COMPUTER NETWORKS

UNIT-1

introduction to computer networks

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COMPUTER NETWORKS

I N T R O

- How computers share data and communicate
- Internet

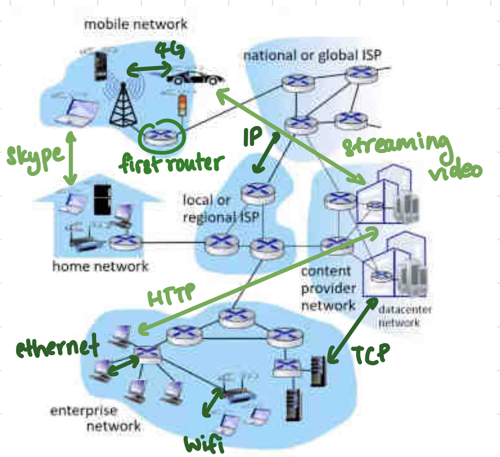
Hardware & Software

- 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

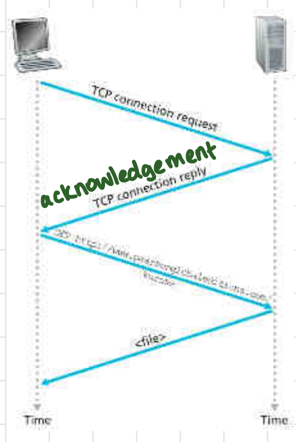


Internet Standards

- 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

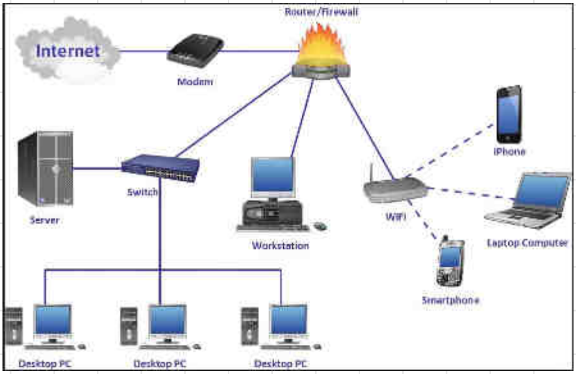


Network Structure

1) Network edge
   hosts: clients and servers, servers in data centres

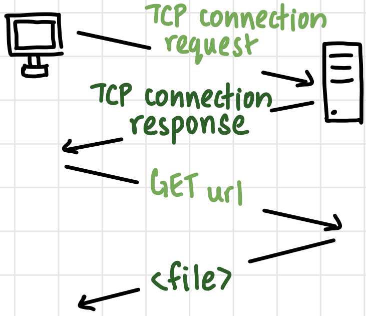
2) Access network, physical media → connecting edge to first router
   wired, wireless communication links

3) Network core
   interconnected routers, network of networks (ISP)



Network Protocols

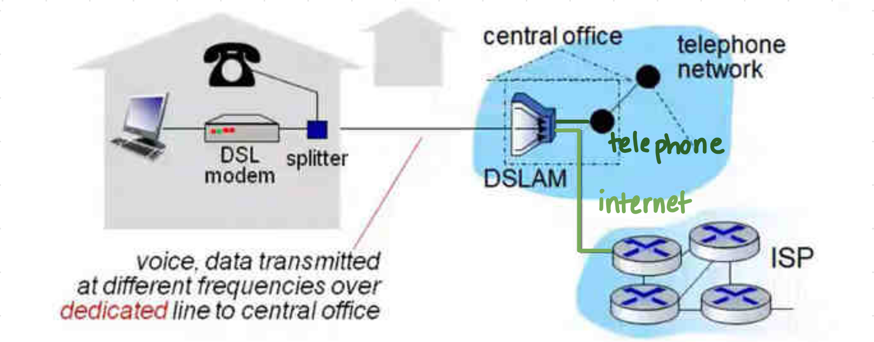
- all communication activity over the internet governed by protocols
- define format, order of messages sent and received, actions taken



Access Networks

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

(a) Digital Subscriber Line

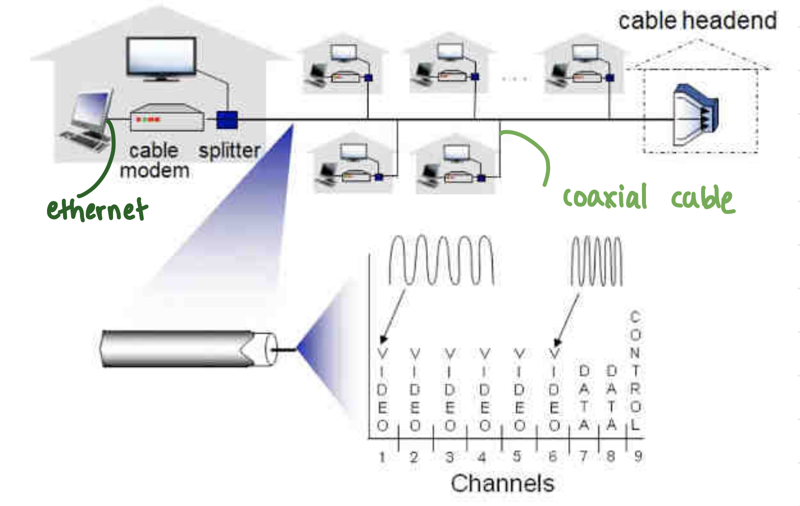


- use existing phone line to central office DSLAM (broadband connection)
  DSL access multiplexer
  - data: over DSL phone line to internet
  - voice: over DSL phone line to telephone net
- High speed (download) downstream channel (50 kHz – 1 MHz)
- Medium speed (upload) upstream channel (4 kHz – 50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

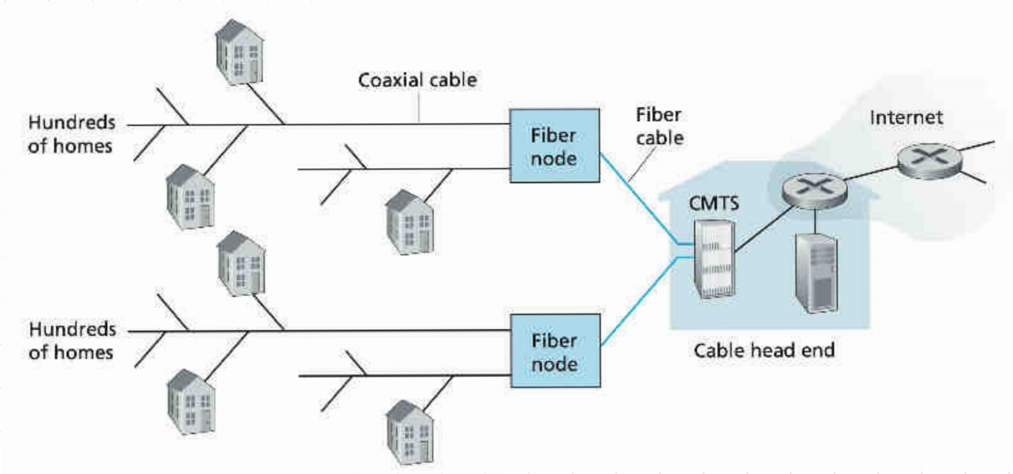
DSL Standard

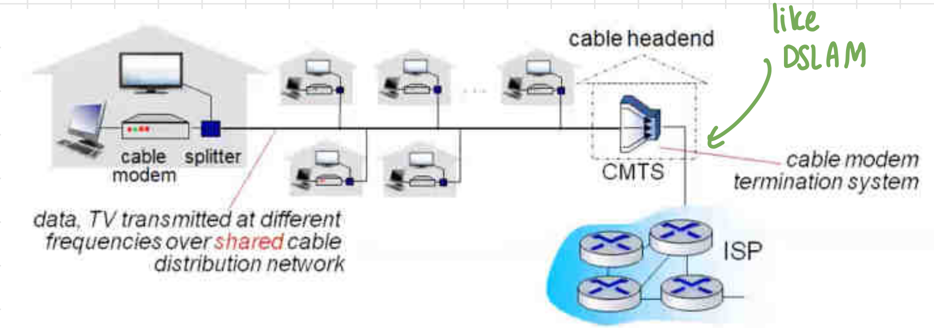
- 24-52 Mbps - downstream transmission rate
- 3.5 - 16 Mbps - upstream transmission rate
- Asymmetric access

(b) Cable-based Access



- use existing cable TV infrastructure
- DOCS (Data Over Cable Service) specification
  - downstream: 40 Mbps – 1.2 Gbps } more than
  - upstream: 30 Mbps – 100 Mbps } DSL
- Frequency Division Multiplexing (FDM): different channels transmitted over different frequency bands
- Amplitude (ADM) and Time (TDM) 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

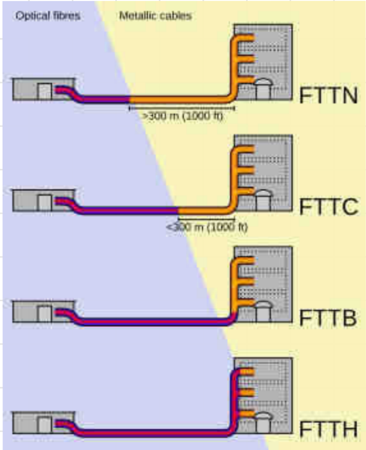




- Network of cable, fibre attaches home to ISP router
  - homes share access network to cable headend

(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)



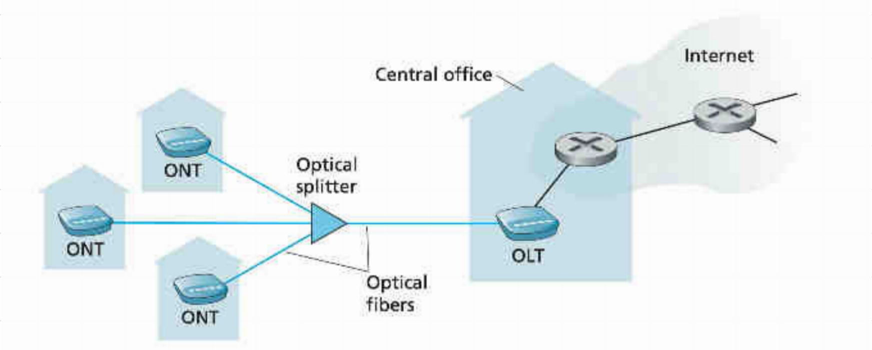
- Direct fibre: one single fibre connects central office to home (in other words, fibre from CO split into customer-specific fibres near homes)

- Two architectures: Active Optical Networks (AONs) and Passive Optical Networks (PONs)

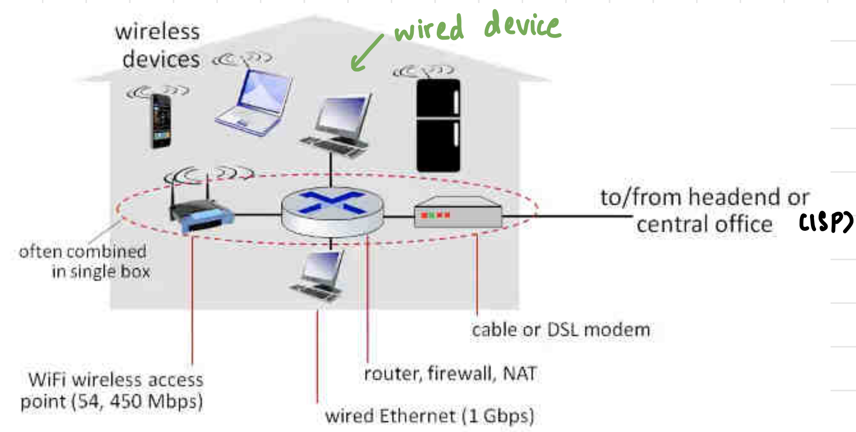
- AON: switched ethernet

- 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 & electrical signals

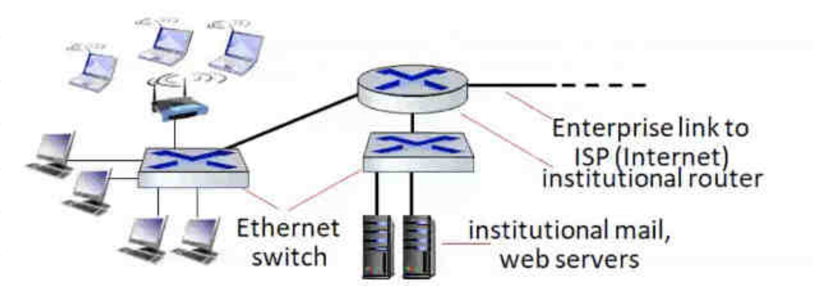


(a) Home Access



- LAN
- wigle.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

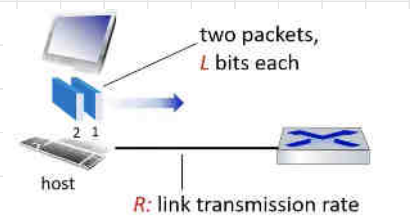
(c) Wireless Access Networks

- 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)



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

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

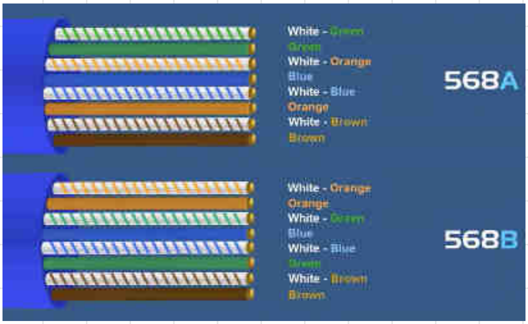
1. Twisted pair (TP)

extra foil shield: industrial

unshielded TP: most common

- 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, commom — for dissimilar devices)
- Crossover cable: both ends wired using different standards (used to connect similar devices — 2 computers, hubs, switches)



standards 568A & 568B

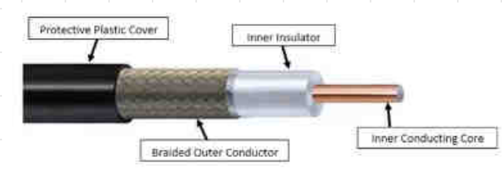
- category : 3,5,5e,6,6a,7 — tightness of twist, maximum transmission rate they can handle without crosstalk (interference)

- 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

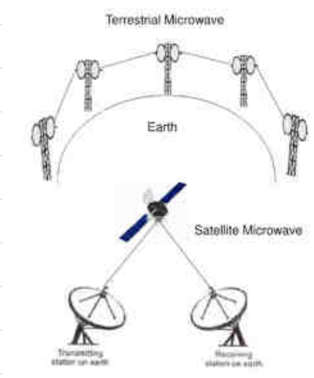
- signal carried in EM spectrum
- broadcast and half duplex
  - simplex: one-way telegram
  - half duplex: one at a time walkie-talkie
  - full duplex: two-way mobile phone
- obstruction, reflection, interference

(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



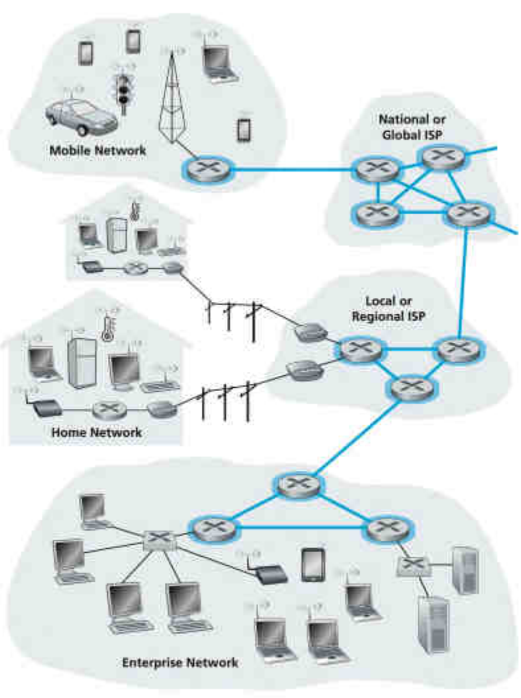
Network Core

- mesh of interconnected routers, packet-switchers and communication links

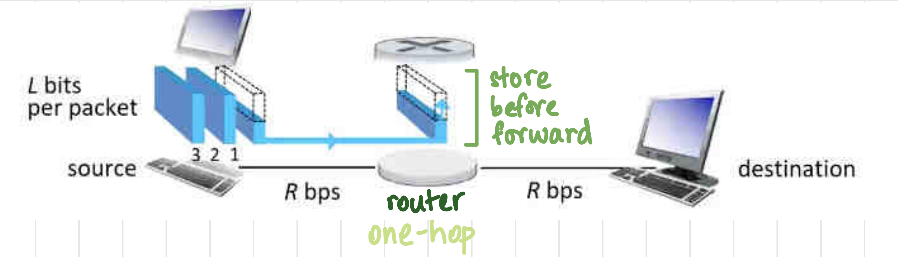
- packet-switching
  - hosts break messages into packets
  - packets forwarded from one router to the next across links
  - each packet transmitted at full link capacity

- Packets transmitted over communication links at full transmission rate of link

- L bits over link with TR R bits/sec, time to transmit packet is L/R seconds (L: packet size)



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)

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

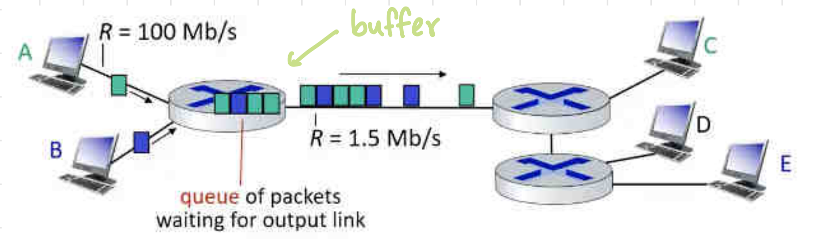
P packets, N links, N-1 routers (assuming zero propagation delay)

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

Q: If L = 10 Kbits/packet, R = 100 Mbps, one-hop transmission delay = ?

$$t_{td} = \frac{10 \times 1024}{100 \times 1024 \times 1024} = \frac{1}{10240} = 9.77 \times 10^{-5}\ s = 97.7\ \mu s$$

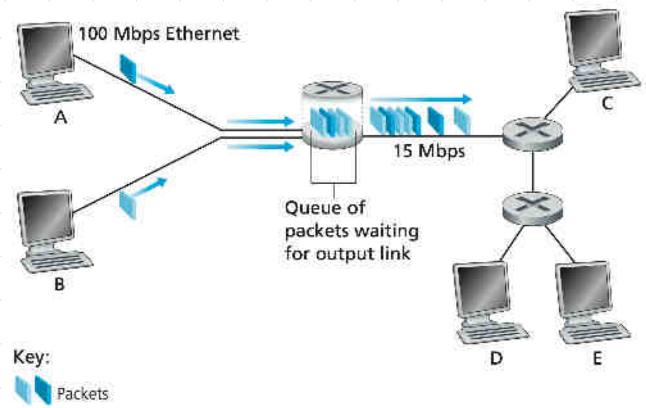
Queuing



Packet Queuing and Loss

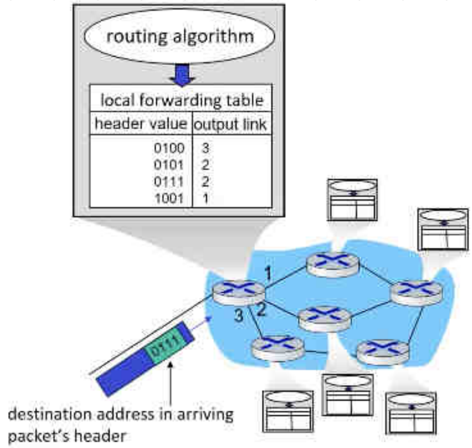
if arrival rate (in bps) to link exceeds transmission rate (in bps) of link for a period of time

- 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



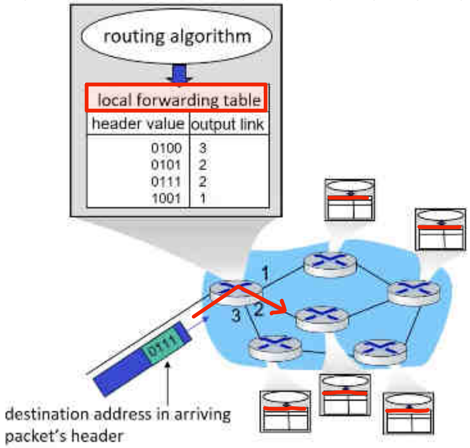
TWO KEY NETWORK CORE FUNCTIONS

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



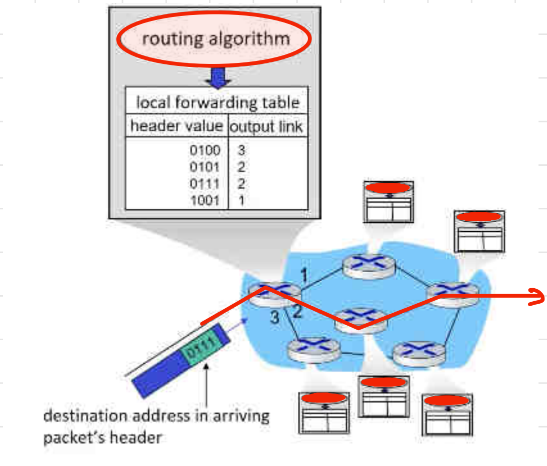
1) Forwarding

- 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

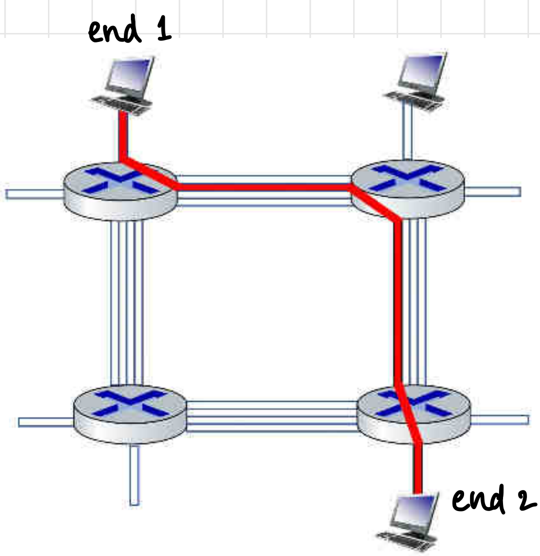


2) Routing

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



Circuit switching



- resources from one end to another allocated to a 'call' (eg: telephone)

- dedicate lines / resources; no sharing

- segments / lines idle when not used for call

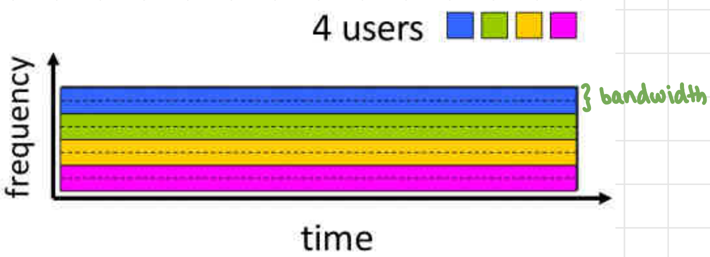
- traditional telephone networks

- reserved resources for a duration

Multiplexing in Circuit Switched Networks

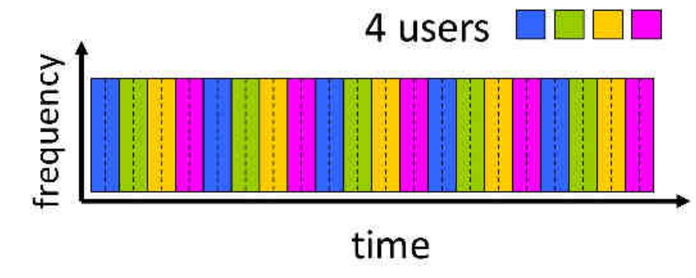
1) Frequency Division Multiplexing (FDM)

- 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)

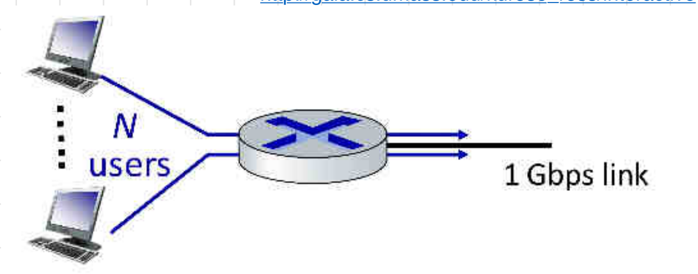
- each call allocated periodic slots
- can transmit at maximum rate of wide frequency band only during its time slot



PACKET SWITCHING vs CIRCUIT SWITCHING

- packet switching allows for more users

http://gaia.cs.umass.edu/kurose_ross/interactive



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

- no. of users in circuit switching: 10 users $\left(\frac{1000}{100}\right)$
- 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

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

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

time to establish connection = 0.5 sec

∴ total time = 10.5 seconds

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

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

∴ time taken = 5 seconds

∴ total time = 5.5 seconds

Packet Switching

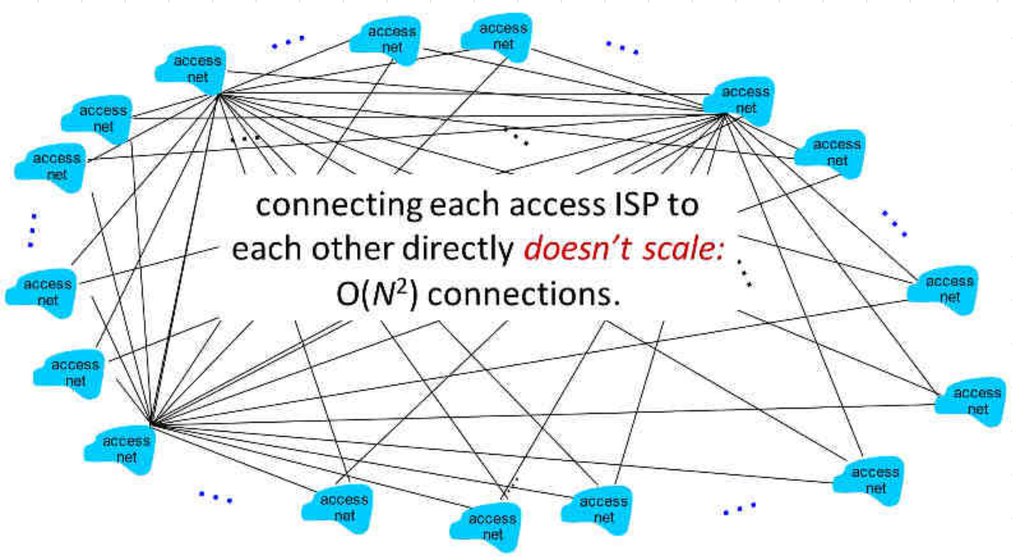
- good for bursty data (resource sharing, no call setup)
- congestion: buffer overflow causes delay and loss
- for audio/video, bandwidth guarantees used
- on-demand allocation vs reserved resources (circuit)

Packet Switching	Circuit Switching
Connectionless	Connection oriented
Designed for data	Designed for voice
Flexible	Inflexible
Out of order, assembled at the dest	Message received in same order
Forward, Store & Fwd	FDM & TDM
Network layer	Physical layer
Bandwidth is saved (dynamic)	Bandwidth is wasted (fixed)
Transmission of data – Source, routers	Transmission of data – source
Transmission delay	Call setup delay

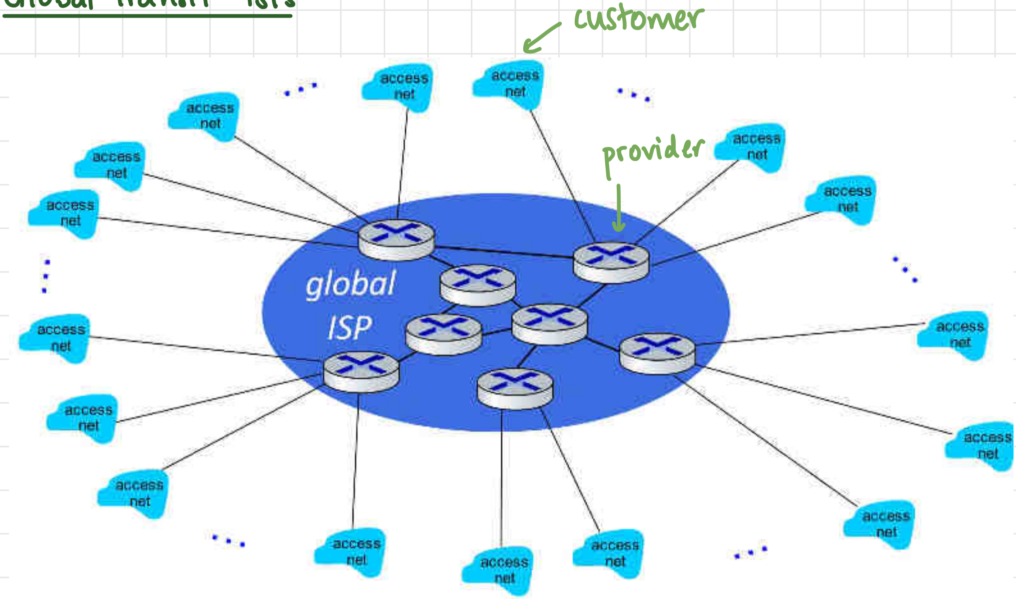
NETWORK OF NETWORKS

- 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

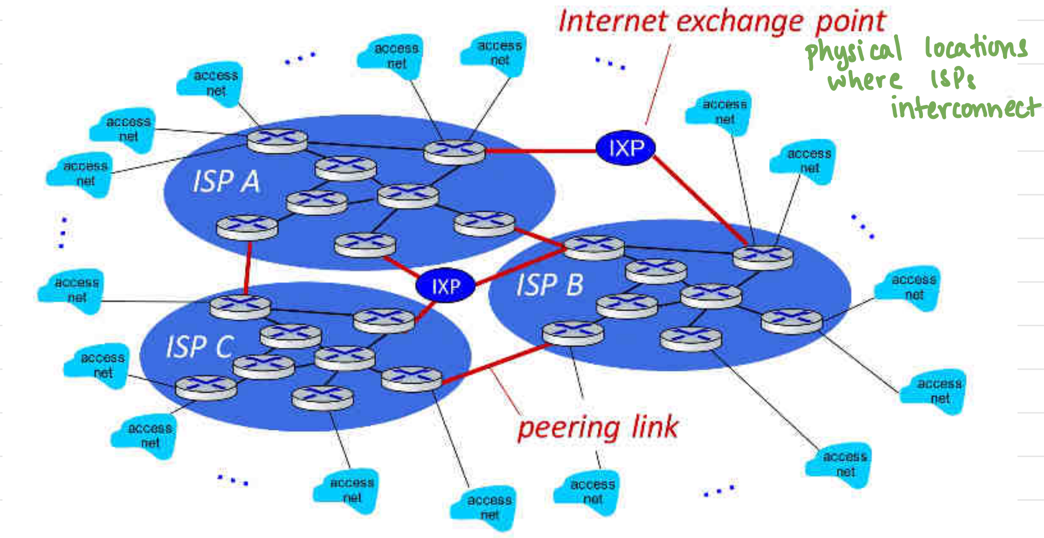
Fully mesh- impossible and wasteful



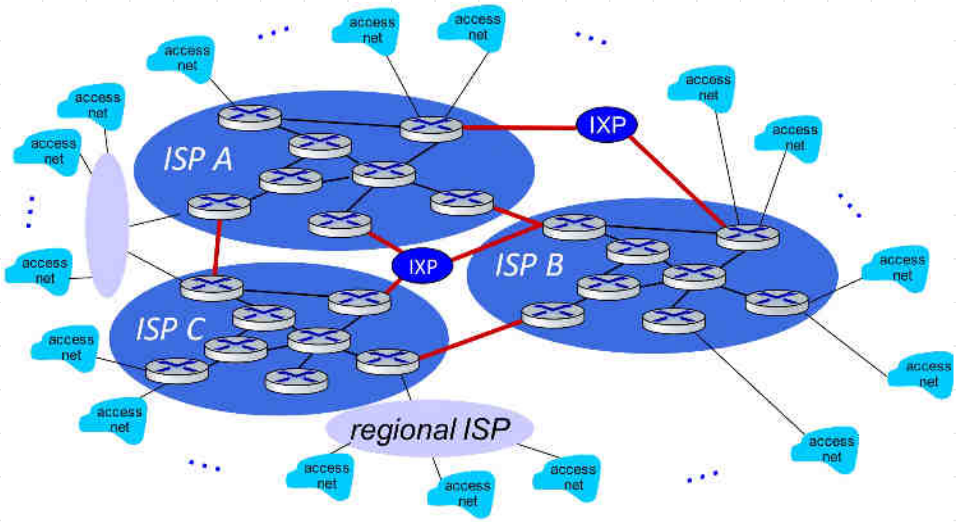
Global transit ISPs



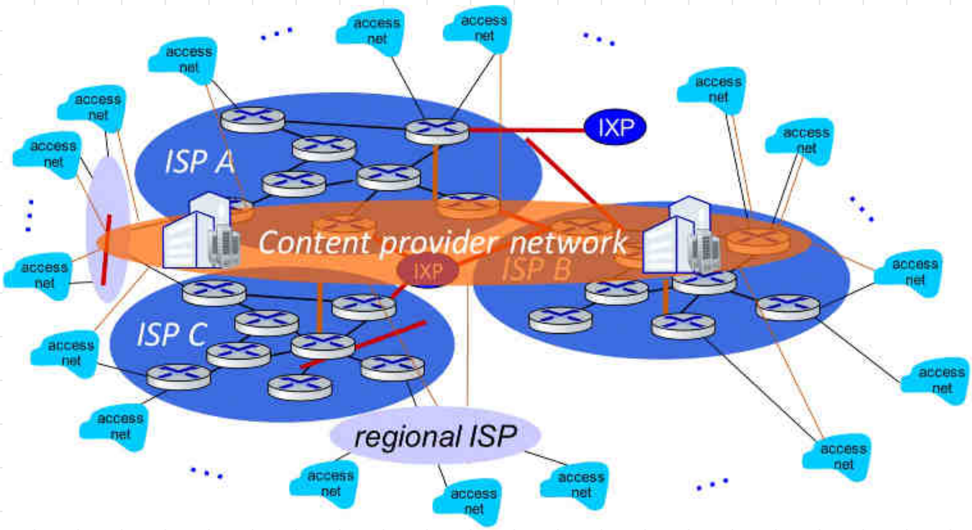
Multi level With IXPs



Regional ISPs

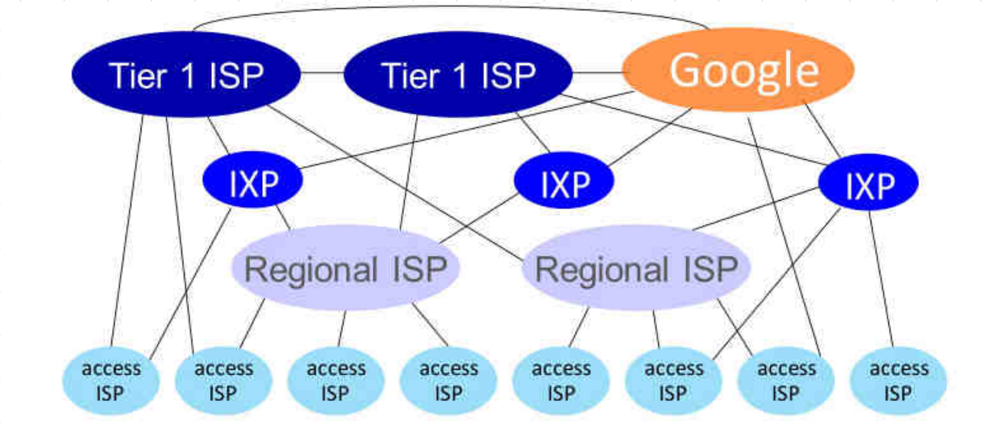


Content Provider Network



- google, own proxy servers

Hierarchy

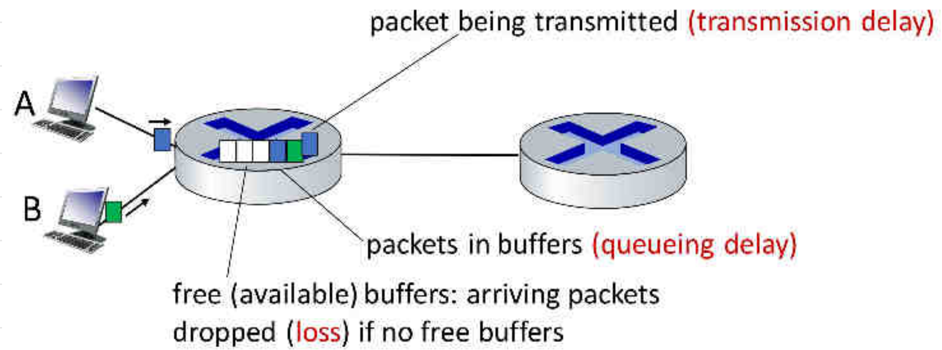


- Tier 1: commercial ISPs (airtel, AT&T, Jio)
- Content Provider Networks: Google, Facebook — pvt networks with their own data centres to the internet

Sprint ISP Network Map 2019

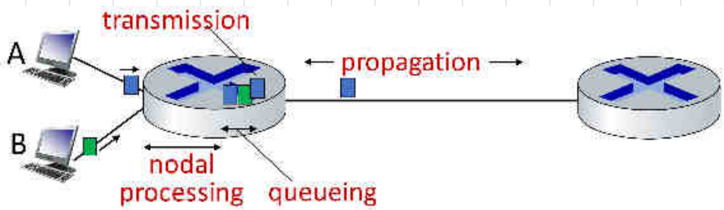
Packet Loss and Delay

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



Total Delay

http://gaia.cs.umass.edu/kurose_ross



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

$d_{prop} = \frac{d}{s}$ ← d: length of physical link; s: prop speed ($\sim 2 \times 10^8 \, ms^{-1}$)

$d_{trans} = \frac{L}{R}$ ← L: no. of bits / packet; R: transmission rate

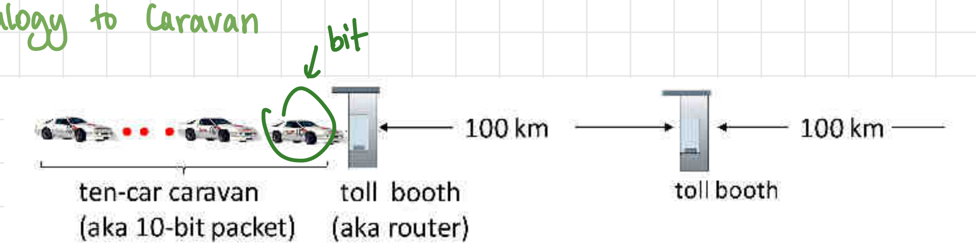
d_{queue} = time waiting in buffer (o/p link) for trans, μs to ms (← congestion)

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

Difference Between d_{trans} and d_{prop}

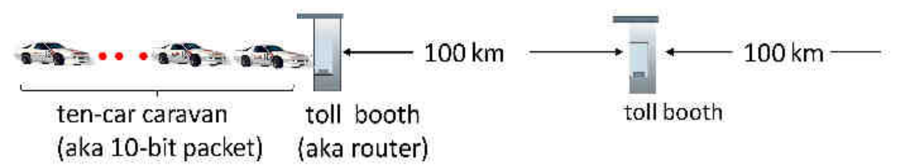
Transmission Delay	Propagation Delay
Time required for the router to push out the packet.	Time it takes a bit to propagate from one router to the next.
A function of the **packet's length** and the **transmission rate** of the link.	A function of the **distance** between the two routers.
$d_{trans} = L/R$	$d_{prop} = d/s$
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 (transmission time)
- time taken to push entire packet/caravan = 12x10 = 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 10th car to get transmitted

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

- time taken for 1st car to reach toll booth #2,

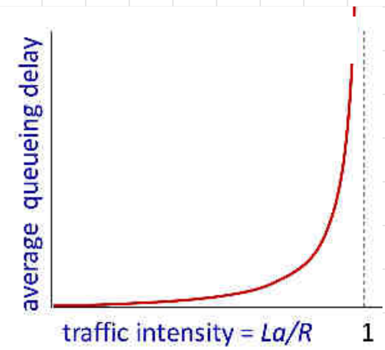
$$1\text{min} + \frac{100 \text{ km}}{1000 \text{ km}} \text{hr} = 1\text{min} + 6\text{min} = 7\text{min}$$

- yes

Queueing Delay

- varies from packet to packet (depends on traffic intensity & queue length at buffer for out link)
- d_{queue} : average, variance, probability that it exceeds a certain value are common statistical measures of d_{queue}
- 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 ≤ 1 : nature of arriving traffic
- La/R ≈ 0 : average queueing delay small
- Assuming infinite queue buffer / capacity

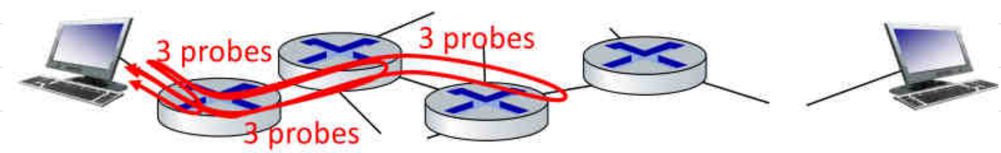


- In reality, queueing delay is not infinite; packets arriving to full queue are dropped and lost (packet loss)
- End-to-end delay $d_{end\text{-}end} = N(d_{proc} + d_{trans} + d_{prop})$ for N-1 routers, N links

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 denstination with time-to-live field value of i)
  - router i will return packets to sender
  - sender measures time interval between transmissim and reply



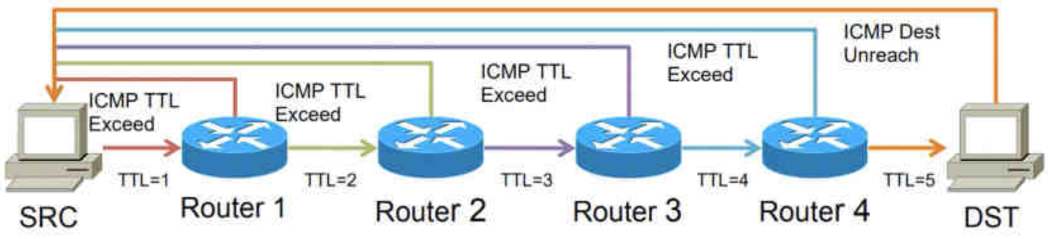
traceroute command (Windows - tracert)

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

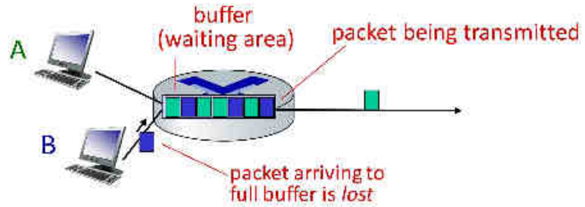
Working of Traceroute



do not always trust traceroute (only 3 packets)

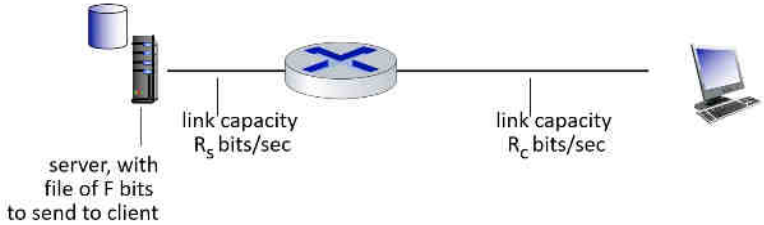
Performance - Packet Loss

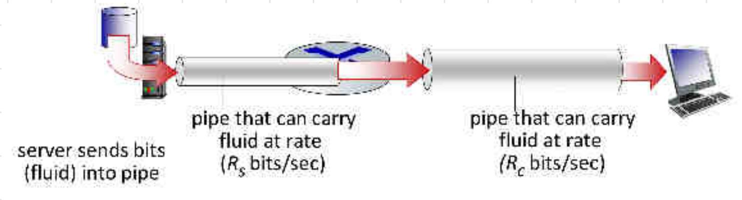
- lost packet may be retransmitted by previous node, source end system or not at all



Performance- Throughput

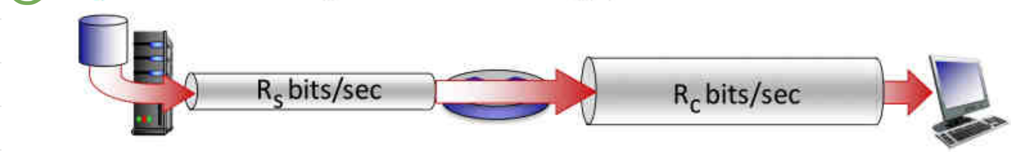
- rate at which data sent from sender to receiver
  - instantaneous
  - average



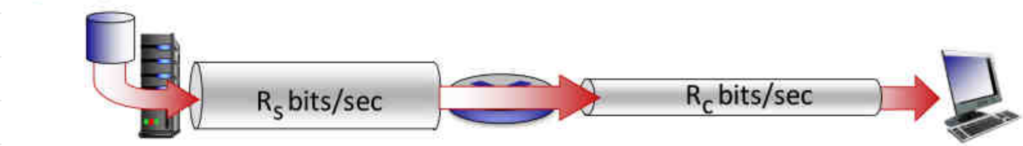


- average: minimum (R_s, R_c)

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



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



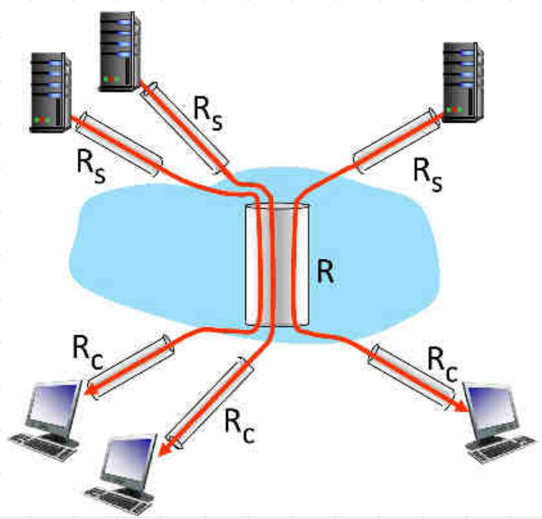
Bottleneck Link

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?

min = 1 Mbps ⇒ $t = 32$ 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

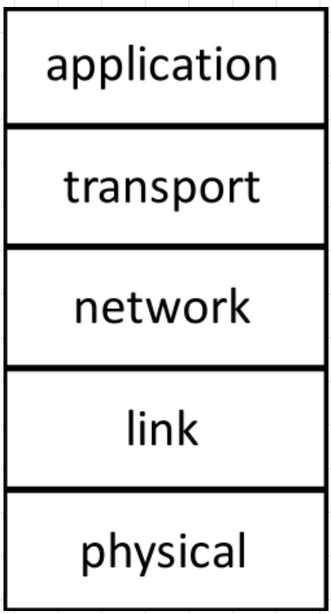
PROTOCOL LAYERS

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

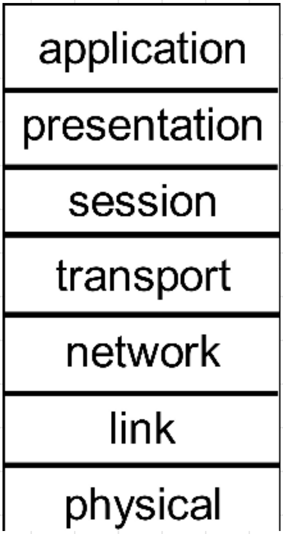
- each layer implements a service
- modularisation : maintenance, updating system

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



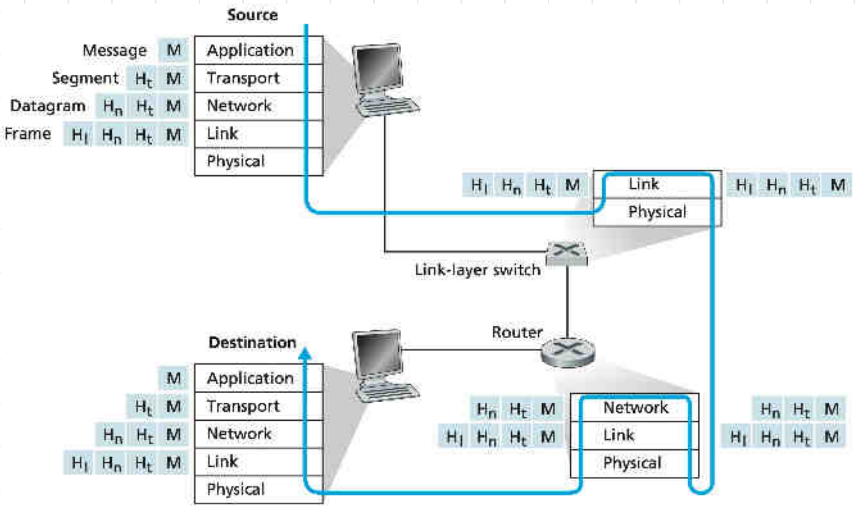
OSI REFERENCE MODEL



presentation → allows apps to interpret meaning of data (encryption, compression, machine-specific conventions)

session → 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

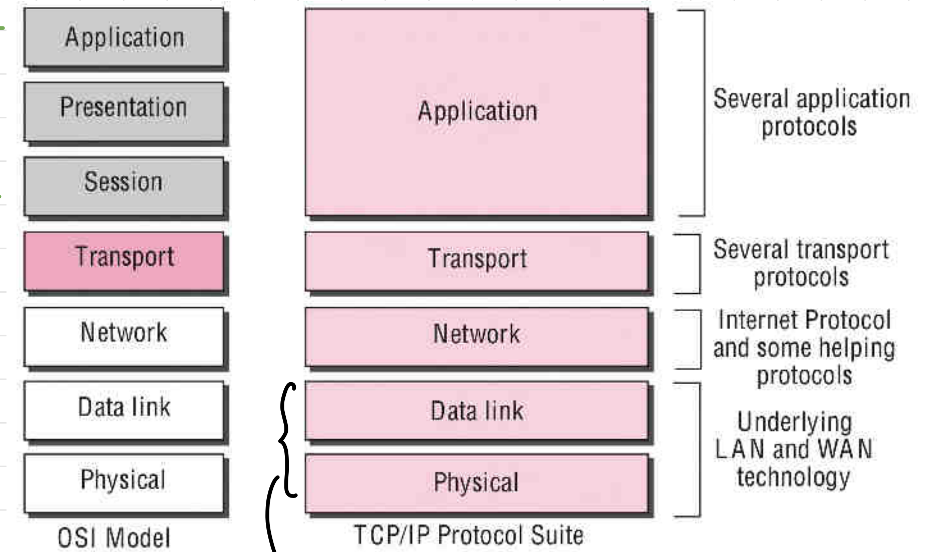
DHCP, DNS, FTP, HTTP, HTTPS, POP, SMTP, SSH etc

TCP, UDP

IP address (IPv4, IPv6)

MAC address

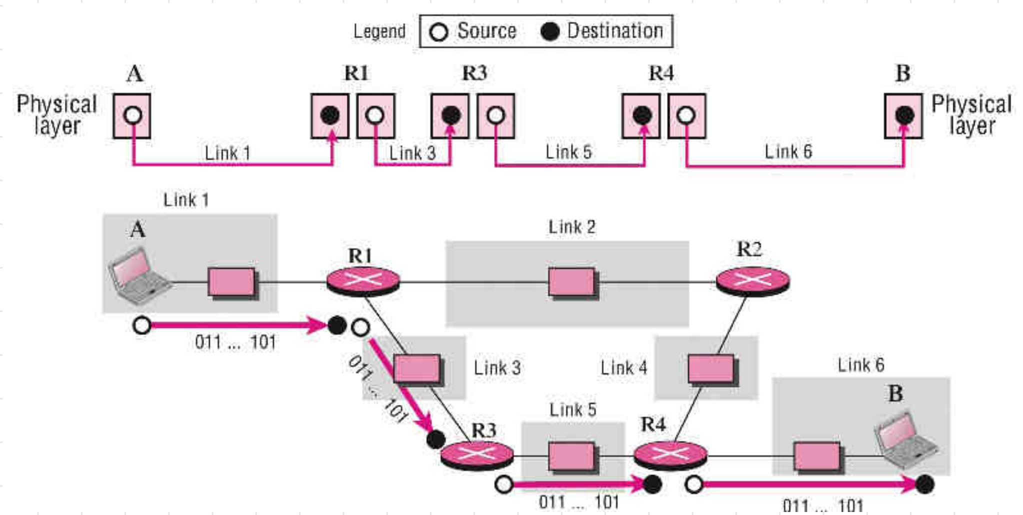
ethernet cable, fibre, coax, wireless



network access

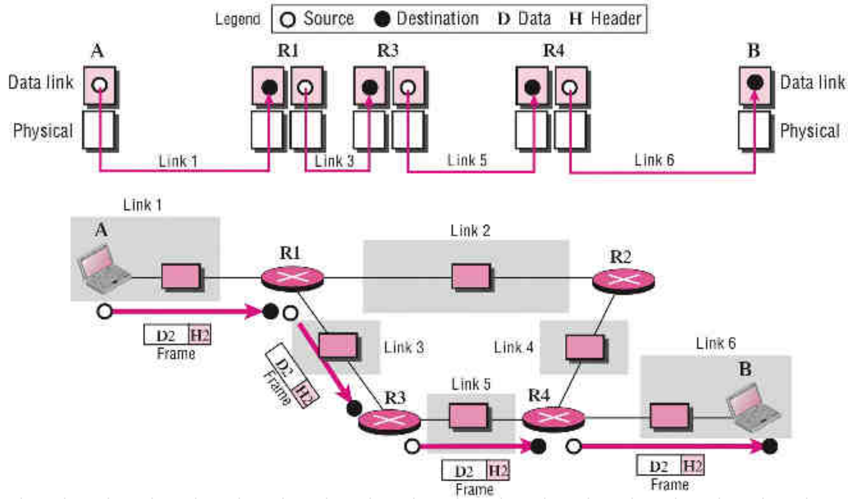
Physical Layer

communication unit: bit



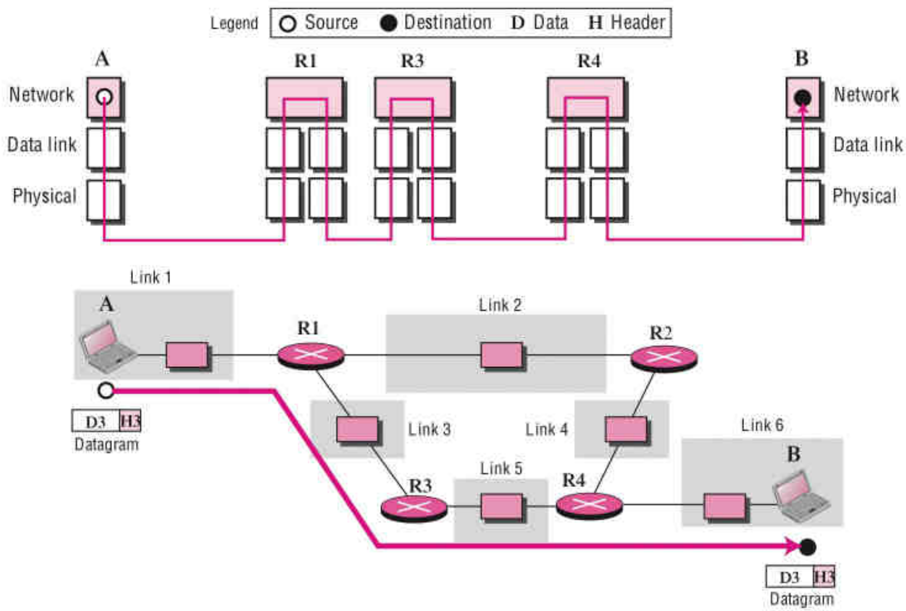
Link Layer

communication unit: frame



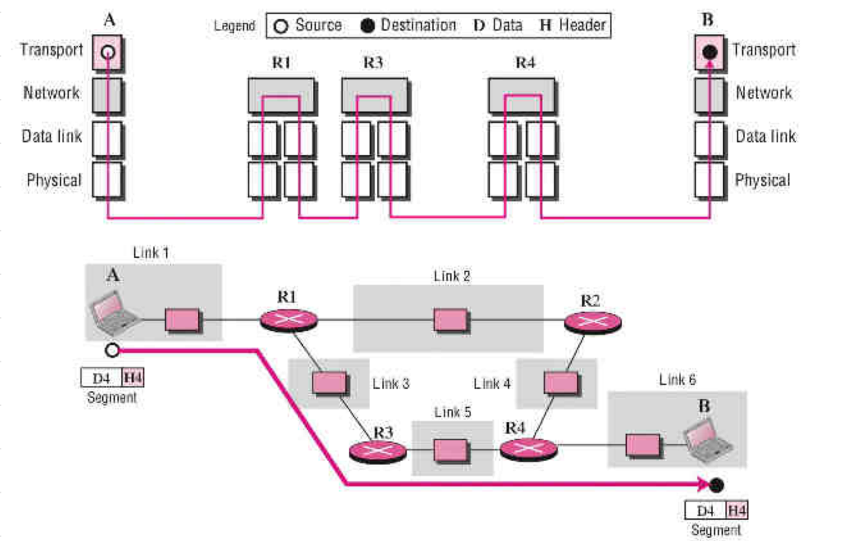
Network Layer

communication unit: datagram



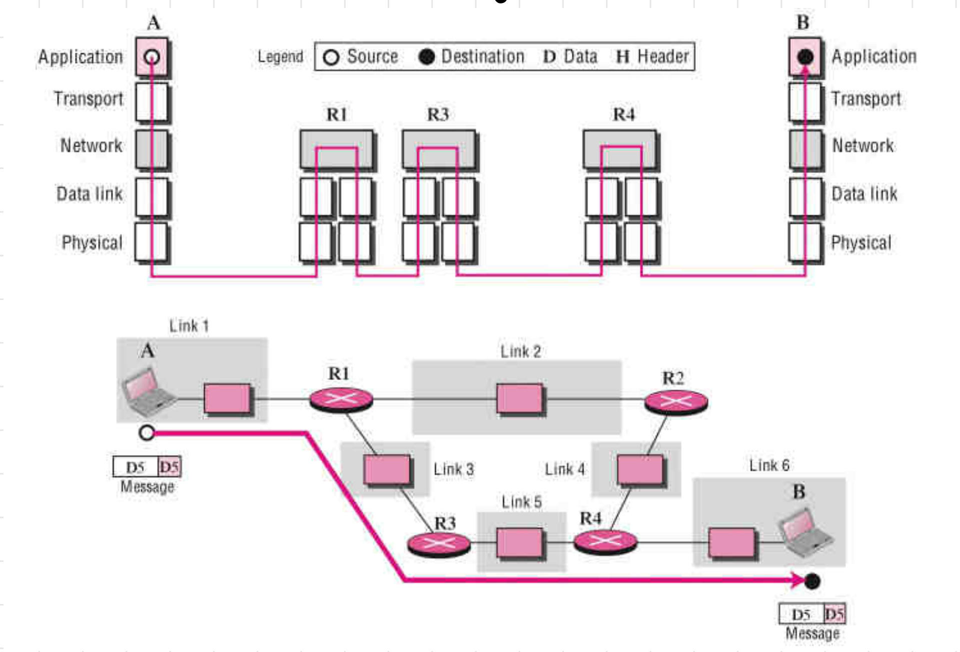
Transport Layer

communication unit: packet / segment

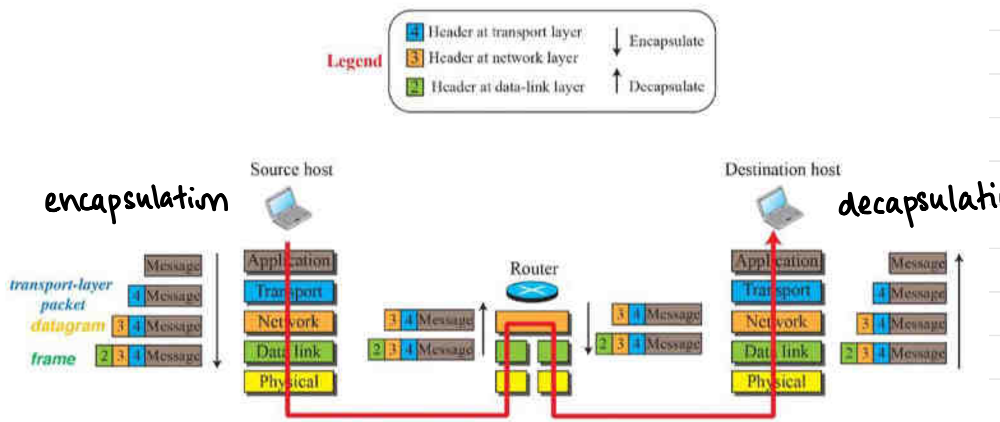


Application Layer

communication unit: message



Encapsulation and Decapsulation



- encapsulation: add headers and go down layers at source

- decapsulation: remove headers and go up layers at destination

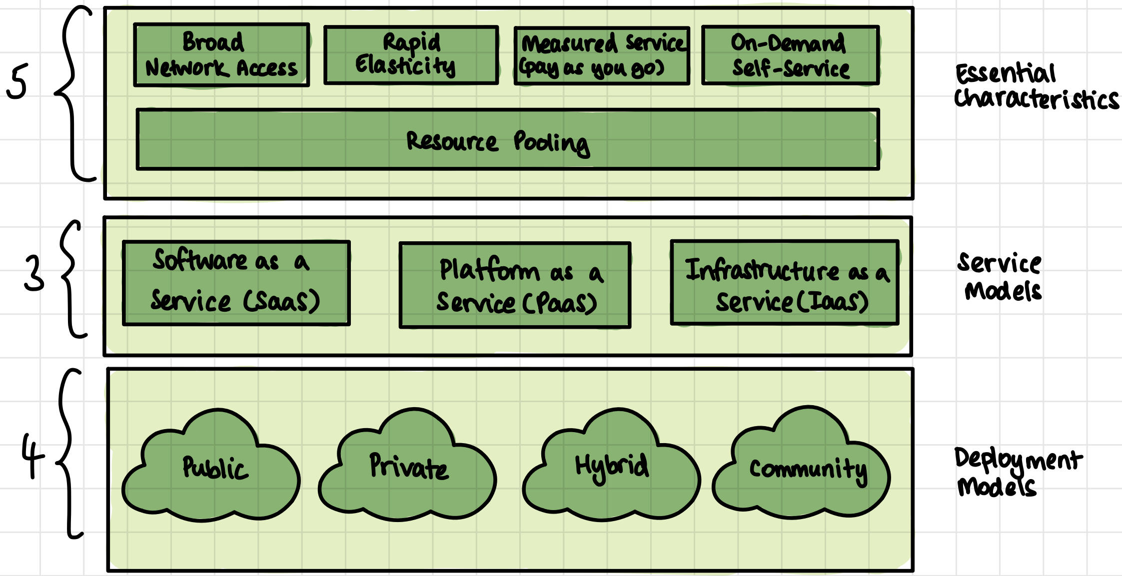
CLOUD COMPUTING

- shared pool of computing resources (networks, servers, storage, apps, services etc.) that are configurable

- on-demand, rapid network access (AWS, Azure etc.)

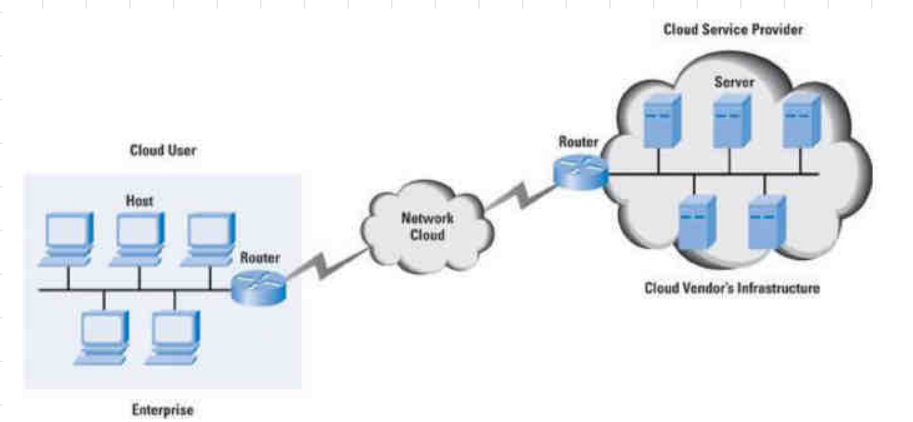
- cloud model composed of
  - five essential characteristics
  - three service models
  - four deployment models

Cloud Computing - NIST Visual Model



Cloud Networking (SD-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

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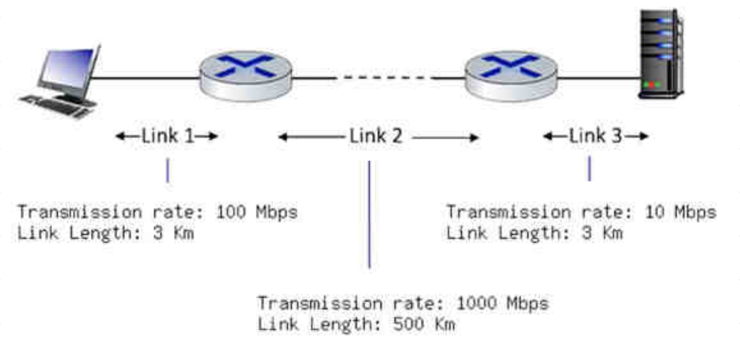
exercises

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 queueing 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 $3 \times 10^8 \ m s^{-1}$.

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.

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

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

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

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

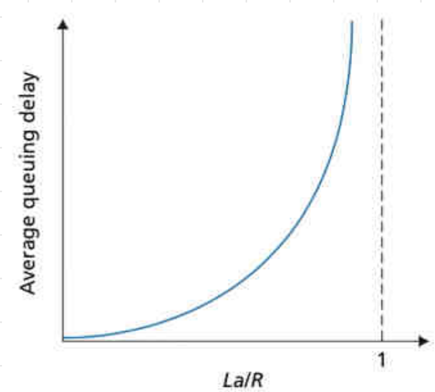
transmission delay 3 = $\frac{8000}{10 \times 10^6} = 8 \times 10^{-4} s$

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

total end-end delay = 2.57 ms

Interactive Exercise -2

Consider the queueing delay in a router buffer.



Assume:

- constant transmission rate R = 1,800,000
- 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. $I = \frac{6700 \times 30}{1.8 \times 10^6} = \frac{67}{600}$

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

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

$d = 0.755$ ms

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

5. $1762 - 956 = 806$ dropped

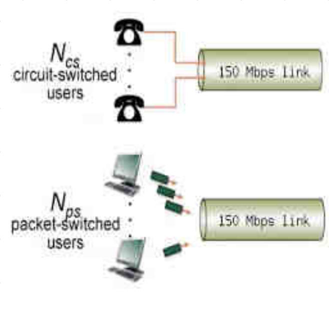
Interactive Exercise -3

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. $\frac{150}{10} = 15$ 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. $N_{ps} = 29$.

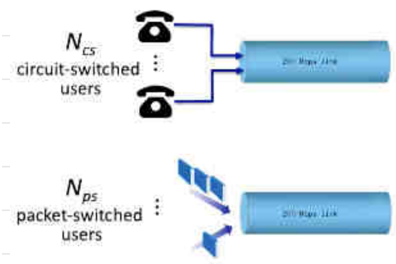
$$\sum_{i=0}^{15} {}^{29}C_i (0.3)^i (0.7)^{29-i} = 0.9959$$

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. $\frac{200}{25} = 8$ 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. $1 - \sum_{i=0}^{8} {^{15}C_i} (0.2)^i (0.8)^{15-i} = 1 - 0.999 = 0.001 = 0.1\%$

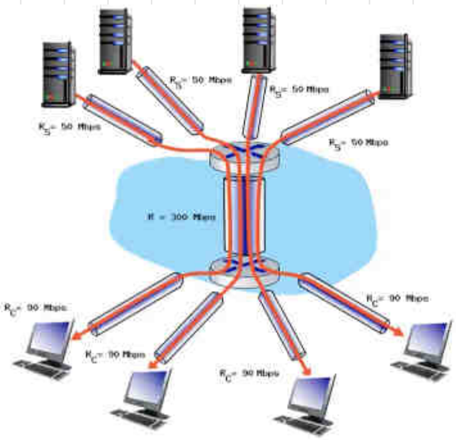
Interactive Exercise -5

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.



1. 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)?
2. Which link is the bottleneck link? Format as Rc, Rs, or R
3. 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
4. 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
5. 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. $\frac{300}{4} = 75$ Mbps

   max = min(50, 75, 90) = 50 Mbps

2. bottleneck = min(50, 75, 90) = 50 Mbps = R_s

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

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

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