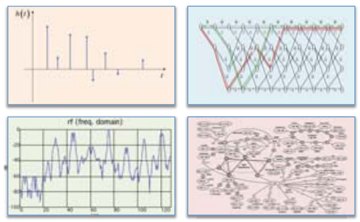
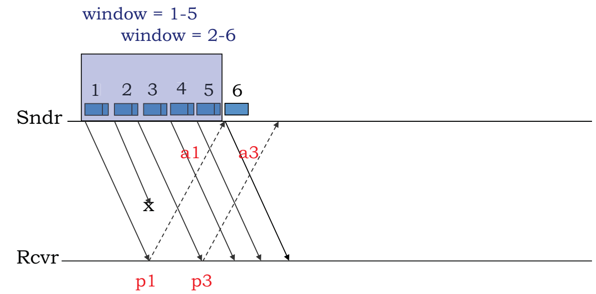


INTRODUCTION TO EECS II
DIGITAL COMMUNICATION SYSTEMS

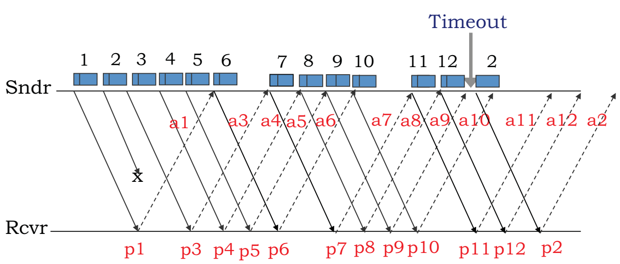
6.02 Fall 2012
Lecture #22

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

Sliding Window: Handling Packet Loss



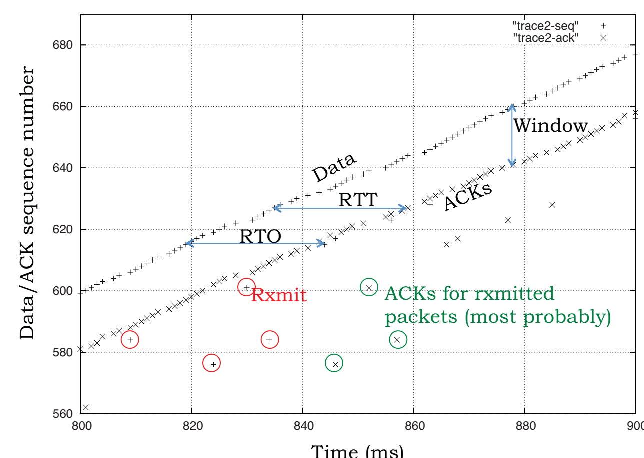
Sliding Window: Handling Packet Loss



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?)

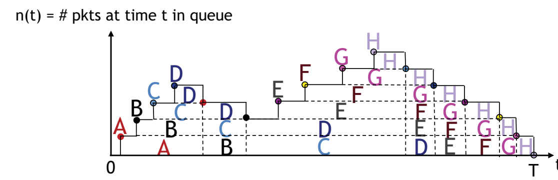
Data/ACK sequence trace



Sliding Window Implementation

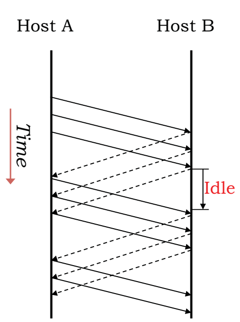
- Transmitter
  - Each packet includes a sequentially increasing sequence number
  - When transmitting, save (xmit time,packet) on un-ACKed list
  - Transmit packets if len(un-ACKed list) ≤ window size W
  - When acknowledgement (ACK) is received from the destination for a particular sequence number, 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



- 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 =** λD ← 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

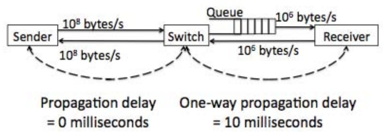


- If we can get Idle to 0, will achieve goal
- W = #packets in window
- B = rate of slowest (bottleneck) link in packets/second
- RTT_{min}= Min RTT along path, in the absence of any queueing (in seconds)
- If $W = B \cdot RTT_{min}$, then path is fully utilized (if no losses occur)
  - $B \cdot RTT_{min}$ 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 $W \le B \cdot RTT_{min}$, = 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: $T = (1\text{-}L) \cdot 1 + L \cdot (1 + T)$, so $T = 1/(1-L)$, where L = Prob(either packet OR its ACK is lost)
  - Therefore, throughput = $(1-L)*B$
- If $W \gg B \cdot RTT_{min}$, then delays too large, timeout too big, and other connections may suffer

Example

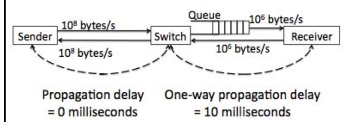


Max queue size = 30 packets
Packet size = 1000 bytes
ACK size = 40 bytes
Initial sender window size = 10 packets

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
ACK size = 40 bytes
Initial sender window size = 10 packets

Q: You would like to roughly louble the throughput of our liding window transport protocol. 'o do so, you can apply <u>one</u> of the ollowing techniques:

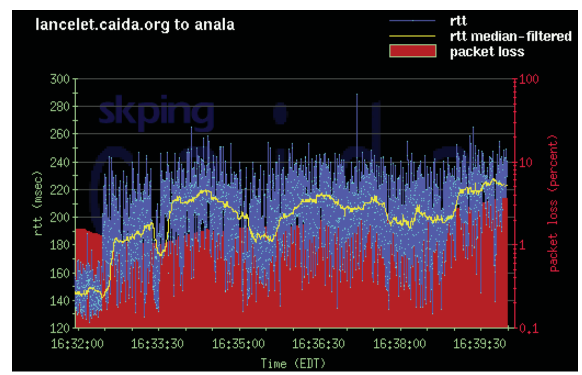
ι. Double window size W
›. Halve the propagation delay of the links
:. Double the rate of the link between the Switch and Receiver

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

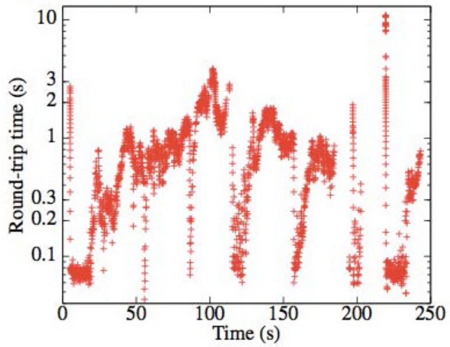
- Note that BW-delay product on given path = 20 packets
- W=10
  - Doubling window size ~doubles throughput (BW-delay product is 20 on path)
  - Halving RTT ~doubles throughput (since now BW-delay product would be 10, equal to window size)
  - Doubling bottleneck link rate won't change throughput much!
- 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

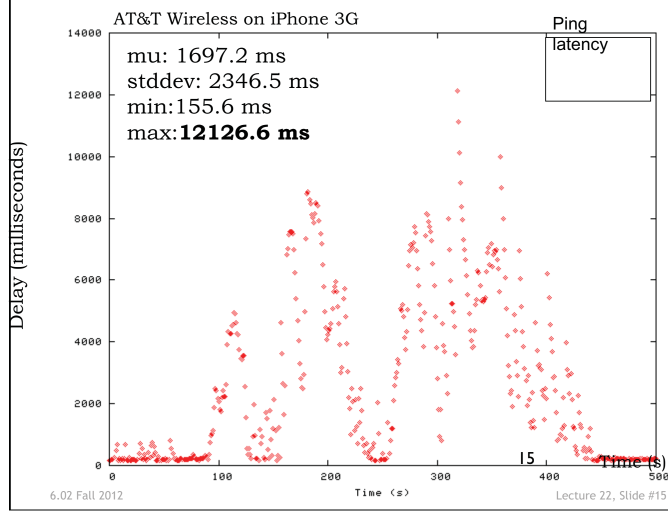


Courtesy of the Cooperative Association for Internet Data Analysis. Used with permission.

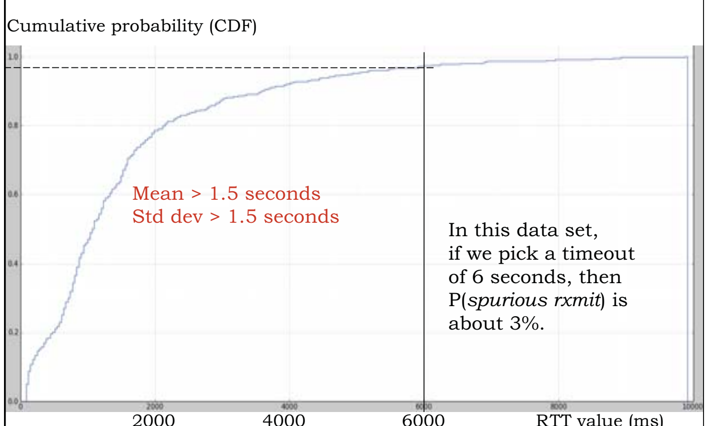
Figure 1: Round-trip time during a TCP download on the Verizon LTE network in Cambridge, Mass., Oct. 14, 2011 at 3 p.m.



http://nms.csail.mit.edu/papers/index.php?detail=208



CDF of RTT over Verizon Wireless 3G Network



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