Computer Communication Networks (UE22EC351A)

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Unit 1 – Internet Architecture & Applications – Class 10 – Numerical Problems

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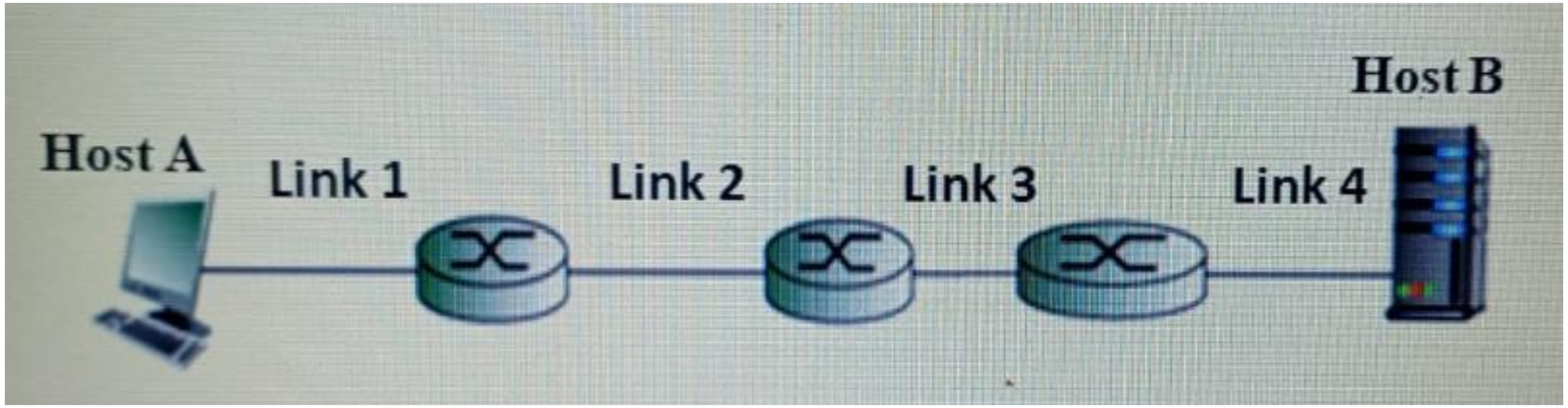
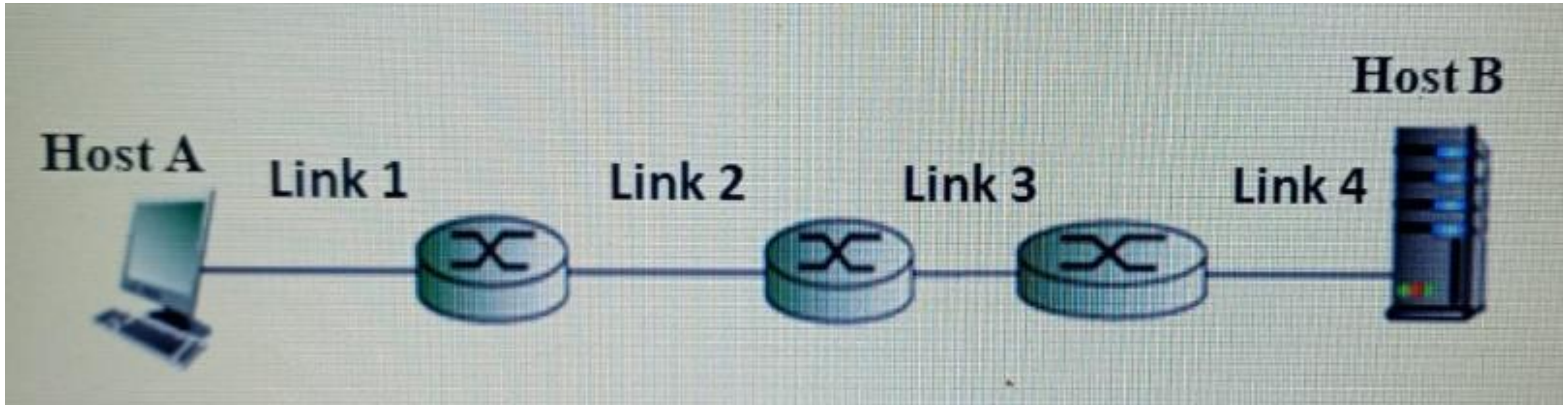
- 1) Suppose a file of 20,000 bits is to be transferred from Host A to Host B as shown in the figure. Suppose that data is divided into 4 packets of equal size. Suppose all four links have an identical rate of 2Mbps and are 10 km long. Assume Optical links, and no processing & queuing delays. Calculate the total time to deliver the packets?





- Speed of light (c_o) in optical fiber is approximately 70% of the speed of light $= c_o = 2 * 10^8$ m/s.
- Propagation delay per link is $t_d = \frac{d}{c_o} = \frac{10*10^3}{2*10^8} = 50\mu s$
- Delay across four links $= 4 * t_d = 4 * 50\mu = 0.200ms$

- 2) A user can directly connect to a server through either long-range wireless or a twisted-pair cable for transmitting a 1500 bytes file. The transmission rates of the wireless & wired media are 2 & 100 Mbps respectively. Assume that the propagation speed in air is 3*10^8 m/s, while the speed in the twisted pair is 2*10^8 m/s. If the user is located 1 km away from the server, what is the nodal delay when using each of the two technologies?
- Solution –

  - $d_{nodal} = d_{proc} + d_{queuing} + d_{trans} + d_{prop}$
  - Assuming processing delay & queuing delay to be negligible.

- 2) Solution –

- **Case 1 - Wireless media**
- $d_{trans} = \frac{L}{R} = \frac{1500}{2*10^6} = 0.75ms$
- $d_{prop} = \frac{d}{c_o} = \frac{1*10^3}{3*10^8} = 3.33\mu s$
- Therefore $d_{nodal} = 0.75m + 3.33\mu = 0.75ms$
- **Case 2 - Twisted-Pair Cable**
- $d_{trans} = \frac{L}{R} = \frac{1500}{100*10^6} = 15\mu s$
- $d_{prop} = \frac{d}{c_o} = \frac{1*10^3}{2*10^8} = 5\mu s$
- Therefore $d_{nodal} = 15\mu + 5\mu = 20\mu s$

- 3) Suppose Host A wants to send a large file to Host B. The path from Host A to Host B has three links, of rates R1 = 500 kbps , R2 = 2 Mbps , R3 = 1 Mbps.

  - Assuming no other traffic in the network, what is the throughput for the file transfer ?
  - Suppose the file is 4 million bytes. Dividing the file size by the throughput, roughly how long will it take to transfer the file to Host B?
  - Repeat (a) & (b), but now with R2 reduced to 100 kbps

- 4) Suppose N packets arrive simultaneously to a link at which no packets are currently being transmitted or queued. Each packet is of length L and the link has transmission rate R. What is the average queuing delay for the N packets?

- Solution - Each packet experiences a queuing delay which is equal to the sum of the transmission delays of the packets ahead of it in the queue.
- So packet 1 has 0 delay, packet 2 has L/R delay, …, packet N has (N-1)L/R delay.
- The average queuing delay is given by $(0+L/R+2L/R+\ldots+(N-1)L/R)/N = (L/R)\times(N-1)/2$

- 5) 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?

- 5) 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 $n \times L/R + (L-x)/R$.
- Based on the data given: the queuing delay = $4 \times 1500 \times 8/2M + (750 \times 8)/2M = 0.027$ sec

- 6) Suppose two hosts, A and B, are separated by 20000 kilometers and are connected by a direct link of 2 Mbps. Suppose the propagation speed over the link is $2.5x10^8$ meters/sec. Answer each sub-question with proper explanation, formulae, units and numerical values.
- How long does it take to send the file of 800,000 bits from host A to host B, assuming it is sent continuously?
- Suppose now the file is broken up into packets with each packet containing 40,000 bits. Suppose that each packet is acknowledged by the receiver and the transmission time of an acknowledgment packet is negligible. Finally, assume that the sender cannot send a packet until the preceding one is acknowledged. How long does it take to send the file?

- 6) Solution - Time taken to transfer one bit across the link (i.e., propagation delay) is given by d_p = d/s =0.08 sec
- Time taken for host A to push one bit onto the link (i.e., one bit time) is given by τ= 1/R = 1/ = 0.5 µs
- By the time the first bit has propagated to host B, the number of bits on the link is given by d_p/τ = R*d_p =160000 bits
- The transmission delay of the entire file is given by d_t = L/R =0.4 sec
- Total time required to send the file from host A to host B will be d_t + d_p = 0.48 sec

- 6) Solution - Since each packet is transmitted one at a time after acknowledgement is received for the previous packet, the total time taken to transmit the file is given by
- $d_{total} = N*(d_t' + d_p)$
- Here, N = 800000/40000 =20 is the number of packets generated by host A
- The transmission delay of each packet is given by $d_t' = L'/R = = 0.02$ sec
- Hence, d_{total} =2 sec

- 7) 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.
- Swap links 1 and 2 and solve the problem. Compare the queuing delay incurred by the 2nd packet with the above problem.

- 7) 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

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

- 7) Solution - In the 1st problem (2nd table in the slide), there was zero queuing delay as 2nd packet always arrived to an empty queue in each router.
- 2nd problem
- When the links 1 and 2 are swapped, then the columns of 1st table in the slide are swapped.
- In this case, packet 1 reaches 1st router at 0.4 seconds. And it takes 1.6 seconds from then onwards to leave the 1st router (i.e., at 2 seconds packet 1 reaches 2nd router). However, while packet 2 is being transmitted packet 1 has reached at 0.65 seconds (i.e., 0.4+0.25) therefore, it has to wait for 1.35 seconds (i.e., time when packet 1 was pushed out minus time when packet 2 arrived = 2 – 0.65 = 1.35 seconds).

- 7) Solution - Now examine the 2nd router.
- Packet 1 is pushed out of 2nd router at 2.8 seconds (i.e., 2+time to push packet 1 on link 3 =2+0.8 =2.8 seconds).
- Packet 2 is fully received by 2nd router only at 3 seconds (i.e., time when packet 1 was pushed out + time taken to push out packet 2 on link 2 = 2 + 1 = 3).
- From this we notice that the 2nd packet was ready to be forwarded as soon as it was stored. Therefore, there was no queuing delay.

- 7) Solution - So the overall queuing delay is equal to 1.35 seconds which was incurred at 1st router because the incoming rate (2Mbps) is more than the outgoing rate (500kbps).
- Note that queuing delay is calculated only after all the bits of a packet are fully received (i.e., after the full packet are stored).
- The queuing delay can be eliminated if the packet transmission is done at a rate of at most 500 kbps (i.e., the lowest link rate along the path between the source and the destination in this example).
- This can be done by reducing the packet sizes to below 500 kb in this example. For a packet size ≥ 500 kb, throughput is always less than 500 kbps. That is why message segmentation can improve throughput.

- 8) 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 $\{L_1 ..., L_P\}$ bits to transmit to host B. Assume that the processing delays and propagation delays are negligible.
- Calculate the end-end delay in transmitting P packets. Explain your calculation.

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.

- 8) Solution of end to end delay with 1 router

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 router 1. 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.

- 8) Solution of end to end delay with 1 router (contd.)

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 $\sum_{i=1}^{P} \frac{L_i}{R} + max\left(\frac{L_1}{R}, \ldots, \frac{L_P}{R}\right)$.

- 8) Solution of end to end delay with M routers

Case 1: Three packets are transmitted by host A ($L_1 > L_2 \wedge L_3$) 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 ($L_2 > L_1 \wedge L_3$) and $M = 2$ routers
Applying the same logic as case 1, the end to end delay is $\frac{L_1}{R} + 3\frac{L_2}{R} + \frac{L_3}{R}$.

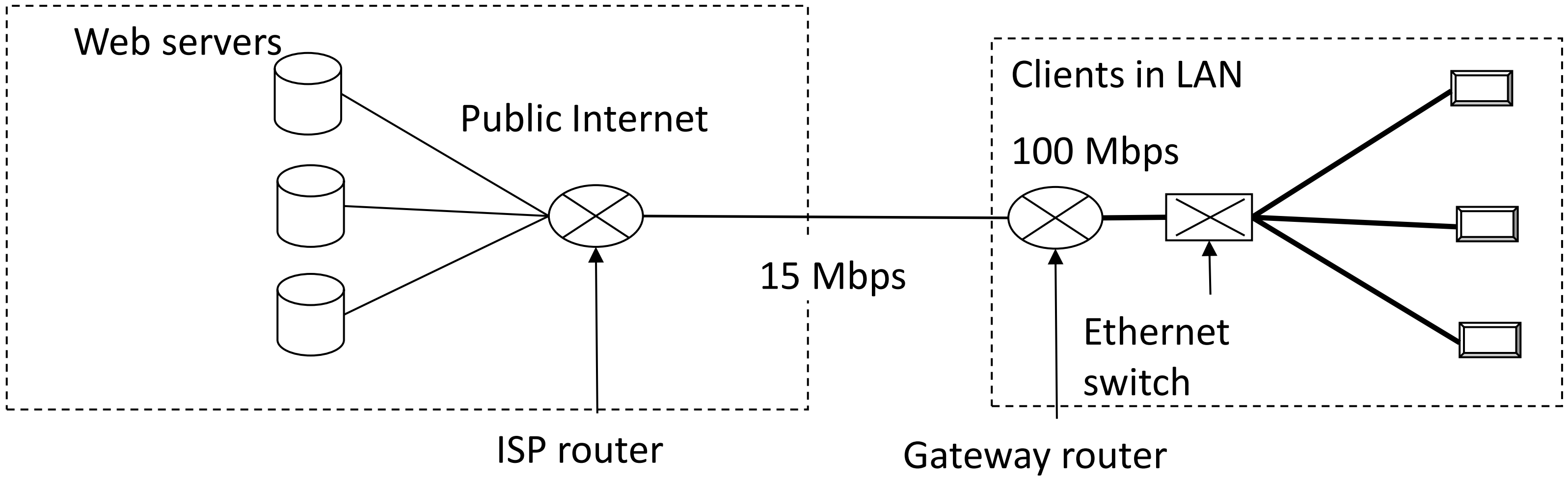
- 8) Solution of end to end delay with M routers (contd.)

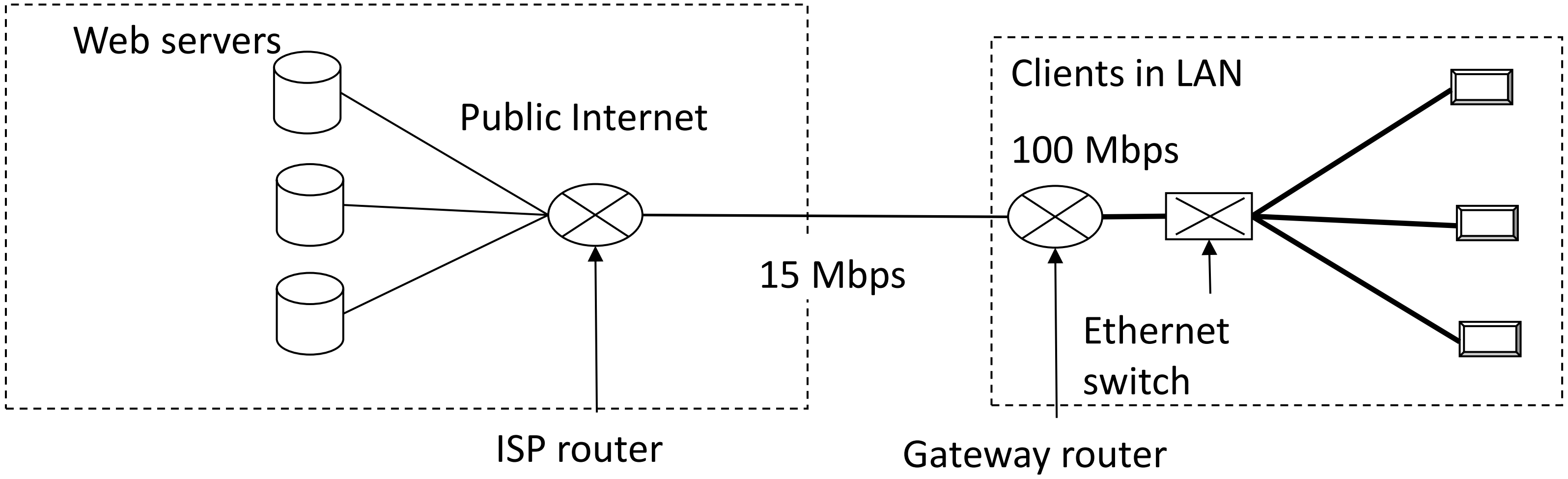
Case 5: Three packets are transmitted by host A ($L_3 > L_1 \wedge L_2$) and $M = 2$ routers

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

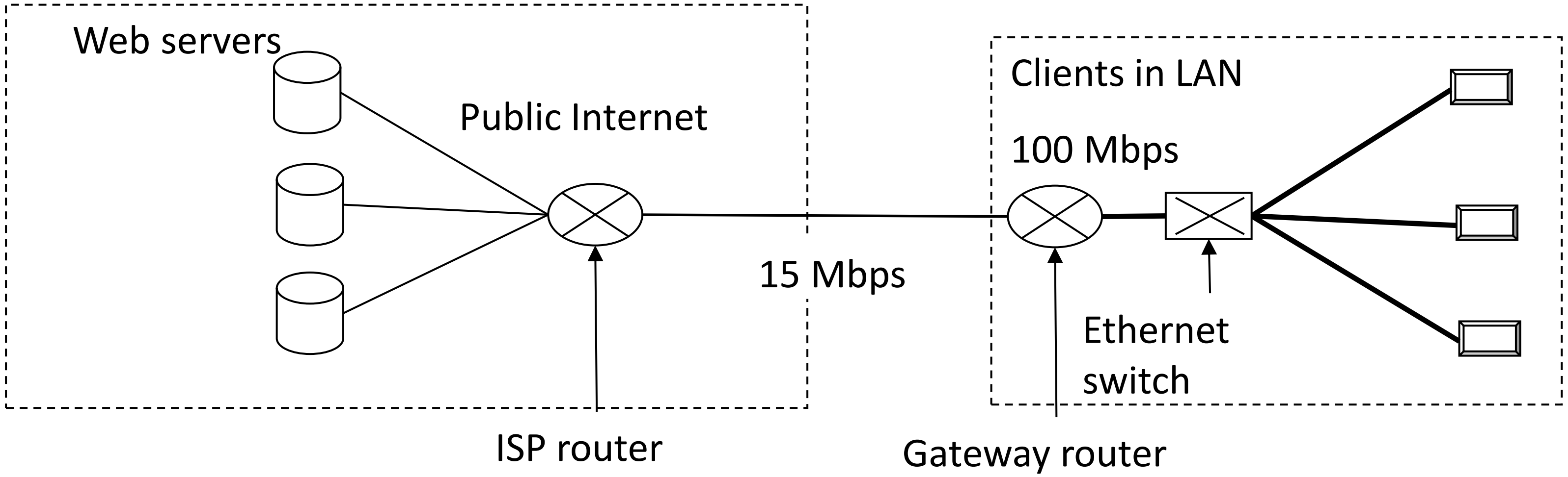
Based on the above cases, a general expression for the end-end delay for transmitting P variable length packets over M routers is equal to $\sum_{i=1}^{P} \frac{L_i}{R} + M \cdot max\left(\frac{L_1}{R}, \ldots, \frac{L_P}{R}\right)$.

- 9) Consider the case (refer figure below) where clients in a LAN request for objects of size 850,000 bits from web servers over the public internet. The LAN generates 16 requests/second on average. Assume the internet delay (RTT between ISP router and web servers) to be equal to 3 seconds.

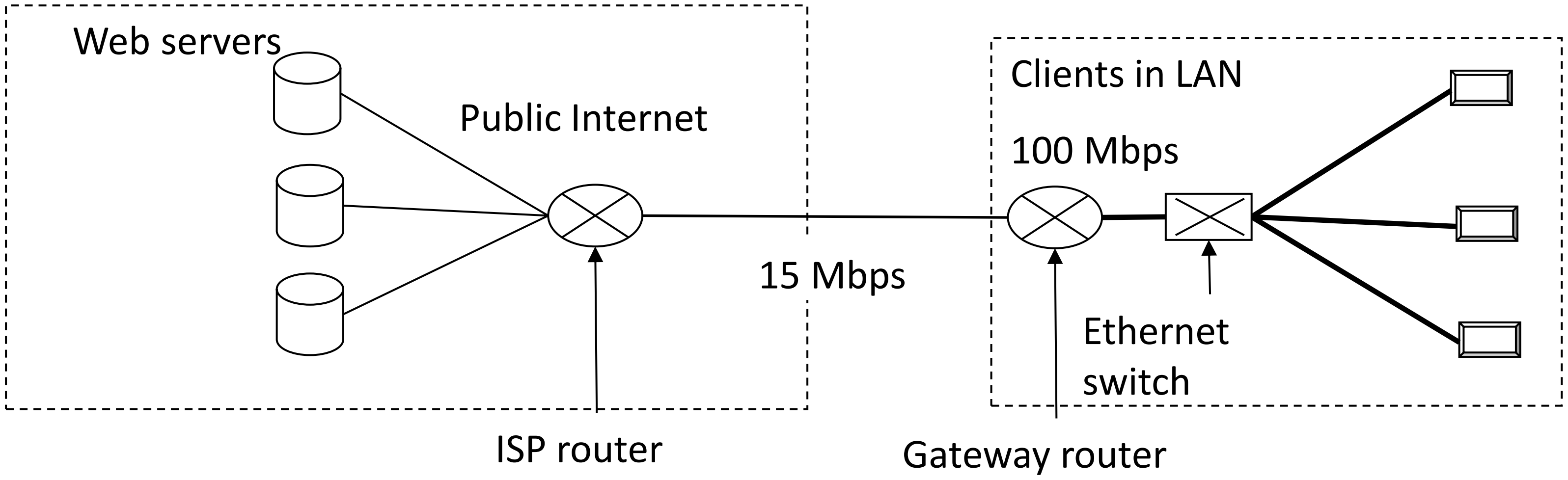




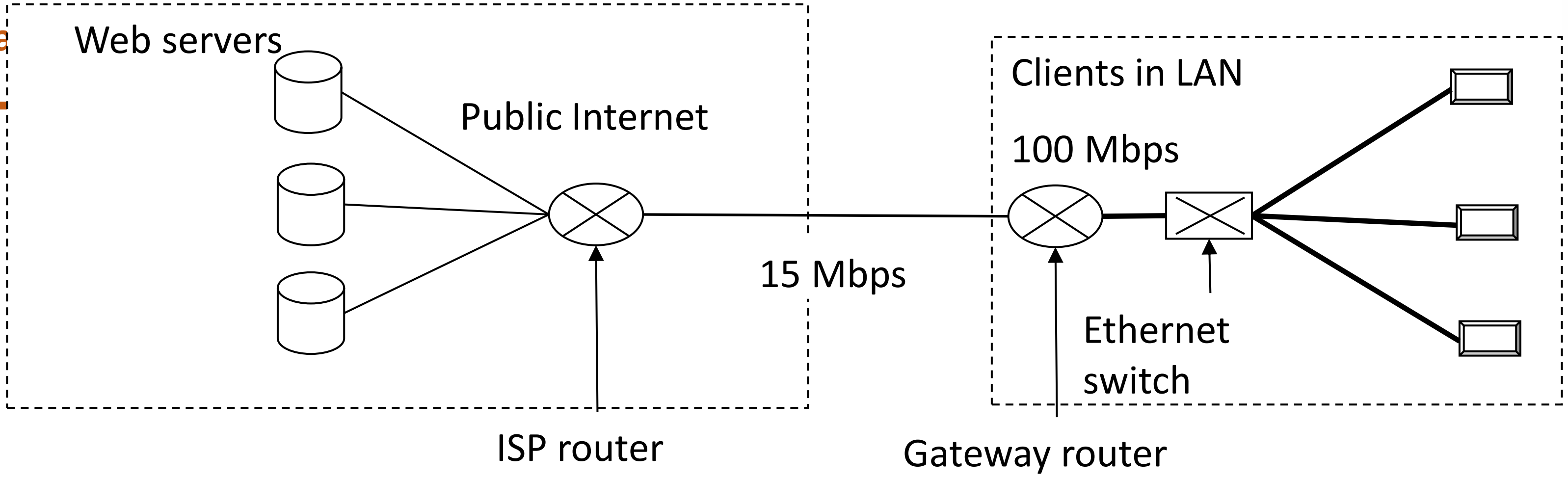
- 9) i) Calculate the total response time assuming negligible time for sending HTTP requests across the LAN and access link. Assume negligible processing delay, transmission delays and propagations delay in the LAN (local area network).



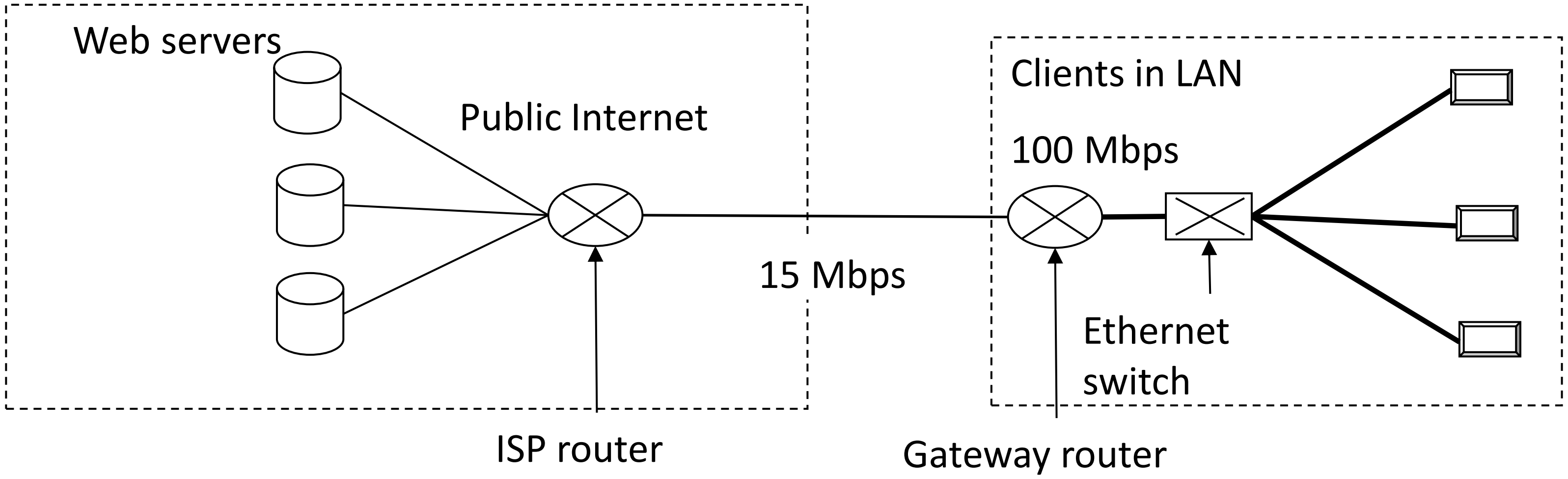
- 9) ii) Calculate traffic intensity at the two routers when downloading the objects.
- iii) At what rate of requesting will packet losses start occurring?
- [<u>*Hint:*</u> *Total response time = queuing delay at the gateway router + queuing delay at the ISP router + internet delay. Calculate queuing delay as 1/(transmission rate-arrival rate).*]



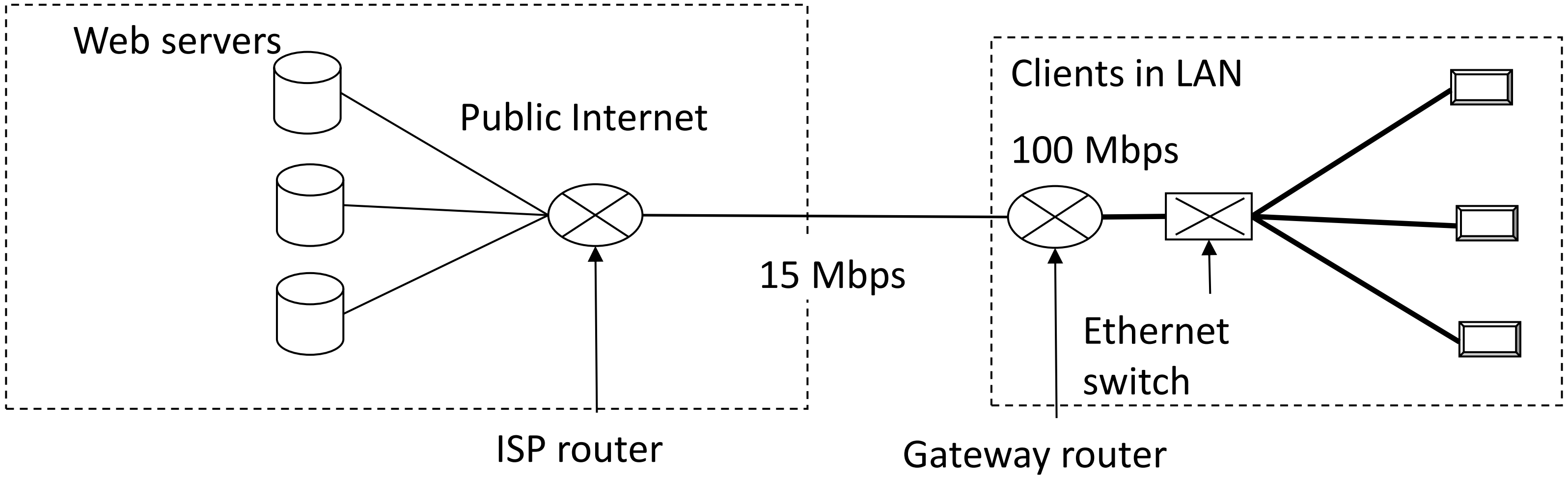
- 9) Solution - Based on the given information, the delay in getting the HTTP requests to reach the ISP can be ignored. So the total response time can be approximated to RTT between ISP router and web servers + queuing delay at the ISP router + queuing delay at gateway router.



- 9) Solution - <u>Calculation of the queuing delay at the ISP router:</u>
- Arrival rate at the ISP router is same as that corresponding to the rate of HTTP requests.
- Length of an object (L) = 850,000 bits.
- Arrival rate at the ISP router λ_1= (16 requests / sec)* (0.85 M bits) = 13.6 Mbps
- Transmission rate of the ISP router R_1 = 15 Mbps.
- Queuing delay at the ISP router = $1/(R_1-\lambda_1)$ = 0.714 s



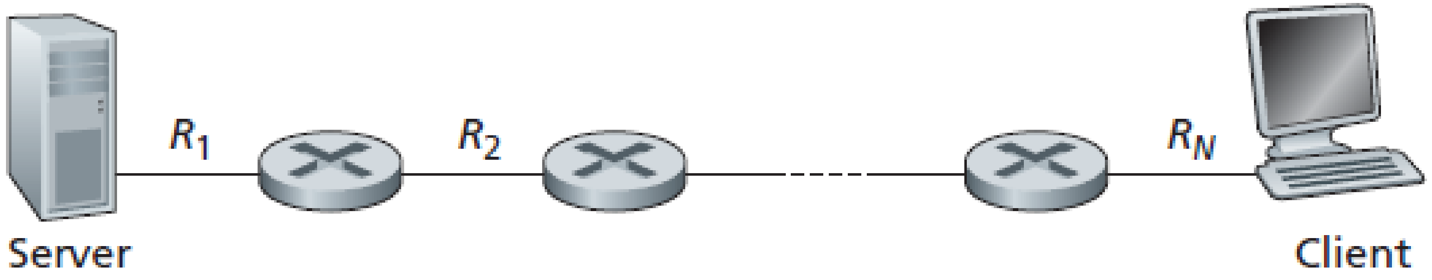
- 9) Solution - <u>Calculation of the queuing delay at Gateway router:</u>
- Arrival rate at the gateway router will be same as that at the ISP router as $R_1 > \lambda_1$
- Transmission rate at the gateway router R_2 = 100 Mbps.
- Queuing delay at the gateway router = $1/(R_2 - \lambda_1)$ = 0.01157 µs



- 9) Solution - <u>Traffic intensity = arrival rate / transmission rate</u>
- Traffic intensity at the gateway router = λ_1/R_2 = 0.316
- Traffic intensity at the ISP router = λ_1 / R_1 = 0.91

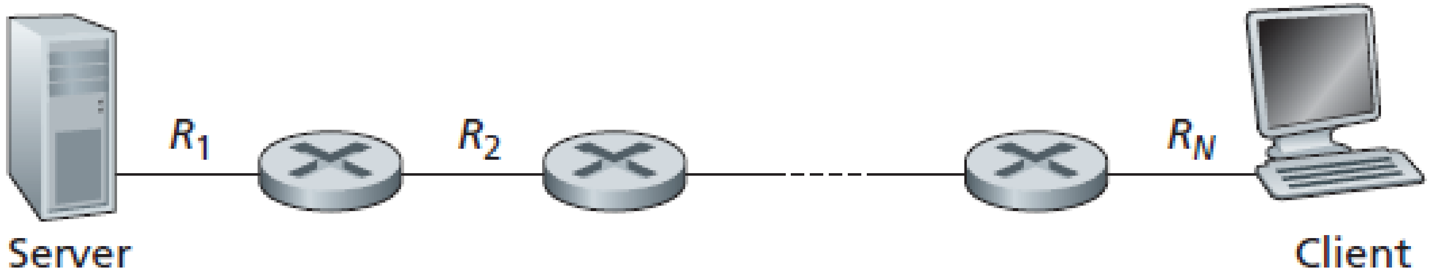
- Packet losses will start occuring when λ_1 and R_1 becomes equal. So the smallest rate of requests for packet loss to occur is R_1 / L = 17.65 requests/sec

- 10) Consider the figure below. Now suppose that there are M paths between the server and the client. No two paths share any link. Path k (k = 1, . . ., M) consists of N links with transmission rates R^k_1, R^k_2, . . ., R^k_N. If the server can only use one path to send data to the client, what is the maximum throughput that the server can achieve? If the server can use all M paths to send data, what is the maximum throughput that the server can achieve?

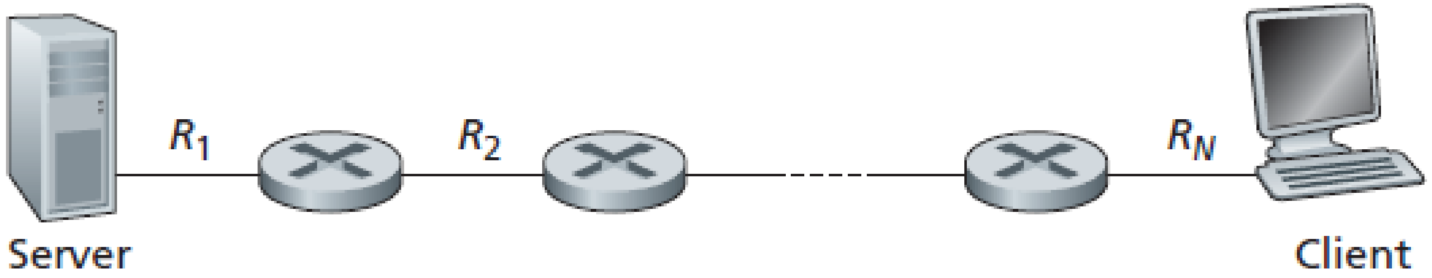


- 10) Solution - The maximum throughput if only one of the paths can be used is $\max(\min(R^1_1, R^1_2, \ldots, R^1_N), \ldots, \min(R^M_1, R^M_2, \ldots, R^M_N))$

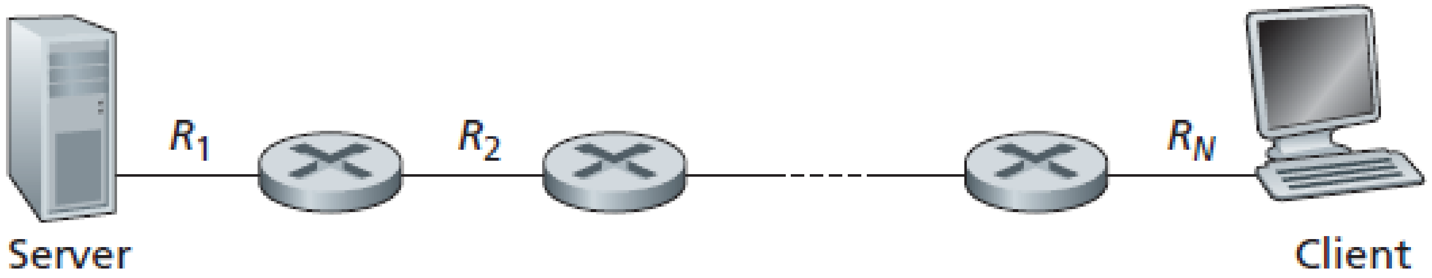
The maximum throughput if all the M paths can be used is $\min(R^1_1, R^1_2, \ldots, R^1_N) + \min(R^2_1, R^2_2, \ldots, R^2_N) + \ldots + \min(R^M_1, R^M_2, \ldots, R^M_N)$

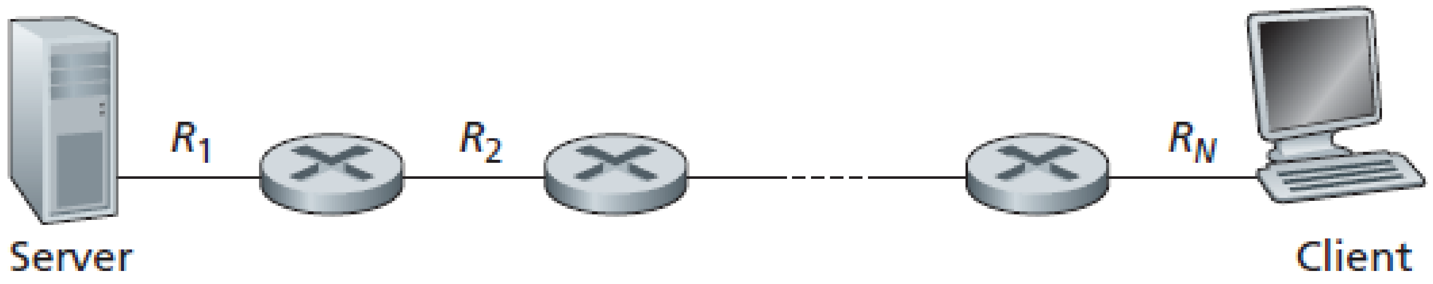


- 11) Suppose that each link between the server and the client has a packet loss probability p, and the packet loss probabilities for these links are independent.
  - What is the probability that a packet (sent by the server) is successfully received by the receiver?



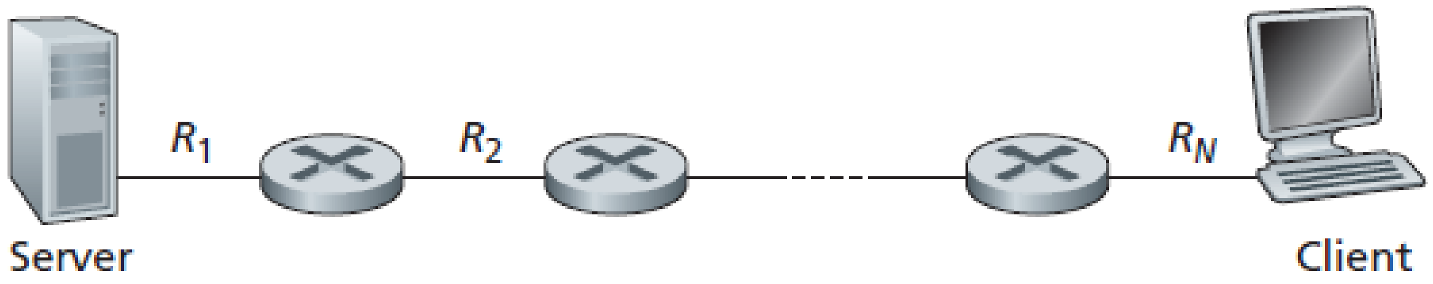
- 11) If a packet is lost in the path from the server to the client, then the server will re-transmit the packet. On average, how many times will the server re-transmit the packet in order for the client to successfully receive the packet?





- 11) Solution - Given the packet loss probability on a link is given by p. As the packet loss probabilities are given to be independent, the probability that a packet successfully traversed the path is given by P(success) = $(1-p)^N$.

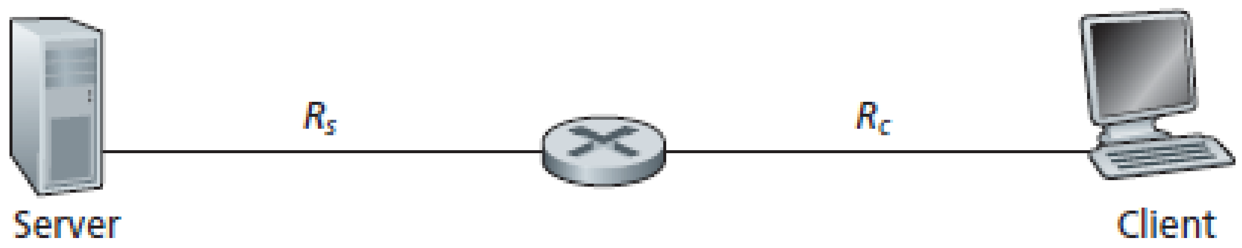
- P(success in i rounds of transmission) = $(1-P(success))^{i-1} \times P(success) = (1-(1-p)^N)^{i-1} (1-p)^N$.



- 11) Solution - As this is a geometric distribution, the mean number of rounds required for success = 1/P(success)

- Hence, the mean no. of retransmissions (i.e., transmissions excluding the first transmission) = 1/P(success) - 1

- 12) Assume that we know the bottleneck link along the path from the server to the client is on the first link at rate R_s bits/sec. Suppose we send a pair of packets back to back from the server to the client, and there is no other traffic on this path. Assume each packet is of size L bits, and both links have the same propagation delay d_{prop}.
  - What is the packet inter-arrival time at the destination?



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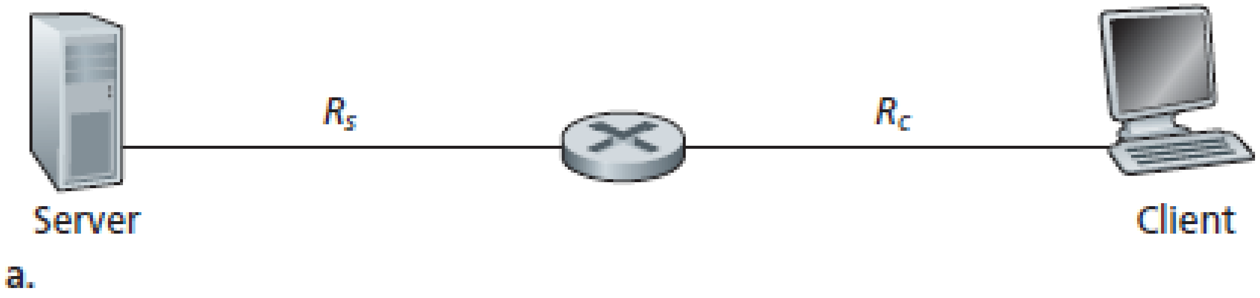
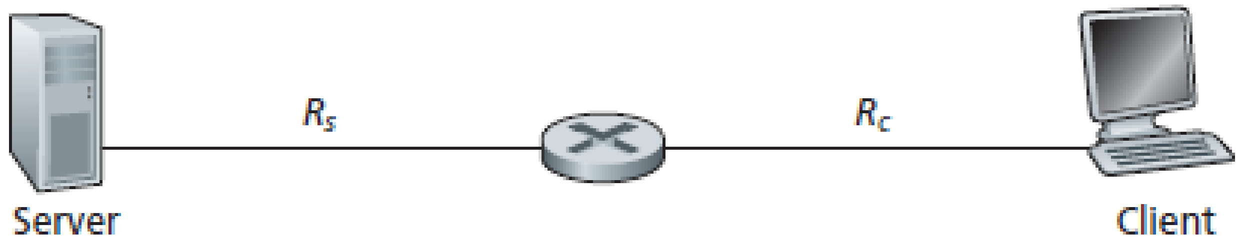
- 12) Solution - The inter-arrival time is L/R_s at the router because the second packet transmission commences only after the last bit of first packet has been pushed out by the server. The propagation delay has no impact here as every bit experiences the same d_{prop}
- As the bottle neck is link 1 (R_s is smaller than R_c), no queuing delay occurs at the router, so the inter-arrival time remains the same at the client.



- 12) Continued Now assume that the second link is the bottleneck link (i.e., $R_c < R_s$). Is it possible that the second packet queues at the input queue of the second link? Explain.
- Now suppose that the server sends the second packet T seconds after sending the first packet. How large must T be to ensure no queuing before the transmission on the second link to the client to successfully receive the packet? Explain



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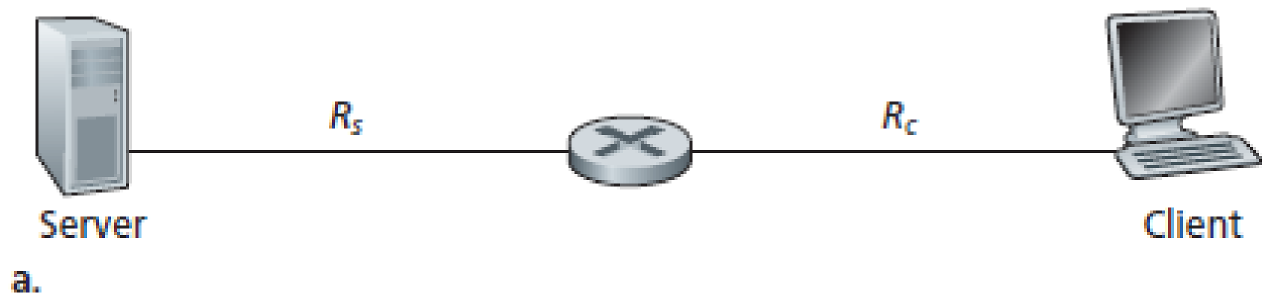

- 12) Solution - Second packet arrives at the router at $L/R_s + L/R_s + d_{prop}$. However, as R_c is less than R_s, the first packet is being transmitted and so second packet has to wait resulting in queuing delay.

- It takes $L/R_s + L/R_c + d_{prop}$ for the first packet to be pushed out of the router. Therefore, the waiting time for the second packet at the router is departure time of first packet minus arrival time of second packet which is equal to $(L/R_s + L/R_c + d_{prop}) – (L/R_s + L/R_s + d_{prop}) = L/R_c – L/R_s$. So queuing delay can be avoided at the router if the second packet at the server is transmitted after a delay of at least $T = L/R_c – L/R_s$

THANK YOU

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