Tutorial 1

Topic: Delay, throughput, Switching and Protocol layers

Computer & Communication Networks

Exercise 1: Packet delay types

Consider a packet sent from a source host to a destination host along a given path.
List the types of delay that contribute to end-to-end delay.
Which of those delays are variable and which are stable?
If the same packet travels along the same path, at two different times with different traffic load, which delay changes and why?

Exercise 1: Packet delay types

Consider a packet sent from a source host to a destination host along a given path.
List the types of delay that contribute to end-to-end delay.

Processing Delay

d_{proc} (ms), includes:

- header processing
- Forwarding-table lookup
- Error checking

Queuing Delay

d_{queue} (ms):
Time the packet spends waiting in the output queue before transmission.

Transmission Delay

$d_{trans} = L/R$, (ms):
Time required to transmit all bits of the packet onto the outgoing link.
L = packet size in bits.
R or C = transmission rate of the link in bps.

Propagation Delay

$d_{prop} = d/s$, (ms):
Time required for the signal to propagate across the link.
d = length of physical link in meters,
s = propagation speed of the signal in the medium in meters/s.

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

Exercise 1: Packet delay types

Consider a packet sent from a source host to a destination host along a given path.
List the types of delay that contribute to end-to-end delay.
Which of those delays are variable and which are stable?

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

Generally, processing and propagation delays are considered constant, while queuing and transmission delay are variable and depend on network conditions, congestion and the data being transmitted.

Exercise 1: Packet delay types

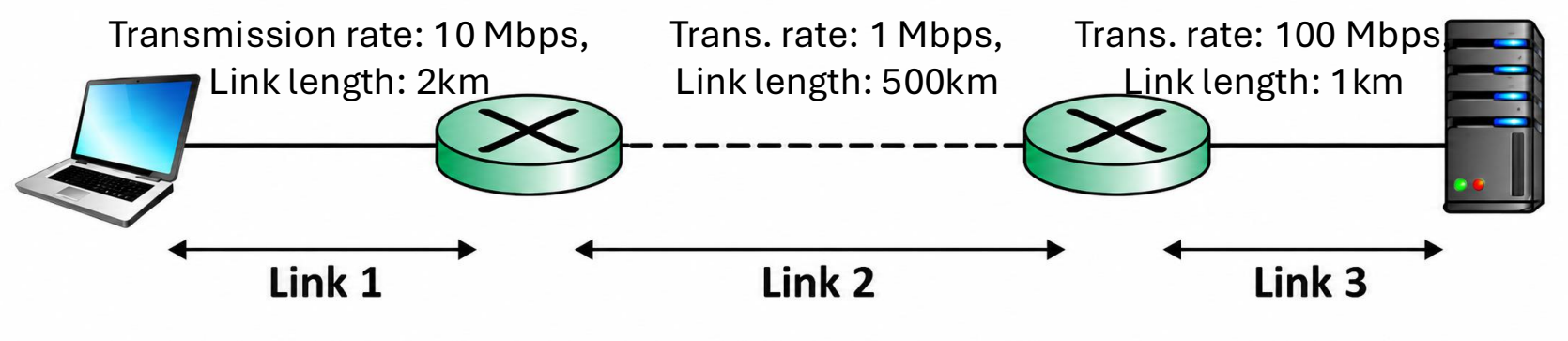
Consider a packet sent from a source host to a destination host along a given path.
List the types of delay that contribute to end-to-end delay.
Which of those delays are variable and which are stable?
If the same packet travels along the same path, at two different times with different traffic load, which delay changes and why?

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

Since we have the same packet and the same path, L is the same and R is the same, thus d_{trans} is the same. Transmission delay does not increase because of network congestion. Congestion causes the packet to spend longer waiting before it is transmitted, which means the delay that changes is d_{queue}.

Exercise 2: End-to-End delay across multiple links

Consider the following network:



Find the end-to-end delay, $D_{end\text{-}to\text{-}end}$, from the moment the leftmost node starts transmitting the first bit of a packet until the moment the last bit of the packet reaches the rightmost node.

Ignore queueing delay and processing delay.

Assume that all three links have a propagation speed equal to the speed of light,

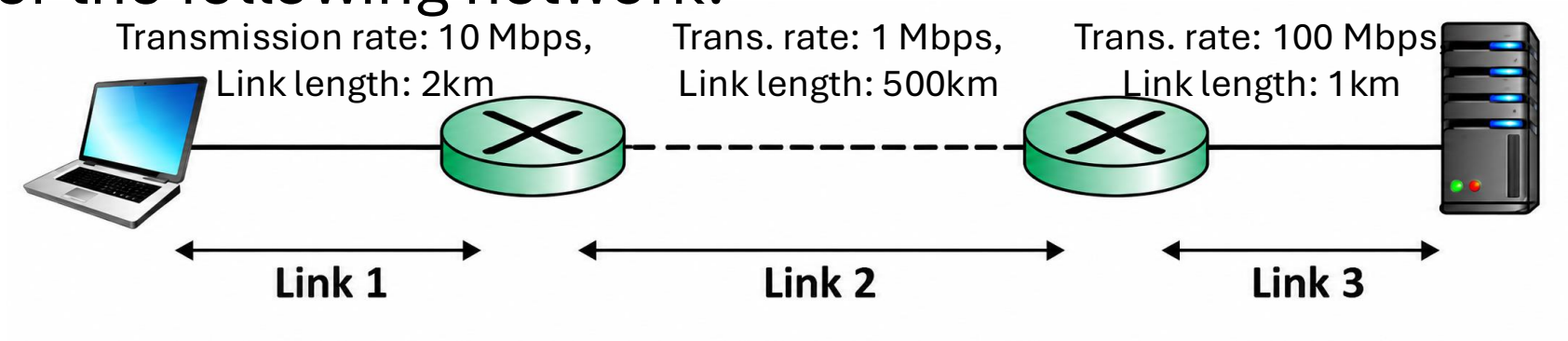
$$s = 3 \times 10^8 \text{ m/s}$$

and that the packet size is

$$L = 4000 \text{ bits}$$

Exercise 2: End-to-End delay across multiple links

Consider the following network:



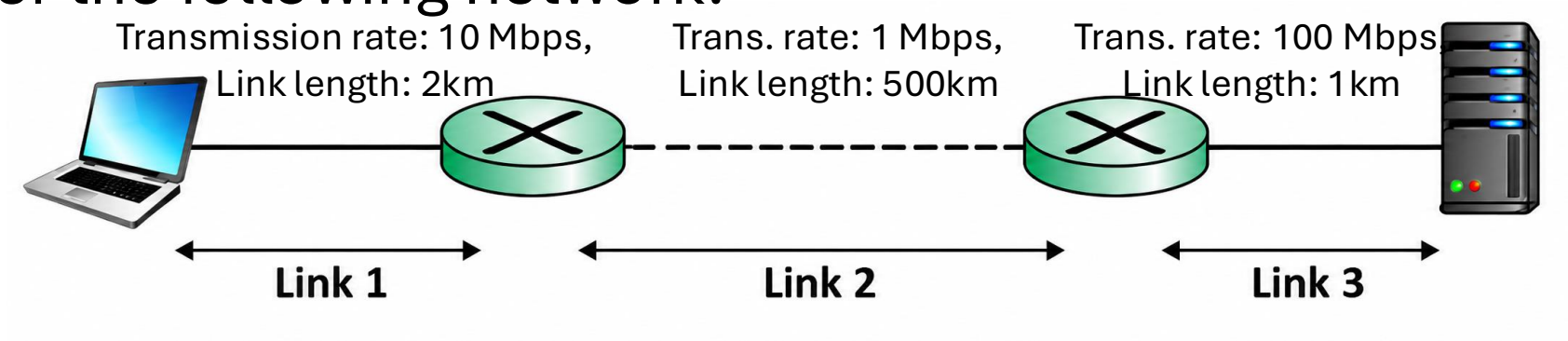
$D_{end\text{-}to\text{-}end} = d_{trans1} + d_{prop1} + d_{trans2} + d_{prop2} + d_{trans3} + d_{prop3}$

Link 1: $d_{trans1} = L/R1 = 4000/10x10^{6} = 0.0004\ s = 0.4\ ms$

$d_{prop1} = d1/s = 2000/3x10^{8} = 6.67x10^{-6}\ s = 0.0067\ ms$

Exercise 2: End-to-End delay across multiple links

Consider the following network:



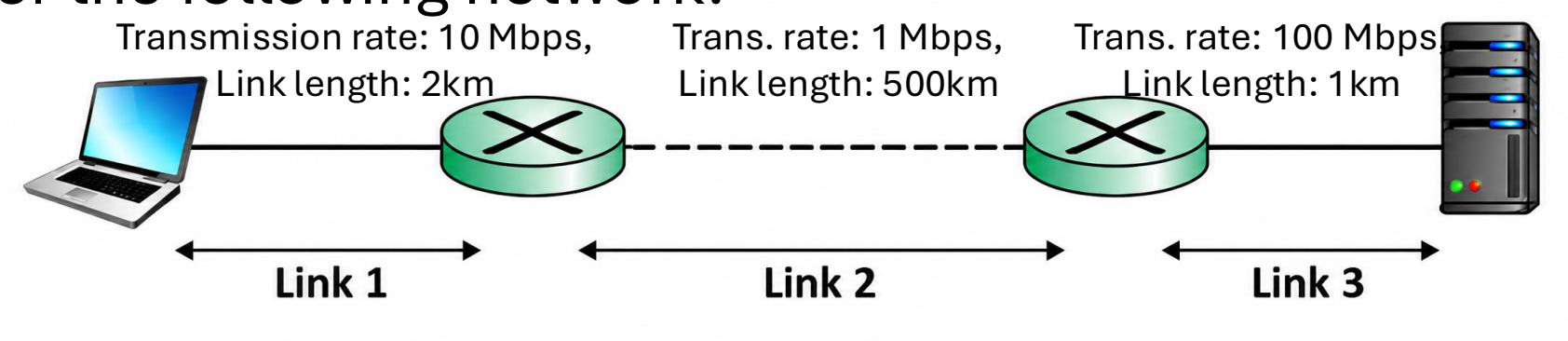
$D_{end\text{-}to\text{-}end} = d_{trans1} + d_{prop1} + d_{trans2} + d_{prop2} + d_{trans3} + d_{prop3}$

Link 2: $d_{trans2} = L/R2 = 4000/1x10^{6} = 0.004$ s = 4 ms

$d_{prop2} = d2/s = 500000/3x10^{8} = 0.001667$ s = 1.667 ms

Exercise 2: End-to-End delay across multiple links

Consider the following network:



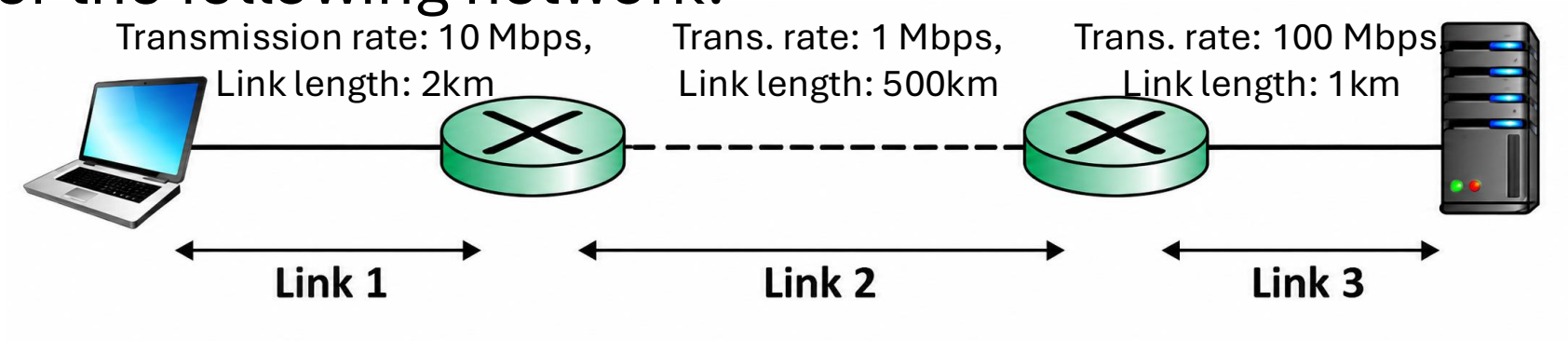
$D_{end\text{-}to\text{-}end} = d_{trans1} + d_{prop1} + d_{trans2} + d_{prop2} + d_{trans3} + d_{prop3}$

Link 3: $d_{trans3} = L/R3 = 4000/100x10^{6} = 0.00004$ s = 0.04 ms

$d_{prop3} = d3/s = 1000/3x10^{8} = 3.33x10^{-6}$ s = 0.0033 ms

Exercise 2: End-to-End delay across multiple links

Consider the following network:



$$D_{end\text{-}to\text{-}end} = d_{trans1} + d_{prop1} + d_{trans2} + d_{prop2} + d_{trans3} + d_{prop3}$$

$$= 0.4\ ms + 0.0067\ ms + 4\ ms + 1.667\ ms + 0.04\ ms + 0.0033\ ms$$

$$= 6.12\ ms$$

Exercise 3: Transmission and Propagation delay

Consider two computers, A and B, connected by a link with a transmission rate of *R* bps. Assume that the distance between the two computers is *dist* meters and the propagation speed along the link is *s* m/s. Computer A sends a packet of size L bits to computer B.

i. Ignoring the queuing and processing delays, express the end-to-end delay for transmitting the packet from A to B.
ii. Suppose A starts transmitting the packet at time t=0. At time $t=d_{trans}$, where is the last bit of the packet?
iii. If $d_{prop}>d_{trans}$, where is the first bit of the packet at time $t=d_{trans}$?
iv. If $d_{prop}<d_{trans}$, where is the first bit of the packet at time $t=d_{trans}$?
v. If $s = 2.5x10^8$ m/s, L = 200 bits and R = 28 Kbps, for what distance dist is $d_{prop}=d_{trans}$?

Exercise 3: Transmission and Propagation delay

Consider two computers, A and B, connected by a link with a transmission rate of *R* bps. Assume that the distance between the two computers is *dist* meters and the propagation speed along the link is *s* m/s. Computer A sends a packet of size L bits to computer B.

i. Ignoring the queuing and processing delays, express the end-to-end delay for transmitting the packet from A to B.

$D_{end\text{-}to\text{-}end} = d_{trans} + d_{prop}$, where d_{trans} = L/R sec and d_{prop} = dist/s sec.

This is the time from when A begins transmitting until B receives the final bit.

Exercise 3: Transmission and Propagation delay

Consider two computers, A and B, connected by a link with a transmission rate of *R* bps. Assume that the distance between the two computers is *dist* meters and the propagation speed along the link is *s* m/s. Computer A sends a packet of size L bits to computer B.

ii. Suppose A starts transmitting the packet at time t=0. At time $t=d_{trans}$, where is the last bit of the packet?

The last bit has just been transmitted. It is at the beginning of the link.

Exercise 3: Transmission and Propagation delay

Consider two computers, A and B, connected by a link with a transmission rate of *R* bps. Assume that the distance between the two computers is *dist* meters and the propagation speed along the link is *s* m/s. Computer A sends a packet of size L bits to computer B.

iii. If $d_{prop} > d_{trans}$, where is the first bit of the packet at time $t=d_{trans}$?

The first bit is still propagating along the link and has not yet reached B.

Exercise 3: Transmission and Propagation delay

Consider two computers, A and B, connected by a link with a transmission rate of *R* bps. Assume that the distance between the two computers is *dist* meters and the propagation speed along the link is *s* m/s. Computer A sends a packet of size L bits to computer B.

iv. If $d_{prop} < d_{trans}$, where is the first bit of the packet at time $t = d_{trans}$?

The first bit has already reached B.

Exercise 3: Transmission and Propagation delay

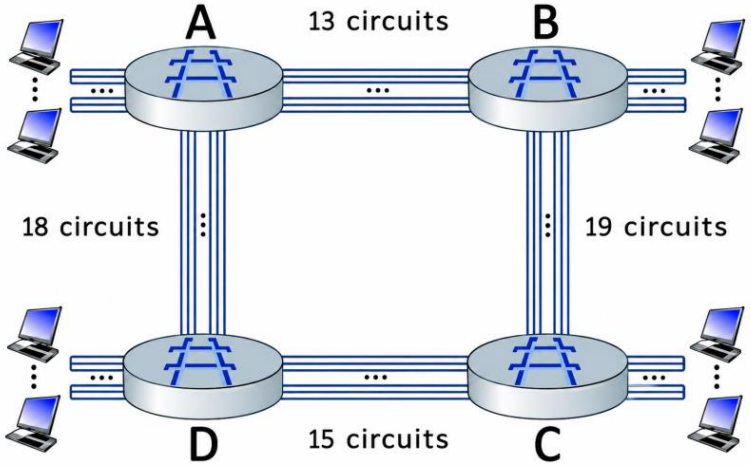
Consider two computers, A and B, connected by a link with a transmission rate of *R* bps. Assume that the distance between the two computers is *dist* meters and the propagation speed along the link is *s* m/s. Computer A sends a packet of size L bits to computer B.

v. If s = 2.5×10^8 m/s, L = 200 bits and R = 28 Kbps, for what distance dist is $d_{prop}=d_{trans}$?

$d_{prop}=d_{trans}$ => dist/s = L/R => dist = L*s/R = $200 \times 2.5 \times 10^8/28000$ = 1785.7 km

Exercise 4: Maximum connections in a circuit switched network

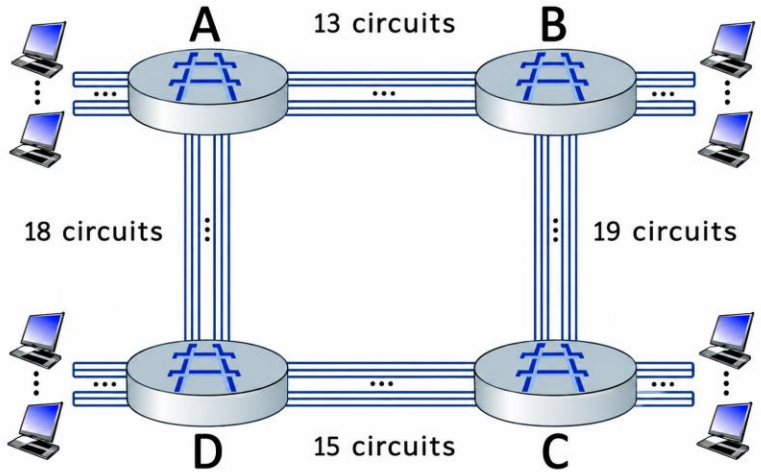
Consider the following circuit-switched network, which includes four switches A, B, C and D. Assume that there are 13 circuits between A and B, 19 circuits between B and C, 15 circuits between C and D, and 18 circuits between D and A.



Assume that each connection requires two consecutive hops, and that all connections are established in the clockwise direction. For example, a connection may be established from A to C, from B to D, from C to A, from D to B. In this case, what is the maximum number of simultaneous connections that can be supported by the network?

Exercise 4: Maximum connections in a circuit switched network

The maximum number of simultaneous connections that can be supported by the network is determined by the minimum number of circuits available on the switch links involved, since each two-hop path passes through two switch links and occupies one circuit on each of them.



A-C connection: the maximum number that can be supported on both links A-B and B-C is 13 circuits.
B-D connection: the maximum number that can be supported on both links B-C and C-D is 19-13=6 circuits, since we are assuming that the A-C circuits are active at the same time.

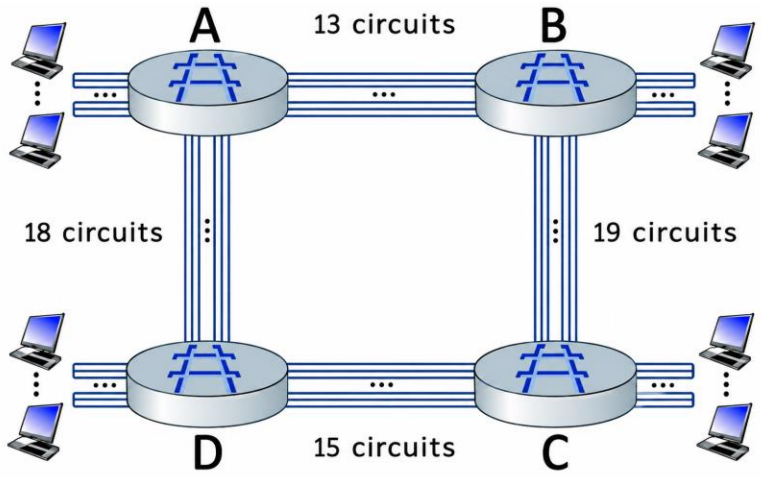
Exercise 4: Maximum connections in a circuit switched network

A-C connection: the maximum number that can be supported on both links A-B and B-C is 13 circuits.

B-D connection: the maximum number that can be supported on both links B-C and C-D is 19-13=6 circuits.

C-A connection: the maximum number that can be supported on both links C-D and D-A is 15-6=9 circuits, since we are assuming that the A-C and B-D circuits are active at the same time.

D-B connection: we cannot support any additional circuits, since the remaining circuits are already being used by the other active connections.
Therefore, the total number of simultaneous connections that can be supported is: 13+6+9+0=28.

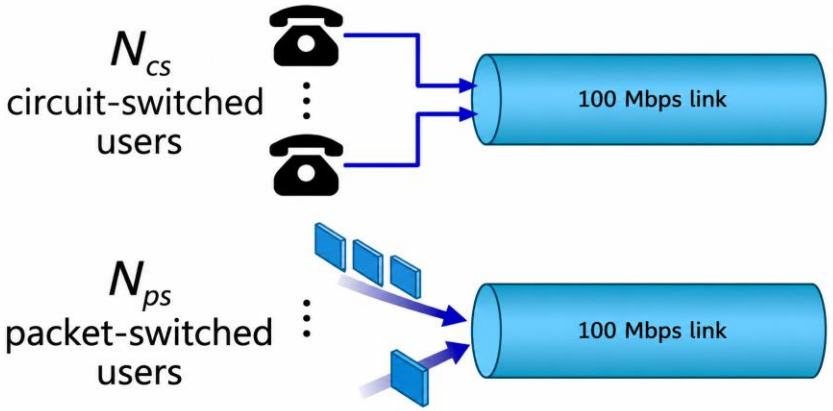


Exercise 5: Circuit switching vs packet switching

Consider the following two scenarios:

A circuit switching scenario in which N_{cs} users share a 100 Mbps link. Each user requires 20 Mbps of bandwidth when transmitting.

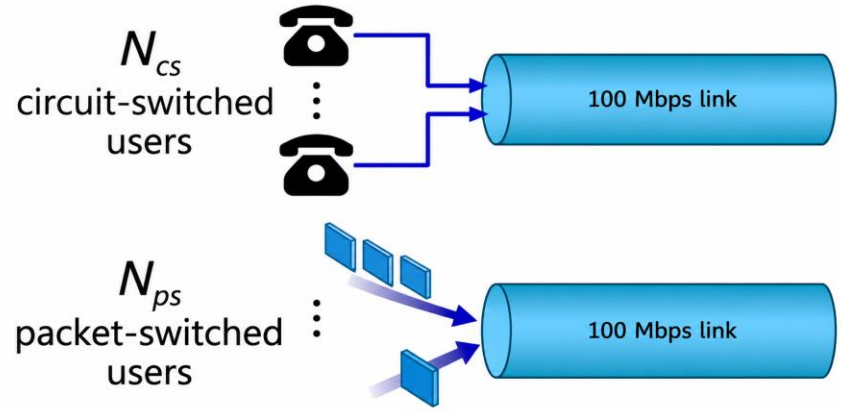
A packet switching scenario in which N_{ps} users share a 100 Mbps link. Each user requires 20 Mbps of bandwidth when transmitting, but transmits only 20% of the time.



i. According to the first scenario (circuit switching), what is the maximum number of users that can be supported?
ii. Suppose that the second scenario (packet switching) is used.
   - What is the probability that a specific user is transmitting while all the other users are not transmitting?
   - What is the probability that one (any one) of the users is transmitting while all the other users are not transmitting?

Exercise 5: Circuit switching vs packet switching

i. According to the first scenario (circuit switching), what is the maximum number of users that can be supported?



In circuit switching 20 Mbps of bandwidth must be allocated to each user.
Since the total capacity is 100 Mbps, at most:

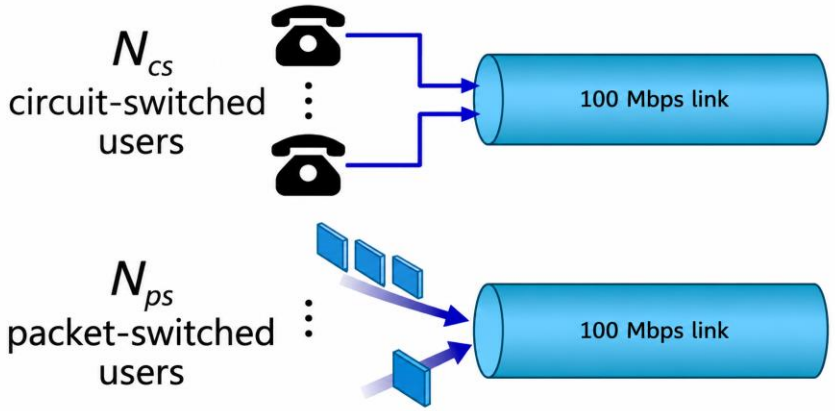
$$100\text{Mbps}/20\text{Mbps} = 5$$

users can be supported.

Exercise 5: Circuit switching vs packet switching

ii. Suppose that the second scenario (packet switching) is used.

- What is the probability that a specific user is transmitting while all the other users are not transmitting?

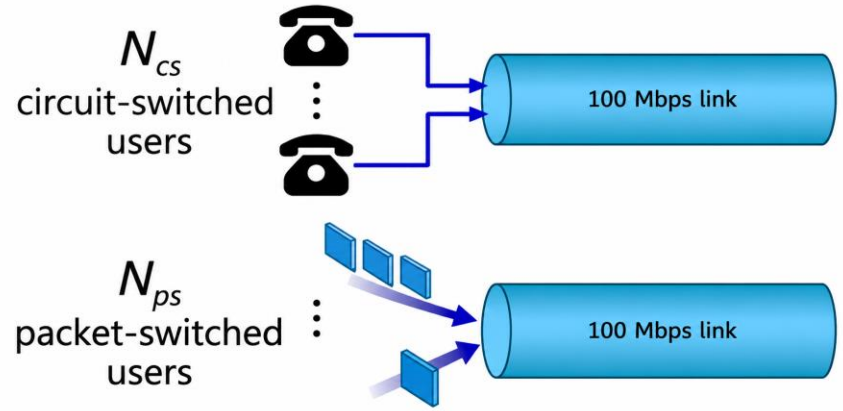


Let p denote the probability that a specific user is transmitting, with p = 0.2, since each user transmits 20% of the time. Correspondingly, the probability that the user is not transmitting is 1 - p = 0.8. The probability that all the other users (N_{ps} –1) are not transmitting is $(1-p)^{N_{ps}-1}$.
Thus, the required probability is: $P = p*(1-p)^{N_{ps}-1}$.
For instance, for $N_{ps} = 9$, we have $P=0.2*(1-0.2)^{9-1} = 0.2*0.8^8 = 0.2*0.168 = 0.033$.

Exercise 5: Circuit switching vs packet switching

ii. Suppose that the second scenario (packet switching) is used.

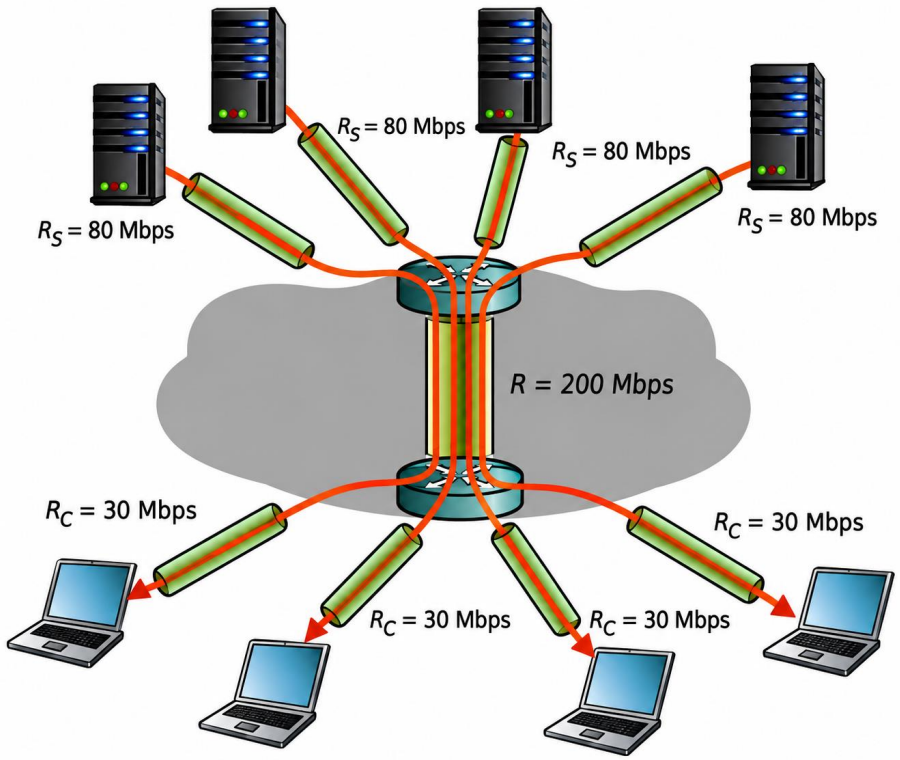
- What is the probability that one (any one) of the users is transmitting while all the other users are not transmitting?



The probability that only one (any one) of the N_{ps} users is transmitting is: P' = N_{ps} x [the probability that a specific user is transmitting, when all other users are not] = N_{ps} x P.
For N_{ps} = 9, the required probability would be P' = 9*0.033 = 0.297.

Exercise 6: End-to-end throughput and Bottleneck

Consider the following scenario, in which 4 servers are connected to 4 clients through 4 three-hop paths. The 4 communicating pairs share, at the intermediate hop of their paths a common link with transmission capacity R=200 Mbps. For the first hop of each path, the links of all four servers have transmission capacity R_s=80Mbps. For the third hop of each path, the links of all four clients have transmission capacity R_c=30 Mbps.

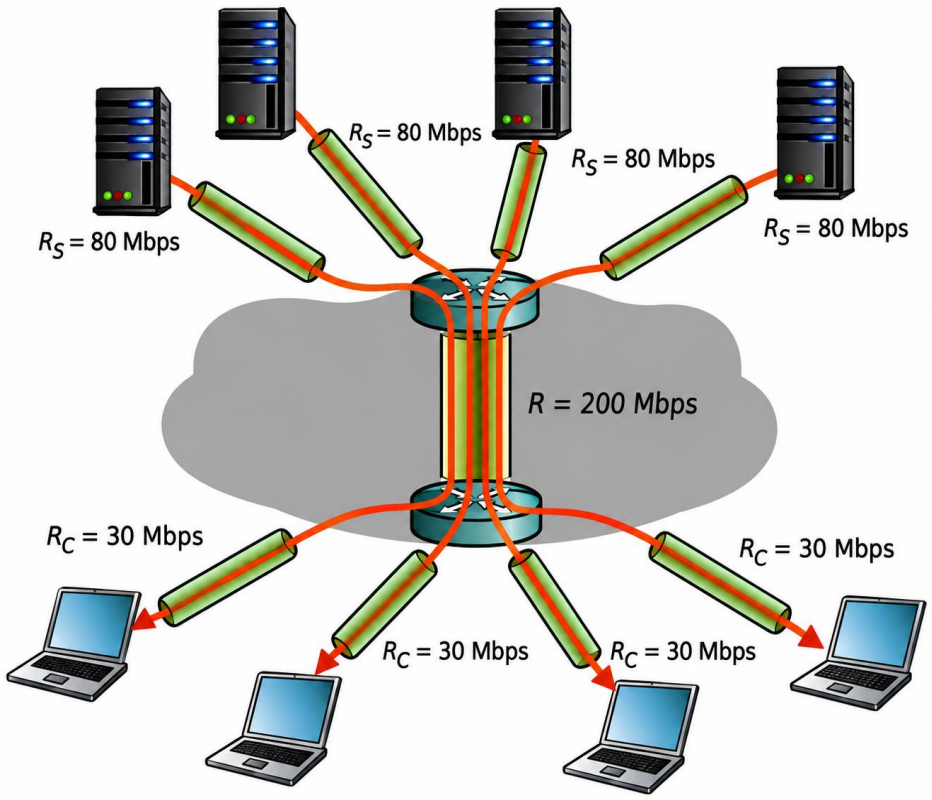


Exercise 6: End-to-end throughput and Bottleneck

(a) What is the maximum end-to-end throughput (in Mbps) for each of the 4 client-server pairs, assuming that the shared link is divided fairly among the four communications?

(b) Which link is the bottleneck in each communication?

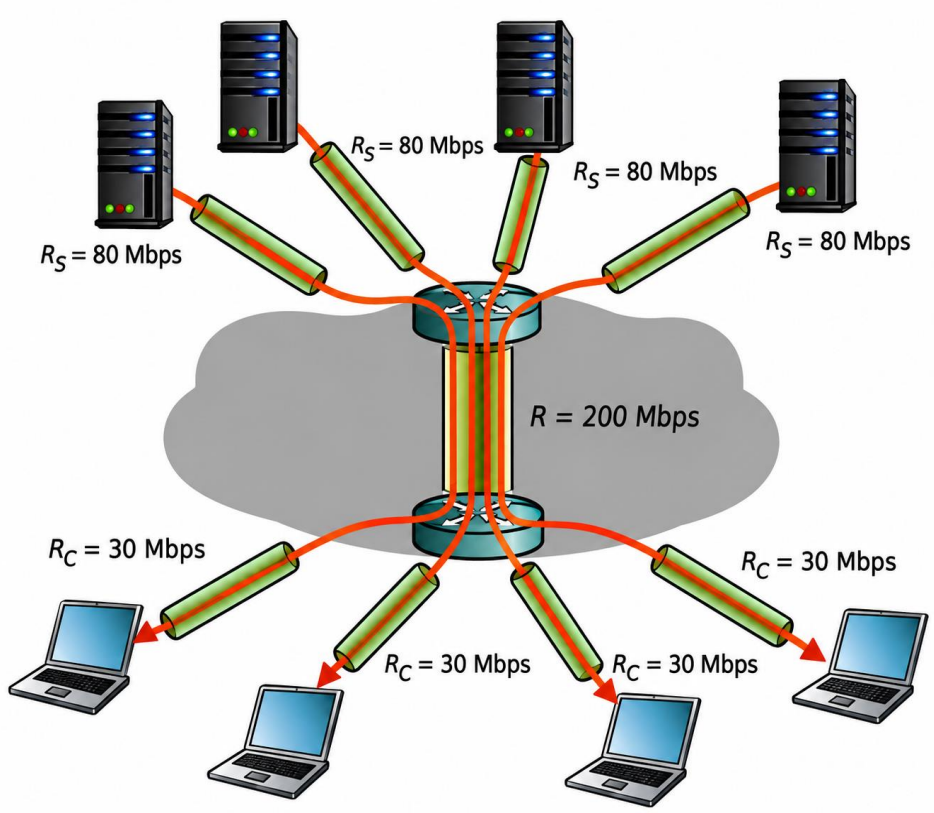
(c) Assume that each server sends data at the maximum rate that can be supported. What is the utilization of the server link (R_s), the client link (R_c), and the shared link (R)?



Exercise 6: End-to-end throughput and Bottleneck

(a) What is the maximum end-to-end throughput (in Mbps) for each of the 4 client-server pairs, assuming that the shared link is divided fairly among the four communications?

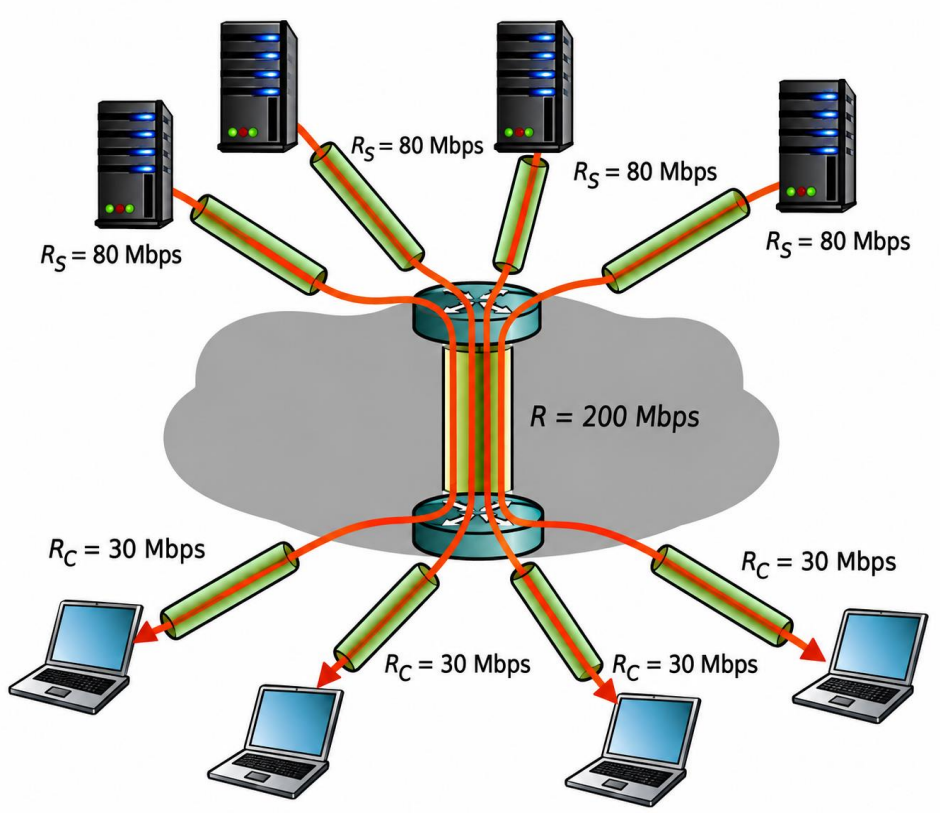
The maximum end-to-end throughput for each of the 4 client-server pairs is the maximum rate that can be supported across every part of the path, meaning 30 Mbps.



Exercise 6: End-to-end throughput and Bottleneck

(b) Which link is the bottleneck in each communication?

The bottleneck is the third hop of the path, namely the client links with a transmission rate of 30 Mbps, which is lower than both R_s=80 Mbps and R/4 = 200/4 = 50 Mbps.

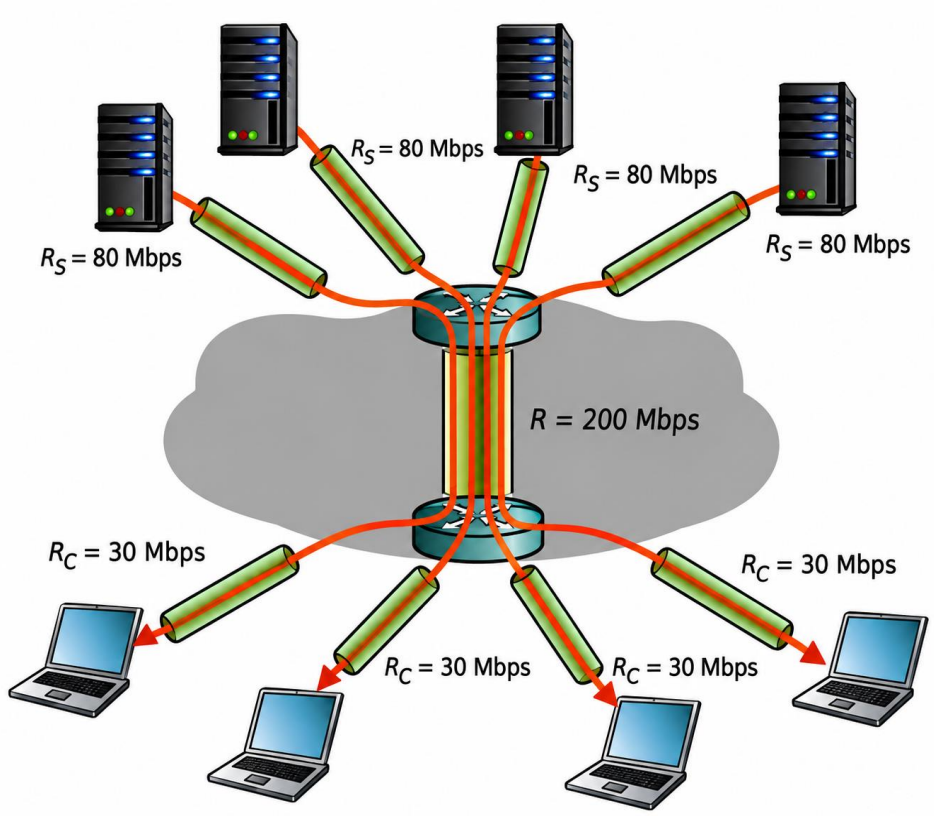


Exercise 6: End-to-end throughput and Bottleneck

(c) Assume that each server sends data at the maximum rate that can be supported. What is the utilization of the server link (R_s), the client link (R_c), and the shared link (R)?

The utilization of a link depends on the transmission rate supported by the link and the maximum throughput of the overall path.

Link utilization = [maximum end-to-end throughput]/[transmission rate of the specific link]



Exercise 6: End-to-end throughput and Bottleneck

(c) Assume that each server sends data at the maximum rate that can be supported. What is the utilization of the server link (R_s), the client link (R_c), and the shared link (R)?

Link utilization = [maximum end-to-end throughput]/[transmission rate of the specific link]

Server link utilization: 30 Mbps/R_s = 30/80 = 0.375 = 37.5%

Client link utilization: 30 Mbps/R_c = 30/30 = 1 = 100%

Shared link utilization: 30 Mbps/50 Mbps = 0.6 = 60%, since each communication is allocated R/4=200/4=50 Mbps.

