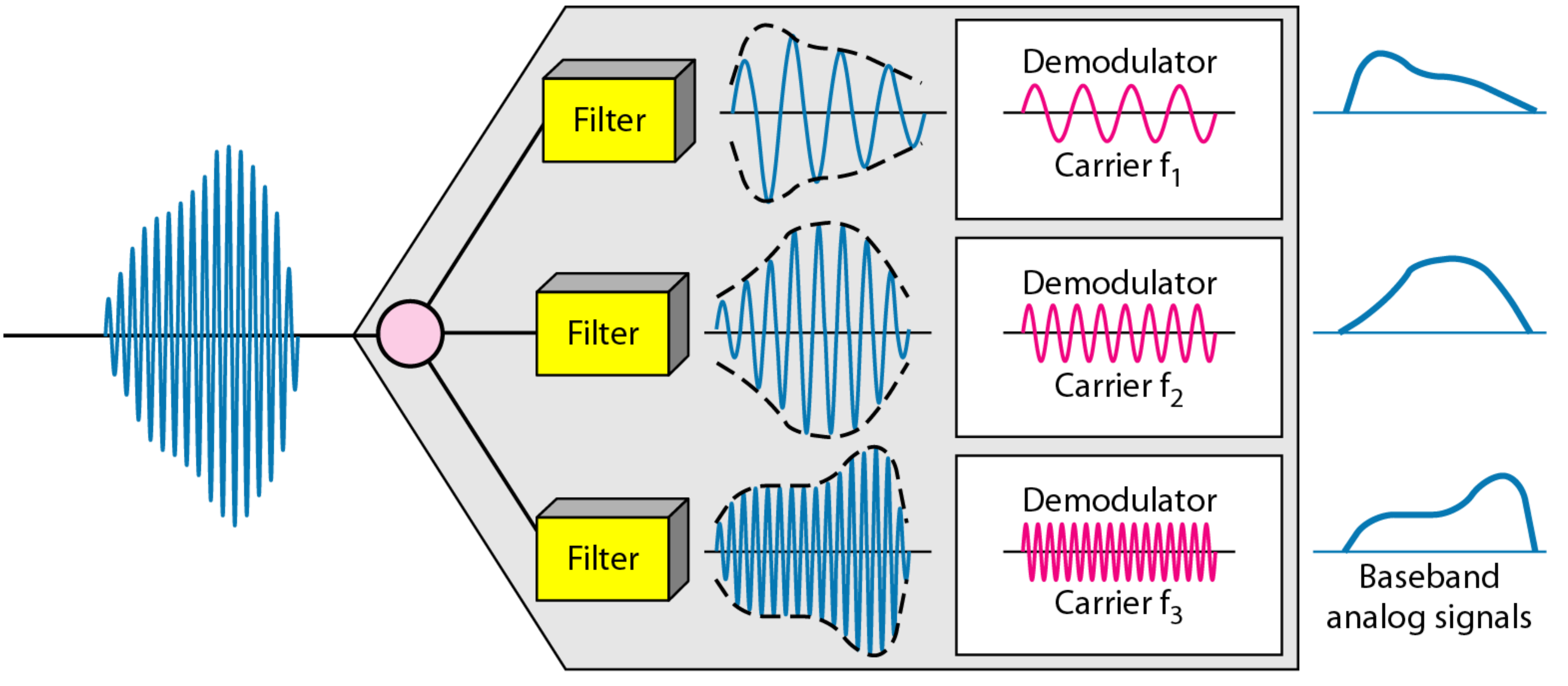
***Note***

**FDM is an analog multiplexing technique that combines analog signals.**

## Figure 6.4 *FDM process*



## Figure 6.5 *FDM demultiplexing example*



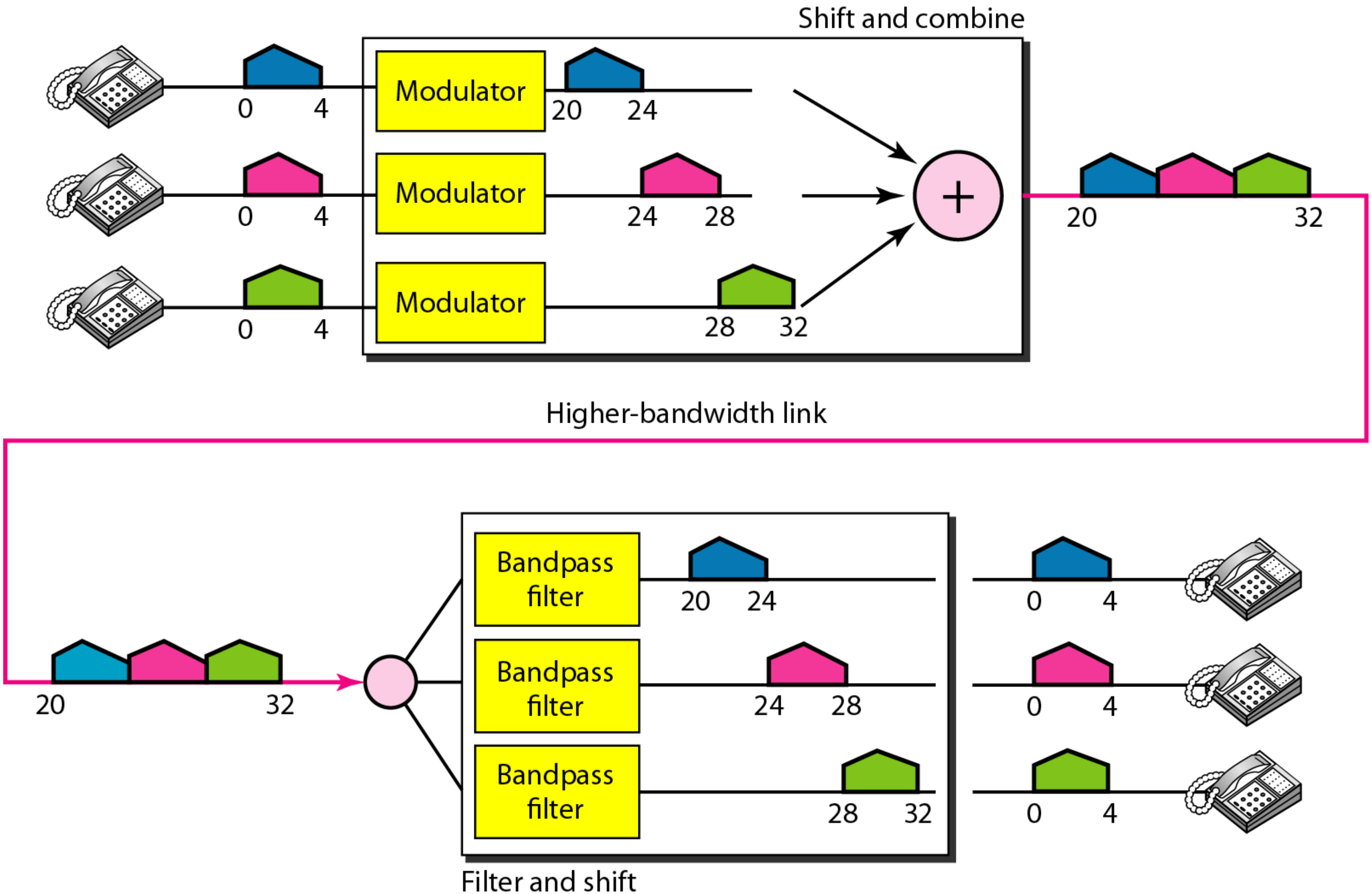
# Example 6.1

***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.***

## Solution

***We shift (modulate) each of the three voice channels to a different bandwidth, as shown in Figure 6.6. We use the 20- to 24-kHz bandwidth for the first channel, the 24- to 28-kHz bandwidth for the second channel, and the 28- to 32-kHz bandwidth for the third one. Then we combine them as shown in Figure 6.6.***

# **Figure 6.6** *Example 6.1*



# Example 6.2

*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?*

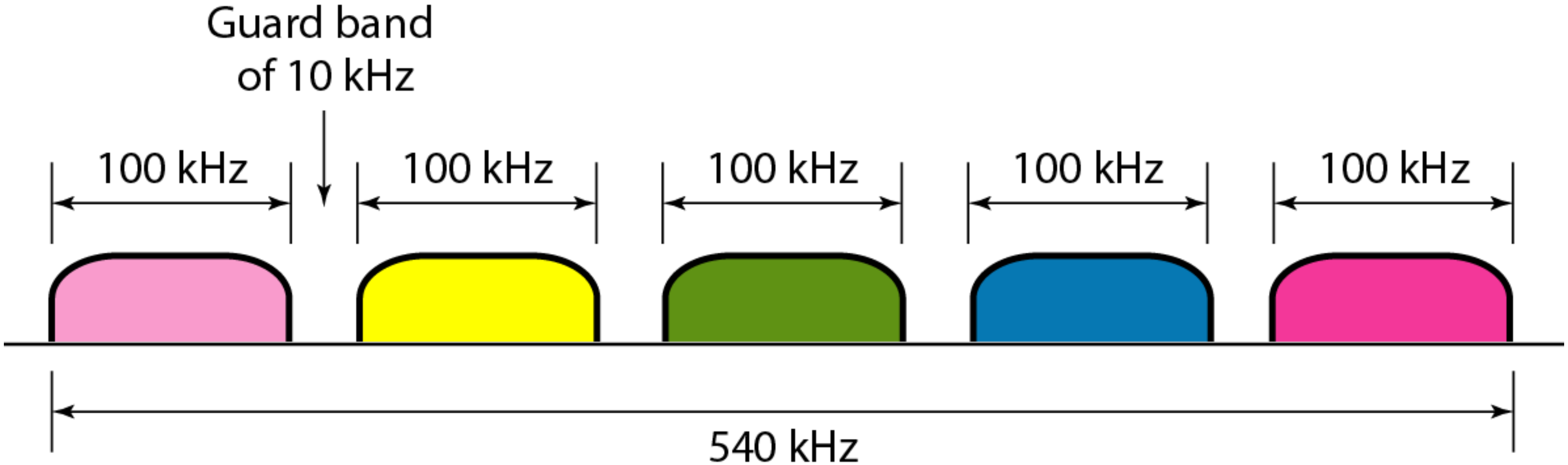
**Solution**

*For five channels, we need at least four guard bands. This means that the required bandwidth is at least*

$$5 \times 100 + 4 \times 10 = 540 \text{ kHz},$$

*as shown in Figure 6.7.*

## **Figure 6.7** *Example 6.2*



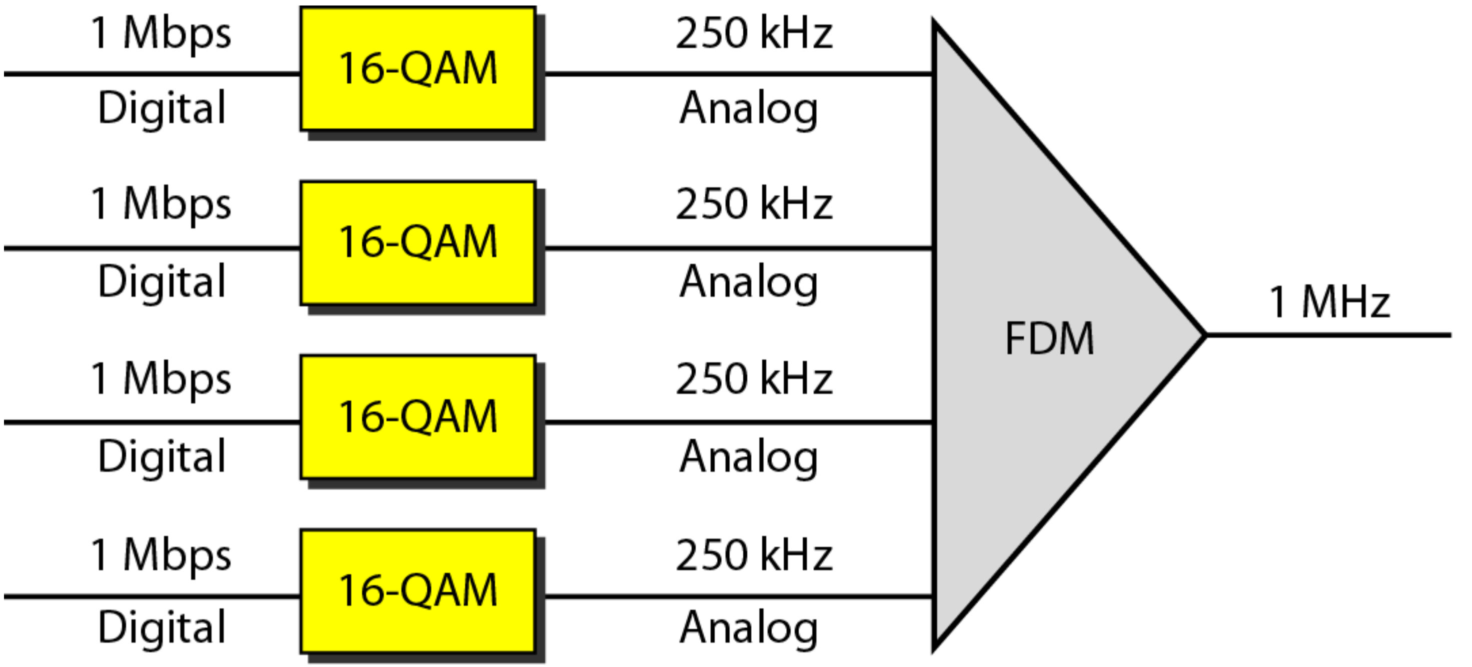
# Example 6.3

***Four data channels (digital), each transmitting at 1 Mbps, use a satellite channel of 1 MHz. Design an appropriate configuration, using FDM.***

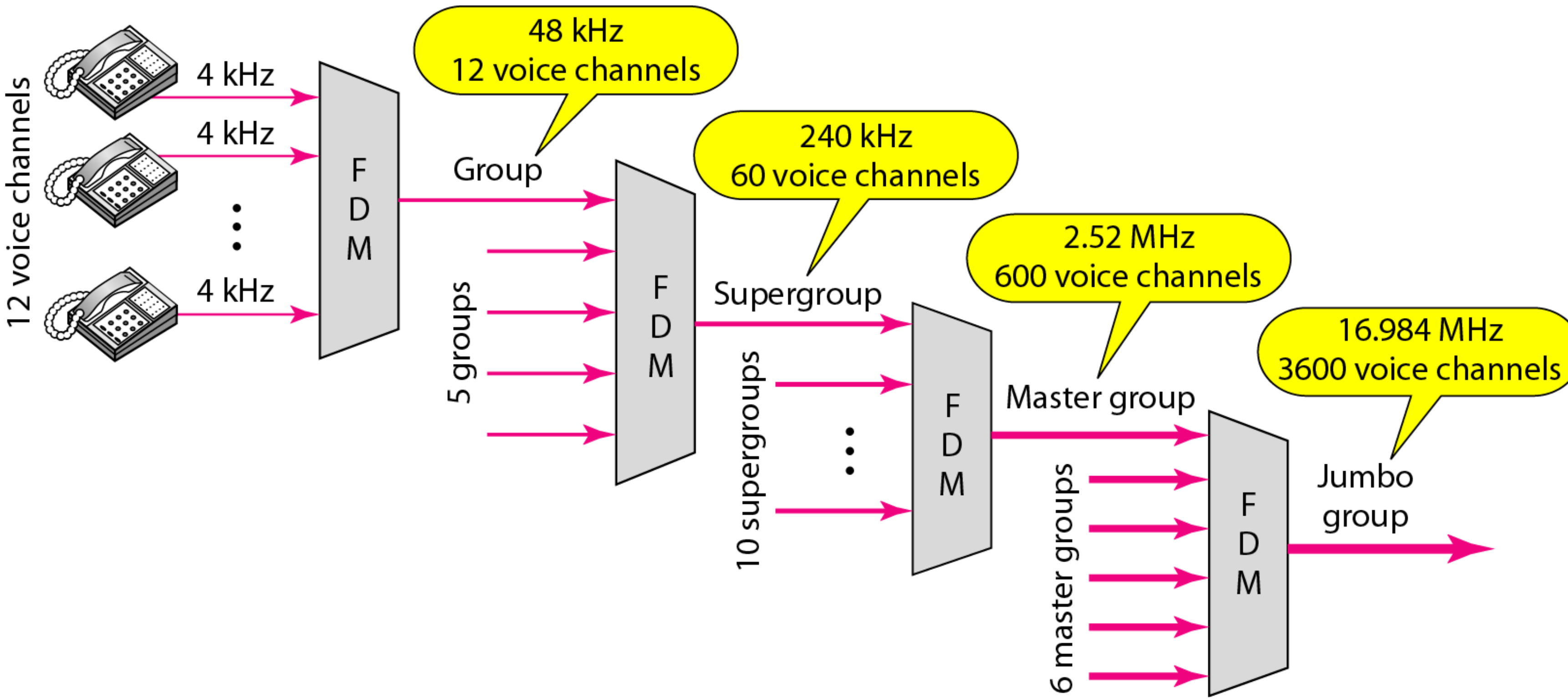
## *Solution*

***The satellite channel is analog. We divide it into four channels, each channel having a 250-kHz bandwidth. Each digital channel of 1 Mbps is modulated such that each 4 bits is modulated to 1 Hz. One solution is 16-QAM modulation. Figure 6.8 shows one possible configuration.***

## Figure 6.8 *Example 6.3*



## **Figure 6.9** *Analog hierarchy*



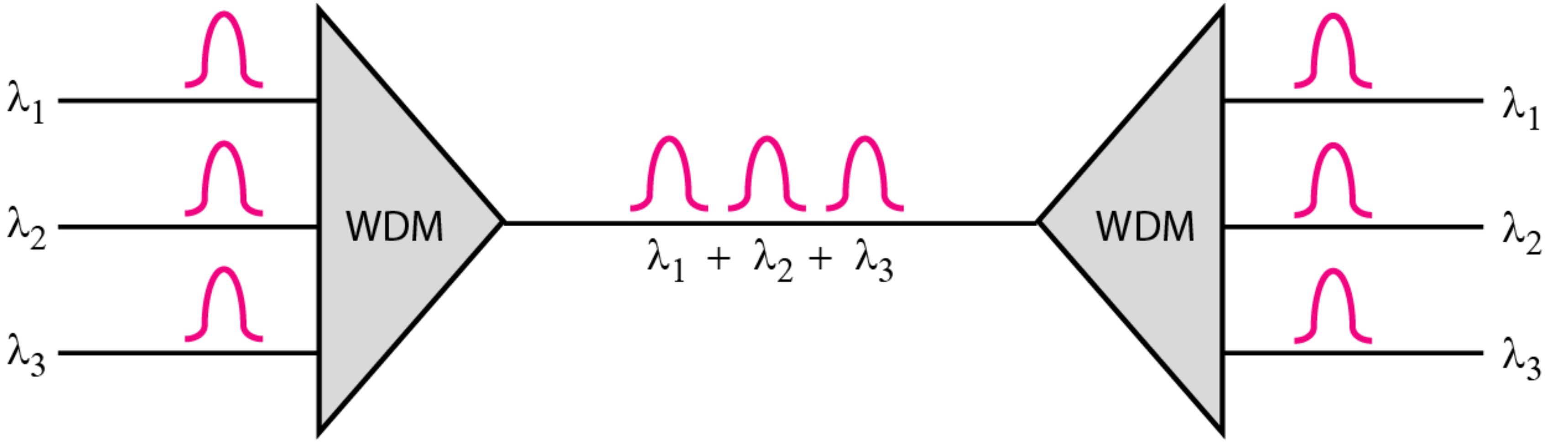
## Example 6.4

*The Advanced Mobile Phone System (AMPS) uses two bands. The first band of 824 to 849 MHz is used for sending, and 869 to 894 MHz is used for receiving. Each user has a bandwidth of 30 kHz in each direction. How many people can use their cellular phones simultaneously?*

### Solution

*Each band is 25 MHz. If we divide 25 MHz by 30 kHz, we get 833.33. In reality, the band is divided into 832 channels. Of these, 42 channels are used for control, which means only 790 channels are available for cellular phone users.*

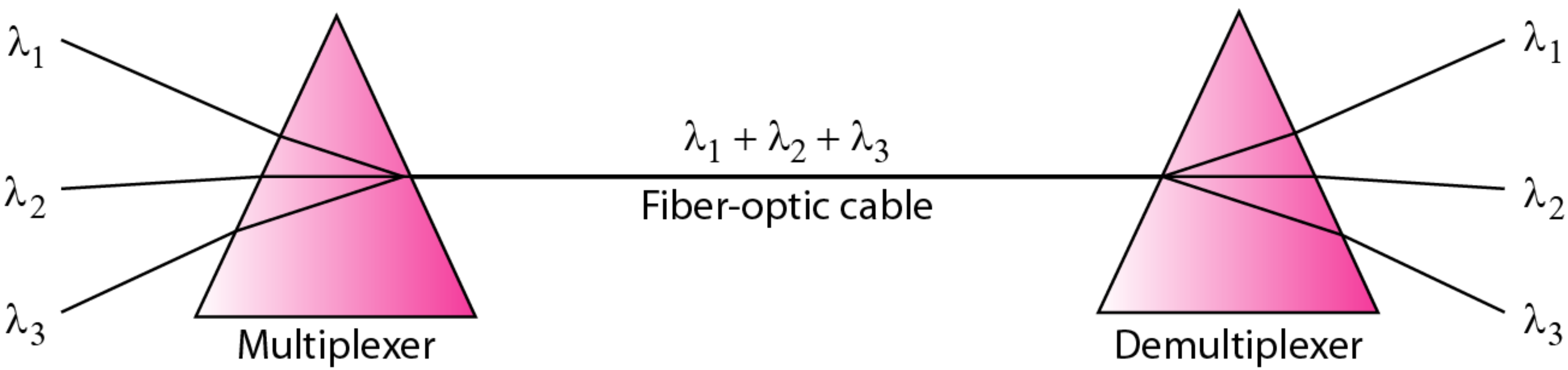
## **Figure 6.10** *Wavelength-division multiplexing*



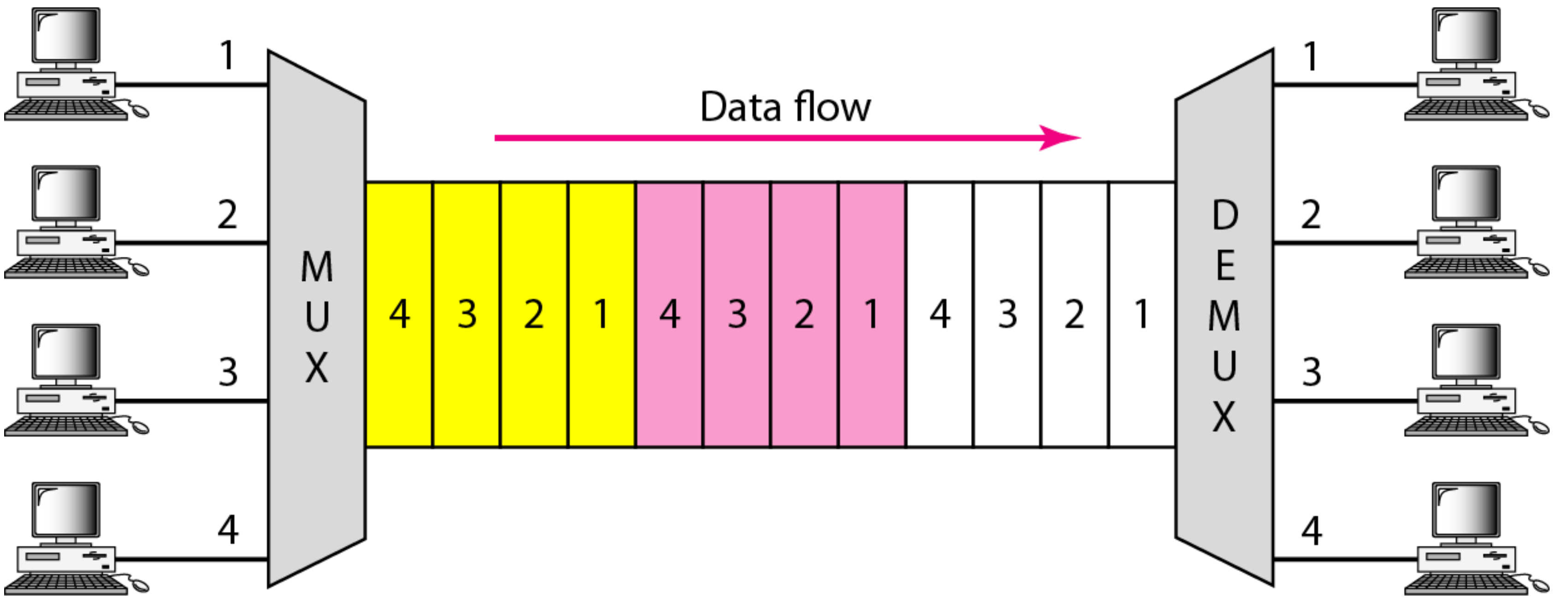
***Note***

**WDM is an analog multiplexing technique to combine optical signals.**

## **Figure 6.11** *Prisms in wavelength-division multiplexing and demultiplexing*



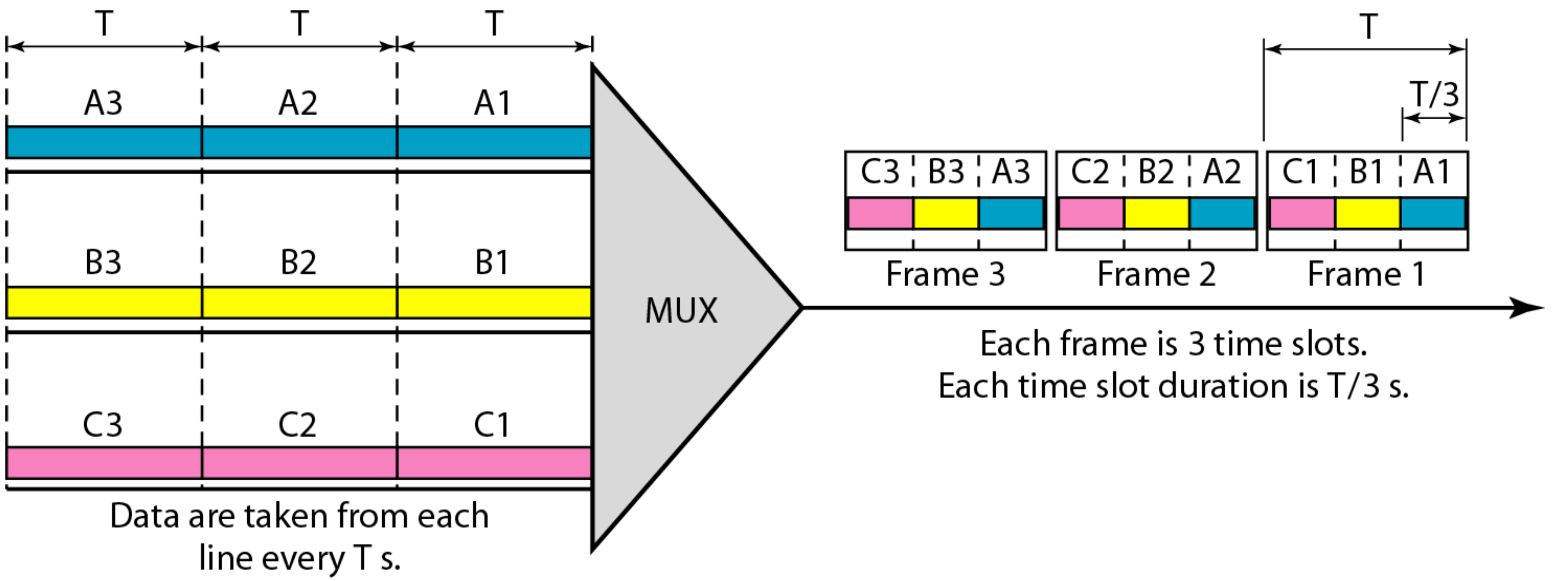
## Figure 6.12 *TDM*



***Note***

**TDM is a digital multiplexing technique for combining several low-rate channels into one high-rate one.**

## Figure 6.13 *Synchronous time-division multiplexing*



***Note***

**In synchronous TDM, the data rate of the link is *n* times faster, and the unit duration is *n* times shorter.**

# Example 6.5

*In Figure 6.13, the data rate for each input connection is 3 kbps. If 1 bit at a time is multiplexed (a unit is 1 bit), what is the duration of (a) each input slot, (b) each output slot, and (c) each frame?*

## *Solution*

*We can answer the questions as follows:*

*a. The data rate of each input connection is 1 kbps. This means that the bit duration is 1/1000 s or 1 ms. The duration of the input time slot is 1 ms (same as bit duration).*

# Example 6.5 (continued)

***b.*** ***The duration of each output time slot is one-third of the input time slot. This means that the duration of the output time slot is 1/3 ms.***

***c.*** ***Each frame carries three output time slots. So the duration of a frame is 3 × 1/3 ms, or 1 ms. The duration of a frame is the same as the duration of an input unit.***

# Example 6.6

*Figure 6.14 shows synchronous TDM with a data stream for each input and one data stream for the output. The unit of data is 1 bit. Find (a) the input bit duration, (b) the output bit duration, (c) the output bit rate, and (d) the output frame rate.*

## Solution

*We can answer the questions as follows:*

a. *The input bit duration is the inverse of the bit rate: 1/1 Mbps = 1 μs.*

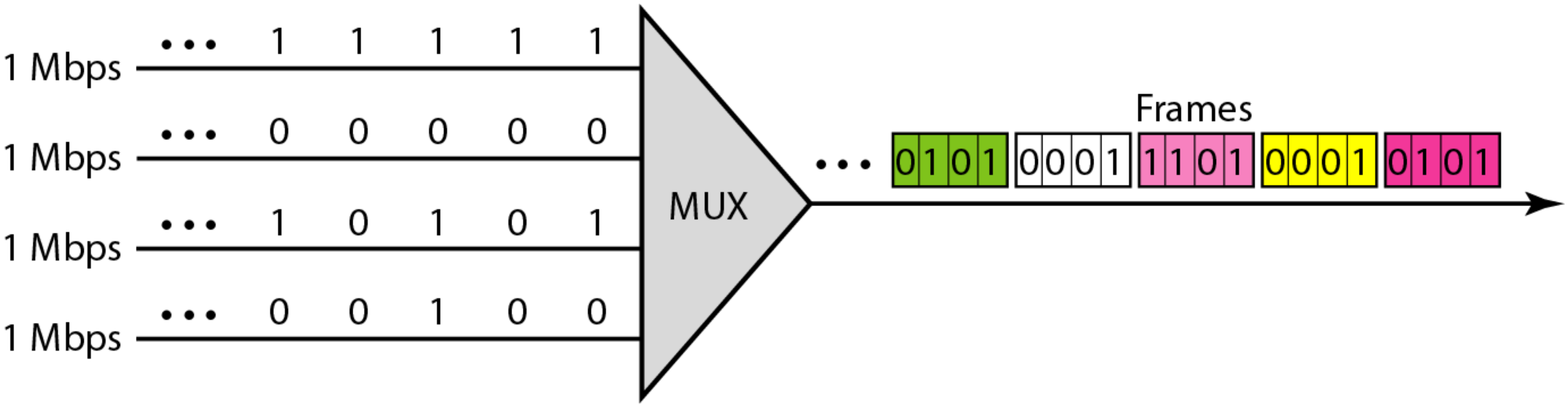
b. *The output bit duration is one-fourth of the input bit duration, or ¼ μs.*

# Example 6.6 (continued)

c. *The output bit rate is the inverse of the output bit duration or 1/(4μs) or 4 Mbps. This can also be deduced from the fact that the output rate is 4 times as fast as any input rate; so the output rate = 4 × 1 Mbps = 4 Mbps.*

d. *The frame rate is always the same as any input rate. So the frame rate is 1,000,000 frames per second. Because we are sending 4 bits in each frame, we can verify the result of the previous question by multiplying the frame rate by the number of bits per frame.*

## **Figure 6.14** *Example 6.6*



# Example 6.7

*Four 1-kbps connections are multiplexed together. A unit is 1 bit. Find (a) the duration of 1 bit before multiplexing, (b) the transmission rate of the link, (c) the duration of a time slot, and (d) the duration of a frame.*

## Solution

*We can answer the questions as follows:*

*a. The duration of 1 bit before multiplexing is 1 / 1 kbps, or 0.001 s (1 ms).*

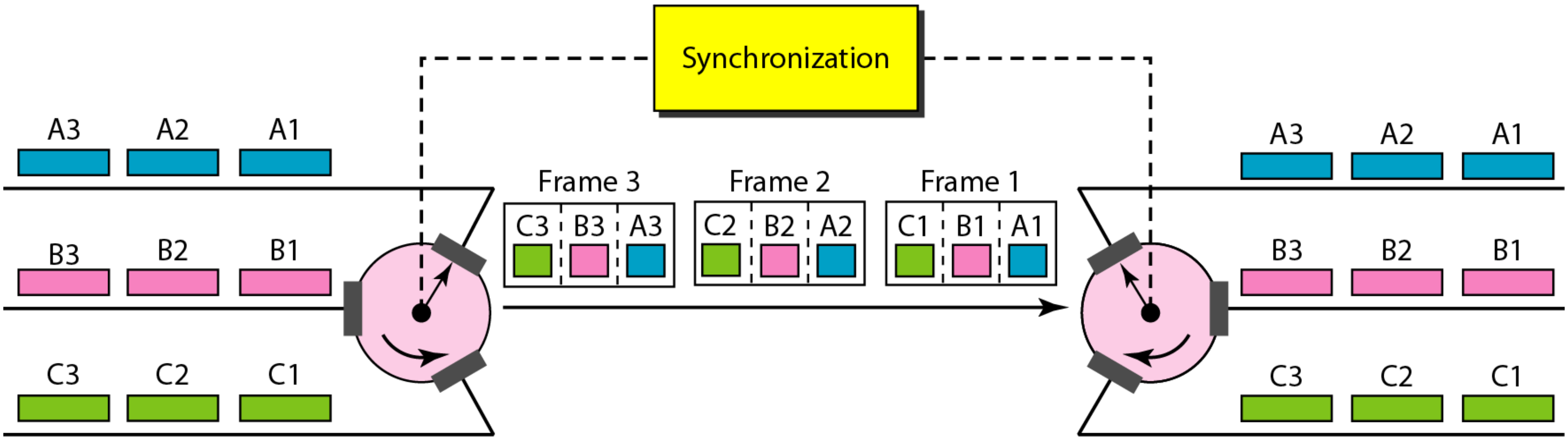
*b. The rate of the link is 4 times the rate of a connection, or 4 kbps.*

# Example 6.7 (continued)

c. *The duration of each time slot is one-fourth of the duration of each bit before multiplexing, or 1/4 ms or 250 μs. Note that we can also calculate this from the data rate of the link, 4 kbps. The bit duration is the inverse of the data rate, or 1/4 kbps or 250 μs.*

d. *The duration of a frame is always the same as the duration of a unit before multiplexing, or 1 ms. We can also calculate this in another way. Each frame in this case has four time slots. So the duration of a frame is 4 times 250 μs, or 1 ms.*

## Figure 6.15 *Interleaving*



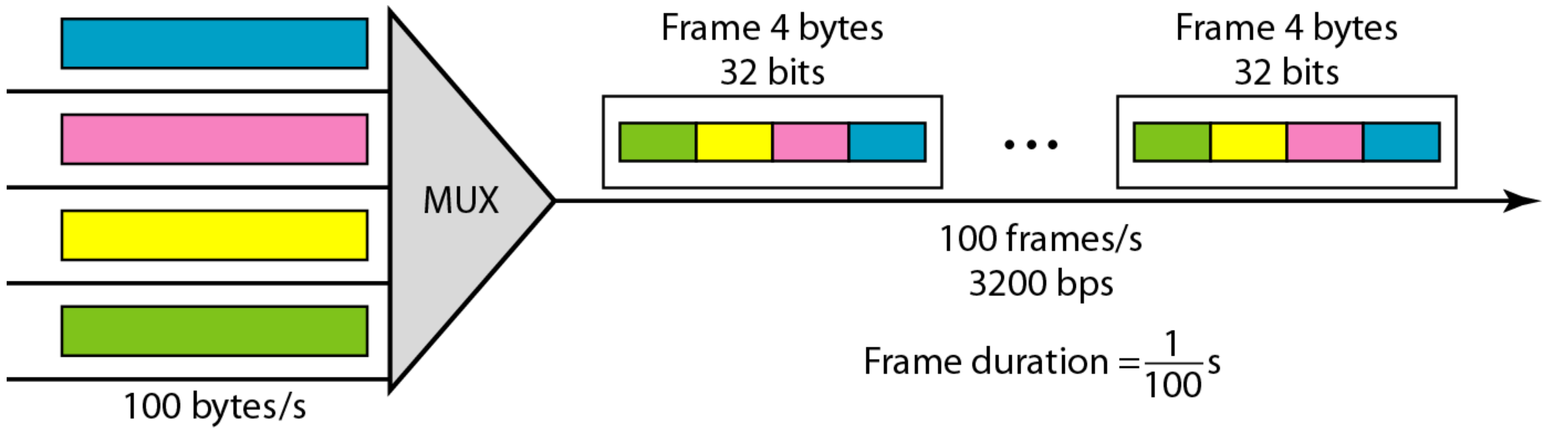
# Example 6.8

***Four channels are multiplexed using TDM. If each channel sends 100 bytes /s and we multiplex 1 byte per channel, show the frame traveling on the link, the size of the frame, the duration of a frame, the frame rate, and the bit rate for the link.***

## Solution

***The multiplexer is shown in Figure 6.16. Each frame carries 1 byte from each channel; the size of each frame, therefore, is 4 bytes, or 32 bits. Because each channel is sending 100 bytes/s and a frame carries 1 byte from each channel, the frame rate must be 100 frames per second. The bit rate is 100 × 32, or 3200 bps.***

## Figure 6.16 *Example 6.8*



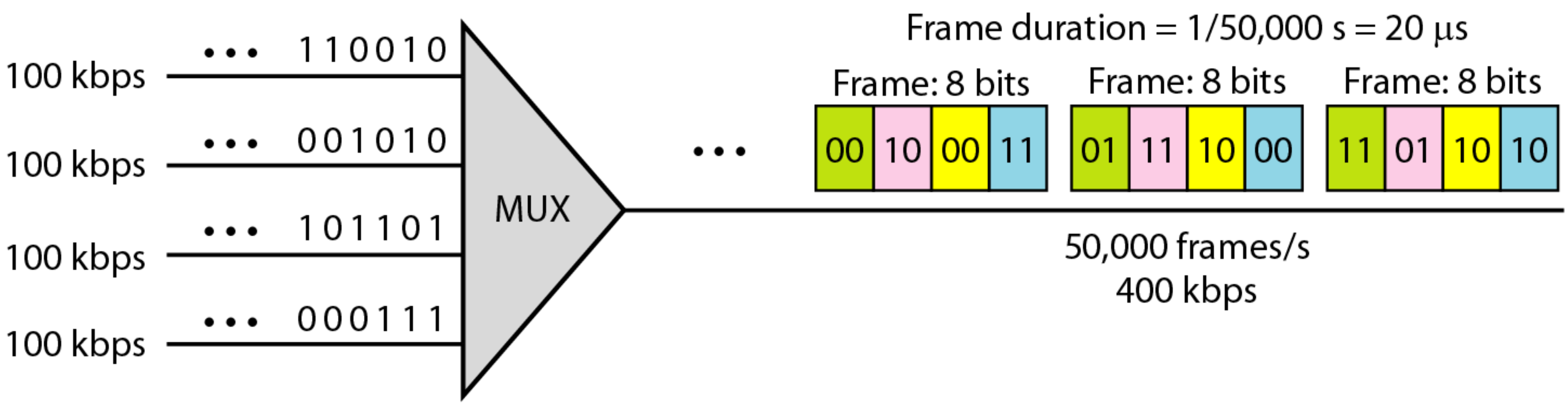
# Example 6.9

***A multiplexer combines four 100-kbps channels using a time slot of 2 bits. Show the output with four arbitrary inputs. What is the frame rate? What is the frame duration? What is the bit rate? What is the bit duration?***

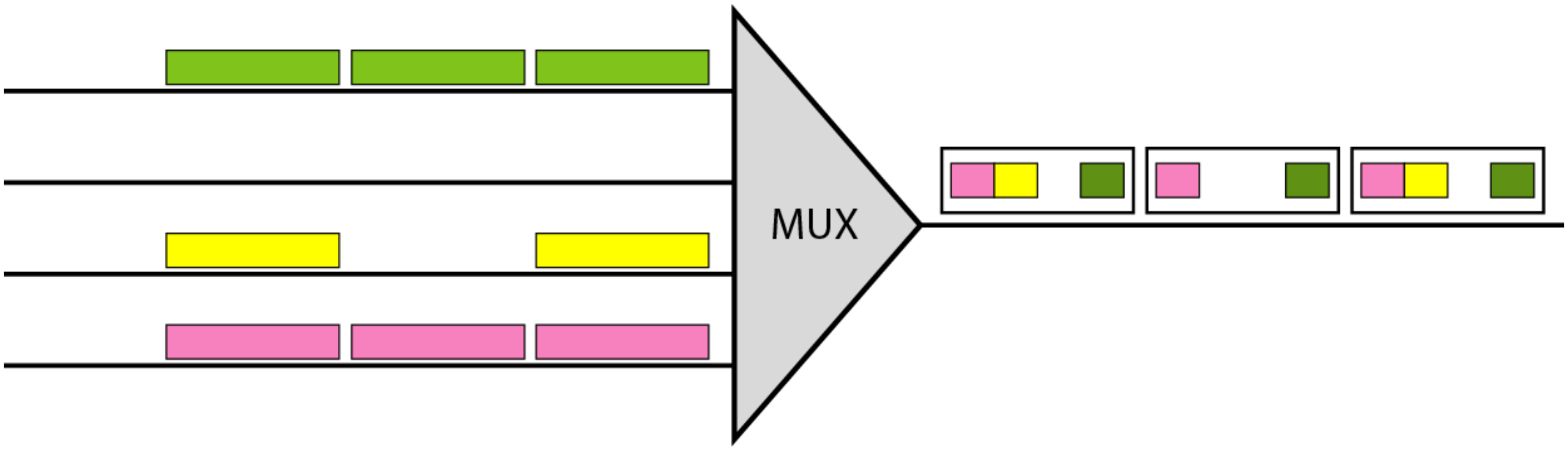
## *Solution*

***Figure 6.17 shows the output for four arbitrary inputs. The link carries 50,000 frames per second. The frame duration is therefore 1/50,000 s or 20 μs. The frame rate is 50,000 frames per second, and each frame carries 8 bits; the bit rate is 50,000 × 8 = 400,000 bits or 400 kbps. The bit duration is 1/400,000 s, or 2.5 μs.***

## Figure 6.17 *Example 6.9*

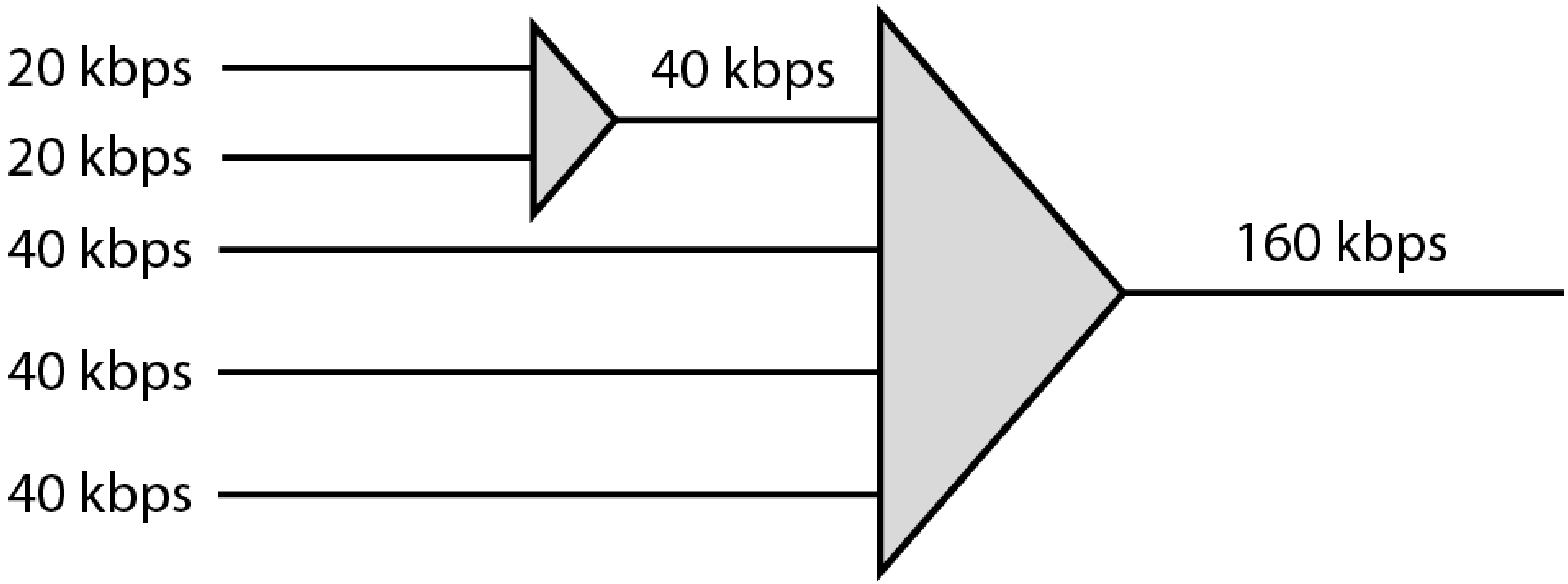


## Figure 6.18 *Empty slots*

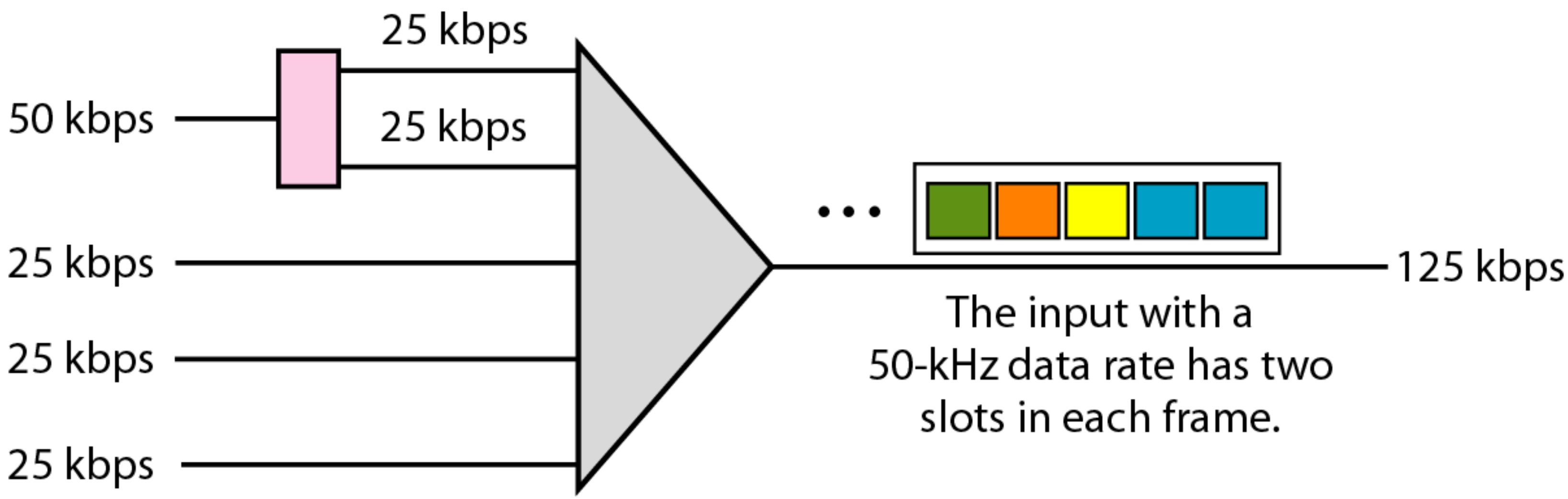


**Data Rate Management : Multilevel multiplexing, multiple-slot allocation, and pulse stuffing.**

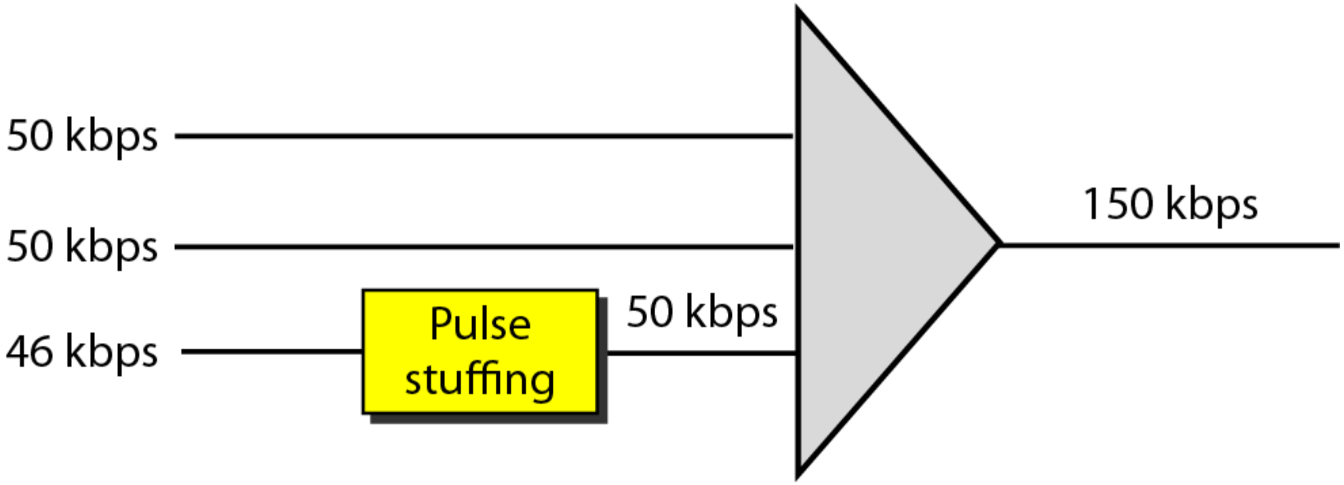
**Figure 6.19** ***Multilevel multiplexing***



## Figure 6.20 *Multiple-slot multiplexing*

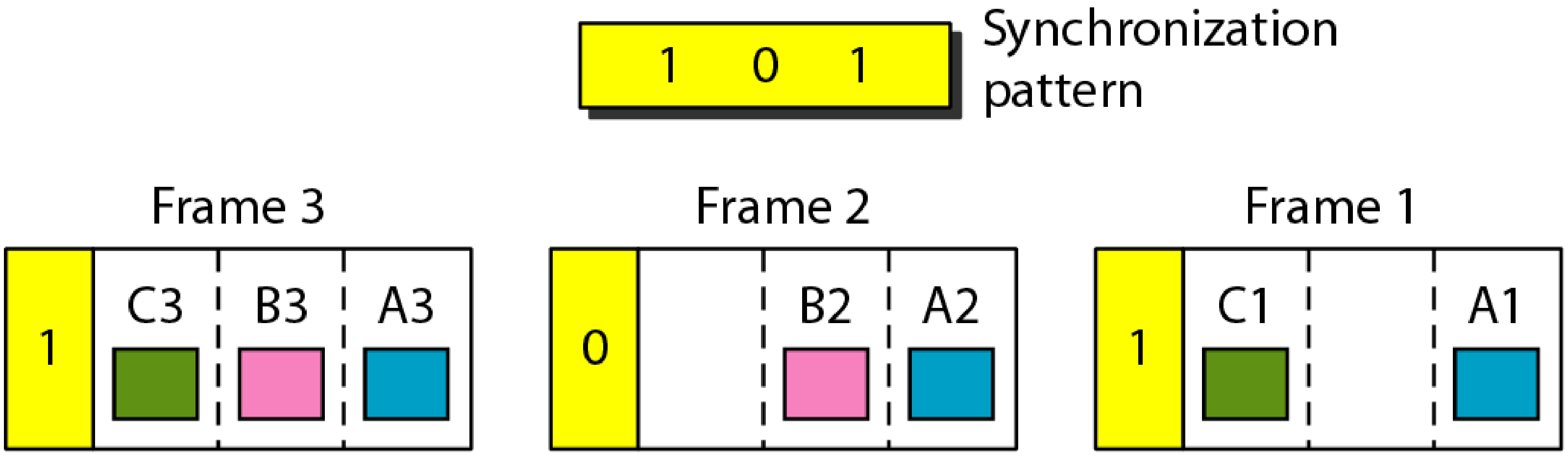


## **Figure 6.21** *Pulse stuffing*



# Frame Synchronizing

## Figure 6.22 *Framing bits*



# Example 6.10

***We have four sources, each creating 250 characters per second. If the interleaved unit is a character and 1 synchronizing bit is added to each frame, find (a) the data rate of each source, (b) the duration of each character in each source, (c) the frame rate, (d) the duration of each frame, (e) the number of bits in each frame, and (f) the data rate of the link.***

**Solution**

***We can answer the questions as follows:***

***a.*** ***The data rate of each source is 250 × 8 = 2000 bps = 2 kbps.***

# Example 6.10 (continued)

*b. Each source sends 250 characters per second; therefore, the duration of a character is 1/250 s, or 4 ms.*

*c. Each frame has one character from each source, which means the link needs to send 250 frames per second to keep the transmission rate of each source.*

*d. The duration of each frame is 1/250 s, or 4 ms. Note that the duration of each frame is the same as the duration of each character coming from each source.*

*e. Each frame carries 4 characters and 1 extra synchronizing bit. This means that each frame is* $4 \times 8 + 1 = 33$ *bits.*

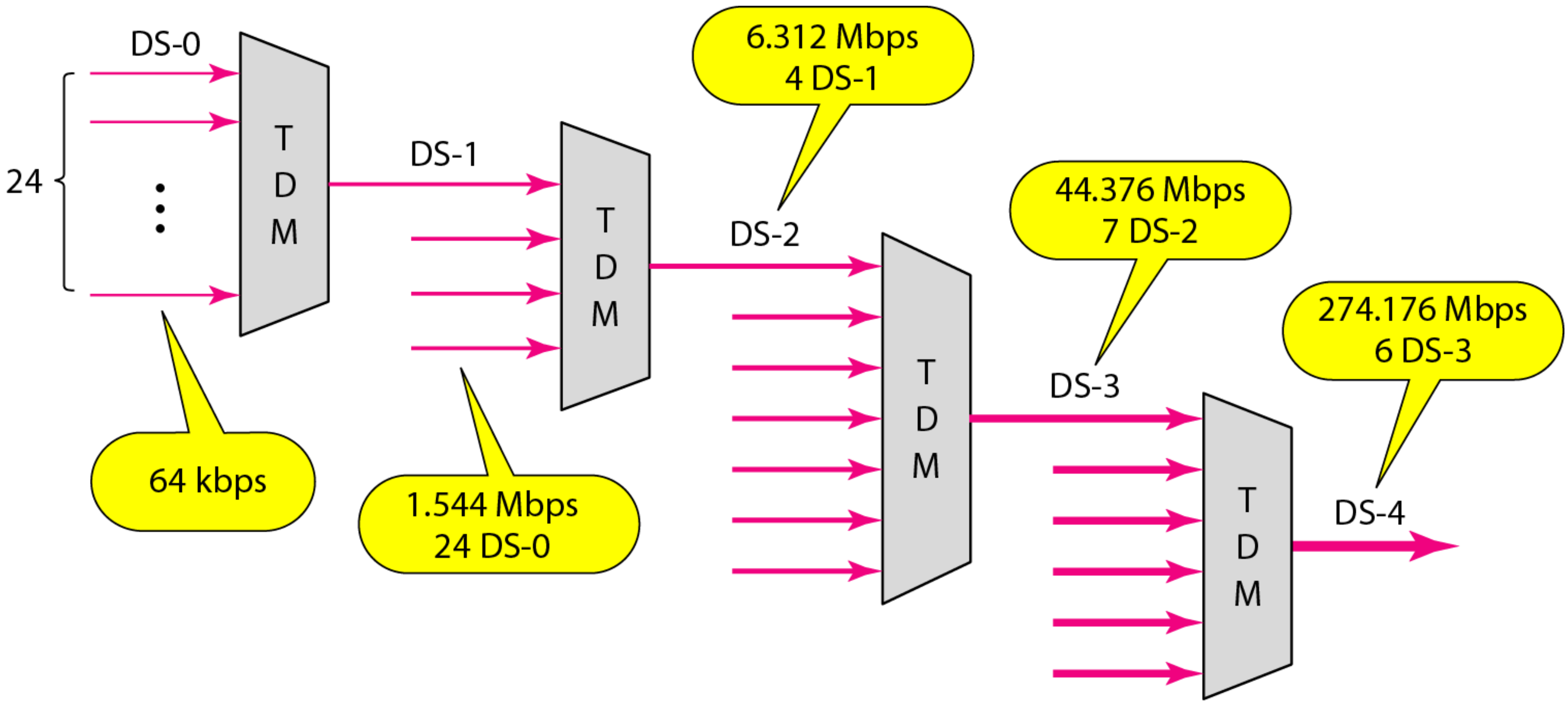
# Example 6.11

***Two channels, one with a bit rate of 100 kbps and another with a bit rate of 200 kbps, are to be multiplexed. How this can be achieved? What is the frame rate? What is the frame duration? What is the bit rate of the link?***

**Solution**

***We can allocate one slot to the first channel and two slots to the second channel. Each frame carries 3 bits. The frame rate is 100,000 frames per second because it carries 1 bit from the first channel. The bit rate is 100,000 frames/s × 3 bits per frame, or 300 kbps.***

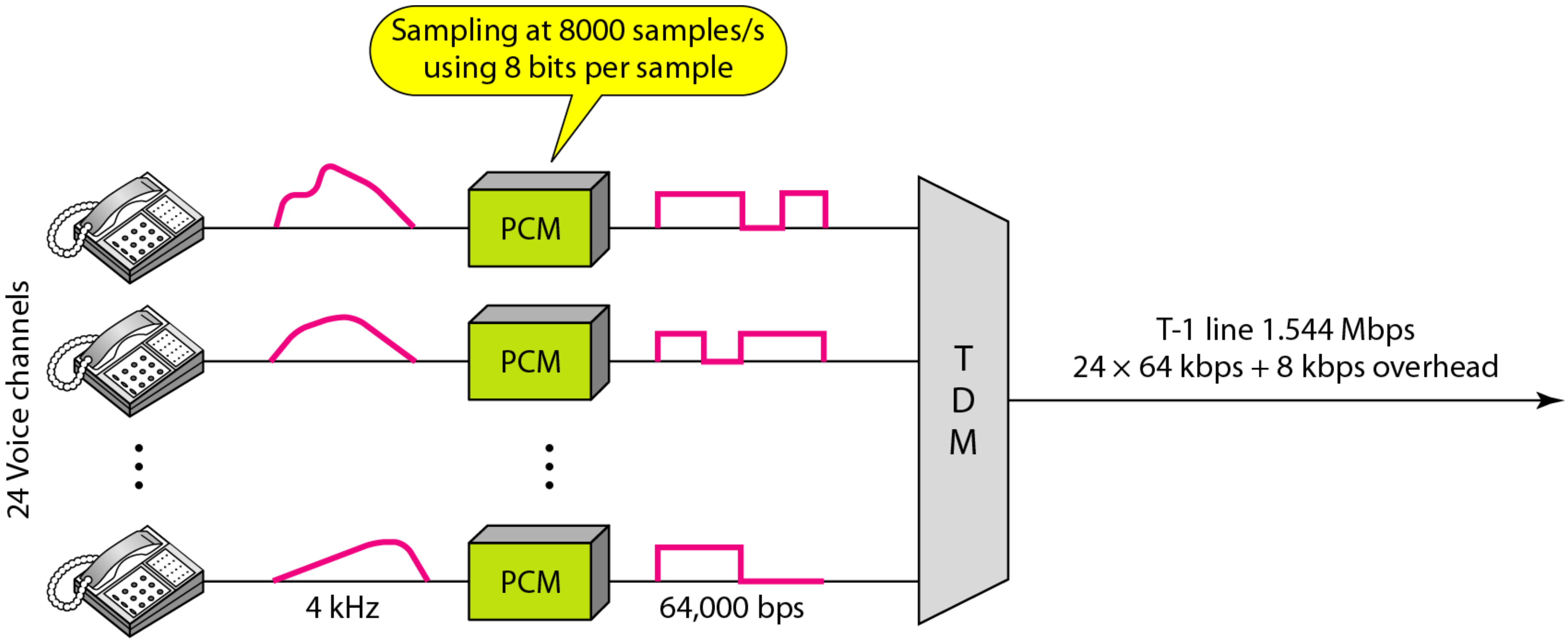
## Figure 6.23 *Digital hierarchy*



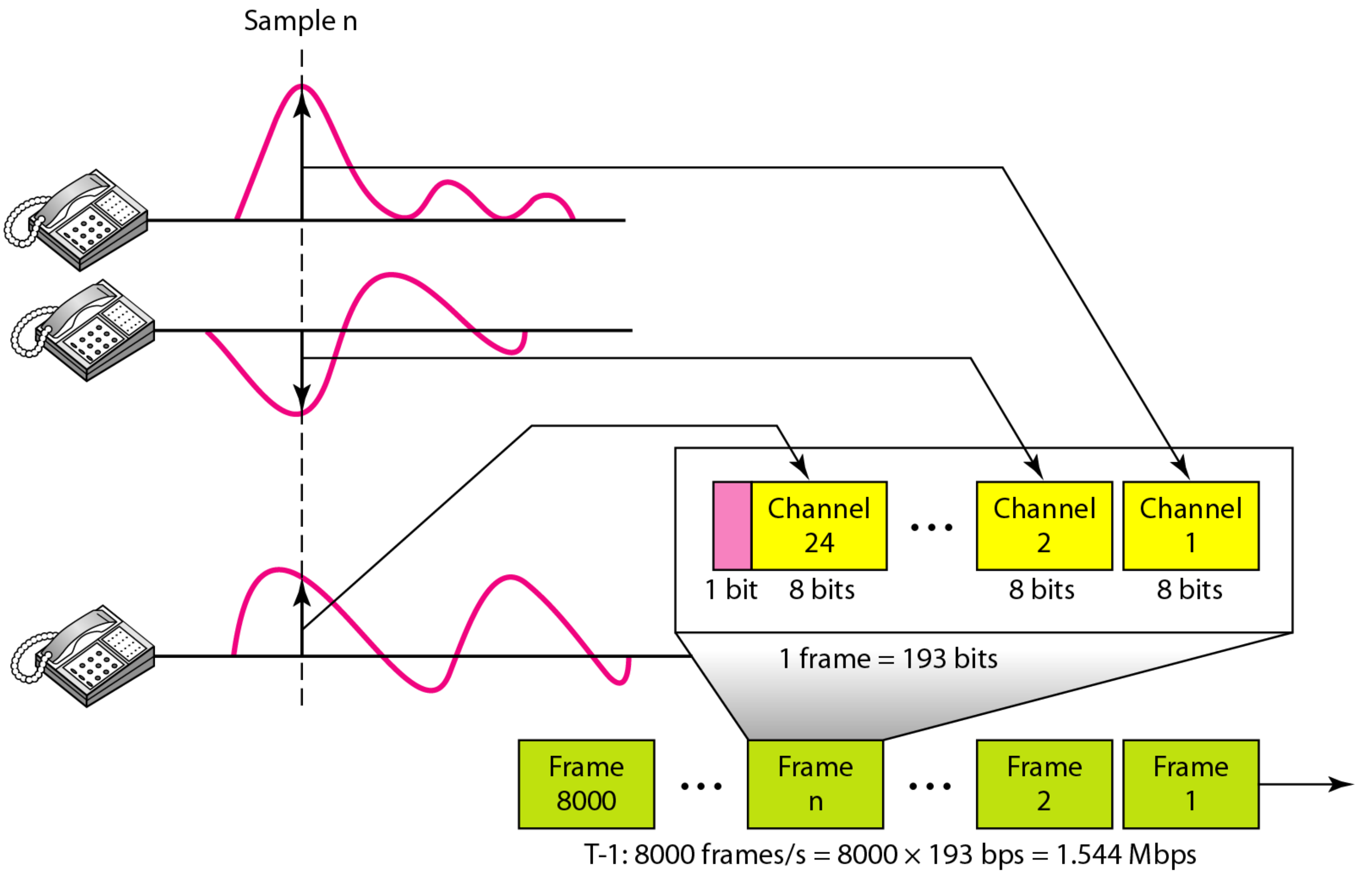
## **Table 6.1** *DS and T line rates*

| *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 |

## Figure 6.24 *T-1 line for multiplexing telephone lines*



## Figure 6.25 *T-1 frame structure*



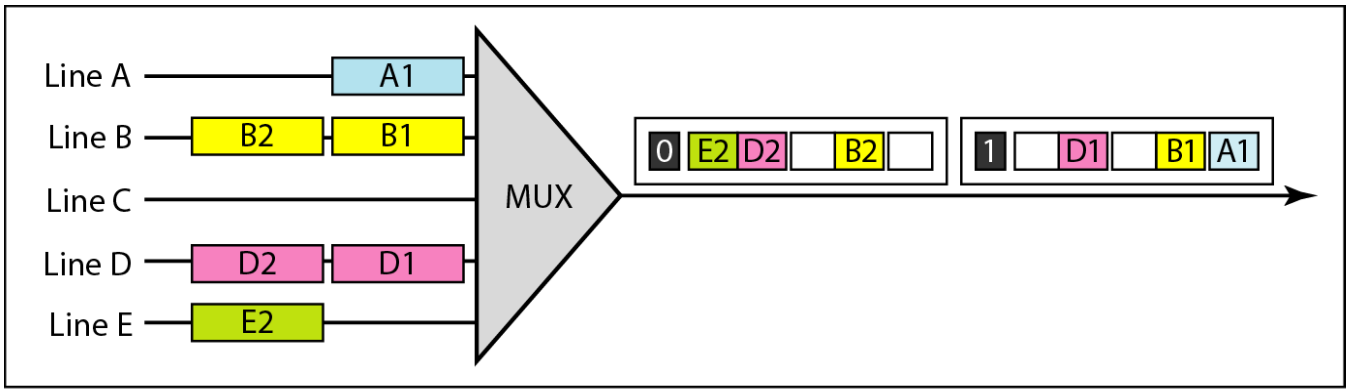
## Table 6.2 *E line rates*

| *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 |

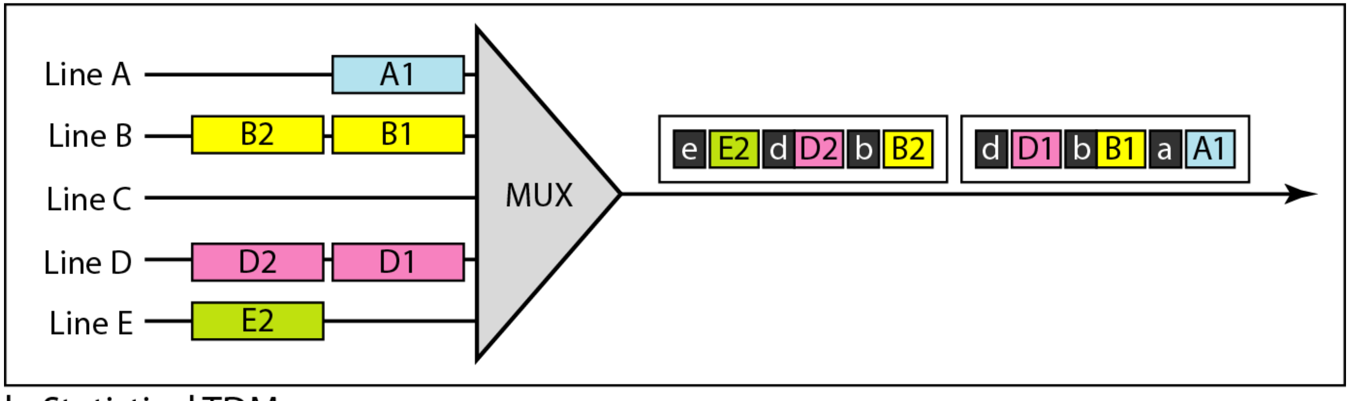
# Statistical Time-Division Multiplexing

- ***In synchronous TDM, each input has a reserved slot in the output frame. This can be inefficient if some input lines have no data to send.***
- ***In statistical time-division multiplexing, slots are dynamically allocated to improve bandwidth efficiency.***
- ***Only when an input line has a slot's worth of data to send is given a slot in the output frame.***
- ***In statistical multiplexing, the number of slots in each frame is less than the number of input lines.***
- ***The multiplexer checks each input line in round-robin fashion; it allocates a slot for an input line if the line has data to send; otherwise, it skips the line and checks the next line.***

# Figure 6.26 *TDM slot comparison*




a. Synchronous TDM



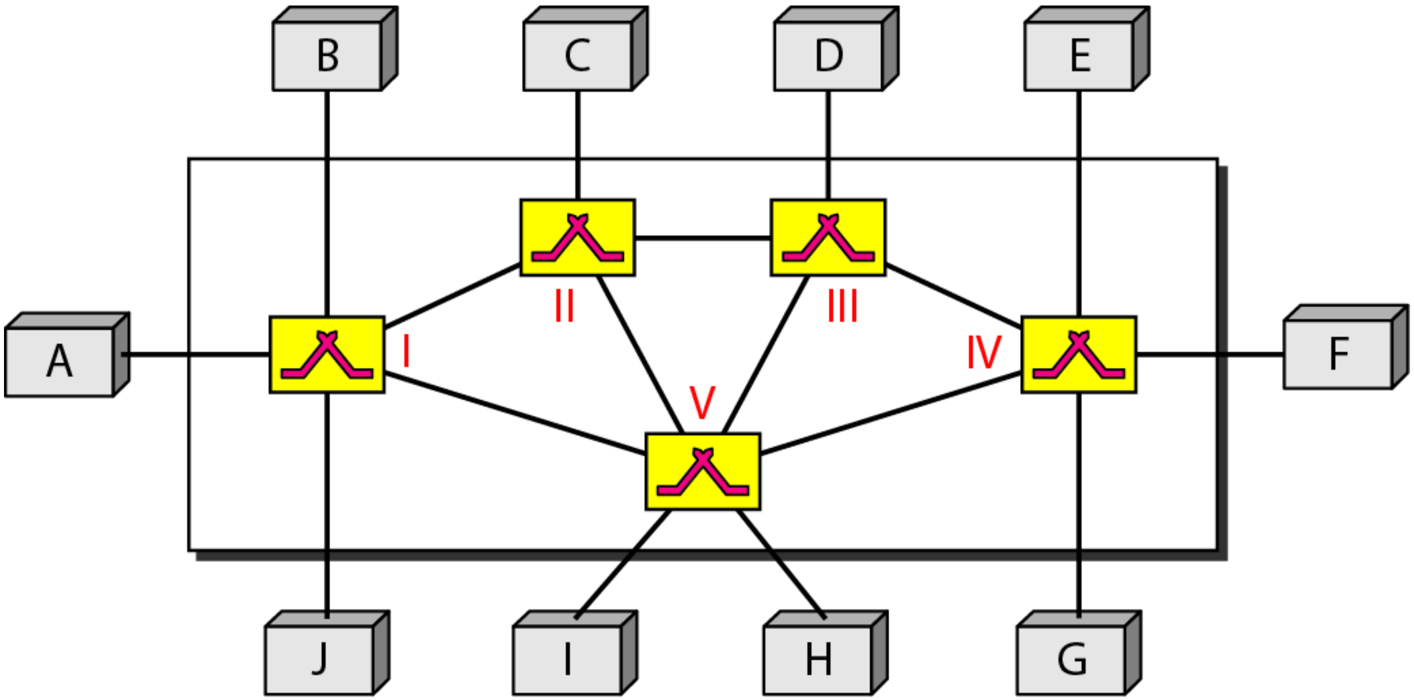

b. Statistical TDM



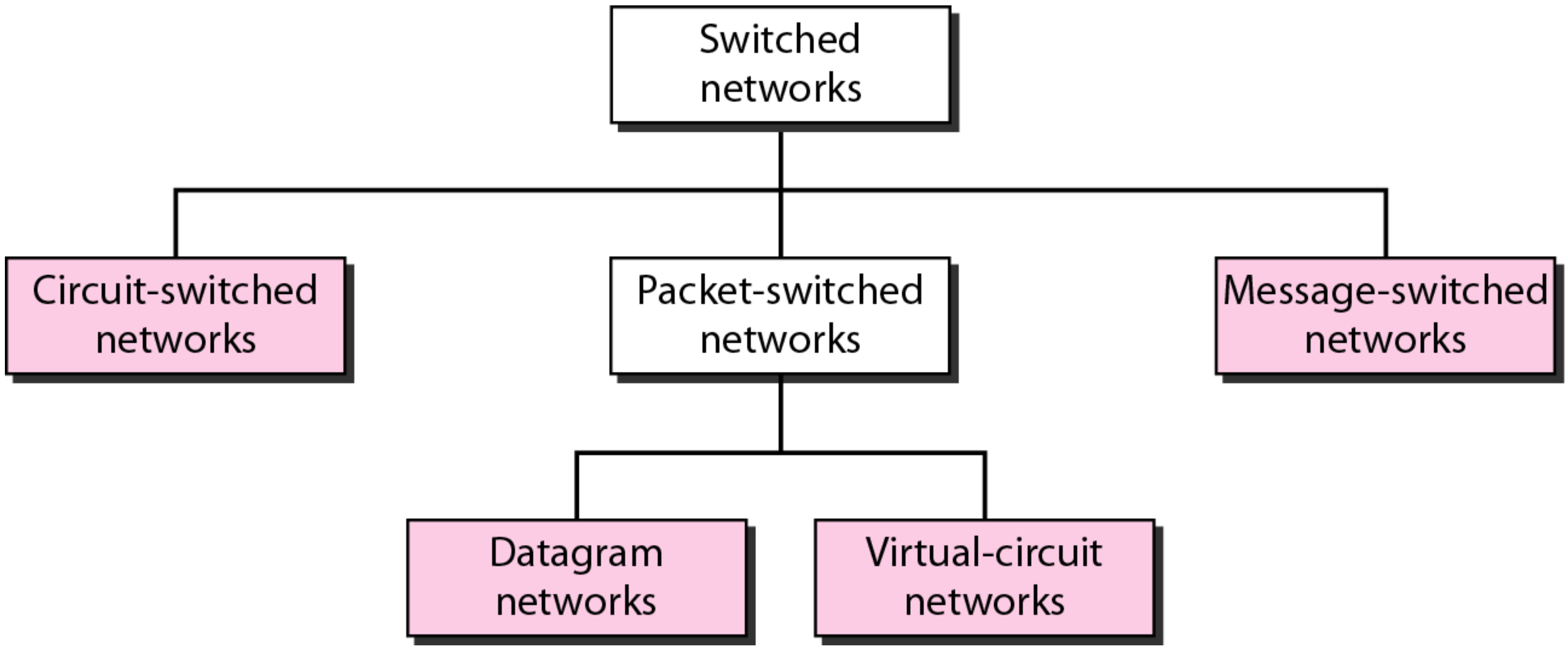
# Chapter 8

# Switching

## **Figure 8.1** *Switched network*



## **Figure 8.2** *Taxonomy of switched networks*



# 8-1 CIRCUIT-SWITCHED NETWORKS

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

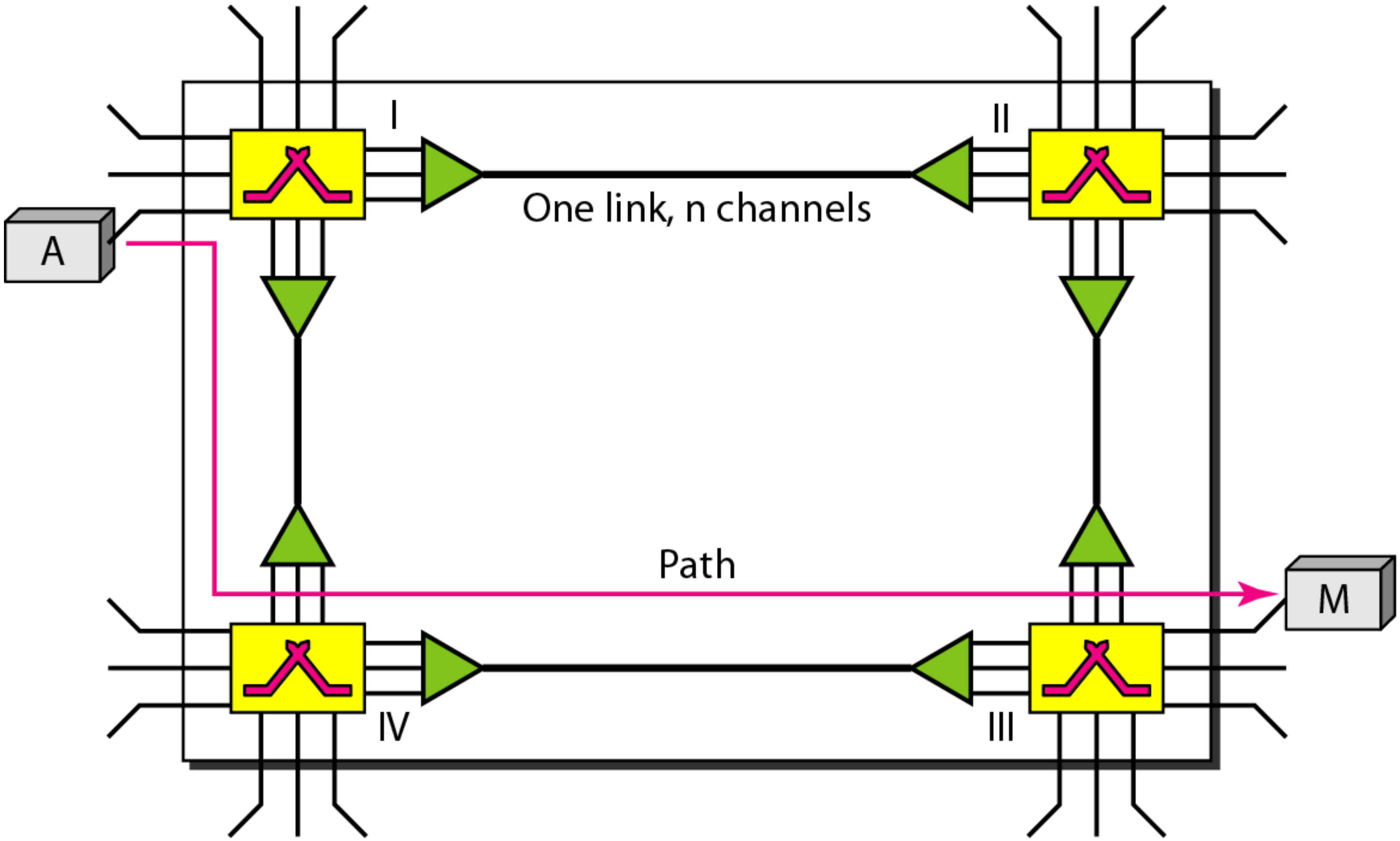
***Topics discussed in this section:***

**Three Phases**
**Efficiency**
**Delay**
**Circuit-Switched Technology in Telephone Networks**

***Note***

**A circuit-switched network is made of a set of switches connected by physical links, in which each link is divided into *n* channels.**

## **Figure 8.3** *A trivial circuit-switched network*



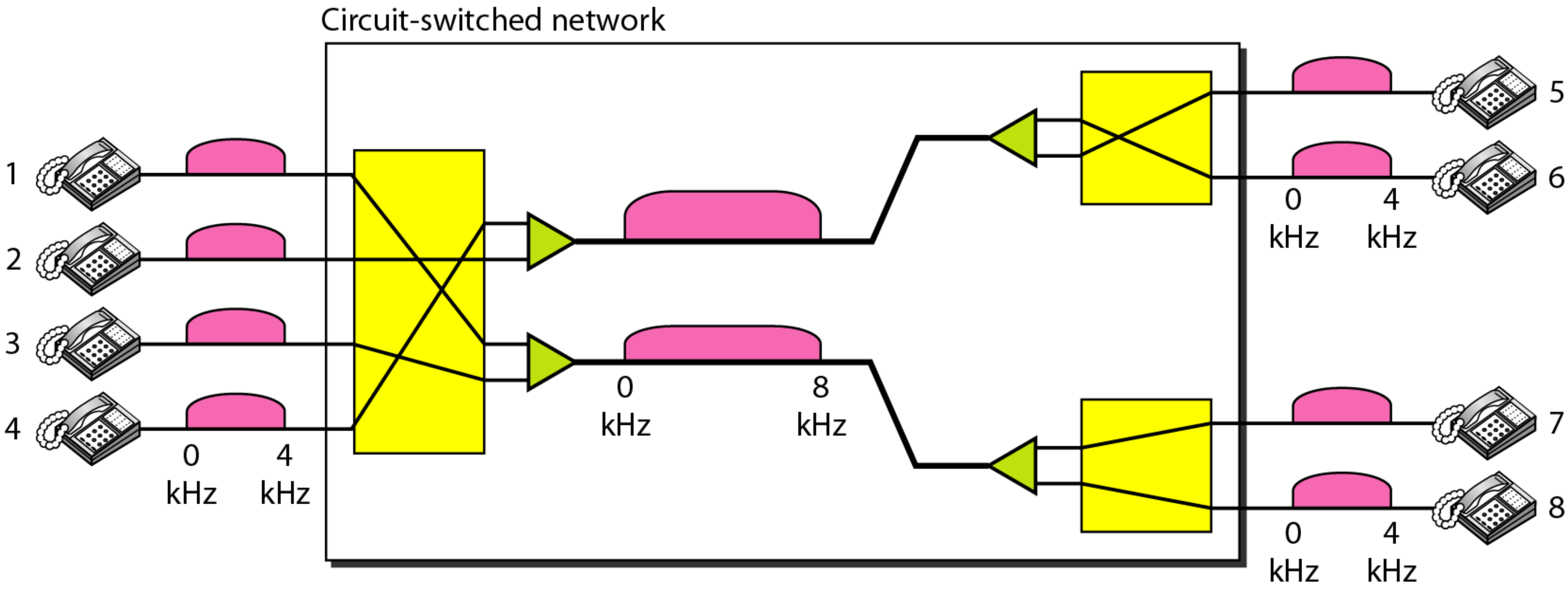
***Note***

**In circuit switching, the resources need to be reserved during the setup phase; the resources remain dedicated for the entire duration of data transfer until the teardown phase.**

# Example 8.1

***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. Figure 8.4 shows the situation. Telephone 1 is connected to telephone 7; 2 to 5; 3 to 8; and 4 to 6. Of course the situation may change when new connections are made. The switch controls the connections.***

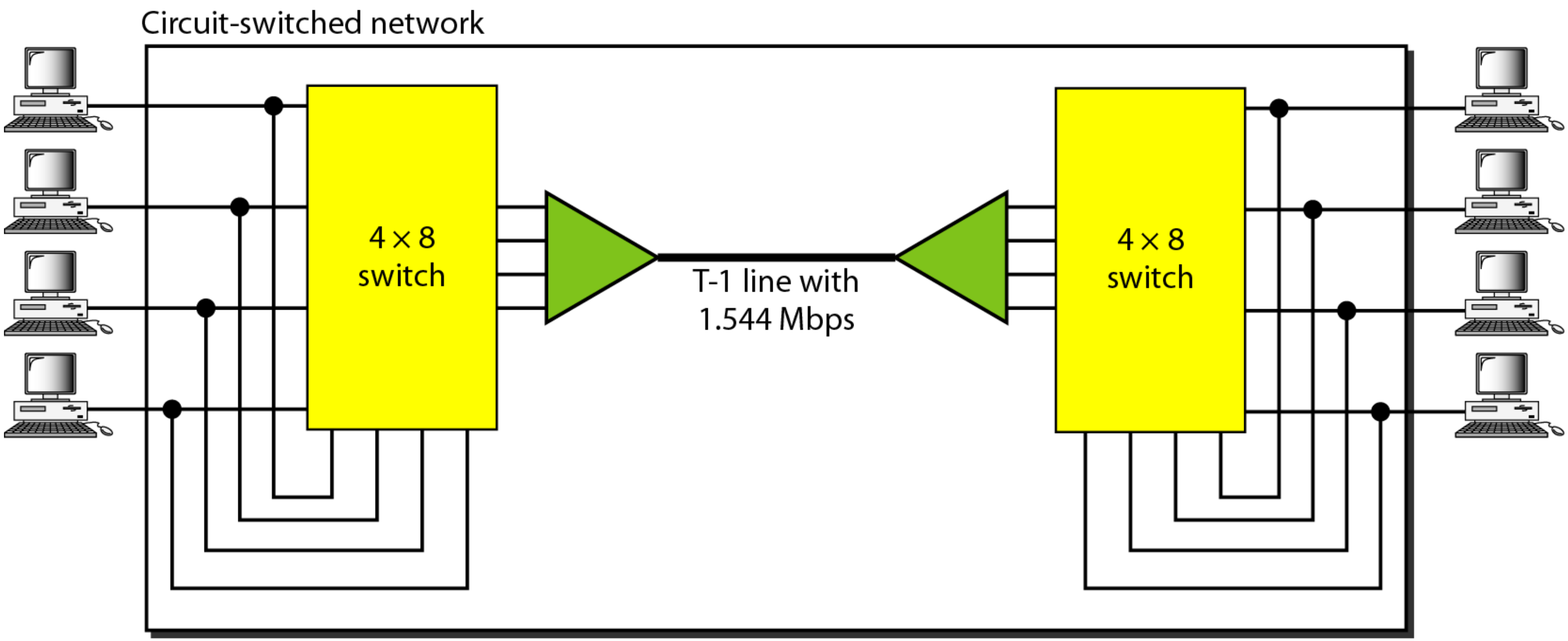
## Figure 8.4 *Circuit-switched network used in Example 8.1*



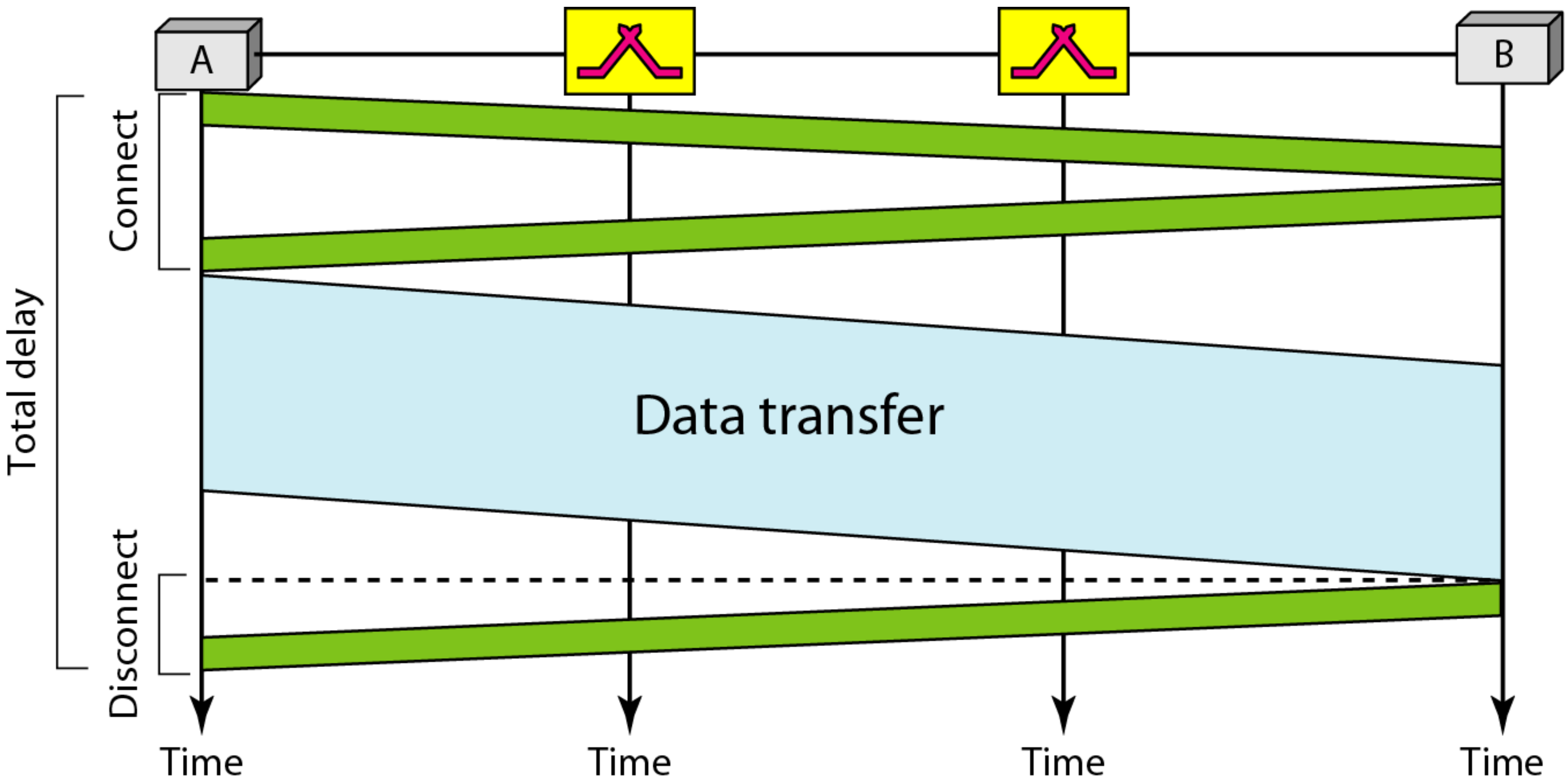
# Example 8.2

***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. For each switch, four output ports are folded into the input ports to allow communication between computers in the same office. Four other output ports allow communication between the two offices. Figure 8.5 shows the situation.***

## **Figure 8.5** *Circuit-switched network used in Example 8.2*



## **Figure 8.6** *Delay in a circuit-switched network*



**Note**

**Switching at the physical layer in the traditional telephone network uses the circuit-switching approach.**

# 8-2 DATAGRAM NETWORKS

***In data communications, we need to send messages from one end system to another. 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.***

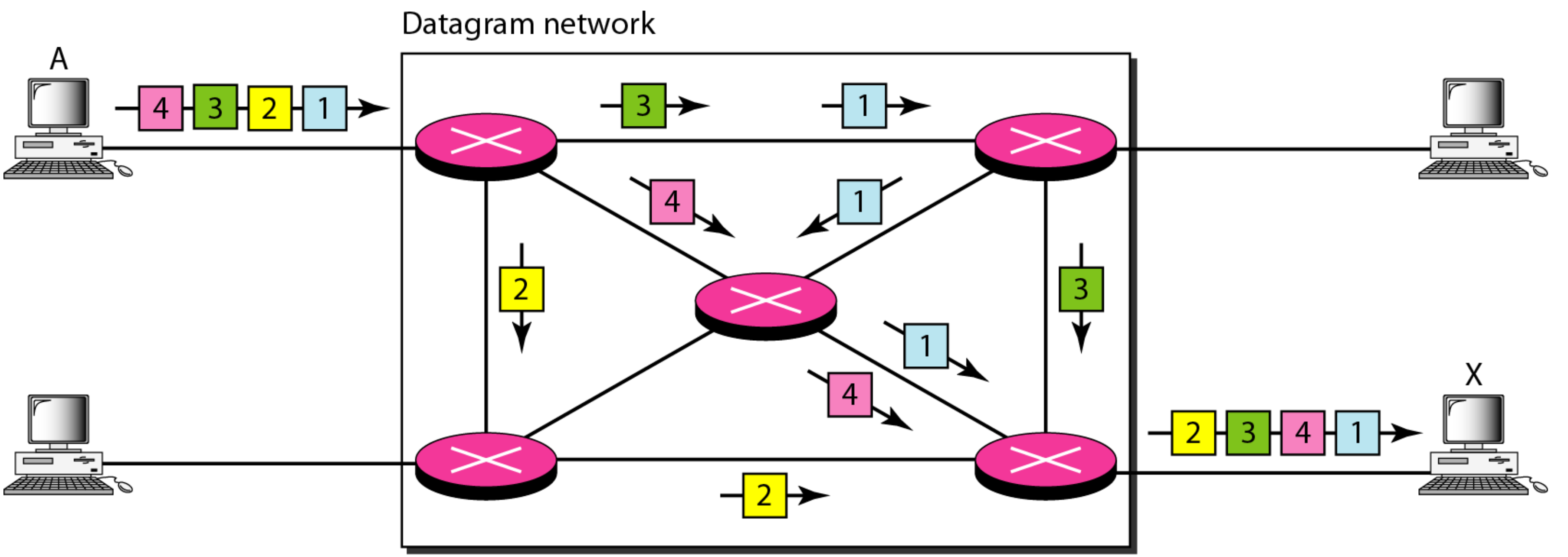
***Topics discussed in this section:***

**Routing Table**
**Efficiency**
**Delay**
**Datagram Networks in the Internet**

***Note***

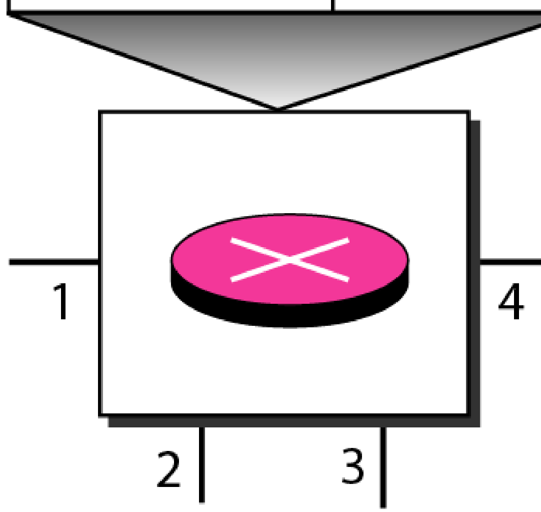
**In a packet-switched network, there is no resource reservation; resources are allocated on demand.**

## **Figure 8.7** *A datagram network with four switches (routers)*



## **Figure 8.8** *Routing table in a datagram network*

| Destination address | Output port |
|---|---|
| 1232 | 1 |
| 4150 | 2 |
| ⋮ | ⋮ |
| 9130 | 3 |



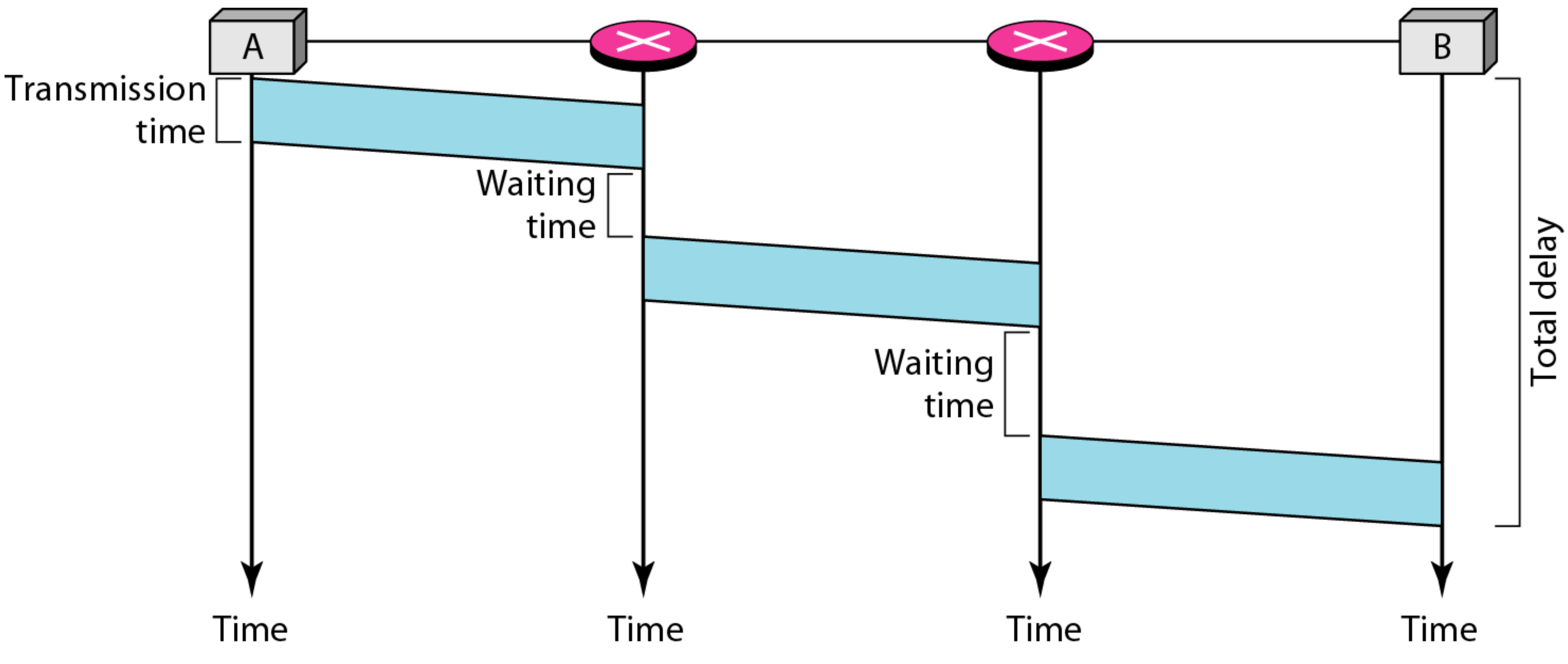
***Note***

**A switch in a datagram network uses a routing table that is based on the destination address.**

***Note***

**The destination address in the header of a packet in a datagram network remains the same during the entire journey of the packet.**

## Figure 8.9 *Delay in a datagram network*



**Note**

**Switching in the Internet is done by using the datagram approach to packet switching at the network layer.**

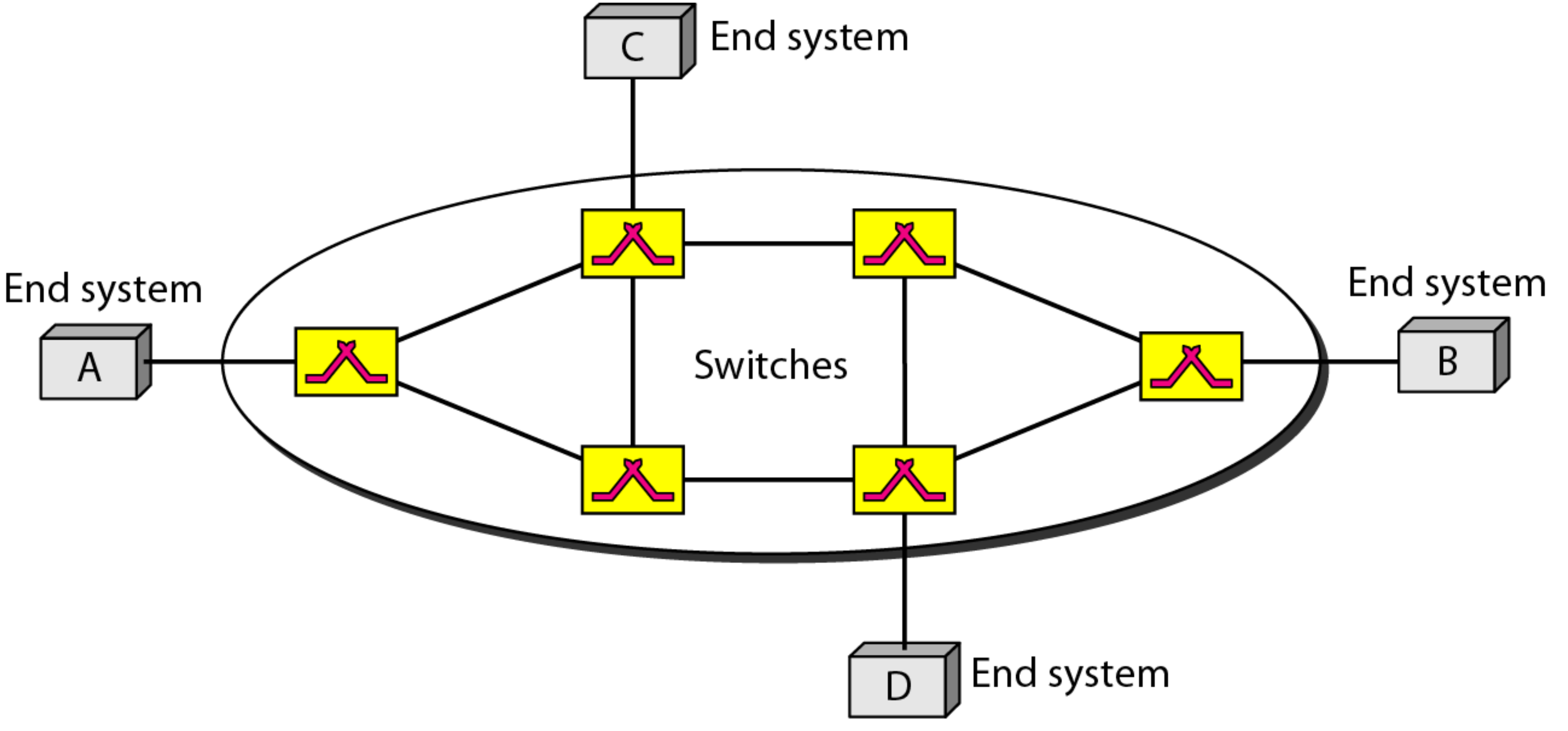
# 8-3 VIRTUAL-CIRCUIT NETWORKS

***A virtual-circuit network is a cross between a circuit-switched network and a datagram network. It has some characteristics of both.***

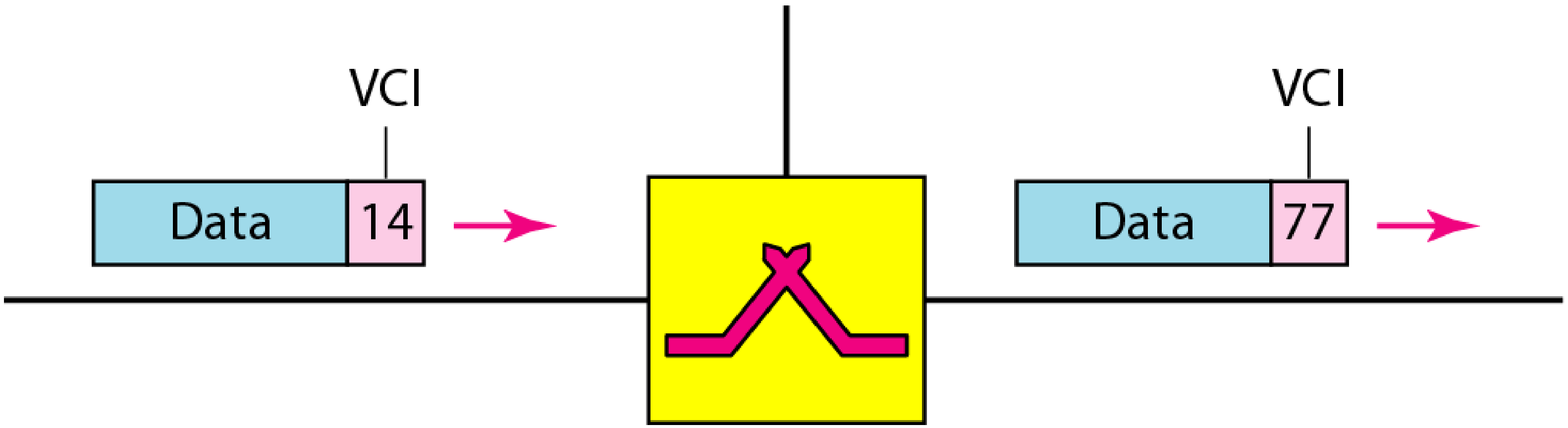
***Topics discussed in this section:***

**Addressing**
**Three Phases**
**Efficiency**
**Delay**
**Circuit-Switched Technology in WANs**

## Figure 8.10 *Virtual-circuit network*

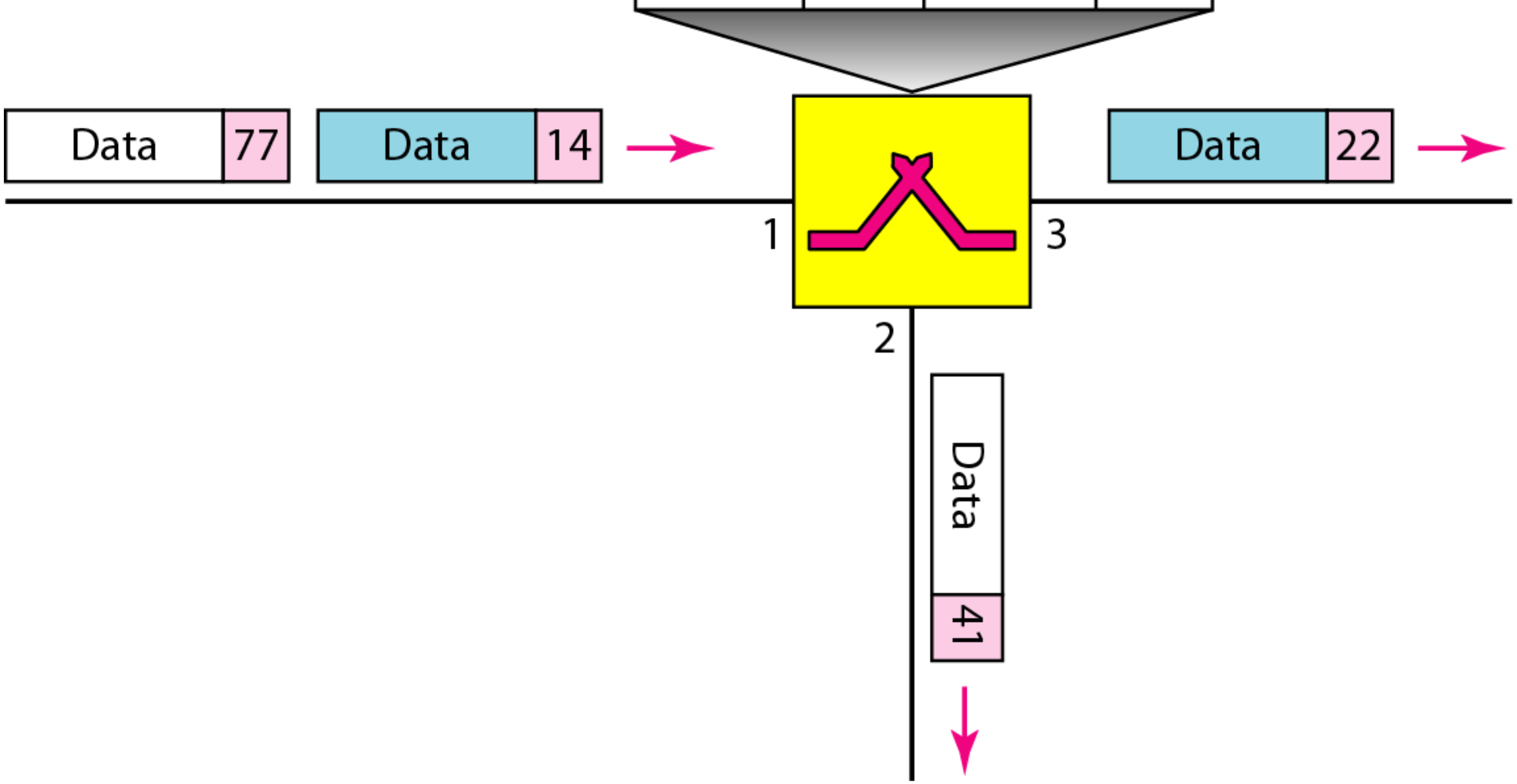


## Figure 8.11 *Virtual-circuit identifier*

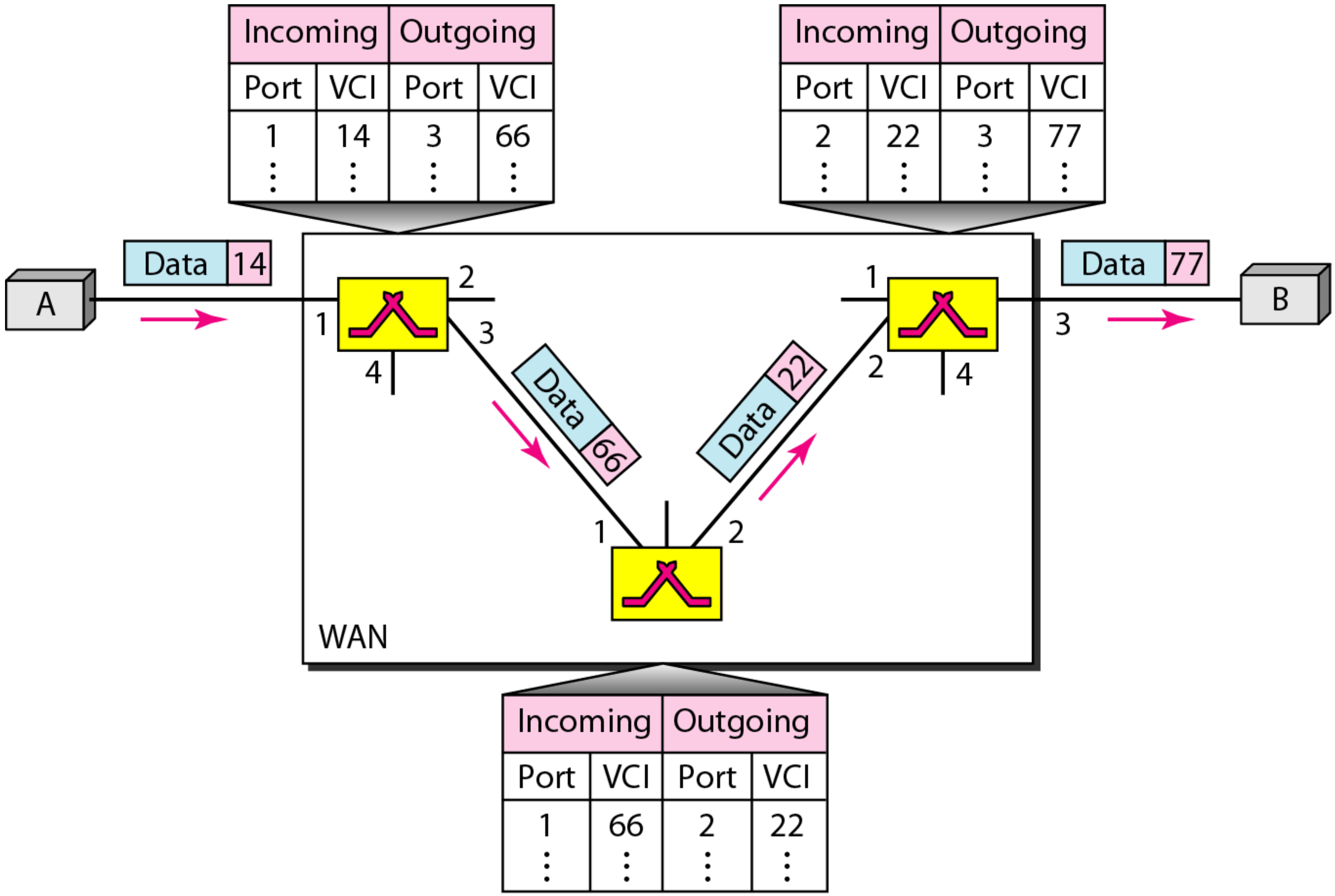


# Figure 8.12 *Switch and tables in a virtual-circuit network*

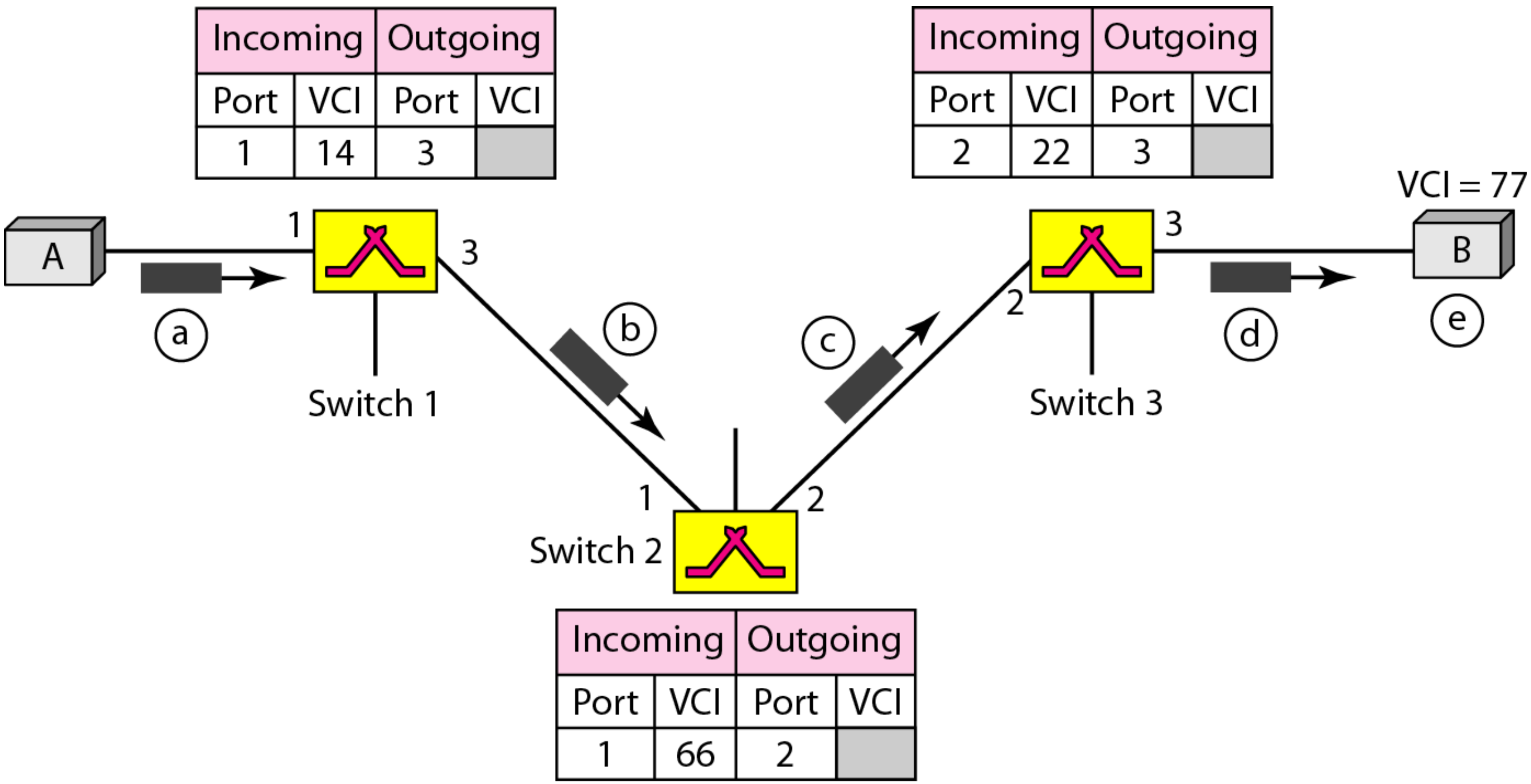
| Incoming | | Outgoing | |
|---|---|---|---|
| Port | VCI | Port | VCI |
| 1 | 14 | 3 | 22 |
| 1 | 77 | 2 | 41 |



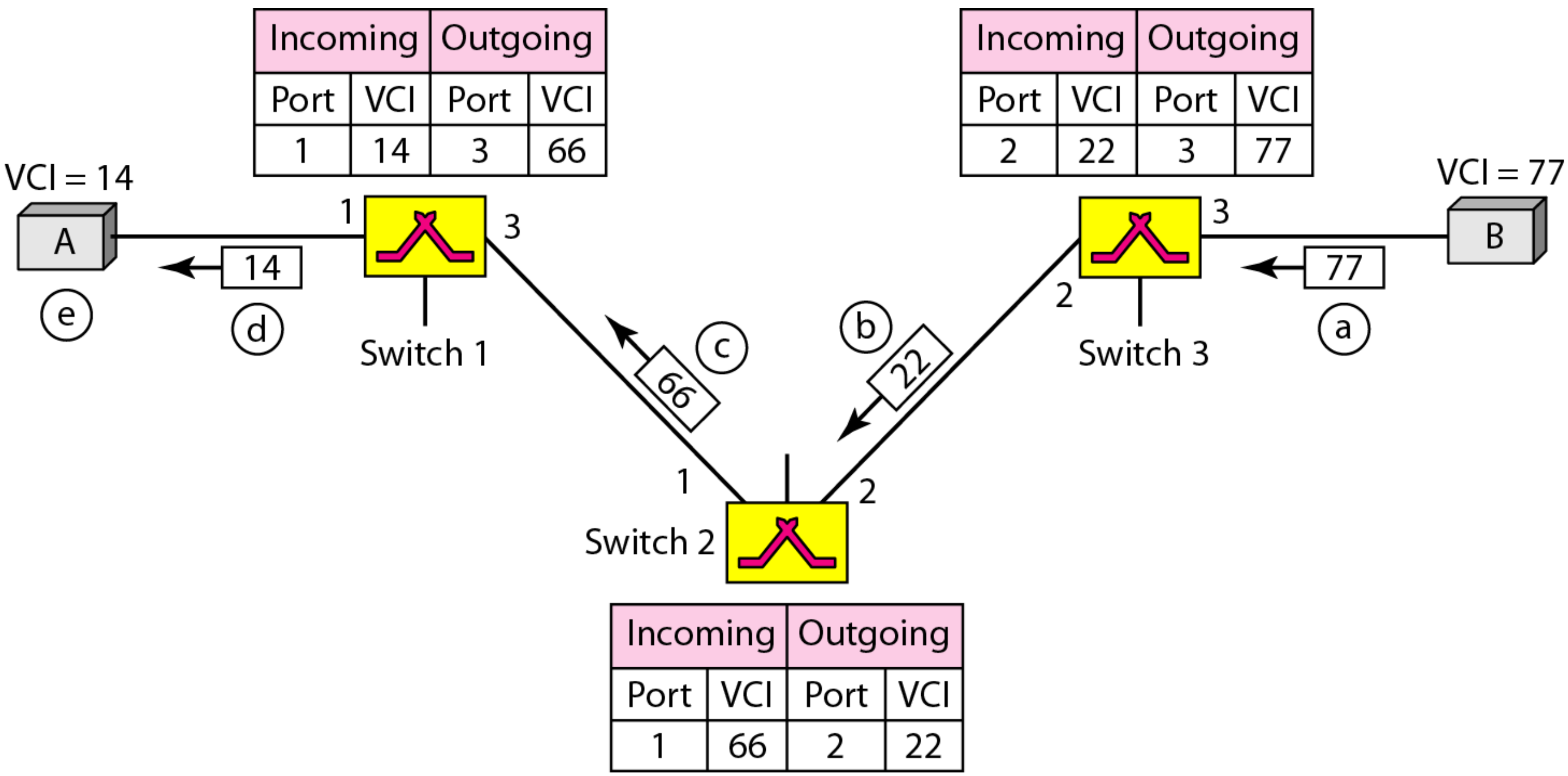
## **Figure 8.13** *Source-to-destination data transfer in a virtual-circuit network*



## **Figure 8.14** *Setup request in a virtual-circuit network*



# Figure 8.15 *Setup acknowledgment in a virtual-circuit network*




Switch 1:

| Incoming | | Outgoing | |
|---|---|---|---|
| Port | VCI | Port | VCI |
| 1 | 14 | 3 | 66 |

Switch 3:

| Incoming | | Outgoing | |
|---|---|---|---|
| Port | VCI | Port | VCI |
| 2 | 22 | 3 | 77 |

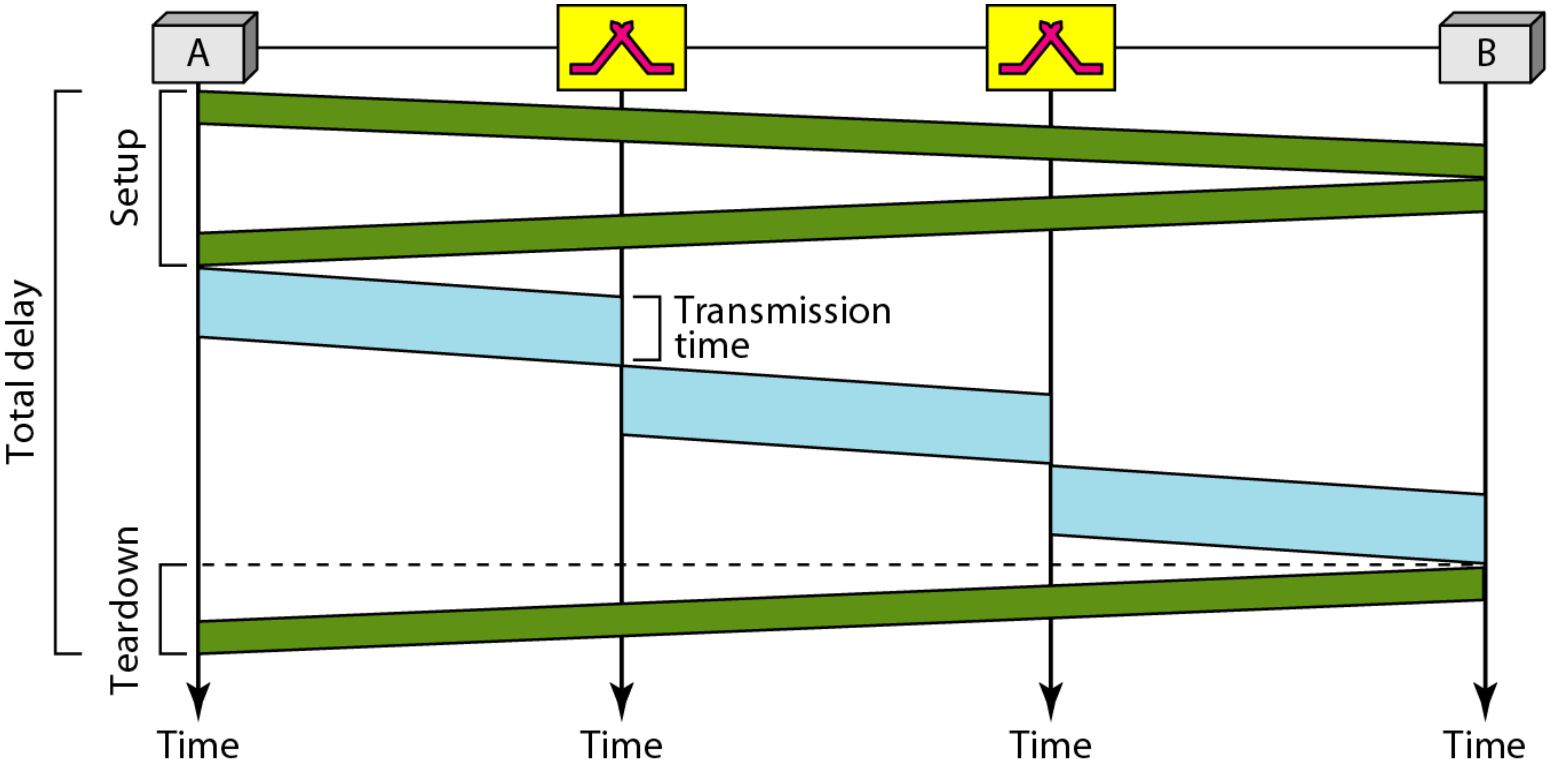
Switch 2:

| Incoming | | Outgoing | |
|---|---|---|---|
| Port | VCI | Port | VCI |
| 1 | 66 | 2 | 22 |

***Note***

**In virtual-circuit switching, all packets belonging to the same source and destination travel the same path; but the packets may arrive at the destination with different delays if resource allocation is on demand.**

## Figure 8.16 *Delay in a virtual-circuit network*



***Note***

**Switching at the data link layer in a switched WAN is normally implemented by using virtual-circuit techniques.**

# Comparison of communication switching techniques

| Circuit Switching | Datagram Packet Switching | Virtual Circuit Packet Switching |
|---|---|---|
| Dedicated transmission path | No dedicated path | No dedicated path |
| Continuous transmission of data | Transmission of packets | Transmission of packets |
| Fast enough for interactive | Fast enough for interactive | Fast enough for interactive |
| Messages are not stored | Packets may be stored until delivered | Packets stored until delivered |
| The path is established for entire conversation | Route established for each packet | Route established for entire conversation |
| Call setup delay; negligible transmission delay | Packet transmission delay | Call setup delay; packet transmission delay |
| Busy signal if called party busy | Sender may be notified if packet not delivered | Sender notified of connection denial |
| Overload may block call setup; no delay for established calls | Overload increases packet delay | Overload may block call setup; increases packet delay |
| Electromechanical or computerized switching nodes | Small switching nodes | Small switching nodes |
| User responsible for message loss protection | Network may be responsible for individual packets | Network may be responsible for packet sequences |
| Usually no speed or code conversion | Speed and code conversion | Speed and code conversion |
| Fixed bandwidth | Dynamic use of bandwidth | Dynamic use of bandwidth |
| No overhead bits after call setup | Overhead bits in each packet | Overhead bits in each packet |

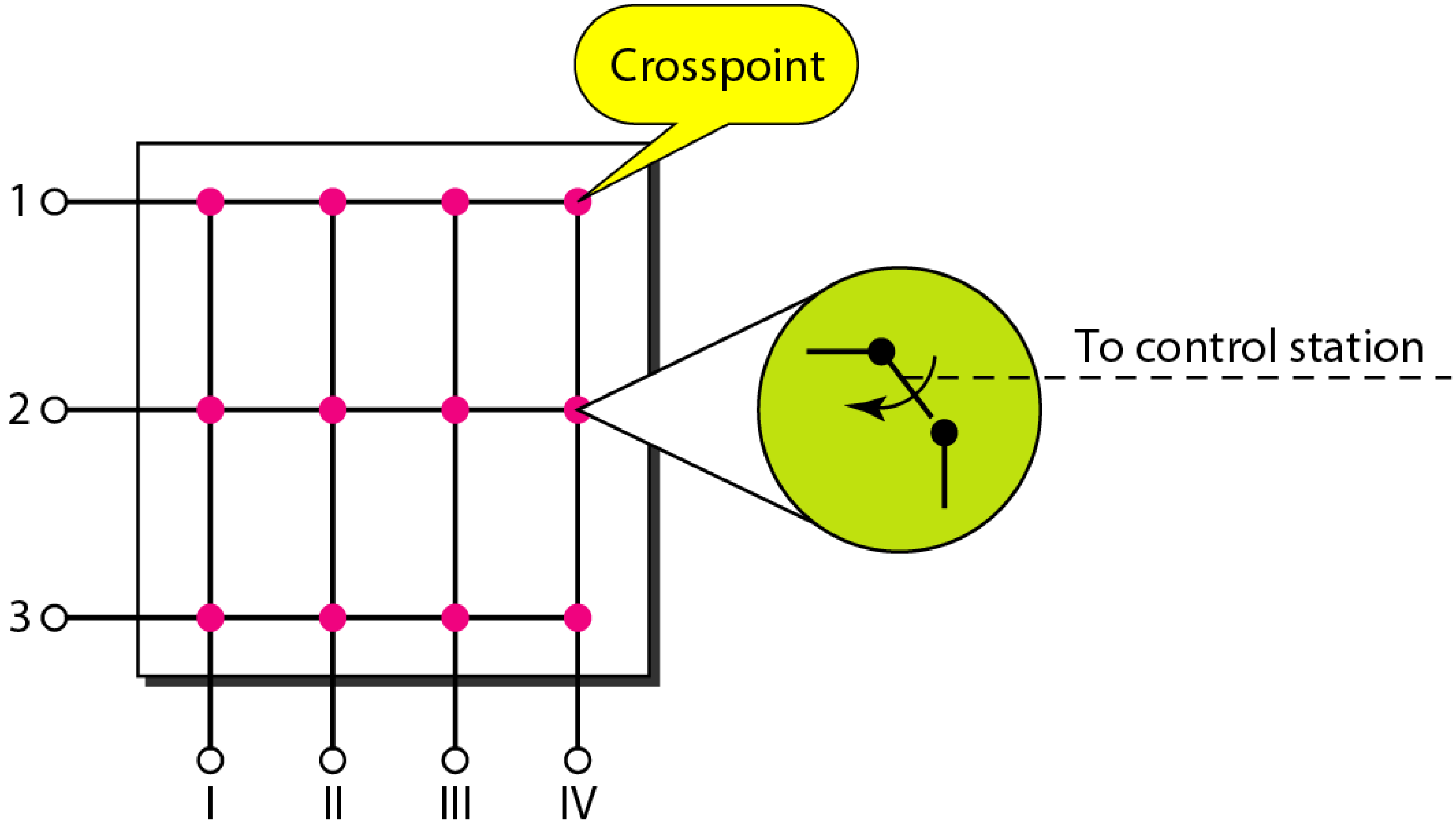
# 8-4 STRUCTURE OF A SWITCH

***We use switches in circuit-switched and packet-switched networks. In this section, we discuss the structures of the switches used in each type of network.***

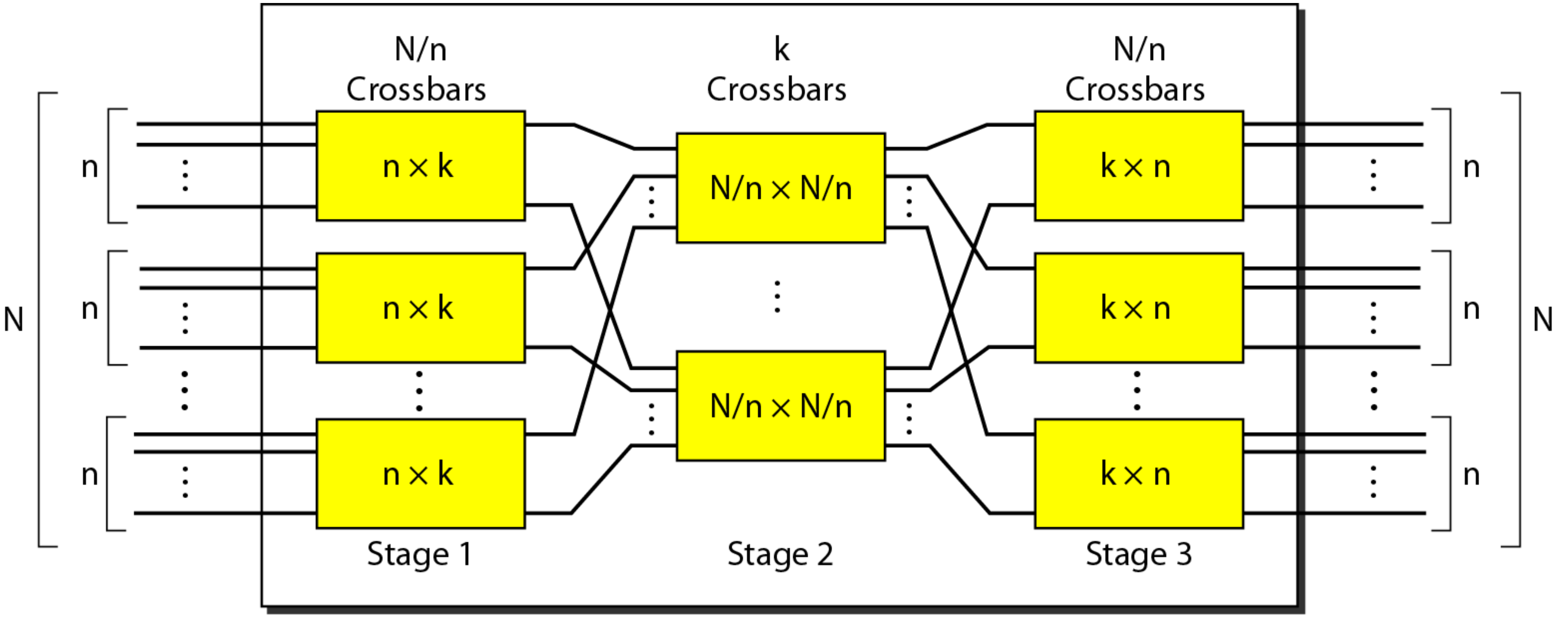
***Topics discussed in this section:***

**Structure of Circuit Switches**
**Structure of Packet Switches**

## **Figure 8.17** *Crossbar switch with three inputs and four outputs*



## Figure 8.18 *Multistage switch*



***Note***

**In a three-stage switch, the total number of crosspoints is**

**$2kN + k(N/n)^2$**

**which is much smaller than the number of crosspoints in a single-stage switch ($N^2$).**

# Example 8.3

***Design a three-stage, 200 × 200 switch (N = 200) with k = 4 and n = 20.***

**Solution**

***In the first stage we have N/n or 10 crossbars, each of size 20 × 4. In the second stage, we have 4 crossbars, each of size 10 × 10. In the third stage, we have 10 crossbars, each of size 4 × 20. The total number of crosspoints is $2kN + k(N/n)^2$, or 2000 crosspoints. This is 5 percent of the number of crosspoints in a single-stage switch (200 × 200 = 40,000).***

***Note***

**According to the Clos criterion:**

$n = (N/2)^{1/2}$

$k > 2n - 1$

**Crosspoints** $\geq 4N [(2N)^{1/2} - 1]$

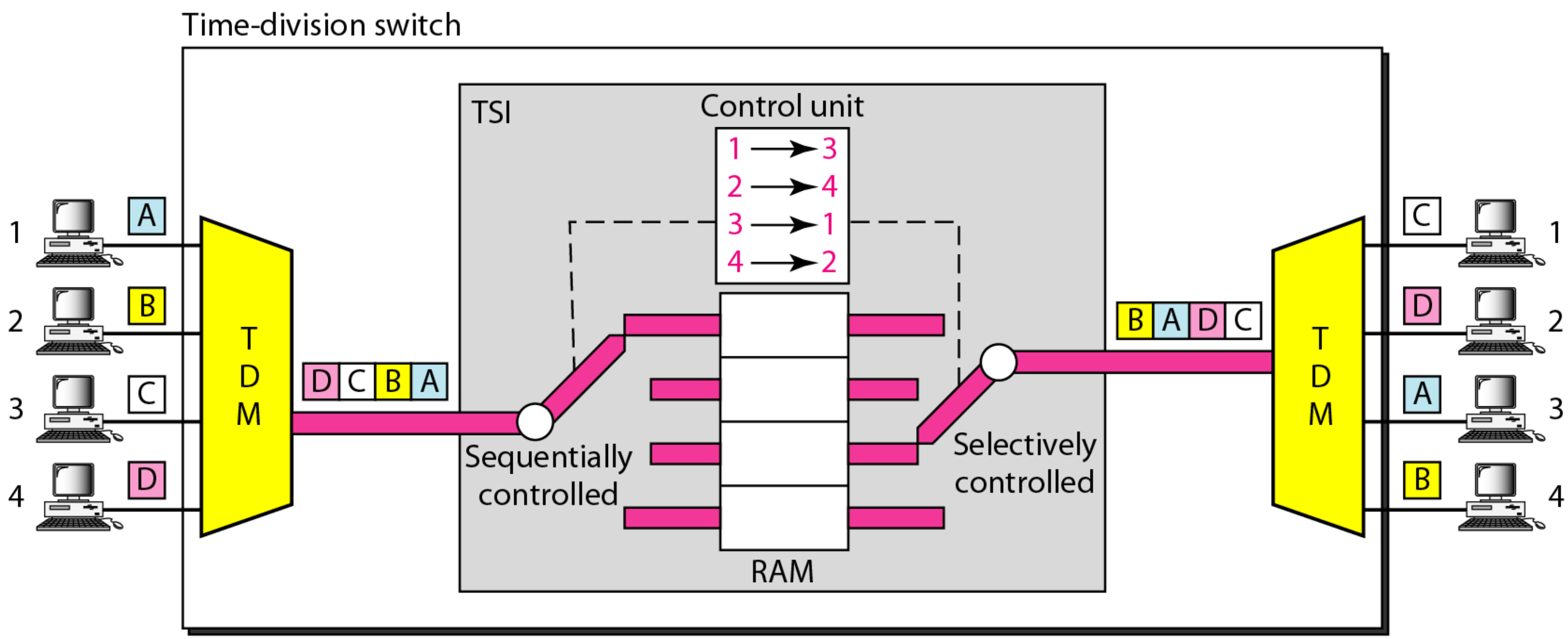
# *Example 8.4*

***Redesign the previous three-stage, 200 × 200 switch, using the Clos criteria with a minimum number of crosspoints.***

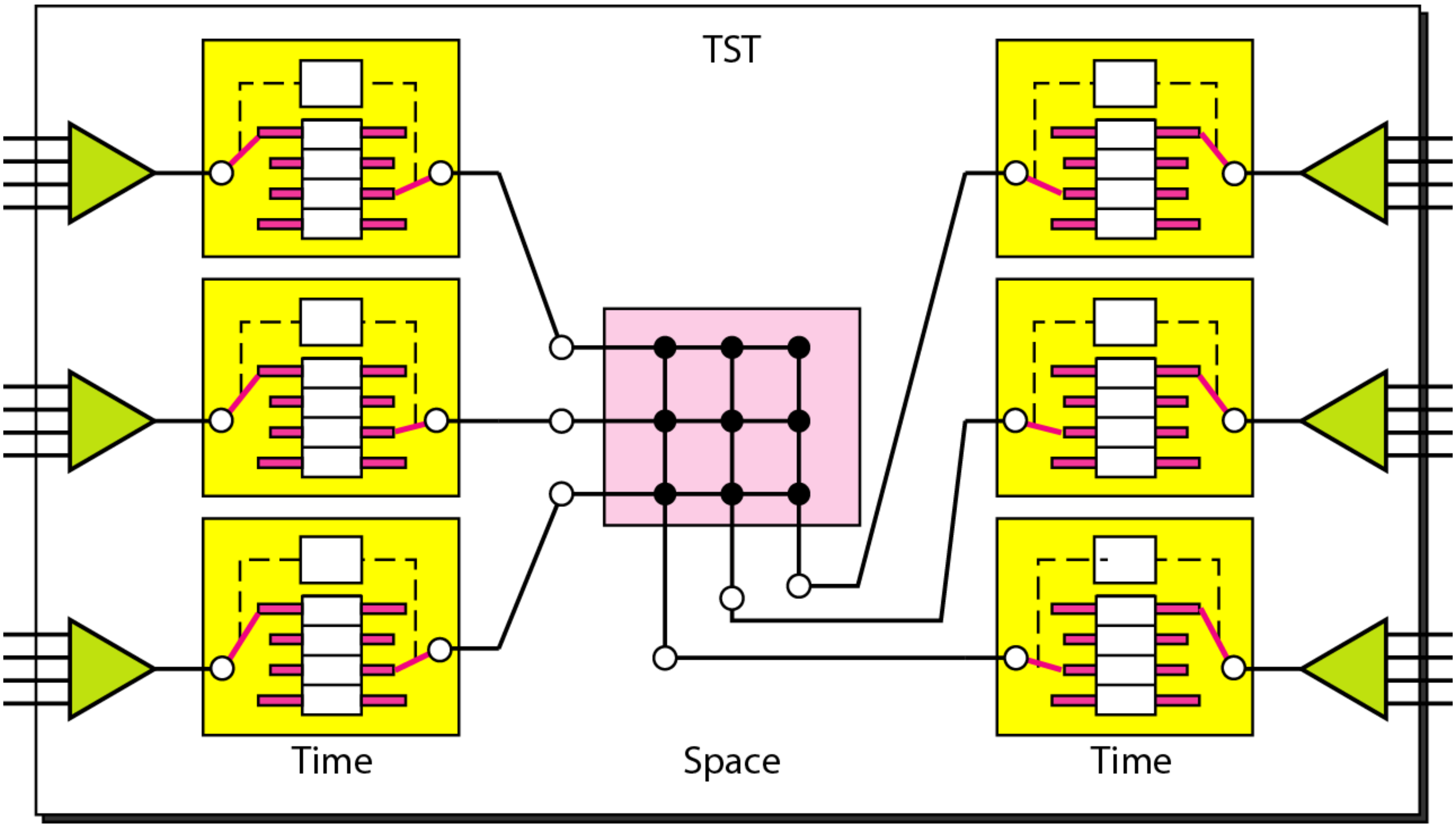
## *Solution*

***We let $n = (200/2)^{1/2}$, or $n = 10$. We calculate $k = 2n - 1 = 19$. In the first stage, we have 200/10, or 20, crossbars, each with 10 × 19 crosspoints. In the second stage, we have 19 crossbars, each with 10 × 10 crosspoints. In the third stage, we have 20 crossbars each with 19 × 10 crosspoints. The total number of crosspoints is 20(10 × 19) + 19(10 × 10) + 20(19 ×10) = 9500.***

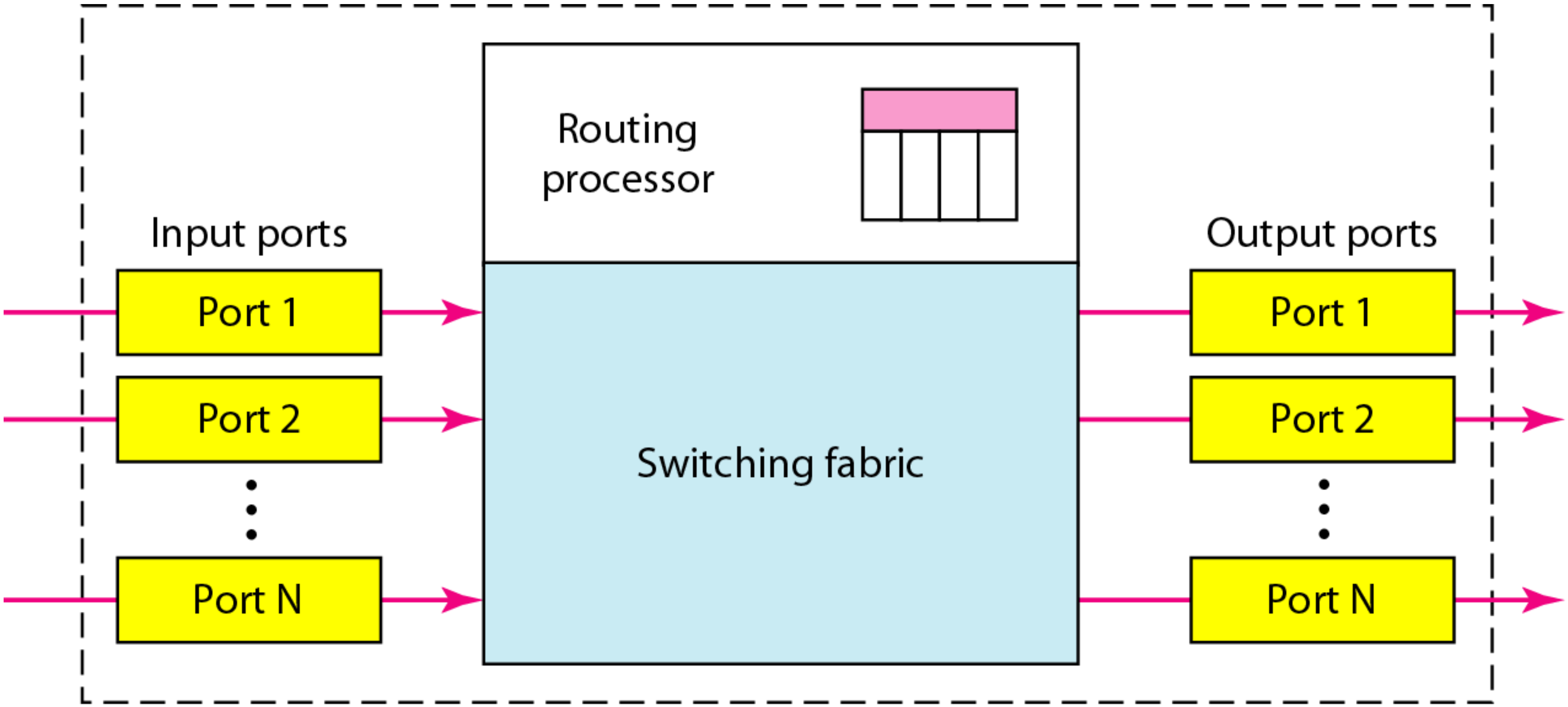
# Figure 8.19 *Time-slot interchange*



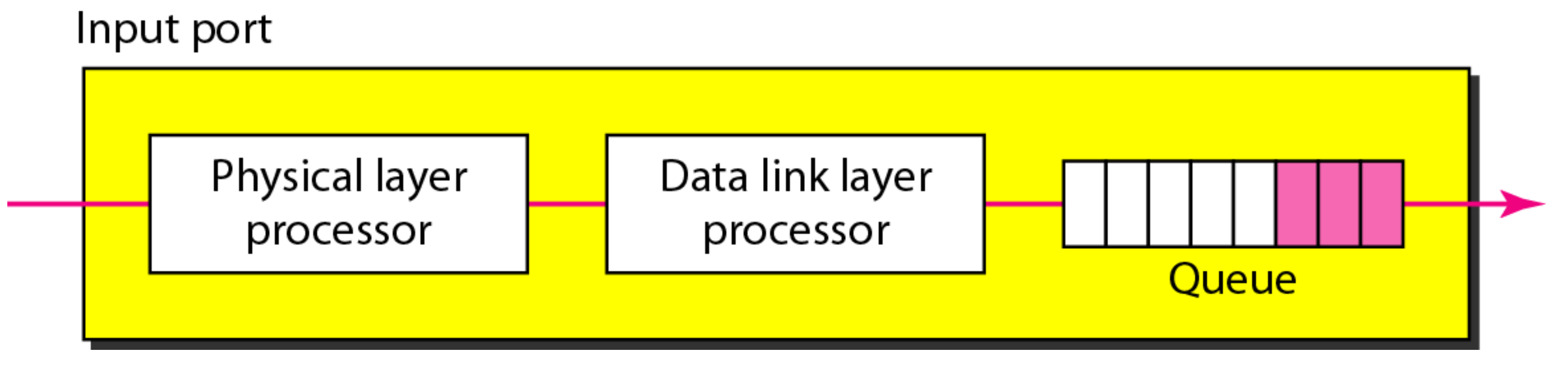
## Figure 8.20 *Time-space-time switch*



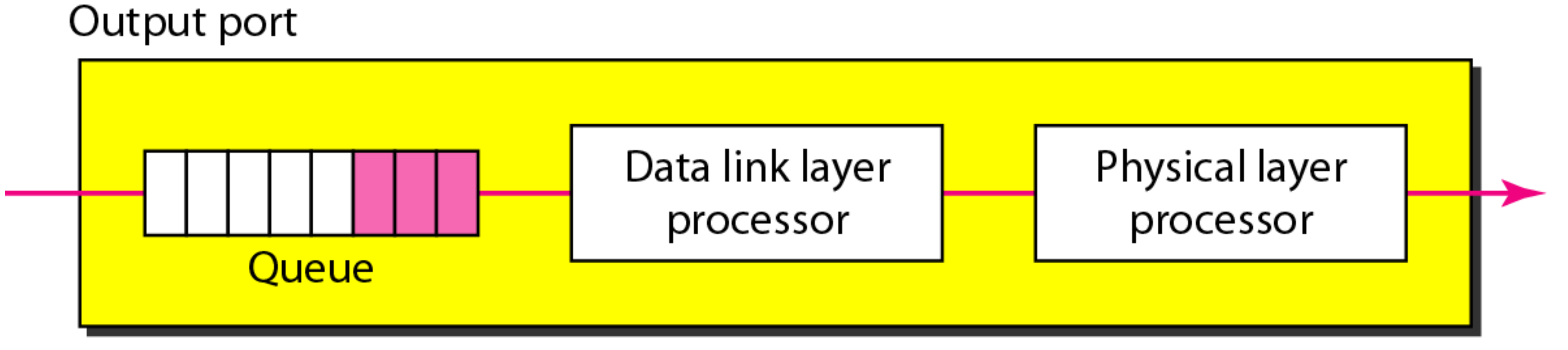
## Figure 8.21 *Packet switch components*



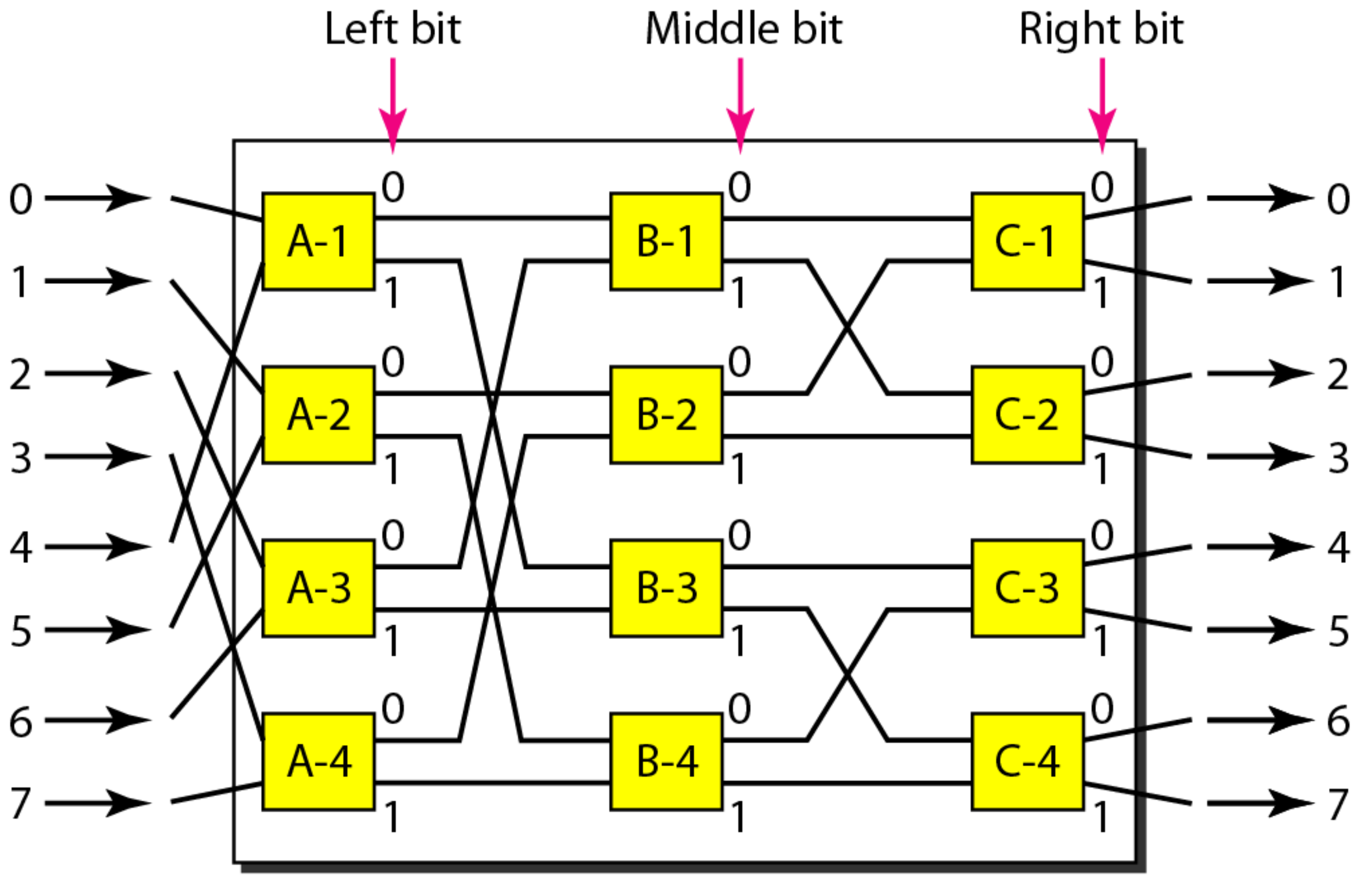
## Figure 8.22 *Input port*



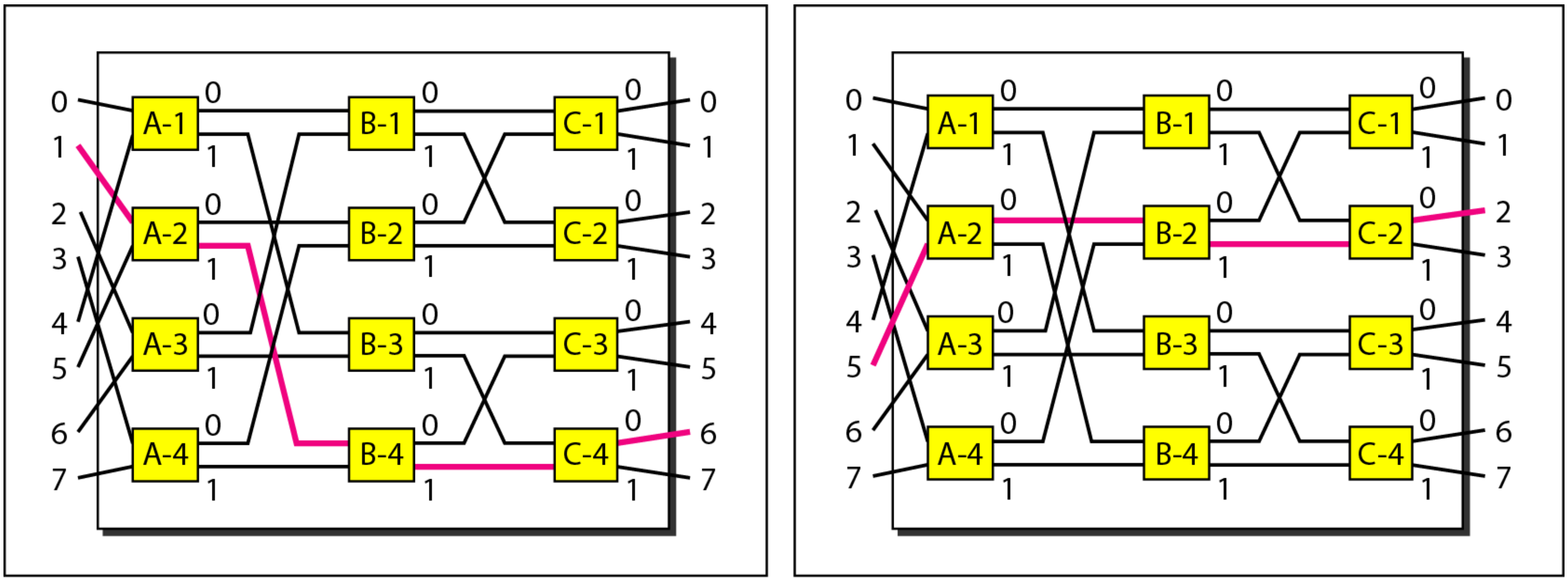
# Figure 8.23 *Output port*



## Figure 8.24 *A banyan switch*



## Figure 8.25 *Examples of routing in a banyan switch*




a. Input 1 sending a cell to output 6 (110)

b. Input 5 sending a cell to output 2 (010)

## Figure 8.26 *Batcher-banyan switch*