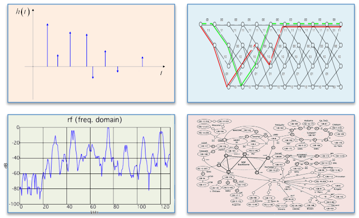
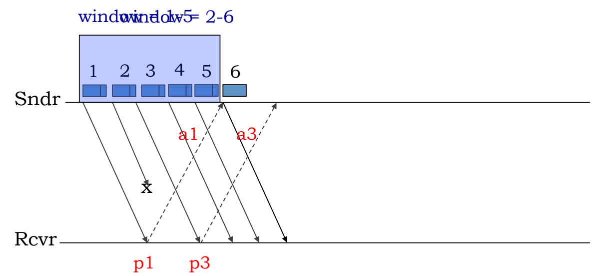


INTRODUCTION TO EECS II
DIGITAL COMMUNICATION SYSTEMS

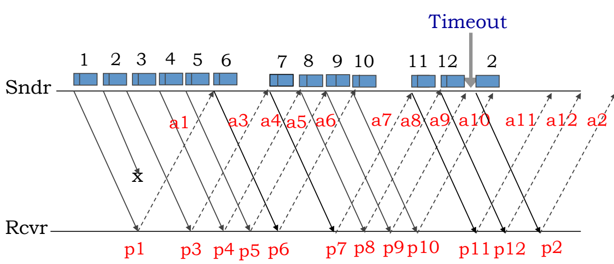
6.02 Fall 2012
Lecture #22

- Sliding window protocol analysis
  - Bandwidth-delay product & queues
  - Packet loss performance
- Little's law

Sliding Window: Handling Packet Loss



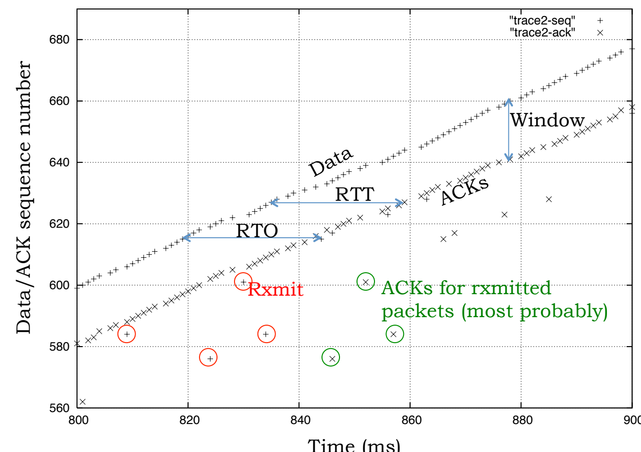
Sliding Window: Handling Packet Loss



Data packet 2 is lost. The receiver must save packets *all later packets* until packet 2 arrives, to deliver them to the *application* in proper order. Note that with our definition of the window, there's no limit to the number of packets that might arrive out of order.

Q: Can the receiver discard these later packets (3, 4, …, 12?)

Data/ACK sequence trace

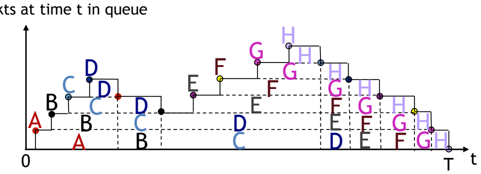


Sliding Window Implementation

- Transmitter
  - Each packet includes a sequentially increasing sequence number
  - When transmitting, save (xmit time,packet) on un-ACKed list
  - Transmit packets if len(un-ACKed list) ≤ window size W
  - When acknowledgement (ACK) is received from the destination for a particular sequence number, remove the corresponding entry from un-ACKed list
  - Periodically check un-ACKed list for packets sent awhile ago
    - Retransmit, update xmit time in case we have to do it again!
    - "awhile ago": xmit time < now – timeout
- Receiver
  - Send ACK for each received packet, reference sequence number
  - Deliver packet payload to application in sequence number order
    - Save delivered packets in sequence number order in local buffer (remove duplicates). Discard incoming packets which have already been delivered (caused by retransmission due to lost ACK).
    - Keep track of next packet application expects. After each reception, deliver as many in-order packets as possible.

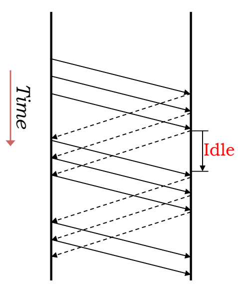
Little's Law

n(t) = # pkts at time t in queue



- P packets are forwarded in time T (assume T large)
- Rate = λ = P/T
- Let *A* = area under the n(t) curve from 0 to T
- Mean number of packets in queue = N = *A*/T
- *A* is aggregate delay weighted by each packet's time in queue. So, mean delay *D* per packet = *A*/P
- Therefore, **N = λ *D*** ← Little's Law
- For a given link rate, increasing queue size increases delay

How to Set the Window Size to Maximize Throughput? Apply Little's Law

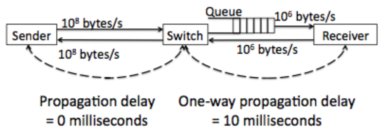


- If we can get Idle to 0, will achieve goal
- W = #packets in window
- B = rate of slowest (bottleneck) link in packets/second
- RTT_{min}= Min RTT along path, in the absence of any queueing (in seconds)
- If *W* = $B \cdot RTT_{min}$, then path is fully utilized (if no losses occur)
  - $B \cdot RTT_{min}$ is the *"bandwidth-delay product"*
  - *A key concept in the performance of windowed transport protocols*

Throughput of Sliding Window Protocol

- If there are no lost packets, protocol delivers W packets every RTT seconds, so throughput is W/RTT
- Goal: to achieve high utilization, select W so that the bottleneck link is never idle due to lack of packets
- Without packet losses:
  - Throughput = W/RTT_{min} if W ≤ $B \cdot RTT_{min}$,
    = B otherwise
  - If W > $B \cdot RTT_{min}$, then W = $B \cdot RTT_{min}$ + Q, where Q is the queue occupancy
- With packet losses:
  - Pick W > $B \cdot RTT_{min}$ to ensure bottleneck link is busy even if there are packet losses
  - *Expected # of transmissions*, T, for successful delivery of pkt and ACK satisfies: T = (1-L) ·1 + L·(1 + T), so T = 1/(1–L), where L = Prob(either packet OR its ACK is lost)
  - Therefore, throughput = (1–L)*B
- If W >> $B \cdot RTT_{min}$, then delays too large, timeout too big, and other connections may suffer

Example

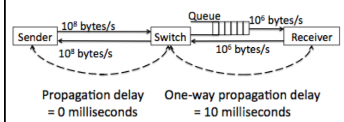


Max queue size = 30 packets
Packet size = 1000 bytes
ACK size = 40 bytes
Initial sender window size = 10 packets

Q: The sender's window size is 10 packets. At what approximate rate (in packets per second) will the protocol deliver a multi-gigabyte file from the sender to the receiver? Assume that there is no other traffic in the network and packets can only be lost because the queues overflow.

A: 10 packets / 21 ms, = 476 packets/second

Example (cont.)



Max queue size = 30 packets
Packet size = 1000 bytes
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Initial sender window size = 10 packets

Q: You would like to roughly double the throughput of our sliding window transport protocol. To do so, you can apply one of the following techniques:

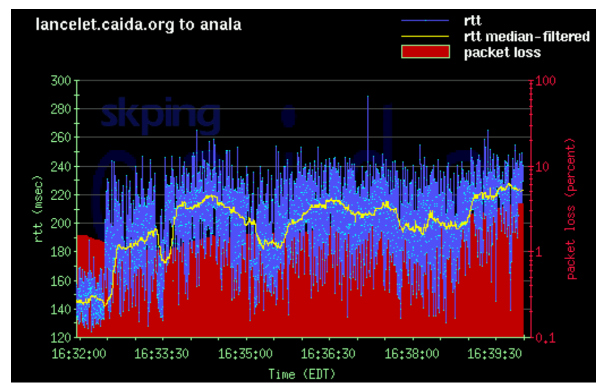
a. Double window size W
b. Halve the propagation delay of the links
c. Double the rate of the link between the Switch and Receiver

Q: For each of the following sender window sizes (in packets), list which of the above technique(s), if any, can approximately double the throughput: W=10, W=50, W=30.

Solutions to Example

- Note that BW-delay product on given path = 20 packets
- W=10
  - Doubling window size ~doubles throughput (BW-delay product is 20 on path)
  - Halving RTT ~doubles throughput (since now BW-delay product would be 10, equal to window size)
  - Doubling bottleneck link rate won't change throughput much!
- W=50
  - Doubling window size won't change throughput (we're already saturating the bottleneck link)
  - Halving RTT won't change throughput (same reason)
  - Doubling bottleneck link speed *will* ~double throughput because new bw-delay product doubles to 40, and W=50 > 40
- W=30 (trickiest case)
  - Doubling window size or halving RTT: no effect
  - Doubling bottleneck link changes BW-delay product to 40. W is still lower than 40, so throughput won't double. But it'll certainly increase, by perhaps about 50% more from before

RTT Measurements



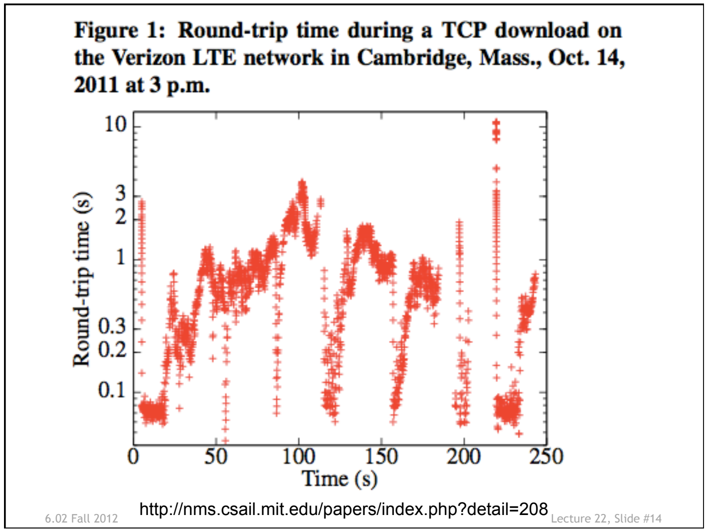


Figure 1: Round-trip time during a TCP download on the Verizon LTE network in Cambridge, Mass., Oct. 14, 2011 at 3 p.m.
Round-trip time (s)
Time (s)
http://nms.csail.mit.edu/papers/index.php?detail=208
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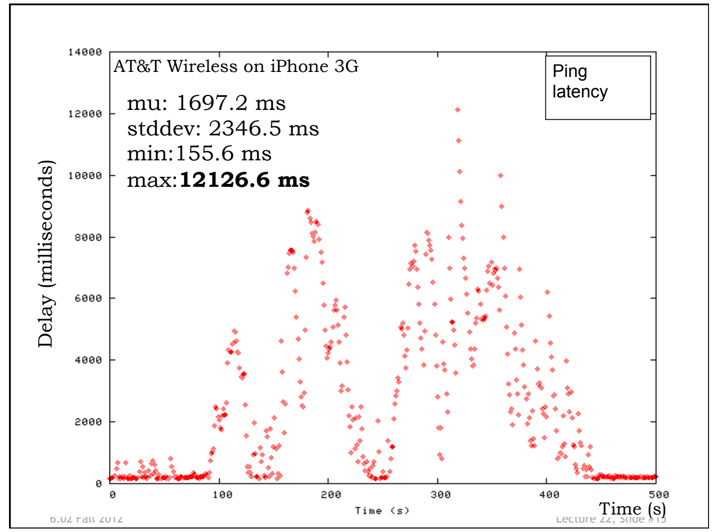
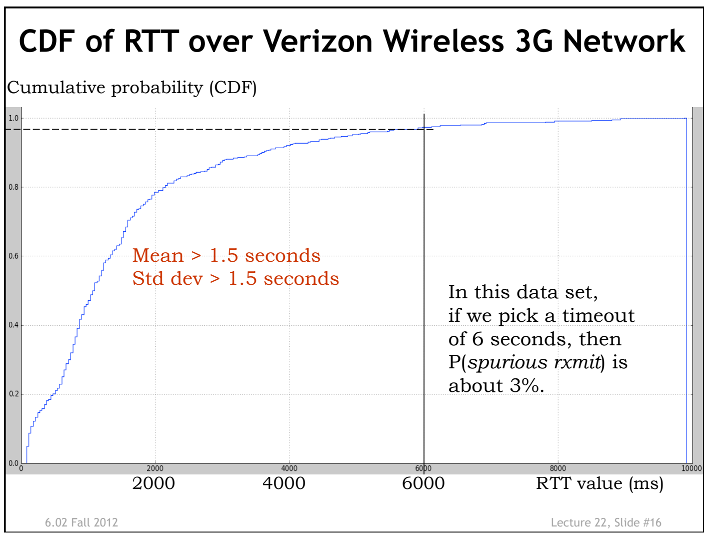

AT&T Wireless on iPhone 3G
Ping latency
mu: 1697.2 ms
stddev: 2346.5 ms
min:155.6 ms
max:12126.6 ms
Delay (milliseconds)
Time (s)


CDF of RTT over Verizon Wireless 3G Network
Cumulative probability (CDF)
Mean > 1.5 seconds
Std dev > 1.5 seconds
In this data set,
if we pick a timeout
of 6 seconds, then
P(spurious rxmit) is
about 3%.
2000
4000
6000
RTT value (ms)
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