Instructions: You are required to work on the homework on your own. Please be legible and state all assumptions clearly. Show all work in order to receive partial credit.

1(a). UDP and TCP use 1’s complement for their checksums. Suppose you have the following three 8-bit words: 01010101, 01110000, 11001100.

- What is the 1’s complement of the sum of these words? Show all work. Why is it that UDP take the 1’s complement of the sum, i.e., why not just use the sum?
- With the 1’s complement scheme, how does the receiver detect errors. Is it possible that a 1-bit error will go undetected? How about a 2-bit error?

1(b). Consider a channel that can lose packets but has a maximum delay that is known. Modify protocol rdt2.1 to include sender timeout and retransmit. Informally argue why your protocol can communicate correctly over this channel.

1(c). Consider a reliable data transfer protocol that uses only negative acknowledgments. Suppose the sender sends data only infrequently.

- Would a NAK-only protocol be preferable to a protocol that uses ACKs? Why?
- Now suppose the sender has a lot of data to send and the end-to-end connection experiences few losses. In this second case, would a NAK-only protocol be preferable to a protocol that uses ACKs? Why?

2(a). Consider transferring an enormous file of L bytes from host A to host B. Assume an MSS of 1460 bytes.

- What us the maximum length of L such that TCP sequence numbers are not exhausted? Recall that the TCP number field has four bytes.
- For the L you obtain in (a), find how long it takes to transmit the file. Assume that a total of 66 bytes of transport, network and data-link header are added to each segment before the resulting packet is sent out over a 10 Mbps link. Ignore flow control and congestion control, so A can pump out the segments back-to-back and continuously.

2(b). Consider the TCP procedure for estimating RTT. Suppose that \( x = .1 \). Let SampleRTT1 be the most recent sample RTT, let SampleRTT2 be the next most recent sample RTT, etc.

- For a given TCP connection, suppose 4 acknowledgements have been returned with corresponding sample RTTs SampleRTT4, SampleRTT3, SampleRTT2, and SampleRTT1. Express EstimatedRTT in terms of the four sample RTTs.
- Generalize your formula for n sample round-trip times.
- For the formula in part (b) let \( n \) approach infinity. Comment on why this averaging procedure is called an exponential moving average.

2(c). Recall that TCP waits until it has received three duplicate ACKs before performing fast retransmit. Why do you think the TCP designers chose not to perform a fast retransmit after the first duplicate ACK for the segment received?

3(a). Recall the idealized model for the steady-state dynamics of TCP. In the period of time from when the connection's window size varies from \((W \times \text{MSS})/2\) to \(W \times \text{MSS}\), only one packet is lost (at the very end of the period).

- Show that the loss rate is equal to \( L = \text{loss rate} = 1/[(3/8) \times W^2 - W/4] \).
- Use the above result to show that if a connection has loss rate \( L \), then its average bandwidth is approximately given by: \( \text{average bandwidth of connection} \approx 1.22 \times \text{MSS} / (\text{RTT} \times \sqrt{L}) \).

3(b). Assume that to achieve a throughput of 10Gbps, TCP could only tolerate a segment loss probability of \( 2 \times 10^{-6} \) (or equivalently, one loss event for every 5,000,000,000 segments). Show the derivation for the values of \( 2 \times 10^{-10} \) (1 out-of 5,000,000) for an RTT of 100ms. If TCP needed to support a 100 Gbps connection, what would the tolerable loss be?

3(c). In our discussion, we implicitly assumed that TCP has data to send. Consider now the case that the TCP sender sends a large amount of data and then goes idle (since it has no more data to send) at \( t_1 \). TCP remains idle for a relatively long period of time and then wants to send more data at \( t_2 \). What are the advantages and disadvantages of having TCP use the Congestion Window and Threshold values from \( t_1 \) when starting to send data at \( t_2 \). What alternative will you recommend? Why?

4. Assume that initially the slow-start-threshold (SST) is 6. Assume that the first packet loss happens at window \( W = 10 \). Make additional assumptions if necessary, but state them.

(a) Draw the timeline of TCP (vertical timeline with packets and ACKs), until TCP steady state is reached.

(b) Say in TCP steady state, RTT = \( X \) msec, the segment-size is \( L \) bytes, and the measured throughput is \( T \) Mbps. What is the minimum sequence number that TCP must use to ensure correctness.

(c) TCP sender has sent packets 32,33,34. The ACKs for packet 32 comes back, but the ACK for 33 does not come. Instead ACK for 34 comes back. What should TCP sender do about packet 33? Show in a TCP timeline. If the appropriate action depends on other events, show timelines for the case of each event.

(d) Suppose TCP sender is past the slow start phase, and now its \( W = 8 \). It has sent out packets 51,52,53,...58, and is waiting for the ACKs. When will the TCP sender send the 59th packet? Explain your answer.