COMPUTER COMMUNICATION NETWORKS

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Performance Parameters (delay, packet loss, throughput)

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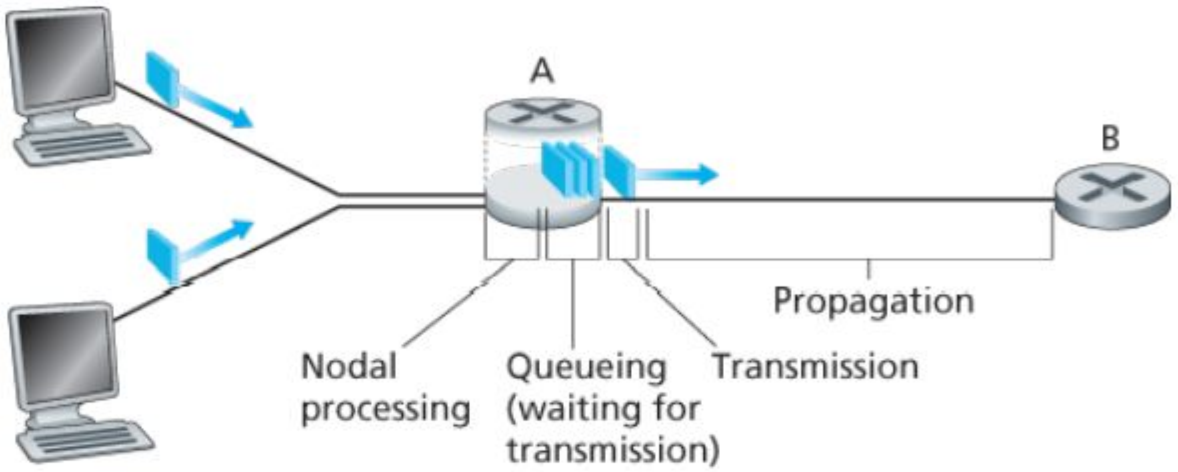
Delay

As a packet travels from one node (host or router) to the subsequent node (host or router) along a path, it suffers from several **types of delays** at each node along the path.

The delays such as **nodal processing delay, queuing delay, transmission delay** and **propagation delay** accumulate to give a **total nodal delay (d_{nodal}).**



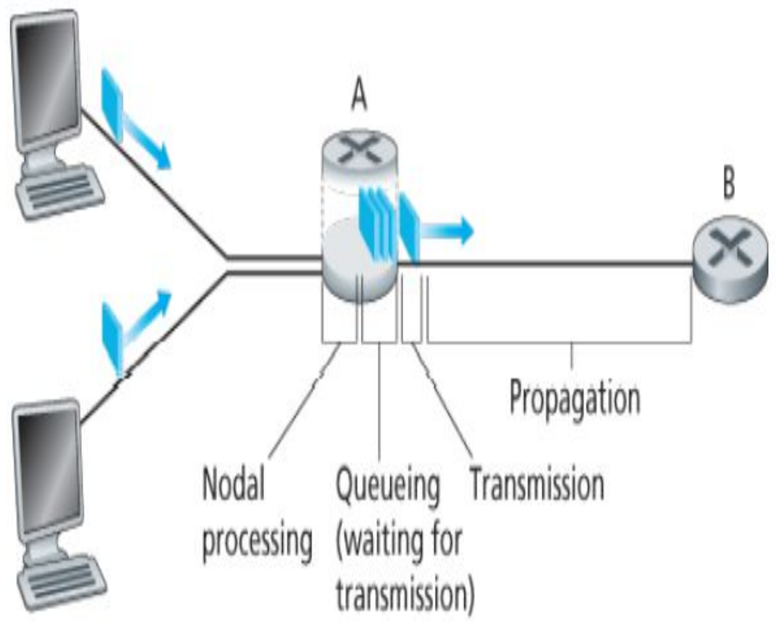
$$d_{nodal} = d_{proc} + d_{queue} + d_{trans} + d_{prop}$$

Processing Delay (d_{proc})

The time required to **examine the packet's header** and **determine where to direct** the packet is called **processing delay.**

It can include other factors, such as the **time needed to check for bit-level errors in the packet** that occurred in transmitting the packet's bits from the upstream node to router A.

After nodal processing (with a delay in the order of **microseconds or less**) , the router directs the packet to the queue that precedes the link to router B.



Performance parameters

Queuing Delay (d queue)

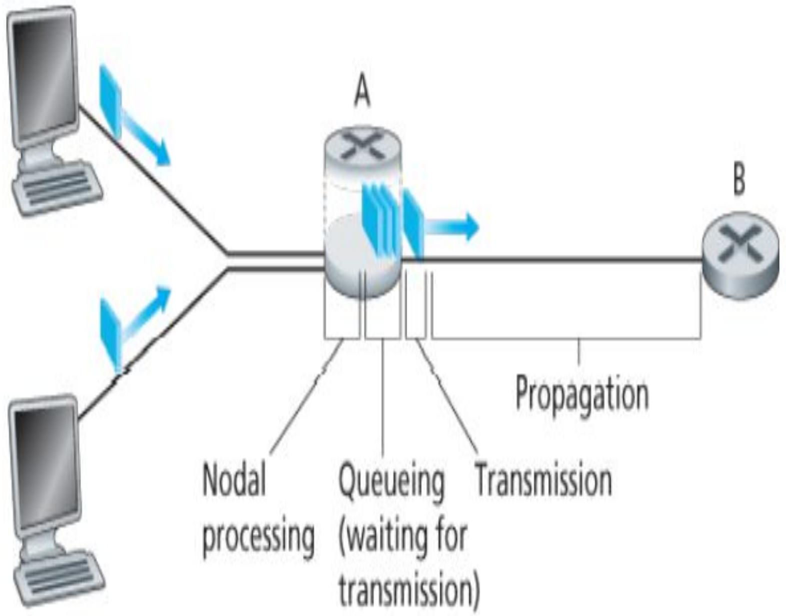
At the queue, the packet experiences a **queuing delay** as it waits to be transmitted onto the link.

The length of the queuing delay of a specific packet will depend on **the number of earlier-arriving packets that are queued and waiting for transmission onto the link**.

If **the queue is empty** and no other packet is currently being transmitted, then our packet's **queuing delay will be zero**.

If **the traffic is heavy** and many other packets are also waiting to be transmitted, **the queuing delay will be long**.

Queuing delays can be on the order of **microseconds to milliseconds**

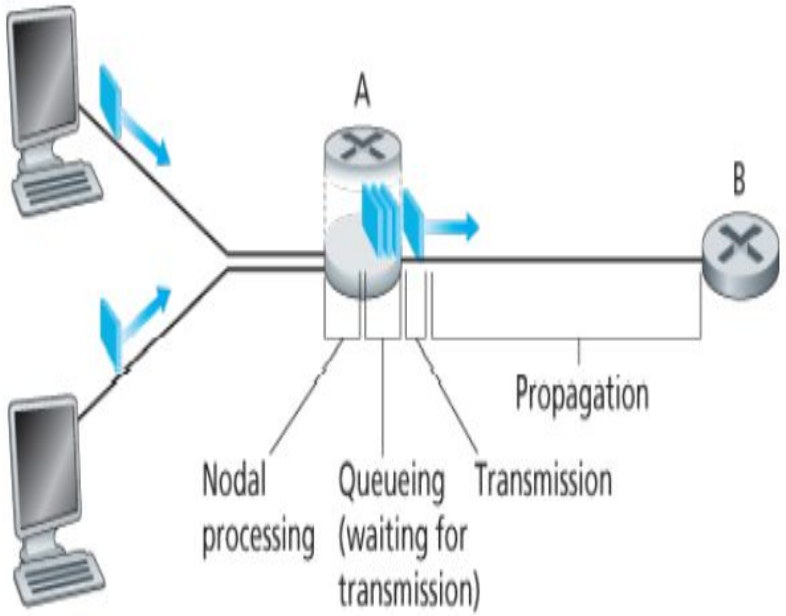


Performance parameters

Queuing Delay (d queue) contd…

The queuing delay can **vary** from packet to packet.

For example, if 10 packets arrive at an **empty queue** at the same time, the **first packet** transmitted will suffer **no queuing delay**, while the **last packet** transmitted will suffer a relatively **large queuing delay** (while it waits for the other nine packets to be transmitted).



Queuing delay $d_q = \bar{q} / \lambda$

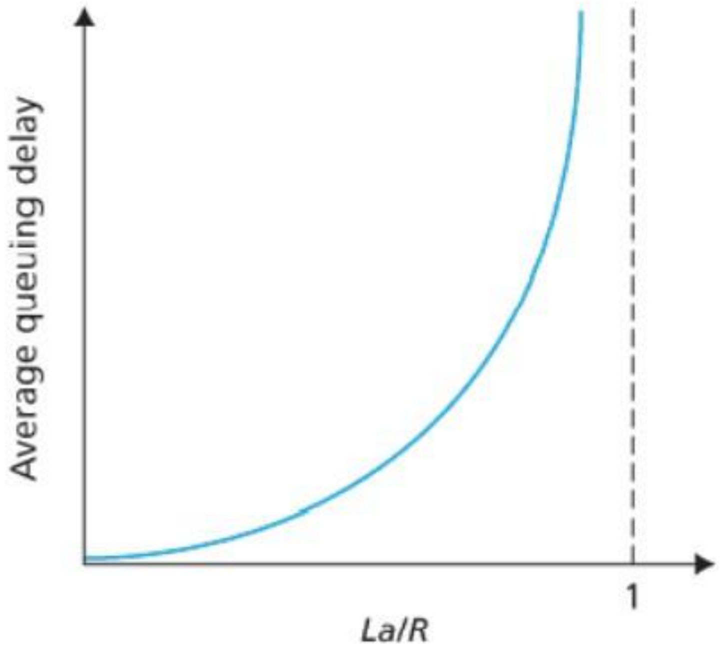
$\bar{q}$ is average queue length and λ is mean packet arrival rate

The average rate at which bits arrive at the queue is *L*a* bits/sec.

a - average rate at which packets arrive at the queue (packets/sec).

R - transmission rate (bits/sec)

L - No of bits in a packet (for all packets)



If the queue is very big (capacity to hold an infinite number of bits)

Traffic intensity = La/R (estimating the extent of the queuing delay)

If **La/R > 1**, then **La** exceeds the rate at which the bits can be transmitted from the queue.

The queue will tend to increase without bound and the queuing delay will approach infinity!

Performance parameters

If **$La/R \leq 1$,** then the nature of the arriving traffic impacts the queuing delay.
For example
If **packets arrive periodically** (one packet arrives every L/R seconds) then every packet will arrive at an empty queue and there will be no queuing delay.
If **packets arrive in bursts but periodically**, there can be a significant average queuing delay

Note: If N packets arrive simultaneously every (L/R)N seconds
The first packet transmitted has no queuing delay
The second packet transmitted has a queuing delay of L/R second

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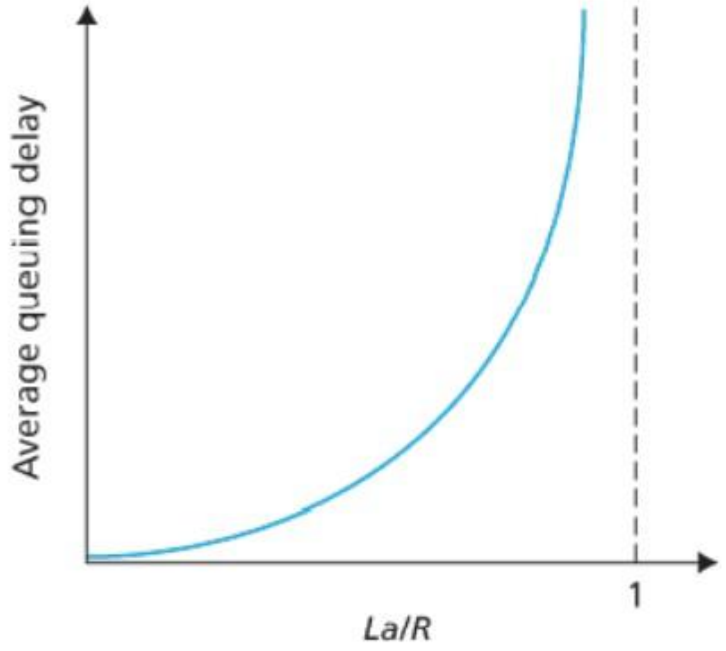
The nth packet transmitted has a queuing delay of (n-1)L/R seconds.

Performance parameters

***La/R* -> 1**

If the **traffic intensity approaches 1**, the **average queuing delay increases** rapidly.

A small percentage increase in the intensity will result in a much larger percentage-wise increase in delay.



Packet loss

- Each switching device has **finite** buffer to store packets before processing and forwarding them one-by-one
- So a queue builds up based on link rates of the arriving links and departing links
- Arriving packets are lost **when buffer is full**
- Lost packet may be retransmitted by previous node, or by source (the end-user), or not at all

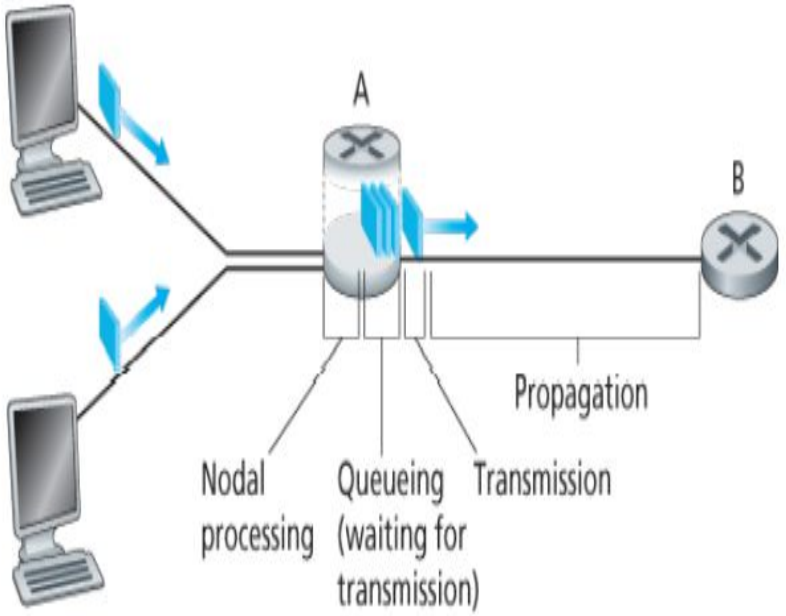
Transmission Delay (d_{trans})

Transmission delay is the amount of time required to push (that is, transmit) all of the packet's bits into the link.

If the the length of the packet is L bits and the transmission rate of the link from router A to router B is R bits/sec, then

Transmission delay is L/R

Transmission delays are typically on the order of **microseconds to milliseconds.**



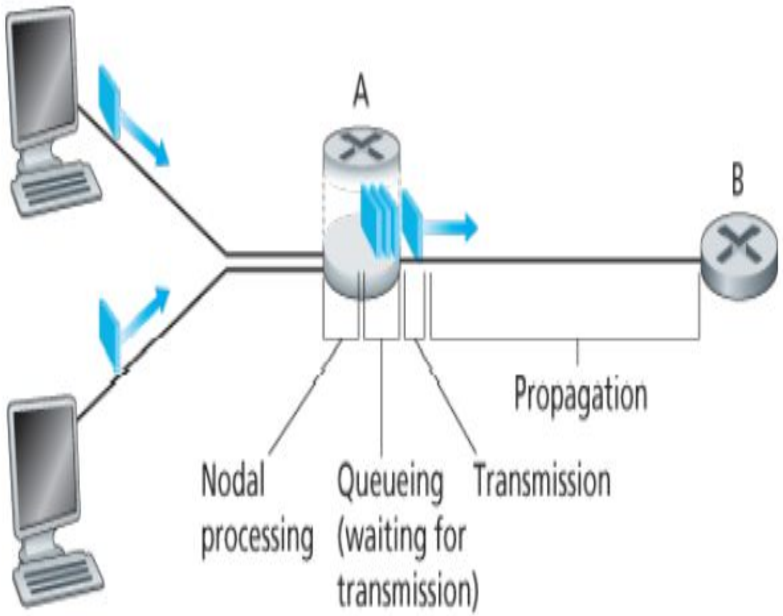
Performance parameters

Propagation Delay (dprop)

The time required to propagate from the beginning of the link to router B is the **propagation delay.**
The bit propagates at the propagation speed of the link (Physical mediums with a speed of $2x10^8$m/sec to air with a speed of light of $3x10^8$ m/sec.)
The **propagation delay** is the distance between two routers divided by the propagation speed.
If **d** is the distance between router A and router B and **s** is the propagation speed of the link, then

The propagation delay is d/s

Propagation delays are on the order of **milliseconds**



End to End Delay

- It is the **total delay** occurring in a **packet transmission** from a source host to the destination host
- The end-to-end delay is computed in terms of the following delays incurred along the path
  Packetization delay, Transmission delay, Propagation delay, Processing delay and Queuing Delay.

- **Packetization delay** depends on the end-user application and processing speed

Numerical 1:

Consider the case where end hosts A and B are connected by a one hop router and the links have the same transmission rate R (Mbps). Assume that the host A has P packets of variable length {L1...,LP} bits to transmit to host B. Assume that the queuing delay, processing delays and propagation delays are negligible.

a) Calculate the end-end delay in transmitting P packets. Explain your calculation.
b) Calculate the end-end delay in transmitting P packets via M routers between A and B. All links have the same transmission rate R. Explain your calculation.

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Solution a)

The end to end delay is deduced using a few case studies.

Case 1: Two packets are transmitted by host A ($L_1 > L_2$)

End-end delay is equal to $2\frac{L_1}{R} + \frac{L_2}{R}$. At $\frac{L_1}{R}$, packet 1 arrives at router 1 and host A starts transmission of packet 2. At $2\frac{L_1}{R}$, packet 1 arrives at host B and packet 2 has already arrived at router 1. At $2\frac{L_1}{R} + \frac{L_2}{R}$, packet 2 arrives at host B.

Case 2: Two packets are transmitted by host A ($L_2 > L_1$)

End-end delay is equal to $\frac{L_1}{R} + 2\frac{L_2}{R}$. At $\frac{L_1}{R}$, packet 1 arrives at router 1 and host A starts transmission of packet 2. At $\frac{L_1}{R} + \frac{L_2}{R}$, packet 1 has already arrived host B and packet 2 arrives at router 1. At $\frac{L_1}{R} + 2\frac{L_2}{R}$, packet 2 arrives at host B.

Case 3: Three packets are transmitted by host A ($L_1 > L_2 \wedge L_3$)

End-end delay is equal to $2\frac{L_1}{R} + \frac{L_2}{R} + \frac{L_3}{R}$. At $\frac{L_1}{R}$, packet 1 arrives at router 1. At $2\frac{L_1}{R}$, packet 1 arrives at host B while packet 2 has arrived at router1. Packet 3 may be in transit or arrived at router 1 depending on how big L_1 and L_2 are compared to L_3. At $2\frac{L_1}{R} + \frac{L_2}{R}$, packet 2 arrives at host B. At $2\frac{L_1}{R} + \frac{L_2}{R} + \frac{L_3}{R}$, packet 3 arrives at host B.

Case 4: Three packets are transmitted by host A ($L_2 > L_1 \wedge L_3$)

Applying the same logic as case 3, the end to end delay is $\frac{L_1}{R} + 2\frac{L_2}{R} + \frac{L_3}{R}$.

Case 5: Three packets are transmitted by host A ($L_3 > L_1 \wedge L_2$)

Applying the same logic as case 3, the end to end delay is $\frac{L_1}{R} + \frac{L_2}{R} + 2\frac{L_3}{R}$.

Based on the above cases, a general expression for the end-end delay for transmitting P variable length packets is equal to $\sum_{i=1}^{P} \frac{L_i}{R} + max\left(\frac{L_1}{R}, \ldots, \frac{L_P}{R}\right)$.

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b)

Case 1: Three packets are transmitted by host A ($L_1 > L_2 \Lambda L_3$) and $M = 2$ routers

End-end delay is equal to $3\frac{L_1}{R} + \frac{L_2}{R} + \frac{L_3}{R}$. At $\frac{L_1}{R}$, packet 1 arrives at router 1 and host A starts transmission of packet 2. At $2\frac{L_1}{R}$, packet 1 arrives at router 2, packet 2 and/or packet 3 has already arrived at router 1 (note packet 3's arrival at router 1 depends on the sizes of L_1 and L_2). At $3\frac{L_1}{R}$, packet 1 arrives at host B, packet 2 has already arrived at router 2 and packet 3 must have arrived at router1 or is in transit to router 2. At $3\frac{L_1}{R} + \frac{L_2}{R}$, packet 2 arrives at host B while packet 3 has arrived at router 2. At $3\frac{L_1}{R} + \frac{L_2}{R} + \frac{L_3}{R}$, packet 3 arrives at host B.

Case 2: Three packets are transmitted by host A ($L_2 > L_1 \Lambda L_3$) and $M = 2$ routers

Applying the same logic as case 1, the end to end delay is $\frac{L_1}{R} + 3\frac{L_2}{R} + \frac{L_3}{R}$.

Case 5: Three packets are transmitted by host A ($L_3 > L_1 \wedge L_2$) and $M = 2$ routers

Applying the same logic as case 1, the end to end delay is $\frac{L_1}{R} + \frac{L_2}{R} + 3\frac{L_3}{R}$.

Based on the above cases, a general expression for the end-end delay for transmitting P variable length packets over M routers is equal to $\sum_{i=1}^{P}\frac{L_i}{R} + M \cdot max\left(\frac{L_1}{R}, \dots, \frac{L_P}{R}\right)$.

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Numerical: 2

A packet switch receives a packet and determines the outbound link to which the packet should be forwarded. When the packet arrives, one other packet is halfway done being transmitted on this outbound link and four other packets are waiting to be transmitted. Packets are transmitted in order of arrival. Suppose all packets are 1,500 bytes and the link rate is 2 Mbps. What is the queuing delay for the packet?

More generally, what is the queuing delay when all packets have length L, the transmission rate is R, x bits of the currently-being-transmitted packet have been transmitted, and n packets are already in the queue?

Solution:

The queuing delay is given by the sum of the transmission delays of n packets ahead of it plus the time taken to push the L-x bits of the current packet which is being transmitted.

Each packets transmission delay is given by L/R seconds

Therefore, the general expression for the queuing delay is given by

$$nL/R + (L-x)/R$$

Based on the data given: the queuing delay =

$$4 \times 1500 \times 8/2M + (750 \times 8)/2M = 0.027 \text{ sec}$$

Numerical 3:

Consider the path from host A to host B traversing three links labeled sequentially. Suppose the rates of links 1, 2 and 3 are 500 kbps, 2 Mbps and 1 Mbps respectively ($k=10^3$ and $M=10^6$). Assume negligible propagation and processing delays. Suppose packet 1 of size 800 kb and packet 2 of size 500 kb leave A sequentially. Calculate the transmission time of each packet on each link. Calculate the total time taken by the packets to reach B. Explain your calculation.

Solution

Packet	Transmission time on link 1	Transmission time on link 2	Transmission time on link 3
1	1.6 s	0.4 s	0.8 s
2	1 s	0.25 s	0.5 s

The total time taken is 3.35 s

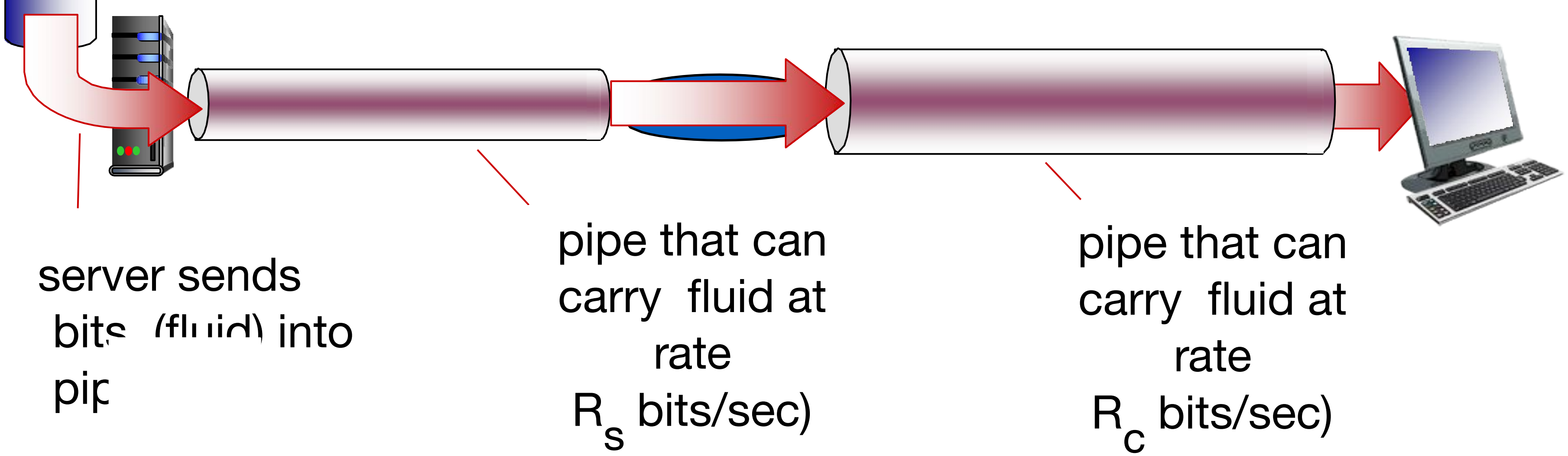
Performance parameters

Time (seconds)	Status of packet 1	Status of packet 2
1.6	Completed transit on link 1 and begins transit on link 2	Begins transmission on link 1
2	Completed transit on link 2 and begins transit on link 3	Still in transit on link 1
2.6	In transit on link 3	Completed transit on link 1 and begins transit on link 2
2.8	Reached B	Still in transit on link 2
2.85	Already at B	Completed transit on link 2 and begins transit on link 3
3.35	Already at B	Reached B

Throughput

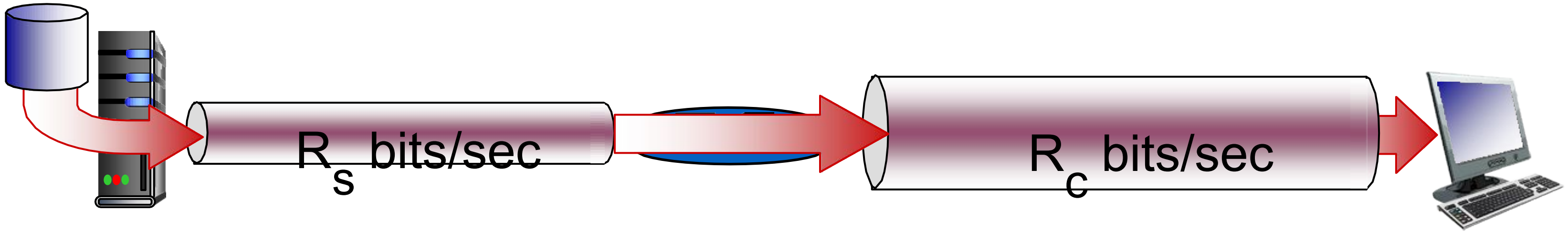
- Packet transmission rate (bits/sec) between a pair of sender-receiver

  - Instantaneous: transmission rate at given point in time
  - Average: transmission rate over longer period of time

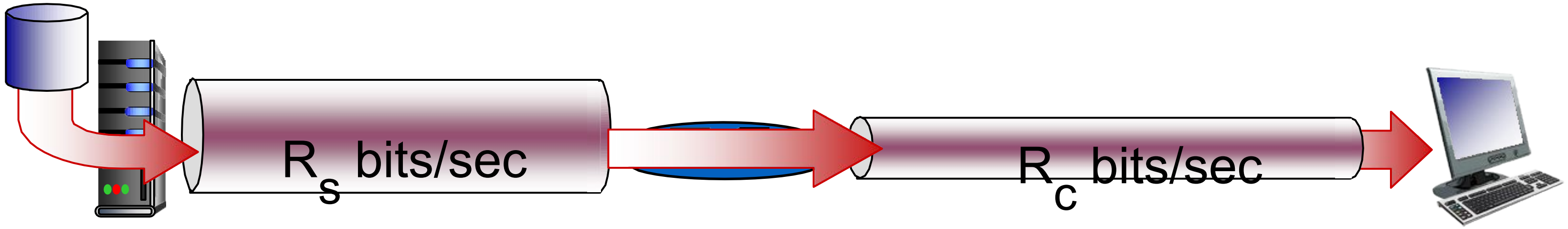


Performance parameters

- $R_s < R_c$ the bits pumped by the server will "flow" right through the router and arrive at the client at a rate of R_s bps, giving a throughput of R_s bps.



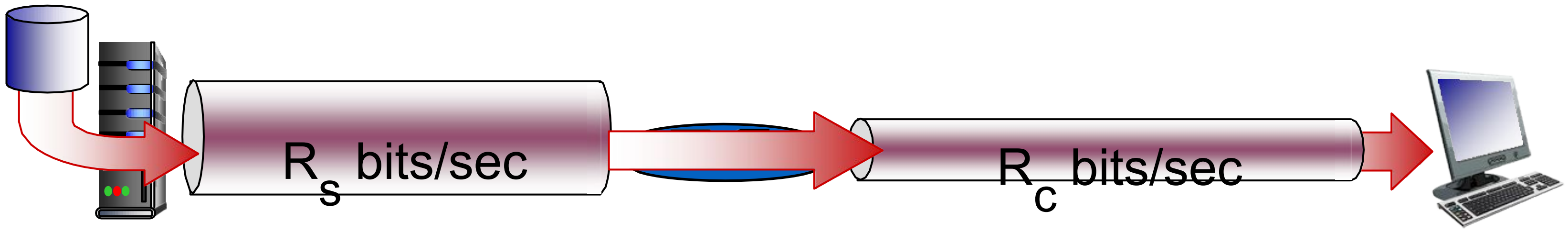
- $R_s > R_c$ The router will not be able to forward bits as quickly as it receives them. In this case, bits will only leave the router at rate R_c, giving an end-to-end throughput of R_c.



Throughput (contd.)

- Note also that if bits continue to arrive at the router at rate R_s, and continue to leave the router at R_C, the backlog of bits at the router waiting for transmission to the client will grow and eventually packet loss will occur

- Thus, for this simple two-link network, the throughput is min{R_C, R_s}, that is, **it is the transmission rate of the bottleneck link**

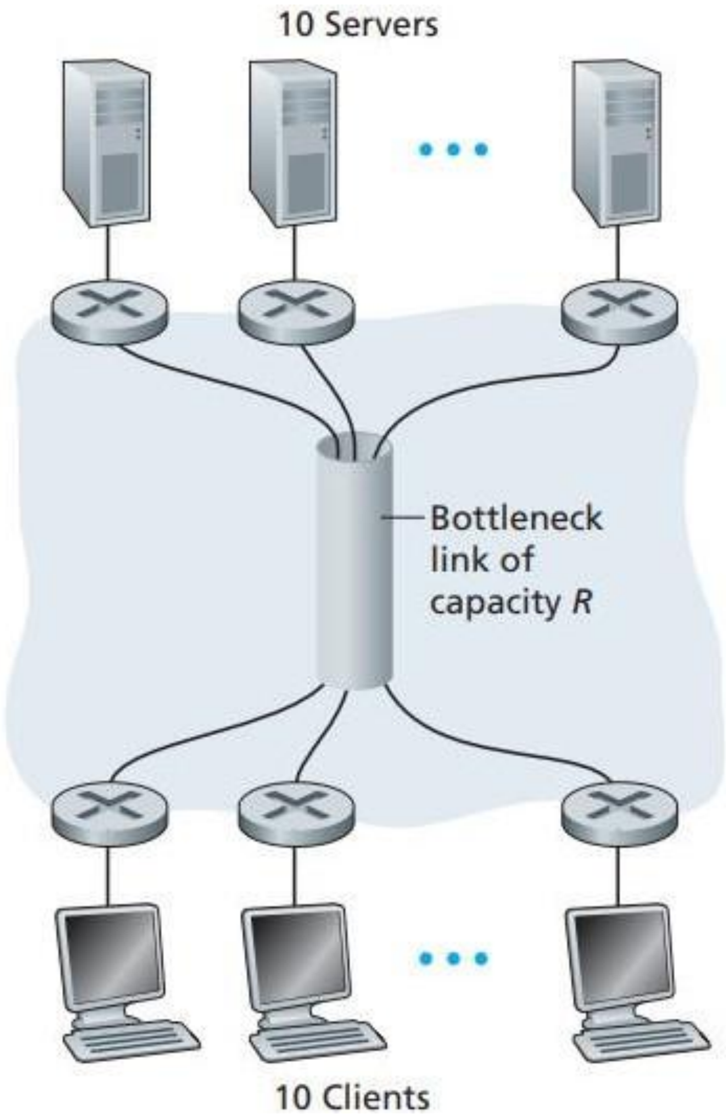


Throughput (contd.)

Consider 10 clients downloading from 10 servers

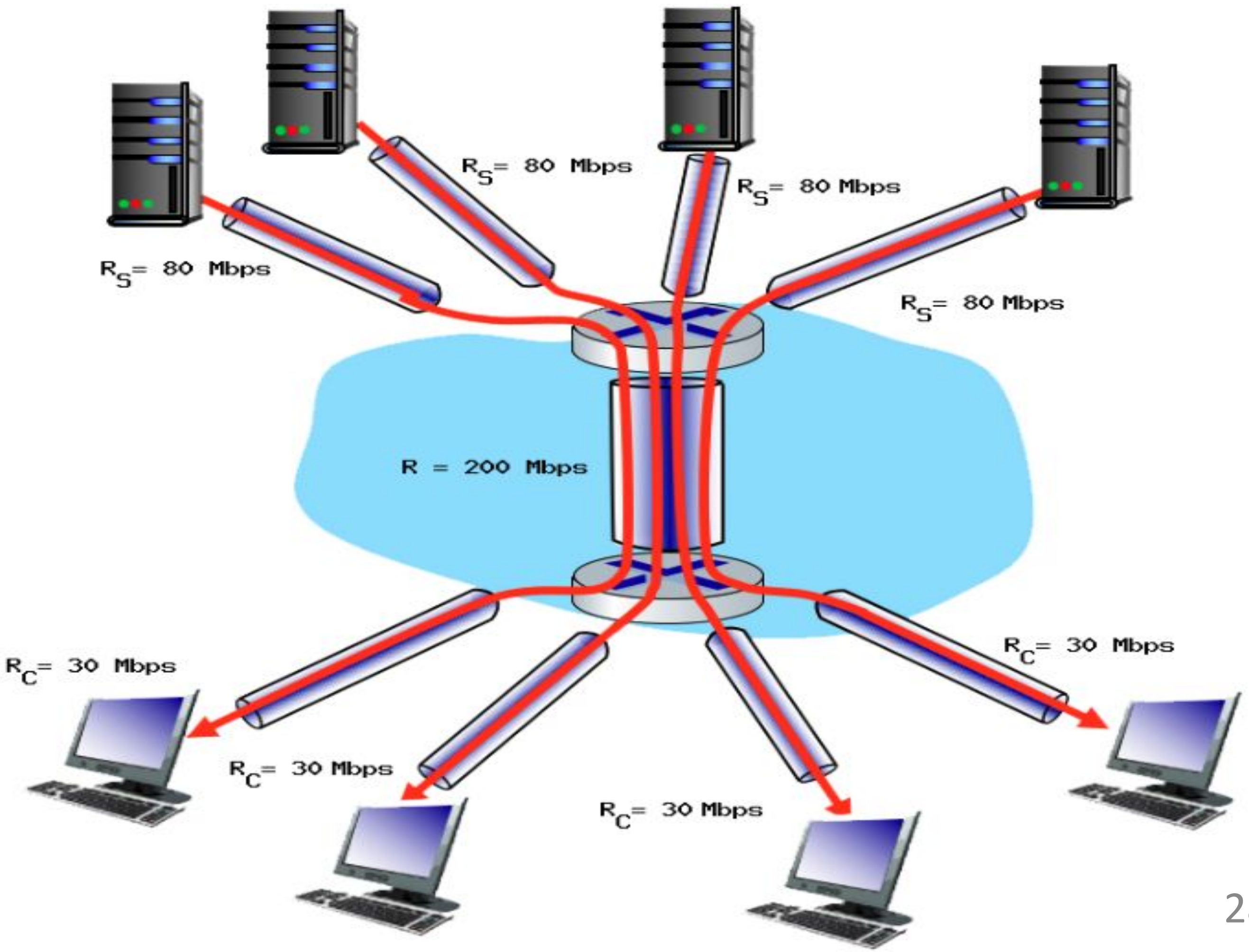
Assume bottleneck link is shared equally among different packet flows

Per-connection end-end throughput: $\min(R_c, R_s, R/10)$



Numerical 4:

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 = 200 Mbps. The four links from the servers to the shared link have a transmission capacity of R_S = 80 Mbps. Each of the four links from the shared middle link to a client has a transmission capacity of R_C = 30 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)?

The maximum achievable end-end throughput is the capacity of the link with the minimum capacity, which is 30 Mbps

2. Which link is the bottleneck link?

The bottleneck link is the link with the smallest capacity between R_S, R_C, and R/4. The bottleneck link is Rc.

Performance parameters

3. Assuming that the servers are sending at the maximum rate possible, what are the link utilizations for the server links (R_S)?

The server's utilization = $R_{bottleneck} / R_S = 30 / 80 = 0.38$

4. Assuming that the servers are sending at the maximum rate possible, what are the link utilizations for the client links (R_C)?

The client's utilization = $R_{bottleneck} / R_C = 30 / 30 = 1$

5. Assuming that the servers are sending at the maximum rate possible, what is the link utilizations for the shared link (R)?

The shared link's utilization = $R_{bottleneck} / (R / 4) = 30 / (200 / 4) = 0.6$

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Numerical 5:

Consider 10 users sharing a 3 Mbps link to a server based on TDMA. Suppose the frame duration is 4 milliseconds and 10% of each slot constitutes the guard time (i.e., silent period). What is the throughput per user? How much time will it take to transfer a file of size 100000 bits? Write appropriate formulae.

Solution:

Throughput per user = 0.3 Mbps

Slot duration = Frame duration / number of users = 4 ms/ 10 = 0.4 ms

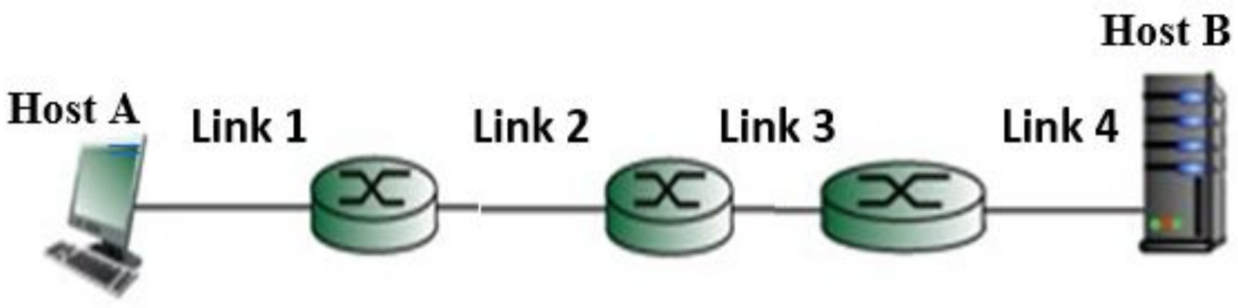
Effective transmission time = 90% of slot duration = 0.36 ms

Number of bits per user in a frame = Effective transmission time × throughput per user = 0.3 M* 0.36 m = 108 bits

Total time required = 100000/108 = 926 s

Numerical 6:

Calculate the total time taken in transmission of 20,000 bits from Host A to Host B. The data is divided into 4 packets of 5000 bits each. All four links have an identical rate of 2 Mbps and are 10 km long. Assume optical links, and no processing & queuing delays.



Performance parameters

Solution:

Speed of light (c_o) in optical fiber is approximately 70% the speed of light $c_o = 2 \times 10^8$

Propagation delay per link is $t_d = \frac{d}{c_o} = \frac{10\times10^3}{2\times10^8} = 50\mu s$ **(1 mark)**

Delay across 4 links = 0.200 ms

Transmission time for all the bits at host A is $t_t = \frac{Total\ bits}{R} = \frac{20000}{2\times10^6} = 0.01\ s = 10\ ms$ **(1 mark)**

The delay across the three routers will be calculated only for the last packet since queuing delays are considered zero. Thus the transmission time across the three routers is $3\frac{L}{R} = 3 \times \frac{5000}{2\times10^6} = 3 \times 0.0025\ s = 7.5\ ms$ **(2 marks)**

Total delay is $7.5\ ms + 10\ ms + 0.2\ ms = 17.7\ ms$ **(1 mark)**

THANK YOU

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