P2. Equation 1.1 gives a formula for the end-to-end delay of sending one packet of length L over N links of transmission rate R (d[end-to-end] = N*(L/R)).Generalize this formula for sending P such packets back-to-back over the N links.

PN*(L/R)

P3. Consider an application that transmits data at a steady rate (for example, the sender generates an N-bit unit of data every k time units, where k is small and fixed). Also, when such an application starts, it will continue running for a relatively long period of time. Answer the following questions, briefly justifying your answer:

a. Would a packet-switched network or a circuit-switched network be more appropriate for this application? Why?

   Circuit switched for more consistency and guaranteed performance

b. Suppose that a packet-switched network is used and the only traffic in this network comes from such applications as described above. Furthermore, assume that the sum of the application data rates is less than the capacities of each and every link. Is some form of congestion control needed? Why?

   No. Queueing delay needed only if arrival rate exceeds transmission rate

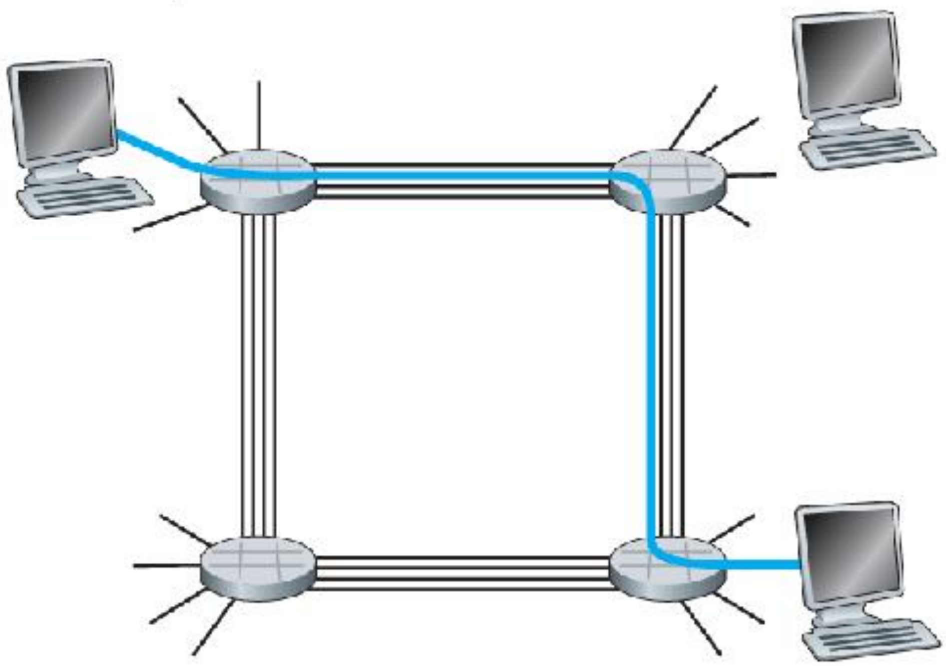

Figure 1.13 ♦ A simple circuit-switched network consisting of four switches and four links

P4. Consider the circuit-switched network in Figure 1.13. Recall that there are 4 circuits on each link. Label the four switches A, B, C and D, going in the clockwise direction.

a. What is the maximum number of simultaneous connections that can be in progress at any one time in this network?

   16

b. Suppose that all connections are between switches A and C. What is the maximum number of simultaneous connections that can be in progress?

   8

c. Suppose we want to make four connections between switches A and C, and another four connections between switches B and D. Can we route these calls through the four links to accommodate all eight connections?

   Yes, send 2 connections off in both directions starting at A, and do the same starting at B

P6. This elementary problem begins to explore propagation delay and transmission delay, two central concepts in data networking. Consider two hosts, A and B, connected by a single link of rate R bps. Suppose that the two hosts are separated by m meters, and suppose the propagation speed along the link is s meters/sec. Host A is to send a packet of size L bits to Host B.

a. Express the propagation delay, dprop, in terms of m and s.

   m/s

b. Determine the transmission time of the packet, dtrans, in terms of L and R.

   L/R

c. Ignoring processing and queuing delays, obtain an expression for the endto-end delay.

   D[prop] + d[trans] = m/s + L/R

d. Suppose Host A begins to transmit the packet at time t = 0. At time t = dtrans, where is the last bit of the packet?

   On the physical wire and not with Host A

e. Suppose dprop is greater than dtrans. At time t = dtrans, where is the first bit of the packet?

   S*d[trans] distance down the link

f. Suppose dprop is less than dtrans. At time t = dtrans, where is the first bit of the packet?

   At Host B

g. Suppose s = 2.5 · 10^8, L = 120 bits, and R = 56 kbps. Find the distance m so that dprop equals dtrans.

   m/s = L/R
   m/(2.5*10^8) = 120b/56000bps
   m = 535714.28

P8. Suppose users share a 3 Mbps link. Also suppose each user requires 150 kbps when transmitting, but each user transmits only 10 percent of the time.

a. When circuit switching is used, how many users can be supported?

   3 Mbps -> 3,000,000 bps
   150 kbps -> 150,000 bps
   3000000/150000 = 20 users

b. For the remainder of this problem, suppose packet switching is used. Find the probability that a given user is transmitting.

   10% = 0.1

In question 8.c & 8.d, it is enough to show the formula/equation without calculating the final value

c. Suppose there are 120 users. Find the probability that at any given time, exactly n users are transmitting simultaneously. (Hint: Use the binomial distribution.)

$$P_x = \binom{n}{x} p^x q^{n-x}$$

$$P_x = \binom{120}{x} p^x (1-q)^{120-x}$$

d. Find the probability that there are 21 or more users transmitting simultaneously.

P10. Consider a packet of length L which begins at end system A and travels over three links to a destination end system. These three links are connected by two packet switches. Let di , si , and Ri denote the length, propagation speed, and the transmission rate of link i, for i = 1, 2, 3. The packet switch delays each packet by d proc.

Assuming no queuing delays, in terms of di , si , Ri , (i = 1,2,3), and L, what is the total end-to-end delay for the packet?

A---o—o--B

D[prop] = L/R

D[trans] = d/s

T = $(\frac{L}{R}+\frac{d}{s})_1$ + $(\frac{L}{R}+\frac{d}{s})_2$ + $(\frac{L}{R}+\frac{d}{s})_3$ + 2*d[proc]

Suppose now the packet is 1,500 bytes, the propagation speed on all three links is 2.5 · 108 m/s, the transmission rates of all three links are 2 Mbps, the packet switch processing delay is 3 msec, the length of the first link is 5,000 km, the length of the second link is 4,000 km, and the length of the last link is 1,000 km. For these values, what is the end-to-end delay?

T = $(\frac{1500}{2,000,000}+\frac{5,000,000}{2.5*10^8})$ + $(\frac{1500}{2,000,000}+\frac{4,000,000}{2.5*10^8})$ + $(\frac{1500}{2,000,000}+\frac{1,000,000}{2.5*10^8})$ + 2*0.003

T = 0.04825s

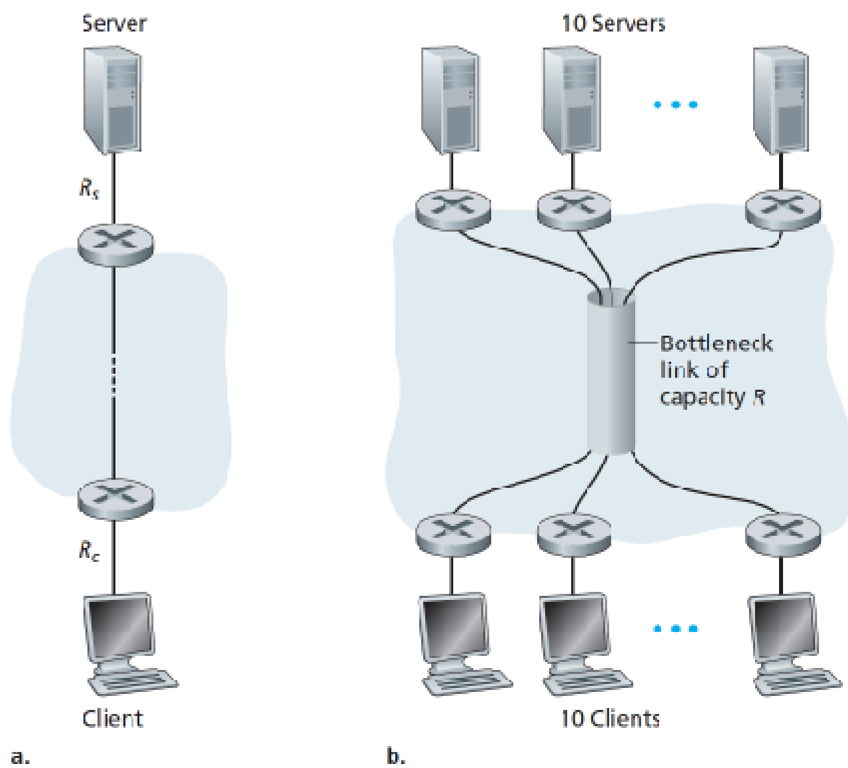

Figure 1.20 ♦ End-to-end throughput: (a) Client downloads a file from server; (b) 10 clients downloading with 10 servers

P20. Consider the throughput example corresponding to Figure 1.20(b). Now suppose that there are M client-server pairs rather than 10. Denote Rs , Rc , and R for the rates of the server links, client links, and network link. Assume all other links have abundant capacity and that there is no other traffic in the network besides the traffic generated by the M client-server pairs. Derive a general expression for throughput in terms of Rs , Rc , R, and M

min (R c , R s , R/M)

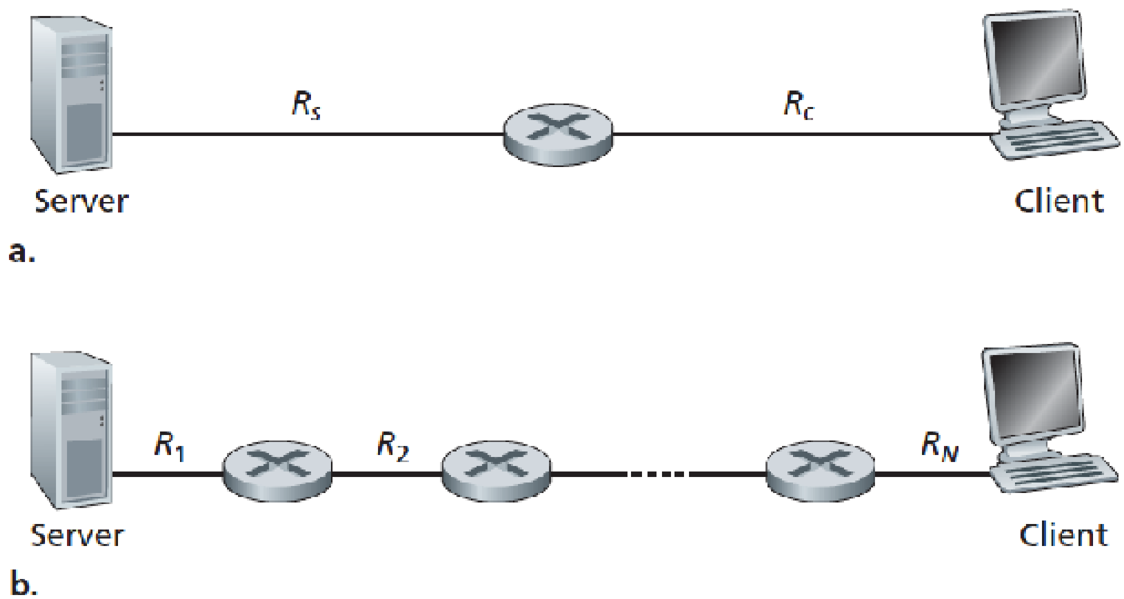

Figure 1.19 ♦ Throughput for a file transfer from server to client

P23. Consider Figure 1.19(a). Assume that we know the bottleneck link along the path from the server to the client is the first link with rate Rs 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 of size L bits, and both links have the same propagation delay d prop.

a. What is the packet inter-arrival time at the destination? That is, how much time elapses from when the last bit of the first packet arrives until the last bit of the second packet arrives?

   3*L/Rs + L/Rc + 2d[prop]

b. Now assume that the second link is the bottleneck link (i.e., Rc < Rs). 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 second link? Explain.

It is possible that the second packet queues at the input queue of the second link if the arrival rate (in bits) to link 2 exceeds transmission rate (capacity) for a period of time. To prevent this, the sever must send the second packet so that it arrives at link 2 after packet 1 has left the output queue of link 2 and has gone far enough on the link as to allow all of packet 2 to be transmitted

T = L/Rs + 2*L/Rc + 2d[prop]

P25. Suppose two hosts, A and B, are separated by 20,000 kilometers and are connected by a direct link of R = 2 Mbps. Suppose the propagation speed over the link is 2.5 * 10^8 meters/sec.

a. Calculate the bandwidth-delay product, R * dprop.

   R * m/s = 2 * (20,000,000/2.5*10^8) = 0.16 Mb

b. Consider sending a file of 800,000 bits from Host A to Host B. Suppose the file is sent continuously as one large message. What is the maximum number of bits that will be in the link at any given time?

   D[prop] = 0.08 s
   R = 2 Mbps = 2,000,000 bps
   160,000 bits

c. Provide an interpretation of the bandwidth-delay product.

   The maximum amount of bits allowed to be propagated onto a link

d. What is the width (in meters) of a bit in the link? Is it longer than a football field?

   20,000,000 m / 160,000 b = 125 m (> football field (91.44m))

e. Derive a general expression for the width of a bit in terms of the propagation speed s, the transmission rate R, and the length of the link m.

   W = m / [R * (m/s)] = s / R

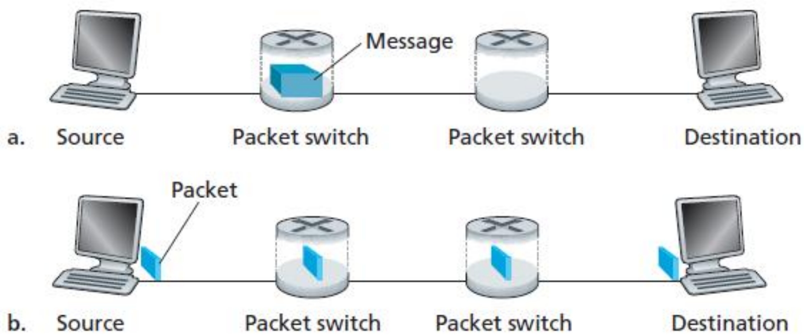

Figure 1.27 ♦ End-to-end message transport: (a) without message segmentation; (b) with message segmentation

P31. In modern packet-switched networks, including the Internet, the source host segments long, application-layer messages (for example, an image or a music file) into smaller packets and sends the packets into the network. The receiver then reassembles the packets back into the original message. We refer to this process as message segmentation. Figure 1.27 illustrates the end-to-end transport of a message with and without message segmentation. Consider a message that is 8 · 10^6 bits long that is to be sent from source to destination in Figure 1.27. Suppose each link in the figure is 2 Mbps. Ignore propagation, queuing, and processing delays.

a. Consider sending the message from source to destination without message segmentation. How long does it take to move the message from the source host to the first packet switch? Keeping in mind that each switch uses store-and-forward packet switching, what is the total time to move the message from source host to destination host?

   d[trans] = L/R = 8,000,000/2,000,000 = 4 sec

b. Now suppose that the message is segmented into 800 packets, with each packet being 10,000 bits long. How long does it take to move the first packet from source host to the first switch? When the first packet is being sent from the first switch to the second switch, the second packet is being sent from the source host to the first switch. At what time will the second packet be fully received at the first switch?

   Packet1 -> switch1: 10,000/2,000,000 = 0.005 sec
   Packet2 -> switch1: 2 * (10,000/2,000,000) = 0.010 sec

c. How long does it take to move the file from source host to destination host when message segmentation is used? Compare this result with your answer in part (a) and comment.

   Packet1 -> destination: 0.015 sec
   Rest (every 0.005 sec, a packet arrives at destination): 799 * 0.005 sec = 3.995 sec
   Total = packet1 + rest = 4.01 sec

P33. Consider sending a large file of F bits from Host A to Host B. There are three links (and two switches) between A and B, and the links are uncongested (that is, no queuing delays). Host A segments the file into segments of S bits each and adds 80 bits of header to each segment, forming packets of L = 80 + S bits. Each link has a transmission rate of R bps. Find the value of S that minimizes the delay of moving the file from Host A to Host B. Disregard propagation delay.

A -------------------------- o -------------------------- o -------------------------- B

F = total bits

S = segment bits

F/S = num segments

L = 80 + S bits per packet

R = R bps

Packet -> destination: 3L/R sec
Rest (every L/R sec, a packet arrives at destination): [(F/S) – 1] * L/R sec
Total delay = packet1 + rest
= 3L/R + [(F/S) – 1] * L/R sec
= 3(80 + S) / R + [(F/S) – 1] * (80 + S) / R
d[total] = $\frac{3(80+S)+\left[\left(\frac{F}{S}\right)-1\right]*L}{R}$
R * d = $3(80+S)+\left[\left(\frac{F}{S}\right)-1\right]*L$
Rd = 240 +3S + [(F-S) / S] * L
Rd = 240 +3S + (LF – LS) / S
Rd = 240 + 3S +LF/S – L
Rd – 240 + L = 3S + LF/S