

**CSE 473S – Introduction to Computer Networks – Fall 2006**

**Exam 2**

Problems, Solutions, and Grading Guidelines

Problem 1 (10 points). A TCP client receives an uncorrupted segment with sequence number 92 and plain-text word "networking" as data. The segment arrives in order, and the client responds immediately by sending a segment to the server. Which number does the responding segment contain in its acknowledgment field?

**Solution:** *TCP counts in bytes. Since the 10 more bytes are delivered in order and numbered 92 through 101, the responding segment contains 102 in the acknowledgment field.*

**Grading guidelines:**

6 points for recognizing that TCP counts in bytes.

4 points for providing the correct answer of 102.

Problem 2 (15 points). In the considered packet-switched store-and-forward network, a client requests an object by sending a packet of size  $L$ , and a server supplies the requested object by sending a packet of size  $2L$ . At time 0, client  $A$  requests two objects from server  $C$  via router  $B$ . Link  $AB$  has capacity  $R$  and propagation delay  $2d$ . Link  $BC$  has capacity  $2R$  and propagation delay  $d$ . Nodal processing delays are negligible. There is no other traffic in the network. When does the client receive the first object? When does the client receive the second object?

Show your derivations. Use mathematical expressions, not their verbal descriptions. Simplify your final analytical expressions. Explain (briefly) your reasonings.

**Solution:** *Transmission delays for links  $AB$ ,  $BC$ ,  $CB$ , and  $BA$  are  $t_{AB} = \frac{L}{R}$ ,  $t_{BC} = \frac{L}{2R}$ ,  $t_{CB} = \frac{L}{R}$ , and  $t_{BA} = \frac{2L}{R}$  respectively.*

*The server receives the first request at time  $t_1^C = t_{AB} + 2d + t_{BC} + d = \frac{3L}{2R} + 3d$ . The client receives the first object at time  $t_1^A = t_1^C + t_{CB} + d + t_{BA} + 2d = \frac{9L}{2R} + 6d$ .*

*Since an object is larger than a request, and link  $BA$  has a smaller capacity than link  $CB$ , link  $BA$  is the bottleneck for the communication session, and the router starts forwarding the second object right after the router finishes forwarding the first object. Hence, the client receives the second object at time  $t_2^A = t_1^A + t_{BA} = \frac{13L}{2R} + 6d$ .*

#### Grading guidelines:

2 points for the correct transmission delays.

4 points for the correct delivery time of the first object (3 points for the general approach and 1 point for the simplified expression).

9 points for the correct delivery time of the second object (8 points for the general approach and 1 point for the simplified expression).

Problem 3 (25 points). Section 3.4.1 of the textbook derives rdt, a protocol for reliable delivery. Does rdt3.0 (the final version of this protocol) ensure reliability if the network can reorder packets? Support your answer by sketching a succinct proof or giving a counterexample.

**Solution:** *No, rdt3.0 does not ensure reliability if the network can reorder packets. Consider a scenario where the application tries to communicate a string “nut” over the rdt3.0 protocol. The rdt3.0 sender transmits “n” using a data packet with sequence number 0. The network buffers the packet. After a timeout, the sender retransmits the packet. The network delivers the retransmitted packet, and the rdt3.0 receiver acknowledges the packet. In response, the sender transmits “u” using a data packet with sequence number 1. The network delivers this packet, and the receiver acknowledges the packet. Even before the acknowledgment reaches the sender, the receiver gets from the network the buffered data packet containing “n”. Since the packet contains the expected sequence number 0, the rdt3.0 receiver erroneously passes a string “nun” to the application.*

**Grading guidelines:**

Subtotal of 10 points for “No”.

Subtotal of 15 points for giving a correct counterexample showing that the rdt3.0 receiver can accept an old packet with the same sequence number as the receiver expects.

Problem 4 (25 points). A network path from node  $A$  to node  $B$  consists of  $n = 10$  links. Each link has capacity  $R = 1$  Mbps and propagation delay  $d = 5$  ms. Node  $A$  sends node  $B$  an infinite-size message using the Go-Back- $N$  protocol. In this protocol, the receiver responds to delivery of a data packet by sending an acknowledgment packet, and the sender does not transmit more than  $N$  unacknowledged data packets. The overall size of a data packet is  $L = 500$  bytes (once again, remember that 1 byte = 8 bits whereas link capacities are measured in bps, or bits per second). The overall size of an acknowledgment packet is  $l = 1,000$  bytes. There is no other traffic in the network. Nodal processing delays are negligible. Let  $U$  be the utilization (in %) of the path capacity from  $A$  to  $B$ . What is the maximum possible value of  $U$ ? What is the smallest  $N$  that provides this value of  $U$ ?

Show your derivations. Use mathematical expressions, not their verbal descriptions. Simplify your final analytical expression. Explain (briefly) your reasonings.

**Solution:** Since  $l > L$ , transmission of acknowledgment packets from  $B$  to  $A$  becomes a bottleneck for utilizing the path capacity from  $A$  to  $B$  efficiently after the initial window of  $N$  data packets is transmitted. When node  $B$  transmits acknowledgment packets continuously, node  $A$  responds to an acknowledgment packet of size  $l$  by sending a data packet of size  $L$ . Therefore, the maximum possible utilization of the path capacity from  $A$  to  $B$  is  $U_{max} = \frac{l}{l} = 50\%$ .

The protocol provides this maximum utilization if node  $B$  does not finish transmitting an acknowledgment packet for data packet  $N$  (i.e., the last packet from the initial window) before node  $B$  receives data packet  $N + 1$ . Hence,  $N$  should be such that  $N \frac{l}{R} \geq n(\frac{l}{R} + d) + n(\frac{L}{R} + d)$ . This expression can be transformed to  $N \frac{l}{R} \geq n(\frac{L+l}{R} + 2d)$  and further to  $N \geq n(1 + \frac{L+2dR}{l})$ . Then, the smallest value of  $N$  that provides the maximum utilization is  $N_{min} = \lceil n(1 + \frac{L+2dR}{l}) \rceil = \lceil 10 \cdot (1 + \frac{500 \cdot 8 \text{ bits} + 2 \cdot 5 \text{ ms} \cdot 1 \text{ Mbps}}{1,000 \cdot 8 \text{ bits}}) \rceil = \lceil 27.5 \rceil = 28$ .

**Grading guidelines:**

Subtotal of 5 points for expressing the minimum round-trip time  $T$  correctly with a formula such as  $T = n(\frac{L+l}{R} + 2d)$ .

Subtotal of 5 points for realizing that transmission of acknowledgment packets from  $B$  to  $A$  is a bottleneck for utilizing the path from  $A$  to  $B$  efficiently.

Subtotal of 3 points for realizing the correct condition “the amount of time to transmit  $N$  **acknowledgment** packets should be at least  $T$ ”.

Subtotal of 2 points for expressing the above condition correctly with an inequality such as  $N \frac{l}{R} \geq n(\frac{L+l}{R} + 2d)$ . **Note that** the left portion  $N \frac{l}{R}$  should contain  $l$ , not  $L$ .

Subtotal of 1 point for transforming the inequality into a correct expression for  $N$ , such as  $N \geq n(1 + \frac{L+2dR}{l})$ .

Subtotal of 3 points for expressing  $N_{min}$  correctly with an expression such as  $N_{min} = \lceil n(1 + \frac{L+2dR}{l}) \rceil$ .

Subtotal of 2 points for calculating  $N_{min}$  correctly as 28.

Subtotal of 3 points for realizing that the maximum utilization of the path from  $A$  to  $B$  after the initial window of  $N$  data packets is  $U_{max} = \frac{l}{l}$ .

Subtotal of 1 point for calculating  $U_{max}$  correctly as 50%.

By the definition of the protocol,  $N$  is a finite number. A solution that assumes that  $N$  can be infinite and provides final answers  $N_{min} = \infty$  and  $U_{max} = 100\%$  receives an overall score of 6 points (out of the 25 points).

Problem 5 (25 points). Over a direct link with capacity  $R$  and propagation delay  $d$  such that  $dR = 200L$ , host A delivers a file to host B after sending 195 data packets with full-size segments via a TCP Tahoe connection where the maximum segment size is equal to  $L$ , the threshold is initially set to  $32L$ , the receive window equals  $200L$ , the retransmission timeout is set to  $8d$ , and the initial congestion window is  $L$ . Host B responds to each uncorrupted segment by sending an immediate acknowledgment packet. Acknowledgment packets as well as headers of data packets have size  $0.1L$ . Host B discards out-of-order segments. Host A uses the byte-counting implementation of the congestion-avoidance mode (the one that increases the congestion window exactly by  $L$  per transmission round). Upon arrival of the 120th data packet that contains a corrupted segment, host B discovers the corruption via an incorrect checksum and discards the packet without sending an acknowledgment. However, the link delivers all the other packets without corruption or loss. There is no other traffic on the link. Nodal processing delays are negligible. What is the size of the file? Explain your reasoning.

**Solution:** Since round-trip time  $RTT = \frac{1.1L}{R} + d + \frac{0.1L}{R} + d = \frac{401.2L}{R}$  is larger than the time to transmit all 195 data packets, the delivery proceeds in rounds that all underutilize the link capacity. The retransmission timeout is large enough to avoid unnecessary timeouts. The receive window is also large enough not to restrict transmission. Hence, it is the congestion window that limits the transmission.

Initially, the congestion window equals  $L$ , and the connection is in the slow-start mode. The congestion window doubles until it becomes equal to the threshold of  $32L$  during the 6th transmission round. Then, the TCP connection switches to the congestion-avoidance mode and increases the congestion window by  $L$  per transmission round. During the 8th round when the congestion window is  $34L$ , host A transmits data packets with segments 97 through 130. Host B acknowledges segments 97 through 119, and these acknowledgments trigger the shorter 9th transmission round when host A transmits data packets with segments 131 through 153. Since host B discards the corrupted 120th packet, packets 121 through 153 deliver out-of-order segments 121 through 153. Host B discards these 33 out-of-order segments and sends 33 duplicate acknowledgments for segment 119. Upon receiving the 3rd duplicate acknowledgment, host A concludes that segment 120 has not been delivered, reduces the congestion window to  $L$ , and transmits data packet 154 containing the retransmitted segment 120. Since there are no other corruptions or losses, data packets 155 through 195 deliver the rest of the file: segments 121 through 161. Hence, the size of the file is  $161L$ .

Transmission round	Congestion window	Segments acknowledged	Packets transmitted	Segments corrupted or out of order	Segments received in order
1	$L$	–	1	–	1
2	$2L$	1	2, 3	–	2, 3
3	$4L$	2, 3	4, ..., 7	–	4, ..., 7
4	$8L$	4, ..., 7	8, ..., 15	–	8, ..., 15
5	$16L$	8, ..., 15	16, ..., 31	–	16, ..., 31
6	$32L$	16, ..., 31	32, ..., 63	–	32, ..., 63
7	$33L$	32, ..., 63	64, ..., 96	–	64, ..., 96
8	$34L$	64, ..., 96	97, ..., 130	120, ..., 130	97, ..., 119
9	$34L$	97, ..., 119	131, ..., 153	131, ..., 153	–
10	$L$	–	154	–	120
11+	$2L+$	120+	155, ..., 195	–	121, ..., 161

**Grading guidelines:** Subtotal of 4 points for showing the multiplicative increase during the first slow start (the congestion window grows from  $L$  to  $32L$  during the first 6 rounds).

Subtotal of 4 points for showing that the connection switches to congestion avoidance because the congestion window reaches the threshold.

Subtotal of 1 point for showing the additive increase during the next two rounds (the congestion window becomes  $34L$  during the 8th round).

Subtotal of 4 points for realizing that segments from the second phase of the 8th round (segments 121,  $\dots$ , 130) are discarded by the receiver.

Subtotal of 4 points for realizing that segments from the first phase of the 8th round (segments 97,  $\dots$ , 119) trigger the shorter 9th transmission round.

Subtotal of 4 points for realizing that segments from the shorter 9th transmission round are discarded by the receiver.

Subtotal of 1 point for showing that upon receiving the 3rd duplicate acknowledgment, the sender reduces the congestion window to  $L$  and retransmits segment 120.

Subtotal of 2 points for realizing that the subsequent segments arrive to the receiver in order.

Subtotal of 1 points for calculating the file size correctly as  $161L$ .

A possible mistake is to omit the 9th round when 23 segments are transmitted, delivered out of order, and therefore discarded by the receiver. The omission results in a final answer of  $184L$ . If this is the only deviation from the correct solution, the overall score is 16 points (-4 points for not realizing that segments from the first phase of the 8th round trigger the transmission of the 23 segments; -4 points for not realizing that the receiver discards these 23 segments; -1 point for not providing the correct final answer of  $161L$ ).