Network Transport Layer:
TCP/Reno Analysis, TCP Cubic, TCP/Vegas

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http://zoo.cs.yale.edu/classes/cs433/

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Admin.

- Programming assignment 4 updated deadlines
  - Part 1: Discussion with instructor or TF checkpoint: Nov. 13; Code checkpoint: 11:55 pm, Nov. 15, 2018
  - Part 2: Design discussion with instructor or TF checkpoint: Nov. 27; Complete code and report due: 1:30 pm, Nov. 29, 2018.

Recap: Transport Reliability Design

- Basic structure of reliability protocol: sliding window protocols, connection management
- Basic analytical technique: execution traces; joint sender/receiver/channel state machine; state invariants
- TCP as an example implementation
  - Hybrid of GBN and SR
  - Full duplex transport
  - Multiple optimizations/adaptation mechanisms
    - Fast retransmit
    - Adaptive RTO
      - mean + variation
    - Adaptive window size (Congestion control)

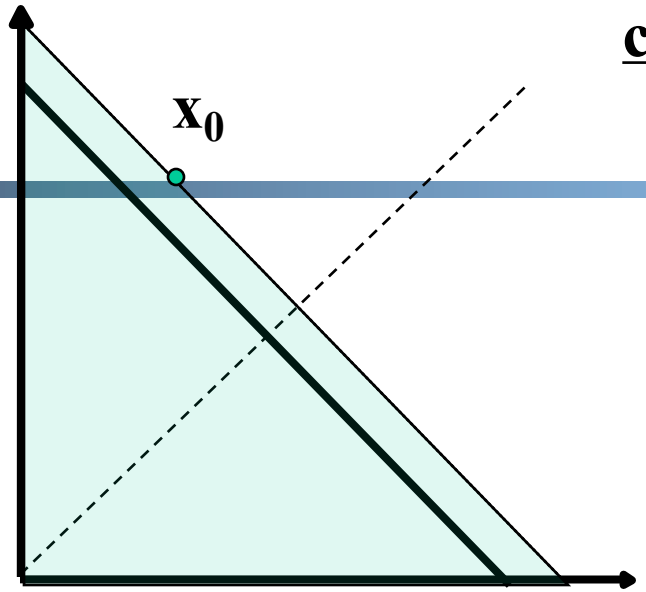
Recap: Transport Congestion Control Design

- What is congestion control
  - Too high rate can lead to unnecessary long delays, collapse due to waste of resources (e.g., large number of retranssmions, zombie packets)
- Desired properties of congestion control alg
  - distributed algorithm to achieve fairness and efficiency
- Linear control model and requirement

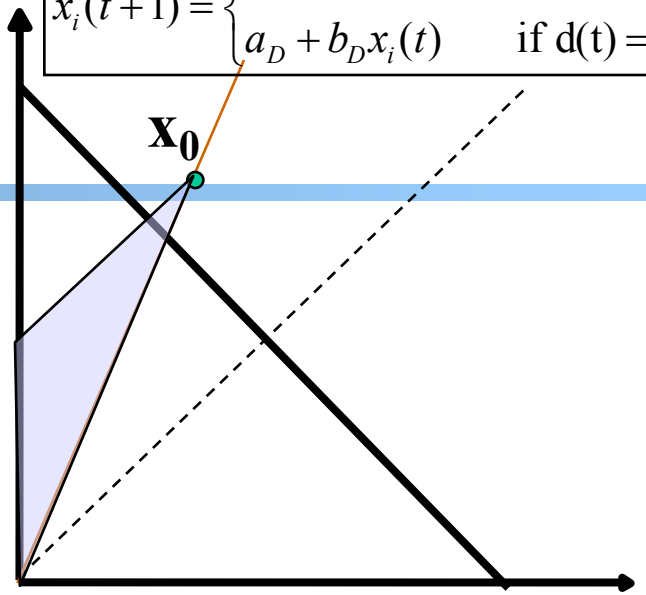
$$x_i(t+1) = \begin{cases} a_I + b_I x_i(t) & \text{if d(t) = no cong.} \\ a_D + b_D x_i(t) & \text{if d(t) = cong.} \end{cases}$$

congestion

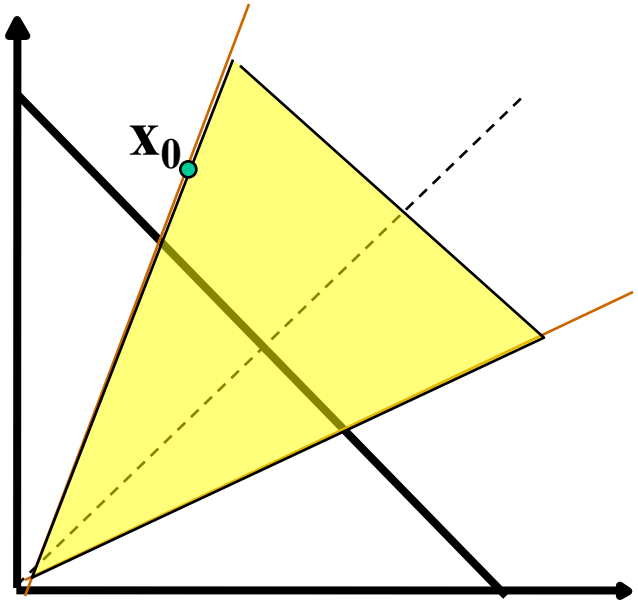
$$x_i(t+1) = \begin{cases} a_I + b_I x_i(t) & \text{if d(t) = no cong.} \\ a_D + b_D x_i(t) & \text{if d(t) = cong.} \end{cases}$$



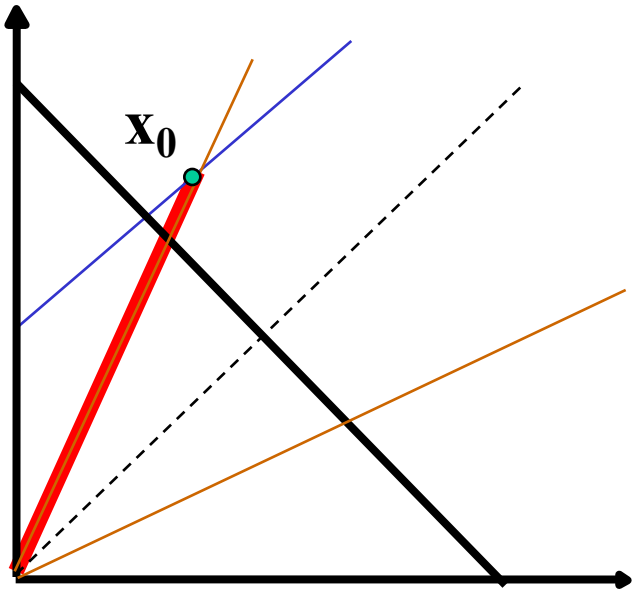
efficiency



efficiency: distributed linear rule



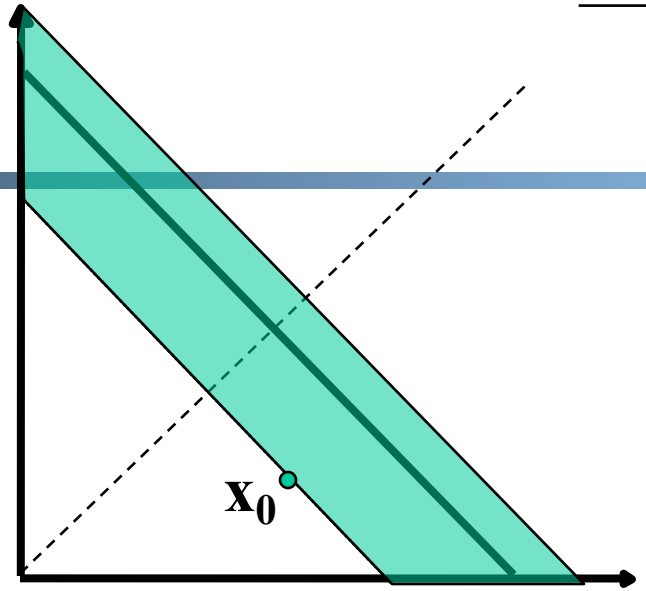
fairness



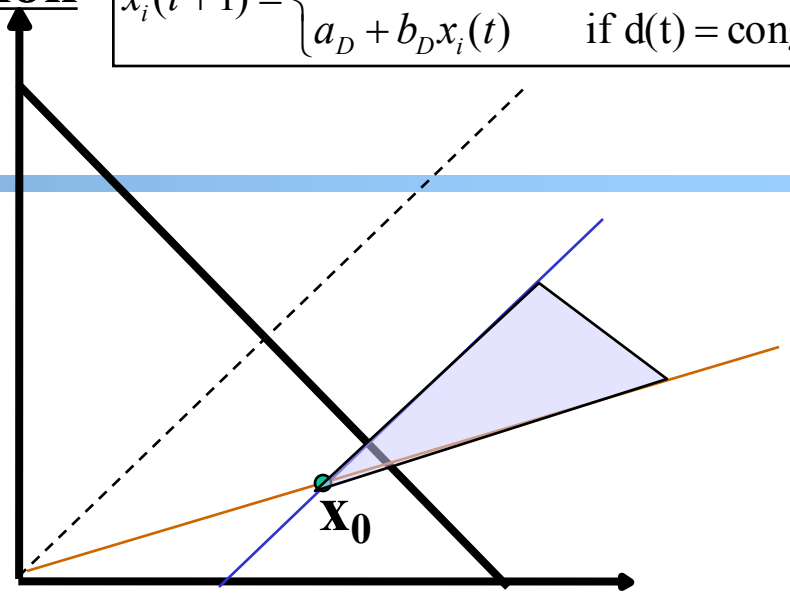
intersection

no-congestion

$$x_i(t+1) = \begin{cases} a_I + b_I x_i(t) & \text{if d(t) = no cong.} \\ a_D + b_D x_i(t) & \text{if d(t) = cong.} \end{cases}$$



efficiency



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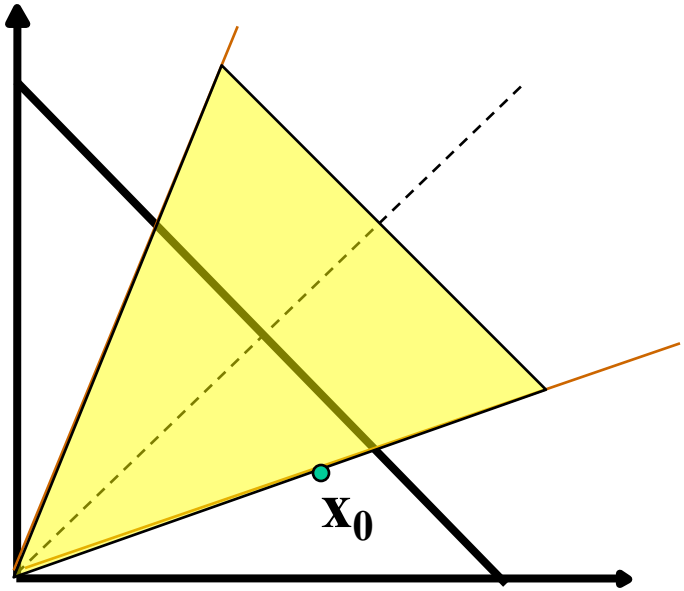
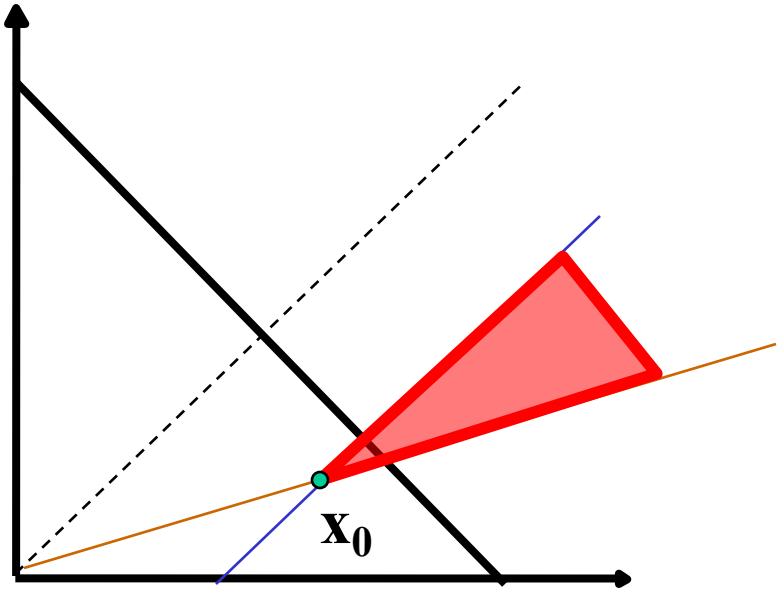
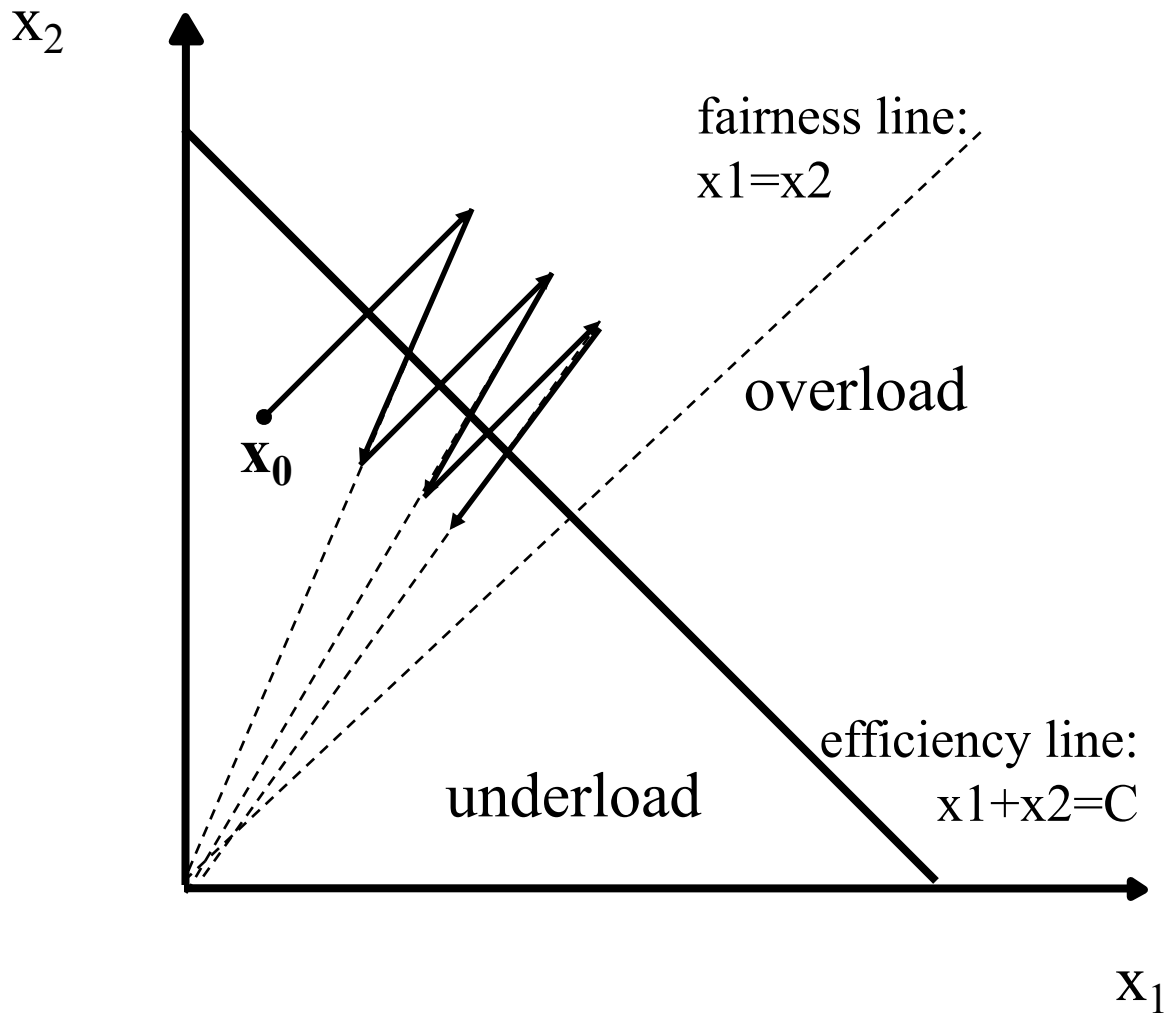


fairness



convergence

Recap: Why AIMD Works by Considering State Transition Trace



Intuition: Another Look

- Consider the difference or ratio of the rates of two flows
  - AIAD
  - MIMD
  - MIAD
  - AIMD

Recap: Realizing A(M)IMD: TCP/Reno

Initially:

```
    cwnd = 1;
    ssthresh = infinite (e.g., 64K);
```

For each newly ACKed segment:

```
    if (cwnd < ssthresh)        // slow start: MI
        cwnd = cwnd + 1;
    else
                                // congestion avoidance; AI
        cwnd += 1/cwnd;
```

Triple-duplicate ACKs:

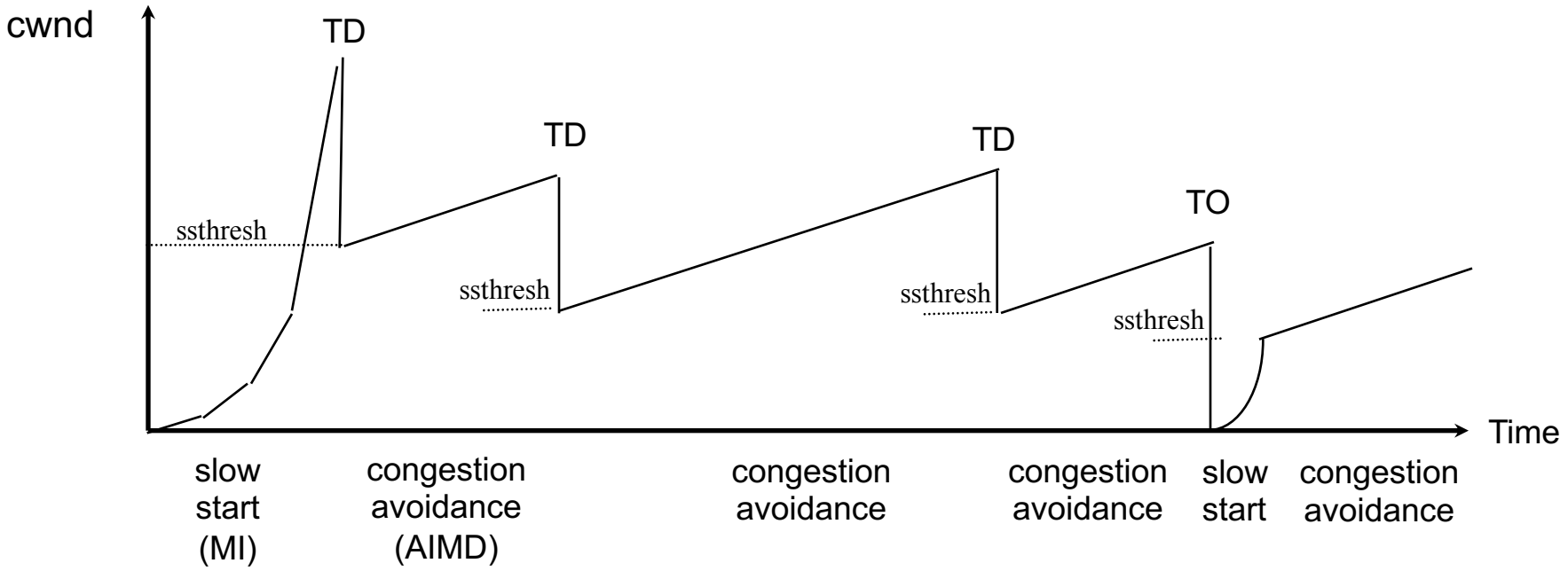
```
                                // MD
    cwnd = ssthresh = cwnd/2;
```

Timeout:

```
    ssthresh = cwnd/2;          // reset
    cwnd = 1;
```

(if already timed out, double timeout value; this is called exponential backoff)

Recap: TCP/Reno: Big Picture



TD: Triple duplicate acknowledgements
TO: Timeout

Outline

- Admin and recap
- Transport congestion control/resource allocation
  - what is congestion (cost of congestion)
  - basic congestion control alg.
  - TCP/reno congestion control
    - design
    - analysis

Objective

- To understand the throughput of TCP/Reno as a function of RTT (RTT), loss rate (p) and packet size
- To better understand system dynamics

- We will analyze TCP/Reno under two different setups

TCP/Reno Throughput Analysis

- mean packet loss rate: p; mean round-trip time: RTT, packet size: S
- Consider only the congestion avoidance mode (long flows such as large files)
- Assume no timeout
- Assume mean window size is W_m segments, each with S bytes sent in one RTT:

$$\text{Throughput} = \frac{W_m * S}{RTT} \text{ bytes/sec}$$

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      - *small fish in a big pond: loss rate given from the environment*

TCP/Reno Throughput Modeling

$$\Delta W = \begin{cases} \frac{1}{W} & \text{if the packet is not lost} \\ -\frac{W}{2} & \text{if packet is lost} \end{cases}$$

$$mean\ of\ \Delta W = (1-p)\frac{1}{W} + p(-\frac{W}{2}) = 0$$

$$\Rightarrow \quad mean\ of\ W = \sqrt{\frac{2(1-p)}{p}} \approx \frac{1.4}{\sqrt{p}}, \text{ when } p \text{ is small}$$

$$\Rightarrow \quad \boxed{throughput \approx \frac{1.4S}{RTT\sqrt{p}}, \text{ when } p \text{ is small}}$$

This is called the TCP throughput sqrt of loss rate law.

Exercise: Application of Analysis

- State of art network link can reach 100 Gbps. Assume packet size 1250 bytes, RTT 100 ms, what is the highest packet loss rate to still reach 100 Gbps?

tcp-reno-tput.xlsx

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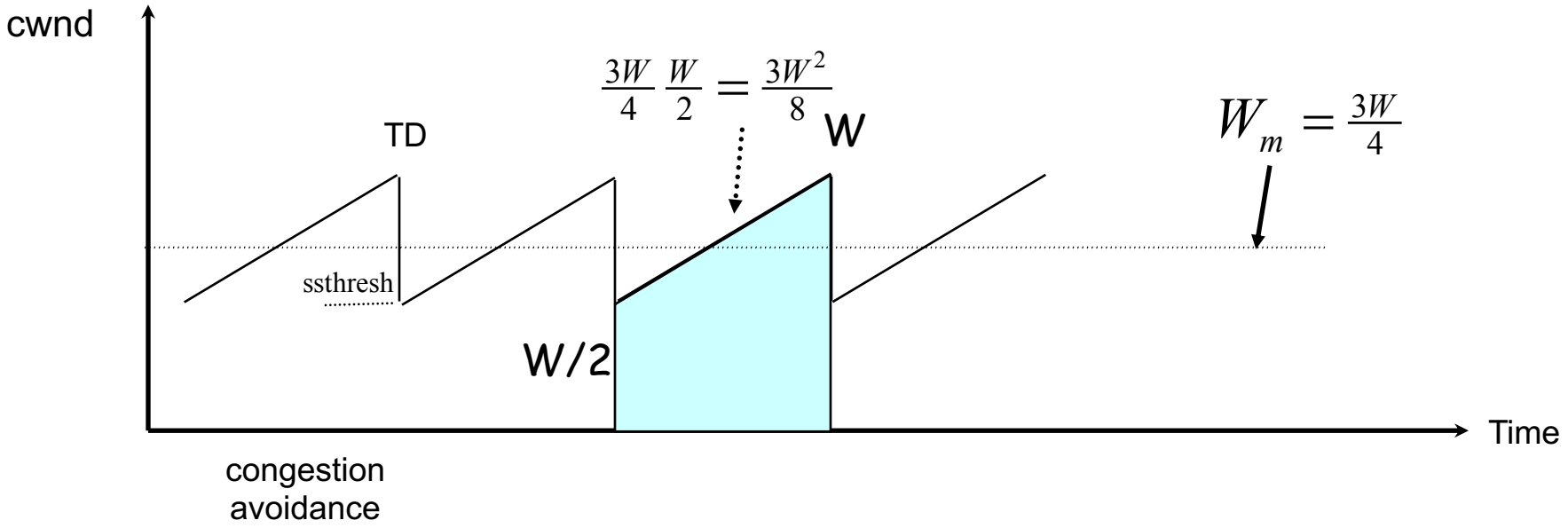
  - TCP/reno congestion control
    - design
    - analysis
      - small fish in a big pond: loss rate given from the environment
      - ➢ *big fish in small pond: growth causes losses*

TCP/Reno Throughput Modeling: Relating W with Loss Rate p



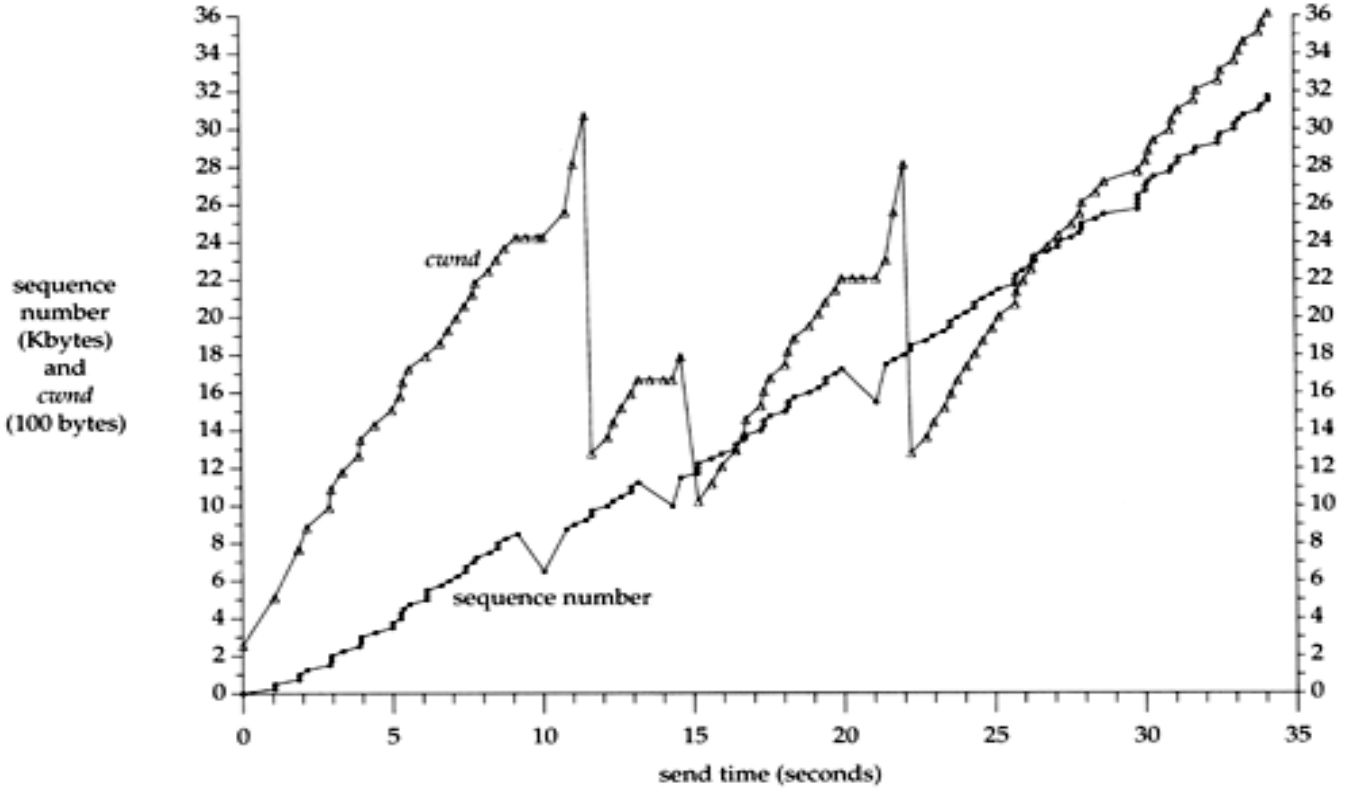
Total packets sent per cycle = (W/2 + W)/2 * W/2 = $3W^2/8$

Assume one loss per cycle => p = $1/(3W^2/8) = 8/(3W^2)$

$$\Rightarrow \quad W = \frac{\sqrt{8/3}}{\sqrt{p}} = \frac{1.6}{\sqrt{p}}$$

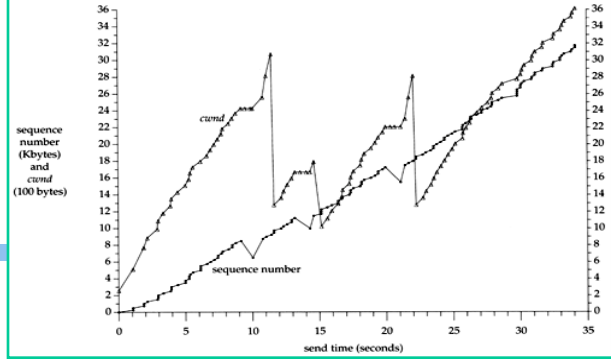
$$\Rightarrow throughput = \frac{S}{RTT}\ \frac{3}{4}\ \frac{1.6}{\sqrt{p}} = \boxed{\frac{1.2S}{RTT\sqrt{p}}}$$

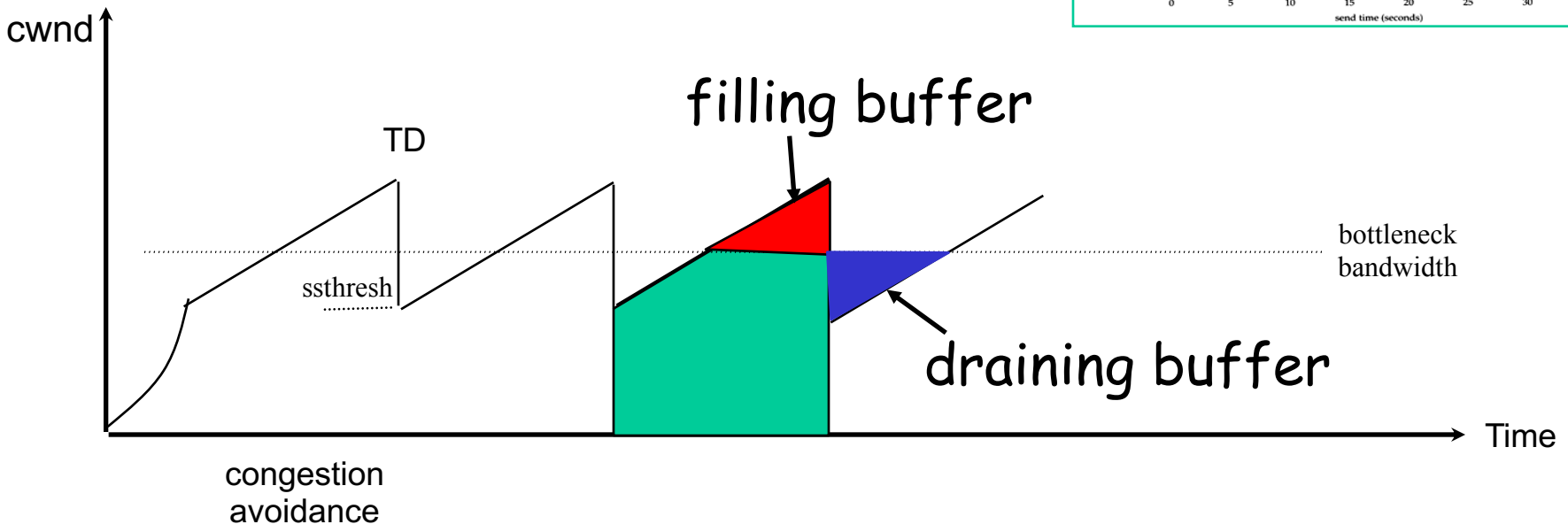
A Puzzle: cwnd and Rate of a TCP Session



Question: cwnd fluctuates widely (i.e., cut to half); how can the sending rate stay relatively smooth?

TCP/Reno Queueing Dynamics



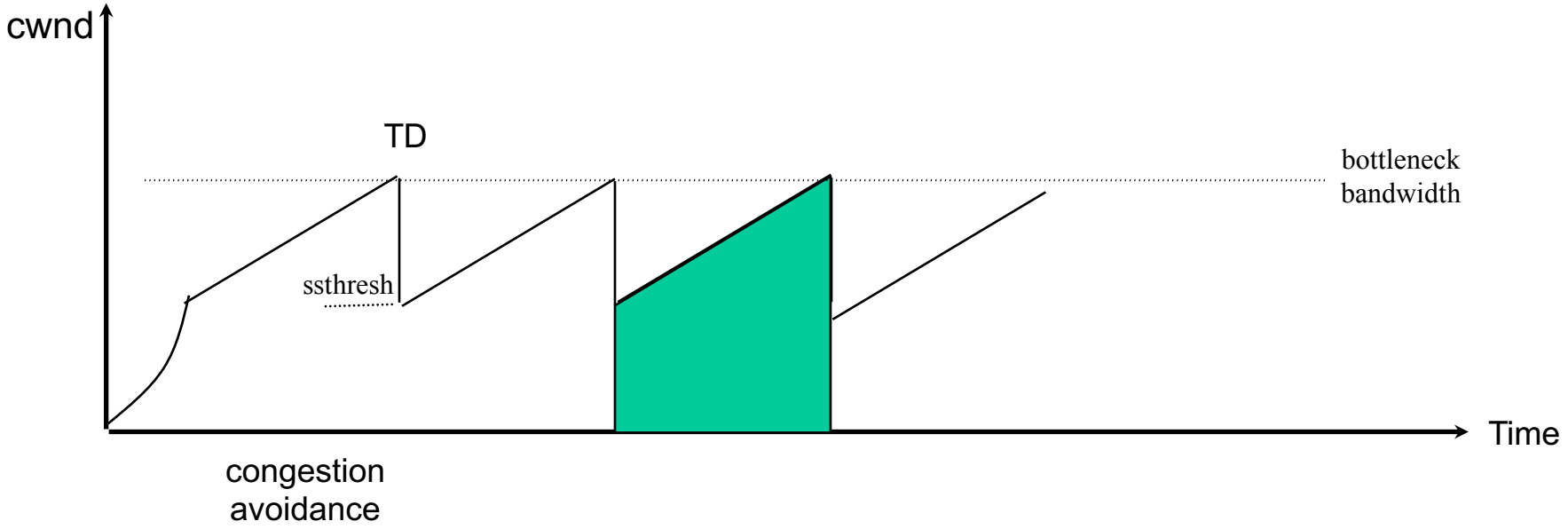


If the buffer at the bottleneck is large enough, the buffer is never empty (not idle), during the cut-to-half to "grow-back" process.

Offline Exercise: How big should the buffer be to achieve full utilization?

Discussion

- If the buffer size at the bottleneck link is very small, what is the link utilization?

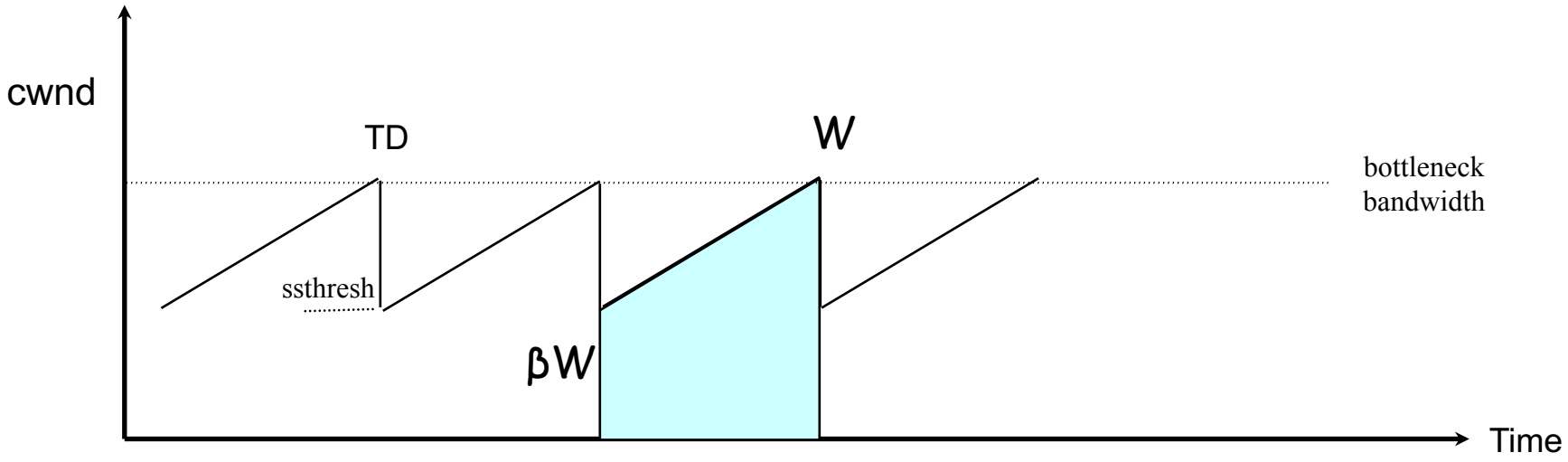


Exercise: Small Buffer

- Assume
  - BW: 10 G
  - RTT: 100 ms
  - Packet: 1250 bytes
  - BDP (full window size): 100,000 packets
- A loss can cut window size from 100,000 to 50,000 packets
- To fully grow back
  - Need 50,000 RTTs => 5000 seconds, 1.4 hours

Discussion

- Assume a generic AIMD alg: reduce to βW after each loss event. What is the avg link utilization when buffer is small?



- If the objective is to maximize link utilization, pick large or small β?
- Why not pick β maximizing utilization?

Outline

- Admin and recap
- Transport congestion control/resource allocation
  - what is congestion (cost of congestion)
  - basic congestion control alg.
  - TCP/Reno congestion control
  - TCP Cubic

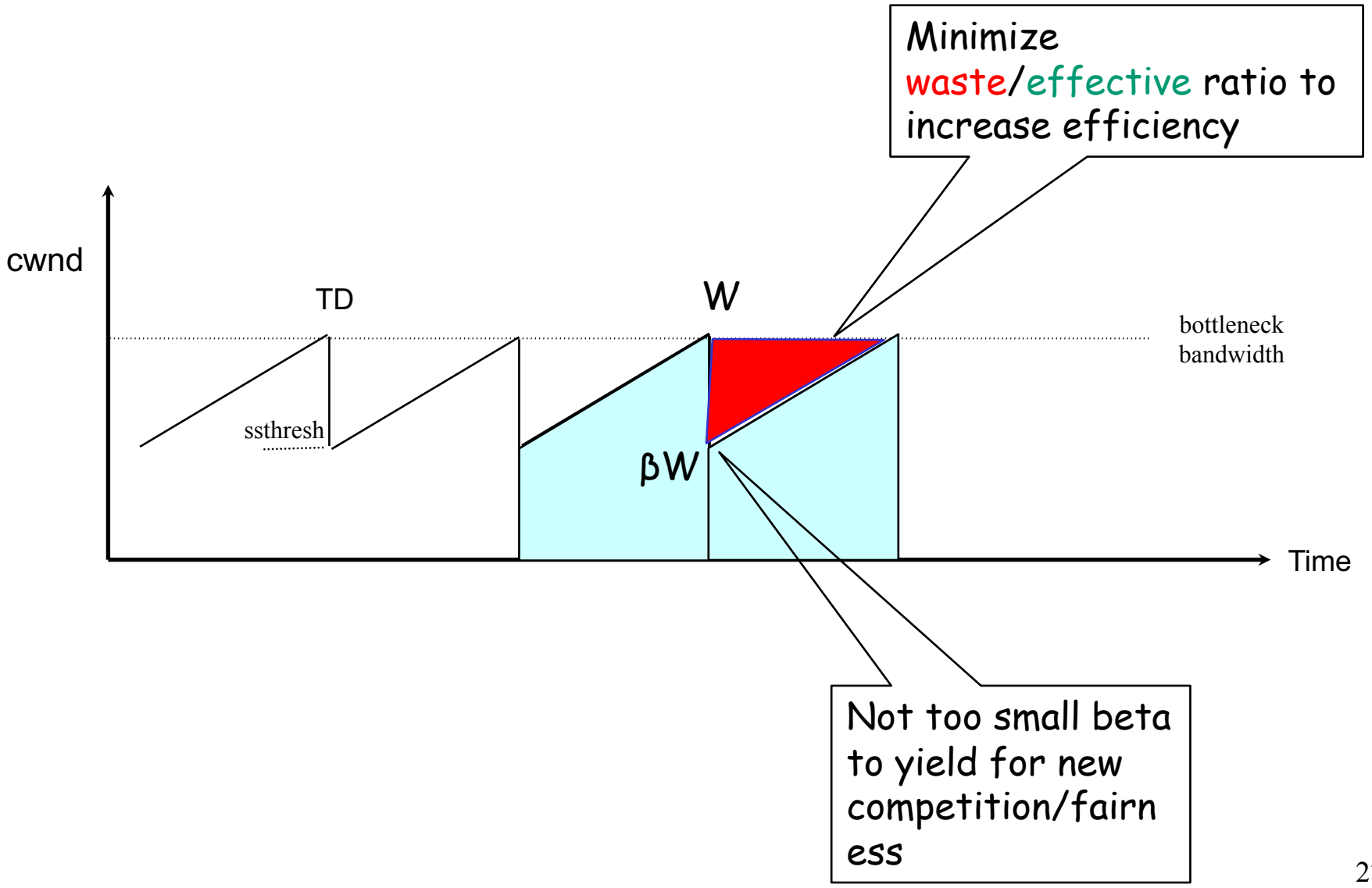
TCP Cubic

- Designed in 2008 by Rhee' group
- Default for Linux
- Most sockets in MAC appear to use cubic as well
  - sysctl -a
    - If you want to see some TCP parameters by a real OS (grep inet.tcp)
    - grep reno cubic

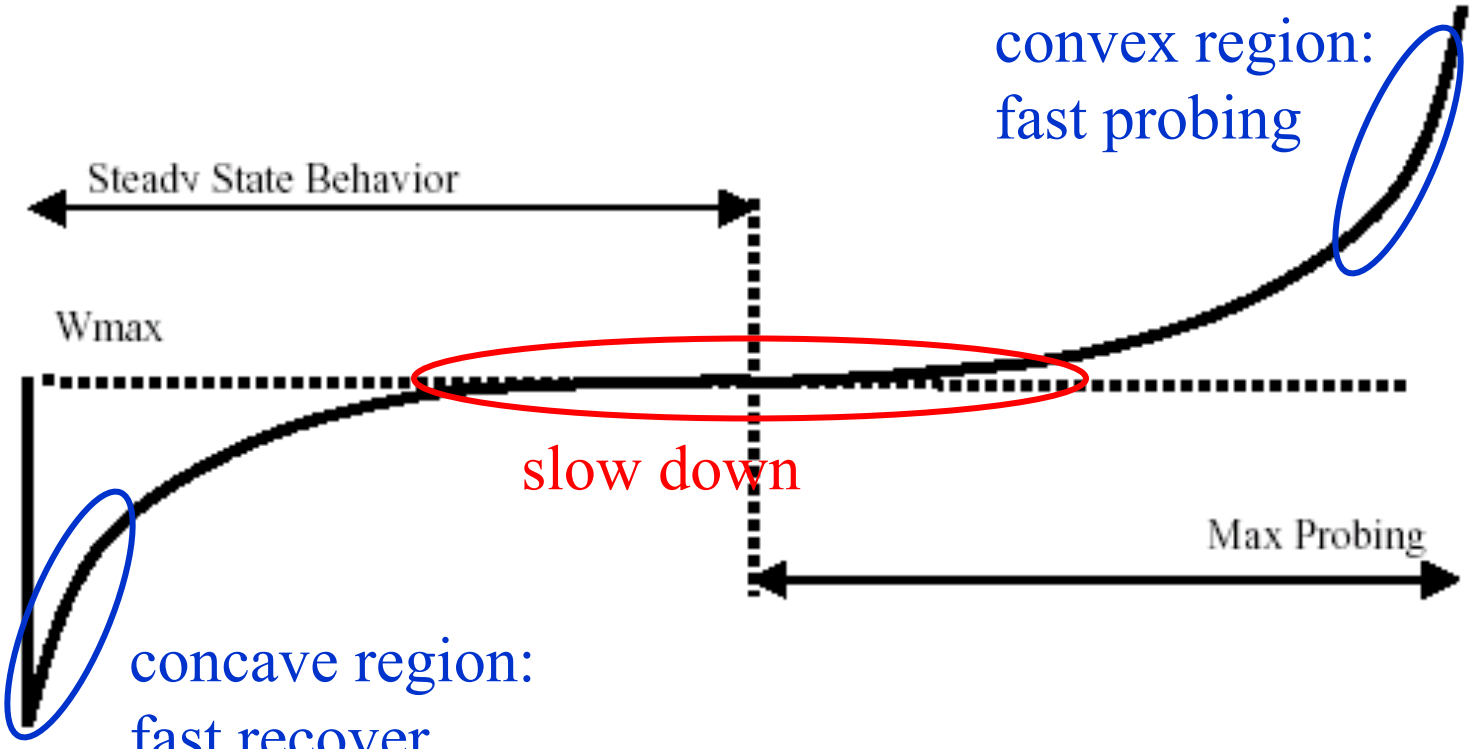
TCP Cubic Goals

- Improve TCP efficiency over fast, long-distance links with limited buffer
- TCP friendliness: Follows TCP if TCP gives higher rate

Basic Idea I


Minimize waste/effective ratio to increase efficiency
cwnd
TD
W
bottleneck bandwidth
ssthresh
βW
Time
Not too small beta to yield for new competition/fairn ess

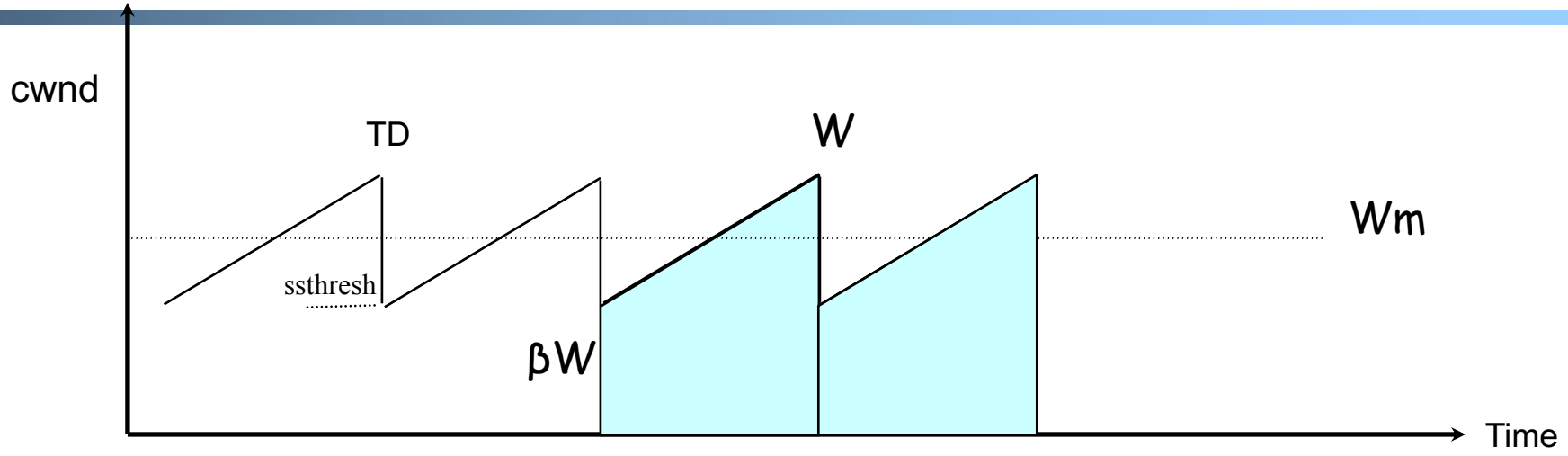
Cubic Window Function



$$W_{cubic} = C(t-K)^3 + W_{\max} \qquad K = \sqrt[3]{W_{\max}\beta/C}$$

where ***C*** is a scaling factor, ***t*** is the elapsed time from the last window reduction, and ***β*** is a constant multiplication decrease factor

Basic Idea II: TCP Friendly Rate with Generic β



Packets per cycle: $\frac{\beta W+W}{2}\frac{(1-\beta)W}{\alpha} = \frac{(1-\beta)(1+\beta)}{2\alpha}W^2$

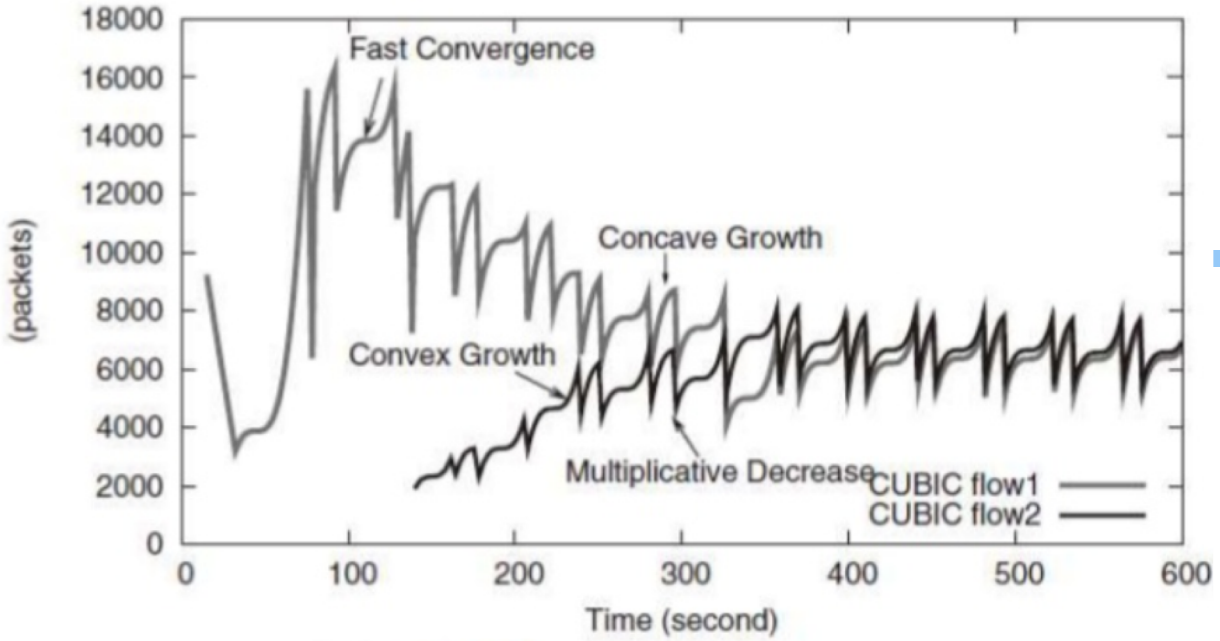
Assume one loss per cycle: $p = \frac{2\alpha}{(1-\beta)(1+\beta)w^2}$ $w = \sqrt{\frac{2\alpha}{(1-\beta)(1+\beta)p}}$

$$\text{tput} = \frac{W_m S}{RTT} = \frac{S}{RTT}\frac{(1+\beta)W}{2} = \frac{S}{RTT}\sqrt{\frac{\alpha(1+\beta)}{2(1-\beta)p}}$$

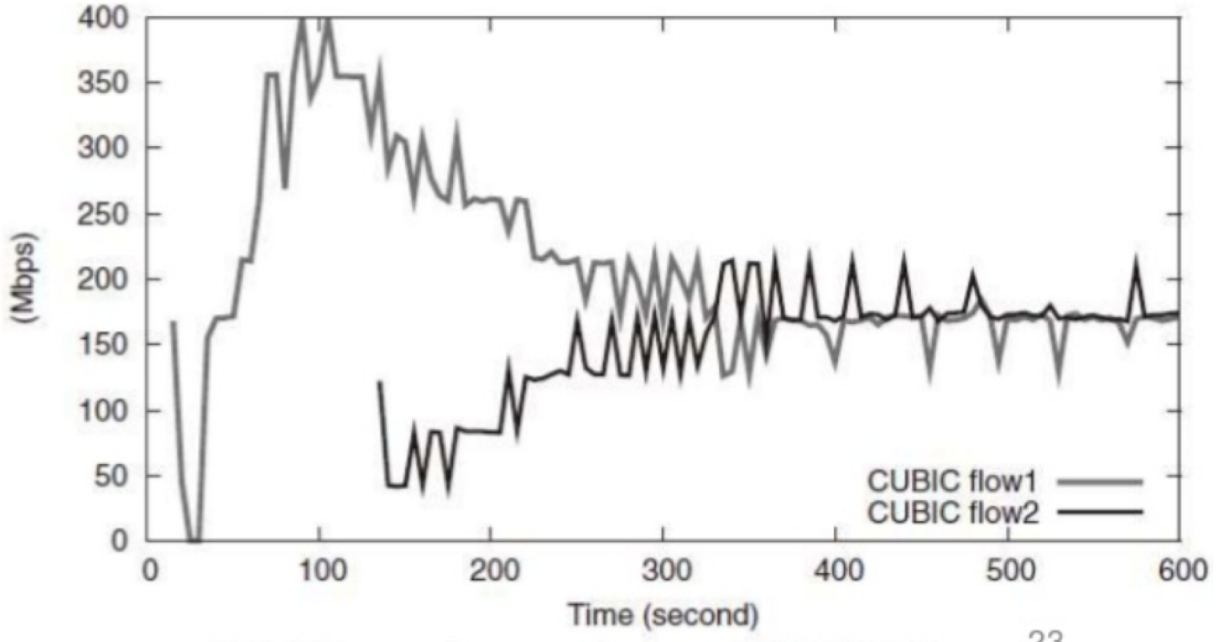
TCP friendly: $\alpha = 3\frac{1-\beta}{1+\beta}$

Cubic High-Level Structure

- If (received ACK && state == cong avoid)
  - Compute $W_{cubic}(t)$
  - Compute $W_{TCP}(t)$ (form?)
  - Pick the larger one



(a) CUBIC window curves.



(b) Throughput of two CUBIC flows.[23]

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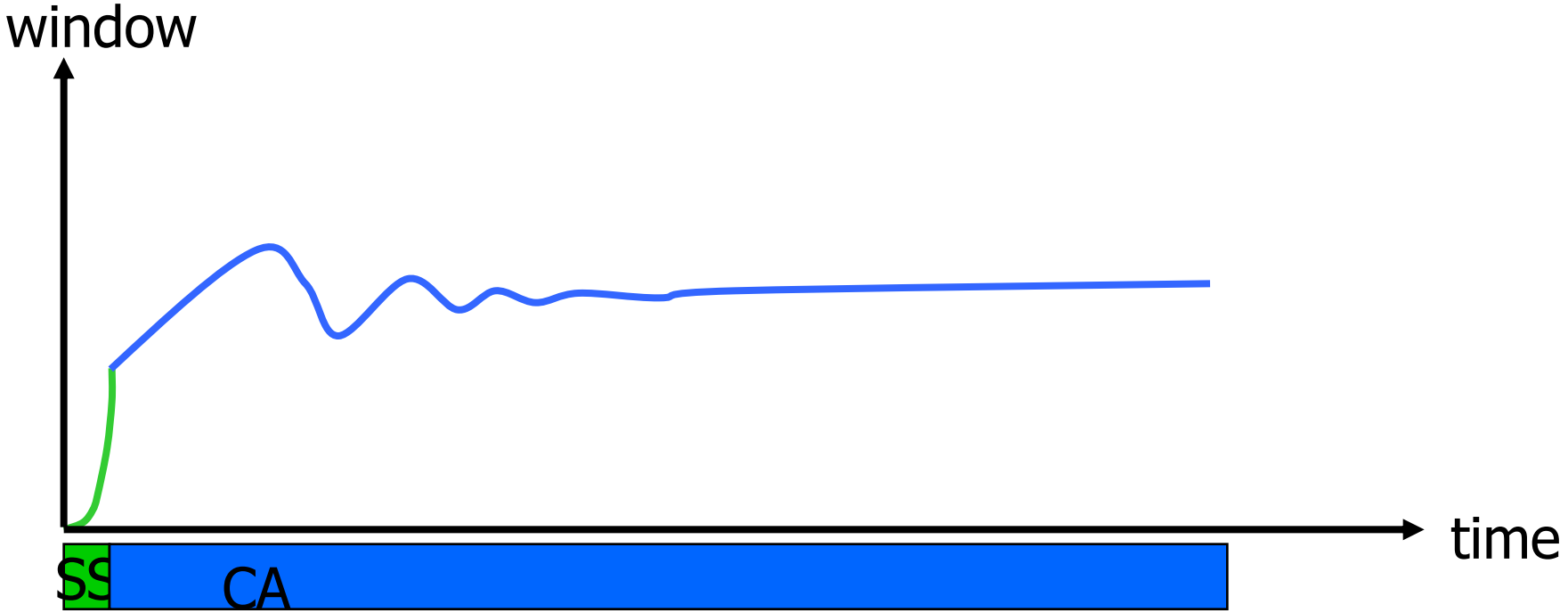
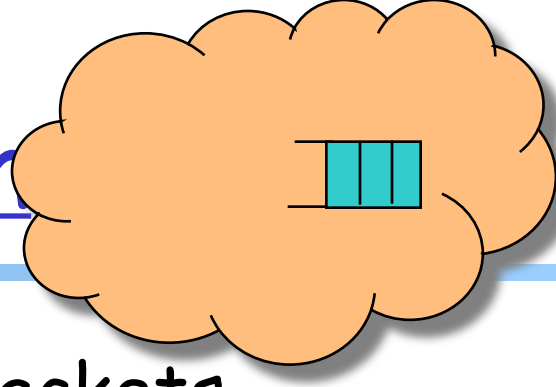
  - TCP/Reno congestion control
  - TCP Cubic
  - TCP/Vegas

TCP/Vegas (Brakmo & Peterson 1994)

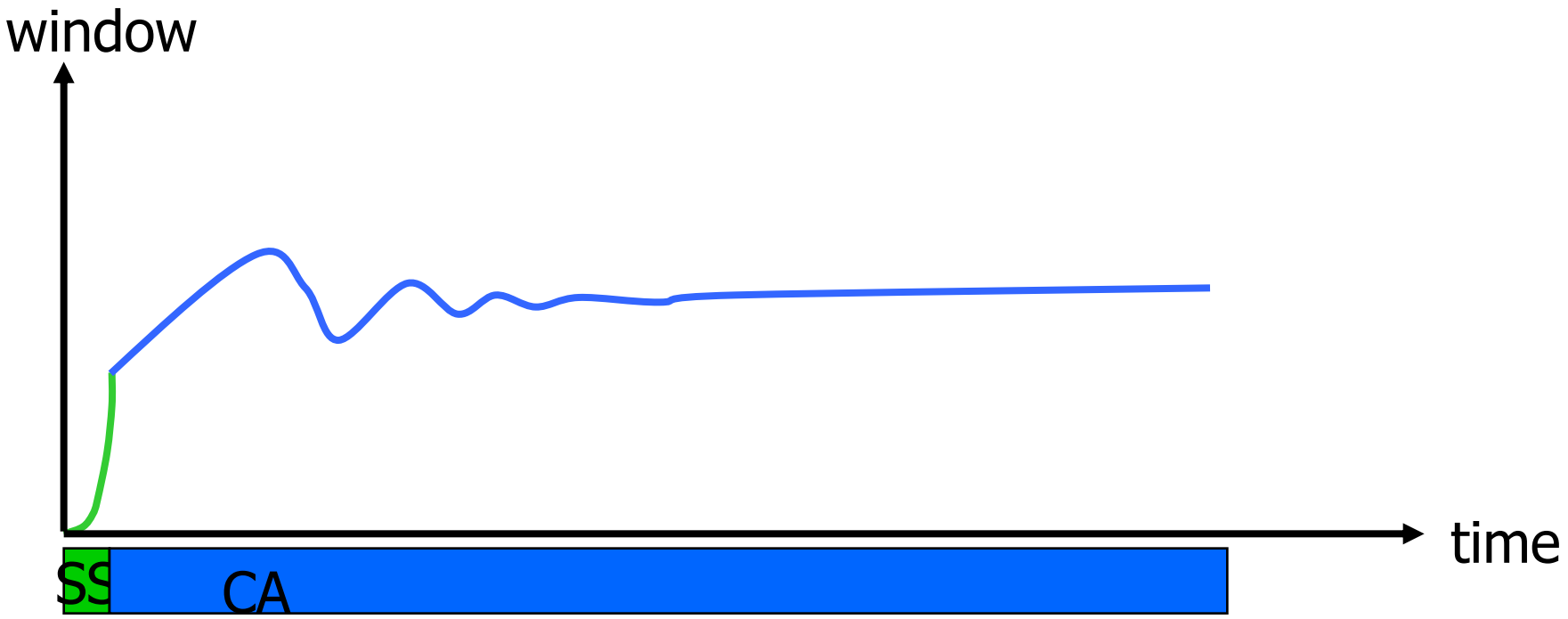


- Idea: try to detect congestion by delay before loss
- Objective: not to overflow the buffer; instead, try to maintain a *constant* number of packets in the bottleneck queue

TCP/Vegas: Key Question

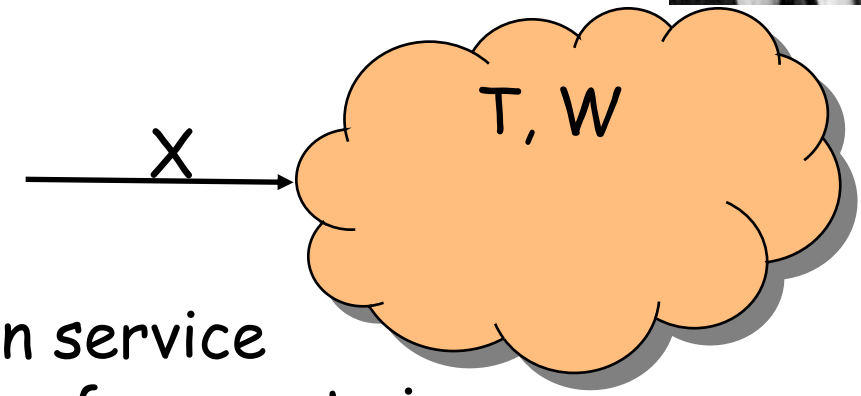


- How to estimate the number of packets queued in the bottleneck queue(s)?



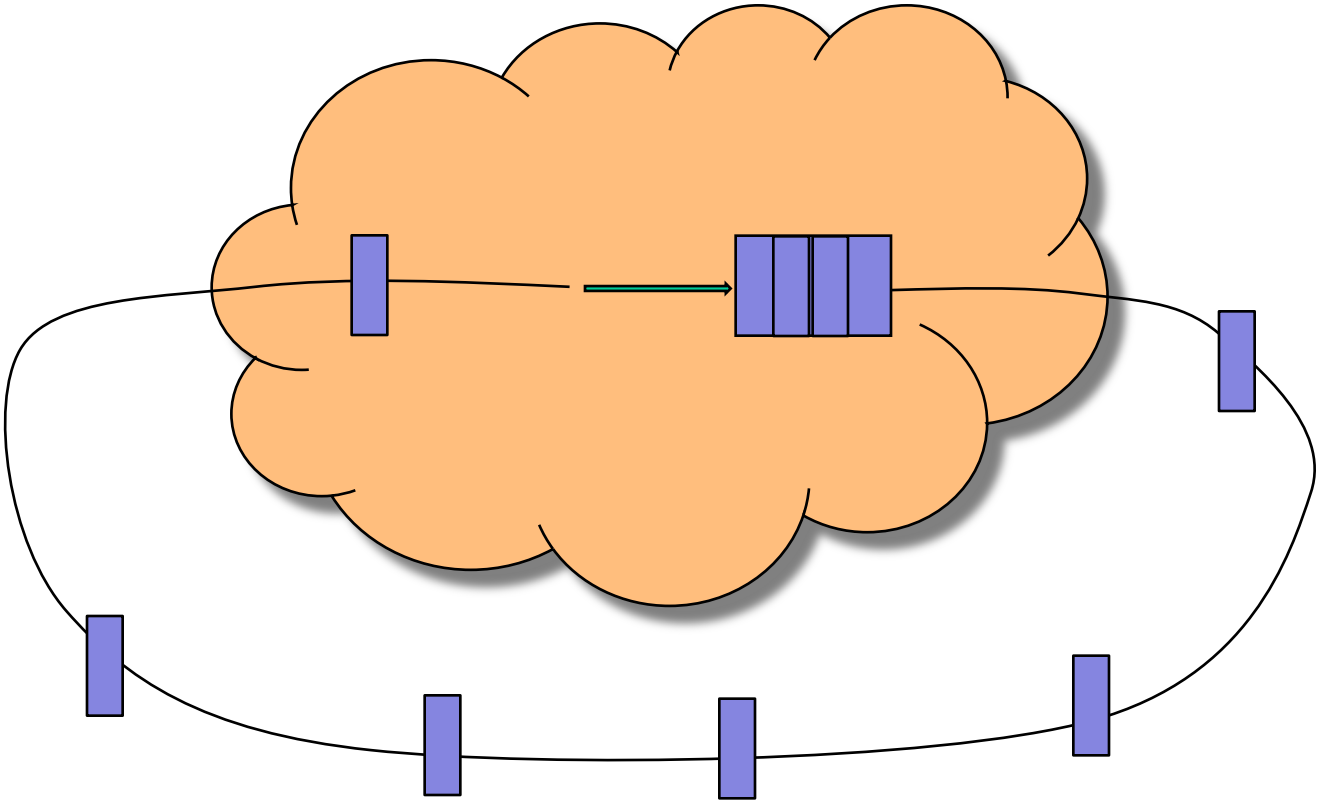
Recall: Little's Law

- For any system with no or (low) loss.
- Assume
  - mean arrival rate X, mean service time T, and mean number of requests in the system W
- Then relationship between W, X, and T:

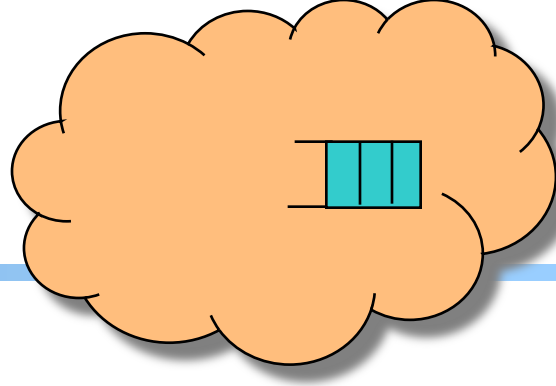


$$W = XT$$

Estimating Number of Packets in the Queue



TCP/Vegas CA algorithm



$$T = T_{prop} + T_{queueing}$$

Applying Little's Law:

$$x_{vegas}\, T = x_{vegas}\, T_{prop} + x_{vegas}\, T_{queueing},$$

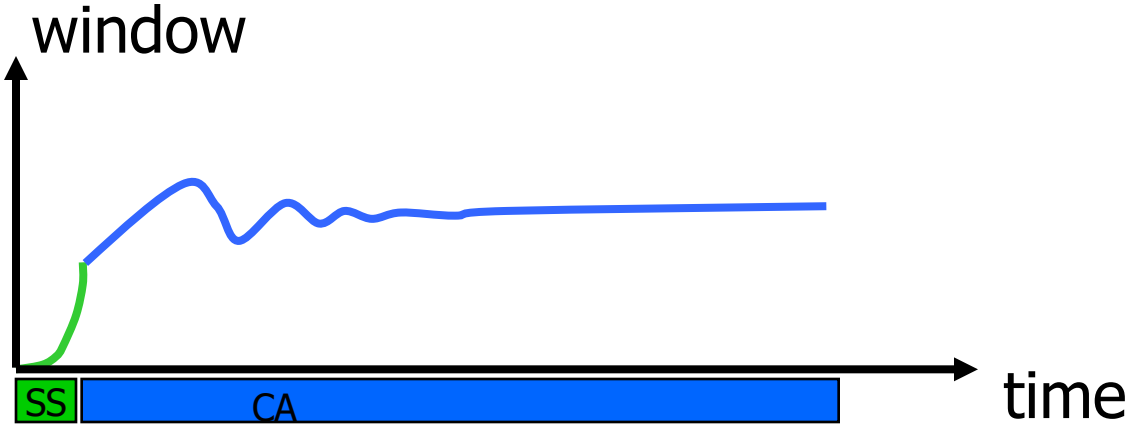
where $x_{vegas} = W / T$ is the sending rate

Then number of packets in the queue is

$$x_{vegas}\, T_{queueing} = x_{vegas}\, T - x_{vegas}\, T_{prop}$$
$$= W - W/T\, T_{prop} \quad \text{(value?)}$$

TCP/Vegas CA algorithm

maintain a *constant* number of packets in the bottleneck buffer




```
for every RTT
{    if W - W/RTT RTT_min < α then W ++
     if W - W/RTT RTT_min > α then W --
}
for every loss
        W := W/2
```

queue size

Discussions

- If two flows, one TCP Vegas and one TCP reno run together, how may bandwidth partitioned be among them?

- What are some other key challenges for TCP/Vegas?