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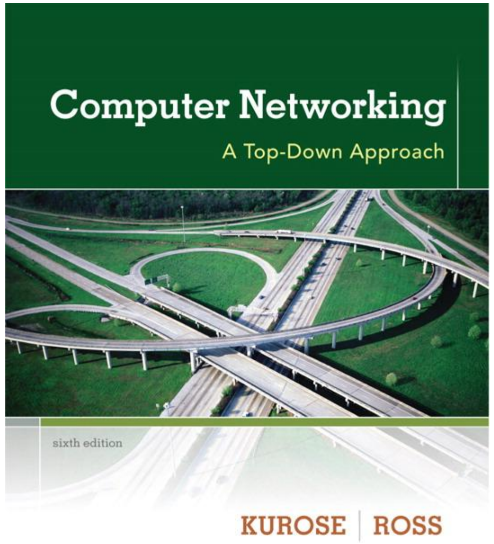


Computer Networking: A Top Down Approach
6th edition
Jim Kurose, Keith Ross
Addison-Wesley
March 2012

Acknowledgement

Course Instructor, Dr. Ahmed Elbadawy, would like to thank the authors of the book (J.F Kurose and K.W. Ross) for allowing him to use these slides.

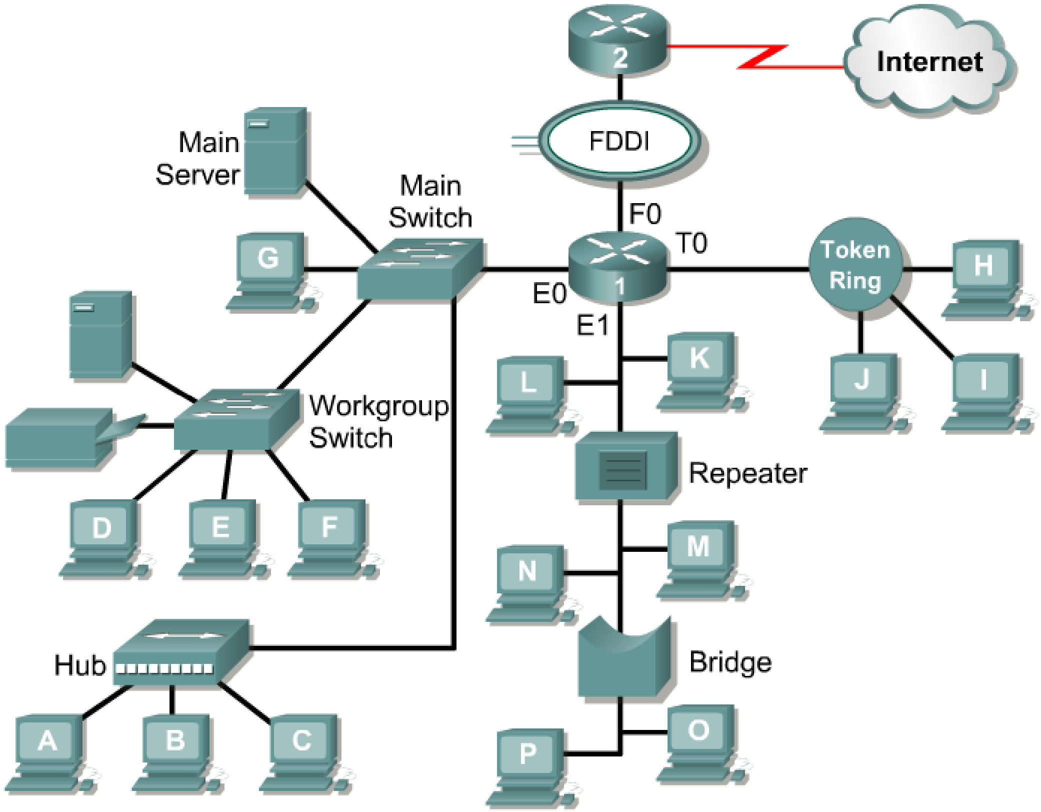
Chapter 1

INTRODUCTION TO COMPUTER NETWORKS & INTERNET

Computer Network: Definition

A computer network is a collection of computers and devices connected by communications channels that facilitate communication among users and allow them to share resources with other users

A Computer Network



Computer Networks - Motivations

Higher Computation Power

Facilitating communications

Sharing hardware

Sharing files, data, and software

Remote access to centralized resources (e.g. databases)

Many useful applications: WWW, e-commerce, e-learning, and multimedia communications

Classification of Computer Nets

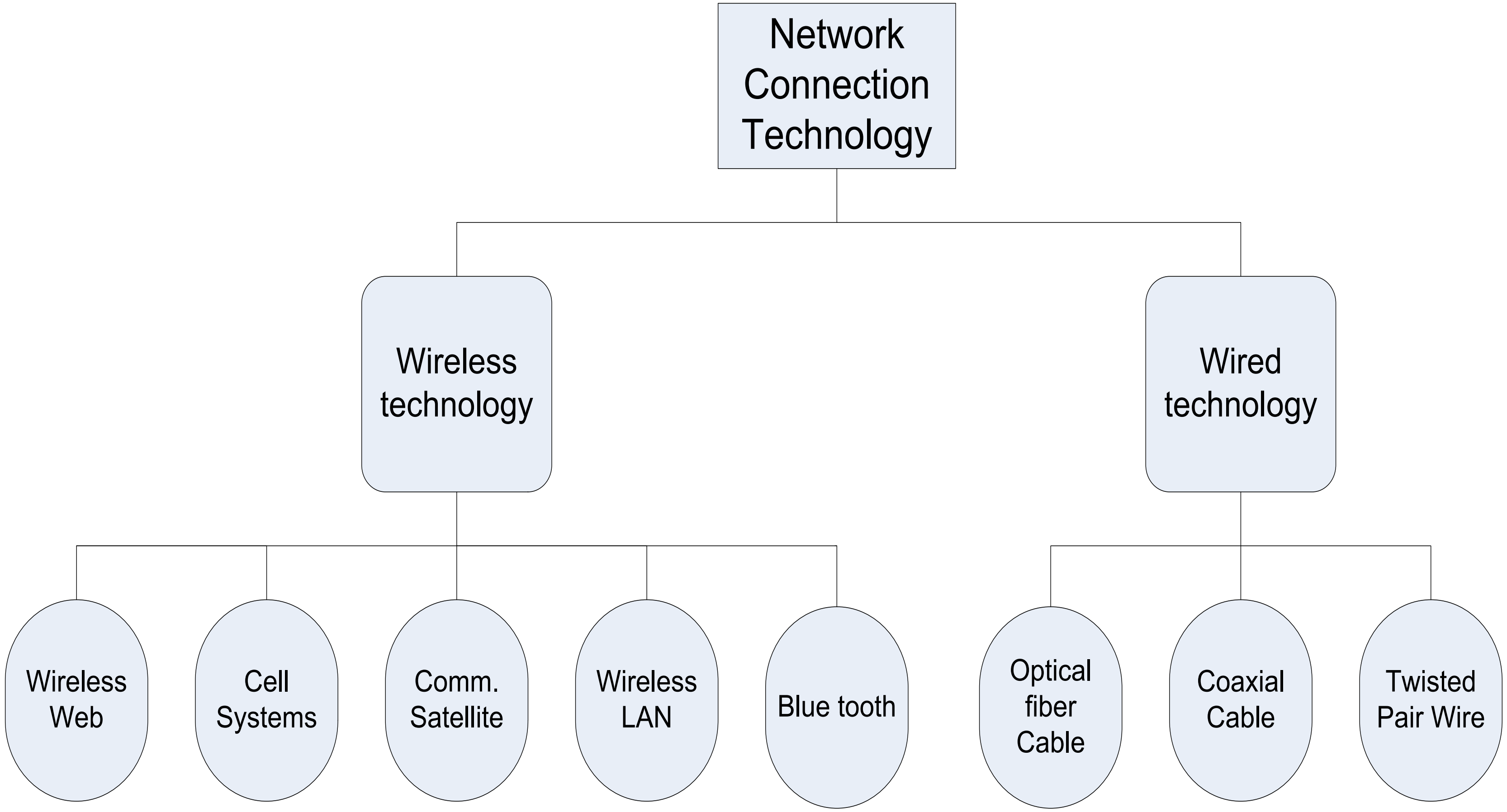
According to Transmission Media

According to Network Scale

According to Network Architecture

According to Network topology

Transmission Media

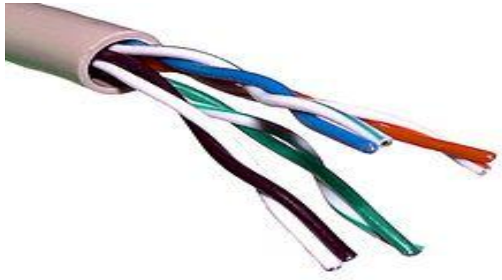


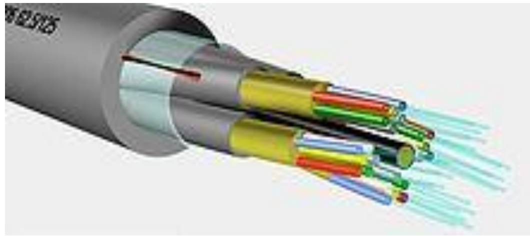
Wire Transmission Media (Ethernet)

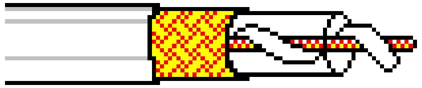
Twisted pair (telephone) wires

Coaxial (TV) cables

Optical fiber cables







TRANSFER RATES FOR VARIOUS TYPES OF LANS USING PHYSICAL TRANSMISSION MEDIA

Type of Cable and LAN	Maximum Transfer Rate
Twisted-Pair Cable	
• 10Base-T (Ethernet)	10 Mbps
• 100Base-T (Fast Ethernet)	100 Mbps
• 1000Base-T (Gigabit Ethernet)	1 Gbps
• Token ring	4 Mbps to 16 Mbps
Coaxial Cable	
• 10Base2 (ThinWire Ethernet)	10 Mbps
• 10Base5 (ThickWire Ethernet)	10 Mbps
Fiber-Optic Cable	
• 10Base-F (Ethernet)	10 Mbps
• 100Base-FX (Fast Ethernet)	100 Mbps
• FDDI (Fiber Distributed Data Interface) token ring	100 Mbps
• Gigabit Ethernet	1 Gbps
• 10-Gigabit Ethernet	10 Gbps

Twisted Pair Wires

The most widely used medium for comm.

Twisted-pair wires are ordinary telephone wires which used for both voice and data transmission.

Twisted in certain pattern to reduce noise, interference and cross talk

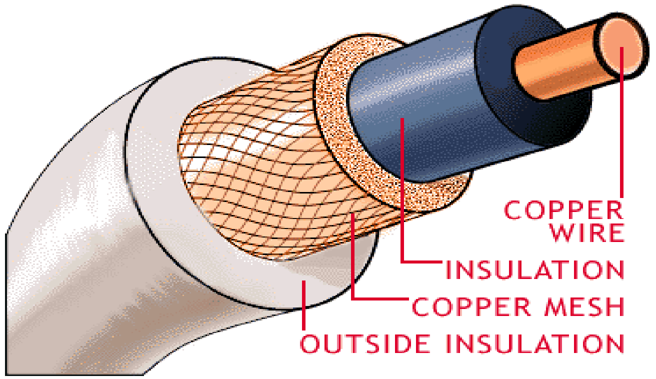
The transmission speed ranges from 2 Mbps to 100 Mbps

Coaxial Cables

Widely used for cable television systems, office buildings, and other worksites for local area networks.

Transmission speed range from 200 Mbps to more than 500 Mbps

Insulation layer in coaxial cable helps minimize interference and distortion.



Optical fiber cables

Consists of one or more filaments of glass fiber wrapped in protective layers.

Transmits **light** which can travel over extended distances without signal loss.

Transmission speed may reach 10’s, 100’s Gbps

The transmission speed of fiber optics is **hundreds** of times faster than for coaxial cables and **thousands** of times faster than for twisted-pair wire

low error rate and immune to electromagnetic noise

Wireless Transmission Media

Infrared

Bluetooth

WLAN (Wi-Fi)

Wi-Max

Communication Satellites

Cellular Systems

TRANSFER RATES FOR VARIOUS TYPES OF WIRELESS TRANSMISSION MEDIA

Transmission Medium	Maximum Transfer Rate
Infrared	115 Kbps to 4 Mbps
Broadcast radio	
• Bluetooth	1 to 2 Mbps
• HomeRF	1.6 Mbps to 10 Mbps
• 802.11b	11 Mbps
• 802.11g	54 Mbps
• 802.11a	54 Mbps
Cellular radio	
• 2G	9.6 Kbps to 19.2 Kbps
• 3G	144 Kbps to 2.4 Mbps
Microwave radio	150 Mbps
Communications satellite	1 Gbps

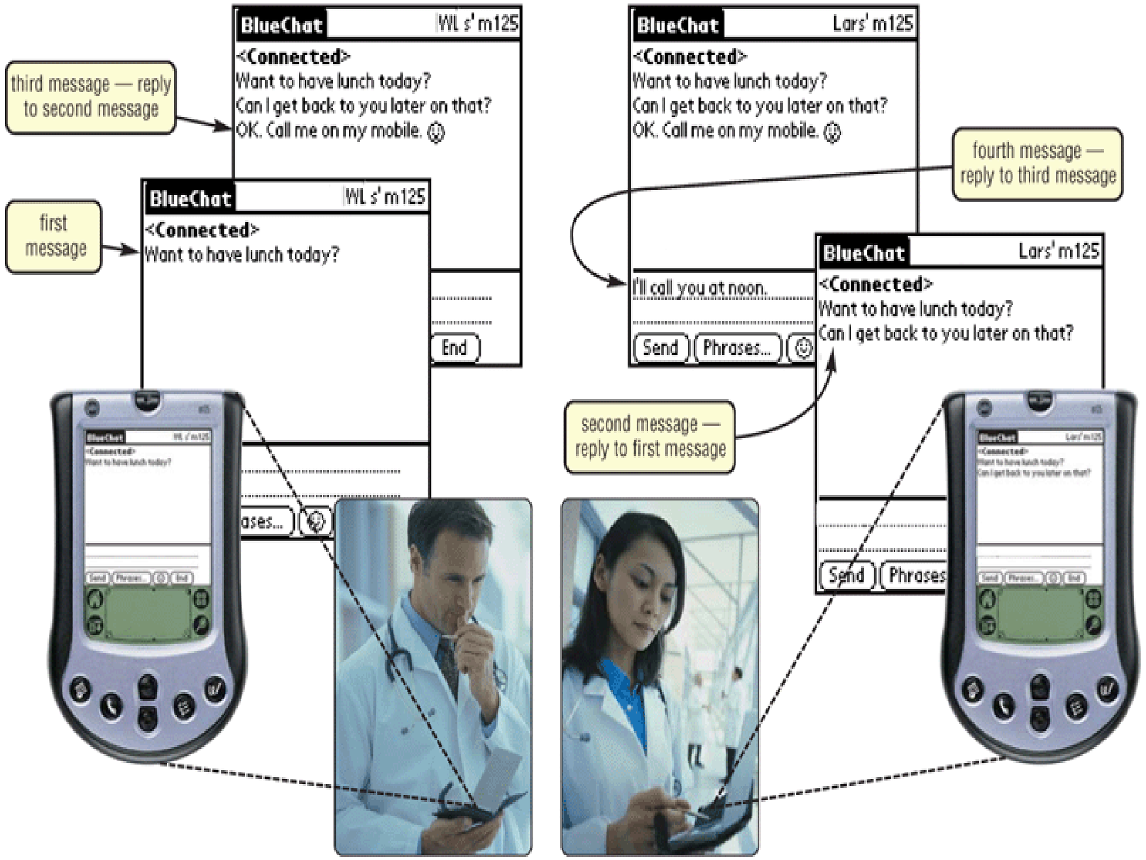
Blue Tooth

A short range wireless technology

Area range from 10 to 100 meters.

Transmission rate 1 Mbps

Use protocol IEEE 802.15



Wireless LANs (Wi-Fi)

Wireless LANs enable communication between multiple devices in a limited area (few 100 meters)

Transmission rate 11-200 Mbps

Use protocol IEEE 802.11

802.11 SERIES OF STANDARDS

Standard	Transfer Rates
802.11	1 or 2 Mbps
802.11a	Up to 54 Mbps
802.11b	Up to 11 Mbps
802.11g	54 Mbps and higher

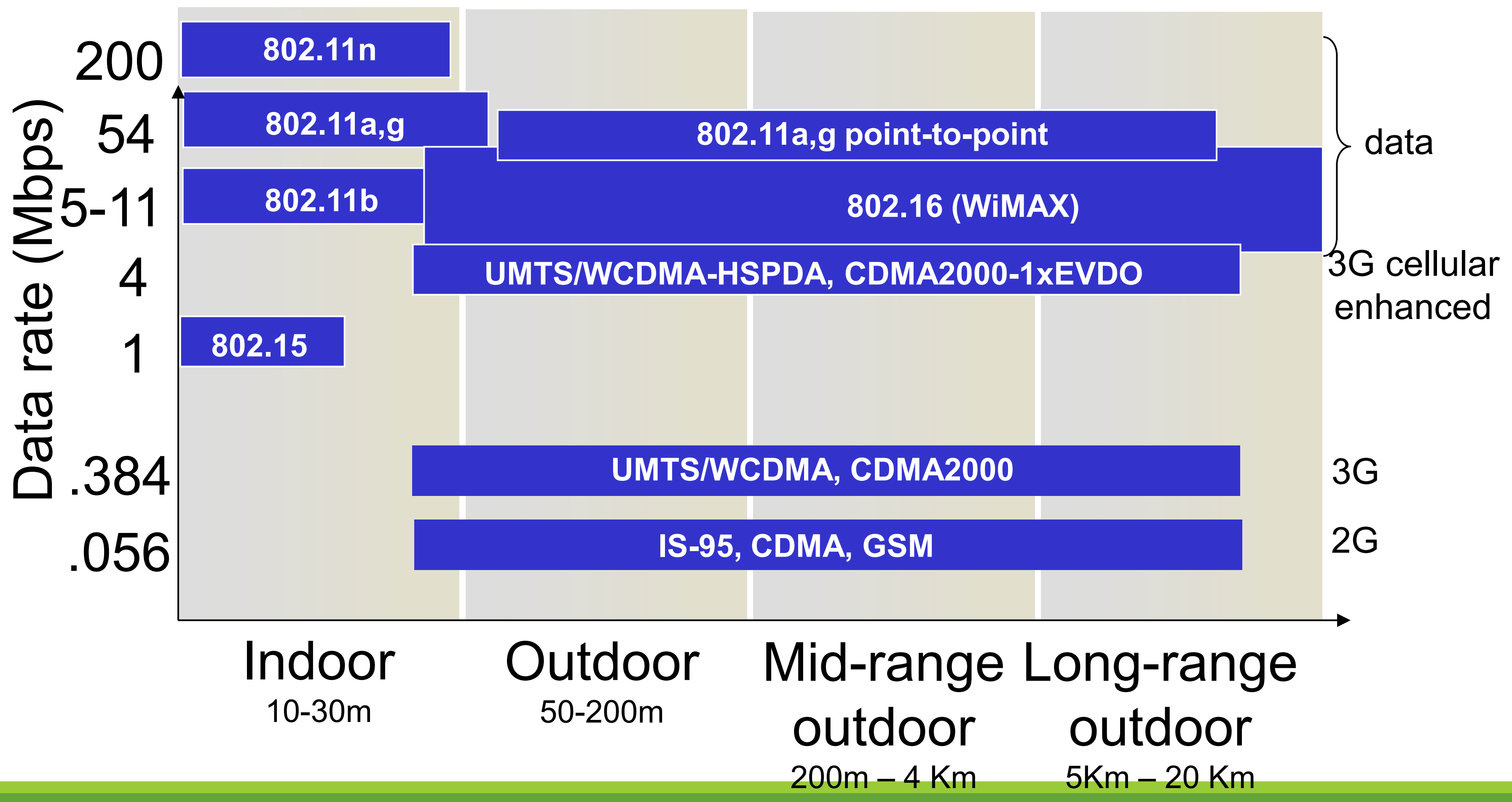
Wi-Max

Range ~ 6 miles (“city rather than coffee shop”)

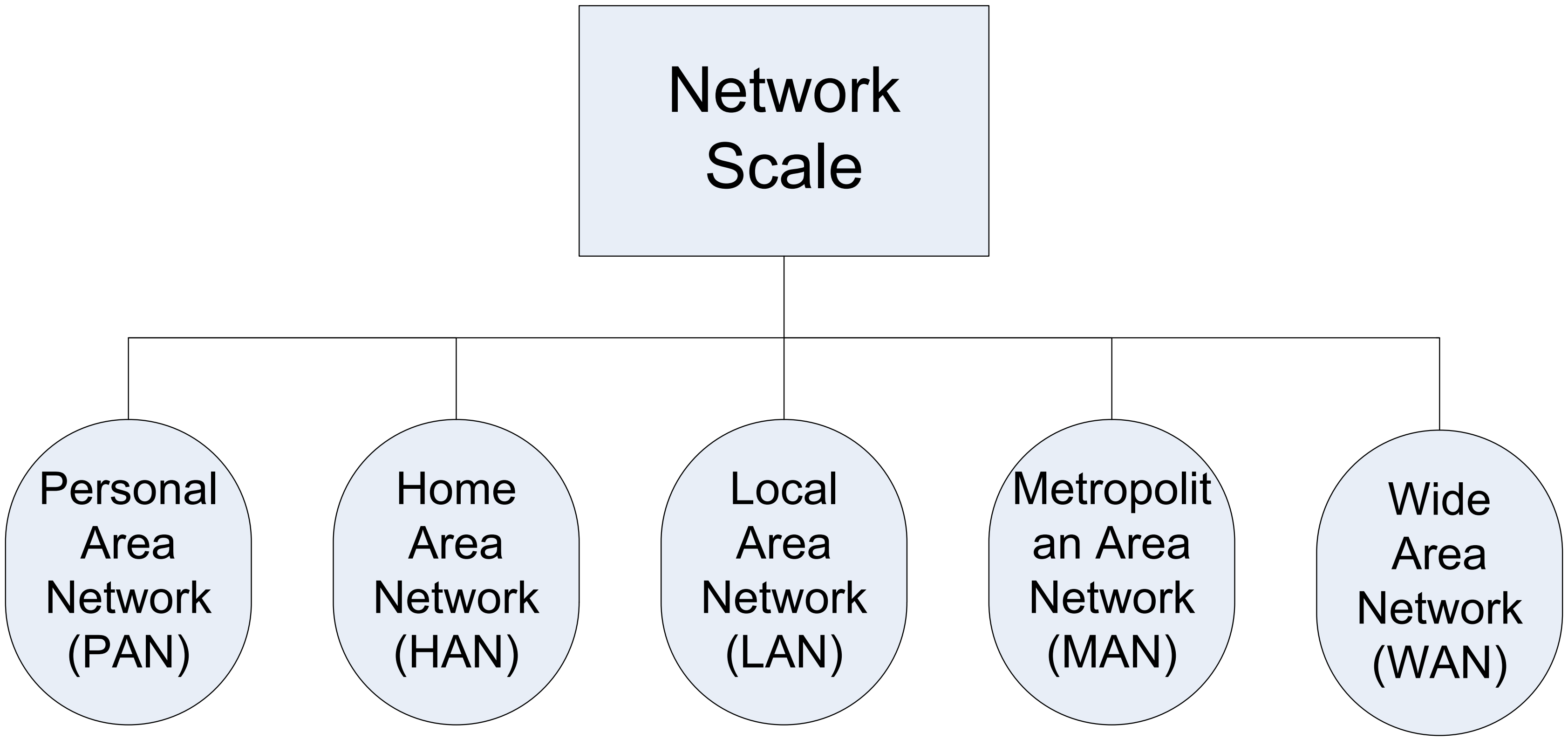
Bit rate ~14 Mbps

Use IEEE 802.16 protocol

Wireless Technologies



Network Scale



Local Area Network (LAN)

A LAN is a network that connects computers and devices in a limited geographical area such as home, school, computer laboratory, office building, or closely positioned group of buildings.

Wired LANs are most likely to be based on Ethernet technology

Wireless LAN mostly use IEEE 802.11 technologies

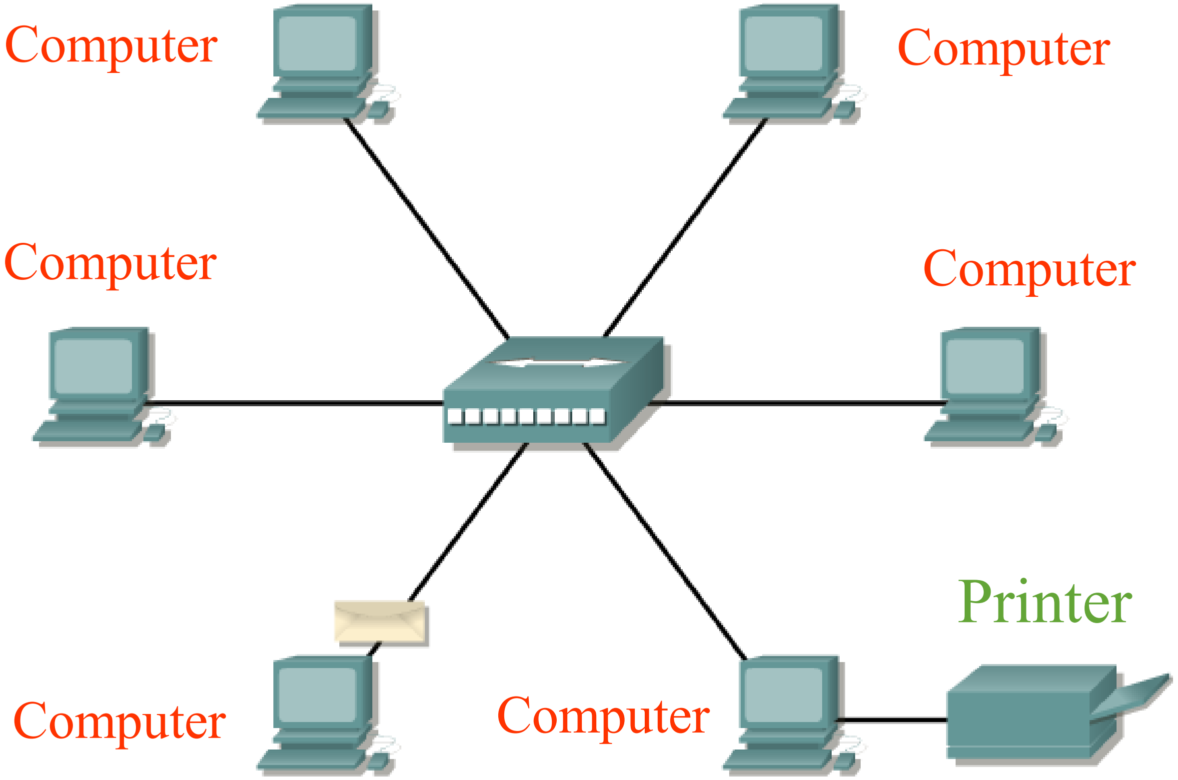
Higher data transfer rates

Smaller geographic range, and no need for leased telecommunication lines.

Current LANs operate at speeds up to 10 Gbps.

IEEE has projects investigating the standardization of 40 and 100 Gbps.

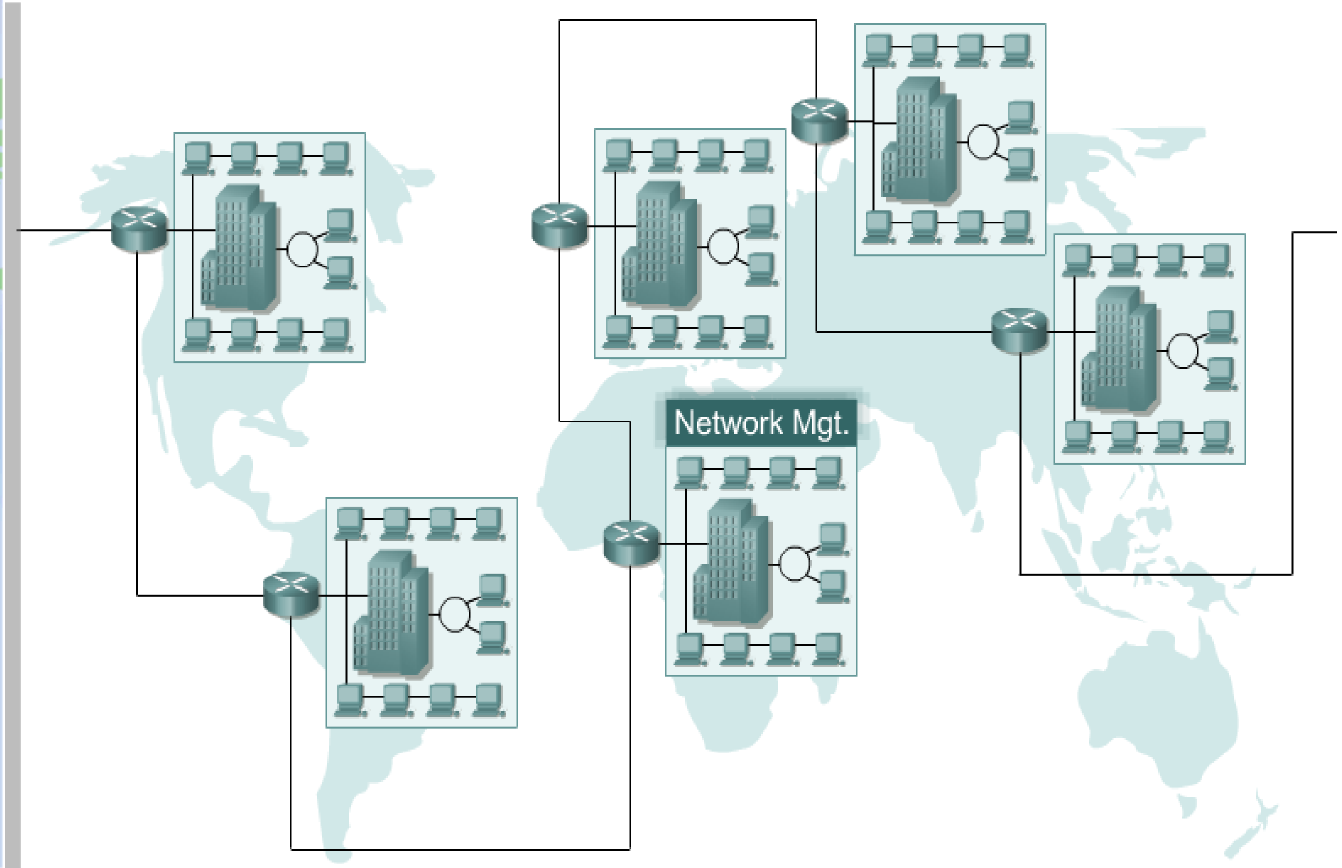
A Local Area Network (LAN)



Wide Area Network (WAN)

A WAN is a computer network that covers a large geographic area such as a city, country, or spans even intercontinental distances, using a communications channel that combines many types of media such as telephone lines, cables, and air waves

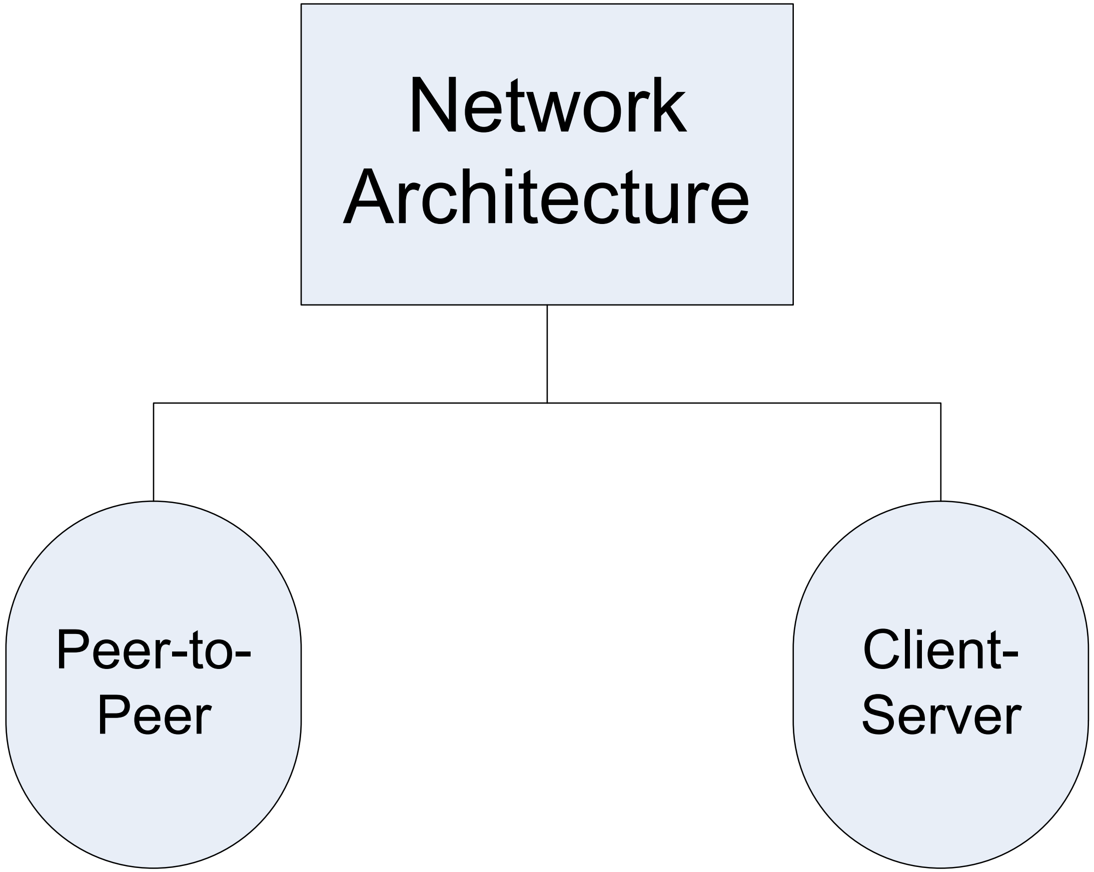
A Wide Area Network (WAN)



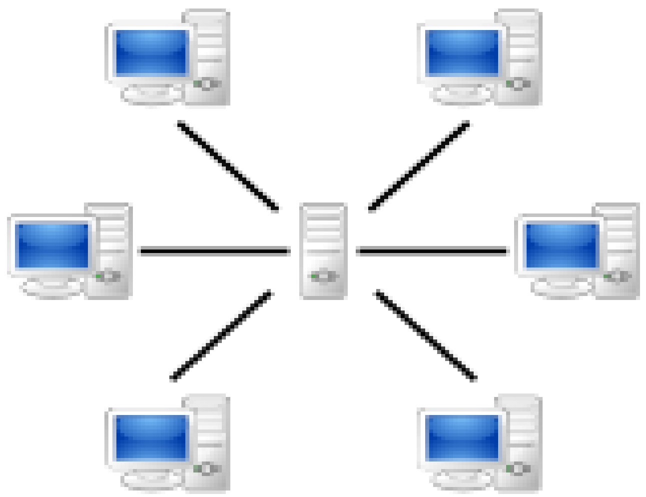
LAN vs. WAN

LAN	WAN
Computers interconnected in short distance (less than few hundreds meters)	Computers interconnected in a long distance (Kms and more)
Primary used to provide higher computation power and to move information within a company, school, campus,…	Used to move information efficiently and quickly, not only within a company, but also from one business to another within a city, country and intercontinental areas

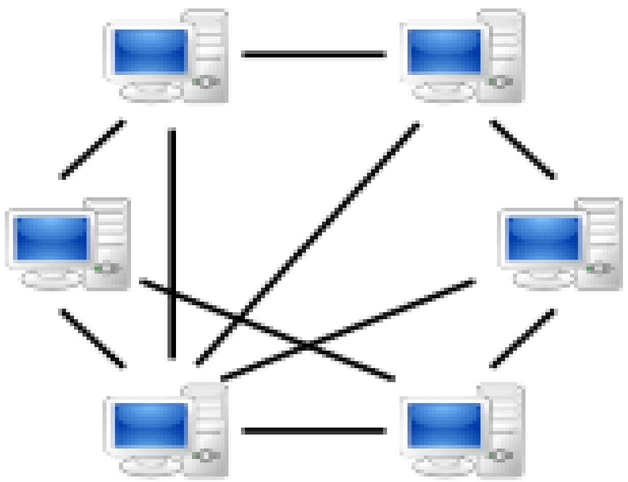
Network Architecture



Client-Server vs. P2P



Client-server architecture

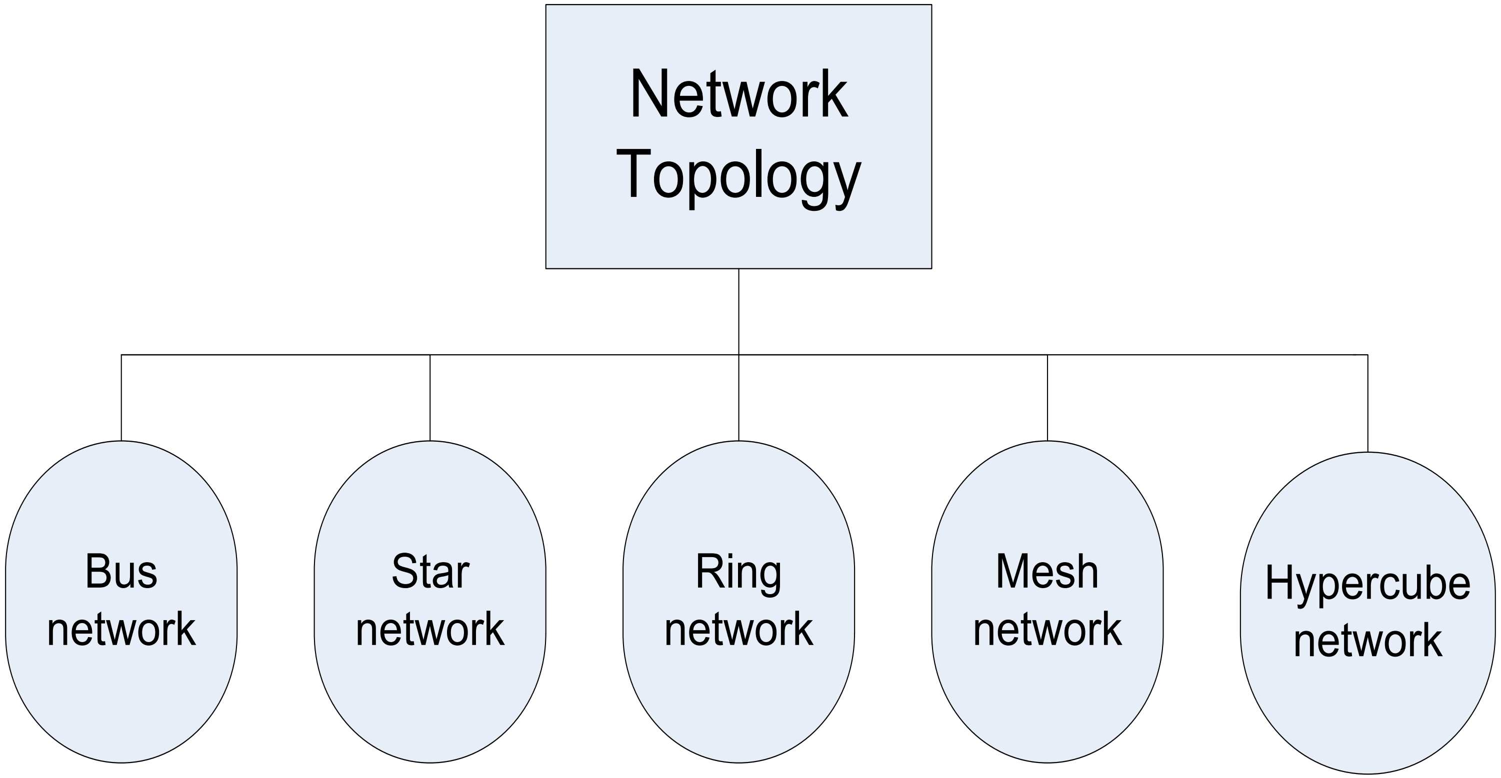


P2P Architecture

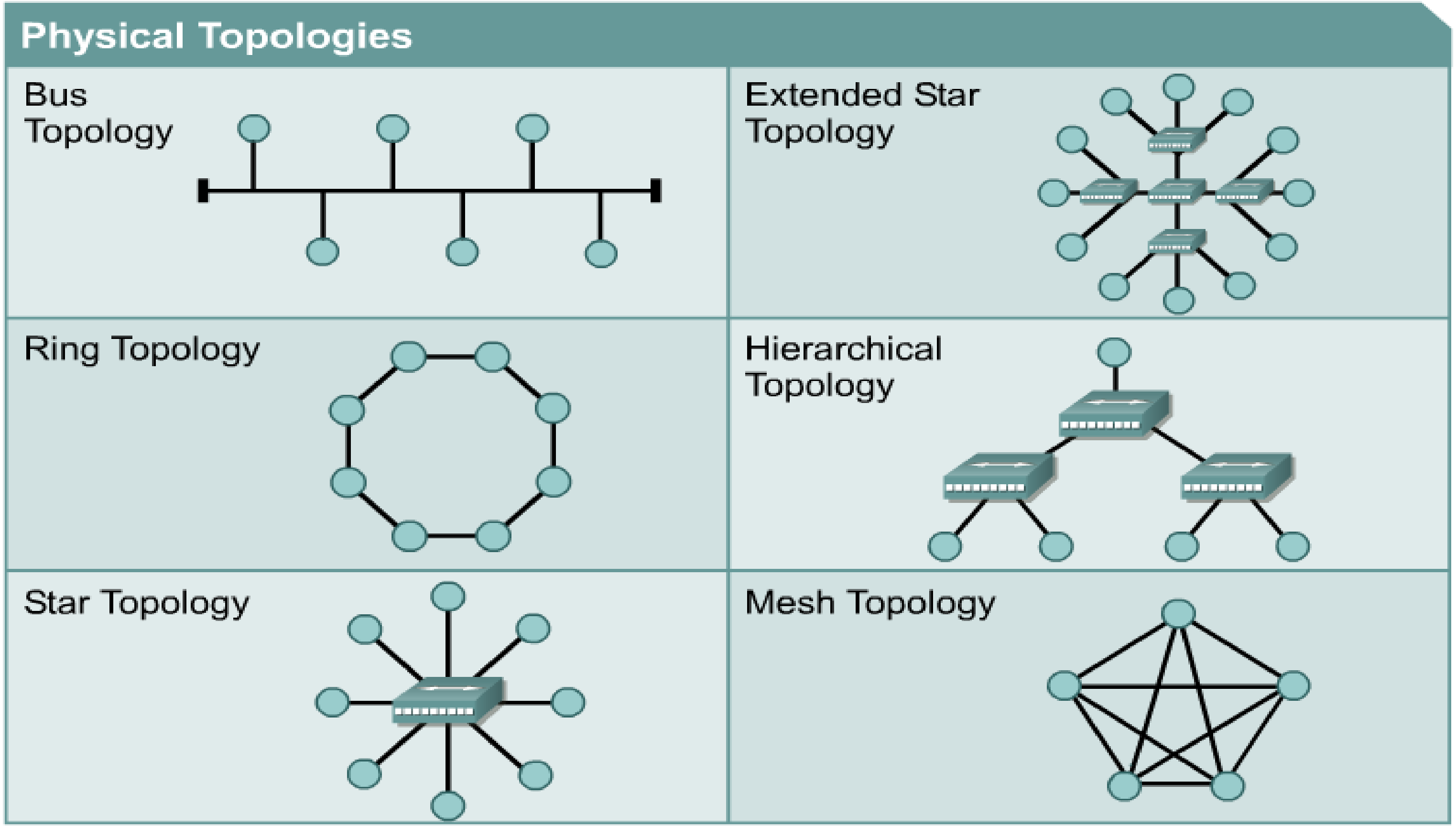
Client-Server vs. P2P

Client-Server	P2P
Needs dedicated server	No dedicated server
Single point of failure	Fault tolerance
Expensive to maintain	Easy to install and maintain
Will work with any applications	Good for file, printer, and resource sharing.
Limited scalability	Scalable
Handles shared database applications	Good for distributed database applications
More secure (dedicated server)	Less secure (server is workstation)

Network Topology



Network Topology



Some Network Devices

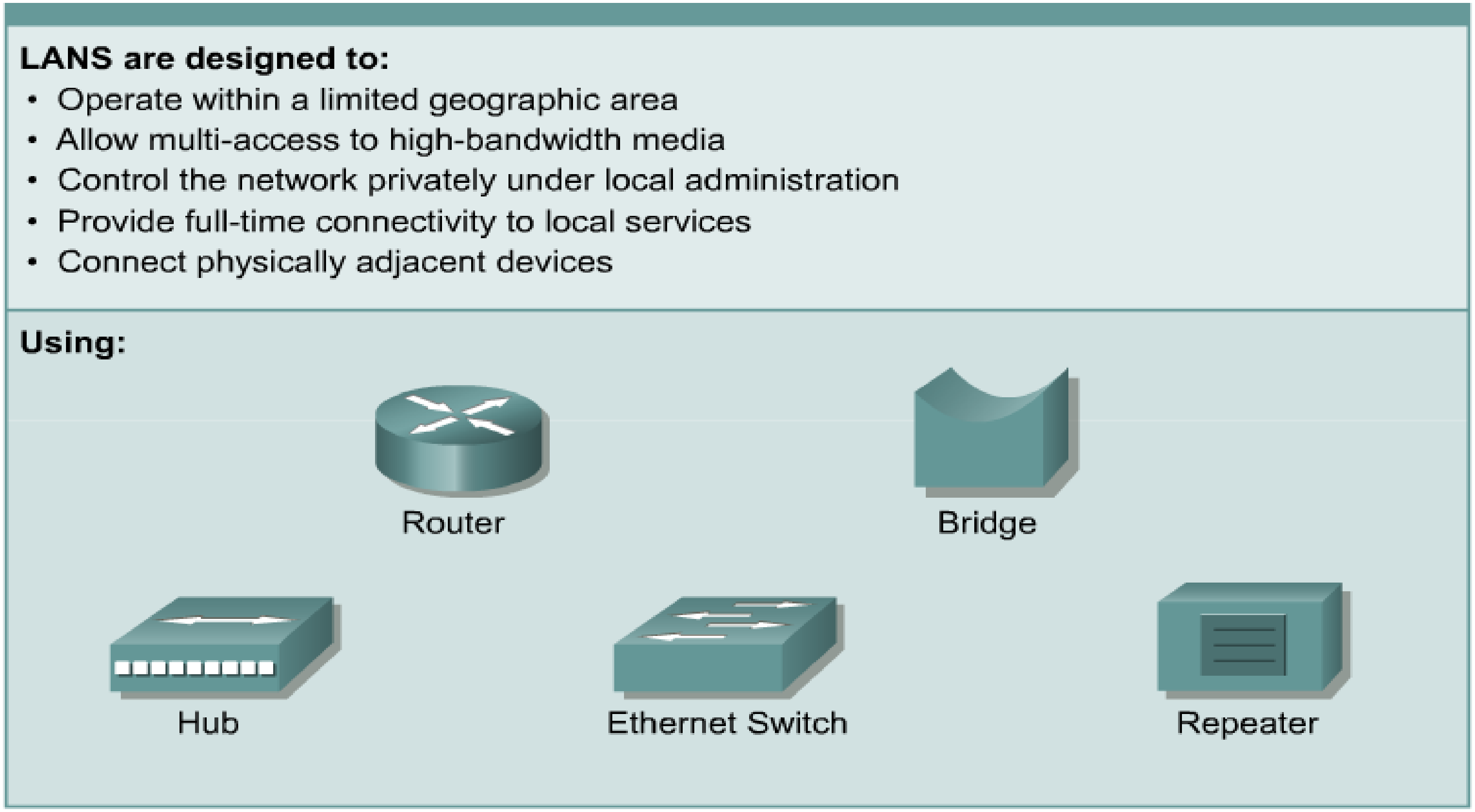
Repeater

Bridge

Hub

Switch

Router



Network Devices

A **repeater** is a device that receives a signal, cleans it from the noise, regenerates it and retransmits it at a higher power level so that the signal can cover longer distances without degradation.

A network **bridge** connects multiple **network segments**

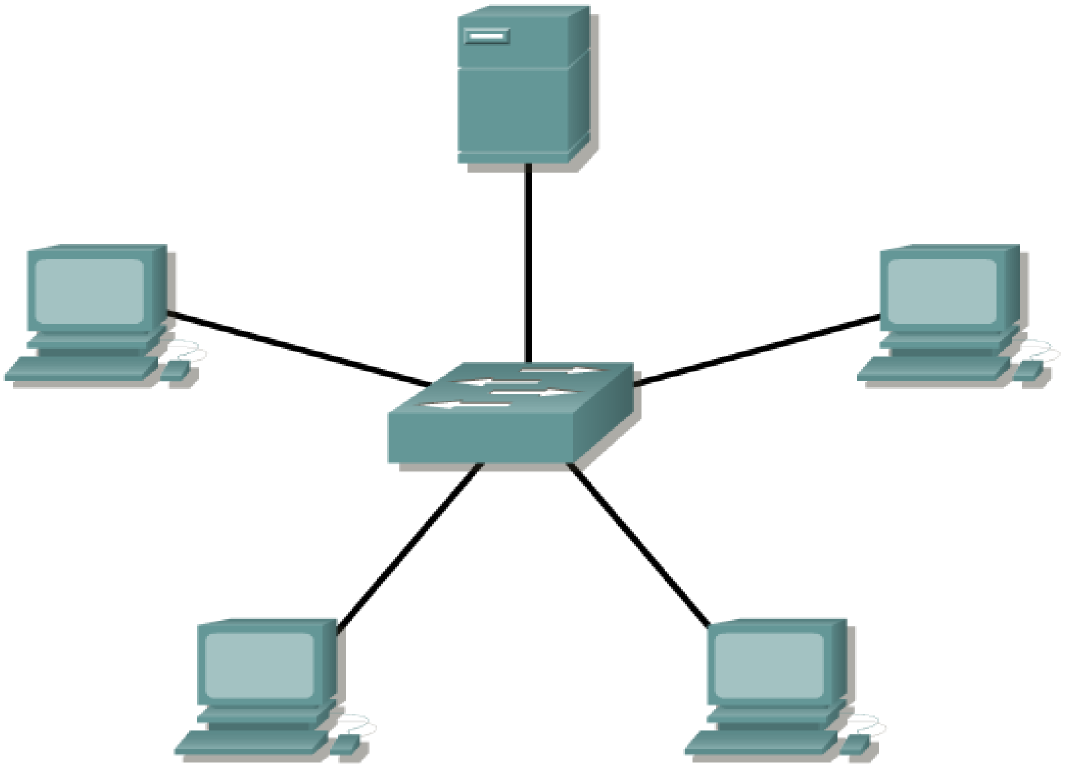
Network Devices

A network **hub** contains multiple ports. When a packet arrives at one port, it is copied ***unmodified*** to ***all*** ports of the hub for transmission

A network **switch** is a device that forwards and filters datagrams (chunk of data communication) between ports (connected cables) based on the MAC addresses in the packets

This is distinct from a hub in that switch only forwards the frames to ***the ports involved in the communication*** rather than all ports connected

Switch



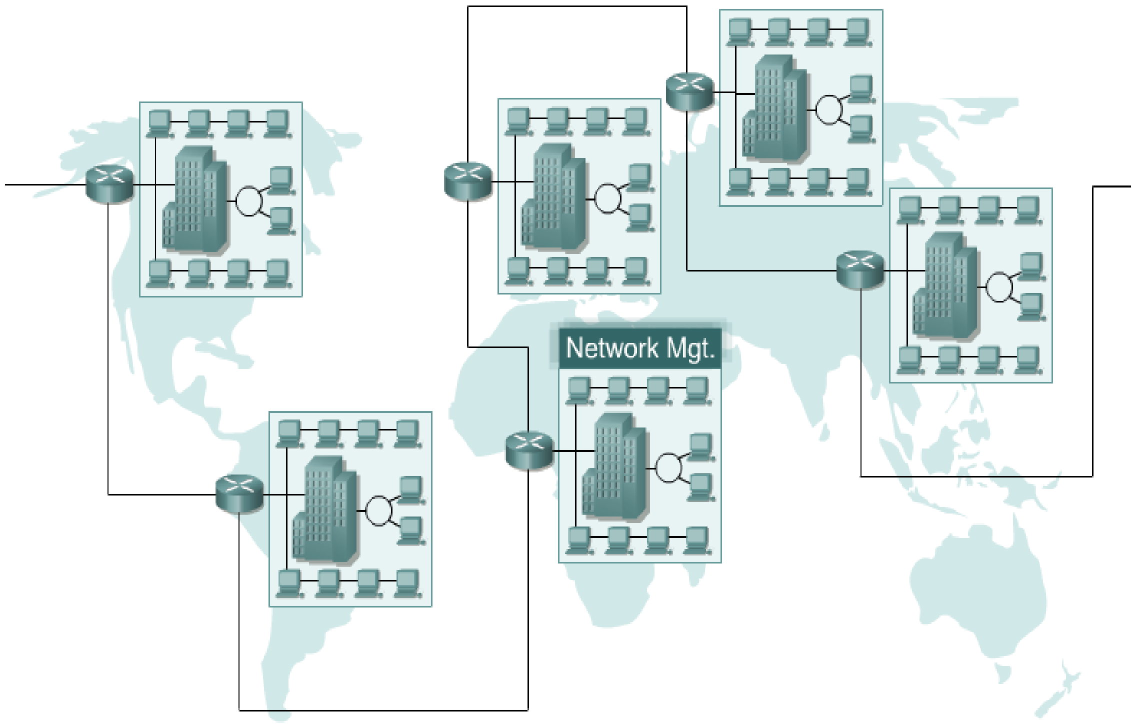
Switch = Amplifier
+ switching with MAC address

Router

A **router** is a networking device that forwards packets between networks using information in protocol headers and forwarding tables (IP address) to determine the best next router for each packet

A **router** takes a chunk of information arriving on one of its incoming communication links and forwards that chunk of information on **one** of its outgoing communication links.

Router



Router = Amplifier
+ switching with **IP address**

Bandwidth

Bandwidth = The carrying capacity of a communications circuit

Digital bandwidth = the number of bits per second (bps) the circuit can carry

Analog bandwidth = the range of frequencies (Hz) the circuit can carry

Network Bandwidth

The amount of information that can flow through a network connection in a given period of time

Unit of Bandwidth	Abbreviation	Equivalence
Bits per second	bps	1 bps = fundamental unit of bandwidth
Kilobits per second	kbps	1 kbps = ~1,000 bps = 10^3 bps
Megabits per second	Mbps	1 Mbps = ~1,000,000 bps = 10^6 bps
Gigabits per second	Gbps	1 Gbps = ~1,000,000,000 bps = 10^9 bps
Terabits per second	Tbps	1 Tbps = ~1,000,000,000,000 bps = 10^{12} bps

Network Throughput

Throughput refers to actual measured bandwidth, at a specific time of day, using specific Internet routes, and while a specific set of data is transmitted on the network

Throughput < Bandwidth

The Internet

What is the Internet?

Internet Views

Internet Structure

- Network edge
- Access networks
- Network core

Delay, loss and throughput in packet-switched networks

Protocol layers, Service models

What is the Internet?

A type of computer networks

A public worldwide computer network

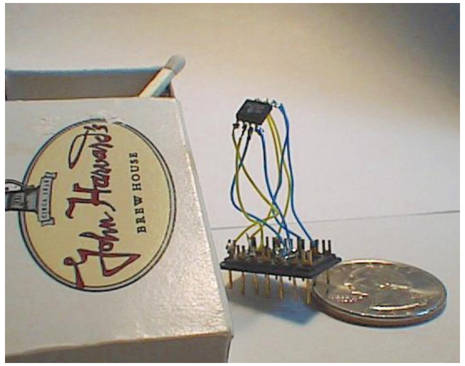
A network of networks that interconnect millions of computing devices throughout the world

Devices connected to the Internet are called hosts (end systems) including PCs, workstations, servers, PDAs, laptops, TVs, cell phones and even appliances

“Cool” Internet appliances

IP picture frame
http://www.ceiva.com/

Web-enabled toaster +
weather forecaster



World’s smallest web server
http://www-ccs.cs.umass.edu/~shri/iPic.html

Internet phones

Different views of Internet

“Nuts and bolts” view

“Service” view

“Layer” view

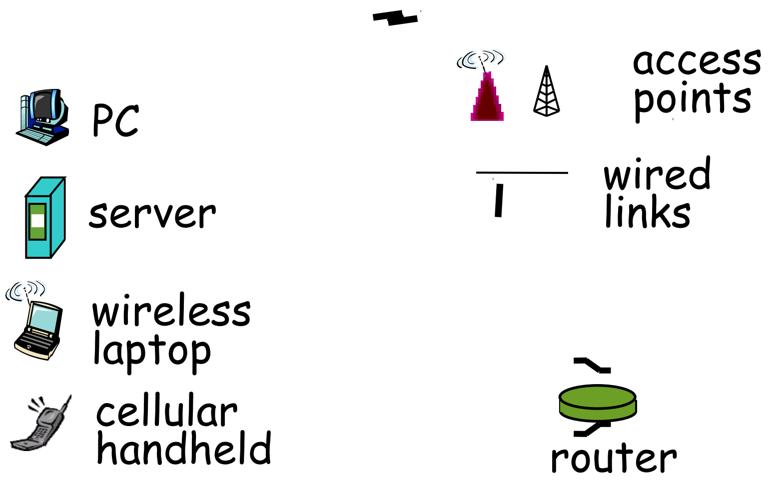
Nuts and bolts View

Hardware components

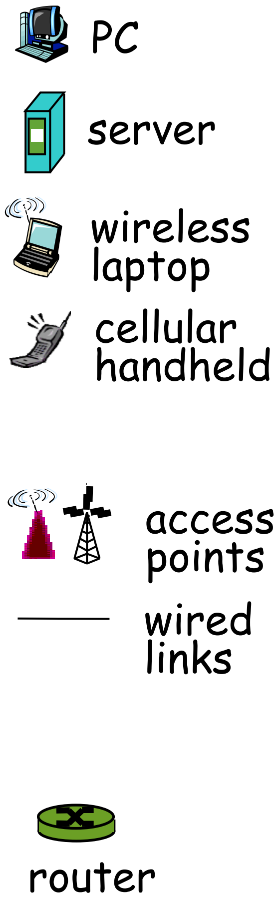
- Hosts (end systems)
- Communication links
- Communication Devices (Routers, switches, etc.)

Software components

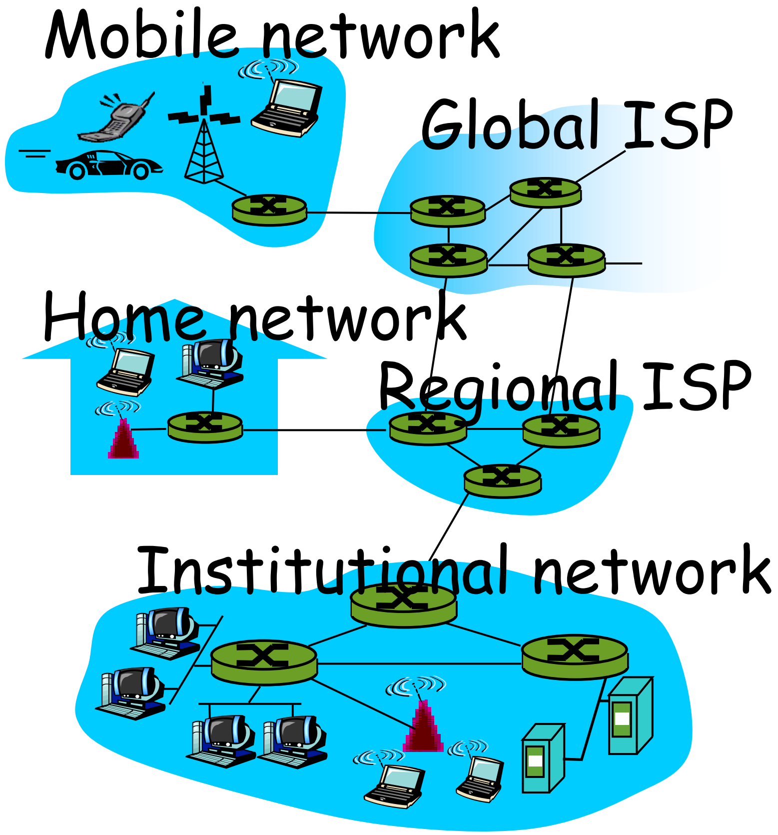
- Data Packets
- Protocols
- Internet Service Providers (ISP)



Hardware Components



- *hosts = end systems*
  - millions of connected computing devices, running network apps
- *communication links*
  - fiber, copper, radio, satellite
  - transmission rate = *bandwidth*
- *routers:* forward packets (chunks of data)



Hardware Components

Hosts (end systems): devices connected to the internet and use it to communicate

Communication links: media that connect hosts together (copper wires, coaxial cables, optical fibers, …)

Routers: hosts are **not** connected together directly through one communication link. However, they are connected indirectly through routers

Route: the path that the packet takes from the sending host (source), through a series of communication links and routers, to the receiving host (destination).

Software Components

Internet Service Provider (ISP): allows hosts to access the Internet through 56kbps modems, DSL, high-speed LAN, wireless access

Packet: a chunk of information

Protocol: a set of rules that control the transmission of information within the Internet

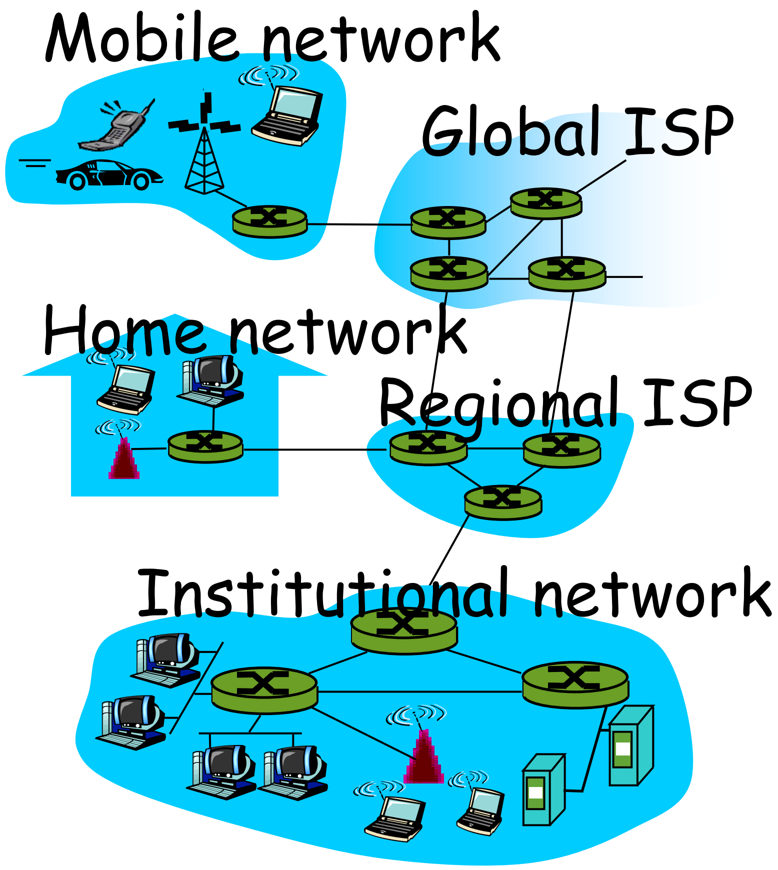
Software Components

Protocols

control sending, receiving of msgs (e.g., TCP, IP, HTTP, Skype, Ethernet)

Internet standards

- RFC: Request for comments
- IETF: Internet Engineering Task Force



“Service” View

Internet enables distributed (network) applications:

- remote login
- email
- web surfing
- chatting
- video conferences, VoIP
- multimedia
- distributed games and databases
- e-learning, e-health, e-business
- Appliance applications

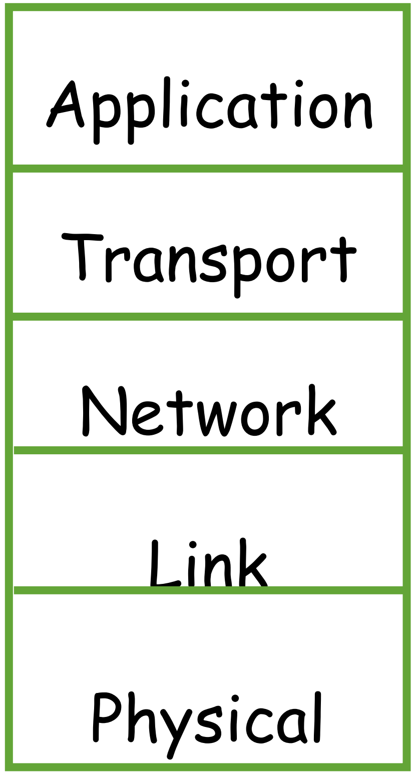
"Layer" View

Internet Layers

- Each layer provides different communication services

Different protocols provide communication services to apps:

- reliable data delivery from source to destination (TCP)
- "best effort" (unreliable) data delivery (UDP)



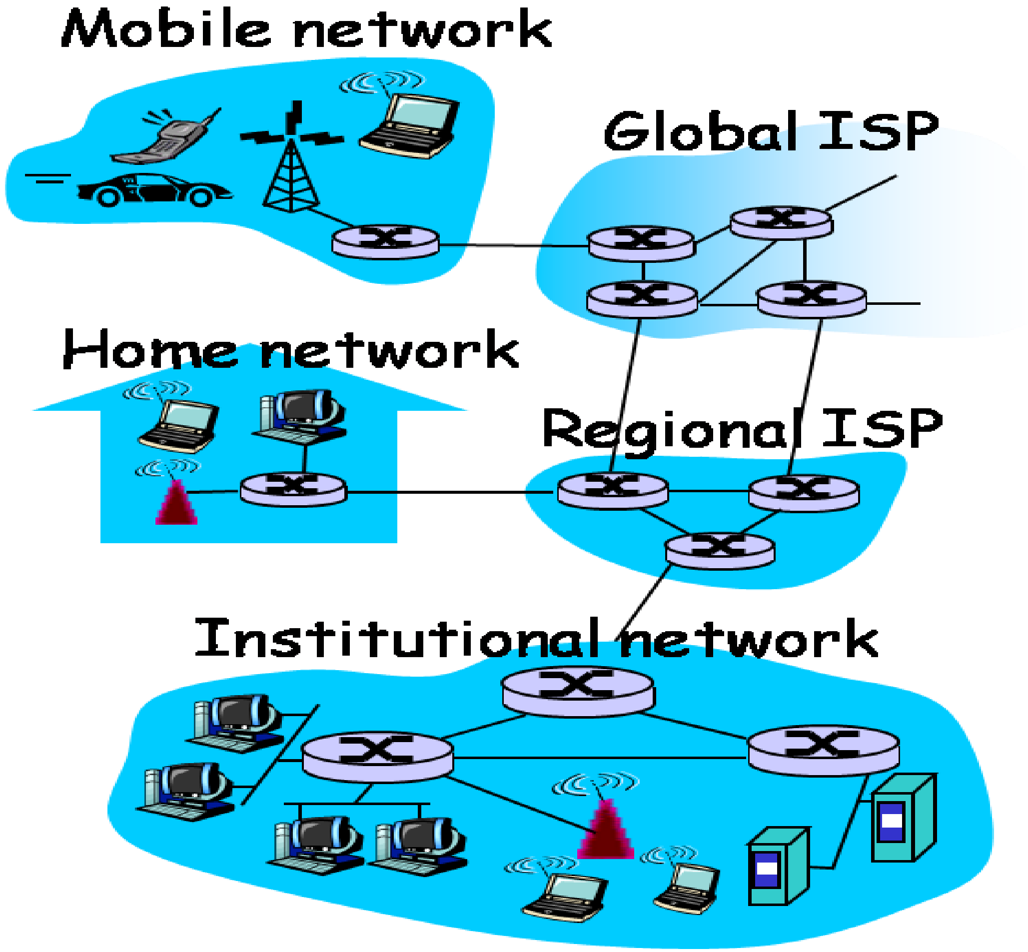
Layer model of Computer Net

Internet: A network of networks

Internet: "A network of networks"

loosely hierarchical

public Internet versus private intranet



Intranet, Extranet

Intranet is an Internal network inside an organization, Makes information accessible to employees

Extranet allows customers or suppliers to access part of company's intranet

Typically includes connection to Internet

Internet Structure

Network Edge (end systems)

- Client / server model
- Peer to peer model

Access Network

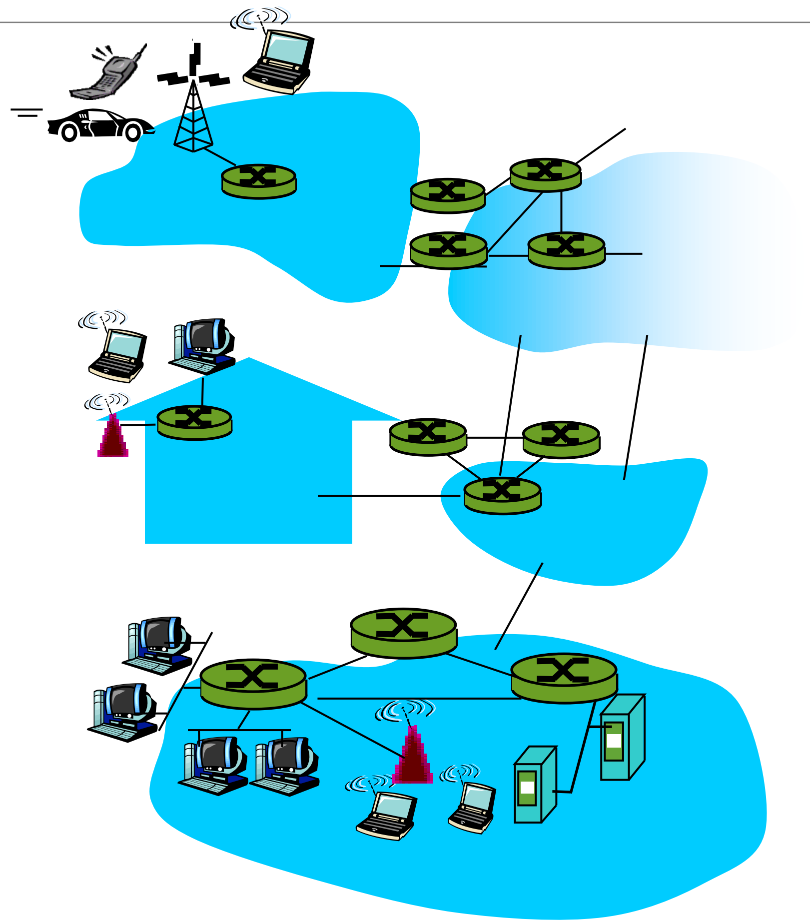
- physical link(s) that connect an end system to its edge router (i.e., the first router on a path from an end system to any other distant end system)

Network Core (routers, comm. links)

- Circuit switching (telephone networks)
- Packet switching (Internet)

A closer look at network structure

- Network edge
- Access networks
- Network core



Network Edge

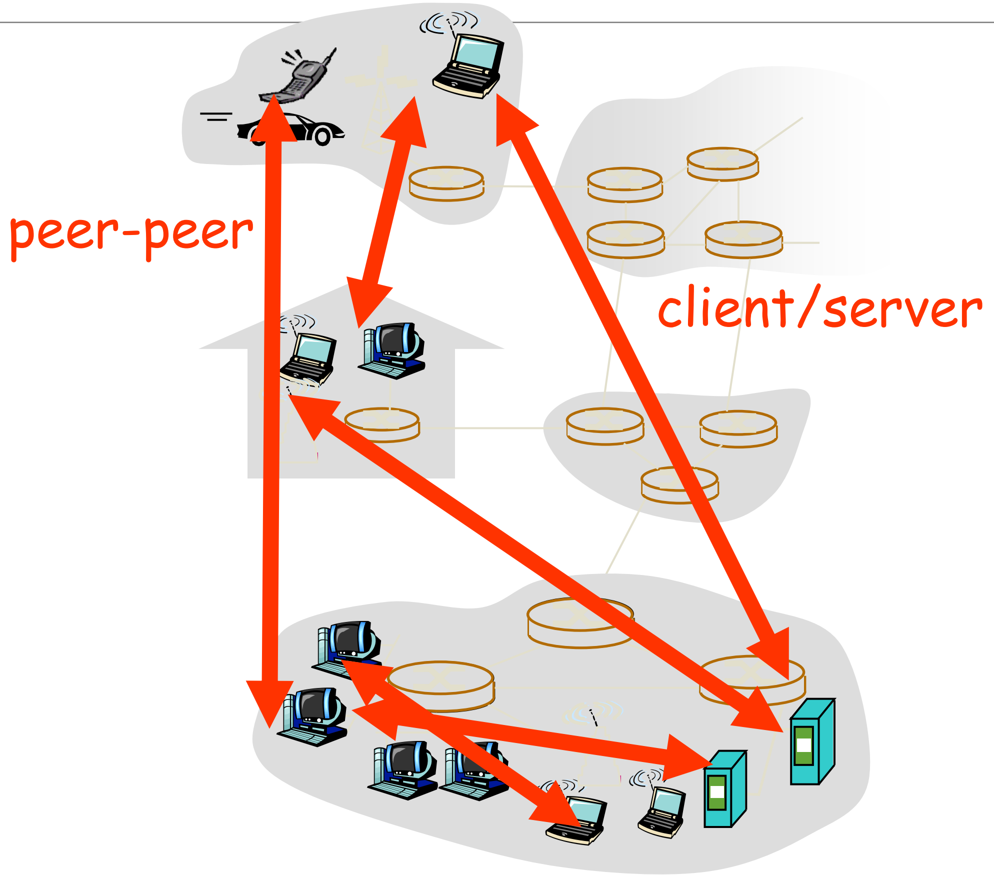
By network edge we mean end systems that are computing devices connected to the Internet. They so called “end systems” because they sit at the edge of the Internet

End systems include: **desktops** (PC, MAC, UNIX-based workstation), **portable and mobile** computers (laptops, pocket PC, PDA), **servers**, powerful machines that host services (web servers, email servers), and **appliance** (TVs, toaster, digital cameras, …)

End systems are sometimes called **hosts** because they host (run) application programs such as web browsers, web servers, email readers, or email server programs.

The Network Edge

- end systems (hosts):
  - run application programs
  - e.g. Web, email
- client/server model
  - client host requests, receives service from always-on server
  - e.g. Web browser/ web server; email client/email server
- peer-peer model:
  - minimal (or no) use of dedicated servers
  - e.g. Skype, BitTorrent



Client/Server model

Client/server a *client program* runs on one computer (client) and the *server program* runs on another computer (server)

A client program is a program running on one end system that *request and receive* a service from a sever program running on another end system (server)

A server program is a program running on one end system that *provides* services as requested to client programs running on another end system

Client/Server model (cont.)

The most common structure for the Internet applications, used for

Email

Web services

File transfer

Remote login (telnet)

Peer-to-Peer model

The end system is not a pure client nor a pure server. It can run both client programs and server programs

Each end system is called _a peer_ and acts as a client when it request a file from another peer; and as a server when it sends file to another peer.

As an example to peer-to-peer system is *Skype*.

Transport Services

End systems use the Internet to communicate with each other (i.e., end system programs use the Internet services to exchange messages).

The links, routers, and other pieces of the Internet provide the means to transport the messages between end systems.

The Internet, provides two types of transport services for the end systems**, connectionless** service and **connection-oriented** service.

Any Internet application such as email, file transfer, web application, or phone application must be build to use one of these services.

Connection-oriented services (TCP)

Handshaking

Reliability

Flow control

Congestion control

Handshaking

Handshaking means that the client program and server program (residing in different end systems) send **control packets** to each other before sending the **real data** (such as email).

The purpose of the handshaking messages is to alert the client and server, allowing them to prepare for packet transmission.

Once the handshaking is finished, a communication is said to be established between the two end systems and transmission of real data begins.

An analogy for handshaking in human interaction is the exchange of “Hi”s

Reliable Data transfer

The application can rely on the connection to deliver all of its data without **error, loss,** and in the **proper order**.

Reliability is achieved through the use of **acknowledgement** and **retransmission**.

Example on reliable transfer: consider an application that has established a connection (via handshaking) between end systems A and B.

When end system B receives a packet from A, it sends an acknowledgment; when end system A receives the acknowledgement, it knows that the corresponding package has definitely been received.

When end system A does not receive an acknowledgment, it assumes that the packet it sent wasn't received by end system B and thus retransmit the packet.

Flow control

Makes sure that neither side of a connection overwhelms the other side by sending too many packets too fast.

The application at one side of the connection may not be able to process information as quickly as it receives the information. Therefore there is a risk of overwhelming either side of an application.

The Internet implements the flow control service by using sender and receiver **buffers** in the communicating end systems

However, buffer can overflow due to its limited capacity.

To avoid overflow, the **flow-control service** forces the sending end system to reduce its rate whenever there is such a risk.

Congestion-control

When a **router** becomes congested, its buffers can overflow and packet loss can occur.

In such circumstances, if every pair of communicating end systems continues to pump packets into the network as fast as they can, few packets will be delivered to their destinations.

The Internet avoids this problem by forcing end systems to diminish the rate at which they send packets into the network during periods of congestion.

End systems are alerted to the existence of severe congestion when they stop receiving acknowledgments for the packets they have sent

Connectionless services (UDP)

No handshaking

No reliability

No flow control

No congestion control

Faster than TCP

UDP (User Datagram Protocol)

There is **no handshaking** with the Internet's connectionless service.

When one side of an application wants to send packets to another side of an application, the sending application simply sends the packets.

Since there is no handshaking procedure prior to the transmission of the packets, data can be delivered faster.

There are **no acknowledgments** either, so a source never knows for sure which packets arrive at the destination.

The service makes **no provision for flow control or congestion control**.

TCP and UDP

Most of the more familiar Internet applications use TCP.

These applications include Telnet (remote login), SMTP (for electronic mail), FTP (for file transfer), and HTTP (for the Web).

UDP, is used by many applications, including many of the emerging multimedia applications, such as Internet phone, and video conferencing

Access Networks and Physical Media

Q: How to connect end systems to edge router?

residential access nets

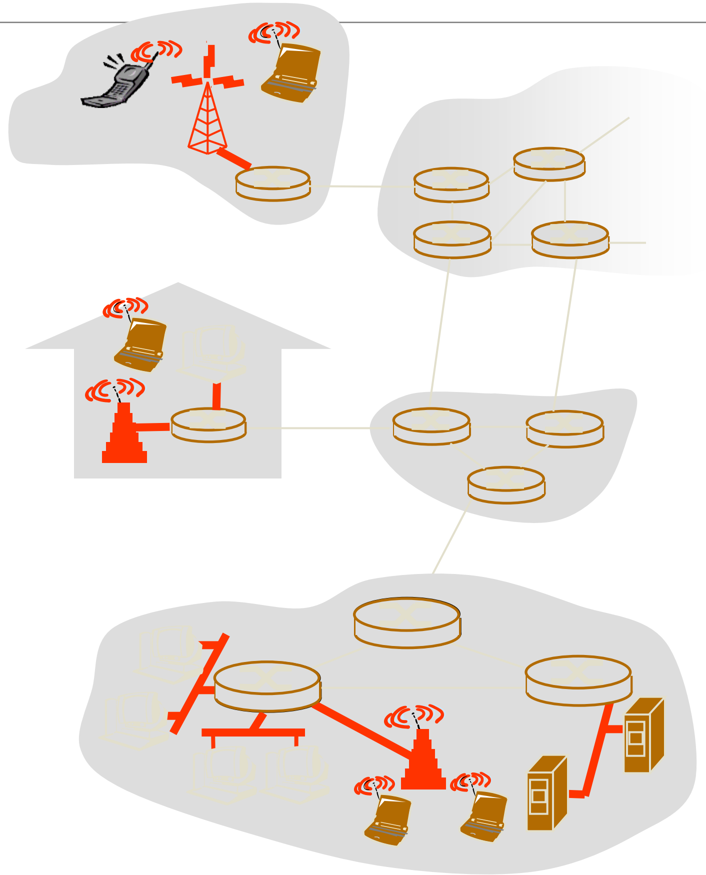
institutional access networks (school, company)

mobile access networks

Keep in mind:

bandwidth (bits per second) of access network?

shared access or **dedicated** access?



Access Networks

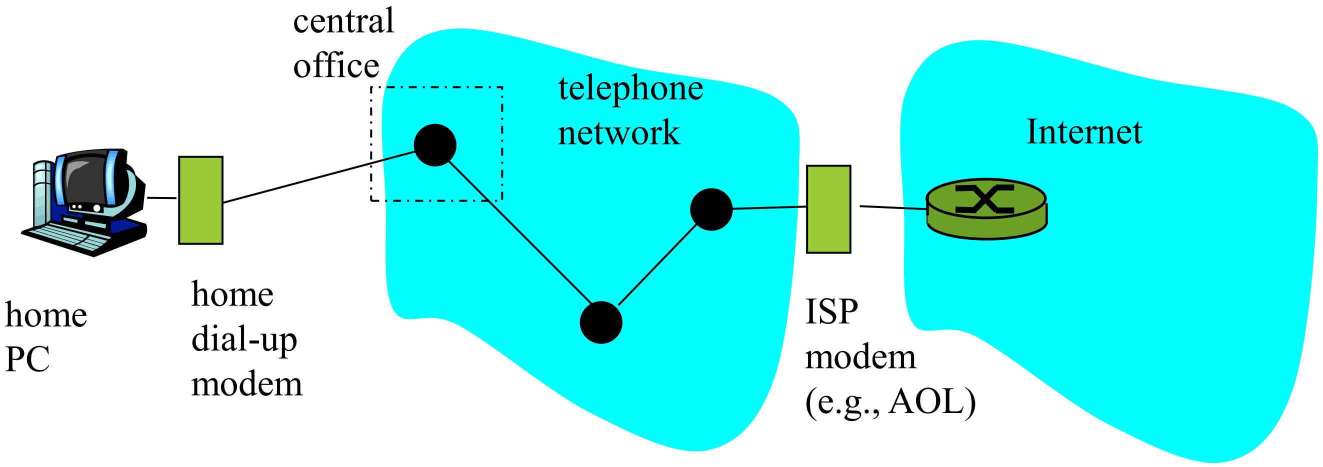
Residential (Home)

- Dial up modem
- DSL modem
- TV modem
- Fiber to home

Institutional

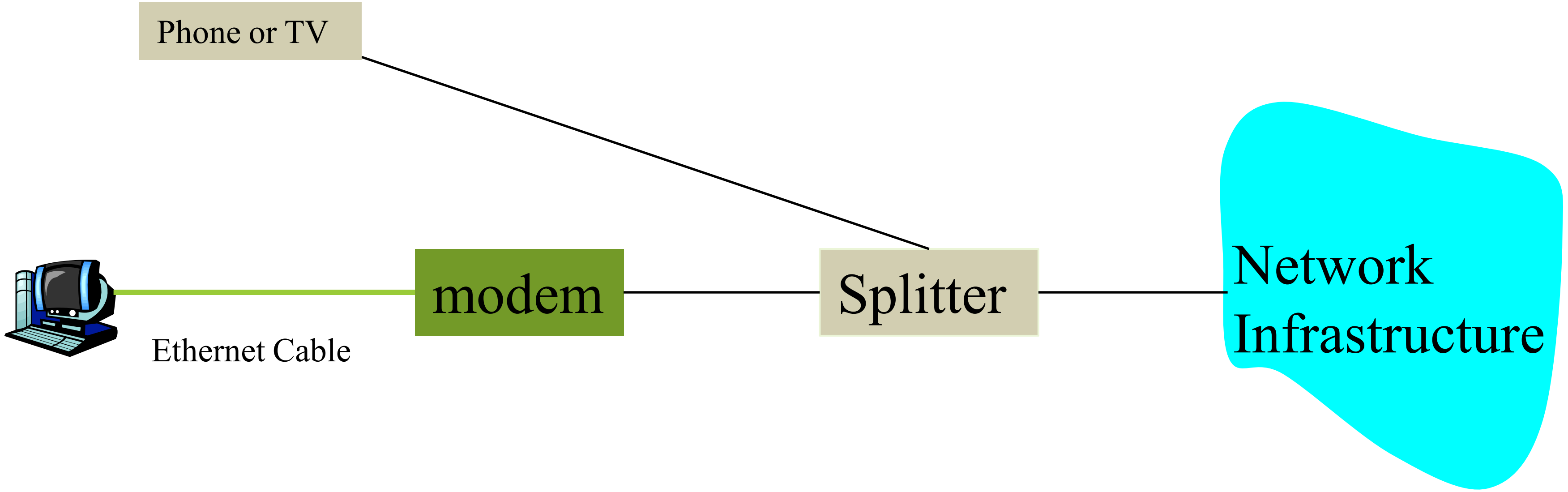
- Ethernet
- Access point

Dial-up Modem

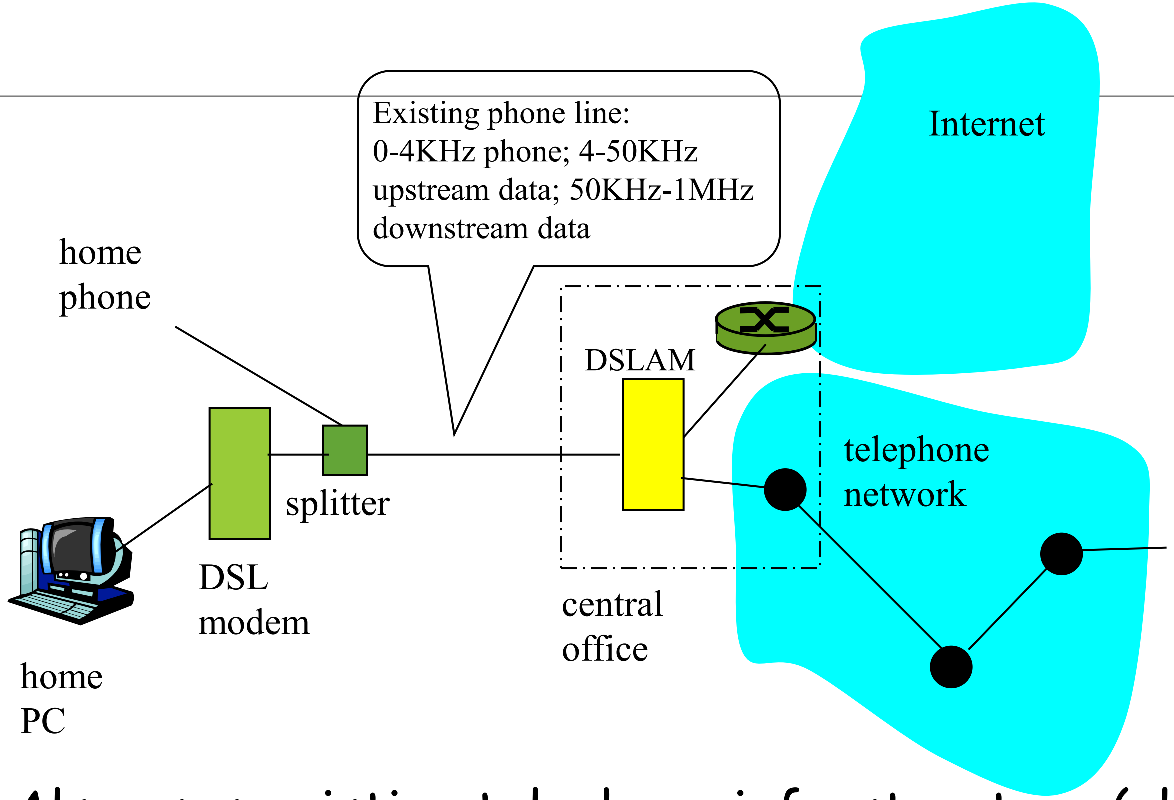


- Uses existing telephony infrastructure
- Home is connected to central office
- Can't surf and phone at same time: not "always on"
- up to **56 Kbps** direct access to router (often less)

Modern Modems



Digital Subscriber Line (DSL)



- Also uses existing telephone infrastructure (always on)
- up to **1 Mbps** upstream for ADSL
- up to **9 Mbps** downstream for ADSL
- **dedicated** physical line to telephone central office

Residential access: TV cable modems

Does not use telephone infrastructure

Instead uses cable TV infrastructure

HFC: hybrid Fiber Coax

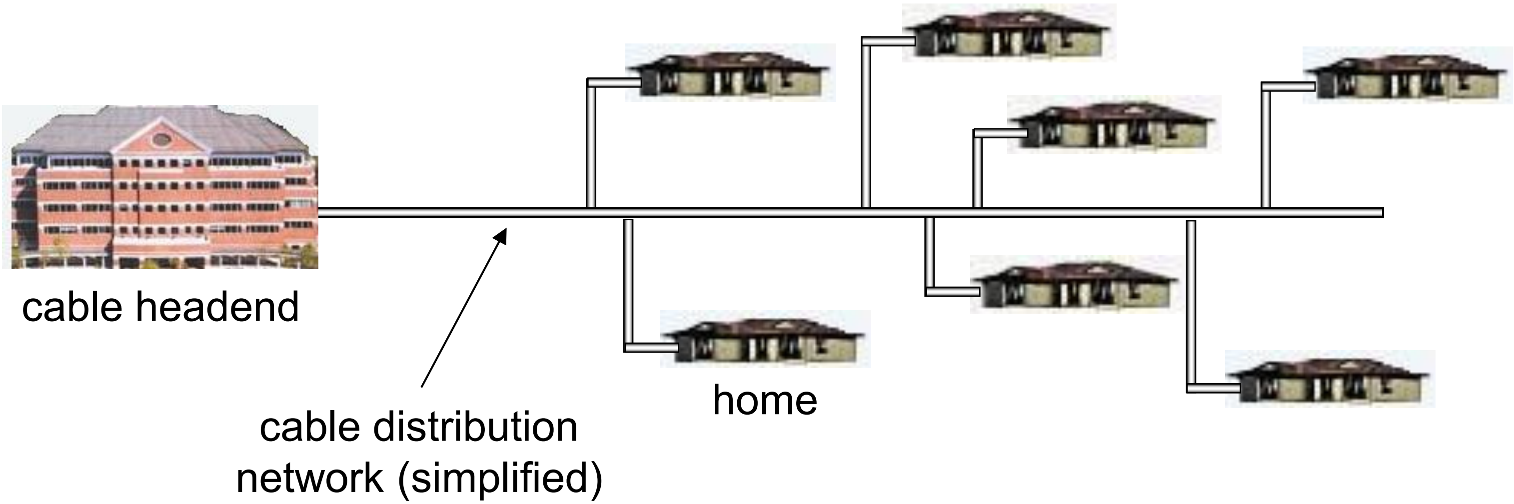
- asymmetric: up to **30 Mbps** downstream, **2 Mbps** upstream

Network of cable and fiber attaches homes to ISP router

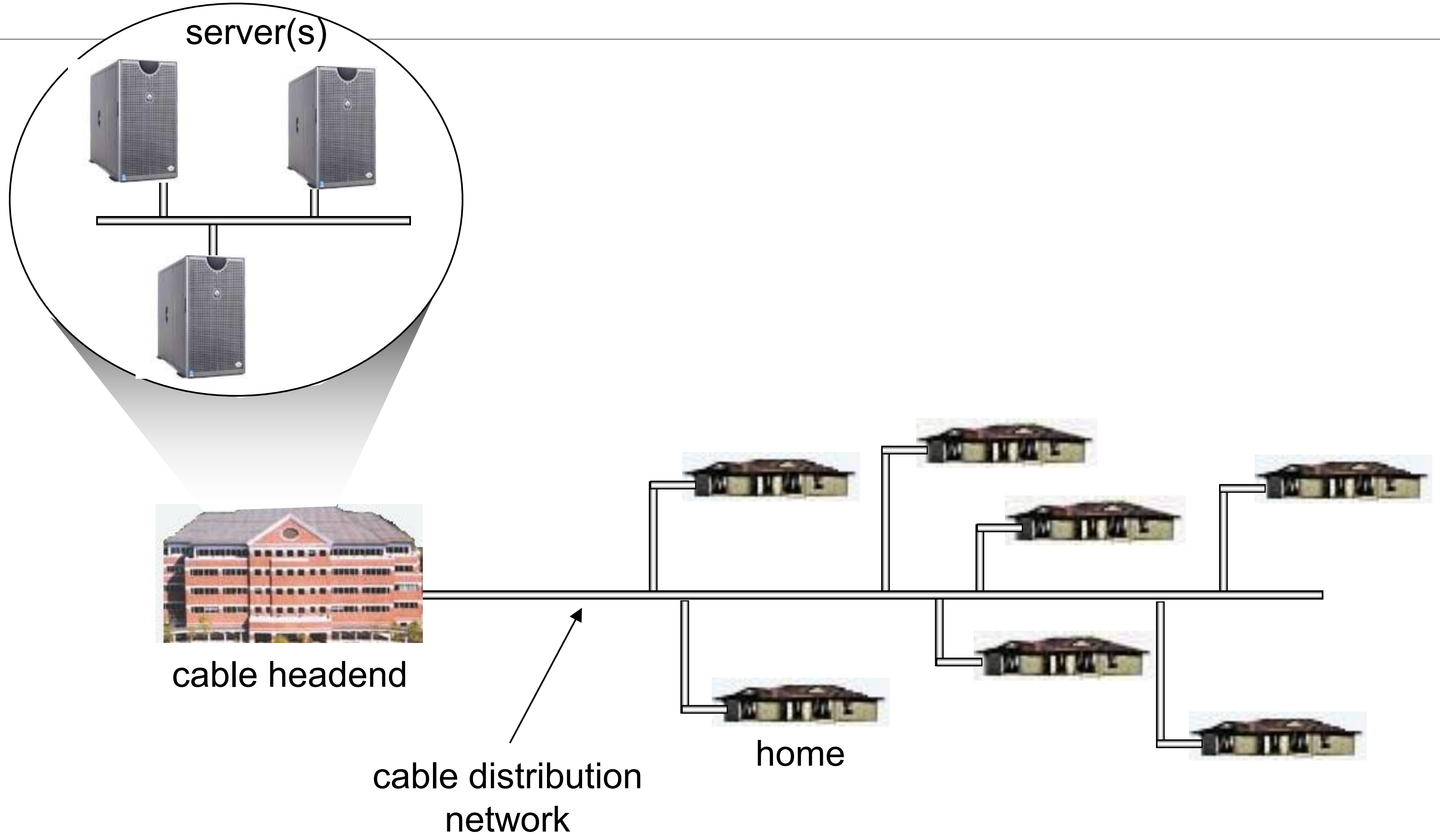
- homes **share access** to router
- unlike DSL, which has **dedicated access**

Cable Network Architecture: Overview

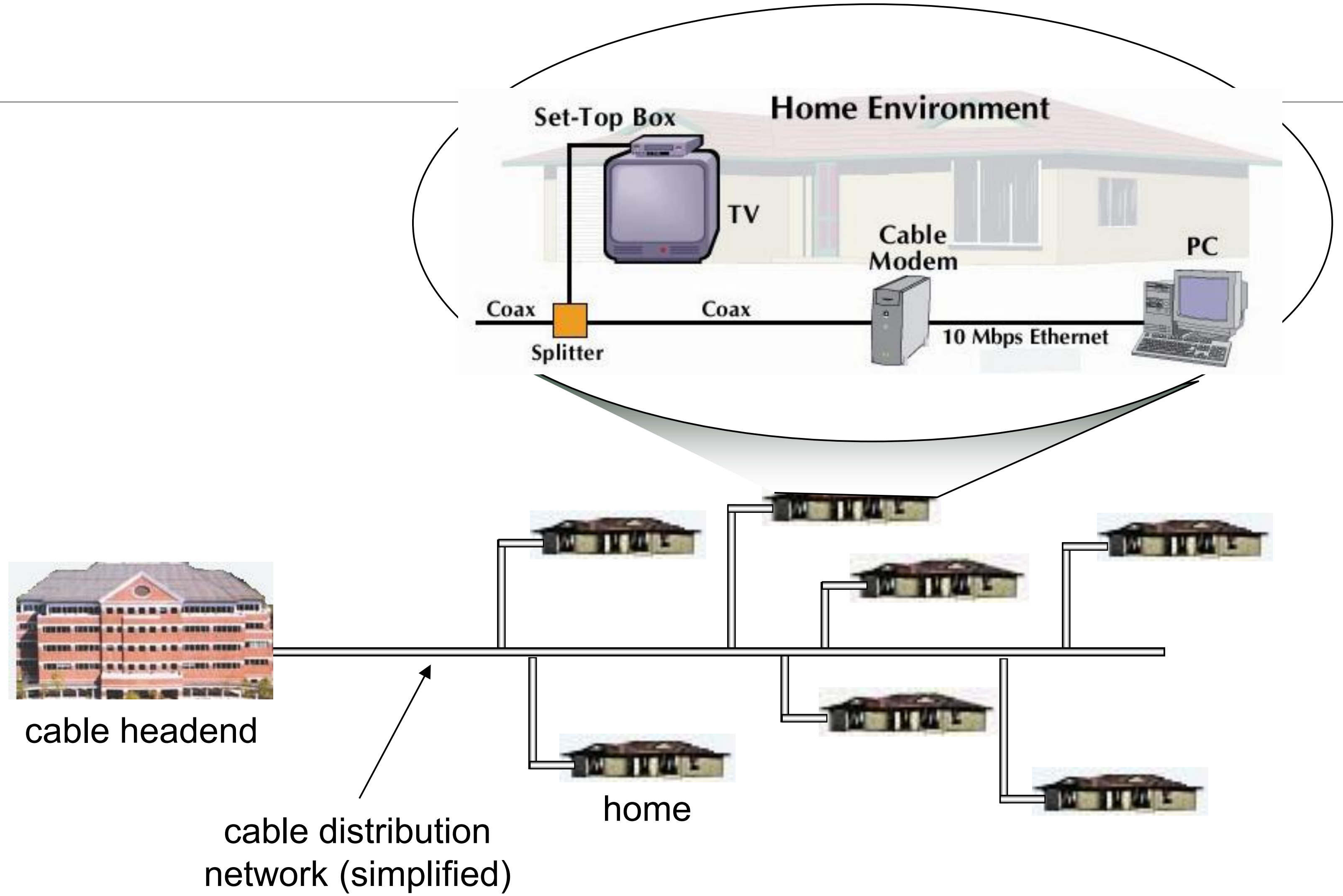
Typically 500 to 5,000 homes



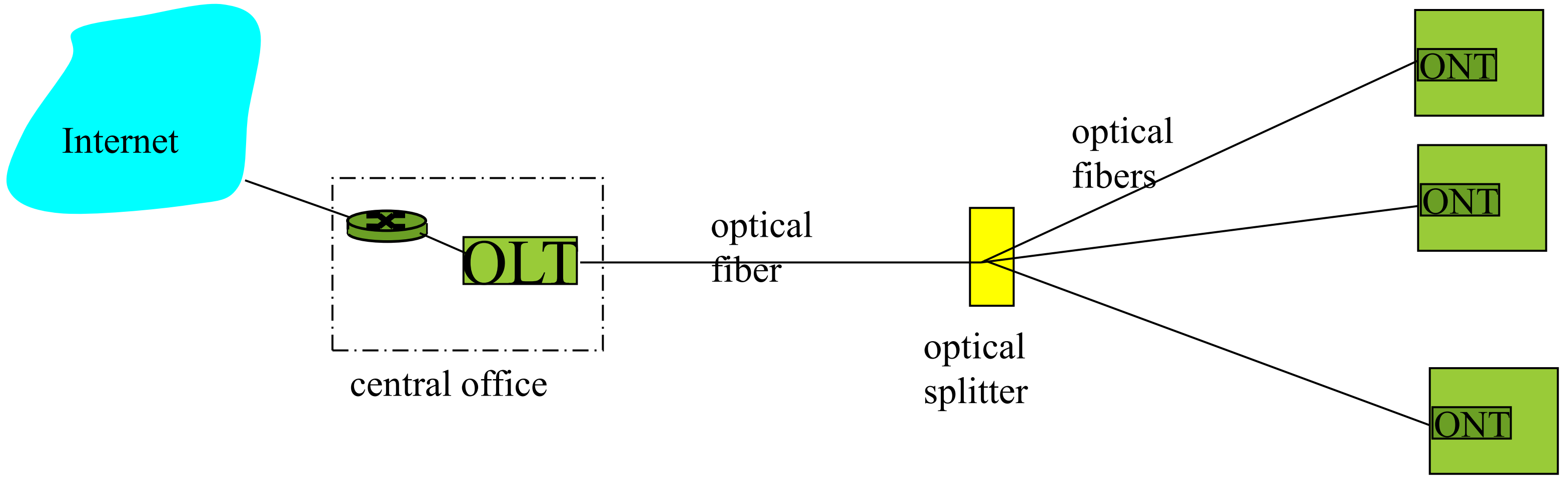
Cable Network Architecture: Overview



Cable Network Architecture: Overview



Fiber to the Home



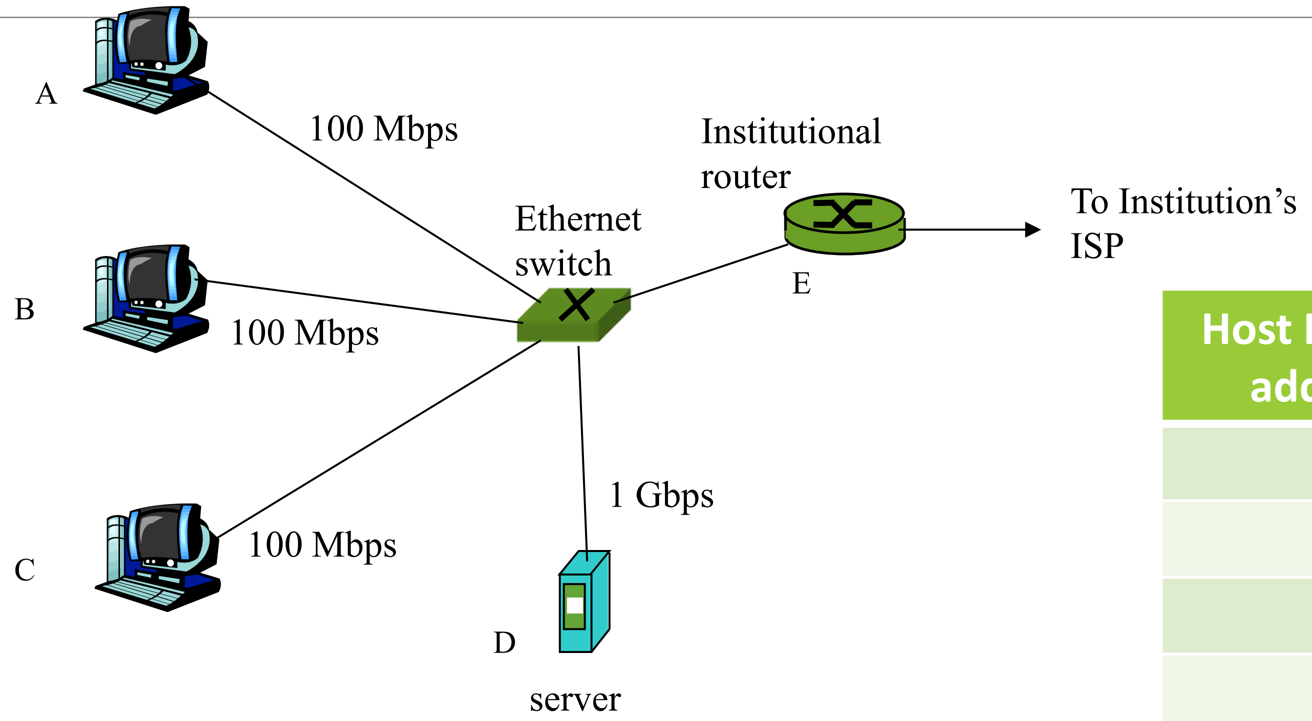
Optical links from central office to the home

Two competing optical technologies:

- Passive Optical network (PON)
- Active Optical Network (PAN)

Much higher Internet rates (Gbps); fiber also carries TV and phone services

Ethernet Internet Access



Host ID (MAC address)	Interface
A	1
B	2
C	3
D	4
E	5

Typically used in companies, universities, etc

- 10 Mbs, 100Mbps, 1Gbps, 10Gbps Ethernet
- Today, end systems typically connect into Ethernet switch

Wireless Access Networks

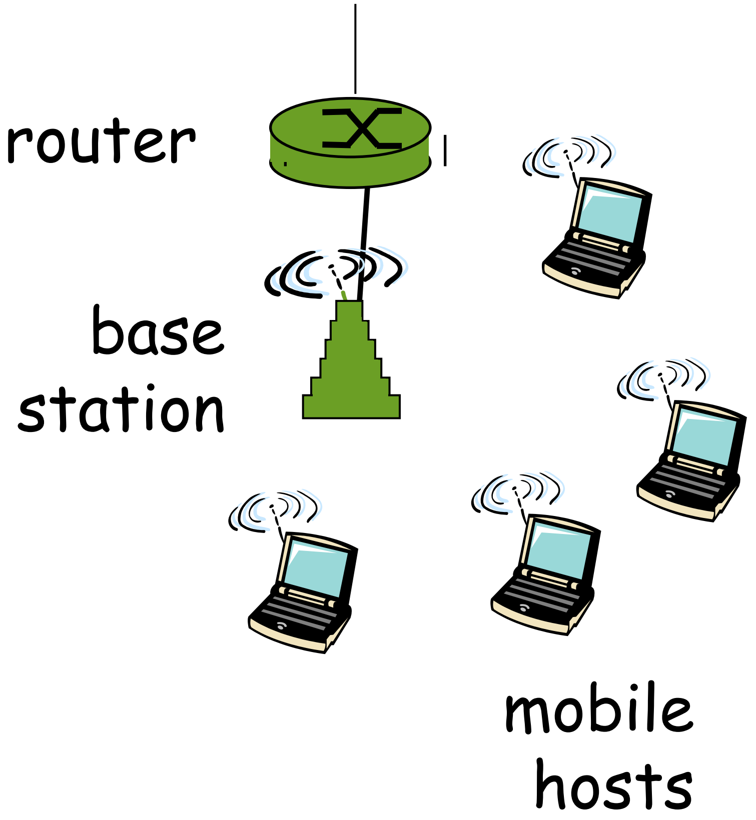
shared *wireless* access network connects end system to router via base station aka “access point”

wireless LANs (WIFI):

- 802.11b/g (WiFi): 11 to 54 Mbps

wider-area wireless access

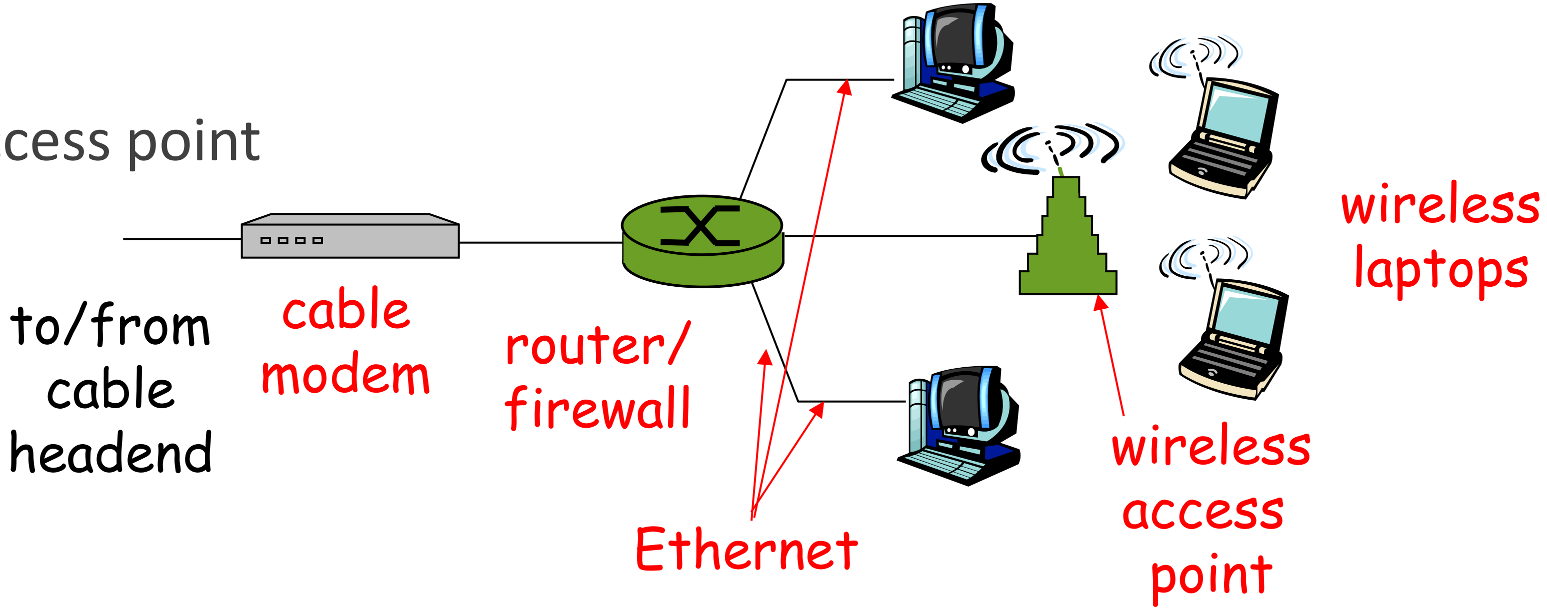
- ~1Mbps over cellular system (EVDO, HSDPA)
- WiMAX (10’s Mbps) over wide area



Home Networks

Typical home network components:

- DSL or cable modem
- router/firewall
- Ethernet
- wireless access point



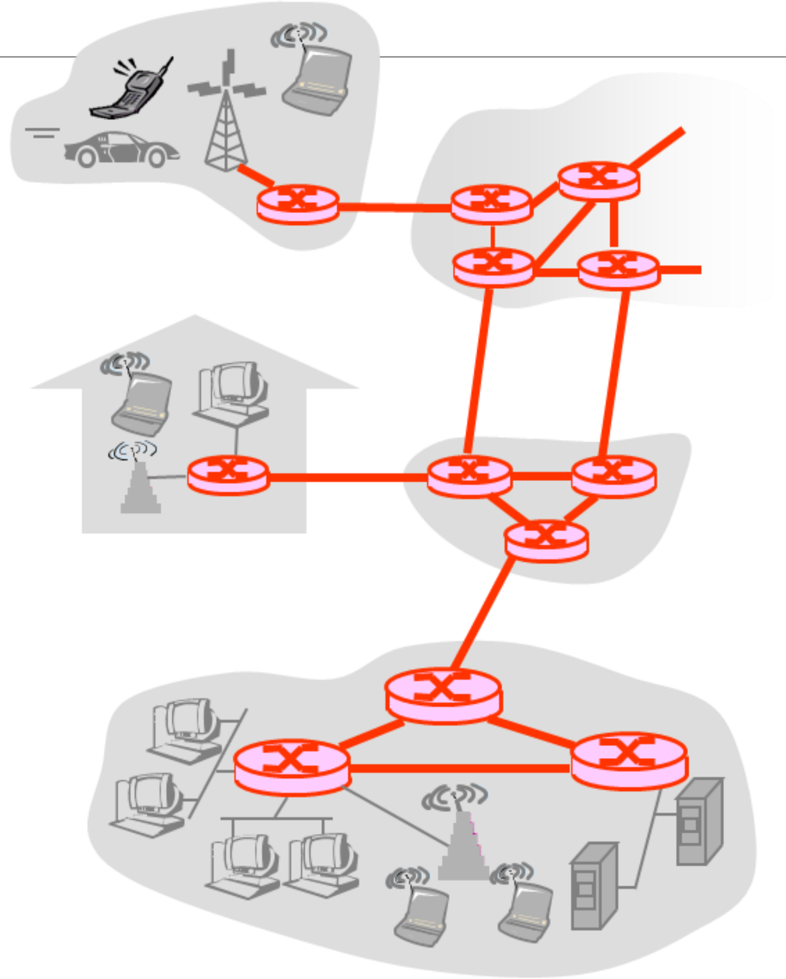
Network Core

The fundamental question: how is data transferred through net?

Network core is a mesh of interconnected routers that help end systems communicate

There are two approaches towards building a network core:

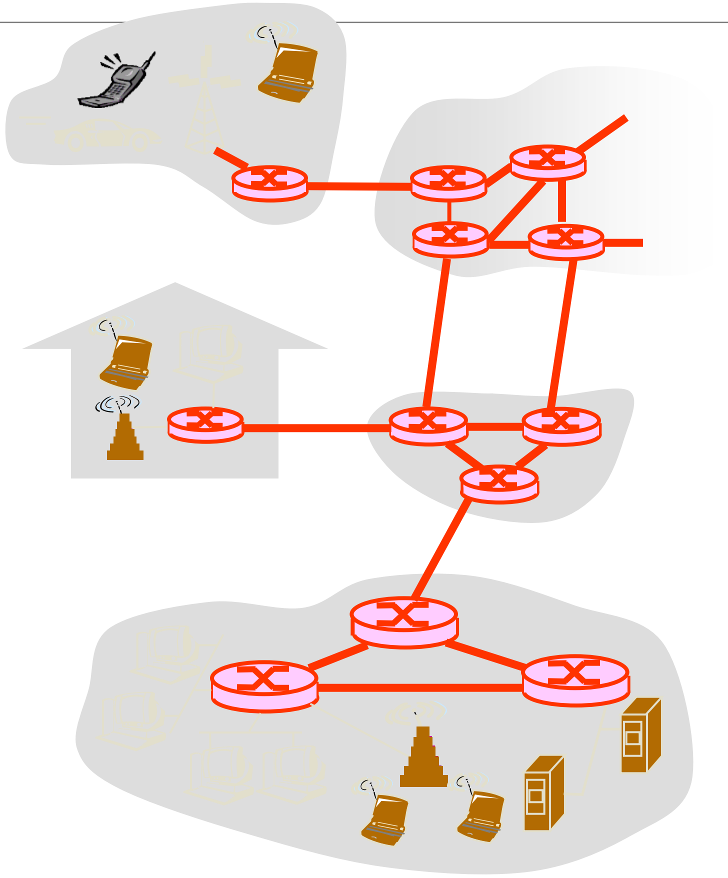
- Circuit switching (telephone)
- **Packet switching (Internet)**



The Network Core

Circuit switching: dedicated circuit per call: telephone net

Packet-switching: data sent through net in discrete “chunks” on shared resources



Human Analogy

Two restaurants -- one which requires reservations and another which neither requires reservations nor accepts them

First restaurant (circuit switching)

- Complex, you have to call or send an email for reservation, but no delays upon arrival

Second restaurant (packet switching)

- Simple, you don’t have to make reservation, but you may wait upon arrival

Circuit Switching

end to end resources reserved for "call". This is called circuit

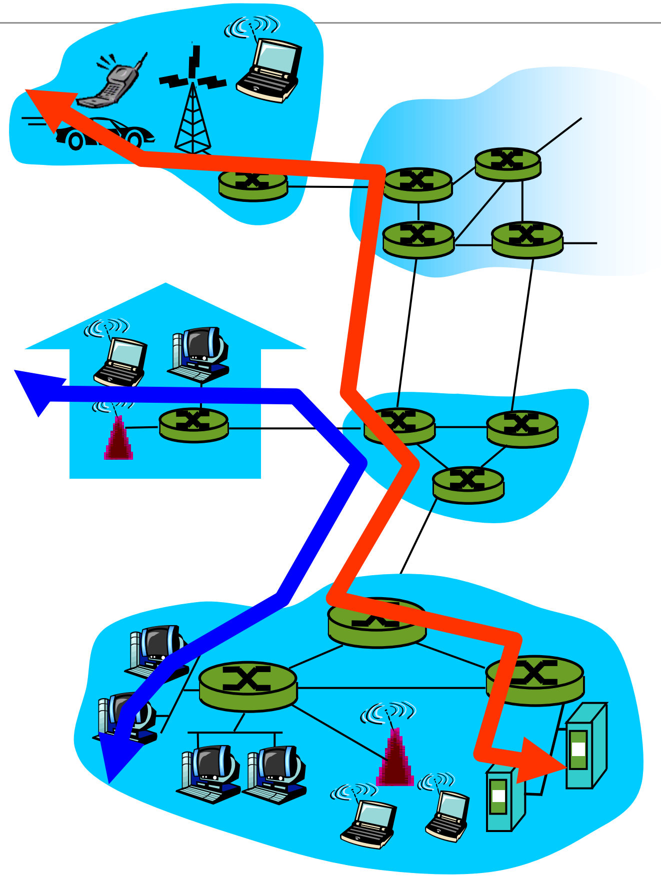
Resources: link bandwidth, switch capacity, buffers

Resources are divided into circuits

Each circuit is dedicated (reserved) along the path between end systems

circuit-like (guaranteed) performance (reserved bw or transmission rate)

call setup required (delay)



Circuit Switching

The telephone networks are examples of circuit-switched networks

Consider what happens when one person wants to send information (voice or facsimile) to another over a telephone network.

Before the sender can send the information, the network must first **establish a connection** between the sender and the receiver

When the network establishes the connection, it also reserves a **constant transmission rate (bw)** in the network's links for the duration of the connection.

This reservation allows the sender to transfer the data to the receiver at the guaranteed constant rate (bw).

Circuit Switching

Each link in a circuit switching net has n circuits (n portions of BW). Thus, it can support n simultaneous connection.

When two hosts want to communicate, the network establishes ***a dedicated end-to-end circuit*** between them.

Thus in order for host A to send messages to host B, the network must first reserve one circuit on each of the links between them

How a circuit is established?

Network resources (e.g., bandwidth) divided into “pieces or circuits”

Pieces allocated to calls (users)

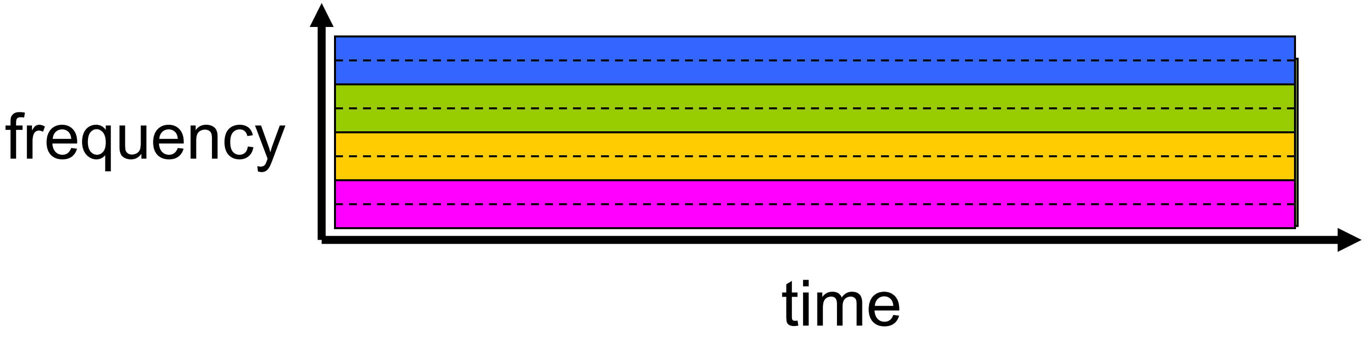
Resource piece **idle** if not used by owning call

Dividing link bandwidth into “pieces”

- Frequency Division Multiplexing (FDM)
- Time Division Multiplexing (TDM)

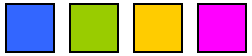
FDM and TDM

FDM

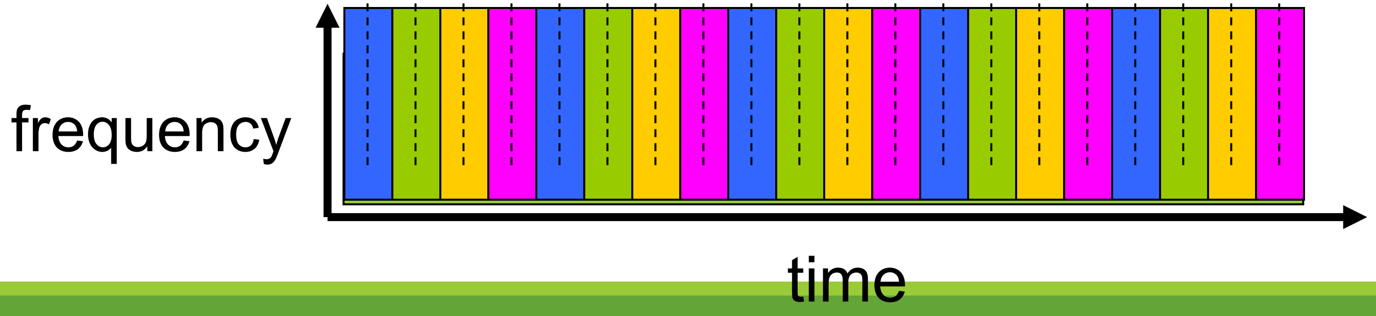


Example:

4 users



TDM



Numerical example

How long does it take to send a file of 640,000 bits from host A to host B over a circuit-switched network?

- All links are 1.536 Mbps (bw)
- Each link uses TDM with 24 slots/sec (users)
- 500 msec to establish end-to-end circuit (call setup delay)

Let's work it out!

Numerical Example (cont.)

Divide the link into n=24 circuits (TDM)

Circuit capacity = b.w/n= 1.536/24= 64kbps

File size (data size) = 640 kb

Transmission time = data size/bit rate

File transmission time = 640/64 = 10 sec

Overall transmission time = 10+0.5=10.5 sec

Packet Switching

Data are divided into packets

A **packet is a chunk of data** that contains control function (handshaking, acknowledgement, …) and real data such as JPEG file, webpage, MP4 audio file, …

Packets are transmitted over the links and routers on-demand (as needed), with the **full transmission rate (full bw)** of the link

Resources are used on demand (i.e. **no division/reservation**)

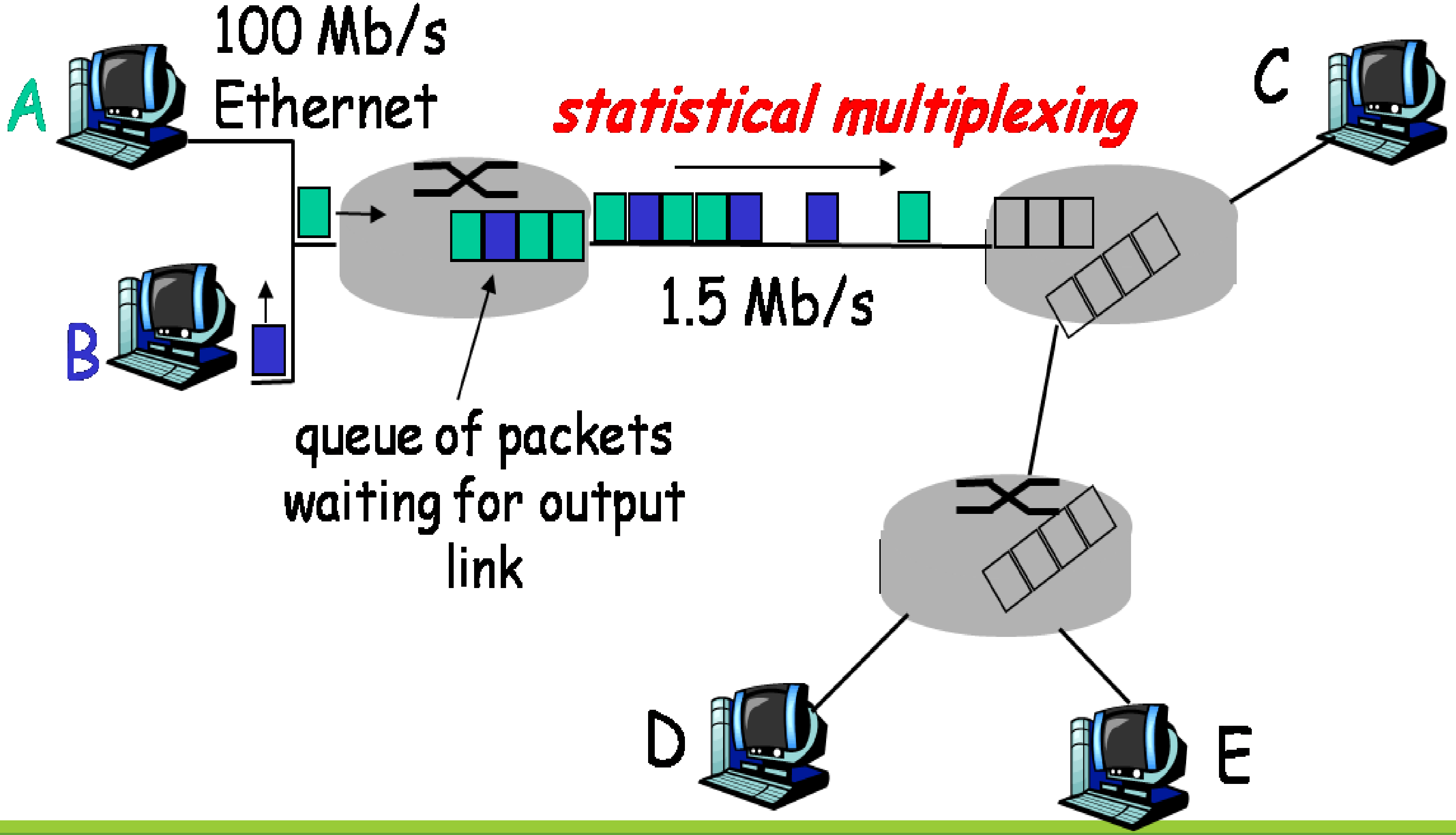
simpler, no call setup

User may wait for resources to be available

excessive congestion: packet delay and loss

- protocols needed for reliable data transfer, congestion control

Packet Switching



Packet Switching

- each end-end data stream divided into packets
- user A, B packets share network resources (on demand)
- each packet uses full link bandwidth
- resources used as needed

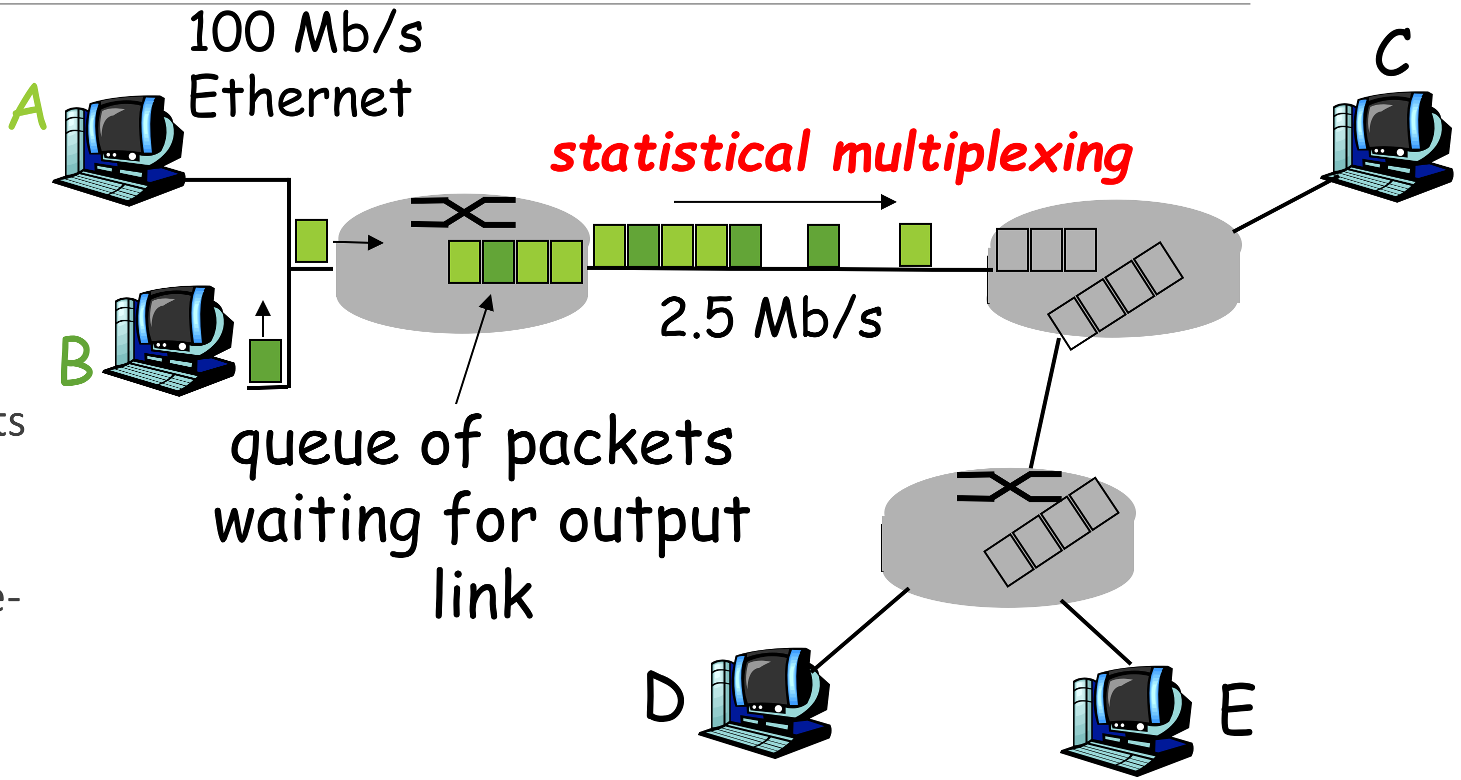
~~Bandwidth division into "pieces"~~
~~Dedicated allocation~~
~~Resource reservation~~

- Reserved resources (circuit switching) versus on-demand resource allocation (packet-switching)

resource contention (competition):

- store and forward: packets move one hop at a time
  - Node receives complete packet before forwarding
- congestion: packets queue, wait for link use results in packet delay
- aggregate (collection) resource demand can exceed amount available results in packet loss

Statistical Multiplexing



Statistical multiplexing: Sequence of A & B packets does not have fixed pattern, bandwidth is shared on demand.

Statistical multiplexing sharply contrasts with time-division multiplexing (TDM),

In TDM: each host gets the same slot in revolving TDM frame (fixed pattern).

Packet switching can support more users

1 Mbps link

each user:

- 100 kbps when "active"
- active 10% of time

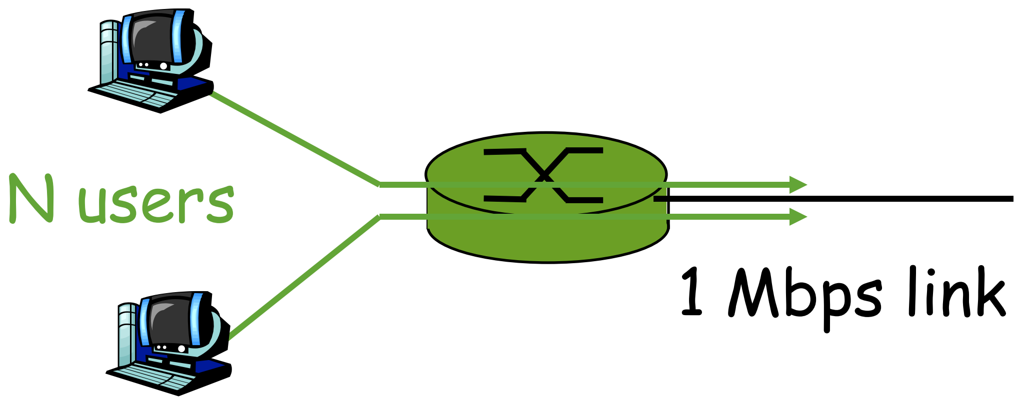
circuit-switching:

- 1Mbps/100kbps=10 users

packet switching:

- with 35 users, probability that more than 10 users active at same time is very small

Packet switching allows more users to use network!



Example

population of N users, a user is active only 10% of time

probability (p) that a given user is transmitting = 10%=0.1

probability that at any given time n users are transmitting simultaneously = $\binom{N}{n} p^n (1-p)^{N-n}$

probability that more than m users transmitting at the same time = $1 - \sum_{n=0}^{m} \binom{N}{n} p^n (1-p)^{N-n}$

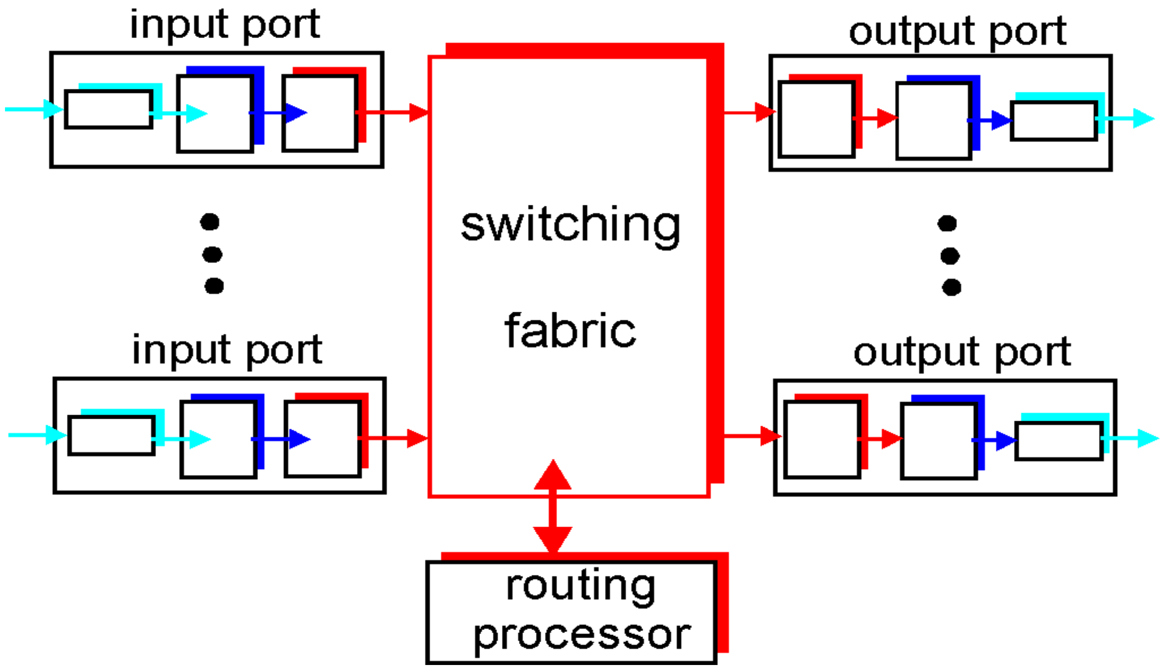
Packet switching vs. Circuit switching

	Packet switching	Circuit switching
Resource allocation	On demand: resources are not reserved; a session's messages use the resource on demand, and as a consequence, may have to wait (i.e., queue) for access to a communication link	Reserved: the resources needed along a path (buffers capacity, link bandwidth) to provide communication between the end systems are reserved (dedicated) for the duration of the session
Delay	Variable and unpredictable delays (store and forward & queuing)	Call set up delay: Smaller delays make it suitable for real time applications telephone calls and video conferences
Data Loss	Packet loss due to queuing	Smaller prob. for data loss
Cost	Less cost, simpler (no call setup required)	Relatively expensive and complex (call setup required)
Efficiency	More efficient, better utilization of BW	Less efficient, waste BW due to idle users
No. of users	more users	less users due to bw division
Usage	Used in computer networks	Used in telephone networks

Store and forward in Packet Switching

Most routers use **store and forward** transmission at the inputs to the links.

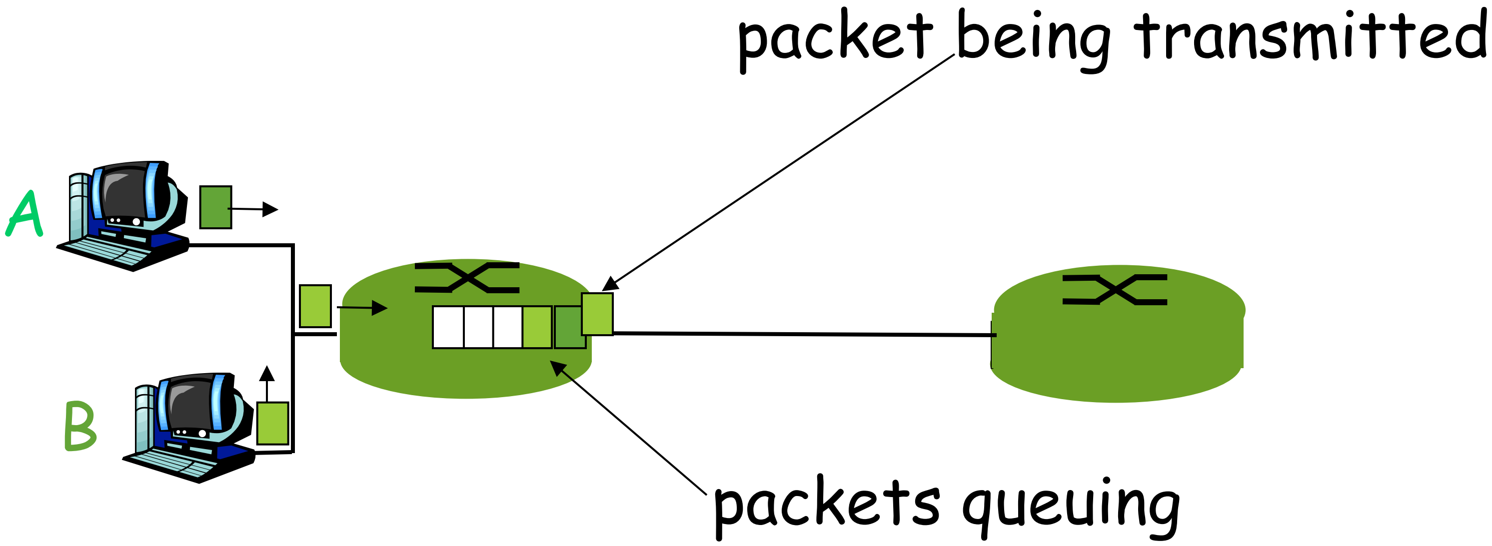
Store-and-forward transmission means that the router must receive the entire packet, store it in its **input buffer**, before it can begin to transmit the first bit of the packet onto the outbound link



Buffer Queue

packets *queue* in router buffers when packet arrival rate to router exceeds output link capacity

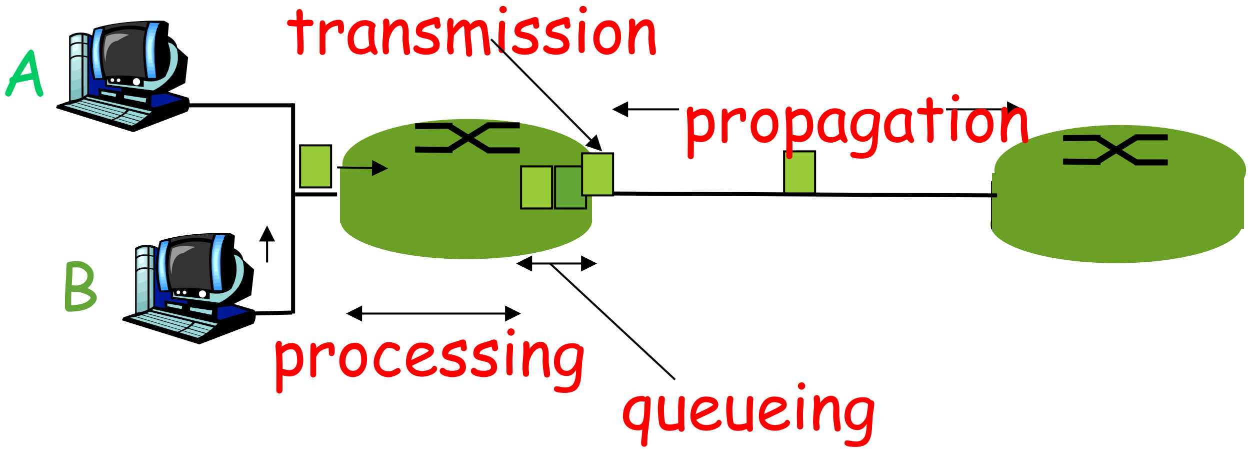
packets queue in the buffer, wait for turn



Delays in Packet Switching

1. processing delay
   - check bit errors
   - determine output link

- 2. queuing delay
  - time waiting at output link for transmission
  - depends on congestion level of router



Delays in Packet Switching (Cont.)

3. Transmission delay:

R=link bandwidth (bps)

L=packet length (bits)

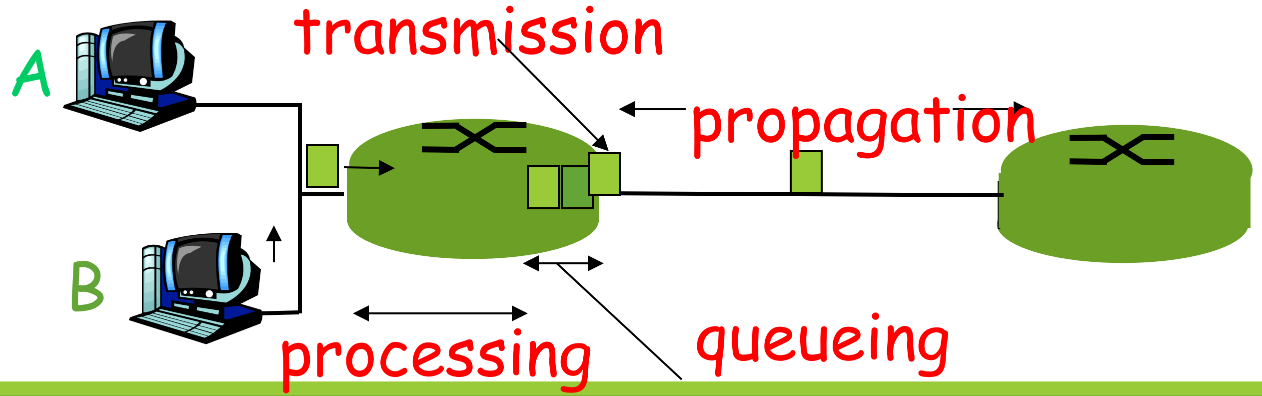
time to send bits into link = L/R

4. Propagation delay:

d = length of physical link

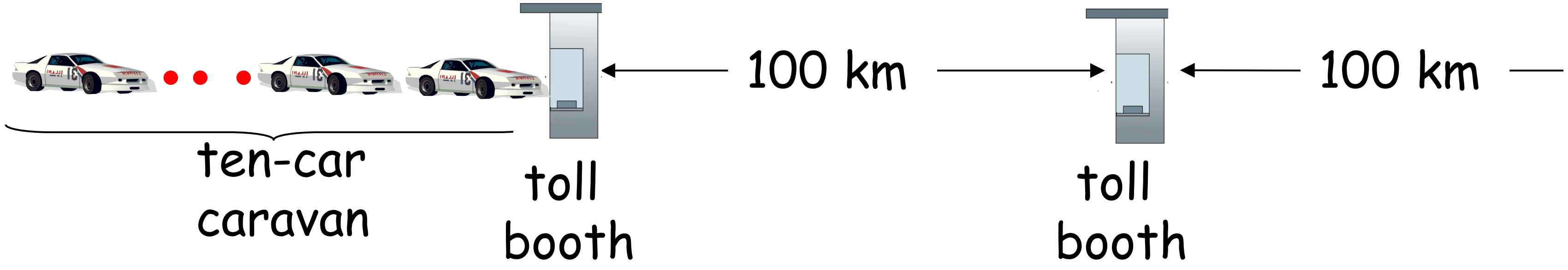
s = propagation speed in medium (~$2x10^8$ m/sec)

propagation delay = d/s



Note: s and R are very different quantities!

Transmission delay vs. propagation delay (Caravan analogy)



cars “propagate” at 100 km/hr

toll booth takes 12 sec to serve a car

car~bit; caravan ~ packet

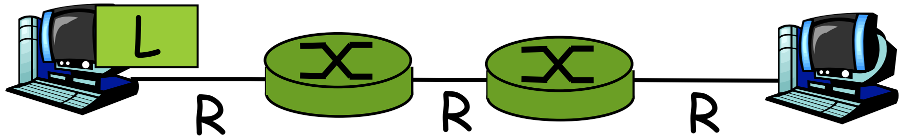
Q: How long until caravan is lined up before 2nd toll booth?

Time to “push” entire caravan through toll booth onto highway = 12*10 = 120 sec = 2 min

Time for **last** car to propagate from 1st to 2nd toll both: 100km/(100km/hr)= 1 hr

A: 62 minutes

Transmission delay



It takes L/R seconds to transmit (push out) packet of L bits on to link at R bps

store and forward: entire packet must arrive at router before it can be transmitted on next link

delay = 3L/R (assuming zero propagation delay)

Example:

Q= no. of links=3

L = 7.5 Mbits

R = 2.5 Mbps

transmission delay = 9 sec

Nodal delay

Nodal delay: delay at a single router

d_{proc} = processing delay
- typically a few microsecs or less

d_{queue} = queuing delay
- depends on congestion

$$\boxed{d_{\text{nodal}} = d_{\text{proc}} + d_{\text{queue}} + d_{\text{trans}} + d_{\text{prop}}}$$

d_{trans} = transmission delay
- = L/R, significant for low-speed links

d_{prop} = propagation delay
- a few microsecs to hundreds of msecs

Assume (Q-1) routers, or Q identical links

End to end delay = $Q(d_{proc}+d_{trans}+d_{prop})$ ignore d_{queue}

Example

Consider a packet of L=1000 Kbits that is to be sent from host A to another host E across a packet-switched network

Let us suppose that there are Q=4 links between A and E, each of rate R=2Mbps

Assume that queuing delays and end-to-end propagation delays are negligible and that there is no connection establishment.

How long does it take to send the message?

End-to-end delay= QL/R = 4 * 1000/2000 = 2 seconds

Queuing delay

Unlike the other three delays (namely, d_{proc} , d_{trans} and d_{prop}), the queuing delay can vary from packet to packet

If ten packets arrive to an empty queue at the same time, the first packet transmitted will suffer no queuing delay, while the last packet transmitted will suffer a relatively large queuing delay (while it waits for the other nine packets to be transmitted)

Queuing delay

when characterizing queuing delay, one typically uses statistical measures, such as average queuing delay, variance of queuing delay and the probability that the queuing delay exceeds some specified value.

When is the queuing delay big and when is it insignificant?

Queuing delay depends mainly on:

- rate at which traffic arrives to the queue (a) --- arrival rate
- transmission rate of the link (R) --- departure rate
- nature of the arriving traffic (periodically, random)

Queuing delay

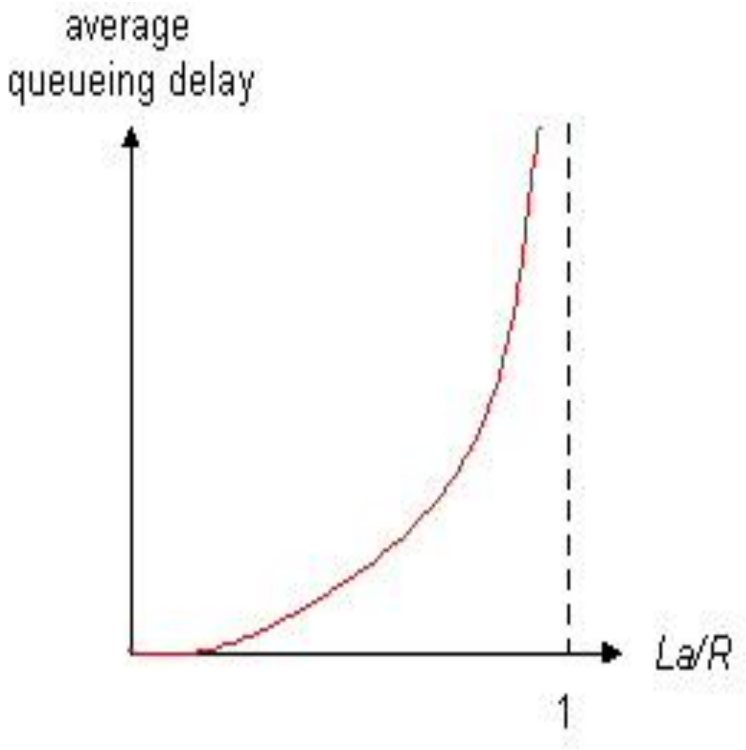
R=link bandwidth =transmission rate =departur

L=packet length (bits)

a=average packet arrival rate

traffic intensity = La/R

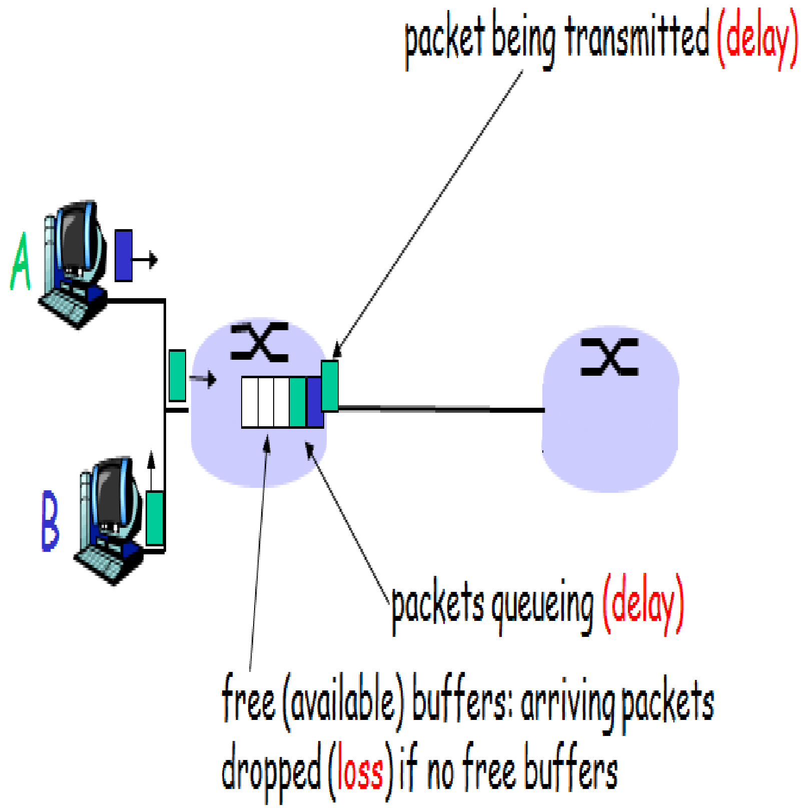
- La/R ~ 0: average queuing delay small
- La/R -> 1: delays become large
- La/R > 1: more "work" arriving than can be serviced, average delay infinite!

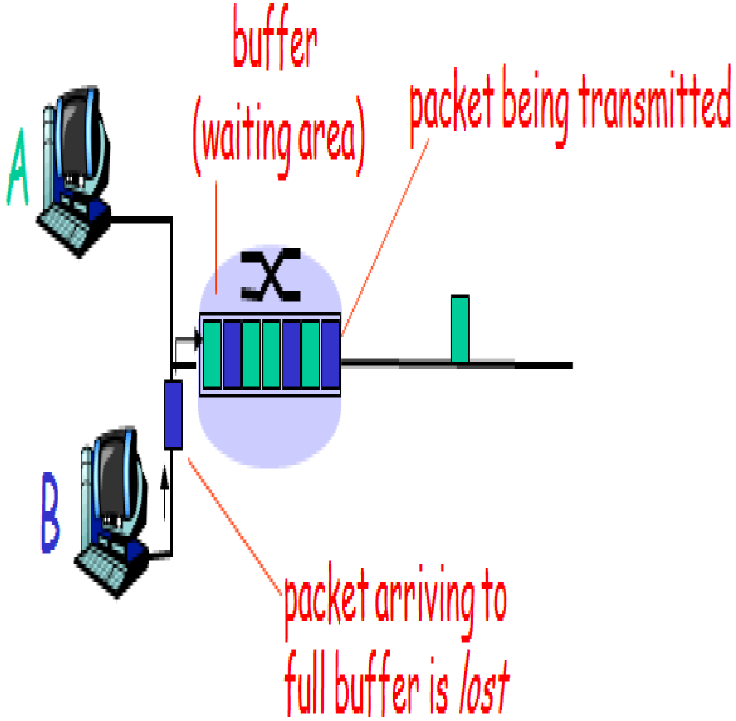


Types of Delay

Delay type	Definition	Order	Comments
Processing delay	Time required to examine the packet's header and determine where to direct the packet	microseconds or less	After this nodal processing, the source router directs the packet to its queue that precedes the link to destination router
Queuing delay	Time for which a packet waits in the router's queue to be transmitted onto the outbound link	microseconds to milliseconds	depend on the number of earlier-arriving packets that are queued and network congestion; and can vary significantly from packet to packet.
Transmission (store-and-forward) delay	the amount of time required to push (transmit) all of the packet's bits into the outbound link	microseconds to milliseconds	=L/R where L: packet length R: transmission rate of the link, total=QL/R, Q is no. of links
Propagation delay	time required for a bit to propagate from the beginning of the link to end of the link	milliseconds	= d/s d: distance between two routers s: propagation speed which depends on type of physical media (fiber optics, twisted-pair, copper wire, …) $2*10^8$ m/s to $3*10^8$ m/s

Packet loss in Packet Switching



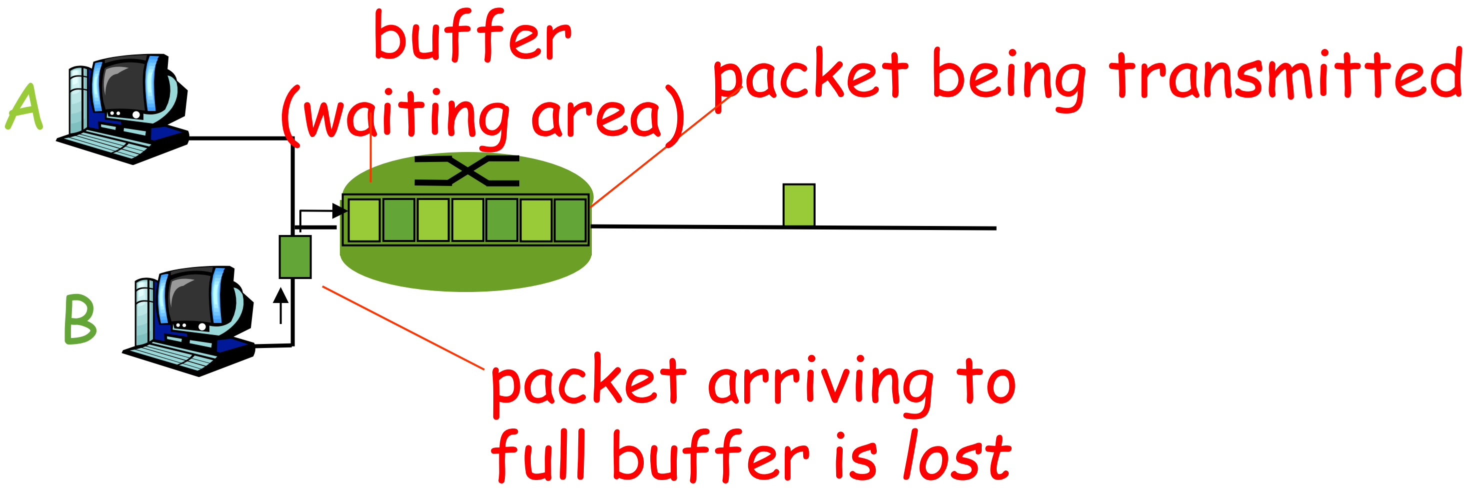


Packet loss

queue (aka buffer) preceding link in buffer has finite capacity

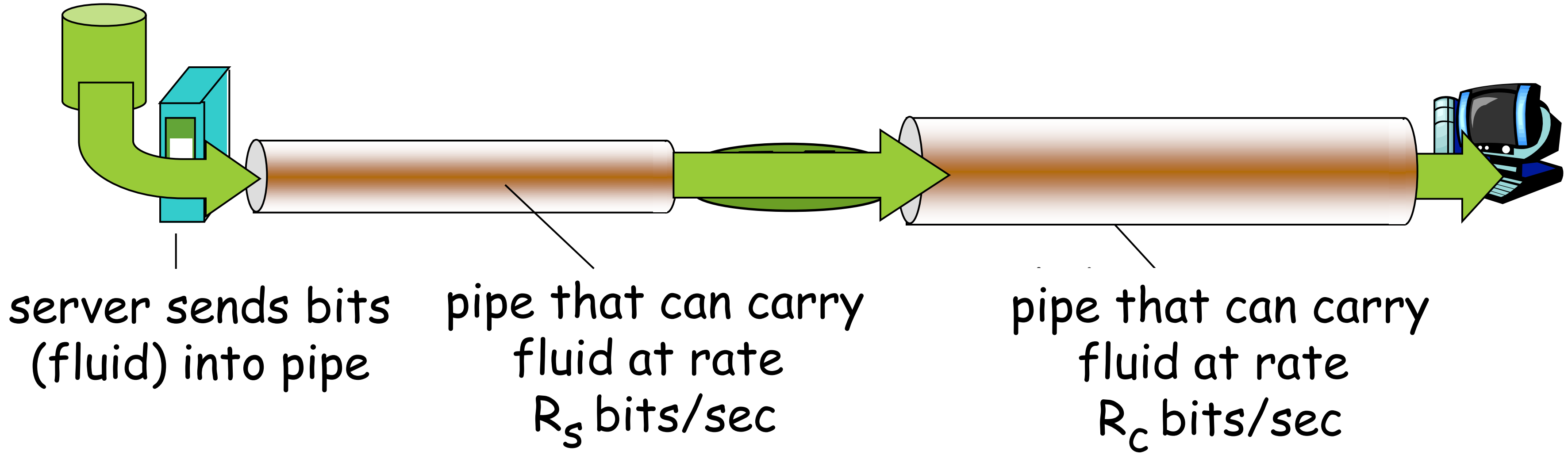
packet arriving to full queue dropped (aka lost)

lost packet may be retransmitted by previous node, by source end system, or not at all



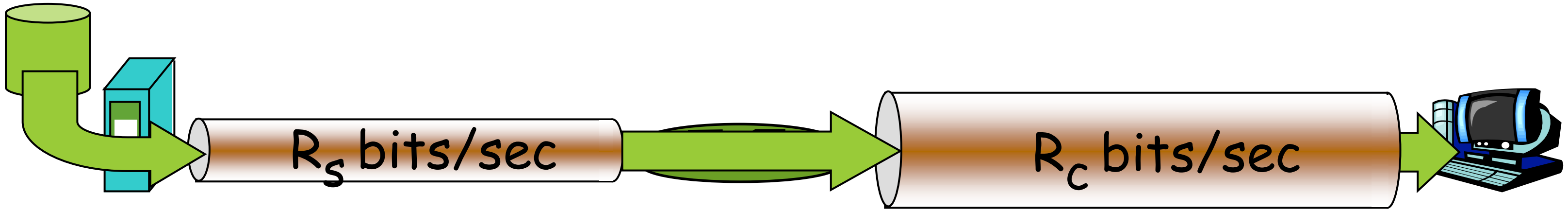
Throughput

Throughput: rate (bits/time unit) at which bits transferred between sender/receiver
- *instantaneous:* rate at given point in time
- *average:* rate over longer period of time

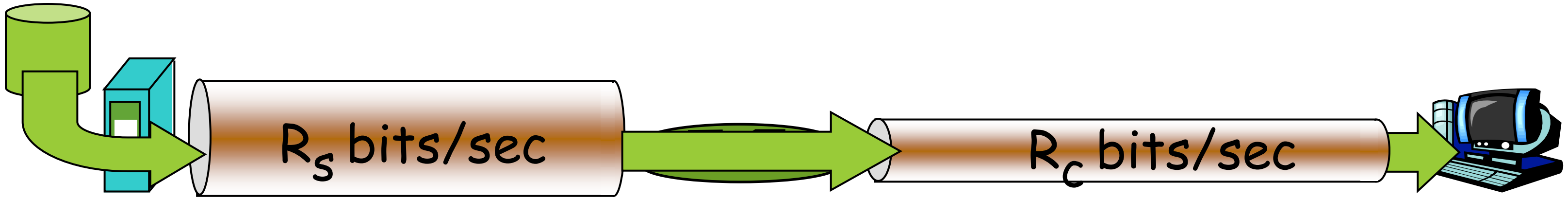


Throughput (cont.)

- Rs < Rc What is average end-end throughput?



- Rs > Rc What is average end-end throughput?

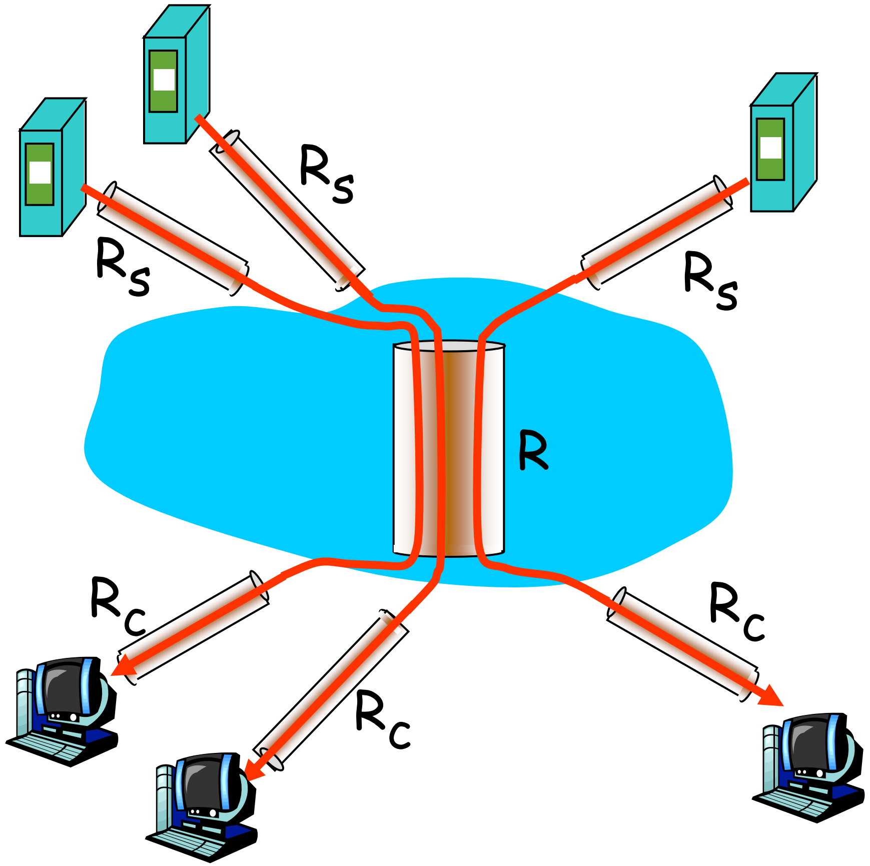


bottleneck link

link on end-end path that constrains end-end throughput
end-to-end transmission rate = min{R_s,R_c}

Throughput: Internet scenario

- 10 connections (fairly) share backbone bottleneck link R bits/sec
- per-connection end-end throughput: min(Rc,Rs,R/10)
- in practice: Rc or Rs is often bottleneck



Network Layers

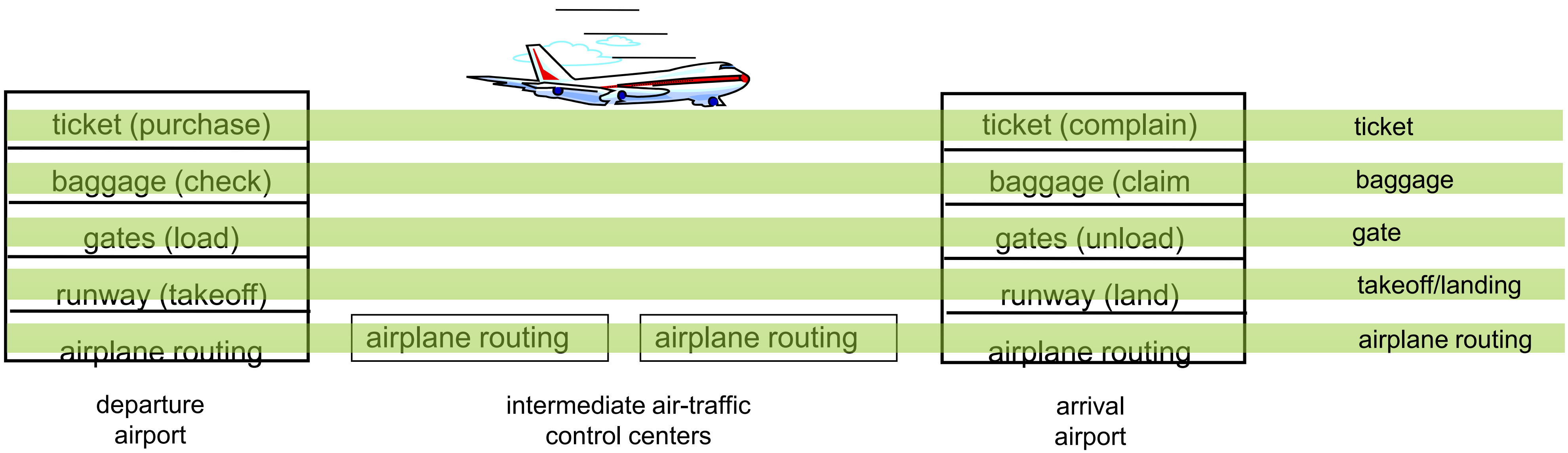
Networks are complex!

many “pieces”:

- hosts
- routers
- links of various media
- applications
- protocols
- hardware, software

Question: Is there any hope of *organizing* structure of network? Or at least our discussion of networks?

Layering of airline functionality



Layers: each layer implements a **service**

- via its own internal-layer actions
- relying on services provided by layer below

Organization of air travel

ticket (purchase)

baggage (check)

gates (load)

runway takeoff

airplane routing

ticket (complain)

baggage (claim)

gates (unload)

runway landing

airplane routing

airplane routing

a series of steps or stages

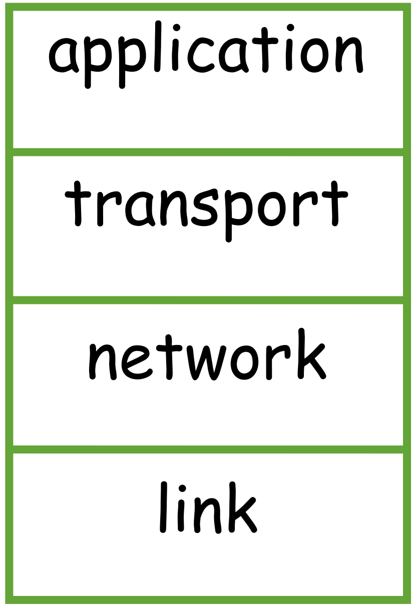
Internet Layers (TCP/IP) model

application: supporting network applications

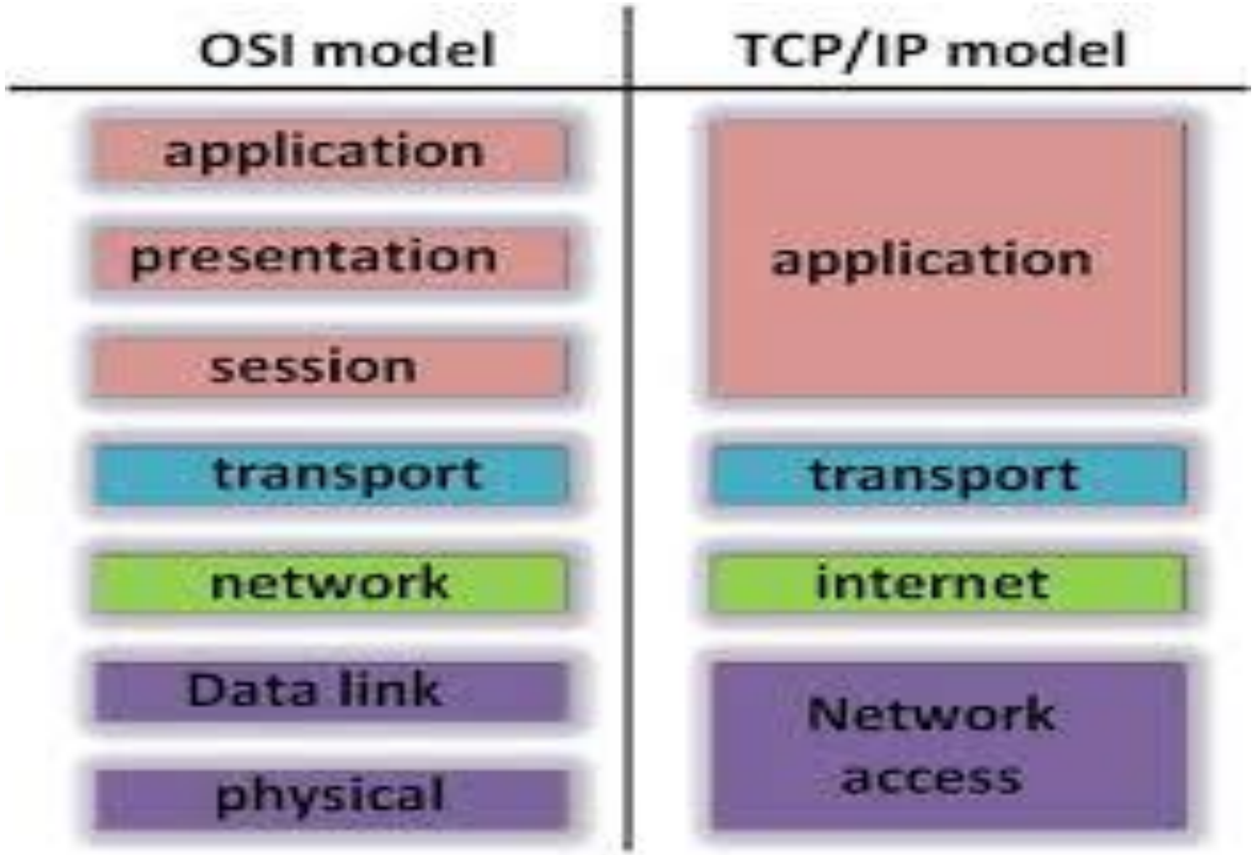
transport: process-to-process data transfer

Network (Internet): routing of datagrams from source to destination (host-to-host data transfer on a route)

link: data transfer between adjacent neighboring network elements over a link



OSI vs TCP/IP


OSI model
TCP/IP model
application
presentation
session
transport
network
Data link
physical
application
transport
internet
Network access

Why Network layering?

Modularization: dividing the complex system into smaller pieces (modules)

- Simplifies the complexity of network systems
- helps identify the functions and the relationships between these pieces
- Assists in protocol design, because protocols that operate at a specific layer have defined information that they act upon and a defined interface to the layers above and below.
- eases maintenance, updating of system
- change of implementation of layer's service doesn't affect the rest of system

Standardization: Provides a common language to describe networking functions and capabilities so products from different vendors can work together

TCP/IP layer model (cont.)

Application layer

- provides network services to the user's applications such as internet browser, email, WWW, e-commerce, e-learning, e-medicine, and video-on-Demand.

Transport layer

- **segment** the data at source, send them, and reassemble them at destination
- handles details of reliable transfer (ensures that the data arrive completely)

Network layer

- many paths for the data **packets** to the destination.
- determines the path (route) using the **IP address** of the destination.

Link layer

- provides means for exchanging data **frames** over a common media
- detect and possibly correct errors that may occur in the transmitted data bits
- **physical (MAC)** addressing, topologies and flow control

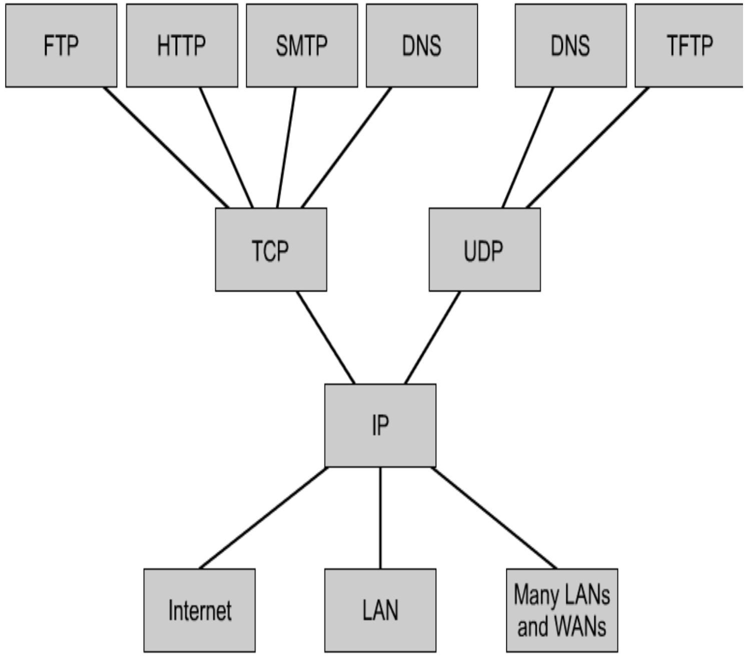
Internet protocols

Application layer protocols
- File Transfer Protocol (FTP)
- Hypertext Transfer Protocol (HTTP)
- Simple Mail Transfer Protocol (SMTP)
- Domain Name System (DNS)
- Trivial File Transfer Protocol (TFTP)

Transport layer protocols
- Transport Control Protocol (TCP)
- User Datagram Protocol (UDP)

Network layer protocol
- Internet Protocol (IP)

Link layer protocol:
- Ethernet



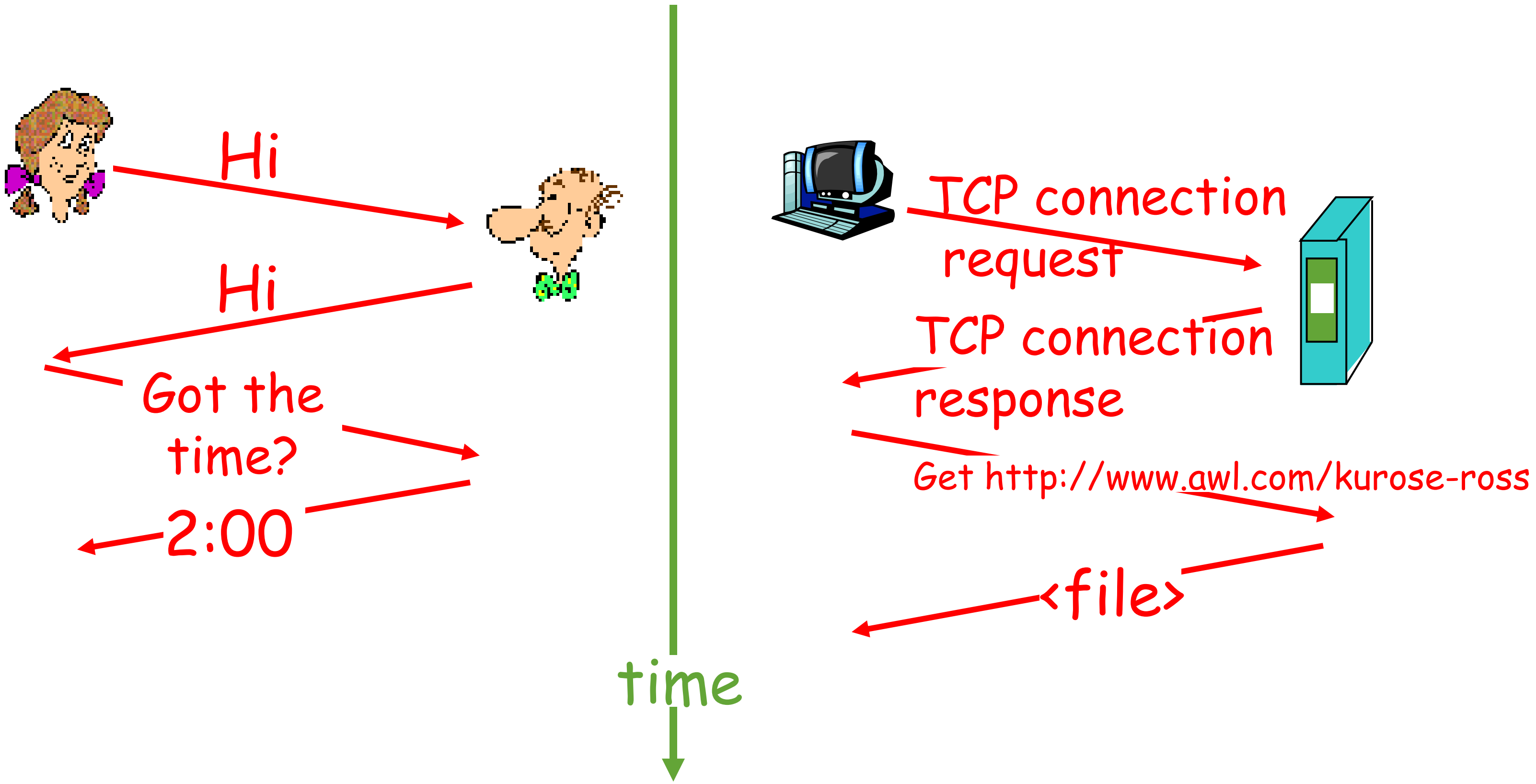
Network Protocol (cont.)

a protocol is a set of rules that defines the format and the order of messages exchanged between two or more communicating entities, as well as actions taken on the transmission and/or receipt of message or other event

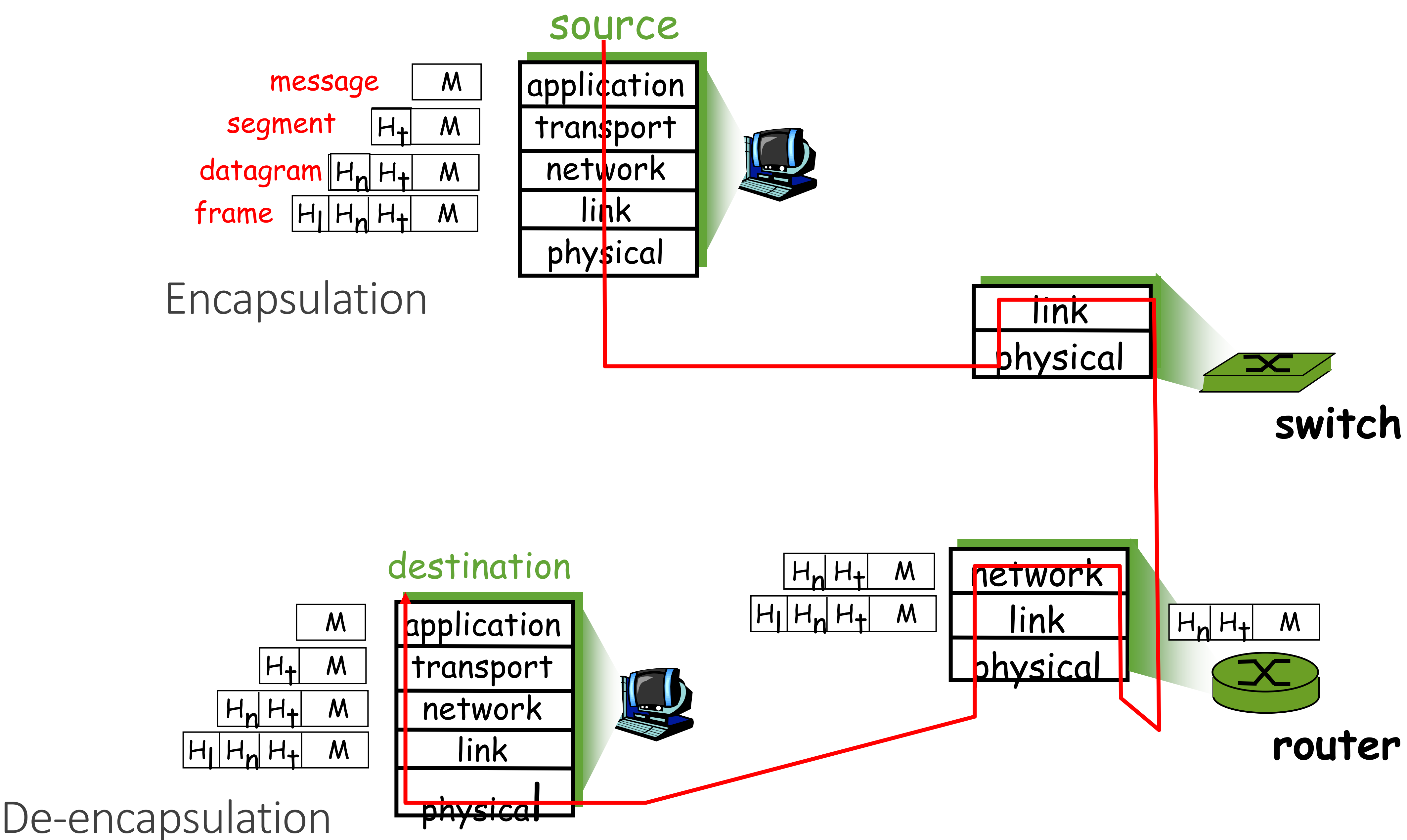
Examples of network protocols

- HTTP, FTP, SMTP
- TCP, UDP
- IP
- Ethernet

Network protocol



a human protocol and a computer network protocol



source
message
M
segment
Ht
M
datagram
Hn
Ht
M
frame
Hl
Hn
Ht
M
application
transport
network
link
physical
Encapsulation
link
physical
switch
destination
M
Ht
M
Hn
Ht
M
Hl
Hn
Ht
M
application
transport
network
link
physical
Hn
Ht
M
Hl
Hn
Ht
M
network
link
physical
Hn
Ht
M
router
De-encapsulation

Network Data Processing