

# COMPUTER NETWORKS

## UNIT - 1

introduction to  
computer networks

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VIBHA MASTI

# COMPUTER NETWORKS

I N T R O



- How computers share data and communicate
- Internet

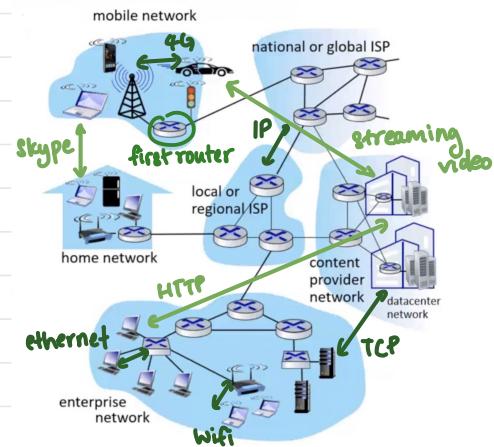
## Hardware & Software

- Cisco, Juniper - hardware
- Amazon, Reliance - software

## The Internet: Nuts and Bolts View

- **hosts:** end systems
- **packet switches:** forward packets - routers, switches
- **communication links:** fibre, copper, radio, satellite; bandwidth - transmission rate bits/s
- **networks:** collection of devices, routers, links
- **network of networks**
- **protocols:** sending, receiving messages - HTTP, TCP, IP, 4G, WiFi

## Services

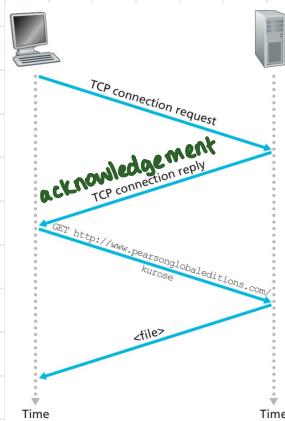


## Internet Standards

- **RFC:** Request for Comments
- **IETF:** Internet Engineering Task Force

## Network Protocols

- format, order for messages to be sent
- TCP/IP
- all communication governed by protocols



## Network Structure

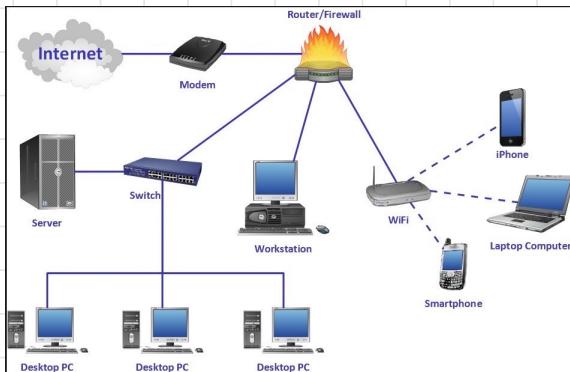
### 1) Network edge

hosts: clients and servers , servers in data centres

### 2) Access network, physical media → connecting edge to first router wired, wireless communication links

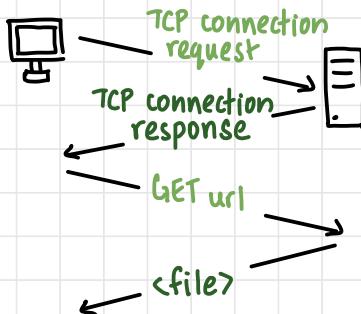
### 3) Network core

interconnected routers, network of networks (ISP)



## Network Protocols

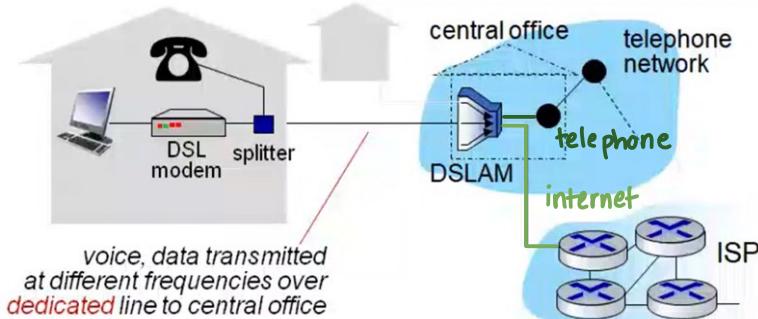
- all communication activity over the internet governed by protocols
- define format, order of messages sent and received , actions taken



## Access Networks

- network that connects network edge to first router (immediate service provider)
- DSL or cable: two kinds of broadband

### (a) Digital Subscriber Line

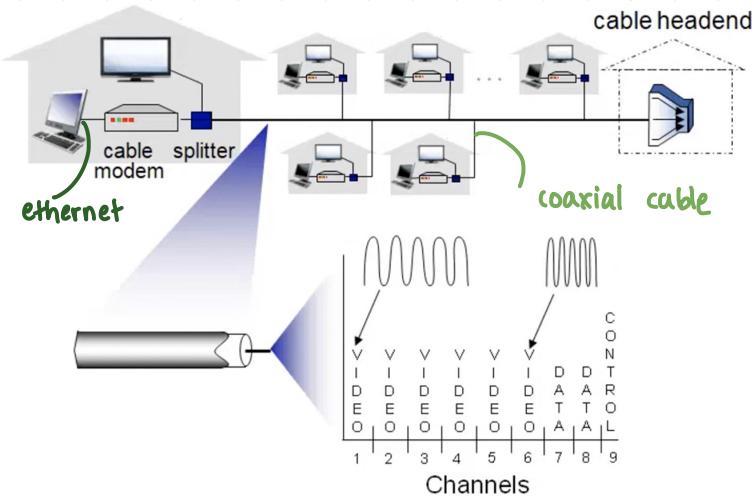


- Use existing phone line to central office DSLAM (broadband connection)
  - **data:** over DSL phone line to internet
  - **voice:** over DSL phone line to telephone net
- High speed downstream channel (50 kHz - 1 MHz)
  - (download)
- Medium speed upstream channel (4 kHz - 50 kHz)
  - (upload)
- Ordinary two-way telephone channel (0 kHz - 4 kHz)

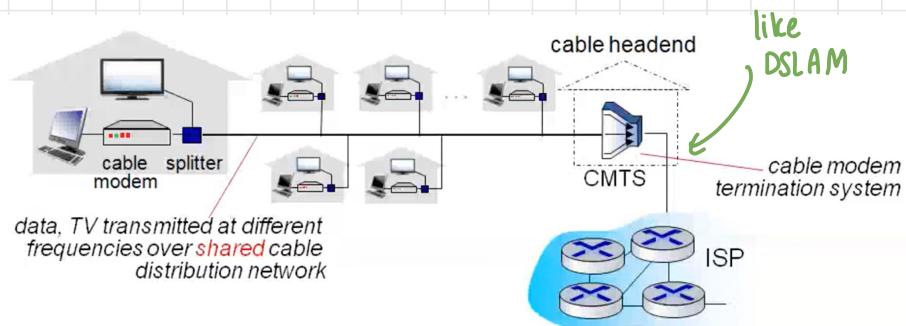
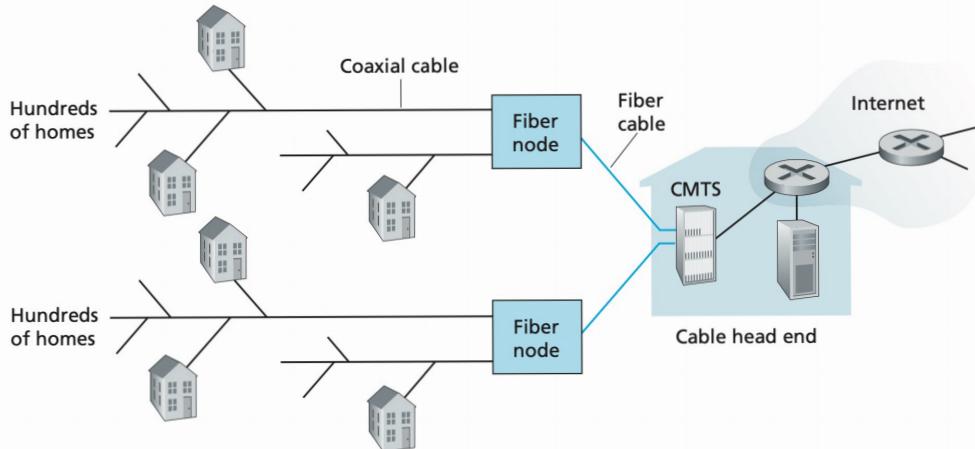
### DSL Standard

- 24-52 Mbps - downstream transmission rate
- 3.5 - 16 Mbps - upstream transmission rate
- Asymmetric access

## (b) Cable-based access



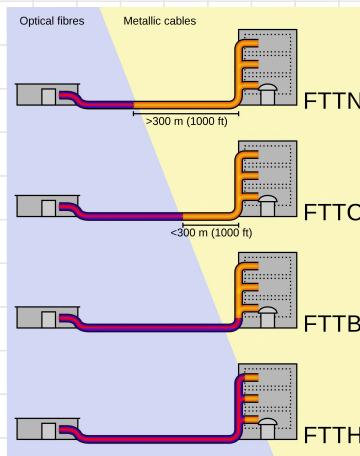
- Use existing cable TV infrastructure
- DOCS (Data Over Cable Service) specification
  - downstream: 40 Mbps - 12 Gbps }
  - upstream: 30 Mbps - 100 Mbps } more than DSL
- Frequency Division Multiplexing (FDM): different channels transmitted over different frequency bands
- Amplitude (ADM) and Time (CTDM) are also multiplexing methods for simultaneous communication
- Hybrid fibre coax (HFC): broadband network that combines optical fibre and coaxial cables
- From cable operators' master headend to neighbourhood junction: fibre optic
- Coaxial cable node: 50-5000 homes



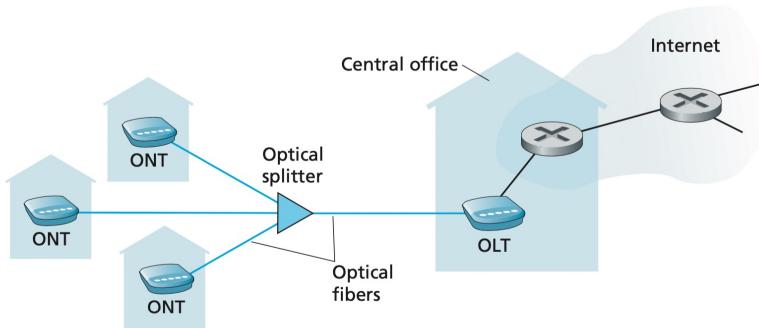
- Network of cable, fibre attaches home to ISP router
  - homes share access network to cable headend

### (c) Fibre to the Home (FTTH)

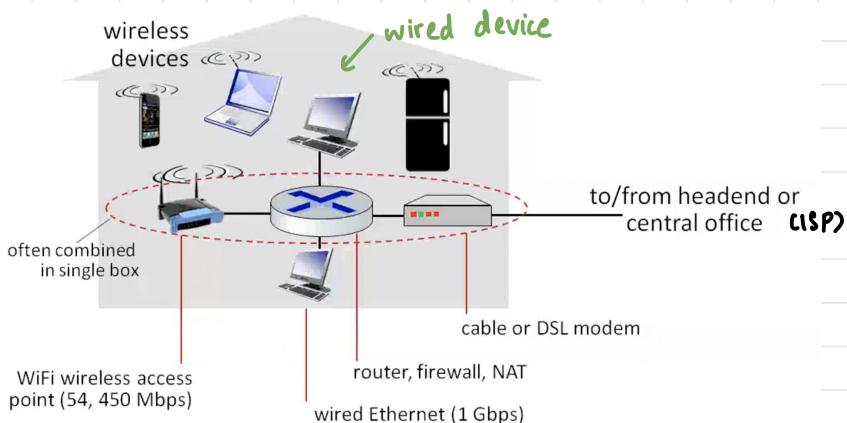
- Use of optical fibre from a central office directly to homes for high speed internet
- order of 100 Mbps (~20x cable or DSL)



- Direct fibre: one single fibre connects central office to home (in other words, fibre from CO split into customer-specific fibres near homes)
- Two architectures: Active Optical Networks (AONs) and Passive Optical Networks (PONs)
- AON: switched ethernet
- PON: each home has Optical Network Terminator (ONT) that connects home router to neighbourhood splitter, which combines all fibres to a single fibre.
- Connects to Optical Line Terminator (OLT) at CO that converts b/w optical signals to electrical signals

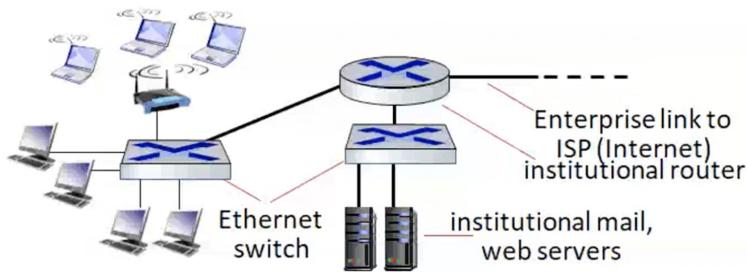


## (a) Home Access



- LAN
- `wifile.net`

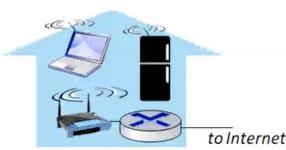
## (b) Enterprise Networks



- companies, universities (LAN)
- mix of wireless, wired link technologies, connecting mix of switches and routers
  - **ethernet:** 100 Mbps, 1 Gbps, 10 Gbps
  - **wifi:** 11, 54, 450 Mbps

## (c) Wireless Access Networks

- shared wireless access network connects end system to router via base station (access point)
- WLAN - within building ; wifi

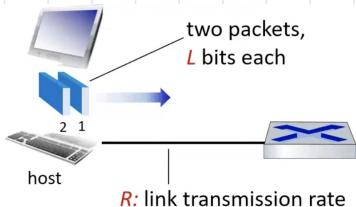


- Wide area cellular access networks - provided by mobile, cellular network operator; 4G, 5G



## HOSTS

- takes application message, breaks into smaller chunks (packets) of length  $L$  bits
- transmits packet into access network at transmission rate  $R$  (link transmission rate/capacity/bandwidth)



$$\text{packet transmission delay} = \frac{\text{time needed to transmit } L\text{-bit packet into link}}{R \text{ (bits/s)}}$$

## PHYSICAL MEDIA

- bit: propagates between transmitter / receiver pairs
- physical link: what lies between transmitter and receiver
- guided media: signals propagate in solid media
  - copper, fibre, coax
- unguided media: signals propagate freely
  - radio

### 1. Twisted pair (TP)

- two insulated copper wires (STP & UTP)
  - twisted to prevent crosstalk
- Category 5: 100 Mbps, 1 Gbps ethernet  
Category 6: 10 Gbps ethernet
- Straight (patch) cable: both ends wired using same standard (used in LANs, common — for dissimilar devices)
- Crossover cable: both ends wired using different standards (used to connect similar devices — 2 computers, hubs, switches)

extra foil shield:  
industrial



unshielded TP: most common



standards

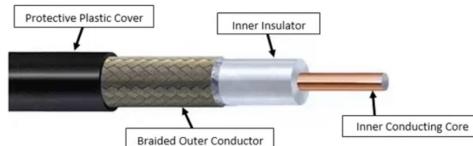
568A ↗

568B

- category : 3,5,5e,6,6a,7 — tightness of twist , maximum transmission rate they can handle without crosstalk (interference)
- category 8: ultimate — 40 Gbps , STP, 4x Cat 6a or Cat 7

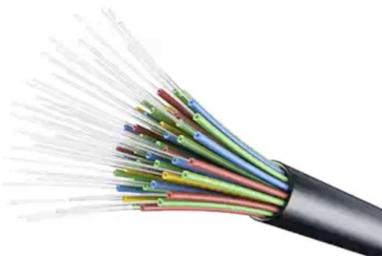
## 2. Coaxial Cable

- two concentric copper conductors (rather than parallel), and bidirectional
- broadband
  - multiple frequency channels on cable
  - 100 Mbps per channel



## 3. Fibre Optic Cable

- glass fibre carrying light pulses , each pulse one bit
- high speed (10 - 100's Gbps)
- low error rate, repeaters far apart, immune to EM noise



#### 4. Wireless Radio

- signal carried in EM spectrum
- broadcast and half duplex
  - simplex: one-way telegram
  - half duplex: one at a time walkie-talkie
  - full duplex: two-way mobile phone
- obstruction, reflection, interference

##### (a) terrestrial microwave

- 45 Mbps

##### (b) Wireless LAN (wifi)

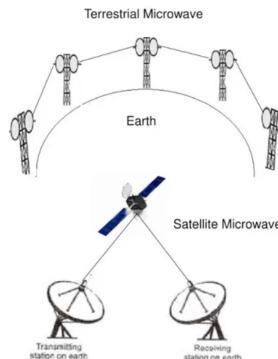
- 100 Mbps

##### (c) wide area (cellular)

- 4G cellular: ~10 Mbps

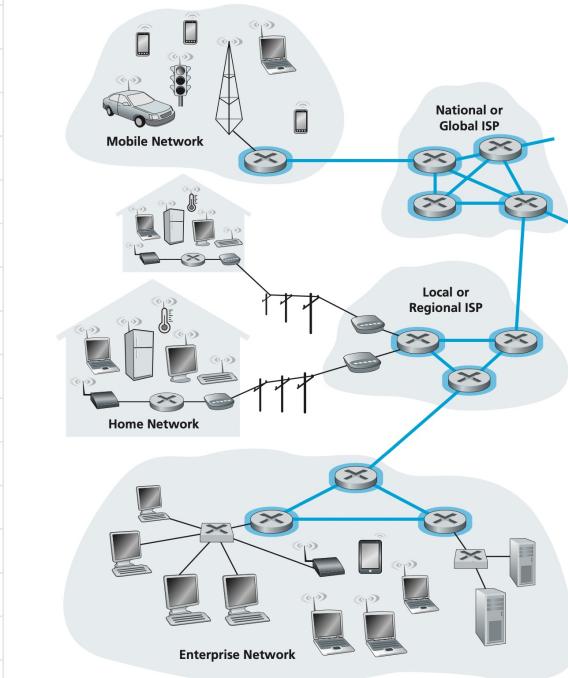
##### (d) satellite

- geosynchronous vs low-earth orbit
- 280 msec end-to-end delay
- 45 Mbps per channel

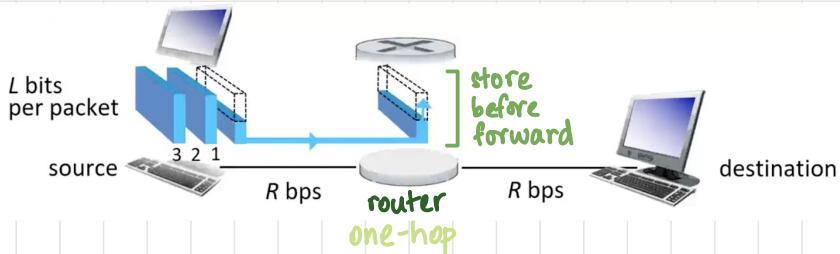


## Network Core

- mesh of interconnected routers, packet-switchers and communication links
- packet-switching
  - hosts break messages into packets
  - packets forwarded from one router to the next across links
  - each packet transmitted at full link capacity
- Packets transmitted over communication links at full transmission rate of link  
*packet size*
- $L$  bits over link with  $R$  bits/sec, time to transmit packet is  $L/R$  seconds



## PACKET SWITCHING



### Transmission delay

takes  $L/R$  seconds to transmit  $L$ -bit packet into link at  $R$  bps

### Store and Forward

entire packet must arrive at router before it can be transmitted to next link

### End-end delay

single packet,  $N$  links,  $N-1$  routers (assuming zero propagation delay)

$$d_{\text{end-to-end}} = N \frac{L}{R}$$

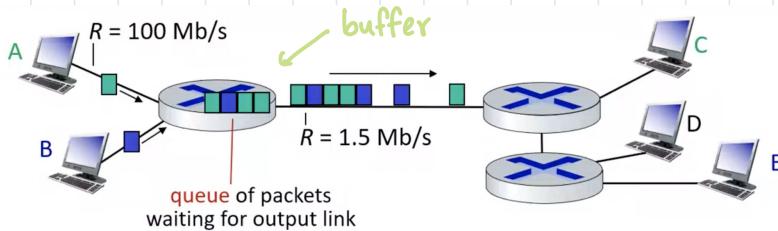
$P$  packets,  $N$  links,  $N-1$  routers (assuming zero propagation delay)

$$d_{\text{end-to-end}} = (N+P-1) \frac{L}{R}$$

Q: If  $L = 10 \text{ Kbytes}$ ,  $R = 100 \text{ Mbps}$ , one-hop transmission delay = ?

$$t_{td} = \frac{10 \times 1024}{10^6 \times 1024 \times 1024} = \frac{1}{10240} = 9.77 \times 10^{-5} \text{ s} = 97.7 \mu\text{s}$$

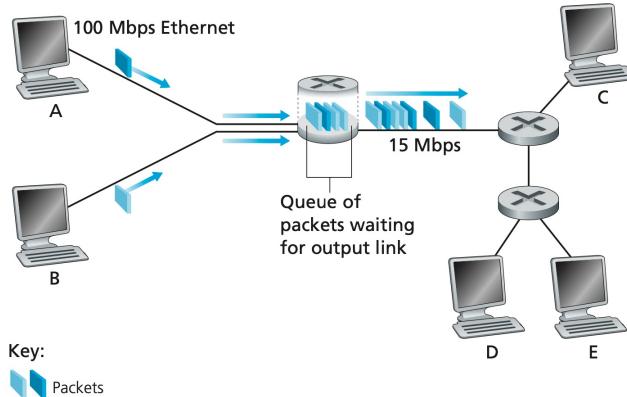
## Queuing



## Packet Queuing and Loss

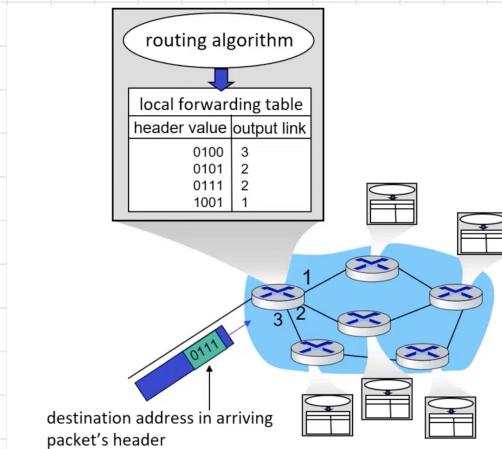
if arrival rate (in bps) to link exceeds transmission rate (in bps) of link for a period of time

- packets will queue to be transmitted (queuing delay ; variable)
- packets can be lost if memory (buffer) in router fills up
- queuing delay depends on network congestion



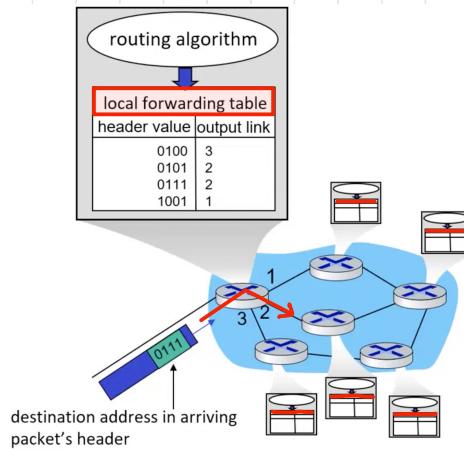
# TWO KEY NETWORK CORE FUNCTIONS

- mesh of interconnected routers: network core
- functions: forwarding and routing



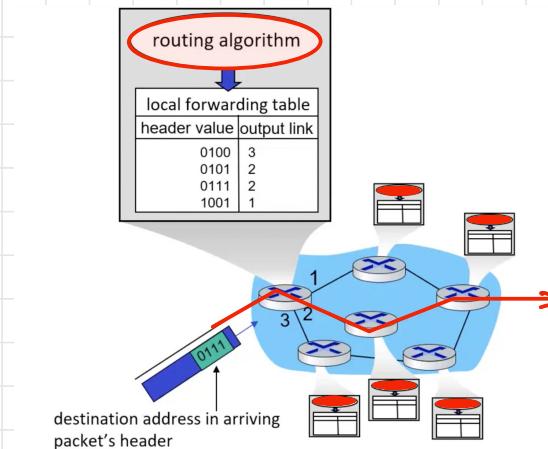
## i) Forwarding

- local action
- move arriving packets from router's input link to appropriate router output link
- each router has forwarding table
- routing protocols automatically set forwarding tables



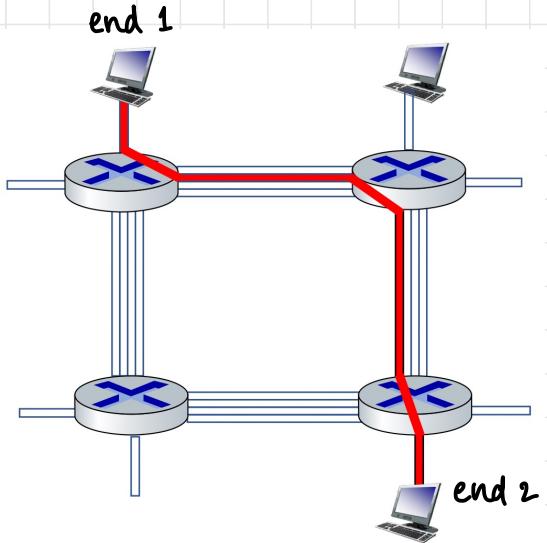
## 2) Routing

- global action
- determine source-destination paths taken by packets
- routing algorithms



## Circuit switching

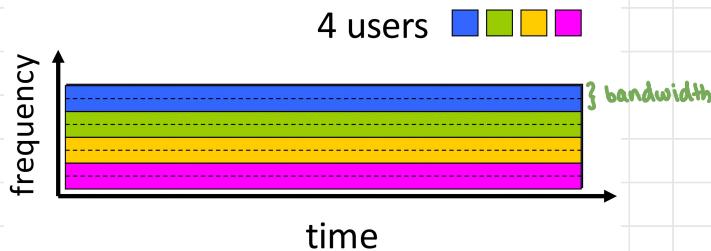
- resources from one end to another allocated to a 'call' (e.g.: telephone)
- dedicate lines / resources; no sharing
- segments / lines idle when not used for call
- traditional telephone networks
- reserved resources for a duration



## — Multiplexing IN Circuit Switched Networks —

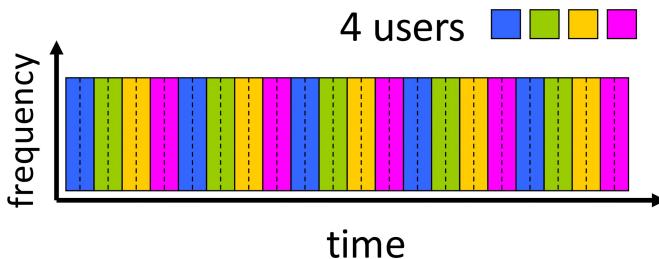
### i) Frequency Division Multiplexing (FDM)

- analog signals divided into frequency bands (narrow)
- each call - one band ; max rate of transmission for that band
- optical, electromagnetic



### 2) Time Division Multiplexing (TDM)

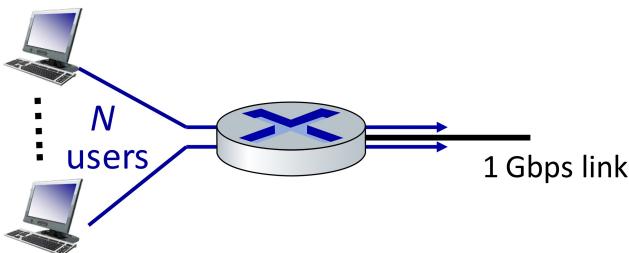
- each call allocated periodic slots
- can transmit at maximum rate of wide frequency band only during its time slot



## PACKET SWITCHING vs CIRCUIT SWITCHING

- packet switching allows for more users

[http://gaia.cs.umass.edu/kurose\\_ross/interactive](http://gaia.cs.umass.edu/kurose_ross/interactive)



Q: 1 Gbps link, 100 Mbps per user when active, active 10% of the time

- no. of users in circuit switching: 10 users ( $\frac{1000}{100}$ )
- packet switching. Only 10 users active at a time, 35 total  
 $p = 0.1$   
probability that  $> 10$  users at once

$$\sum_{i=10}^{35} {}^{35}C_i (0.1)^i (0.9)^{35-i} = 1 - 0.99958 = 0.0004$$

10 or fewer active users,  $P = 0.9996$

Q: 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 1.536 Mbps
- TDM, 24 slots/sec - each link
- 500 ms to establish end to end circuit

$$\text{each user : } \frac{1.536}{24} = 64 \text{ kbps bandwidth}$$

$$\text{time to transfer : } \frac{640000}{64 \times 1000} = 10 \text{ sec}$$

$$\text{time to establish connection} = 0.5 \text{ sec}$$

$$\therefore \text{total time} = 10.5 \text{ seconds}$$

Q: For above problem, if each channel had 12 slots/second, how does answer change?

$$\text{each user : } \frac{1.536}{12} = 128 \text{ kbps bandwidth}$$

$$\therefore \text{time taken} = 5 \text{ seconds}$$

$$\therefore \text{total time} = 5.5 \text{ seconds}$$

## Packet Switching

- good for bursty data (resource sharing, no call setup)
- congestion: buffer overflow causes **delay and loss**
- for audio/video, bandwidth guarantees used
- on-demand allocation vs reserved resources (circuit)

### Packet Switching

- Connectionless
- Designed for data
- Flexible
- Out of order, assembled at the dest
- Forward, Store & Fwd
- Network layer
- Bandwidth is saved (dynamic)
- Transmission of data – Source, routers
- Transmission delay

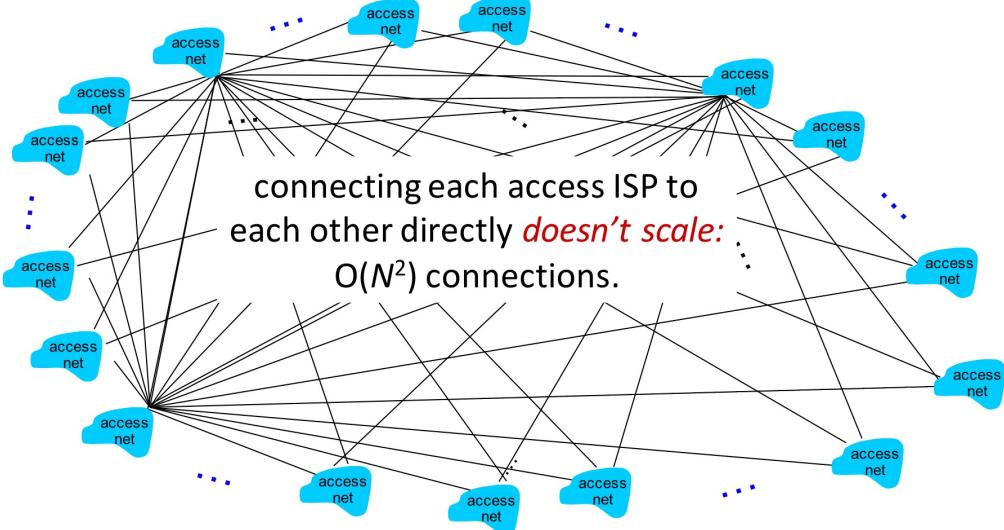
### Circuit Switching

- Connection oriented
- Designed for voice
- Inflexible
- Message received in same order
- FDM & TDM
- Physical layer
- Bandwidth is wasted (fixed)
- Transmission of data – source
- Call setup delay

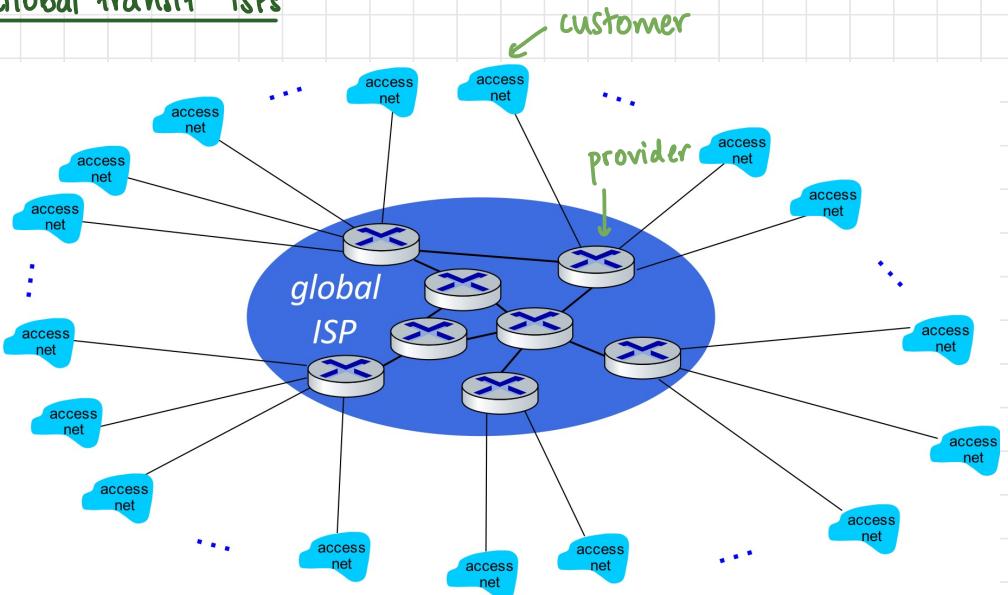
## NETWORK of NETWORKS

- end systems connect to the Internet via access ISPs (residential, company, university)
- access ISPs interconnected so that all hosts can send/receive packets to all other hosts
- network of networks

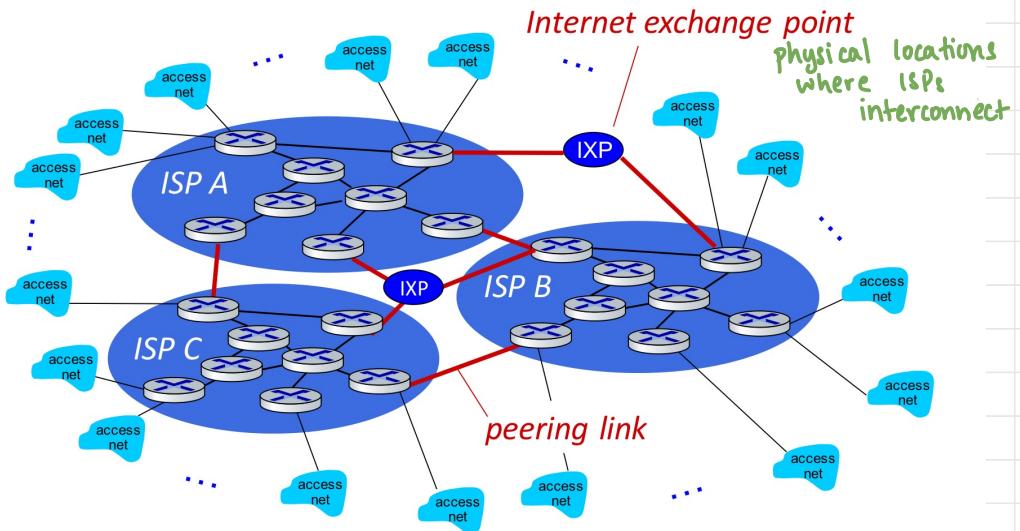
Fully mesh-impossible and wasteful



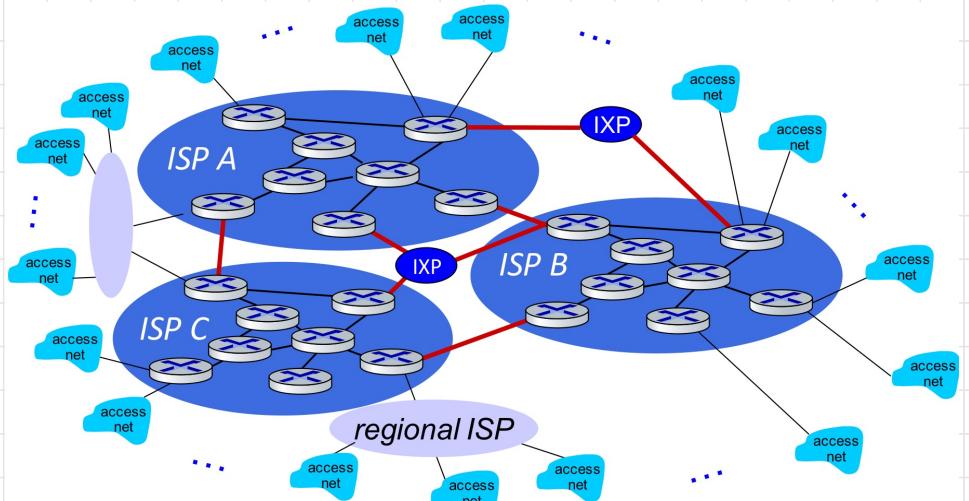
## Global transit ISPs



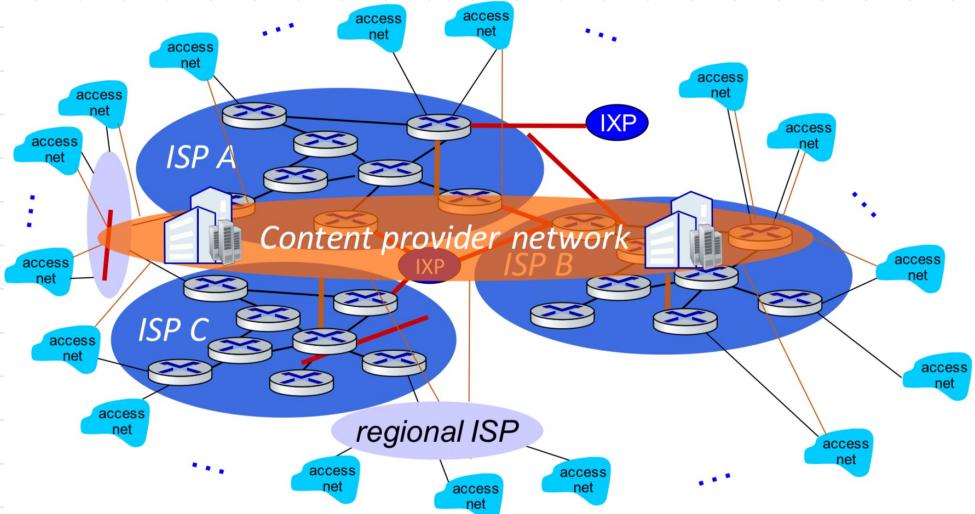
## Multi level with IXPs



## Regional ISPs

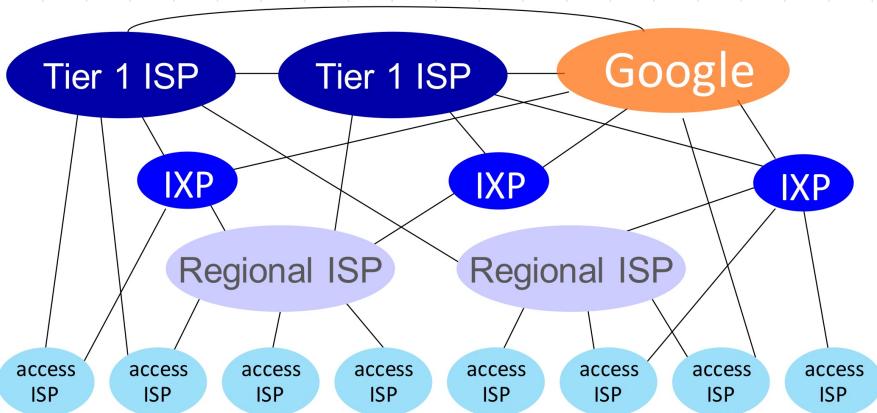


## Content Provider Network



- google , own proxy servers

## Hierarchy



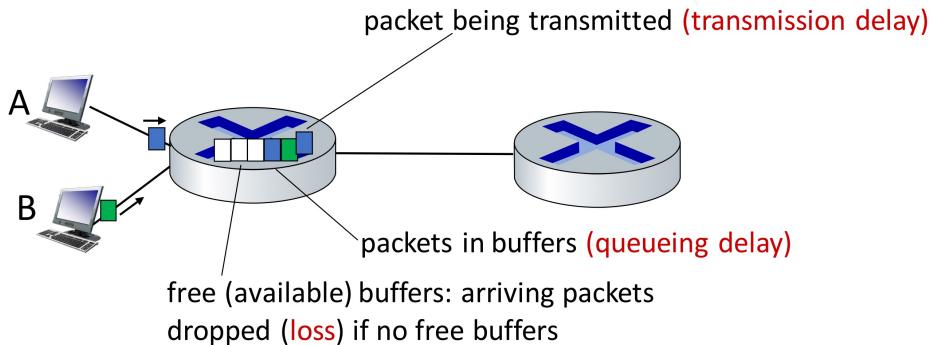
- Tier 1: commercial ISPs: (airtel, AT&T, Jio)
- Content Provider Networks: Google, Facebook – put networks with their own data centres to the internet

## Sprint ISP Network Map 2019



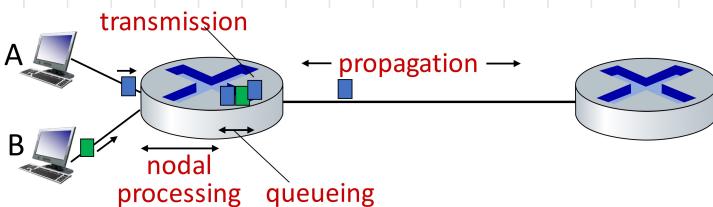
## Packet Loss and Delay

- packets queue in local buffers
- loss: arrival rate > transmission rate



## Total Delay

[http://gaia.cs.umass.edu/kurose\\_ross](http://gaia.cs.umass.edu/kurose_ross)



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

$$d_{\text{prop}} = \frac{d}{s}$$

length of physical link  
prop speed ( $\sim 2 \times 10^8 \text{ m/s}$ )

$$d_{\text{trans}} = \frac{L}{R}$$

no. of bits/packet  
transmission rate

$$d_{\text{queue}} = \text{time waiting in buffer (o/p link) for trans, } \mu\text{s to ms}$$

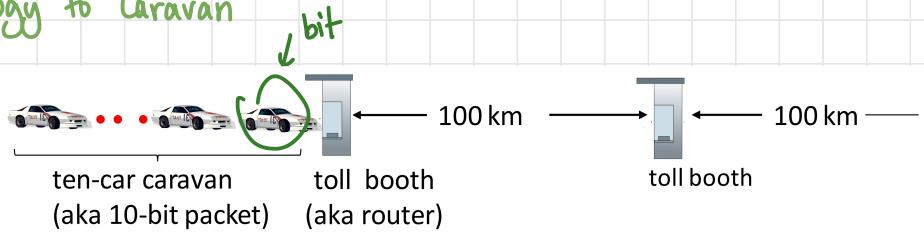
congestion

$$d_{\text{proc}} = \text{nodal processing, determine output link, typically } < \text{ms (from header)}$$

## Difference Between $d_{trans}$ and $d_{prop}$

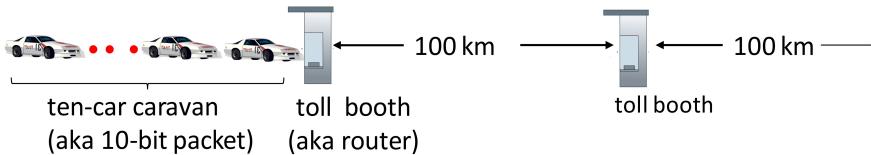
Transmission Delay	Propagation Delay
Time required for the router to push out the packet.	Time it takes a bit to propagate from one router to the next.
A function of the <b>packet's length</b> and the <b>transmission rate</b> of the link.	A function of the <b>distance</b> between the two routers.
$d_{trans} = L/R$	$d_{prop} = d/s$
Nothing to do with the distance between the two routers.	Nothing to do with the packet's length or the transmission rate of the link.

### Analogy to Caravan



- cars propagate at 100 kmph
- toll booth takes 12 sec to service car ( $d_{trans}$  time)
- time taken to push entire packet/caravan =  $12 \times 10 = 120$  sec  
*transmission delay*
- time taken by car to move from router 1 to router 2 = 1 hr  
*propagation delay*

Q: In caravan analogy, suppose cars propagate at 1000 kmph and transmission time per car is one min. Will cars arrive to second booth before all cars serviced at first booth?



- time taken for 10<sup>th</sup> car to get transmitted

$$10 \times 1 = 10 \text{ mins}$$

- time taken for 1<sup>st</sup> car to reach toll booth #2,

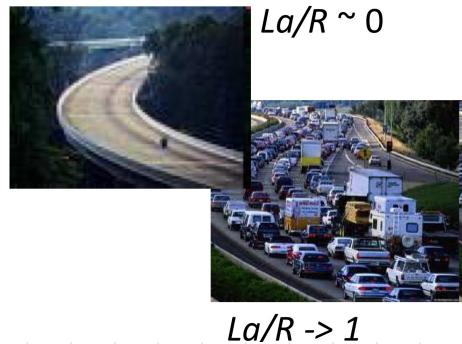
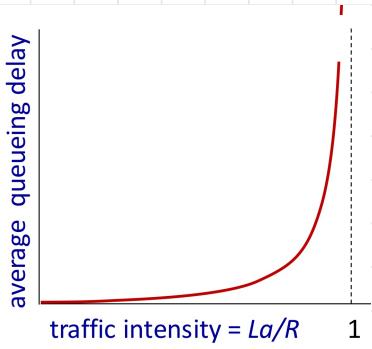
$$1 \text{ min} + \frac{100 \text{ km}}{1000 \text{ km}} \text{ hr} = 1 \text{ min} + 6 \text{ min} = 7 \text{ min}$$

- yes

## Queueing Delay

- varies from packet to packet (depends on traffic intensity & queue length at buffer for out link)
- d<sub>queue</sub>: average, variance, probability that it exceeds a certain value are common statistical measures of d<sub>queue</sub>
- depends on traffic arrival rate, nature of arriving traffic (periodically or bursts)

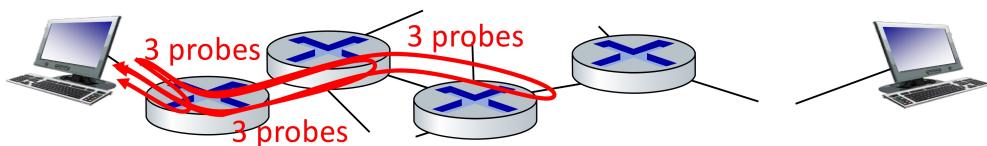
- $R$ : link bandwidth (bits per second - bps)
- $L$ : packet length (bits)
- $a$ : average packet arrival rate (packets per second - pps)
- $La$ : average arrival rate of bits
- $La/R > 1$ : average delay infinite (more bits arriving than serviceable)
- $La/R \leq 1$ : nature of arriving traffic
- $La/R \approx 0$ : average queueing delay small
- Assuming infinite queue buffer / capacity



- In reality, queueing delay is not infinite; packets arriving to full queue are dropped and lost (packet loss)
- End-to-end delay  $d_{\text{end-end}} = N(d_{\text{proc}} + d_{\text{trans}} + d_{\text{prop}})$  for  $N-1$  routers,  $N$  links

## Real Internet Delays and Routes

- traceroute program: delay measurement from source to router along end-to-end internet path towards destination (RFC 1393)
- for all  $i$ :
  - sends 3 packets to router  $i$  on path towards destination with time-to-live field value of  $i$ )
  - router  $i$  will return packets to sender
  - sender measures time interval between transmission and reply



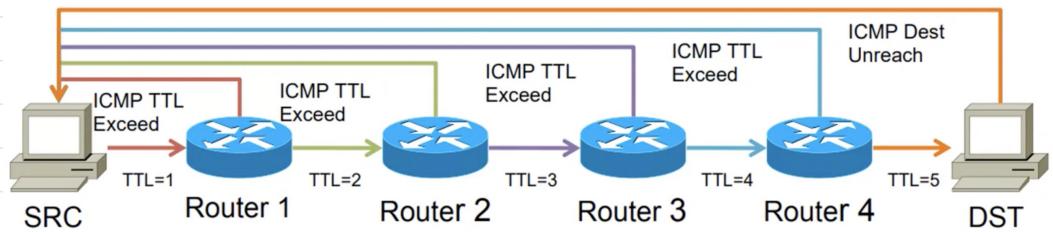
### traceroute command (Windows - tracert)

3 values (2x prop time)

```
→ ~ sudo traceroute google.com
traceroute to google.com (142.250.76.78), 64 hops max, 52 byte packets
1 192.168.4.1 (192.168.4.1) 4.885 ms 2.149 ms 2.585 ms ←
2 192.168.1.1 (192.168.1.1) 2.081 ms 1.929 ms 2.220 ms
3 abts-kk-dynamic-001.4.179.122.airtelbroadband.in (122.179.4.1) 5.015 ms 6.212 ms 5.172 ms
4 125.21.0.229 (125.21.0.229) 8.150 ms
nsg-corporate-169.118.185.122.airtel.in (122.185.118.169) 6.815 ms
125.21.0.229 (125.21.0.229) 6.513 ms
5 116.119.68.247 (116.119.68.247) 13.725 ms
116.119.57.97 (116.119.57.97) 17.669 ms
116.119.57.201 (116.119.57.201) 14.563 ms
6 72.14.216.192 (72.14.216.192) 16.076 ms
72.14.208.234 (72.14.208.234) 15.047 ms 14.259 ms
7 10.23.216.62 (10.23.216.62) 15.241 ms
10.252.56.254 (10.252.56.254) 16.707 ms
116.119.50.115 (116.119.50.115) 14.127 ms
8 72.14.208.234 (72.14.208.234) 13.134 ms 13.751 ms
142.250.228.220 (142.250.228.220) 13.170 ms
9 142.250.228.187 (142.250.228.187) 15.881 ms
108.170.253.119 (108.170.253.119) 15.517 ms
10.252.69.222 (10.252.69.222) 14.630 ms
10 maa05s14-in-f14.1e100.net (142.250.76.78) 13.364 ms 13.501 ms 11.653 ms
```

↓ name      ↓ address

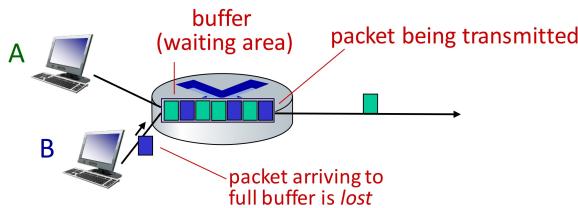
## Working of Traceroute



do not always trust traceroute (only 3 packets)

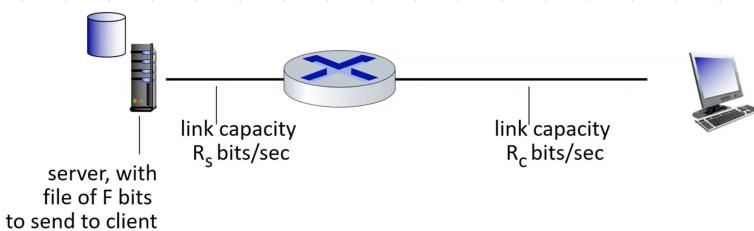
## Performance - Packet Loss

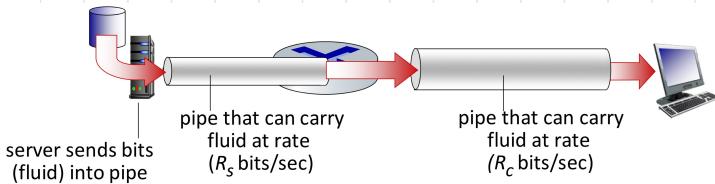
- lost packet may be retransmitted by previous node, source end system or not at all



## Performance - Throughput

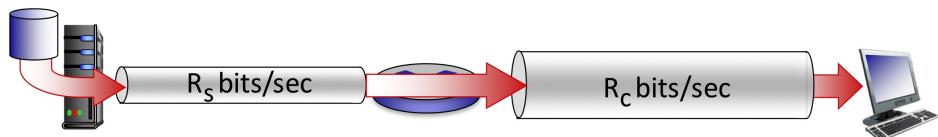
- rate at which data sent from sender to receiver
  - instantaneous
  - average



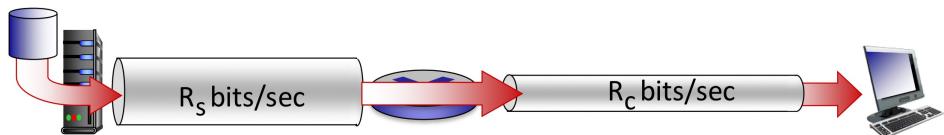


- average: minimum ( $R_s, R_c$ )

$(R_s < R_c)$  What is average end-end throughput?



$R_s > R_c$  What is average end-end throughput?



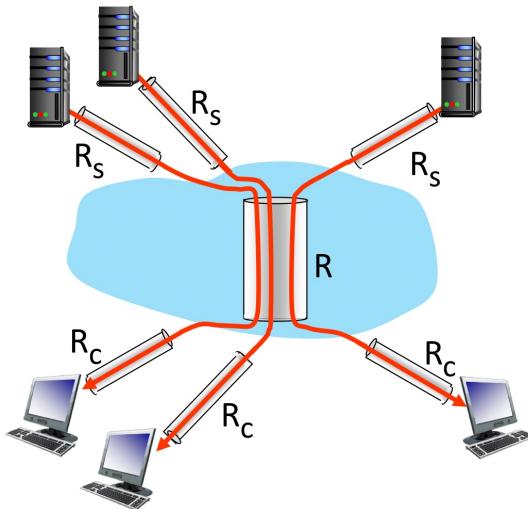
## Bottleneck Link

link on end-end path that constrains end-end throughput

Q: Suppose you are downloading an mp3 file of  $F = 32$  million bits. The server has a transmission rate of  $R_s = 2$  Mbps and you have an access link of  $R_c = 1$  Mbps. What is the time needed to transfer the file?

$$\text{min} = 1 \text{ Mbps} \Rightarrow t = 32 \text{ seconds}$$

## Throughput - Network Scenario



- suppose there are 10 users sharing bandwidth
- per-connection end-end throughput =  $\min(R_s, R_c, R/10)$
- 10 connections fairly share backbone bottleneck link  $R$  bits /sec

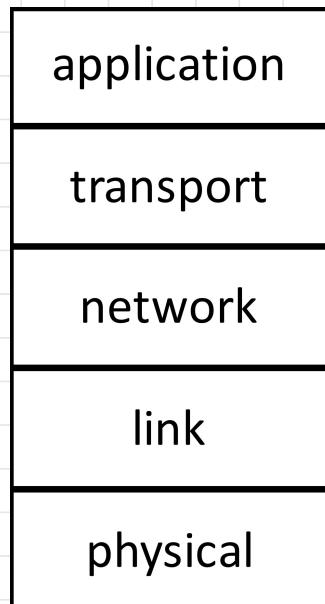
## PROTOCOL LAYERS

- OSI reference model
- network pieces
  - hosts
  - routers
  - links of various media
  - applications
  - protocols
  - hardware, software

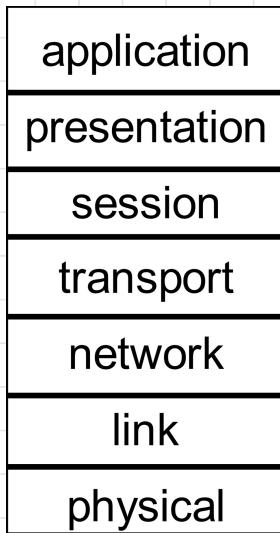
- each layer implements a service
- modularisation: maintenance, updating system

## — internet protocol stack —

1. Application: supports net apps — IMAP, SMTP, HTTP, DNS — message
2. Transport: process-process data transfer (segmentation and reassembly, sockets, connection, flow and error control) — TCP, UDP — segment
3. Network: routing of datagrams from source to destination (addressing, routing) — IP, routing protocols — datagram
4. Link: data transfer between neighbouring network elements (framing, addressing, flow and error control) — ethernet, 802.11 (wifi), PPP — frame
5. Physical: bits on the wire — bits



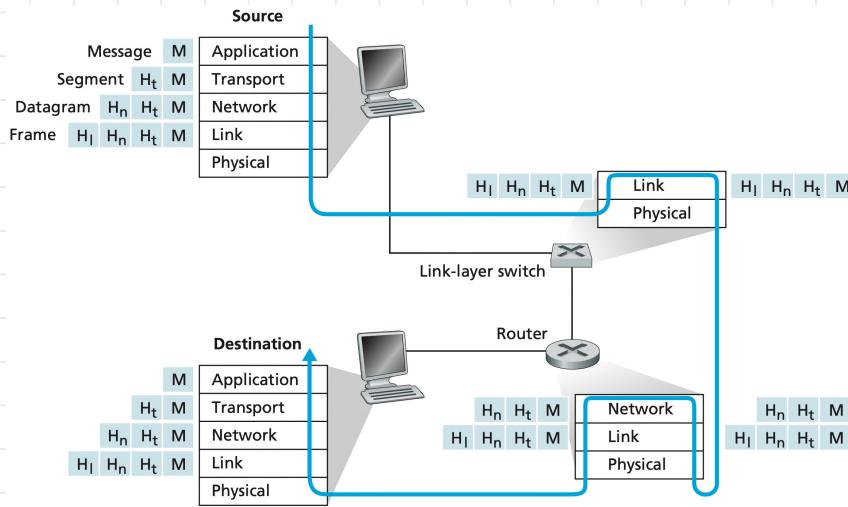
# OSI REFERENCE MODEL



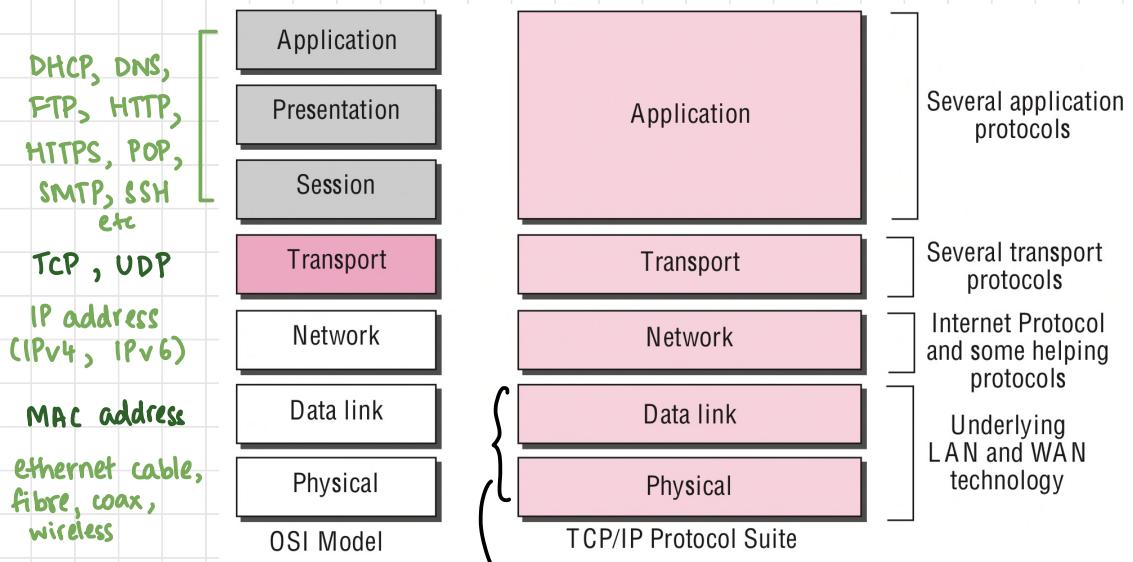
→ allows apps to interpret meaning of data  
cryptography, compression, machine-specific conventions)

→ synchronisation, checkpointing, recovery of data exchange (sessions established)

- internet stack missing these layers
- application layer can implement
- Open System Interconnection - 1970s by ISO

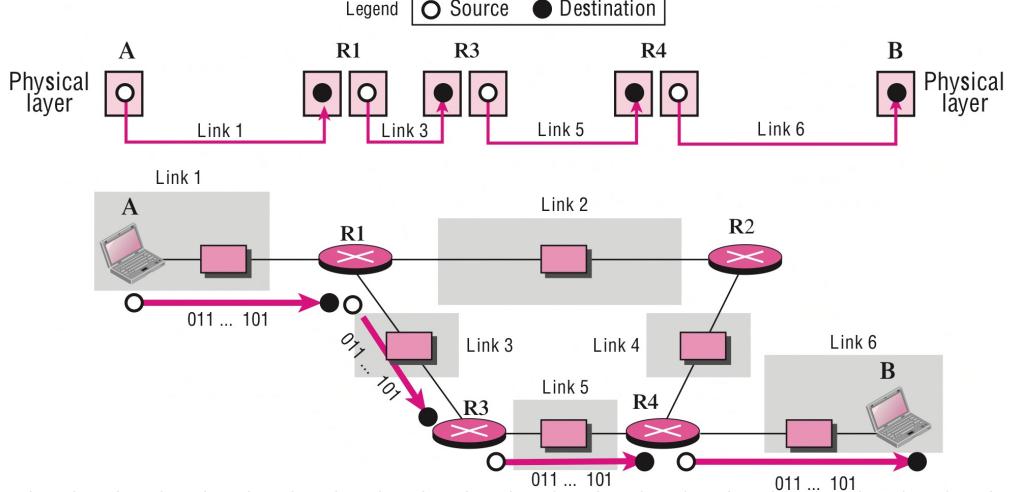


## TCP/IP vs OSI



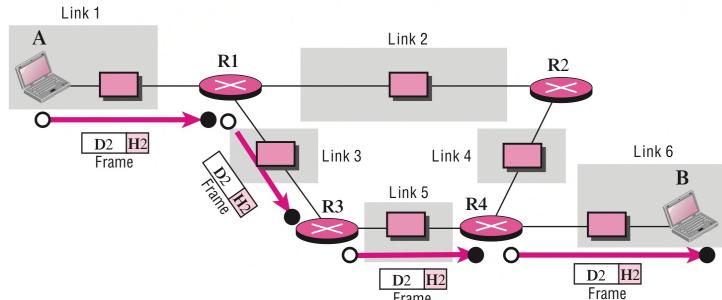
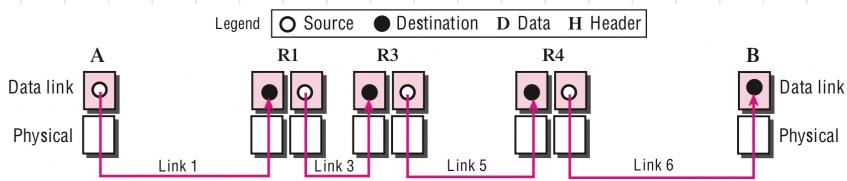
## Physical layer

Communication unit: bit



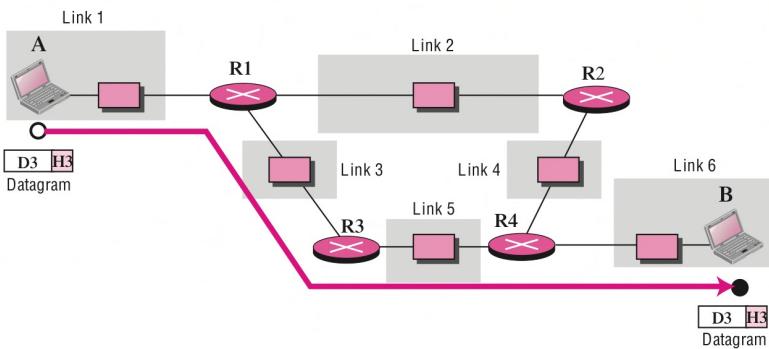
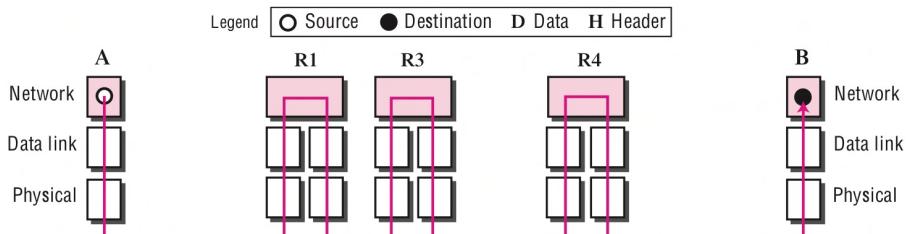
## Link Layer

communication unit: frame



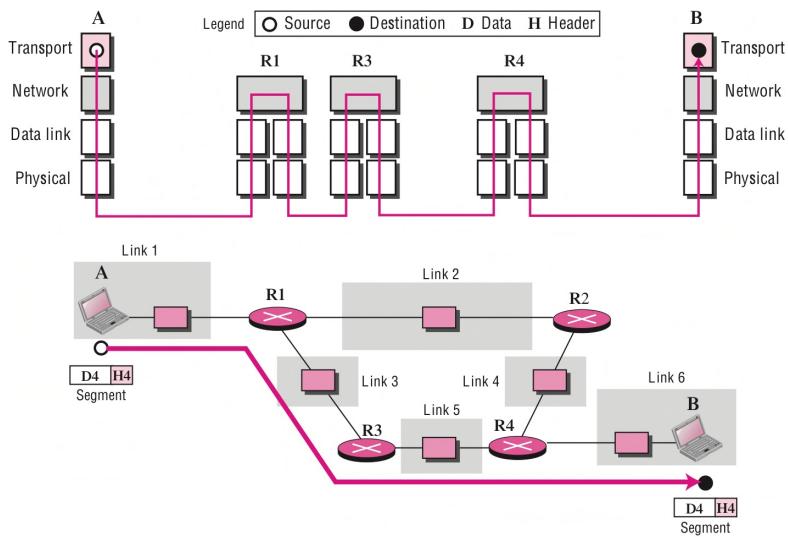
## Network Layer

communication unit: datagram



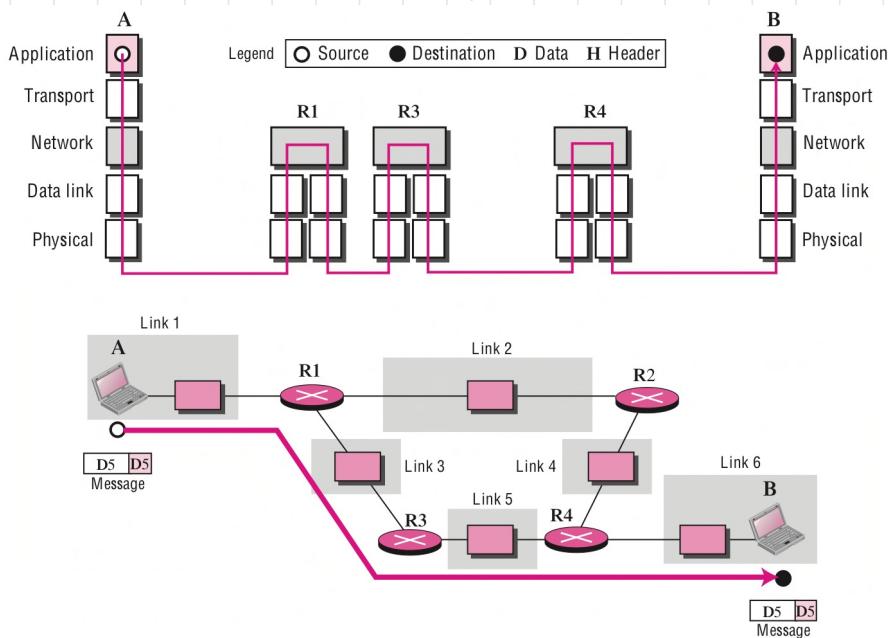
## Transport Layer

communication unit: packet / segment

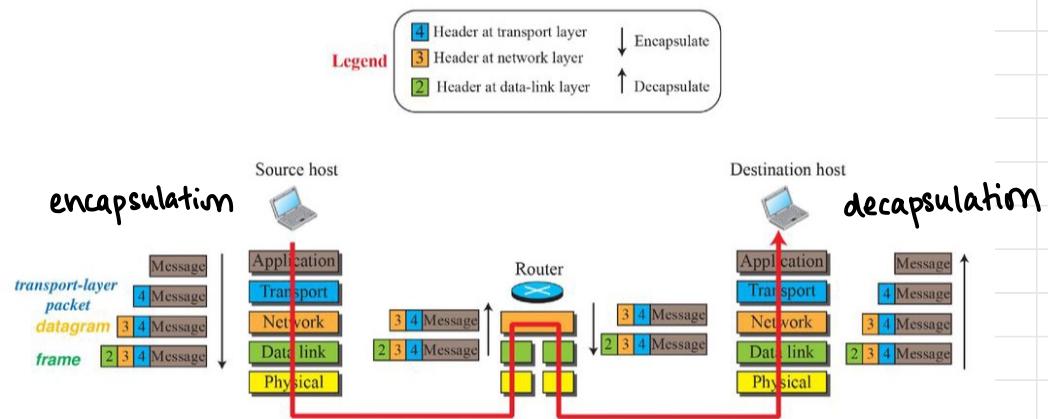


## Application Layer

communication unit: message



## Encapsulation and Decapsulation

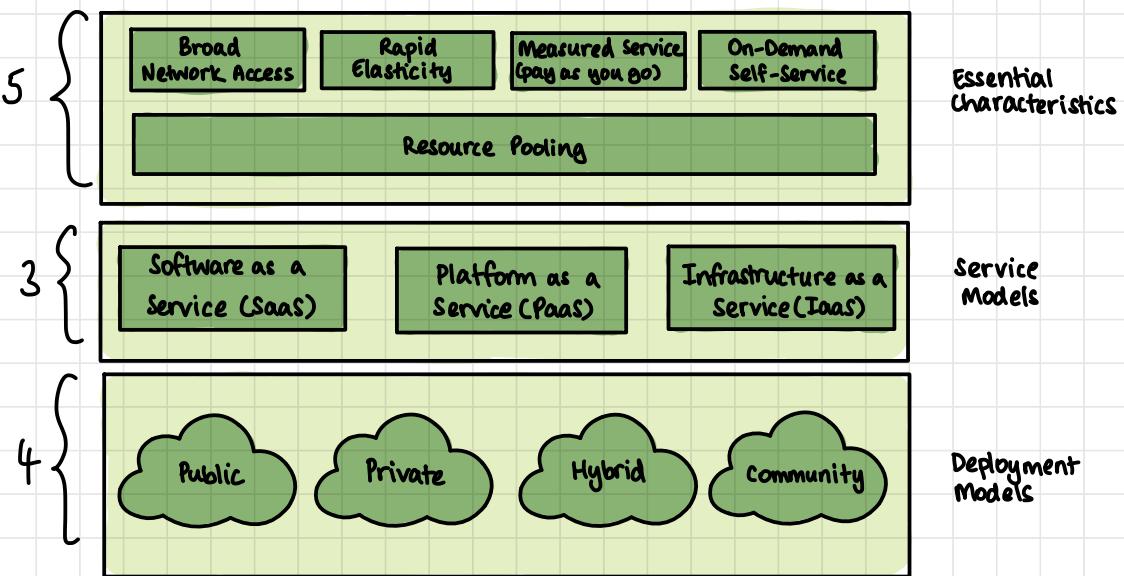


- encapsulation: add headers and go down layers at source
- decapsulation: remove headers and go up layers at destination

## CLOUD COMPUTING

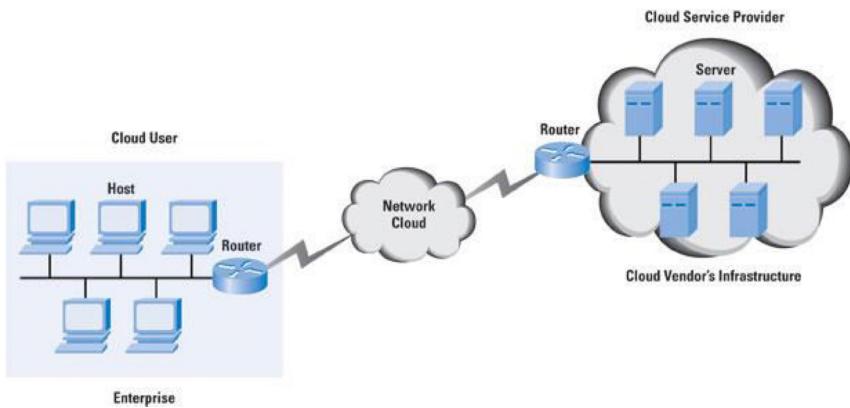
- shared pool of computing resources (networks, servers, storage , apps, services etc.) that are configurable
- on-demand, rapid network access (AWS, Azure etc.)
- cloud model composed of
  - five essential characteristics
  - three service models
  - four deployment models

## Cloud Computing - NIST Visual Model



## Cloud Networking (CSD-CN)

- networking resources (some/all) hosted on cloud
- software-defined cloud networking



## Cloud Enabled Networking

- Network on premises
- Some or all resources used to manage it are in the cloud
- Core net infrastructure (packet forwarding, routing, data) are in-house
- Network management, monitoring, maintenance and security services done through cloud

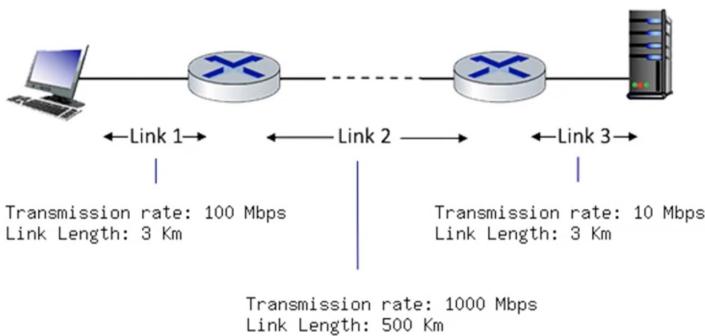
## Cloud-Based Networking

- entire network in the cloud
- network management and physical hardware

## exercises

### Interactive Exercise -1

Consider the figure below, with three links, each with the specified transmission rate and link length.



Find the end-end delay (ignore queuing and processing delays) from when the host begins transmitting the first bit of a packet to the time when the last bit of that packet is received at the server.

The speed of light propagation delay on each link is  $3 \times 10^8 \text{ m s}^{-1}$ .

Note that the transmission rates are in Mbps and link distances are in km. Assume a packet length of 8000 bits. Give your answer in ms.

$$\text{transmission delay } 1 = \frac{8000}{100 \times 10^6} = 8 \times 10^{-5} \text{ s}$$

$$\text{propagation delay } 1 = \frac{3000}{3 \times 10^8} = 10^{-5} \text{ s}$$

$$\text{transmission delay } 2 = \frac{8000}{1000 \times 10^6} = 8 \times 10^{-6} \text{ s}$$

$$\text{propagation delay } 2 = \frac{500 \times 1000}{3 \times 10^8} = \frac{1}{600} \text{ s}$$

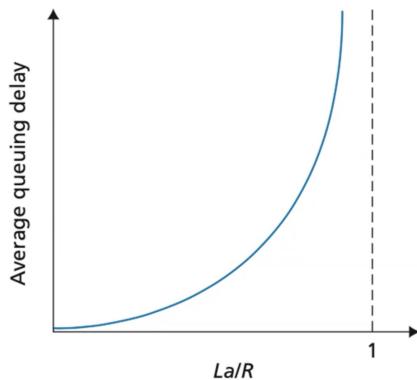
$$\text{transmission delay } 3 = \frac{8000}{10 \times 10^6} = 8 \times 10^{-4} \text{ s}$$

$$\text{propagation delay } 3 = \frac{3000}{3 \times 10^8} = 10^{-5} \text{ s}$$

$$\text{total end-end delay} = 2.57 \text{ ms}$$

## Interactive Exercise -2

Consider the queueing delay in a router buffer.



Assume:

- constant transmission rate  $R = 1800000$
- constant packet length  $L = 6700$  bits
- average rate of packets/sec =  $a$
- traffic intensity  $I = La/R$
- queueing delay =  $I \left( \frac{L}{R} \right) (1-I)$  for  $I < 1$

1. In practice, does queueing delay tend to vary a lot?
2. If  $a=30$ , what is queueing delay?
3. If  $a=76$ , what is queueing delay?
4. Assuming router's buffer infinite,  $qd = 0.8647$  ms and 1762 packets arrive. How many packets will be in the buffer 1 second later?
5. If buffer has max. size of 956 packets, how many packets would be dropped upon arrival from prev question?

1. Yes. Formulas are an estimate.

$$2. I = \frac{6700 \times 30}{1.8 \times 10^6} = \frac{67}{600}$$

$$d = I \left( \frac{L}{R} \right) (1 - I) = 3.72 \text{ ms}$$

$$3. I = \frac{6700 \times 76}{1.8 \times 10^6} = \frac{1273}{4500}$$

$$d = 0.755 \text{ ms}$$

$$4. \text{ packets left} = 1762 - \left\lfloor \frac{1}{d} \right\rfloor = 606 \text{ packets}$$

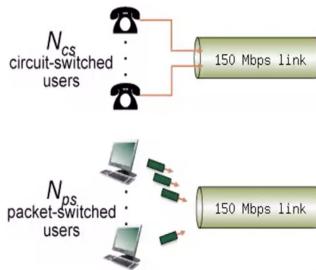
$$5. 1762 - 956 = 806 \text{ dropped}$$

## Interactive Exercise - 3

### Quantitative comparison of Packet Switching and Circuit Switching.

Consider the two scenarios below:

1. A circuit-switching scenario in which  $N_{cs}$  users, each requiring a bandwidth of 10 Mbps must share a link capacity 150 Mbps.
2. A packet-switching scenario with  $N_{ps}$  users sharing a 150 Mbps link where each user requires 10 Mbps of bandwidth while transmitting but only needs to transmit 30% of the time



Answer the following:

1. When circuit-switching is used, what is the maximum number of circuit-switched users that can be supported? Explain your answer.
2. For rest of the questions, suppose packet switching is used. Suppose there are 29 packet-switching users (i.e.,  $N_{ps} = 29$ ). Can this many users be supported under circuit-switching? Explain.
3. What is the probability that a given (*specific*) user is transmitting, and the remaining users are not transmitting?
4. What is the probability that one user (*any one among the 29 users*) is transmitting, and the remaining users are not transmitting? When one user is transmitting, what fraction of the link capacity will be used by this user?
5. What is the probability that any 15 users (of the total 29 users) are transmitting and the remaining users are not transmitting? (Hint: you will need to use the binomial distribution [1, 2]).
6. What is the probability that *more* than 15 users are transmitting? Comment on what this implies about the number of users supportable under circuit-switching and packet-switching.

$$1. \frac{150}{10} = 15 \text{ users (all users at all times)}$$

2. No.

3. Probability of transmission at any time = 30%.

$$P = (0.3)^1 (0.7)^{28} = 0.0014\%$$

$$4. {}^{29}C_1 (0.3)^1 (0.7)^{28} = 4 \times 10^{-4} = 0.04\%$$

$$\text{fraction} = \frac{10}{150} = 0.067$$

$$5. {}^{29}C_{15} (0.3)^{15} (0.7)^{14} = 7.55 \times 10^{-3} = 0.755\%$$

$$6. N_{pe} = 29.$$

$$\sum_{i=0}^{15} {}^{29}C_i (0.3)^i (0.7)^{29-i} = 0.9959$$

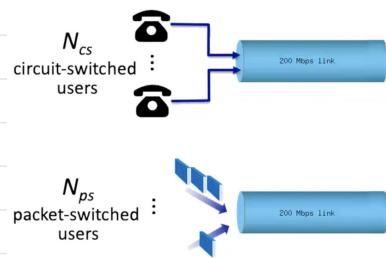
or 0.41% chance of more than 15 users at once

## Interactive Exercise - 4

### Quantitative comparison of Packet Switching and Circuit Switching.

A circuit-switching scenario in which  $N_{cs}$  users, each requiring a bandwidth of 25 Mbps, must share a link of capacity 200 Mbps.

A packet-switching scenario with  $N_{ps}$  users sharing a 150 Mbps link, where each user again requires 25 Mbps when transmitting, but only needs to transmit 20 percent of the time.



### Answer the following

1. When circuit switching is used, what is the maximum number of users that can be supported?
2. Suppose packet switching is used. If there are 15 packet-switching users, can this many users be supported under circuit-switching? Yes or No.
3. Suppose packet-switching is used. What is the probability that a given (specific) user is transmitting, and the remaining users are not transmitting?
4. Suppose packet-switching is used. What is the probability that one user (*any* one among the 15 users) is transmitting, and the remaining users are not transmitting?
5. When one user is transmitting, what fraction of the link capacity will be used by this user? Write your answer as a decimal.
6. What is the probability that any 10 users (of the total 15 users) are transmitting and the remaining users are not transmitting?
7. What is the probability that *more* than 8 users are transmitting?

1.  $\frac{200}{25} = 8 \text{ users}$

2. No.

$$3. (0.2)^1 (0.8)^{14} = 0.88\%$$

$$4. {}^{15}C_1 (0.2)^1 (0.8)^{14} = 13.19\%$$

$$5. \frac{25}{200} = 0.125 = 12.5\%$$

$$6. {}^{15}C_{10} (0.2)^{10} (0.8)^5 = 0.01\%$$

$$7. 1 - \sum_{i=0}^8 {}^{15}C_i (0.2)^i (0.8)^{15-i} = 1 - 0.999 = 0.001 = 0.1\%$$

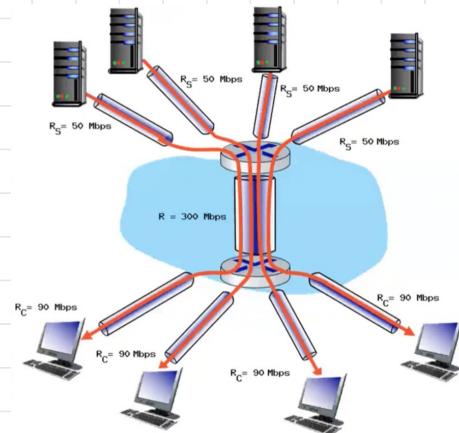
### Interactive Exercise - 5

Consider the scenario shown below, with four different servers connected to four different clients over four three-hop paths.

The four pairs share a common middle hop with a transmission capacity of  $R = 300$  Mbps.

The four links from the servers to the shared link have a transmission capacity of  $R_S = 50$  Mbps.

Each of the four links from the shared middle link to a client has a transmission capacity of  $R_C = 90$  Mbps.



- What is the maximum achievable end-end throughput (in Mbps) for each of four client-to-server pairs, assuming that the middle link is fairly shared (divides its transmission rate equally)?
- Which link is the bottleneck link? Format as  $R_c$ ,  $R_s$ , or  $R$
- Assuming that the servers are sending at the maximum rate possible, what are the link utilizations for the server links ( $R_s$ )? Answer as a decimal
- Assuming that the servers are sending at the maximum rate possible, what are the link utilizations for the client links ( $R_c$ )? Answer as a decimal
- Assuming that the servers are sending at the maximum rate possible, what is the link utilizations for the shared link ( $R$ )? Answer as a decimal

$$1. \frac{300}{4} = 75 \text{ Mbps}$$

$$\max = \min(50, 75, 90) = 50 \text{ Mbps}$$

$$2. \text{bottleneck} = \min(50, 75, 90) = 50 \text{ Mbps} \\ = R_s$$

$$3. \text{Server utilisation} = \frac{R_{\text{bottleneck}}}{R_s} = \frac{50}{50} = 1$$

$$4. = \frac{50}{90} = 0.56$$

$$5. = \frac{50}{75} = \frac{2}{3} = 0.67$$