Chapter 1
Computer Networks and the Internet

1.1 What Is the Internet?

- We will use the public Internet as our principle vehicle for discussing computer networks
- What is the Internet?
  - Nuts and bolts description
  - Services description

1.1.1 Nuts and Bolts Description

- The Internet is a computer network that interconnect billions of computing devices throughout the world
  - PCs
  - Workstations
  - Servers that store and transmit information (such as Web pages or email messages)
  - Laptops
  - Smartphones
  - Tablets
  - TVs
  - Gaming consoles
  - Watches
  - Cars

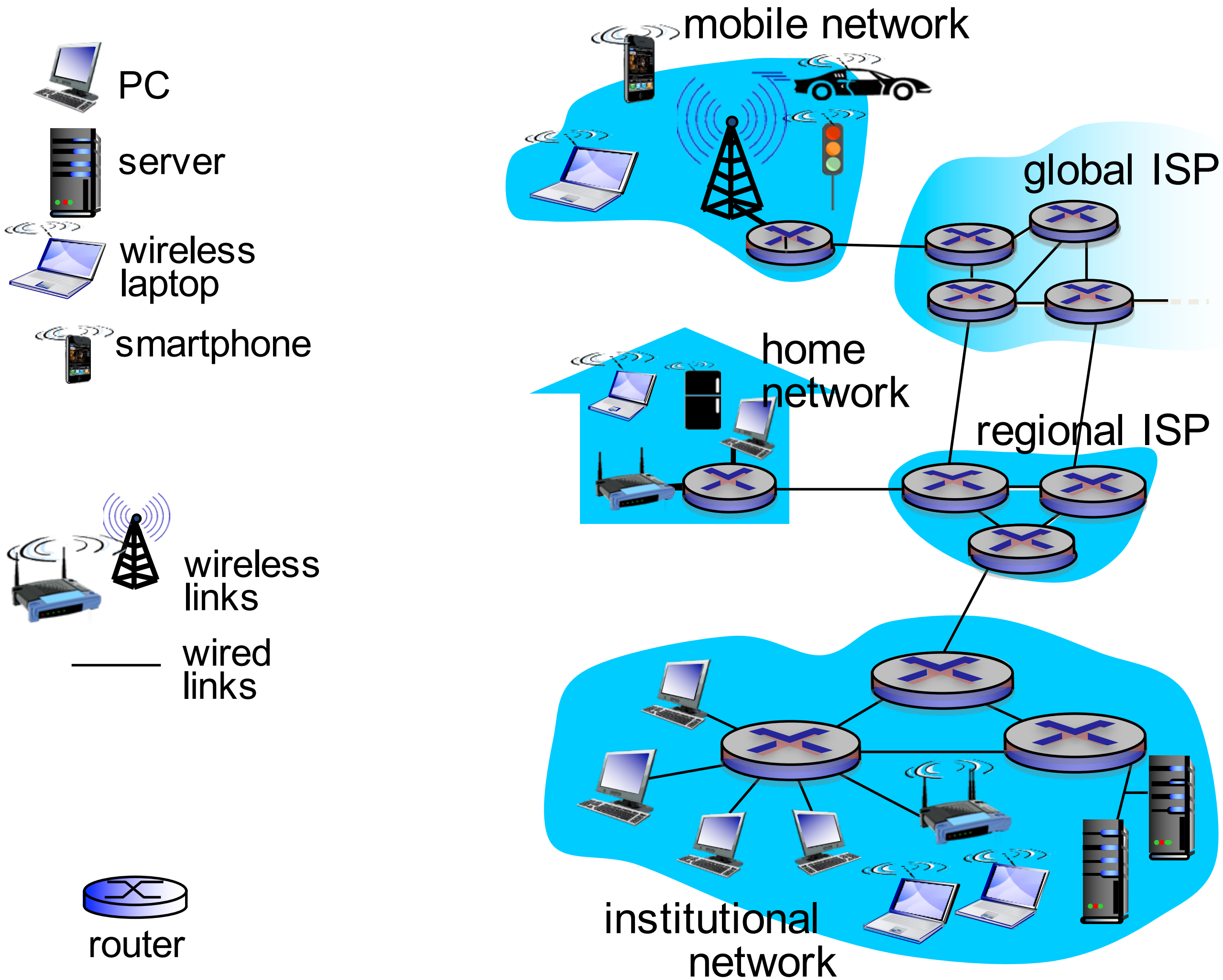
1.1.1 Nuts and Bolts Description

- In Internet, all these devices are called **hosts** or **end systems**
- End systems are connected together by a network of **communication links** and **packet switches**
- Communications links (made by different physical media)
  - Coaxial cable, cooper wire, optical fiber, radio spectrum to provide different **transmission rates** (measured in bit/sec)
- Packets
  - When one end system has data to be sent to another end system, the sender end system segments data 分段
  - Add some header bytes to each segment
  - Each segment with header is known as a **packet**
  - The destination end system reassemble all the received packets into original data

1.1.1 Nuts and Bolts Description

- Packet switchers
  - Takes a packet arriving on one of its incoming communication links
  - Forwards that packet on one of its outgoing communications links
  - **Link-layer switches**: used in access network
  - **Routers**: used in the network core
- Path or route
  - A sequence of communication links and packet switches traversed by a packet from the sending end system to the the receiving end system
- End systems access the Internet through **Internet Service Providers (ISPs)**
  - Lower tier and higher tier ISPs

1.1.1 Nuts and Bolts Description



1.1.2 A Services Description

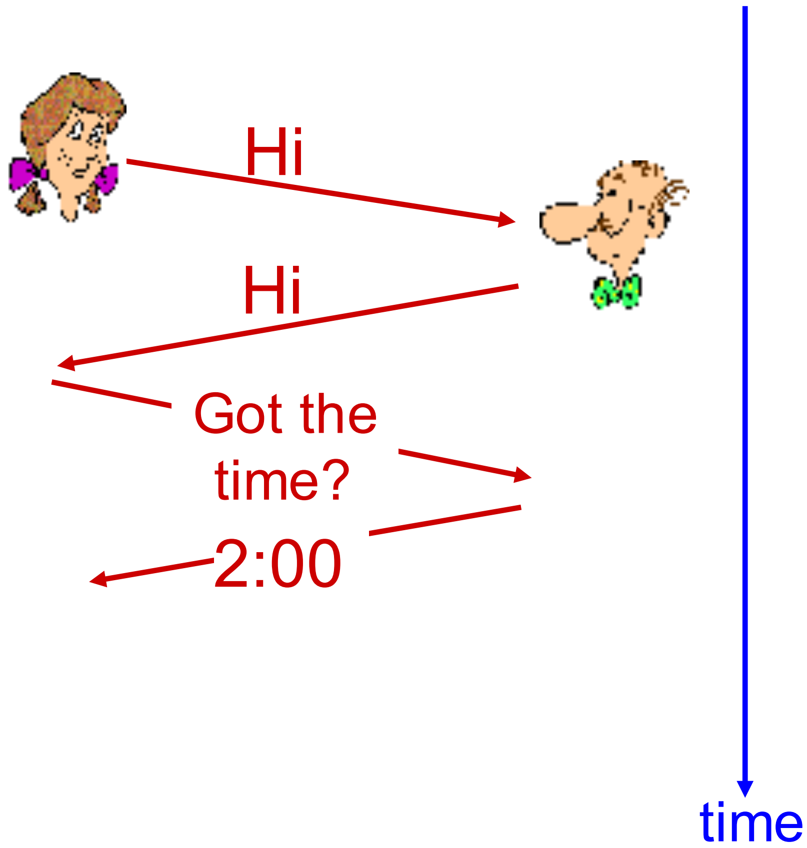
- Internet can be described in a different angle of *an infrastructure that provides services to applications*
- Internet applications include
  - Email
  - Web surfing
  - Messaging
  - On-line social networks
  - Video streaming
  - Multi-person games
- Applications run on end systems, instead of packet switches

1.1.2 A Services Description

- End systems attach to the Internet through a **socket interface**
  - Specifies how a program running on one end system asks the Internet infrastructure to deliver data to a specific destination program on another end system
- If Alice wishes to send a letter to Bob using the postal services
  - Put the letter into an envelop
  - Write Bob's name, address, zip code in the right format on the envelop
  - Seal the envelop and put a stamp on the envelop
  - Drop the envelop into an official postal service mailbox

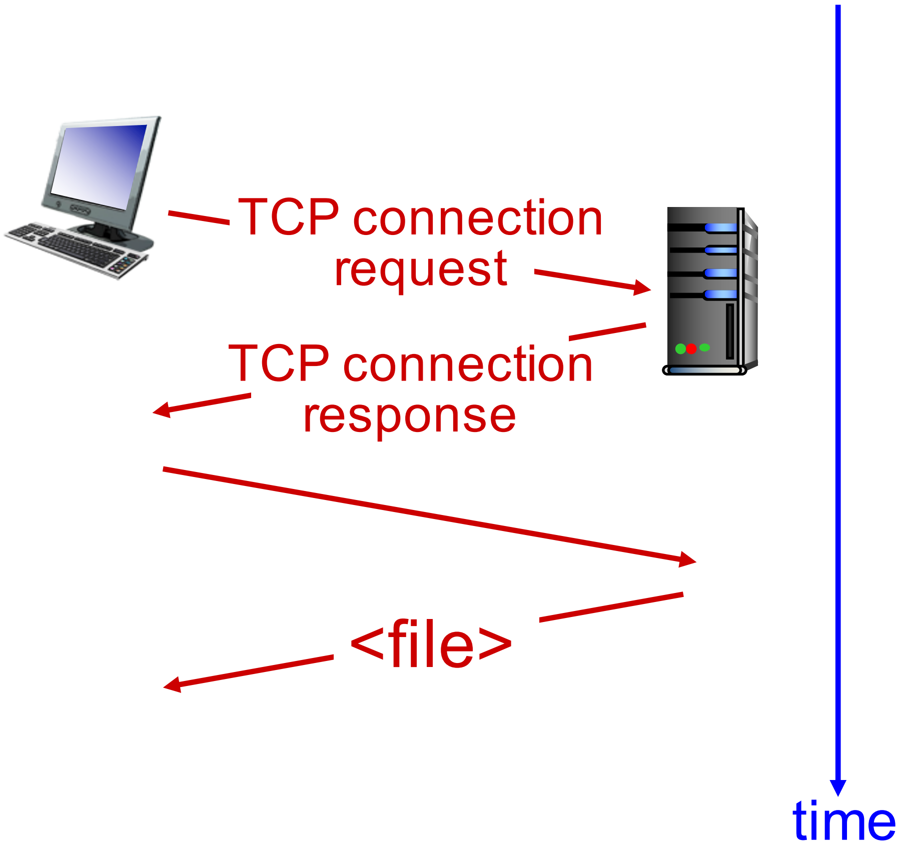
1.1.3 What Is a Protocol?

- A human analogy



1.1.3 What Is a Protocol?

- Network protocols



1.1.3 What Is a Protocol?

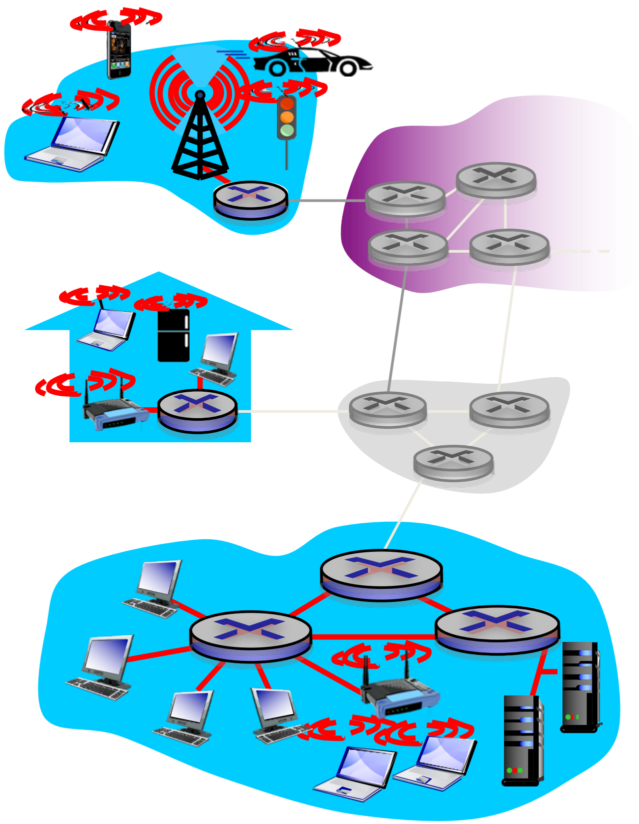
Definition. *A* ***protocol*** *defines the format and the order of messages exchanged between two or more communicating entities, as well as the actions taken on the transmission and/or reception of a message or other event.*

1.2 The Network Edge

- We are now going to delve a bit more deeply into the component of a computer network
  - **Network edge** and **network core**
- End systems sit at the edge of the Internet
  - Also referred as **hosts** as they host application programs
- Hosts are further divided into two categories
  - **Clients**: PCs, smartphone, etc.
  - **Servers**: data centers for Web pages, email, video, social networks, games

1.2.1 Access Networks

- **Access network** physically connects an end system to the first (edge router)



1.2.1 Access Networks

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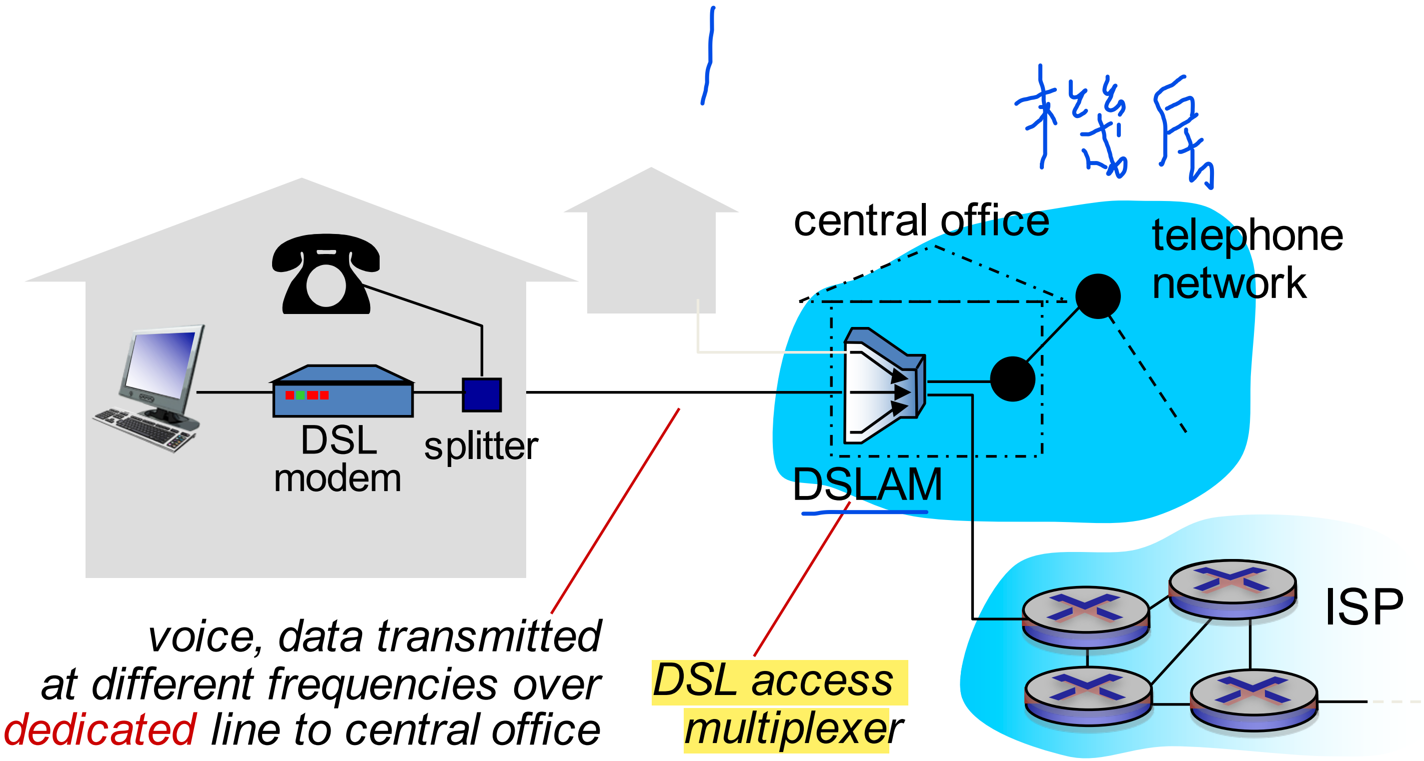
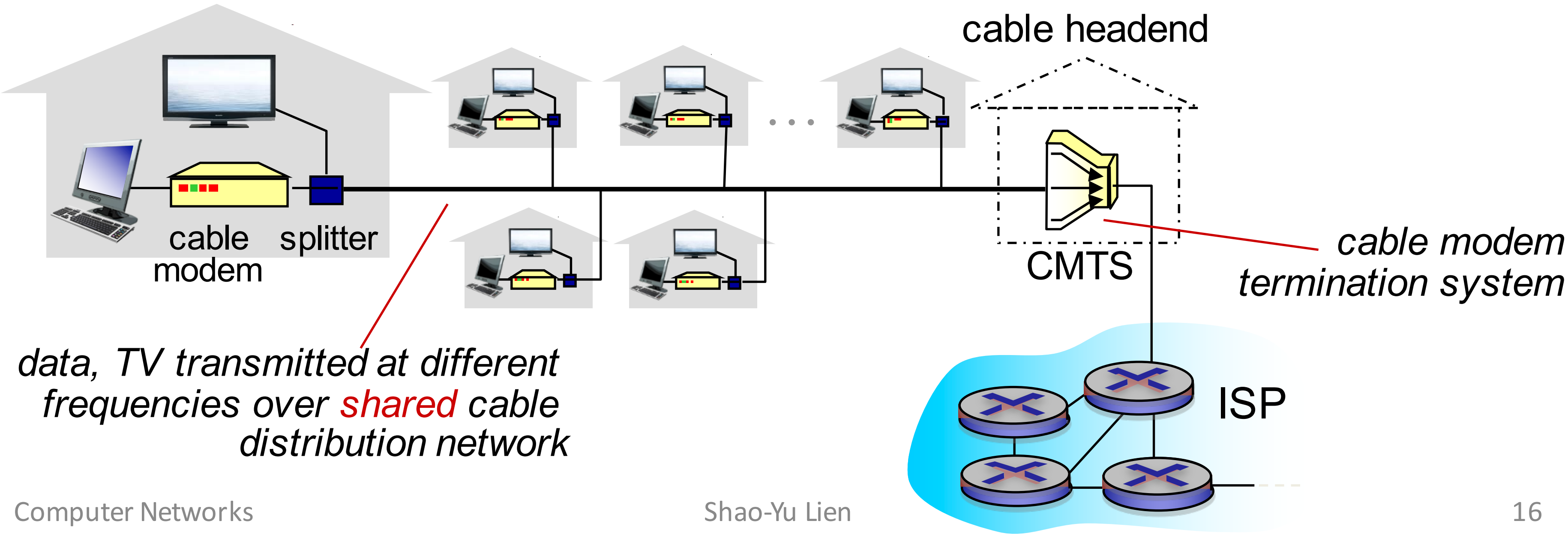
- Home access
  - Two most prevalent types of broadband residential access are digital subscriber line (DSL) and cable
- A residence typically obtains DSL Internet access from the same local telephone company (telco); that is, telco is the ISP
  - Each DSL modem uses the existing telephone line to exchange data with a DSL access multiplexer (DSLAM)
- The residence telephone line carries both data and telephone signals simultaneously onto different frequencies
  - An ordinary two-way telephone channel in the 0 – 4 kHz band
  - A medium-speed upstream channel in the 4 – 50 kHz band 上
  - A high-speed downstream channel in the 50 kHz – 1 MHz band 下

1.2.1 Access Networks



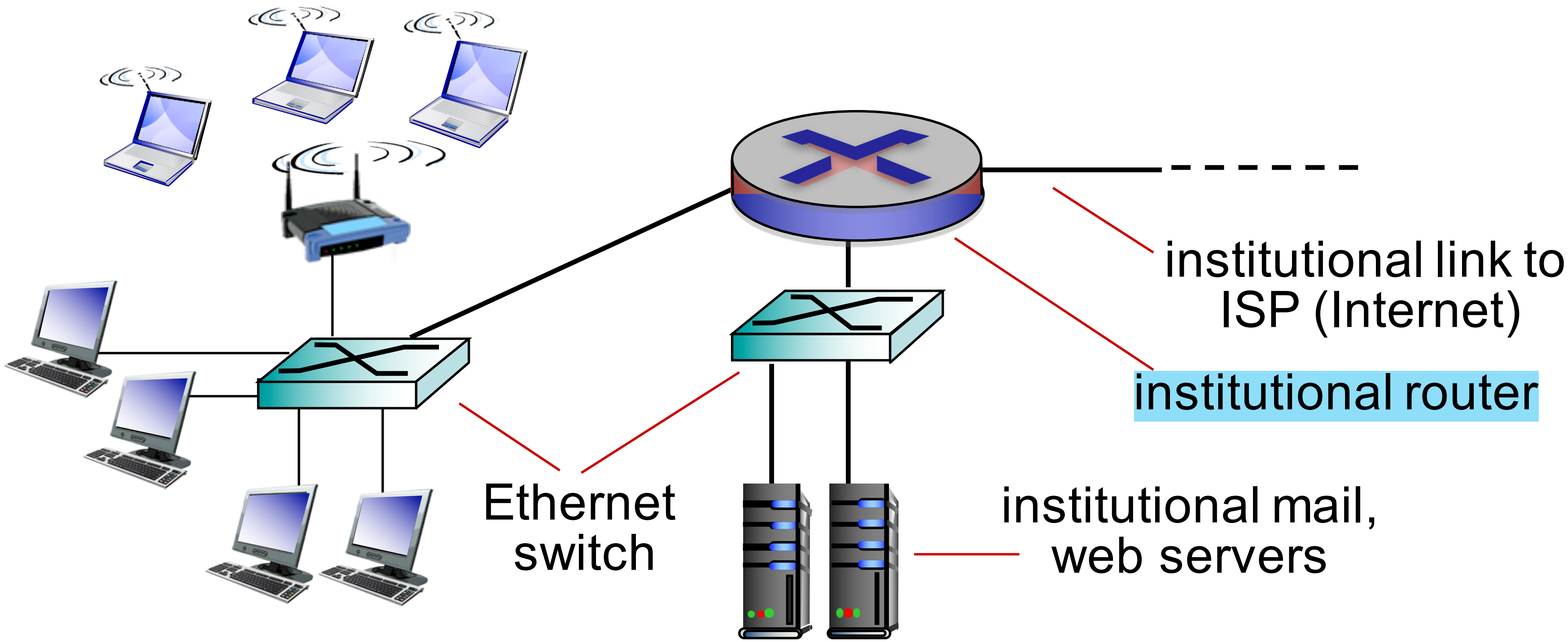
1.2.1 Access Networks

- Cable Internet access uses cable television company's existing cable television infrastructure
  - Since both fiber and coaxial cable are employed in this system, it is often referred to as hybrid fiber coax (HFC)
  - DOCSIS 2.0 specifies downstream rates up to 42.8 Mbps and upstream rates up to 30.7 Mbps



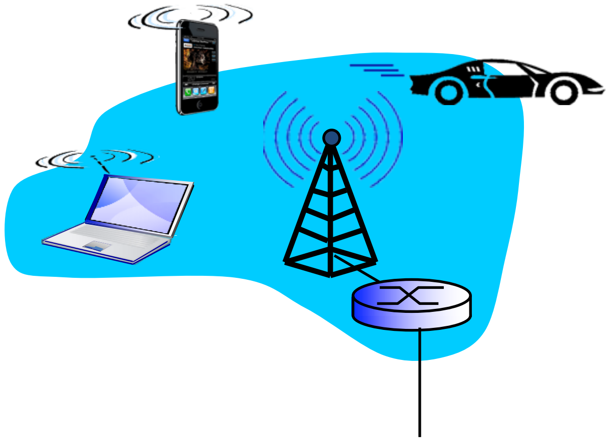
1.2.1 Access Networks

- Access in the enterprise (and the home)
  - Local area network (LAN) is used to connect an end system to an edge router
  - Ethernet and wireless Ethernet



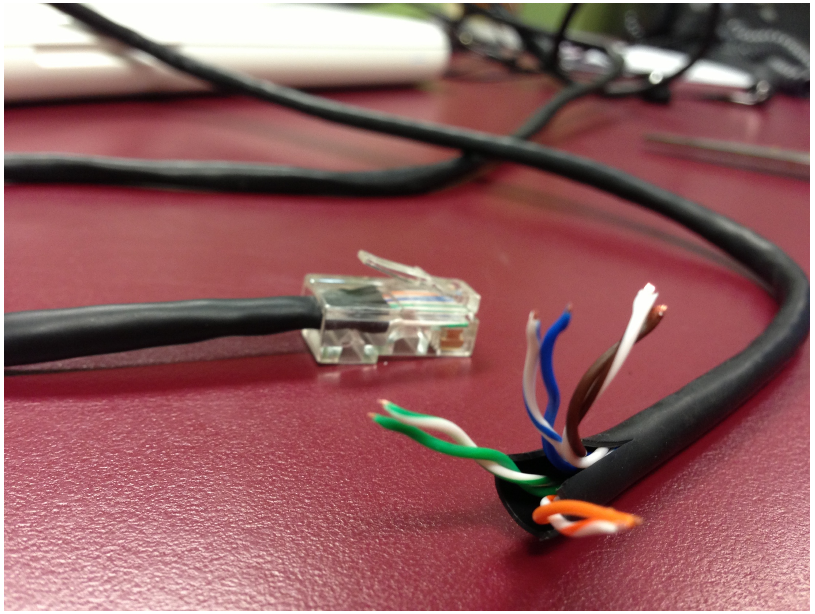
1.2.1 Access Networks

- Wide-area wireless access
  - GPRS, UMTS, LTE/LTE-A, New Radio (NR)



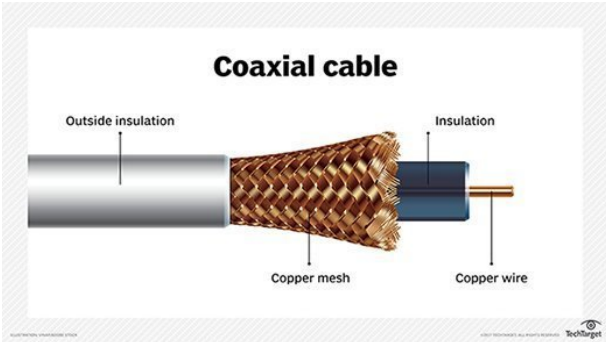
1.2.2 Physical Media

- Physical media fall into two categories
  – **Guided media**: Waves are guided along a solid medium, such as fiber-optical cable, twisted-pair copper wire, coaxial cable, etc.
  – **Unguided media**: Waves propagate in the space, such as radio signals
- Twisted-pair cooper wire 傳播
  – Data rates: 10 Mbps to 10 Gbps



1.2.2 Physical Media

- Coaxial cable
  - Data rates: Tens of Mbps

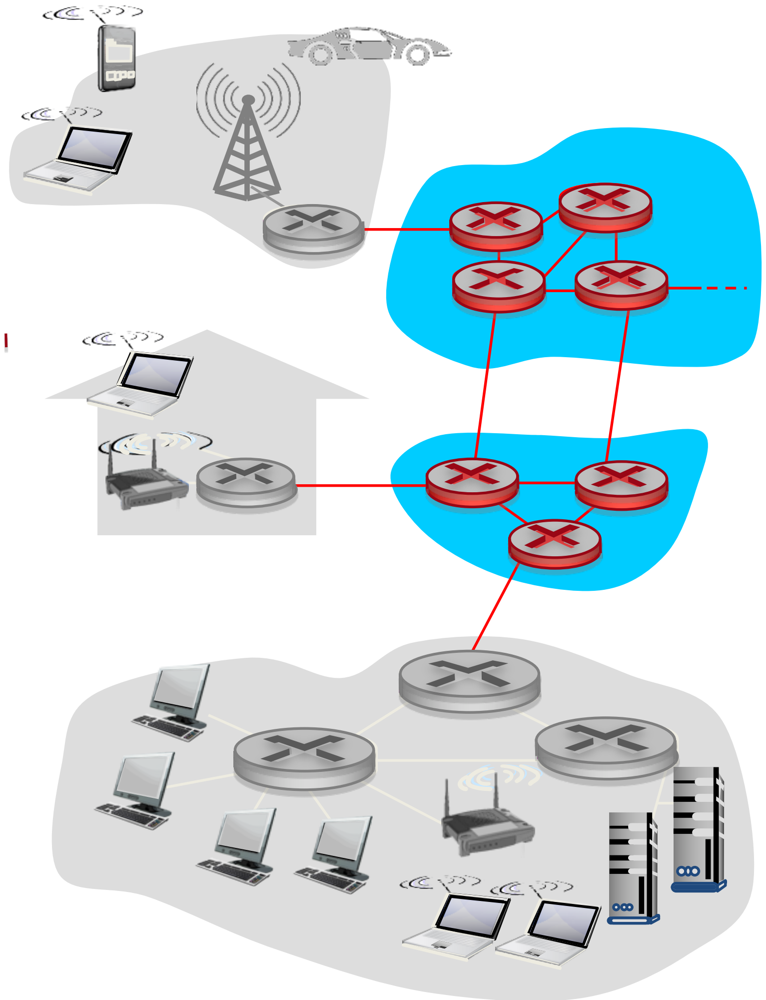


- Fiber optics
  - Data rates: 51.8 Mbps to 39.8 Gbps

1.2.2 Physical Media

- Terrestrial radio channels
  - Before 2020, popular commercial radio services are deployed to spectrum below 6 GHz
  - Since 2020, spectrum up to 100 GHz will be utilized
- Satellite radio channels
  - **Geostationary satellites**
    - In the orbit at 36,000 km above Earth's surface
    - Signal propagation delay: 280 ms
    - Data rates: hundreds of Mbps
  - **Low-Earth orbiting (LEO) satellites**
    - Many LEO satellites need to be deployed to provide continuous coverage of an area

1.3 The Network Core

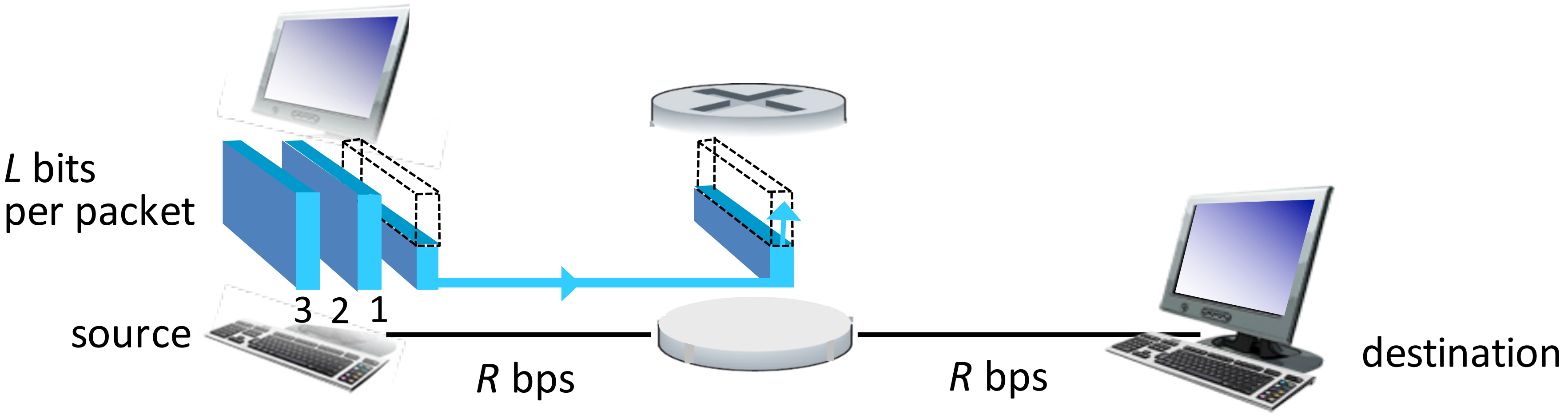


1.3.1 Packet Switching

- In a network application, end systems exchanges **messages** with each other
- The source end system breaks long messages into smaller chunks of data known as **packets**
- Between source and destination end systems, each packet travels through **communication links** and **packet switches**
- Packets are transmitted over each communication link using the full transmission rate of the link
  - Sending a packet of L bits over a link with transmission rate R bits/s
  - The time to transmit the packet is L/R sec.

1.3.1 Packet Switching

- Store-and-Forward Transmission
  - Most packet switches (routers) use this scheme
  - A packet switch receives the entire packet at the input
  - After the entire packet being received, a packet switch forwards the packet to its output link
  - A packet switch needs a buffer to store a packet before it is completely received



1.3.1 Packet Switching

- The amount of time elapsing from when a source begins to send a packet until a destination has received the entire packet
  - Source begins to transmit at time 0
  - Source has transmitted the entire packet and the switch (router) has received the entire packet at time at time L/R
  - Switch has transmitted the entire packet and the destination (router) has received the entire packet at time at time $2L/R$
  - The total delay is $2L/R$

1.3.1 Packet Switching

The end-to-end latency to send one packet from source to destination over a path consisting of N links each of rate R is

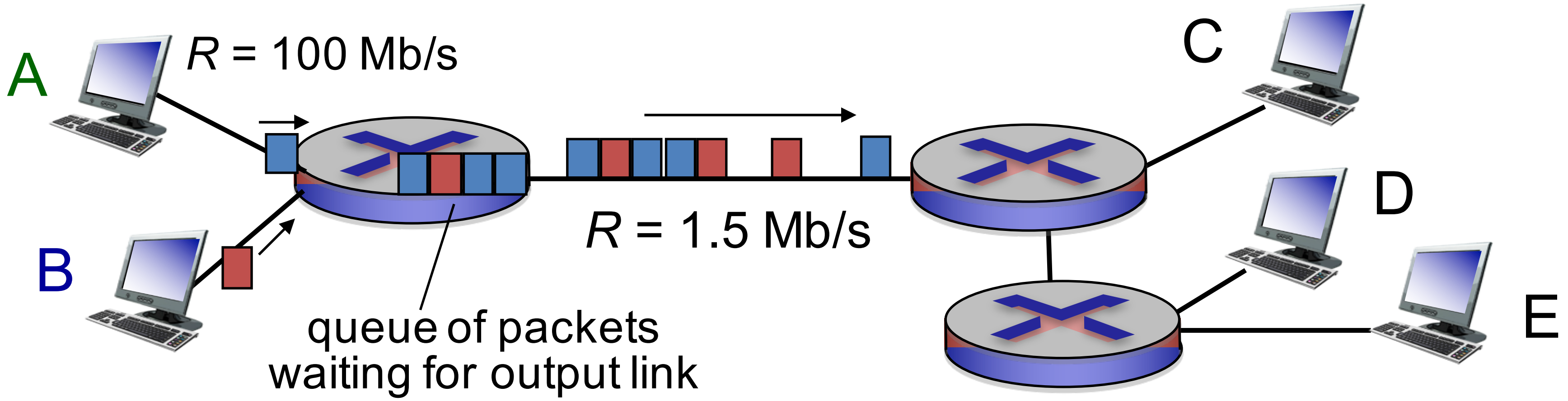
$$d_{\text{end-to-end}} = NL/R$$

1.3.1 Packet Switching

- The amount of time elapsing from when a source begins to send the first packet until a destination has received the entire three packets
  - Source begins to transmit at time 0
  - Source has transmitted the entire first packet and the switch (router) has received the entire packet at time at time L/R
  - At time L/R, source begins to transmit the second packet and the switch begins to transmit the first packet and receive the second packet
  - At time $2L/R$, source begins to transmit the third packet, the switch begins to transmit the second packet and receive the third packet, destination has received the entire first packet
  - At time $3L/R$, the switch begins to transmit the third packet, and destination has received the entire second packet
  - At time $4L/R$, destination has received the entire third packet

1.3.1 Packet Switching

- Queueing delay and Packet loss
  - A switch may receive packets from more than one end systems



  - Each switch (router) has an **output buffer** (or **queue**) to store the packets that a switch is about to send into that link

1.3.1 Packet Switching

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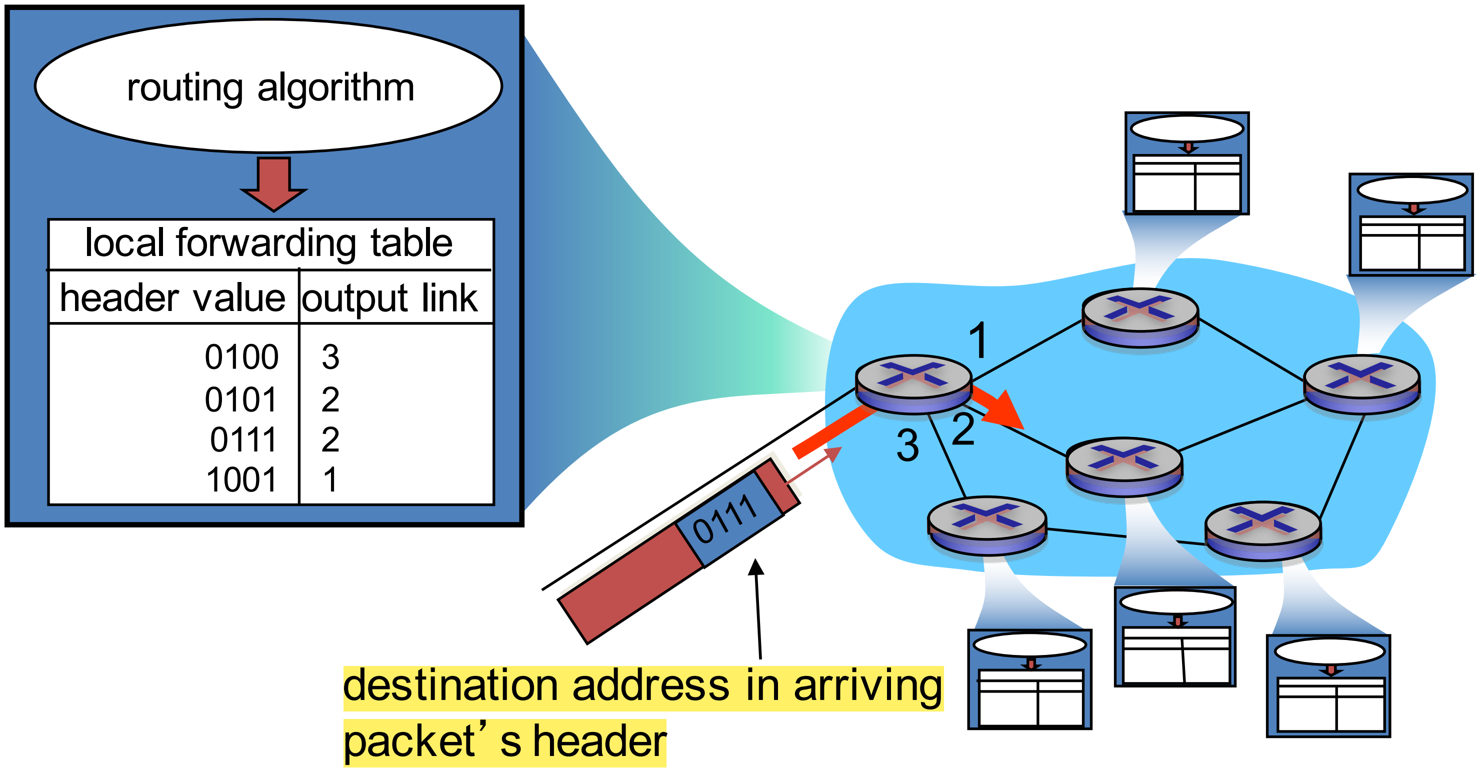
- If an arriving packet needs to be transmitted onto a link but the link is busy with the transmission of another packet, the arriving packet must wait in the output queue
- Packets suffer output buffer **queueing delays**. The delays are variable depending on the level of congestion
- The buffer size is finite. When a buffer is full, the upcoming packets will be discarded. In this case, **packet loss** occurs

1.3.1 Packet Switching

- Forward table and routing protocols
  - How does the switch (router) determine which link it should forward the packet onto?
  - Different networks have different schemes to determine packet forwarding
  - In the Internet, every end system has an address, called **Internet Protocol (IP) address**
  - IP addresses are hierarchical structure
  - When a packet arrives at a router, the router examines a portion of the packet's destination address, and forward the packet to the adjacent router
  - Each router has a **forwarding table** that maps the destination addresses to that router's outbound links

1.3.1 Packet Switching

- How to construct a forwarding table?
  - There are a number of **routing protocols** used to automatically set the forwarding tables

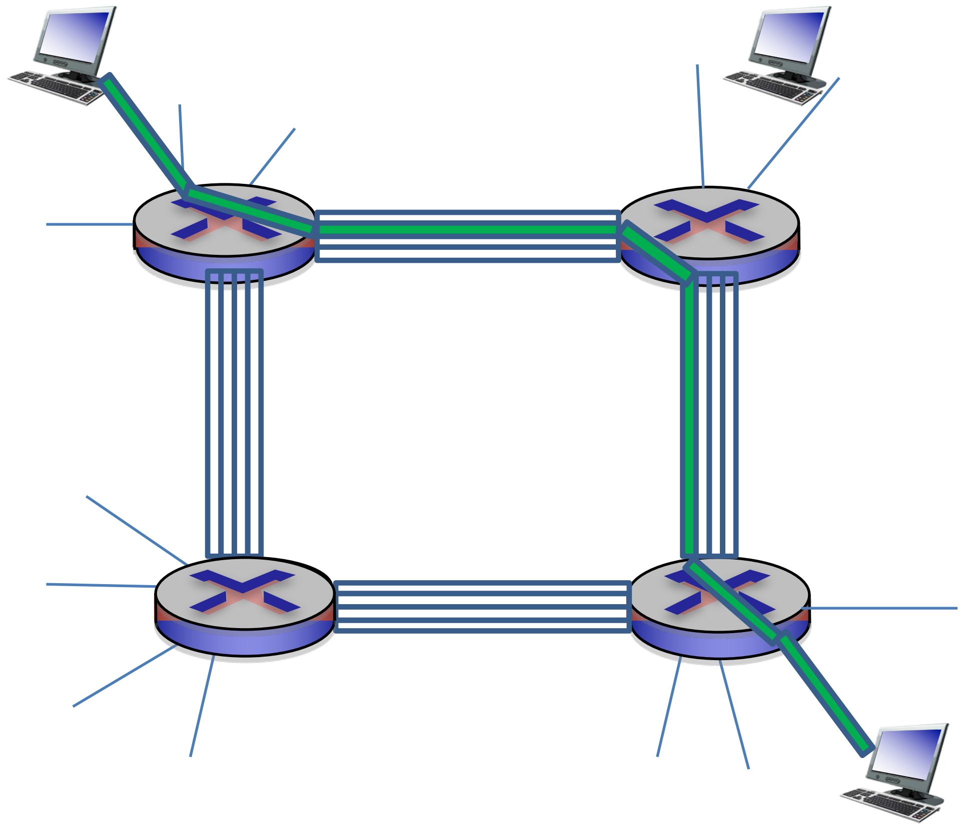


1.3.2 Circuit Switching

- Resources needed along a path (buffer, link transmission rate, etc.) to provide for communications between the end systems are **reserved**
  - In packet-switched networks, these resources are not reserved and are shared by all end systems
- Circuit-switched networks need a setup procedure to reserve resources along a path (i.e., create an **end-to-end connection**)
  - In packet-switched networks, a setup procedure is not needed

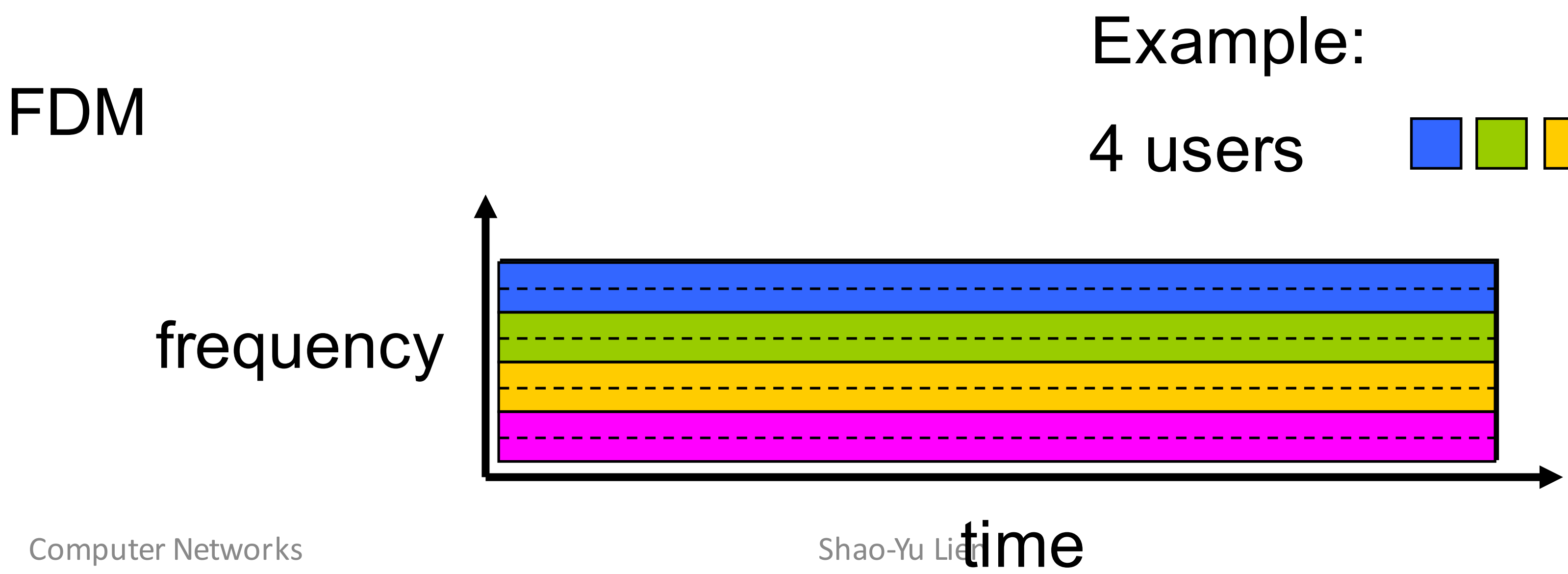
1.3.2 Circuit Switching

- A simple circuit-switched network consisting of four switches and four links



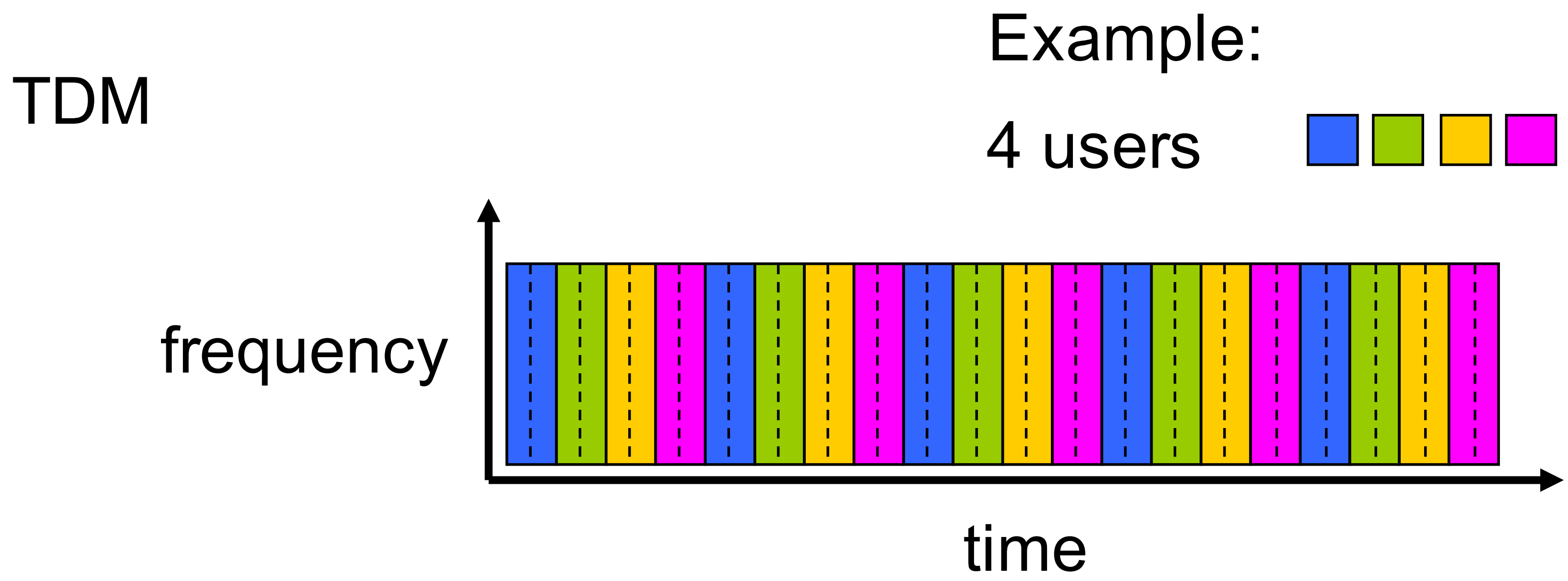
1.3.2 Circuit Switching

- Multiplexing in circuit-switched networks
  - **Frequency division multiplexing (FDM)**
    - Frequency spectrum of a link is divided into several **frequency bands**
    - The network dedicates a frequency to each connection
    - The width of the band is called the **bandwidth**



1.3.2 Circuit Switching

- **Time division multiplexing (TDM)**
  - Time is divided into **frames** of fixed duration
  - Each frame is divided into a fixed number of **time slots**
  - The network dedicates one time slot in every frame to a connection



1.3.2 Circuit Switching

- **Example: How long it takes to send a file of 640,000 bits from Host A to Host B over circuit-switched network?**
  - Suppose that all links use TDM with 24 slots and have a bit rate of 1.536 Mbps
  - It takes 500 ms to establish an end-to-end circuit
  - Each circuit has a transmission rate of (1.536 Mbps)/24=64 kbps, so it takes (640,000 bits)/(64 kbps)=10 sec.
  - The total time is 10+0.5=10.5 sec.

1.3.2 Circuit Switching

- Packet switching v.s. circuit switching
- Cons. of packet switching
  - Packet switching is not suitable for real-time services (e.g., telephone calls, video conference calls) due to unpredictable end-to-end delay
- Pros. of packet switching
  - Packet switching offers better sharing of transmission capacity than circuit switching
  - Packet switching is simpler, more efficient, and less costly to implement then circuit switching

1.3.2 Circuit Switching

- **Example [Why is packet switching more efficient?].**
  - Users share a 1 Mbps link
  - Each user alternates between periods of activity (for 10% of the time) and inactivity (for 90% of the time)
  - Active period: user generates data at a constant rate of 100 kbps
  - Inactive period: user generates no data
- With circuit-switching
  - 100 kbps must be **reserved** for each user
  - 10 users can be supported (i.e., = 1 Mbps/100 kbps)

1.3.2 Circuit Switching

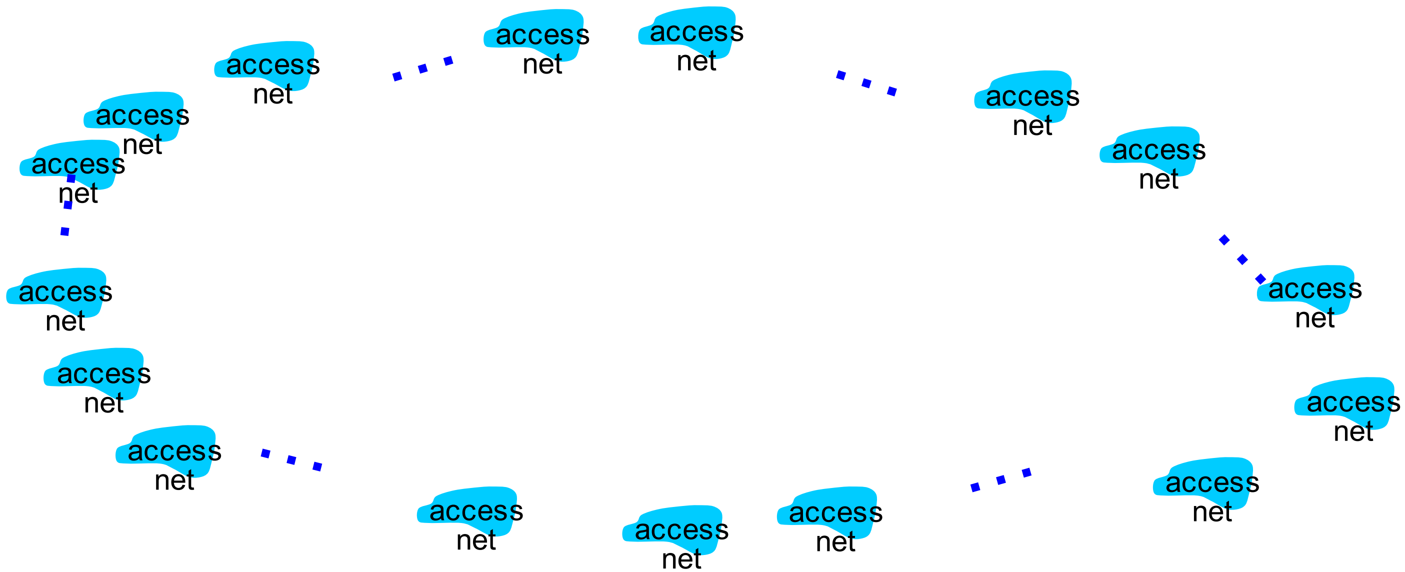
- With packet-switching
  - The probability that a specific user is active is 0.1
  - If there are 35 users, the probability that there are 11 or more simultaneously active users is approximately 0.0004
  - The probability that there are 10 or fewer simultaneously active users is approximately 0.9996

1.3.2 Circuit Switching

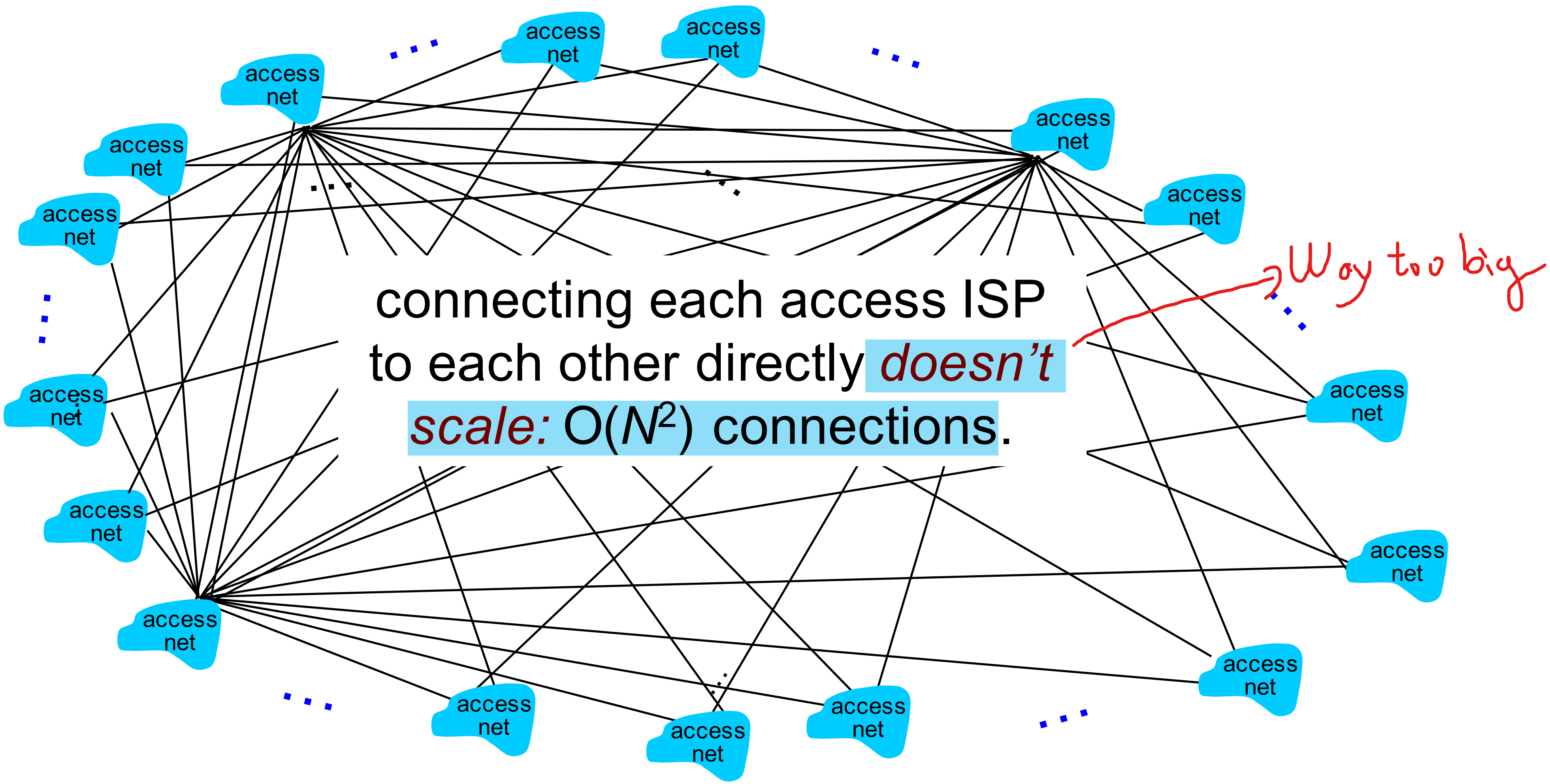
Item	Circuit switched	Packet switched
Call setup	Required	Not needed
Dedicated physical path	Yes	No
Each packet follows the same route	Yes	No
Packets arrive in order	Yes	No
Is a switch crash fatal	Yes	No
Bandwidth available	Fixed	Dynamic
Time of possible congestion	At setup time	On every packet
Potentially wasted bandwidth	Yes	No
Store-and-forward transmission	No	Yes
Charging	Per minute	Per packet

1.3.3 A Network of Networks

- End systems connect into the Internet via an access ISP
- Access ISP does not have to be a telco or a cable company
  - Also can be a university or a company
- ISPs themselves should be interconnected
- This is done by by creating a **network of networks**

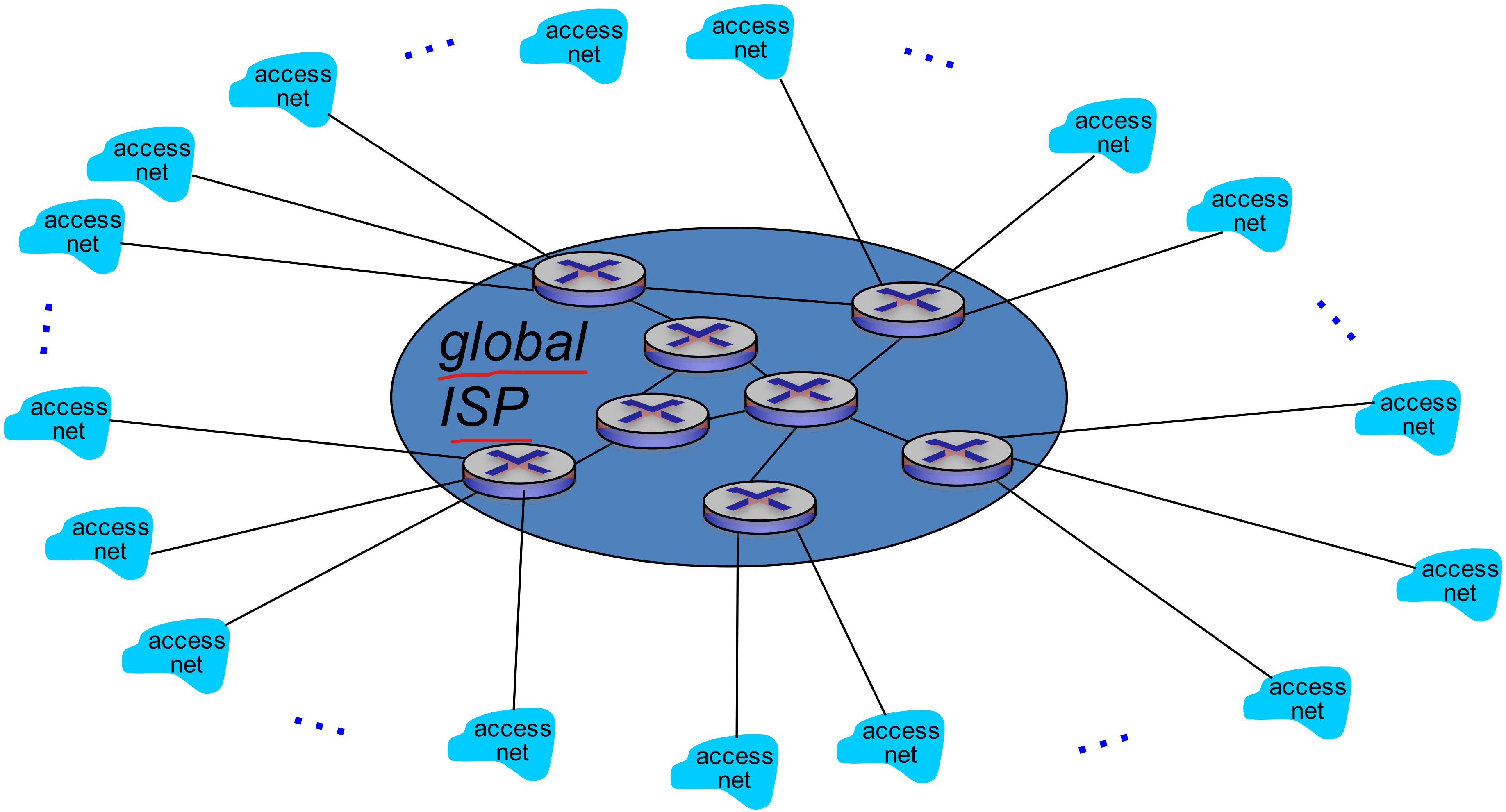


1.3.3 A Network of Networks



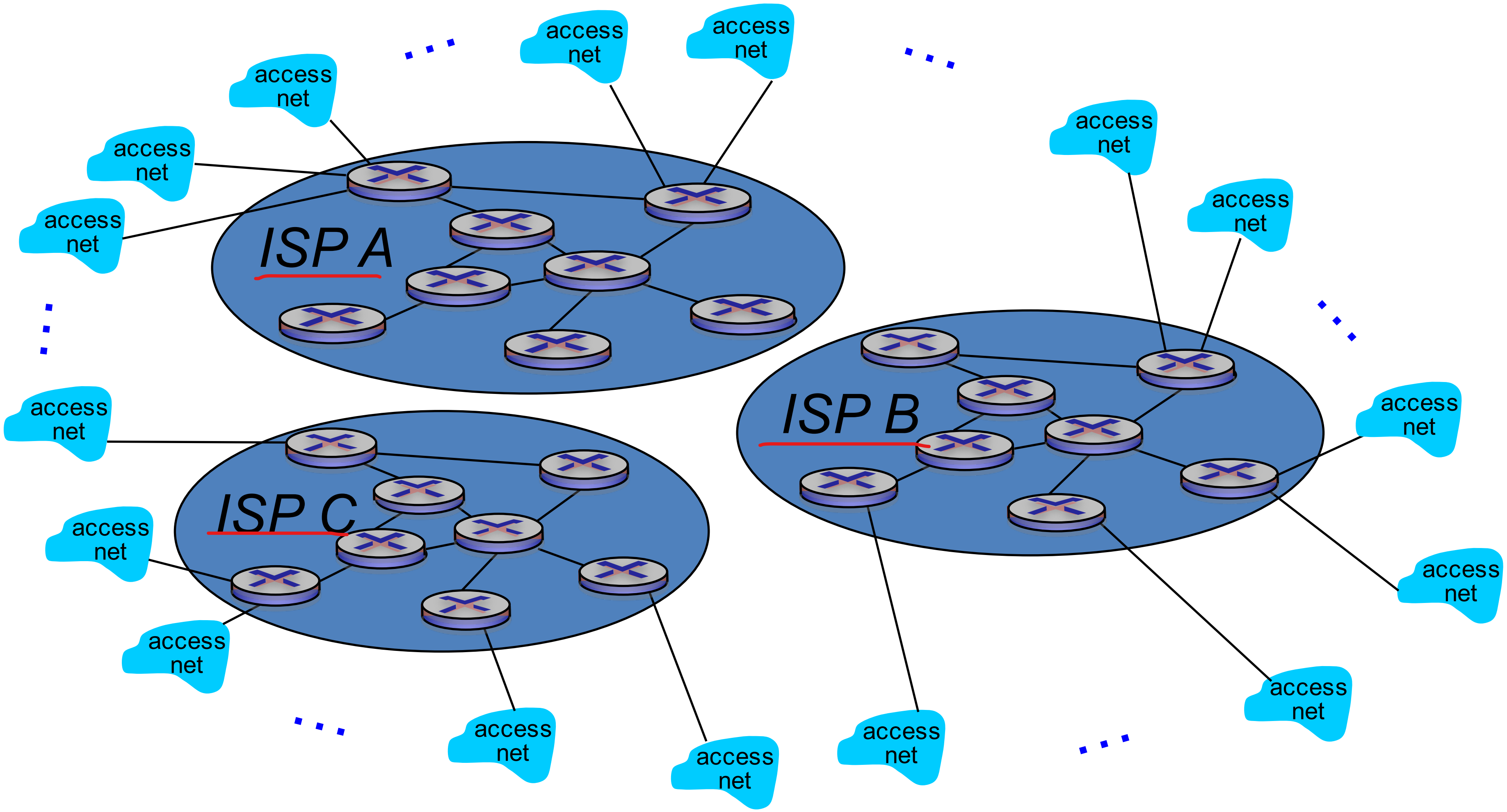
1.3.3 A Network of Networks

- Network Structure 1



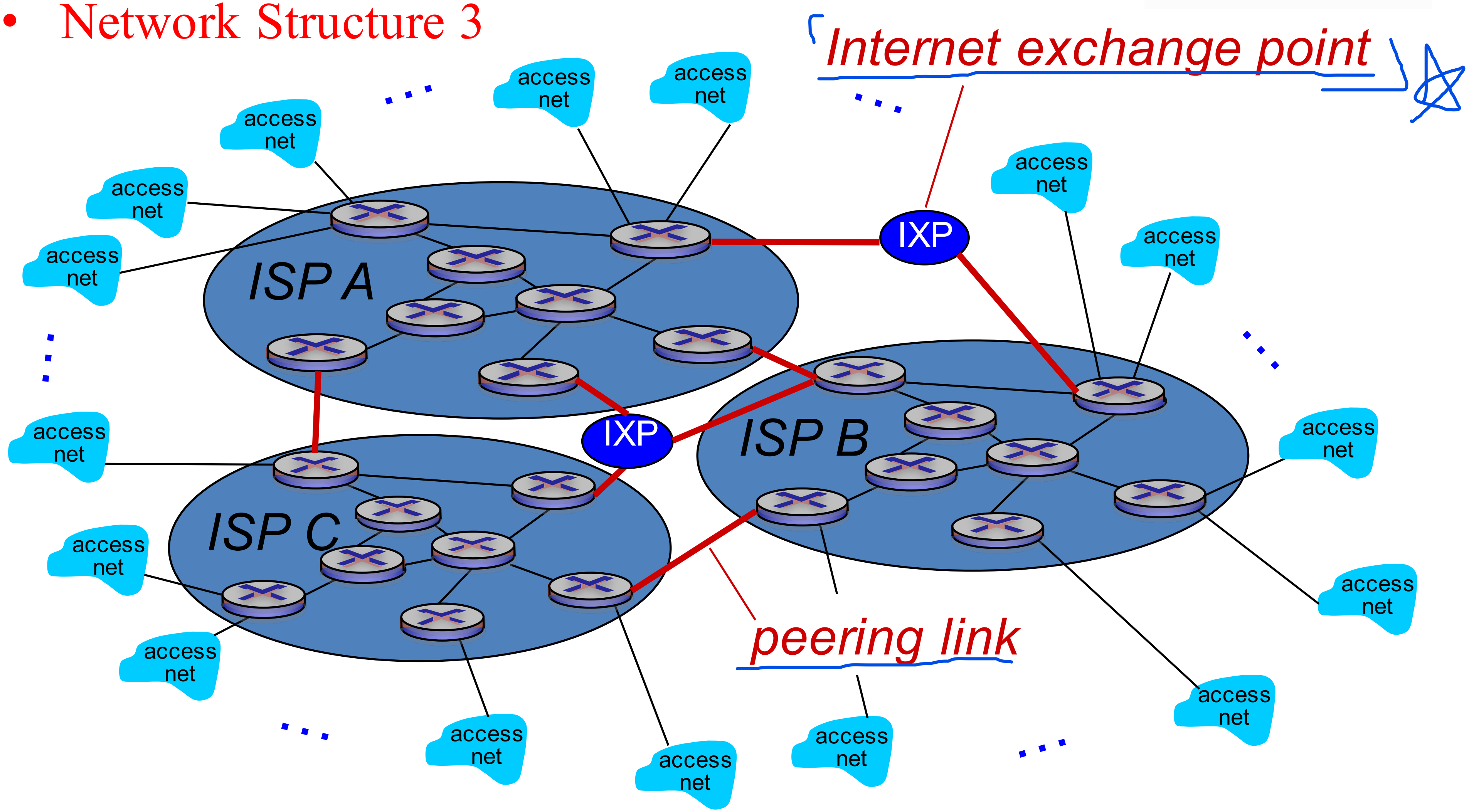
1.3.3 A Network of Networks

- Network Structure 2



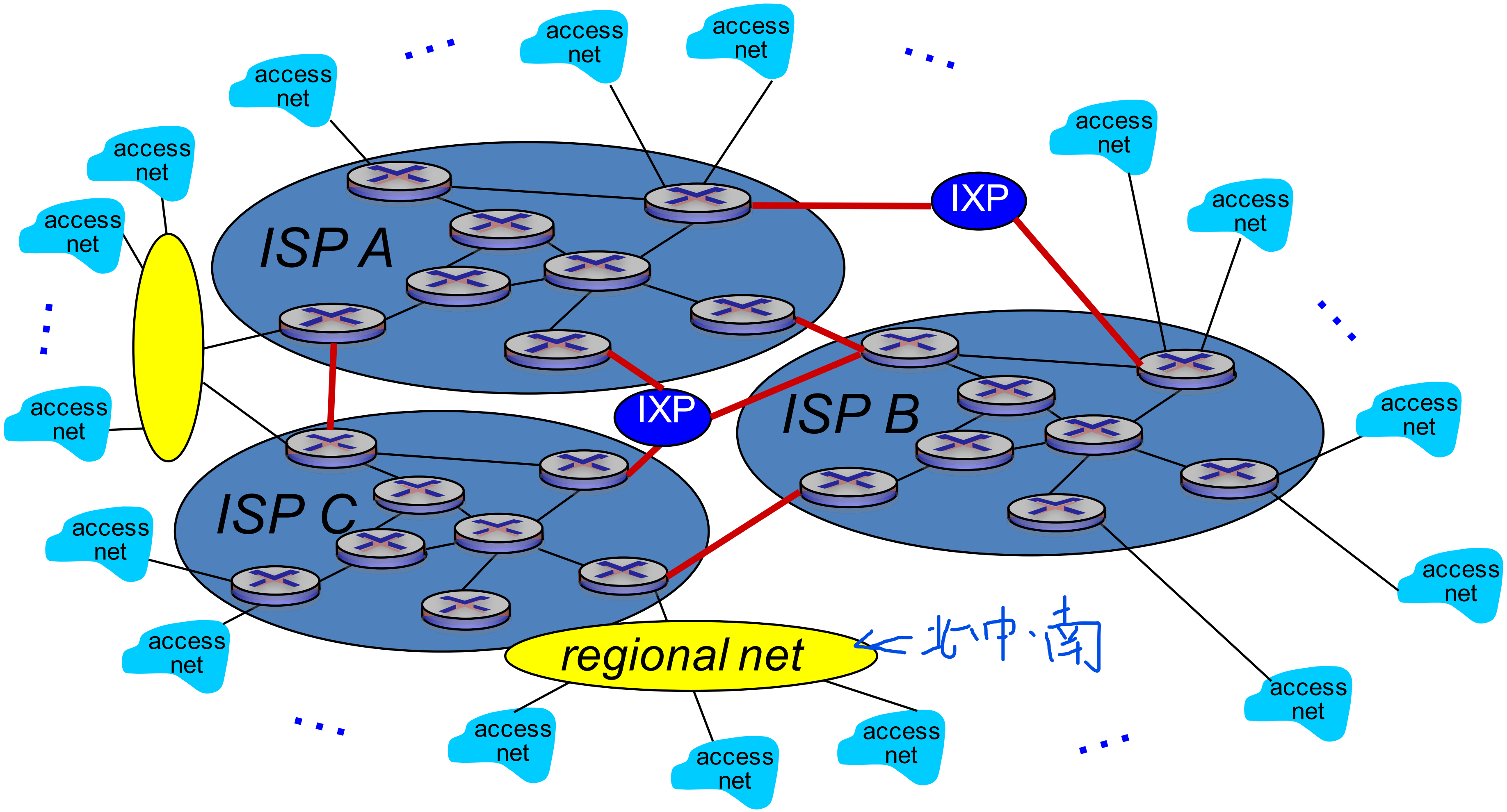
1.3.3 A Network of Networks

- Network Structure 3



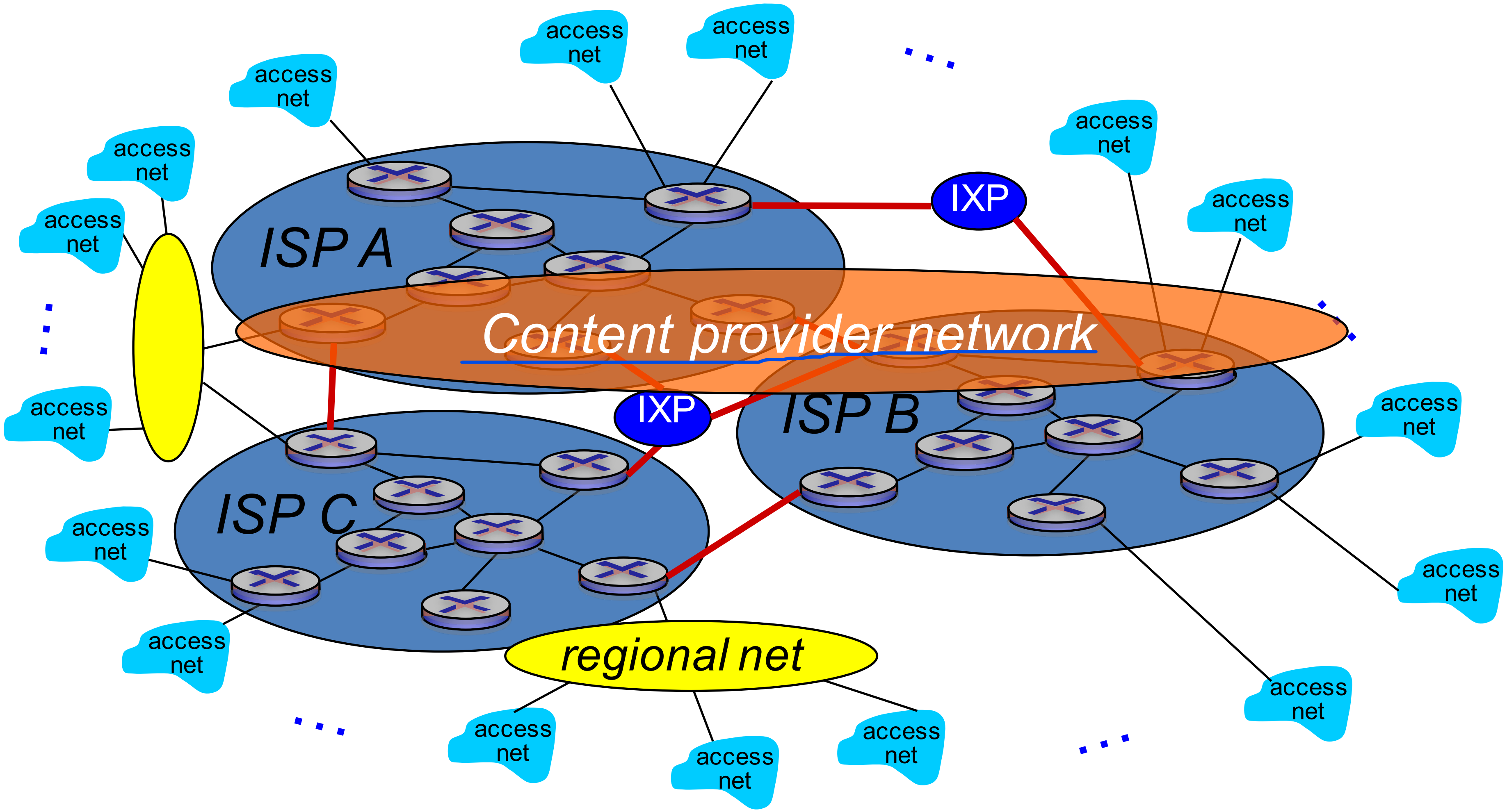
1.3.3 A Network of Networks

- Network Structure 4



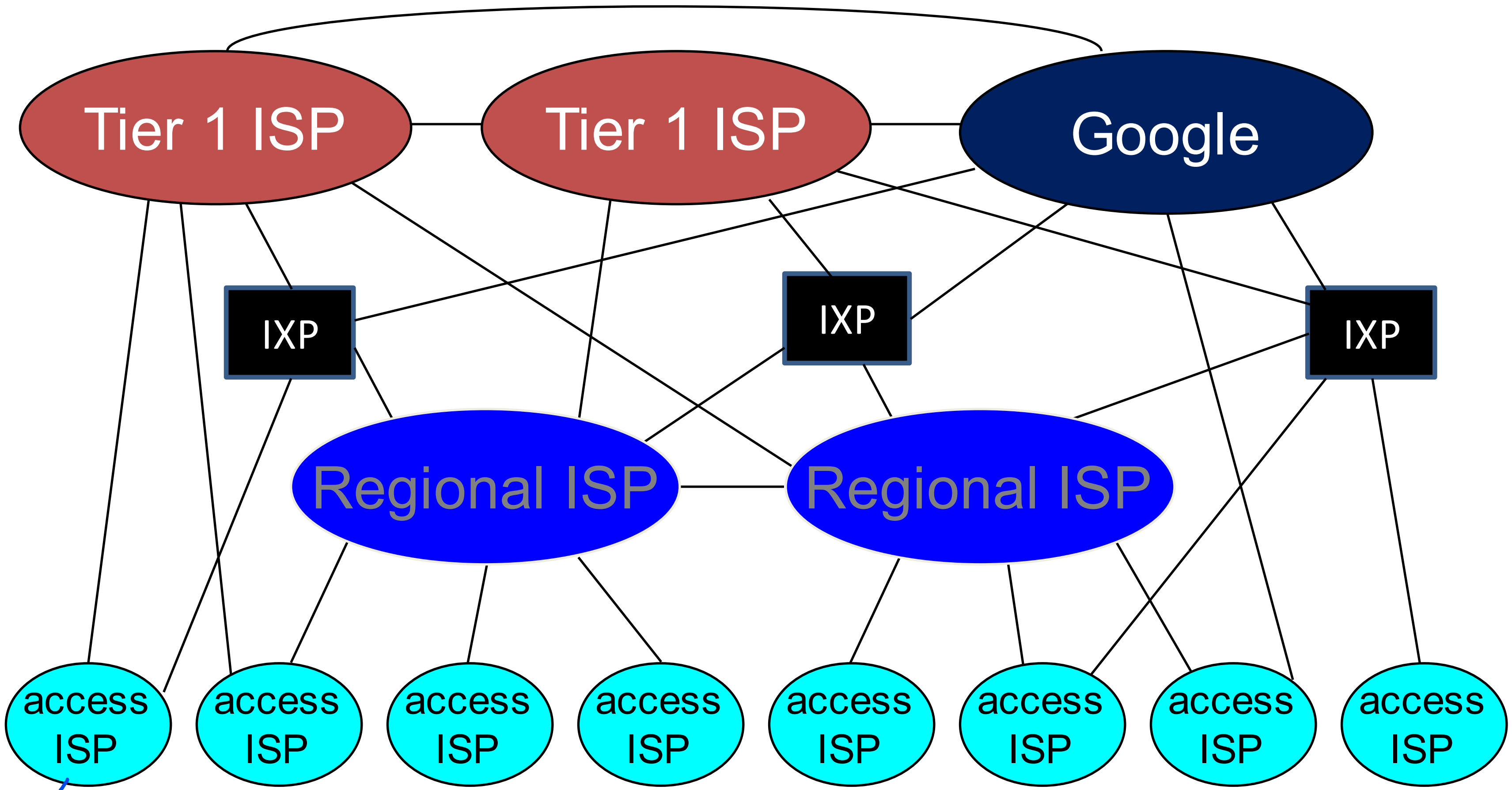
1.3.3 A Network of Networks

- Network Structure 5



1.3.3 A Network of Networks

- Interconnection of ISPs



end system

1.4 Delay, Loss, and Throughput in Packet-Switched Networks

- Computer networks may impose the following limitations
  - **Throughput:** the amount of data per second that can be transferred
  - **Delay:** required time to send data from an end system to another
  - **Loss:** packets may be loss in transmissions due to buffer overflow, physical media error, router error, etc.

1.4.1 Delay, Loss, and Throughput in Packet-Switched Networks

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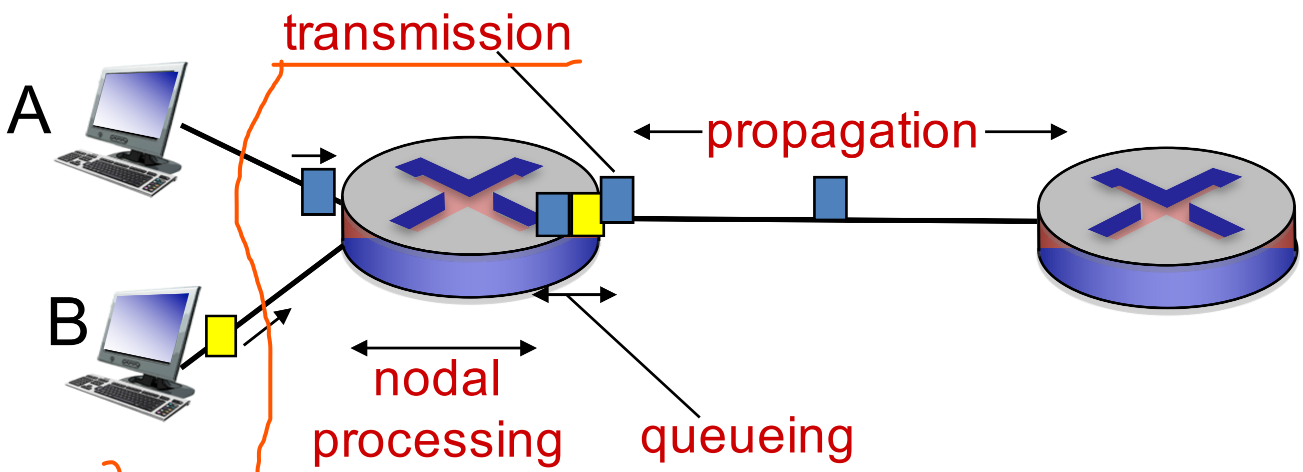
- Types of delay



header

A 00
B 01
C 10
D 11

看的時間

symbol duration

1.4.1 Delay, Loss, and Throughput in Packet-Switched Networks

- Processing delay
  - Time to examine the packet's header and determine where to direct the packet
  - Time to check bit-level errors
  - On the order of microseconds
- Queueing delay Critical
  - Time for a packet waiting to be transmitted onto a link
  - Length of this delay depends on the number of earlier-arriving packets waiting in the queue
  - On the order of microseconds to milliseconds

1.4.1 Delay, Loss, and Throughput in Packet-Switched Networks

- Transmission delay
  - Denote the length of the packet by *L* bits, and the transmission rate of the link by *R* bit/sec
  - Transmission delay is *L/R*
- Propagation delay
  - Time to required to propagate from the beginning of the link to next router
  - Denoted by *d/s*, where *d* is the propagation distance, and propagation speed, *s*, depends on the physical medium of the link
  - In the range of $2*10^8$ m/s to $3*10^8$ m/s

1.4.1 Delay, Loss, and Throughput in Packet-Switched Networks

- The total nodal delay d_{nodal} (delay at a signal router) can be expressed by

$$d_{\text{nodel}} = \underline{d_{\text{proc}} + d_{\text{queue}} + d_{\text{trans}} + d_{\text{prop}}}$$

delay

  - d_{proc}: processing delay
  - d_{queue}: queueing delay critical
  - d_{trans}: transmission delay (negligible)
  - d_{prop}: propagation delay (negligible)

1.4.2 Queueing Delay and Packet Loss

- The most complicated and interesting component of nodal delay is the queueing delay
- Let a (packets/s) denote the average rate at which packets arrive at the queue
  - The average rate at which bits arrive at the queue is La bits/s
- La/R is called the traffic intensity in estimating queueing delay
- Design your system so that La/R is not larger than 1

overflow

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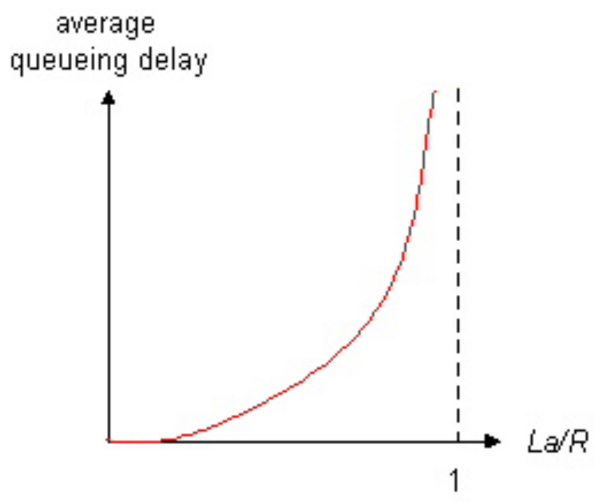
$$\frac{La}{R}$$

In

out



1.4.2 Queueing Delay and Packet Loss

- Consider that case $La/R<1$, the nature of arriving traffic impacts the queueing delay
  - If packets arrive periodically (i.e., one packet arrives every L/R sec.), then every packet arrives at an empty queue
  - If packets arrive in bursts (i.e., N packets arrives simultaneously every NL/R)
    - 0 queueing delay for the 1^{st} packet
    - L/R queueing delay for the 2^{nd} packet
    - $2L/R$ queueing delay for the 3^{rd} packet
    - $(n-1)\,L/R$ queueing delay for the n^{th} packet

1.4.2 Queueing Delay and Packet Loss

- Packet loss
  - The size of queue (buffer) is limited and finite
  - When a packet arrives at a full queue, a router should **drop** this this packet
- When the traffic intensity increase, the number of lost packet also increases

1.4.3 End-to-End Delay

- Nodal delay: delay at a single router
- Suppose there are N-1 routers between a source host and a destination host

擁擠

- If the network is not congested (i.e., d_{queue} is negligible), the end-to-end delay is

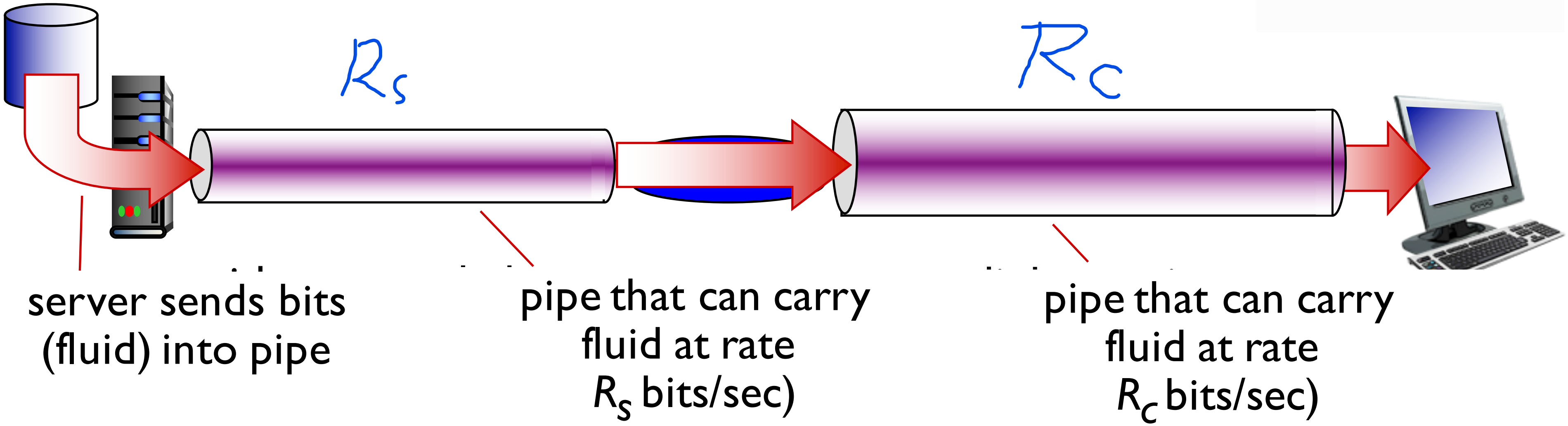
$$d_{\text{end-to-end}} = N(d_{\text{proc}} + d_{\text{trans}} + d_{\text{prop}})$$

1.4.4 Throughput in Computer Networks

- How to define throughput?
- Consider transferring a large file from Host A to Host B across a computer network
- 瞬時

  The **instantaneous throughput** at any instant of time is the rate (bps) at which Host B is receiving the file
- If the file consists of F bits and the transfer takes T seconds for Host B to receive, the **average throughput** is F/T bps

1.4.4 Throughput in Computer Networks



- R_s: Rate of the link between the server and router
- R_c: Rate of the link between the router and client
- $R_s<R_c$: The bits pumped by the server will flow right through the router and arrive at the client at the rate R_s
- $R_c<R_s$: The router will not be able to forward bits as quickly as it receives them

1.4.4 Throughput in Computer Networks

- In this example, the throughput is $\min\{R_s, R_c\}$, that is the transmission rate of the **bottleneck link**
- To transfer a file of F bits, the transmission time is $F/\min\{R_s, R_c\}$
- For a network with N links, the throughput is $\min\{R_1, R_2, \ldots, R_N\}$

1.4.4 Throughput in Computer Networks

- **Example.** There are 10 servers (each with a rate R_s) and 10 clients (each with a rate R_c) connected to the core ~~of~~ of the computer network
  - 10 simultaneous downloads take place, involving 10 client-server pairs
  - There is a link in the core traversed by all the 10 downloads (with a rate R)

10

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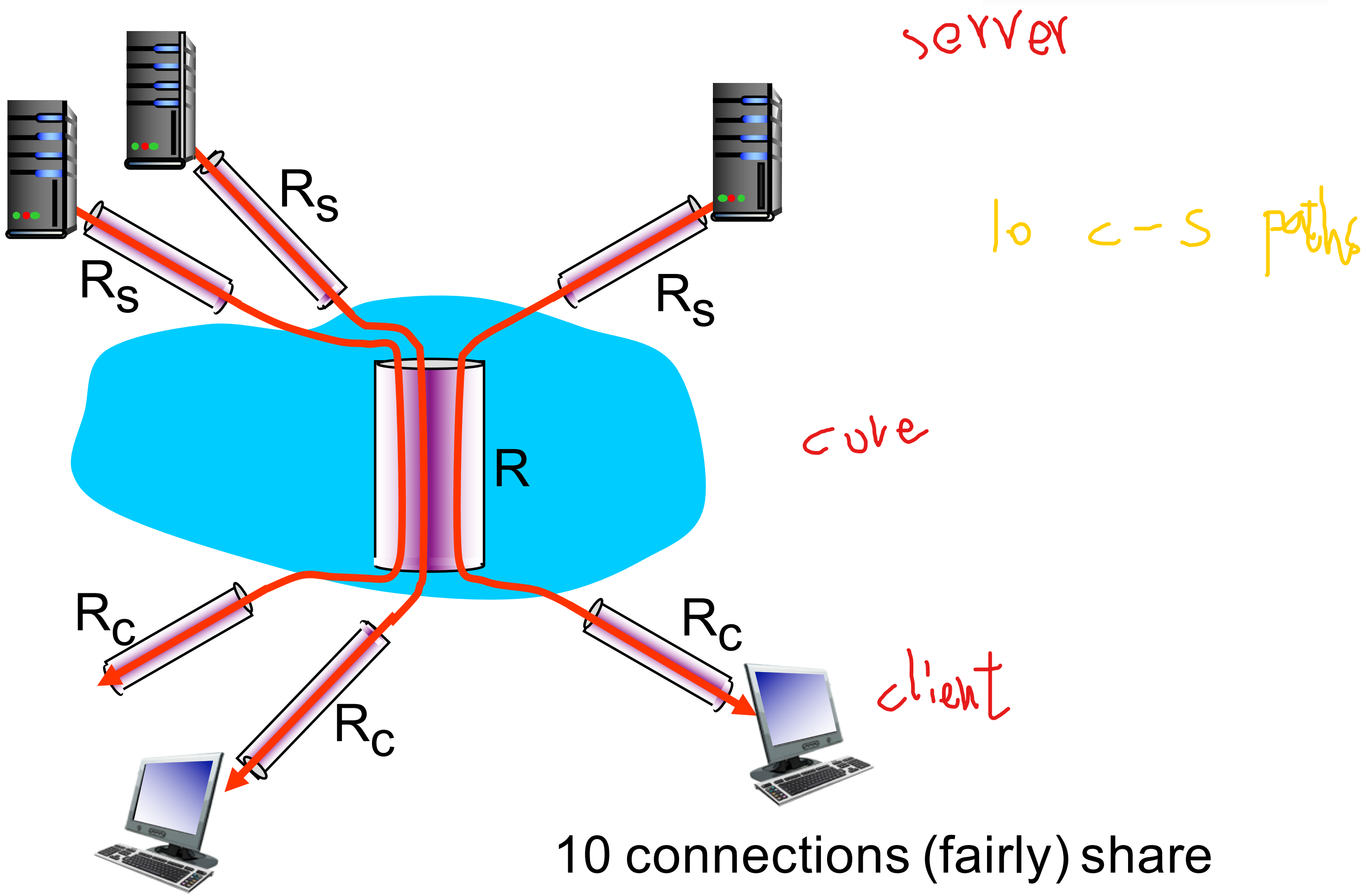
1.4.4 Throughput in Computer Networks



10 connections (fairly) share backbone bottleneck link R bits/sec

1.4.4 Throughput in Computer Networks

- If R>>min{R_s, R_c}, then the throughput is min{R_s, R_c} OK
- 若不及 If R~min{R_s, R_c}, then the throughput is R at the common link and the throughput of each client-server pair is $\boxed{R/10}$

- **Example.** R_s=2 Mbps, R_c=1 Mbps, R=5 Mbps.

- Throughput of each download is 500 kbps

$\min(R_s, R_c) = 1$

$R \sim R_c$

$\frac{5000}{10} = 500$

2

$\boxed{5}$

1

1.5 Protocol Layers and Their Service Models

- Pieces to the Internet
  - Applications
  - Protocols
  - Various types of end systems
  - Packet switches
  - Various types of link-level media
- Internet seems an extremely complicated system
- How to organize a network architecture?

1.5.1 Layers Architecture

- **Example.** How to find the structure to describe a complex system like airline system?
  - Ticket agent
  - Baggage checkers
  - Gate personnel
  - Pilots
  - Airplanes
  - Air traffic control
  - Worldwide system for routing airplanes

1.5.1 Layers Architecture

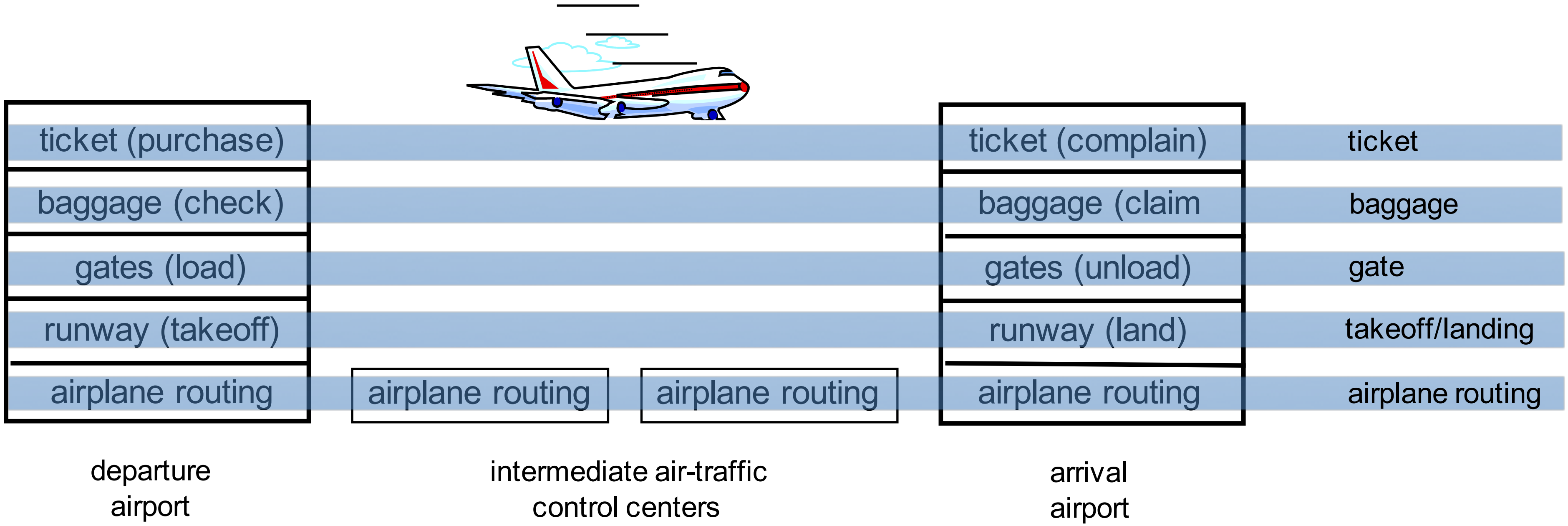
- An airplane trip

ticket (purchase)	ticket (complain)
baggage (check)	baggage (claim)
gates (load)	gates (unload)
runway takeoff	runway landing
airplane routing	airplane routing

airplane routing

1.5.1 Layers Architecture

- Horizontal layering of airlines functionality



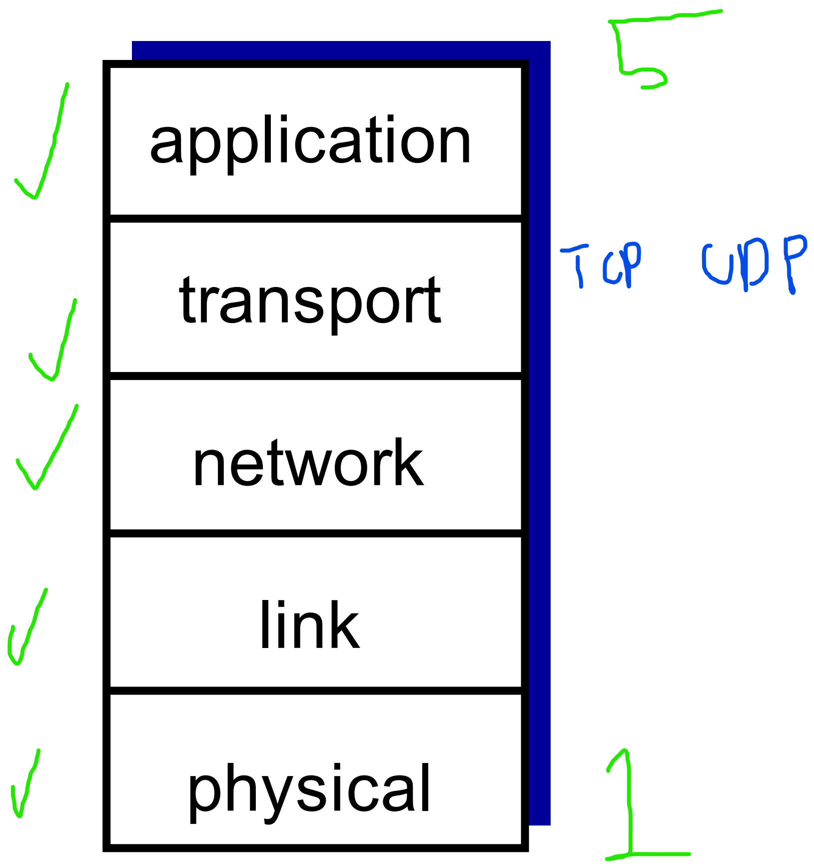
- Each layer provides its service by
  - Performing certain actions within that layer
  - Using the services of the layer directly below it

1.5.1 Layers Architecture

- Protocols layering
  - For network protocols, we are again interested in the **services** that a layer offers to the layer above
  - This is called the **service model** of a layer
- Again, each layer provides its service by
  - Performing certain actions within that layer
  - Using the services of the layer directly below it
- The protocols of the various layers are called the **protocol stack**

1.5.1 Layers Architecture

- The Internet protocol stack consists of 5 layers
  - Physical layer (Layer 1)
  - Link layer (Layer 2)
  - Network layer (Layer 3)
  - Transport layer (Layer 4)
  - Application layer (Layer 5)



1.5.1 Layers Architecture

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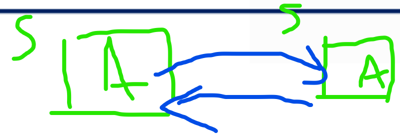

- Application layer

message

  - Network applications and their application-layer protocols reside
  - Application-layer protocols include HTTP, SMTP, FTP, DNS, etc.
  - Application-layer protocols are distributed over multiple end systems
  - With the application in one end system uses the protocol to exchange packets of information with the application in another system
  - We refer the packet of information at the application layer as a **message**
- Transport layer

segments

  - Guaranteed delivery of application layer messages to the destination
  - Flow control (sender/receiver speed matching)
  - TCP and UDP
  - TCP breads long messages into shorter segments (transport-layer packets are called **segments**)

1.5.1 Layers Architecture

datagrams

- Network layer
  - Network-layer packets are called **datagrams**
  - Moving datagrams from one host to another (routing)
  - **Route a datagrams from the source host to the destination host through a series of routers**

frames

- Link layer
  - Different physical media may lead to different transmission reliability
    - Bit error rate in fiber optics: 10^{-9}
    - Bit error rate in coaxial cables or twisted-pair cooper wire: 10^{-6}
    - Bit error rate in radio: 10^{-3}
  - Adapt to different physical media to provide reliable delivery from one end system to another
  - Link-layer packets are called as **frames**

1.5.1 Layers Architecture

- Physical layer
  - Move the **individual bits** within the frame from one end system to another
  - **The protocols in this layer are link dependent and depend on the actual physical medium**

1.5.1 Layers Architecture

- The Internet protocol stack is not the only protocol stack
- In 1970s, the International Organization for Standardization (ISO) proposed the Open System Interconnection (OSI) model
- Seven layers in OSI model
  - Application layer
  - Presentation layer
  - Session layer
  - Transport layer
  - Network layer
  - Link layer
  - Physical layer

1.5.1 Layers Architecture

- Presentation layer
  - Provide services that allow communicating applications to interpret the meaning of data exchanged
  - Data compression and encryption
- Session layer
  - Delimiting and synchronization of data exchange
  - Build a checkpoint and recovery scheme

1.5.2 Encapsulation封裝

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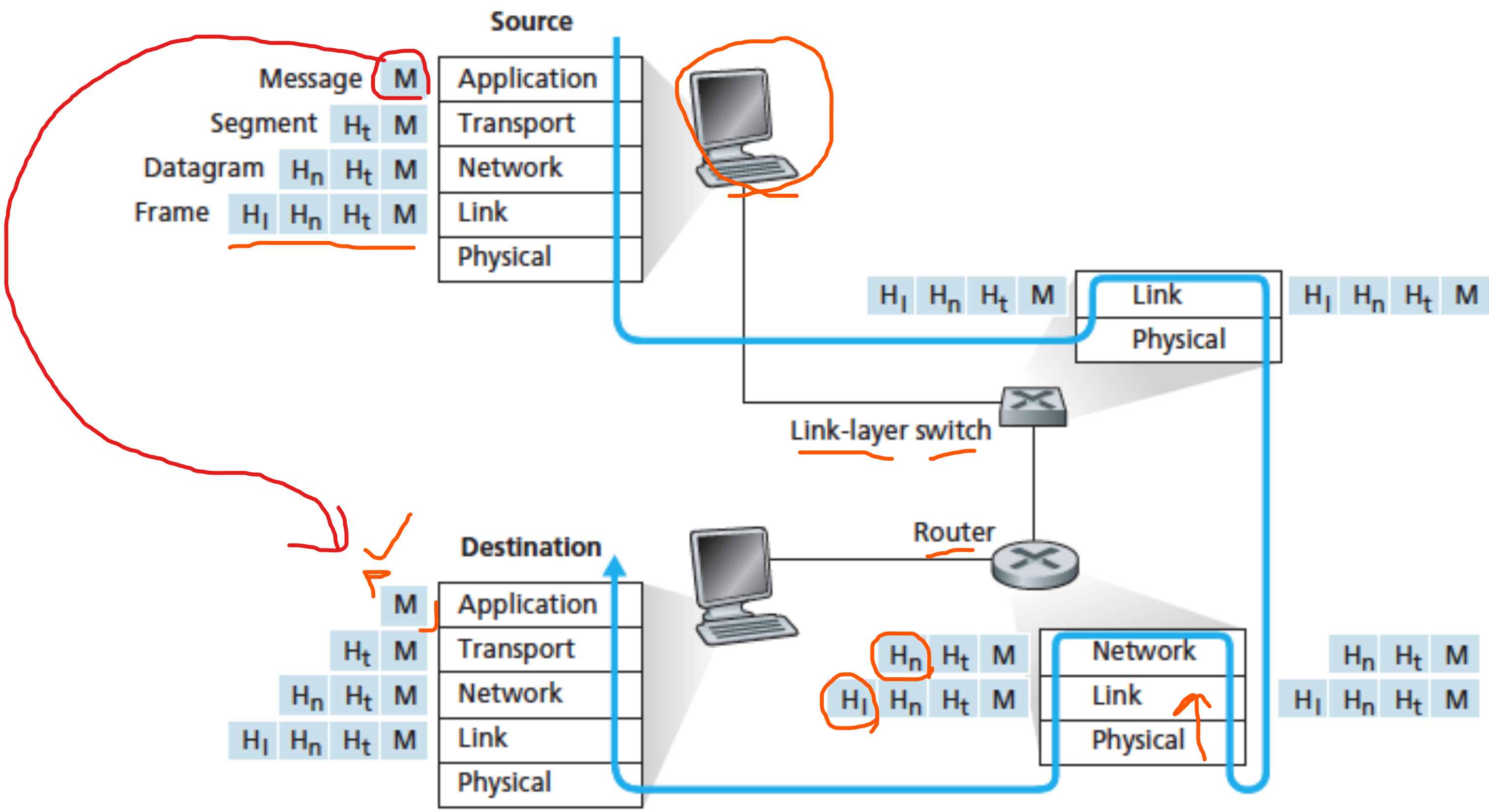
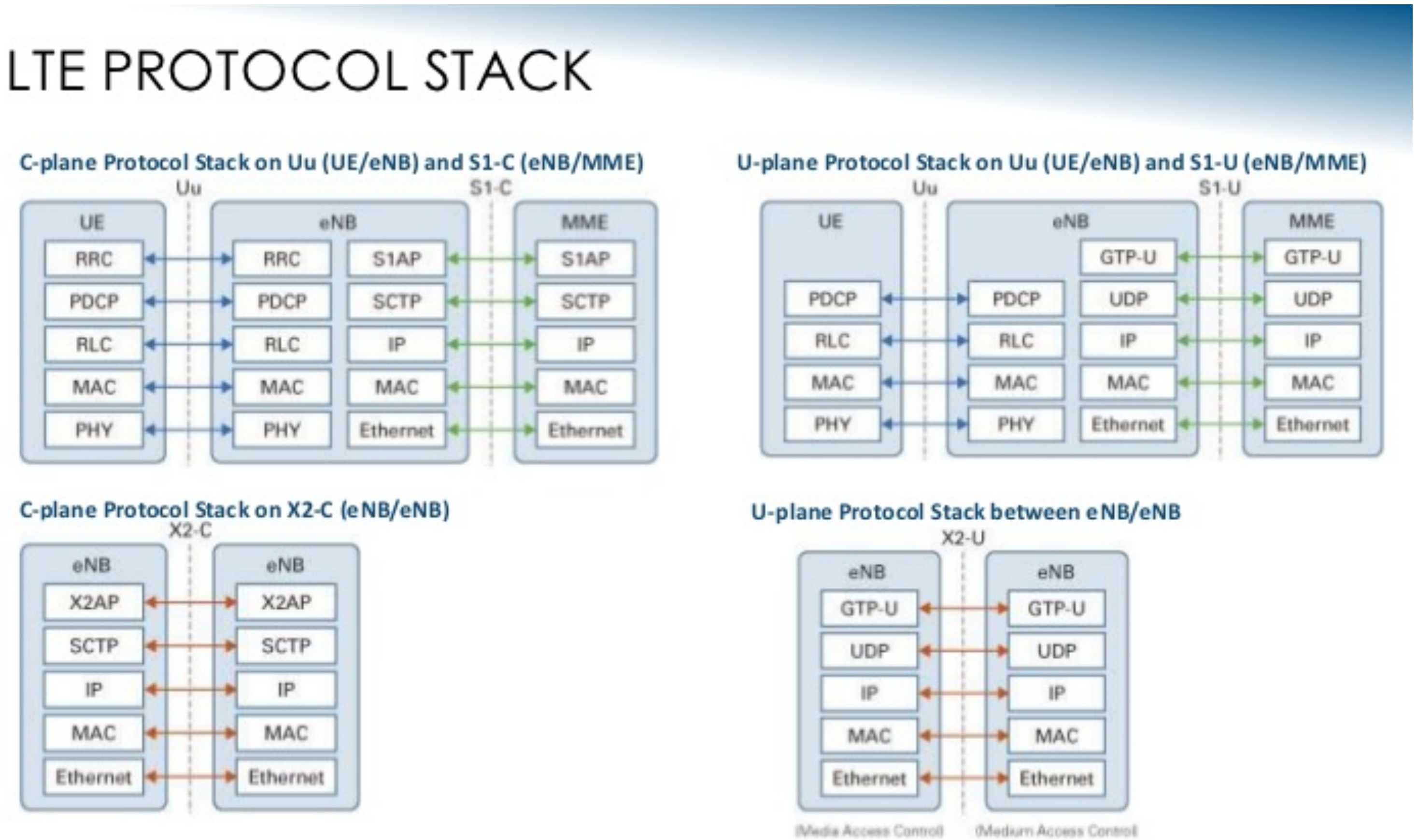
- In each layer, a packet has two types of fields: **header** field and **payload** field



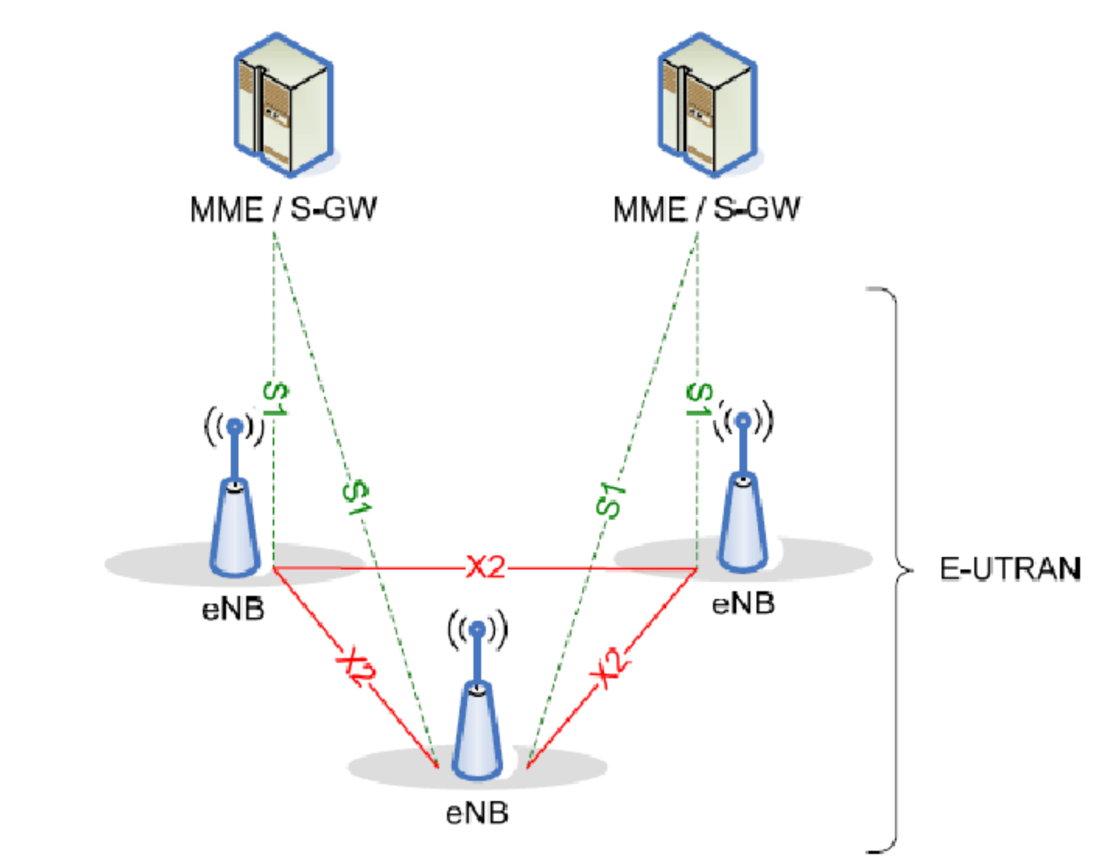
1.5.2 Encapsulation

- LTE Protocol Stack



1.5.2 Encapsulation

- Routing (paging) in LTE



1.6 Network Under Attack

- The field of network security is about how the bad guys can attack computer networks, and about how we can defend networks against those attacks
- The bad guys can put malware into your host via the Internet
  - **Malware**: a collection of malicious stuff
  - Detecting our files
  - Installing spyware to collect our private information
- **Viruses**: malware that require some form of user interaction to infect the user's device
- **Worms**: malware that can enter a device without any explicit user interaction

1.6 Network Under Attack

- The bad guys can attack servers and network infrastructure using **denial-of-service (DoS)**
  - DoS attack renders a network, host, or router unusable
- Three categories of DoS attacks
  - **Vulnerability attack:** sending a few well-crafted messages to a vulnerable applications or operation system running on a targeted host, to stop or crash the host
  - **Bandwidth flooding:** sends a deluge of packets to the targeted host, so that the target's access link becomes clogged
  - **Connection flooding:** establishes a large number of half-open or fully open TCP connection at the target host, so the host can become so bogged down to stop accepting more connection 佔滿連線

1.6 Network Under Attack

- The bad guys can sniff packets
  - Easily happen to wireless Internet access
  - A sniffer may place a passive receiver in the vicinity of the wireless transmitter
  - To obtain packets containing sensitive information, such as password, ID number, trade secrets
  - Packet sniffers are difficult to be detected as they are passive
- The bad guys can masquerade as someone you trust 偽裝
  - Create packets with hand-crafted source address, packet content, and destination address
  - **End-point authentication** may be needed to determine the certainty if a message originates from where we think it does.