Flow control recap

Goal: Match sending speed to receiver's capacity

3 increasingly complex and increasingly efficient solutions

- Stop and wait
- Sliding window: go back N
- Sliding window: selective repeat

Go back N

Sender sent packets 42, 43, 44, 45, …

If 43 is lost, all of 43, 44, 45 must be resent

Receiver does not buffer out of order packets (simple)

Receiver Sliding Window – Selective Repeat

- Receiver passes data to app in order, and buffers out-of-order segments to reduce retransmissions
- ACK conveys highest in-order segment, plus hints about out-of-order segments
  - Ex: I got everything up to 42 (LAS), and got 44, 45
- TCP uses a selective repeat design; we'll see the details later

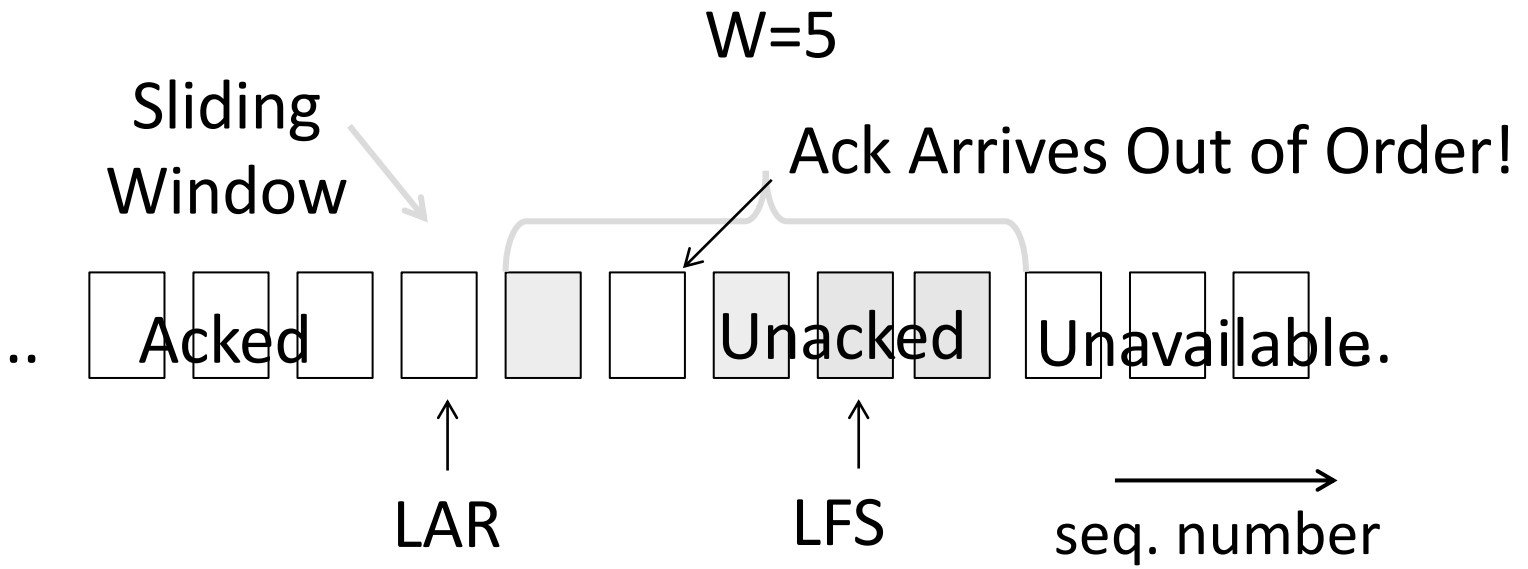
Receiver Sliding Window – Selective Repeat (2)

- Buffers W segments, keeps state variable LAS = LAST ACK SENT

- On receive:
  - Buffer segments [LAS+1, LAS+W]
  - Send app in-order segments from LAS+1, and update LAS
  - Send ACK for LAS regardless

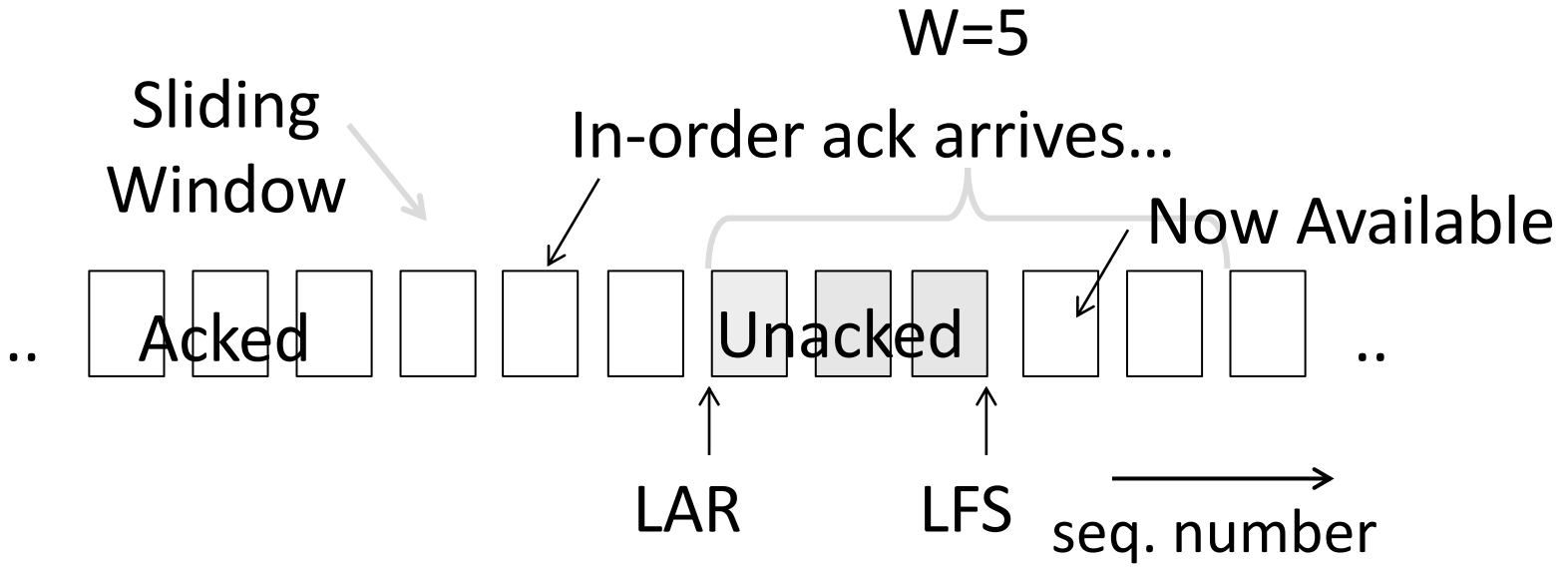
Sender Sliding Window – Selective Repeat

- Keep normal sliding window
- If out-of-order ACK arrives
  - Send LAR+1 again!



Sender Sliding Window – Selective Repeat (2)

- Keep normal sliding window
- If in-order ACK arrives
  - Move window and LAR, send more messages



Sliding Window – Retransmissions

- Go-Back-N uses a single timer to detect losses
  - On timeout, resends buffered packets starting at LAR+1
- Selective Repeat uses a timer per unacked segment to detect losses
  - On timeout for segment, resend it
  - Hope to resend fewer segments

Sequence Numbers

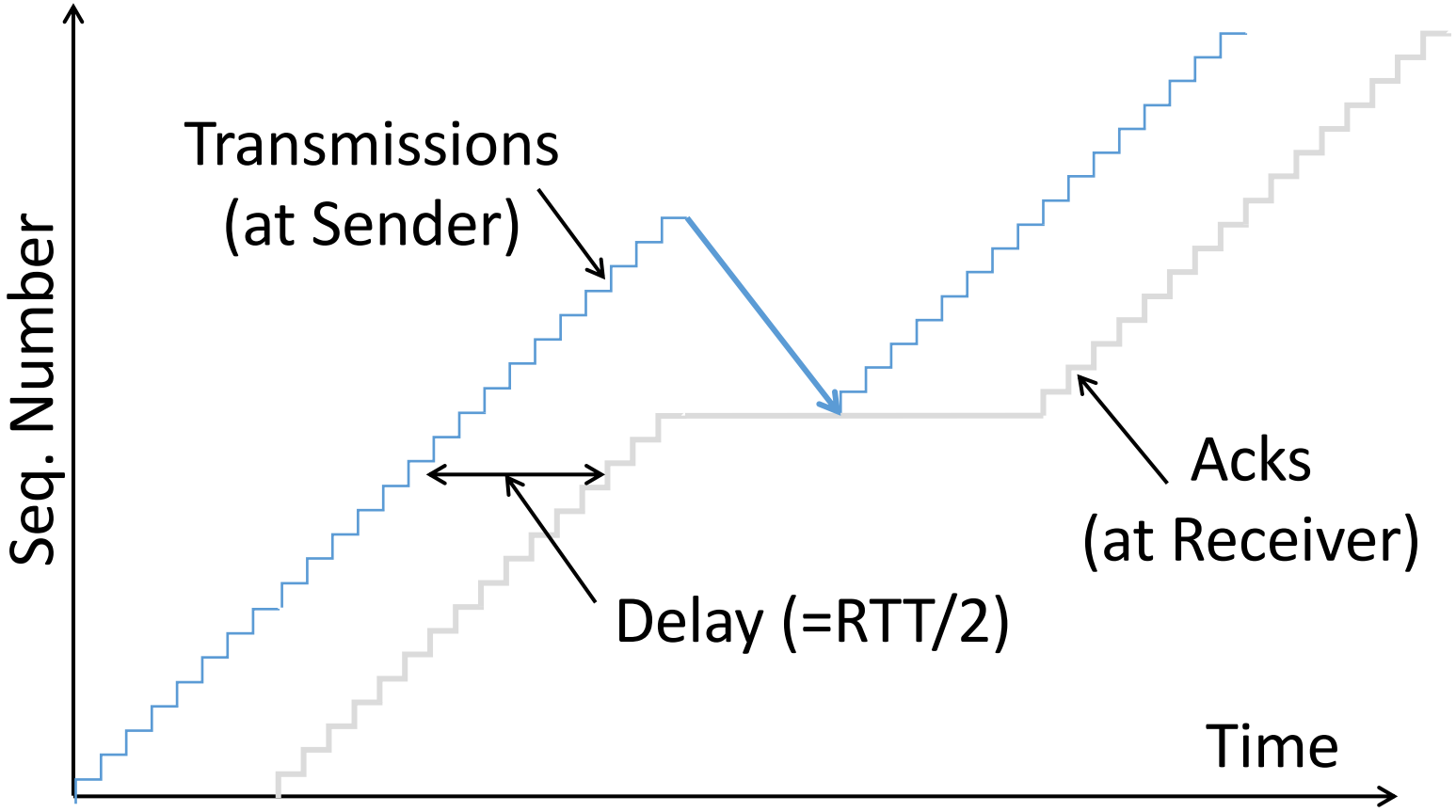
Need more than 0/1 for Stop-and-Wait … but how many?

- For Selective Repeat: 2W seq numbers
  - W for packets, plus W for earlier acks
- For Go-Back-N: W+1 sequence numbers

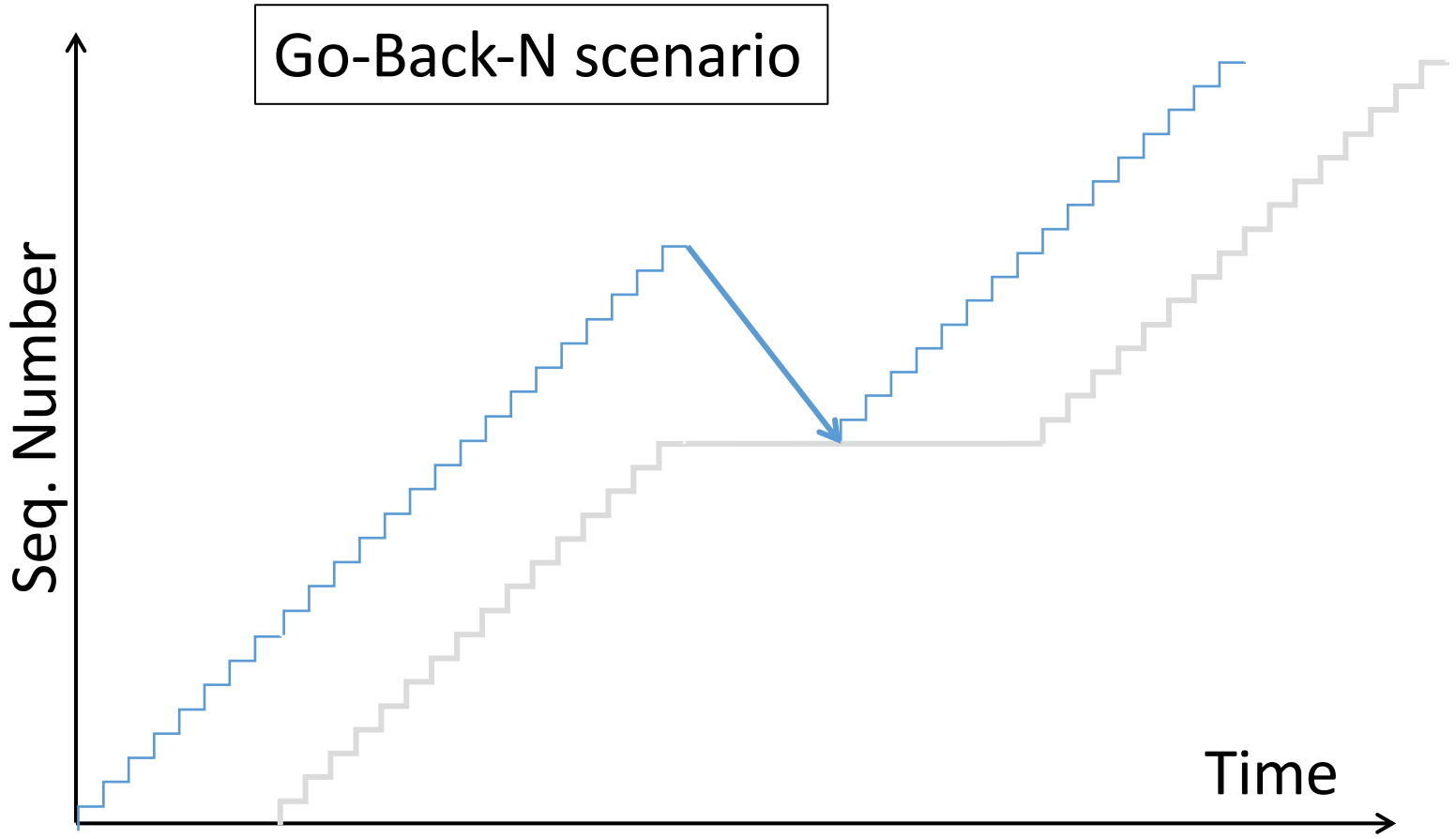
Typically implement seq. number with an N-bit counter that wraps around at $2^N—1$

- E.g., N=8: …, 253, 254, 255, 0, 1, 2, 3, …

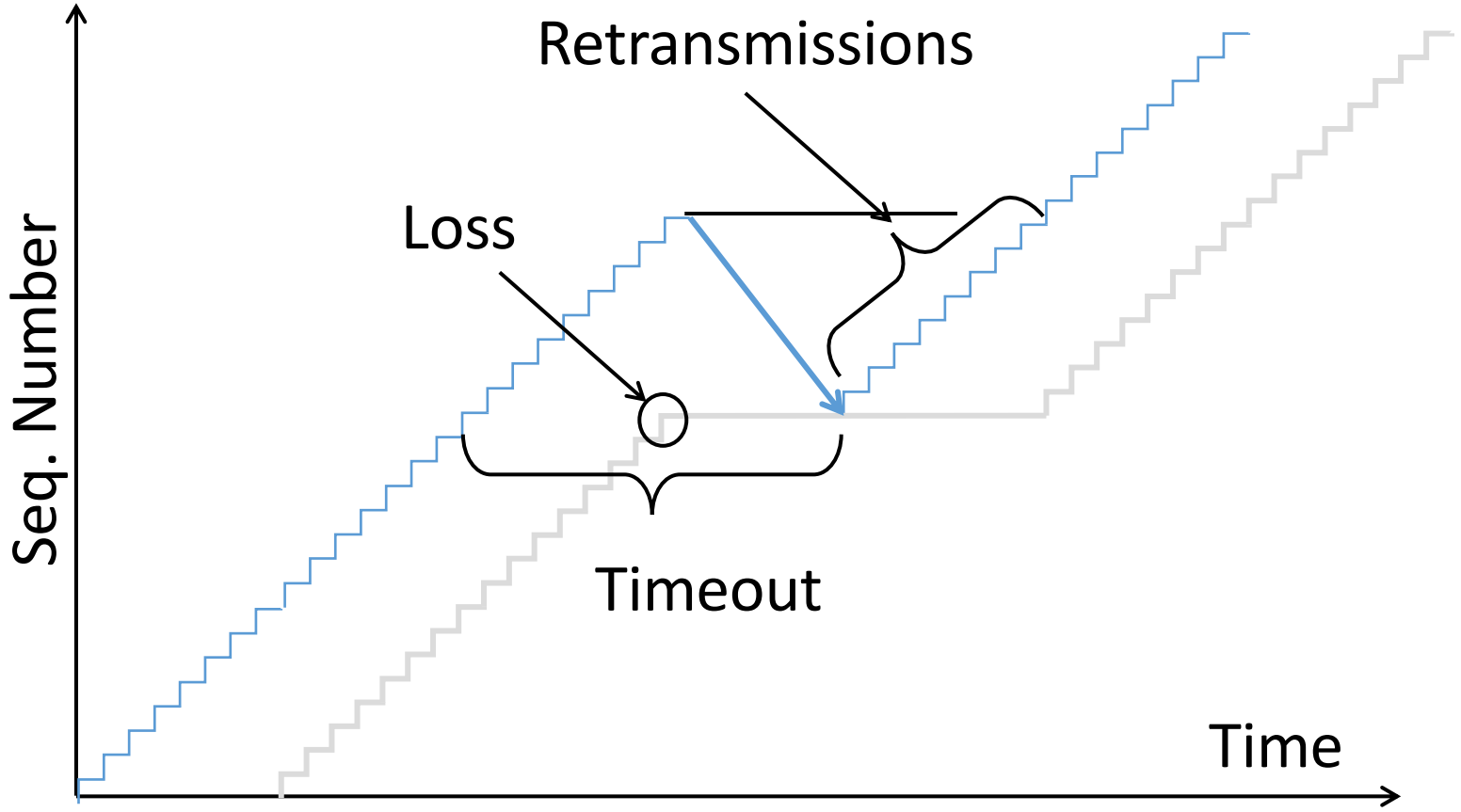
Sequence Time Plot



Sequence Time Plot (2)



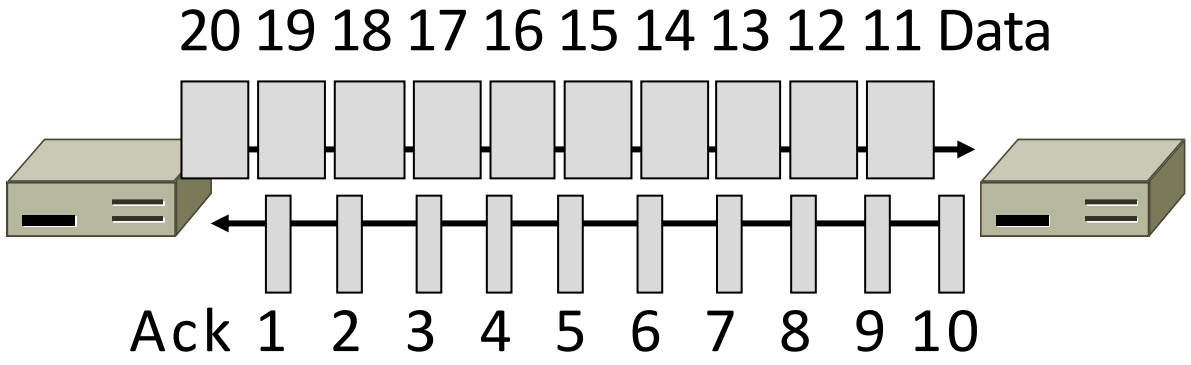
Sequence Time Plot (3)



ACK Clocking

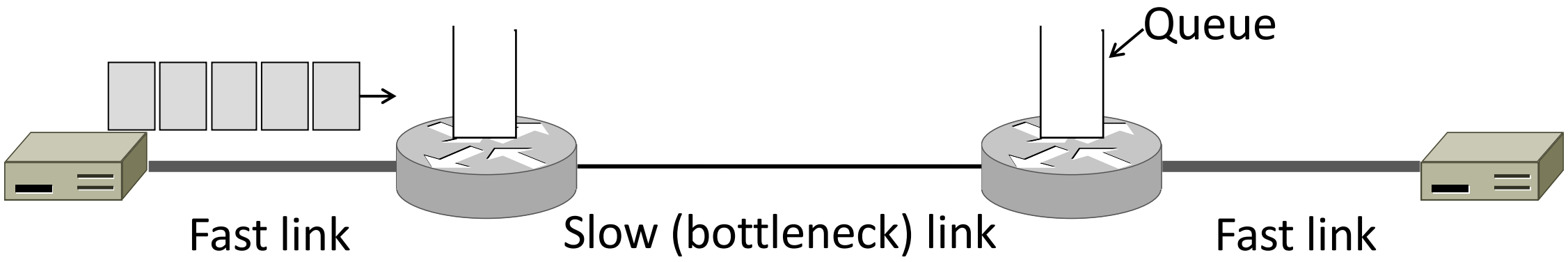
Sliding Window ACK Clock

- Typically, the sender does not know B or D
- Each new ACK advances the sliding window and lets a new segment enter the network
  - ACKs "clock" data segments



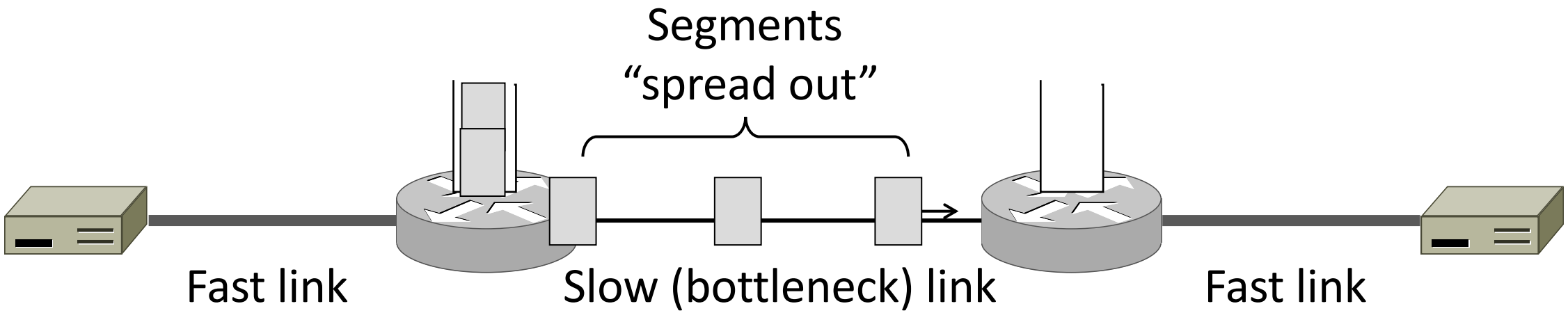
Benefit of ACK Clocking

- Consider what happens when sender injects a burst of segments into the network



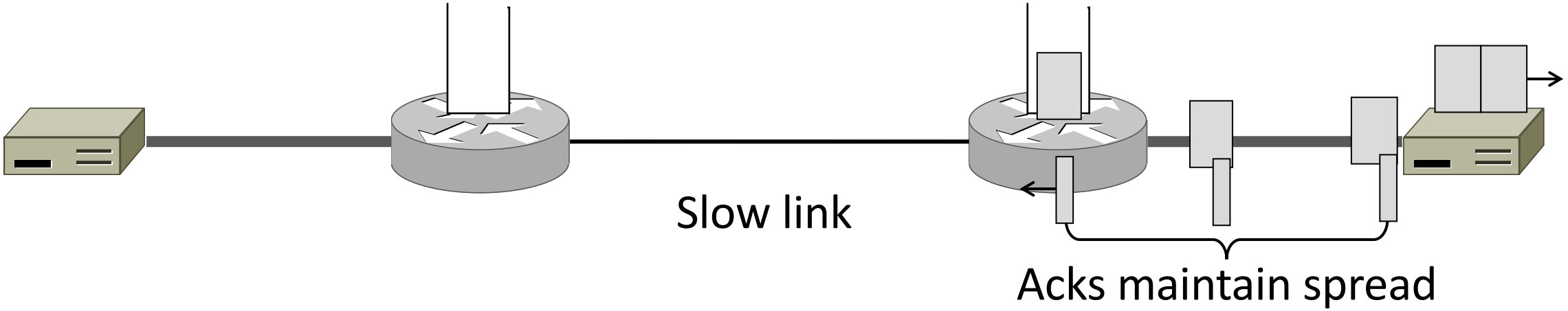
Benefit of ACK Clocking (2)

- Segments are buffered and spread out on slow link



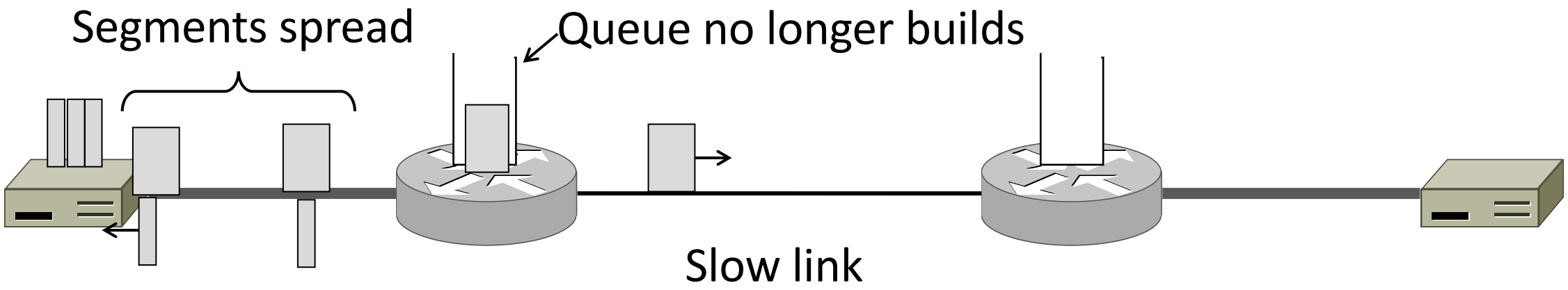
Benefit of ACK Clocking (3)

- ACKs maintain the spread back to the original sender



Benefit of ACK Clocking (4)

- Sender clocks new segments with the spread
  - Now sending at the bottleneck link without queuing!



Benefit of ACK Clocking (4)

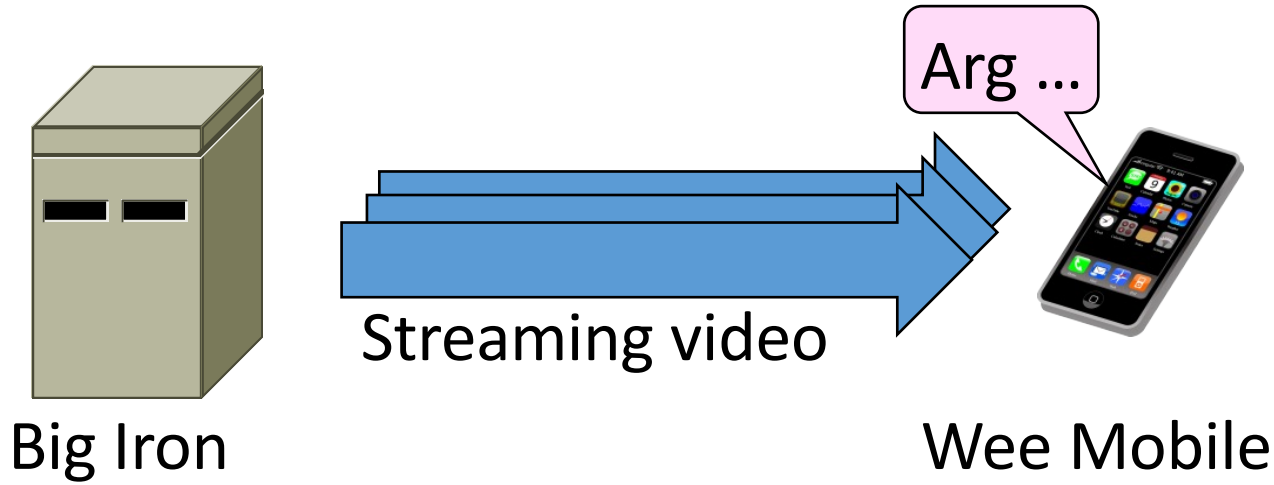
- Helps run with low levels of loss and delay!
- The network smooths out the burst of data segments
- ACK clock transfers this smooth timing back to sender
- Subsequent data segments are not sent in bursts so do not queue up in the network

TCP Uses ACK Clocking

- TCP uses a sliding window because of the value of ACK clocking
- Sliding window controls how many segments are inside the network
- TCP only sends small bursts of segments to let the network keep the traffic smooth

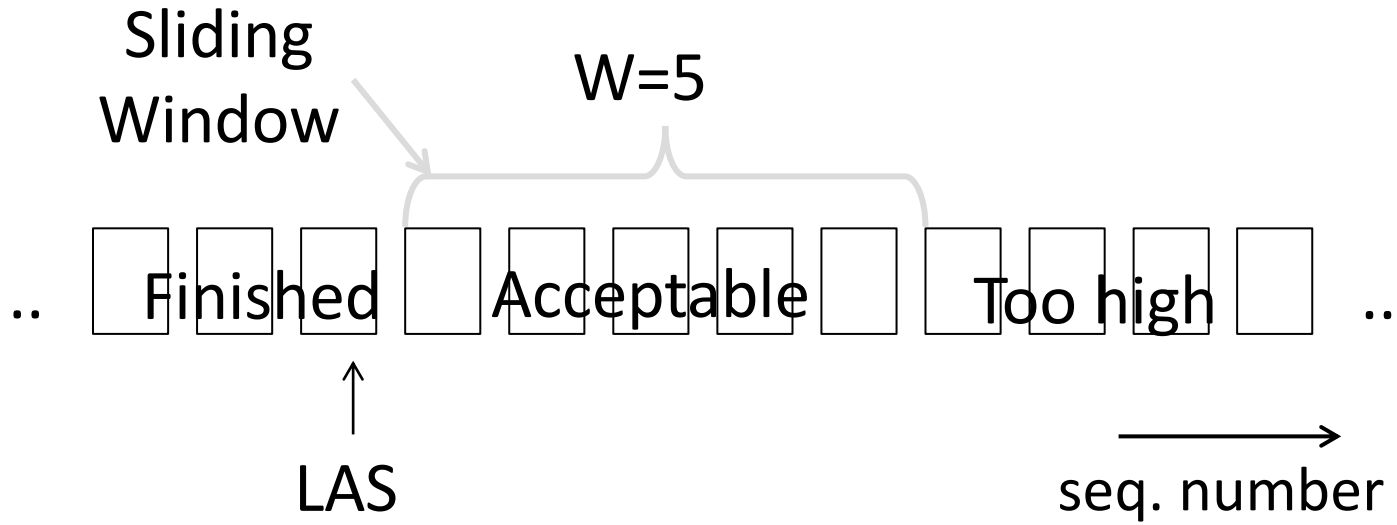
Problem

- Sliding window has pipelining to keep network busy
  - What if the receiver is overloaded?



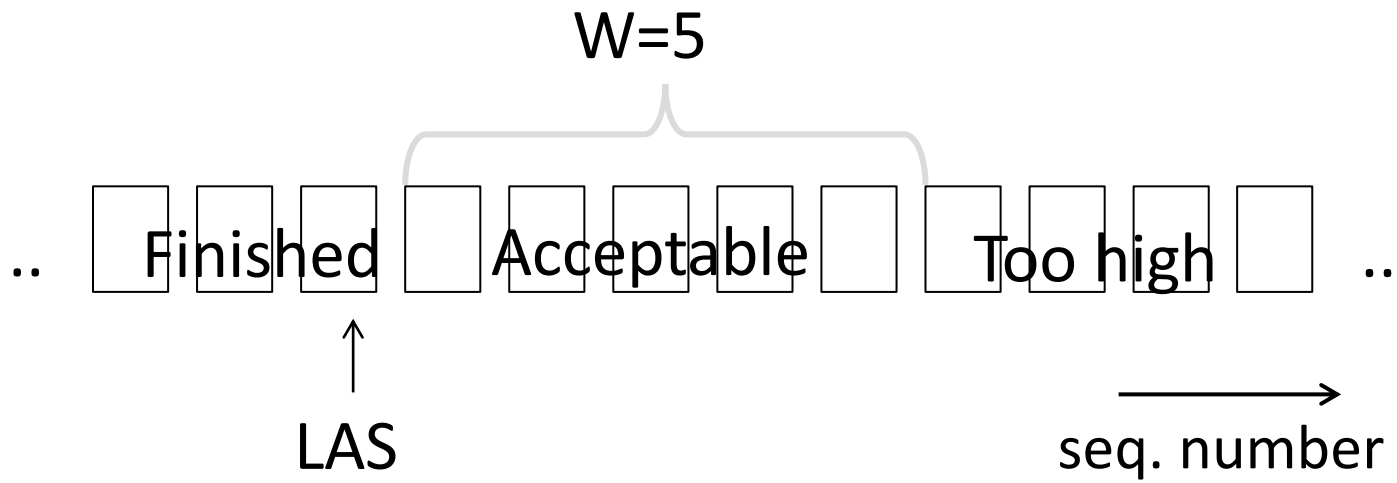
Receiver Sliding Window

- Consider receiver with W buffers
  - LAS=LAST ACK SENT
  - app pulls in-order data from buffer with recv() call



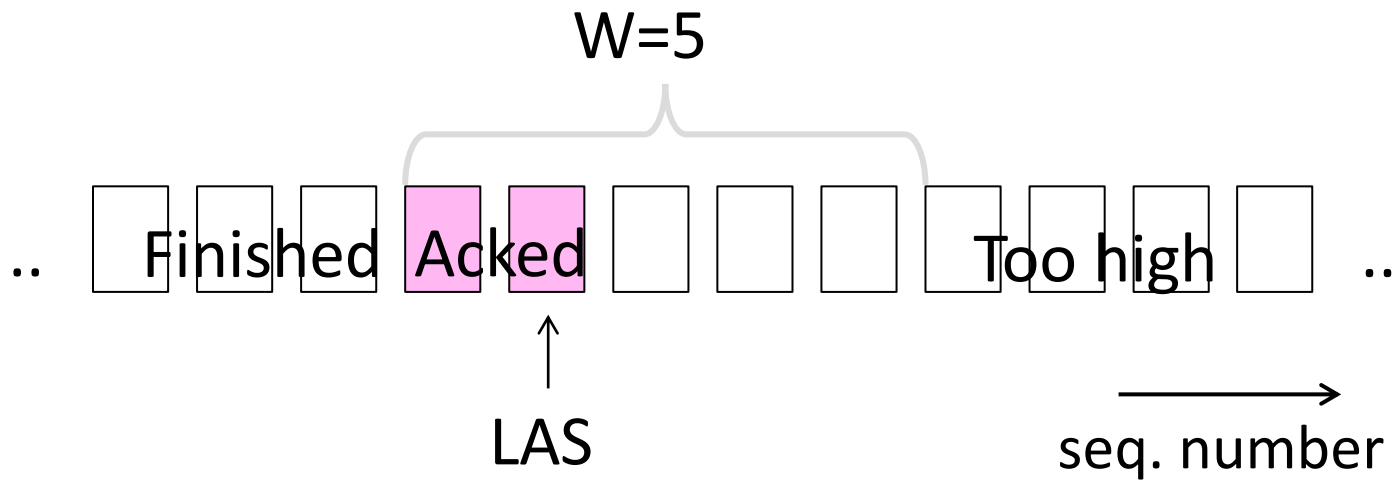
Receiver Sliding Window (2)

- Suppose the next two segments arrive but app does not call recv()



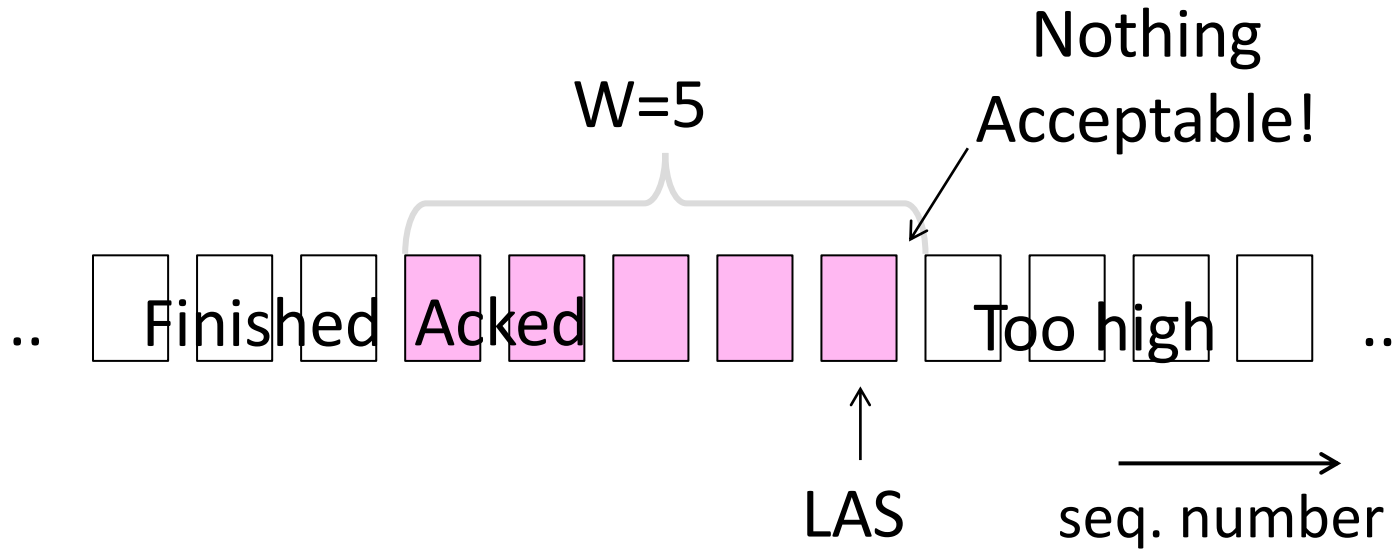
Receiver Sliding Window (3)

- Suppose the next two segments arrive but app does not call recv()
  - LAS rises, but we can't slide window!



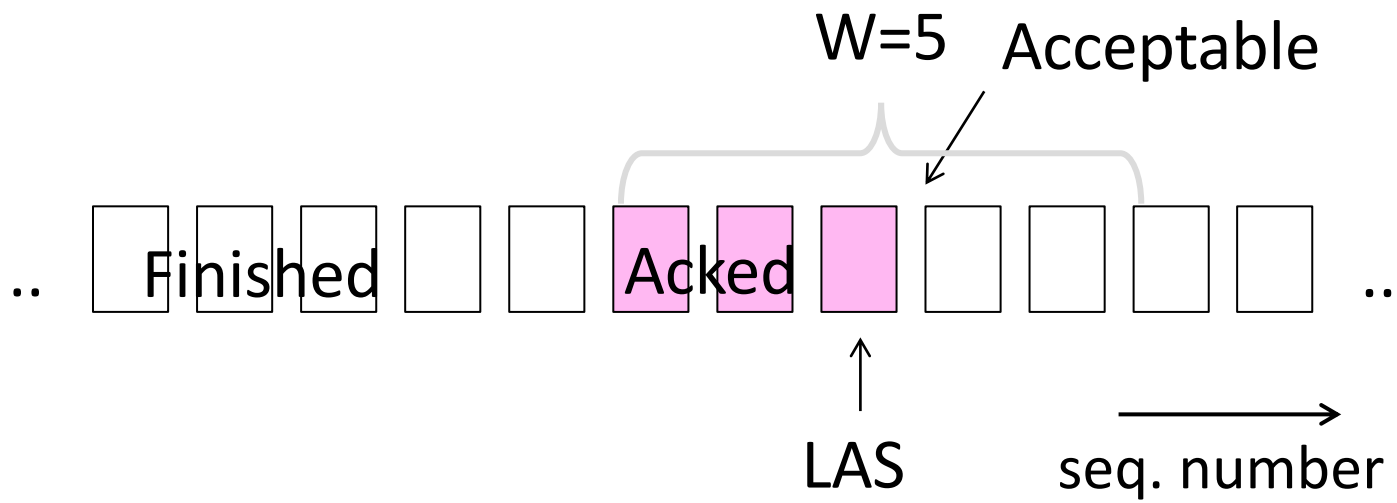
Receiver Sliding Window (4)

- Further segments arrive (in order) we fill buffer
  - Must drop segments until app recvs!



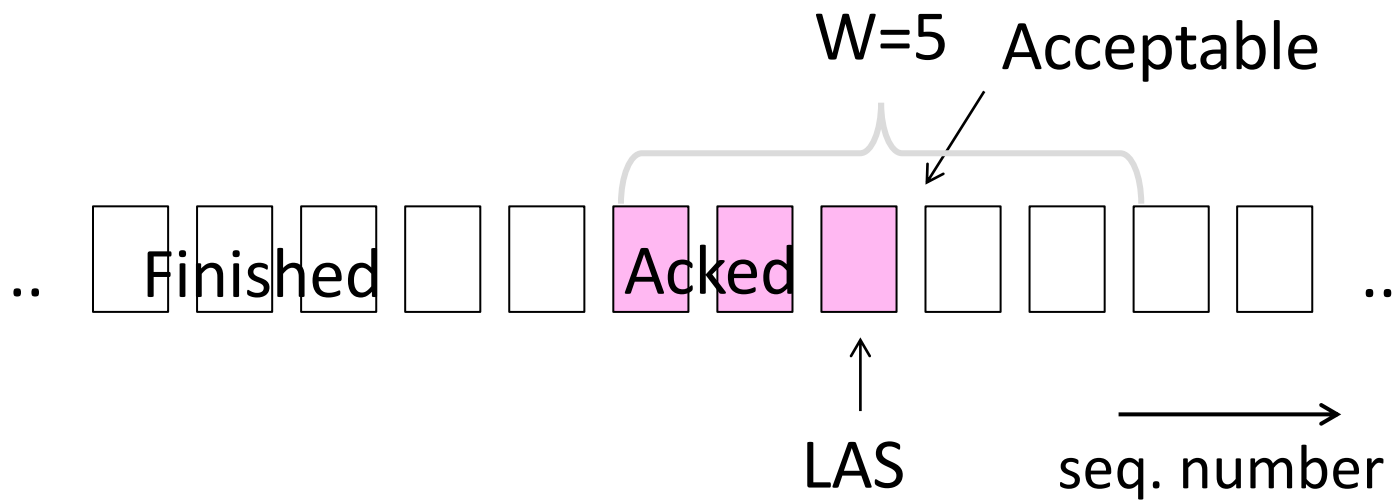
Receiver Sliding Window (5)

- App recv() takes two segments
  - Window slides (phew)



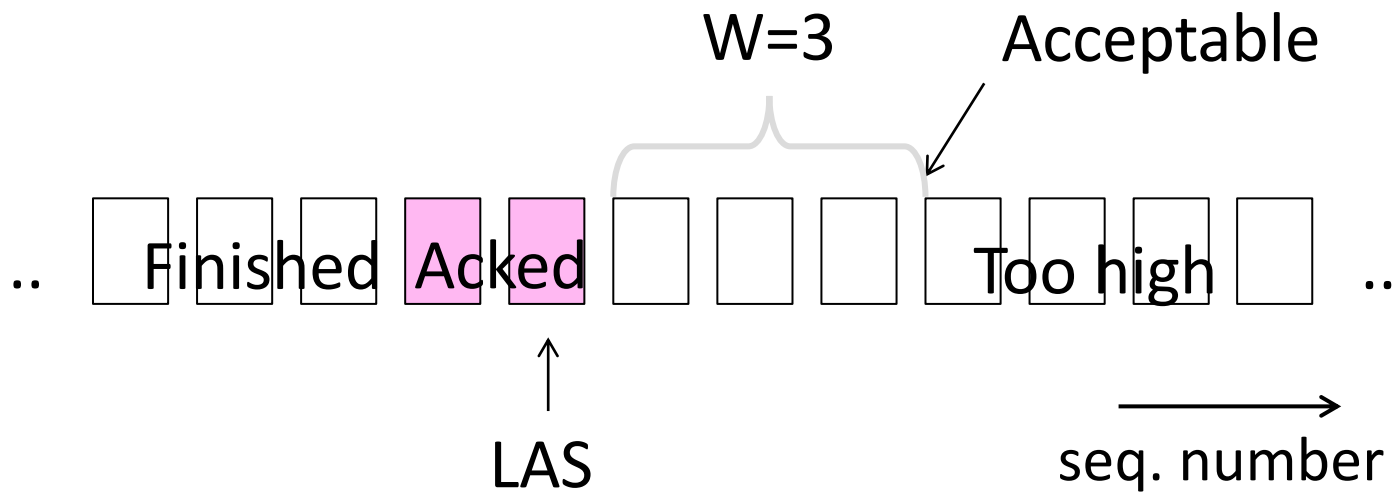
Flow Control

- Avoid loss at receiver by telling sender the available buffer space
  - WIN=#Acceptable, not W (from LAS)



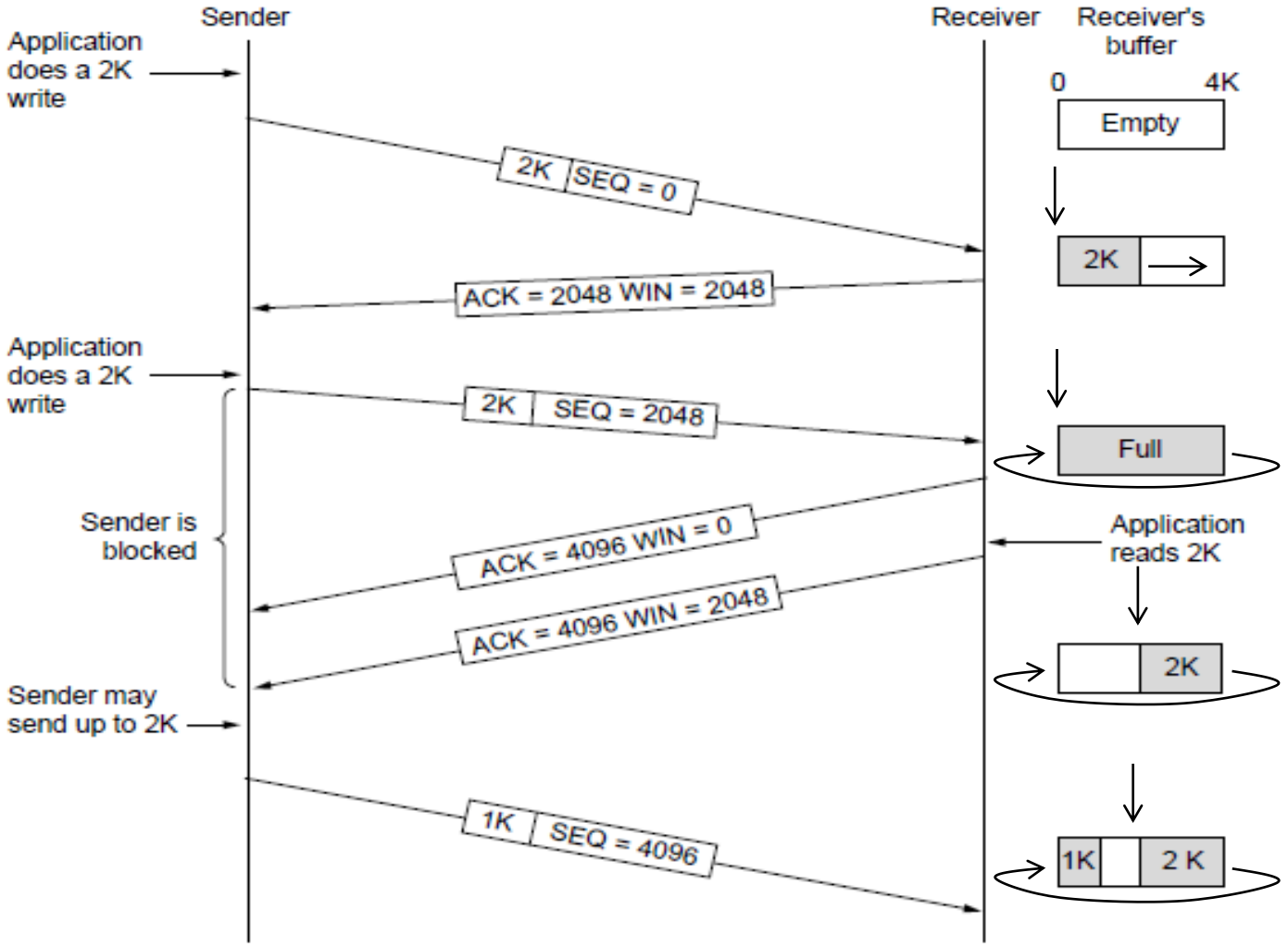
Flow Control (2)

- Sender uses lower of the sliding window and flow control window (WIN) as the effective window size



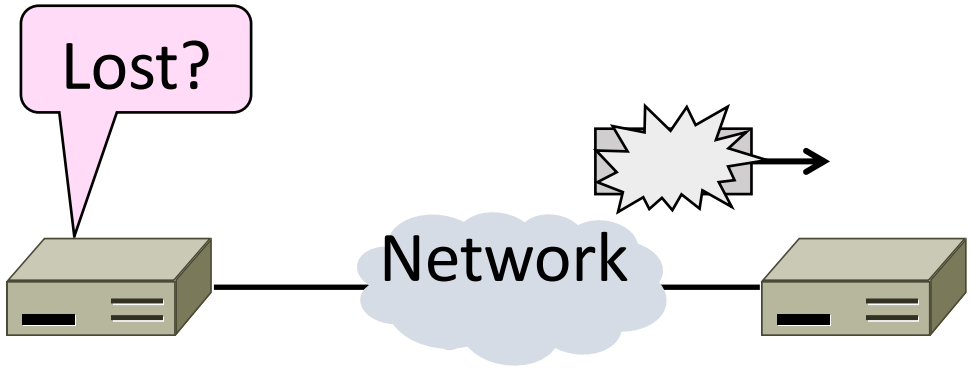
Flow Control (3)

- TCP-style example
  - SEQ/ACK sliding window
  - Flow control with WIN
  - SEQ + length < ACK+WIN
  - 4KB buffer at receiver
  - Circular buffer of bytes



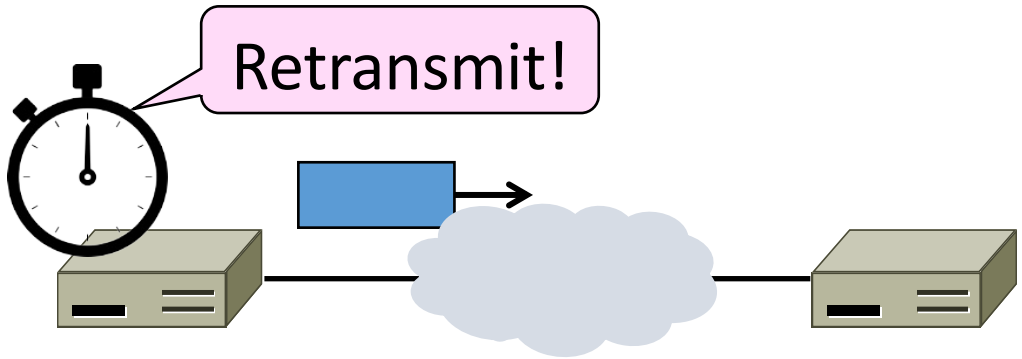
Topic

- How to set the timeout for sending a retransmission
  - Adapting to the network path



Retransmissions

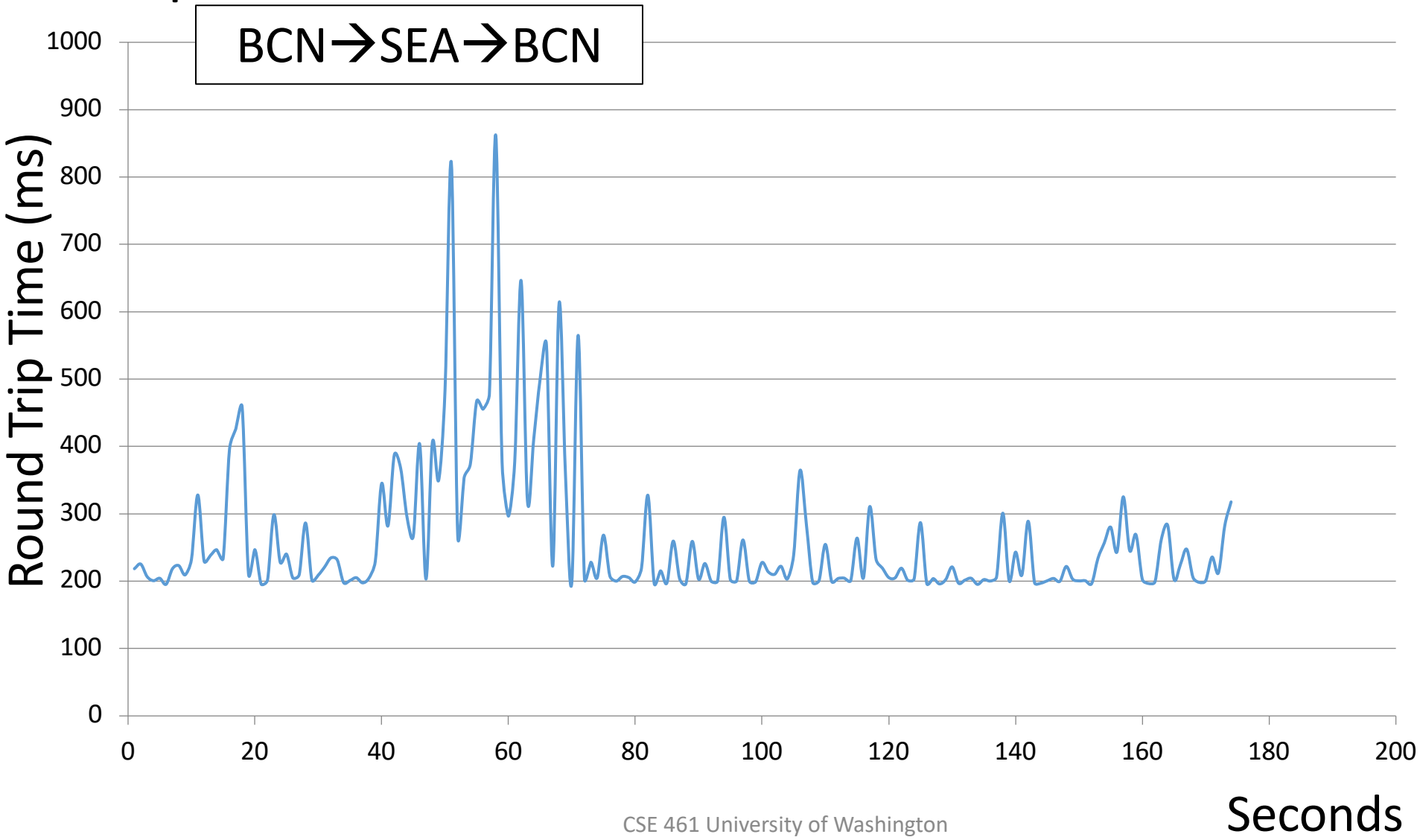
- With sliding window, detecting loss with timeout
  - Set timer when a segment is sent
  - Cancel timer when ack is received
  - If timer fires, retransmit data as lost



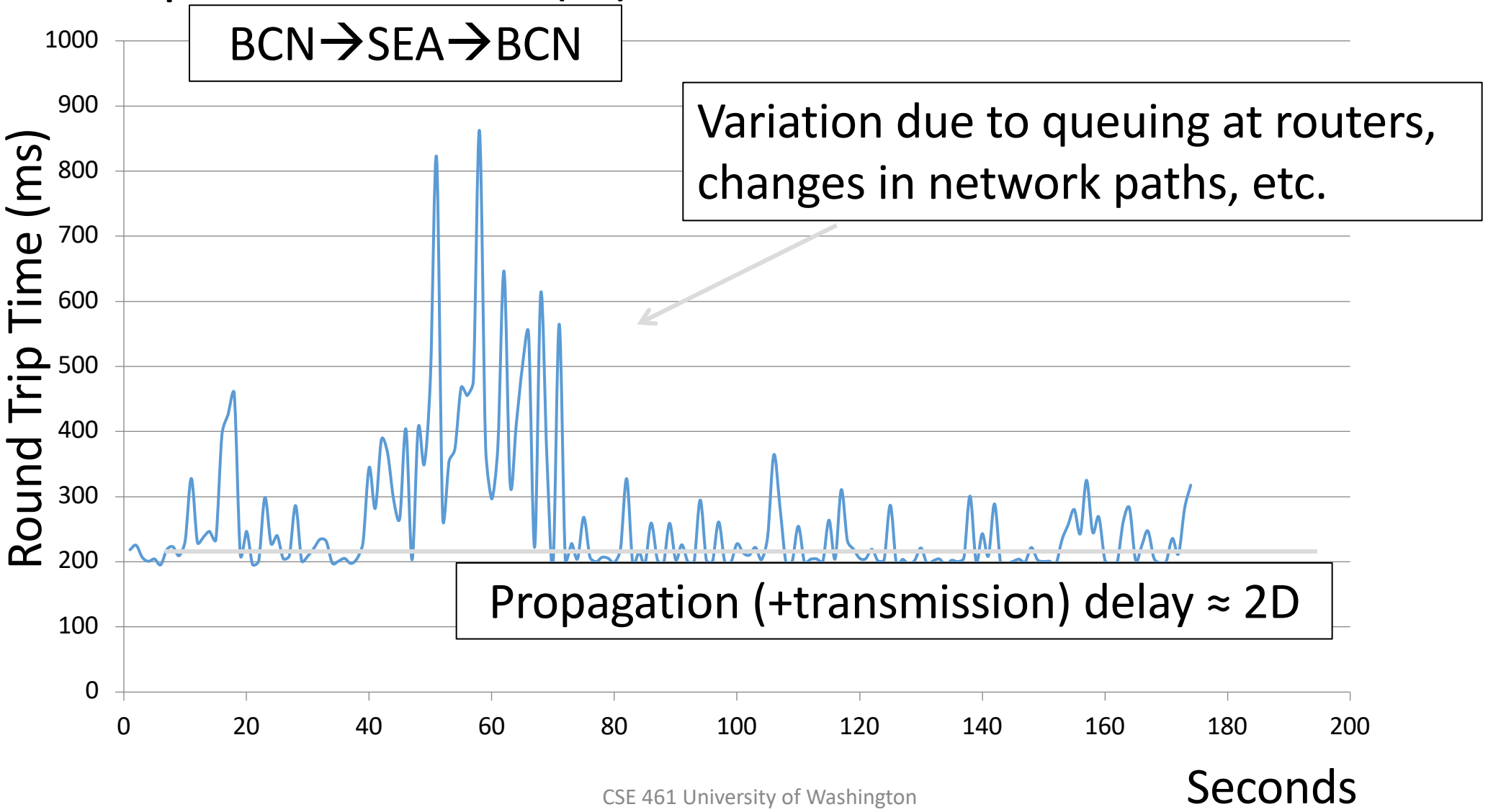
Timeout Problem

- Timeout should be “just right”
  - Too long → inefficient network capacity use
  - Too short → spurious resends waste network capacity
- But what is “just right”?
  - Easy to set on a LAN (Link)
    - Short, fixed, predictable RTT
  - Hard on the Internet (Transport)
    - Wide range, variable RTT

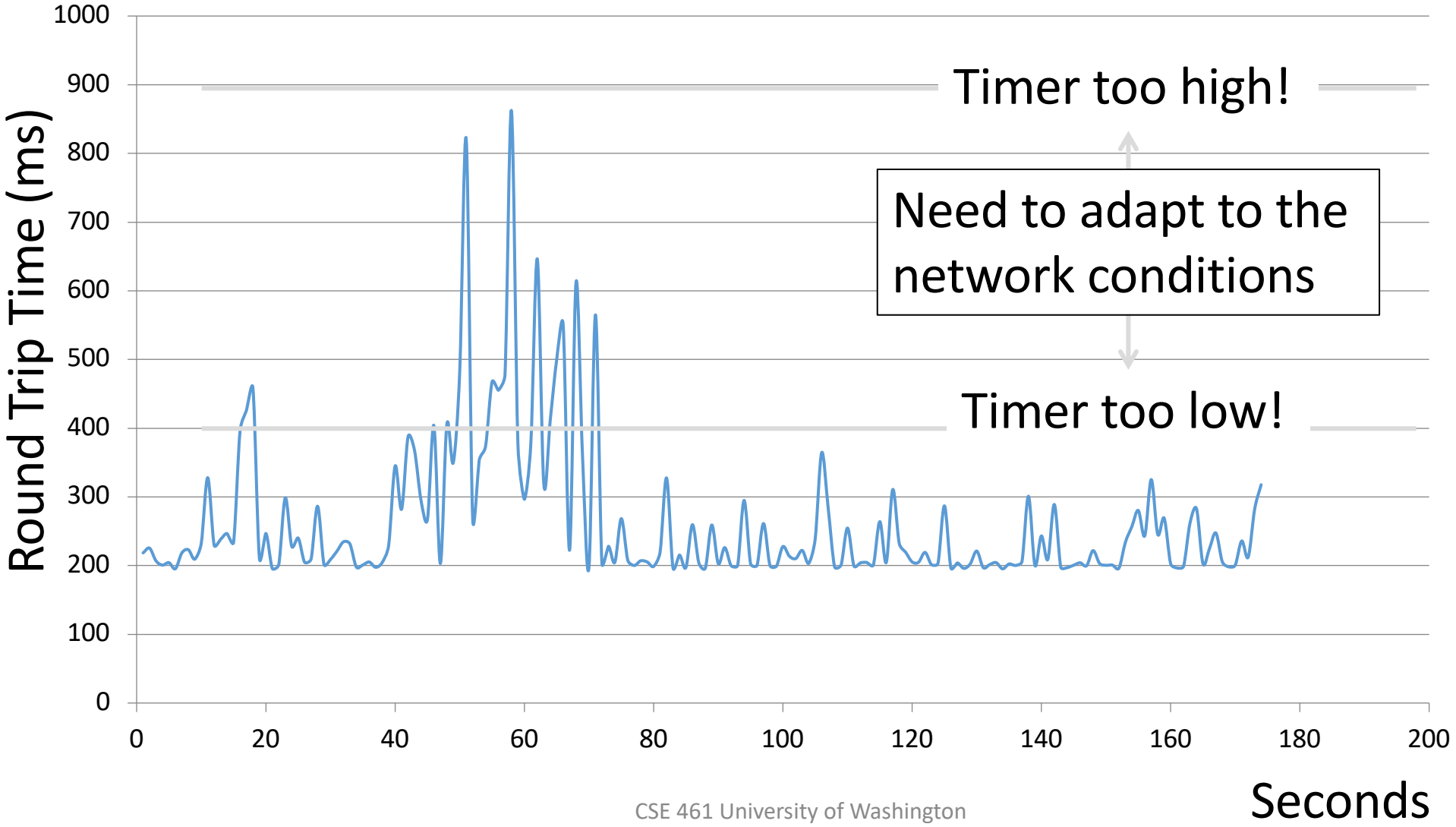
Example of RTTs



Example of RTTs (2)



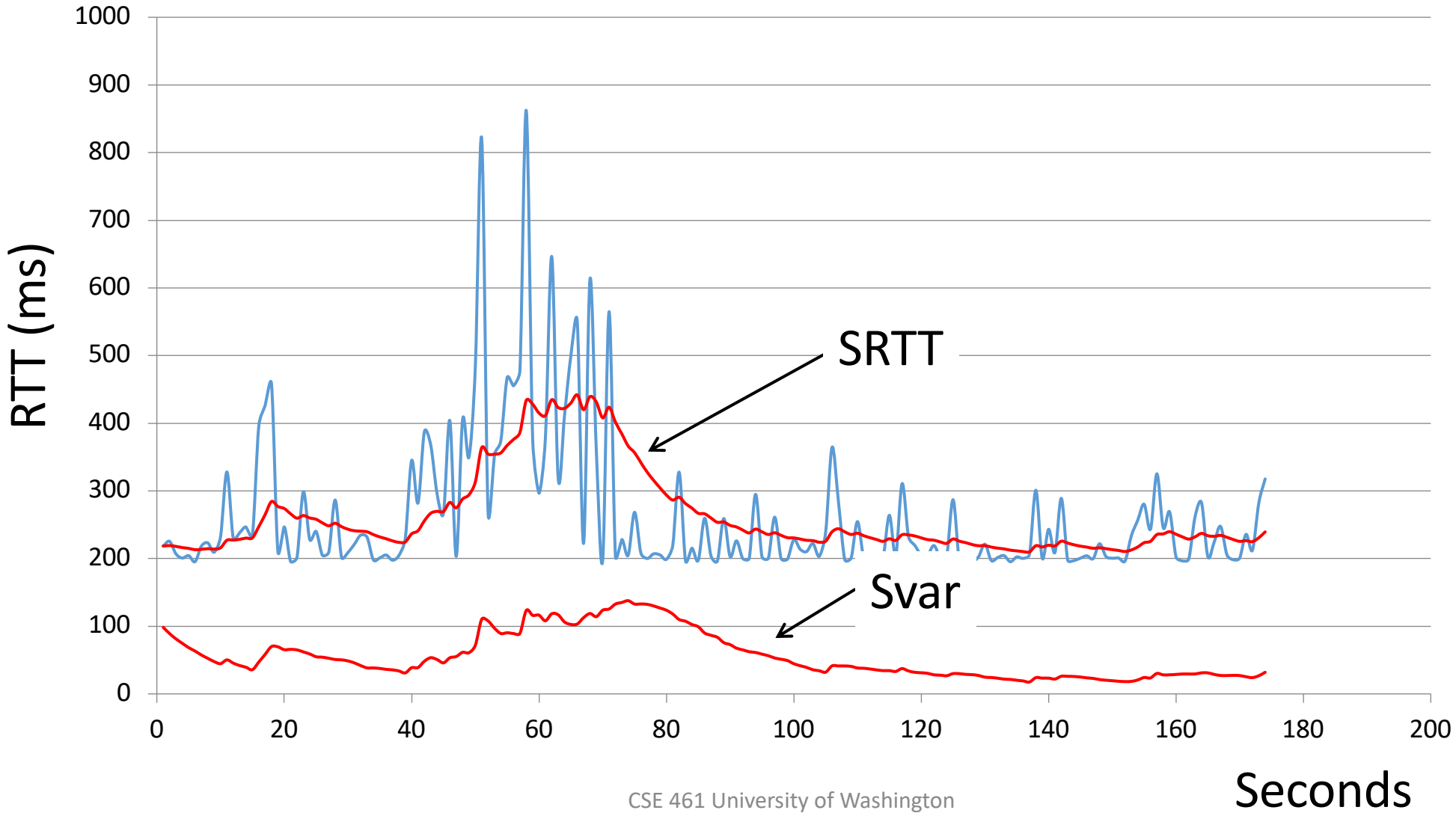
Example of RTTs (3)



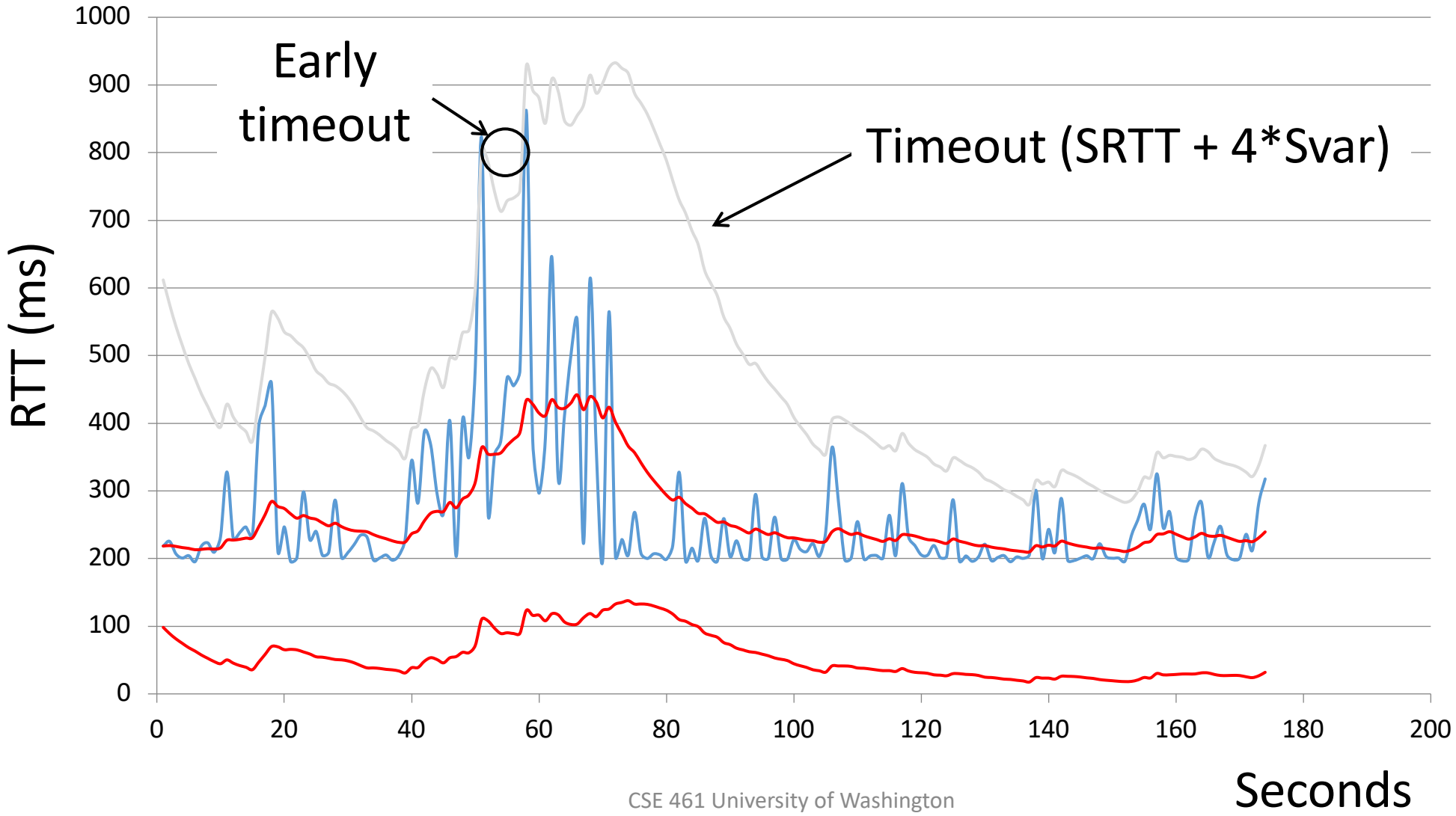
Adaptive Timeout

- Smoothed estimates of the RTT (1) and variance in RTT (2)
  - Update estimates with a moving average
  1. $SRTT_{N+1} = 0.9*SRTT_N + 0.1*RTT_{N+1}$
  2. $Svar_{N+1} = 0.9*Svar_N + 0.1*|RTT_{N+1} - SRTT_{N+1}|$
- Set timeout to a multiple of estimates
  - To estimate the upper RTT in practice
  - TCP $Timeout_N = SRTT_N + 4*Svar_N$

Example of Adaptive Timeout



Example of Adaptive Timeout (2)



Adaptive Timeout (2)

- Simple to compute, does a good job of tracking actual RTT
  - Little “headroom” to lower
  - Yet very few early timeouts
- Turns out to be important for good performance and robustness