INSTRUCTIONS:

There are 12 pages (numbered at the bottom). Make sure you have all of them.

Please write your name on this cover and put your initials at the top of each page in this booklet except the last.

If you find a question ambiguous, be sure to write down any assumptions you make.

It is better to partially answer a question than to not attempt it at all.

Be clear and concise. Limit your answers to the space provided.

<table>
<thead>
<tr>
<th>Question</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Points</td>
<td>/ 27</td>
<td>/ 19</td>
<td>/ 16</td>
<td>/ 15</td>
<td>/ 21</td>
<td>/ 2</td>
</tr>
</tbody>
</table>
A Short Answers

1. (3 points) Packet switching was chosen for Internet because
   A. it allows for very bursty communications;
   B. it is considered more reliable than circuit switching;
   C. it supports applications of variable data-rates better;
   D. it is considered easier and cheaper to store and forward each packet respectively;
   E. it appeared earlier than circuit switching used for telephone network.

List all answers that apply:

Solution: A, C

2. (3 points) In the original Internet model, TCP and IP were combined in one layer. Can you explain briefly why they were later separated?

Solution: Services (e.g. voice, live video) are loss-tolerant thus don’t require reliable delivery. Splitting the layer into two, IP became a building block for “best effort” service, upon which other services (e.g. TCP, UDP) could provide reliable or unreliable delivery.

3. (3 points) TCP sees each packet loss as a congestion signal from the network and therefore reduces sender’s transmission rate by a half. Why does this mechanism cause performance problem in wireless network?

Solution: In wireless network the link is lossy in nature thus a packet loss may not be due to congestion.
4. (3 points) Both wireless network and ethernet are based on a shared medium, explain briefly why RTS/CTS is used in wireless network rather than in ethernet.

Solution: There is no exposed or hidden terminal problem in ethernet as data transmission can be heard by every node sharing the wire.

5. (3 points) Which of the following is true about BGP:
   A. An AS does not export announcements to its peering ASes.
   B. ASes can use IBGP instead of some other internal routing protocol such as RIP or OSPF.
   C. BGP uses path vector instead of distance vector to remove routing loops.
   D. BGP prefers less specific prefixes to more specific ones.
   E. For two prefixes of the same length, BGP will always pick the prefix with the shortest AS Path length.

Solution: C

6. (6 points) Inspired by Estan and et al (“Bitmap Algorithms for Counting Active Flows on High Speed Links”), Bin realized that the probabilistic approach of counting the number of flows can also be applied to indicate if a given flow has been seen or not, but with certain false positive probability. The false positive probability means that (1) if the given flow is truly seen before, the algorithm will always return TRUE; (2) if the flow is not seen yet, it will not always return FALSE;

(a) (3 points) how to use a direct bitmap to achieve this purpose?

Solution: Given a flow ID, hash the ID to a single bit on the bitmap. If the bit is set to 1, then with false positive rate we claim that the flow is counted already. In fact, a direct bitmap can be treated as a bloom filter with only one hash function.

(b) (3 points) can you do it by a virtual bitmap and why?

Solution: No. The reason is that a flow may be mapped to the non-sampled part of the virtual bitmap.

7. (6 points) XCP needs to estimate the number of flows, $N$, going through the core routers during one control interval. This is so that it can split its throughput increase/decrease appropriately across flows. The duration of the control interval is $T$ (recall that this is the average RTT of all flows). During this interval, the router sees many packets each of which is marked with the round-trip time of the flow (RTT) and the sender’s congestion window ($C_{wnd}$). Assume that $C_{wnd}$ is given as a packet count

(a) (3 points) Each packet belongs to one particular XCP flow. How many packets will that flow send during one control interval of length $T$?

Solution: The packet will send $C_{wnd} \times \frac{T}{RTT}$ packets during its own RTT. Therefore, it will send $\frac{C_{wnd}}{RTT}$ packets during a control interval.

(b) (3 points) Whenever a router receives a packet, it must update the counter that keeps track of the number of flows. By how much should it increase the counter for a packet with the above markings?
Solution: For every packet, it should increment the counter by

\[
\frac{1}{\text{Number of packets the flow will send in a control interval}}
\]

, which is simply \( \frac{\text{RTT}}{C_{\text{wnd}}} \).
B  Network Coding in The Air

8. (9 points) Inspired by COPE ("XORs in The Air: Practical Wireless Network Coding"), Bin wants to build a wireless mesh network in his apartment.

(a) (5 points) To help Bin to obtain higher gain by using coding, please pick one or multiple following decisions:

A force all packets to have same length
B increase buffer size of the router
C generate traffic to different destination nodes
D have backlogged nodes that continuously have some traffic ready to send

**Solution:** A C D

A: Having packets of similar length increases encoding efficiency;
B: Coding+MAC gain where packet drop rate at a bottleneck router is reduced due to improved throughput;
C: Diversed packets benefit coding as it creates more coding opportunities; D: Full queue creates more coding opportunities.

**Common mistake:** B

(b) (4 points) Bin found that in his system TCP traffic does not have much gain at presence of hidden terminals, can you help Bin explain that?

**Solution:** Collision rate is higher when there are hidden terminals. In this case, TCP does not have enough outstanding packets to utilize the medium which leads to less coding opportunities.

**Common mistake:** Pointing out that low TCP throughput is due to hidden terminals only gets partial points.

9. (5 points) Bin wanted to update his system to MORE ("Trading Structure for Randomness in Wireless Opportunistic Routing"). But he found that in MORE each relay node, after receiving some coded packets, will make a random linear combination of these received packets and forward them, even these received packets are already coded from upstream nodes. Bin was worrying that if packets are also encoded along the route, the destination may not be able to decode. Can you explain to Bin why this is fine?

**Solution:**

1 The linear combination of coded packets is still a linear combination of the corresponding native packets, so the destination can still use linear algebra to decode.
2 The coefficient vector of each coded packet is carried with each packet so the destination can know what are the coefficient vectors for each received packet.
10. (5 points) Amazed by network coding, Bin plans to implement a new TCP congestion control mechanism called TCP-NC. Namely, Bin wants the sender to send a random linear combination of all packets in the congestion window when allowed to transmit data. Bin hopes this TCP-NC can improve TCP performance over lossy links by masking the packet loss. To help Bin, how would you design the ACK mechanism?

Solution: This problem is open ended. There are several different possible ways:

(1) ack a batch of native packets after these packets are decoded from received coded packets;
(2) instead of acking the number of received native packets, ack the number of linear independent coded packets;
(3) instead of acking the number of received native packets, ack the received packets with their coefficient vectors (a valid answer given by one or two students)
C Routers

The iSLIP scheduling algorithm has three main steps:

1. REQUEST step where input queues send requests to corresponding output queues,
2. GRANT step where each output queue accepts one request, and
3. ACCEPT step where each input queue examines all grants and accept one.

11. (3 points) Briefly (i.e. couple sentences) describe how iSLIP ensures that all inputs get fair access to the outputs.

Solution:
Output queues keep a round robin scheduler to ensure fairness.

Common mistake: Randomization

12. (7 points) Consider an $N \times N$ switch ($N$ input ports, $N$ output ports) that implements iSLIP scheduling algorithm. Assume the traffic is uniform distributed and each input port has queued cells for every output.

(a) (2 points) What is the probability for a given input port to receive grant from a particular output port?

Solution: $1/N$

(b) (3 points) What is the probability to receive no grant for this input port?

Solution: $(1 - 1/N)^N$

(c) (2 points) What is the asymptotic approximation when $N$ tends to be infinity?

Solution: $\lim_{N \to \infty} (1 - 1/N)^N = 1 - 1/e$

13. (6 points) Authors of the “Scaling Internet Routers Using Optics” paper proposed a load balanced architecture of scalable switches to achieve 100% throughput. The router consists of two stages of identical switching and one stage of intermediate inputs with buffers.

(a) (3 points) What is the first stage of switching used for?

Solution: it is a load balancer used to distribute packets across different intermediate inputs.

(b) (3 points) Where is packet switching really happening?

Solution: It happens at the intermediate stage. Packets are routed to the corresponding VOQ according to their destinations
Consider the wireless network pictured below. Assume that links experience independent losses. The labeled edges indicate the combined delivery ratio (i.e., the probability that a packet is successfully received in the forward direction and that the acknowledgement is received in the reverse direction). If there is no edge, assume that no packets make it through.

Note that there are two loop-free paths from A to D:

- Path 1. A → B → D
- Path 2. A → C → D

14. (7 points) Assume the routing link metric is ETX.
   (a) (4 points) What are the aspects taken into account for the metric ETX of? Can you list two?

   **Solution:** the link loss rate, retransmission. So the ETX metric estimates the total number of transmissions along the path of this route.

   **Common mistake:** transmission rate

   (b) (3 points) There are some aspects in reality not taken into account for the metric ETX, e.g. opportunistic listening. Can you list one more?

   **Solution:** potential concurrent transmission; link interference; queuing delays;

15. (8 points) Compute the ETX metrics for both two paths.
   (a) (4 points) Path 1. A → B → D

   **Solution:** $3 + 5 = 8$

   (b) (4 points) Path 2. A → C → D

   **Solution:** $4 + 5 = 9$
E Analyze TCP

Bin is given the responsibility of configuring the packet queuing component of a new router. The link speed of the router is $BW$ (in byte/sec) and he expects the average two-way propagation delay of connections through the router is $RTT$ (in sec). Bin realizes that he needs to size the buffers appropriately.

You can assume the following:

- You're dealing with exactly one TCP connection.
- The source is a long-running TCP connection implementing additive-increase (increase window size by 1 packet after an entire window has been transmitted) and multiplicative-decrease (factor-of-two window reduction on congestion).
- The advertised window is always much larger than the congestion window.
- The loss recovery is perfect and has no impact on performance.
- The overhead due to headers can be ignored.

You can use $BW$ and $RTT$ as notations in your answers. Also feel free to draw graphs if you find they can help explain your results, e.g. the figure of congestion window size over time.

16. (3 points) If no buffer is used in the router, what is the link utilization?

**Solution:** \( \frac{(100\% + 50\%)}{2} = 75\% \),

17. (3 points) To keep the router always busy, at least how large does the TCP window need to be?
18. (3 points) Bin argues that because the two-way propagation delay is $RTT$ sec, the average one-way delay is $RTT/2$ sec. Therefore, the amount of buffering he needs for high link utilization should be $BW \cdot RTT/2$. With this size of buffer, what is the maximum window size Bin will see (in Bytes)?

Solution:

$$BW \cdot RTT/2 + BW \cdot RTT = 1.5BW \cdot RTT$$

19. (6 points) Assume queuing delay does not increase the propagation RTT, approximately what bandwidth will TCP achieve with this size of buffer?

Solution: 10 points.

The buffering is not enough for TCP to fill the link. The window size with this buffering will go between $1.5BW \cdot RTT$ and $0.75BW \cdot RTT$.

The above graph shows the rough behavior of the congestion window over time. The overly simplified analysis:

During $\frac{1}{3}$ of the connection, the window will be too small, using an average of $(0.75 + 1)/2 = \frac{2}{3}$ of the capacity. During the other two thirds of the time, it will fill the link. The total utilization will be $\frac{23}{24}$ of the capacity, or about $0.958$ $BW$ byte/sec.

20. (6 points, hint: this problem may be hard) If we take into account the fact that the delay increases by one packet’s worth each round trip, when we’re sending a larger window than the buffer can handle, approximately what bandwidth will TCP achieve with this buffering?

Solution: Assume each packet size is of size $X$ bytes. In going from a window of $0.75BW \cdot RTT/X$ packets to a window of $1.5BW \cdot RTT/X$ packets, the source sends:

$$1.5BW \cdot RTT/X \sum_{i=0.75BW \cdot RTT/X}^{i} i$$

packets. During this same amount of wall-clock time, an optimal scheme could have transmitted

$$0.75BW \cdot RTT/X \sum_{i=0.75BW \cdot RTT/X}^{i} i + 0.25BW \cdot RTT/X \sum_{i=0}^{i} i$$
packets. (The missing packets from the underutilized periods). Or:

\[
\text{throughput} = \frac{\sum_{i=0.75}^{1.5} \frac{BW \cdot RTT}{X} \cdot i \cdot BW}{\sum_{i=0.75}^{1.5} \frac{BW \cdot RTT}{X} + \sum_{i=0}^{0.25} \frac{BW \cdot RTT}{X} \cdot i} \\
\approx 0.965BW
\]
Survey!

F  2 Free Points for Tearing Off Page: Anonymous Feedback

List one thing you liked about the class and would like to see more of or see continued (any topic - lectures, homework, projects, discussion site, topics covered or not covered, etc., etc.):

List one thing you would like to have changed or have improved about the class: