CS 356: Computer Network Architectures
Lecture 20: Congestion Avoidance
Chap. 6.4 and related papers

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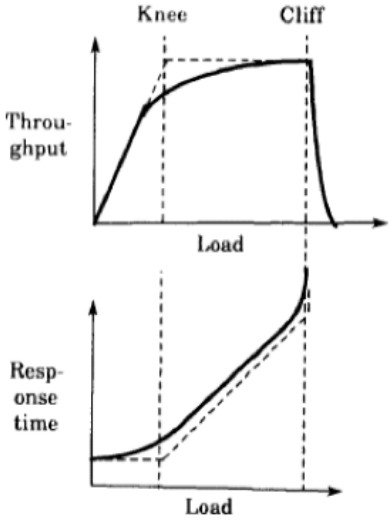
TCP Congestion Control

History

- The original TCP/IP design did not include congestion control and avoidance
  - Receiver uses advertised window to do flow control
  - No exponential backoff after a timeout

- It led to congestion collapse in October 1986
  - The NSFnet phase-I backbone dropped three orders of magnitude from its capacity of 32 kbit/s to 40 bit/s, and continued until end nodes started implementing Van Jacobson's congestion control between 1987 and 1988.
  - TCP retransmits too early, wasting the network's bandwidth to retransmit packets already in transit and reducing useful throughput (goodput)

Design Goals



- Congestion avoidance: making the system operate around the knee to obtain low latency and high throughput
- Congestion control: making the system operate left to the cliff to avoid congestion collapse

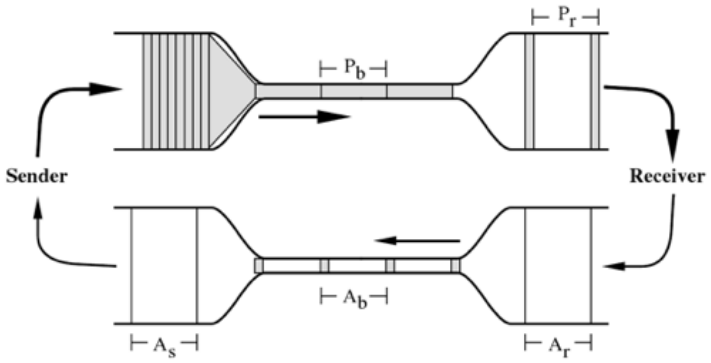
Key Improvements

- RTT variance estimate
  - Old design: $RTT_{n+1} = \alpha\ RTT\ + (1- \alpha)\ RTT_n$
  - $RTO = \beta\ RTT_{n+1}$
- Exponential backoff
- Slow-start
- Dynamic window sizing
- Fast retransmit

Challenge

- Send at the “right” speed
  - Fast enough to keep the pipe full
  - But not to overrun the “pipe”
  - Share nicely with other senders

Key insight: packet conservation principle and self-clocking



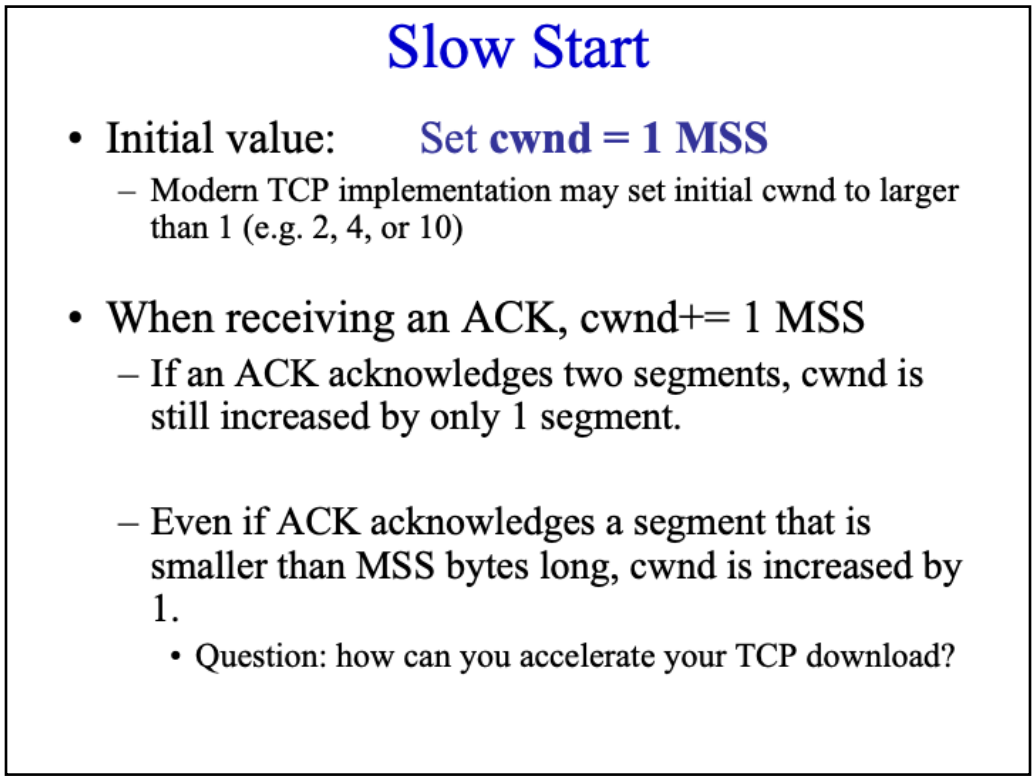
- When pipe is full, the speed of ACK returns equals to the speed new packets should be injected into the network

Solution: Dynamic window sizing

- Sending speed: SWS / RTT
- → Adjusting SWS based on available bandwidth
- The sender has two *internal* parameters:
  - **Congestion Window (cwnd)**
  - **Slow-start threshold Value (ssthresh)**
- SWS is set to the minimum of (cwnd, receiver advertised win)

Two Modes of Congestion Control

1. Probing for the available bandwidth
   - **slow start** (cwnd < ssthresh)
2. Avoid overloading the network
   - **congestion avoidance** (cwnd >= ssthresh)



Note: Unit is a segment size. TCP actually is based on bytes and increments by 1 MSS (maximum segment size). To increase, one may ack every byte rather than a full sized segment. But this attack has been fixed.

Increasing TCP's Initial Window. doi:10.17487/RFC3390. RFC 3390.

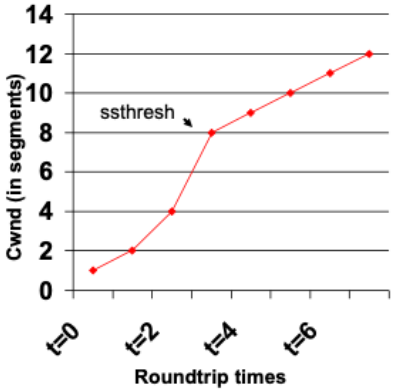
Corbet, Jonathan. "Increasing the TCP initial congestion window". LWN. Retrieved 10 October 2012.

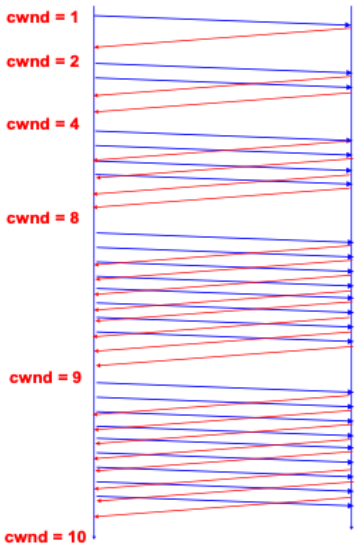
Congestion Avoidance

- If cwnd >= ssthresh then each time an ACK is received, increment cwnd as follows:
  - cwnd += MSS * (MSS / cwnd) (cwnd measured in bytes)
- So *cwnd* is increased by one MSS only if all *cwnd*/MSS segments have been acknowledged.

Example of Slow Start/Congestion Avoidance

Assume *ssthresh = 8 MSS*





Congestion detection

- What would happen if a sender keeps increasing cwnd?
  - Packet loss
- TCP uses packet loss as a congestion signal
- Loss detection
  1. Receipt of a duplicate ACK (cumulative ACK)
  2. Timeout of a retransmission timer

Reaction to Congestion

- Reduce cwnd
- Timeout: severe congestion
  - cwnd is reset to one MSS:

    cwnd = 1 MSS
  - ssthresh is set to half of the current size of the congestion window:

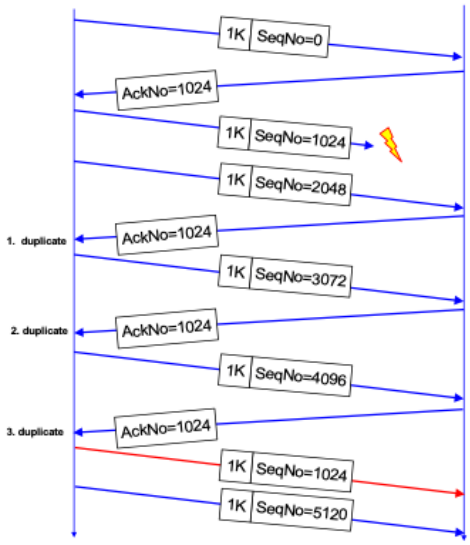
    ssthressh = cwnd / 2
  - entering slow-start

Reaction to Congestion

- Duplicate ACKs: not so congested (why?)
- Fast retransmit
  - Three duplicate ACKs indicate a packet loss
  - Retransmit without timeout

Answer to why: because some packets arrived at the destination to trigger the duplicate acks. So the network is not congested enough to lose all packets in a window.

Duplicate ACK example



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Reaction to congestion: Fast Recovery

- Avoiding slow start
  - ssthresh = cwnd/2
  - cwnd = cwnd+3MSS
  - Increase cwnd by one MSS for each additional duplicate ACK
- When ACK arrives that acknowledges "new data," set:

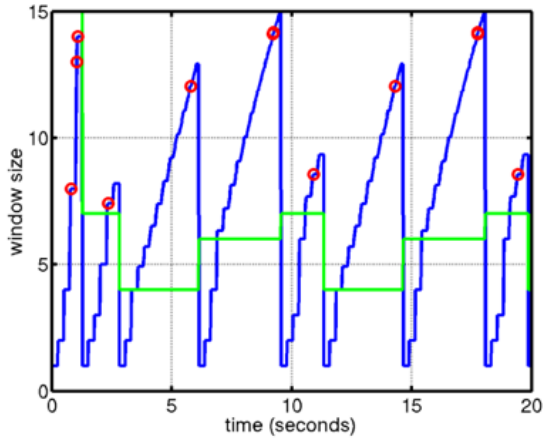
  cwnd=ssthresh

  enter congestion avoidance

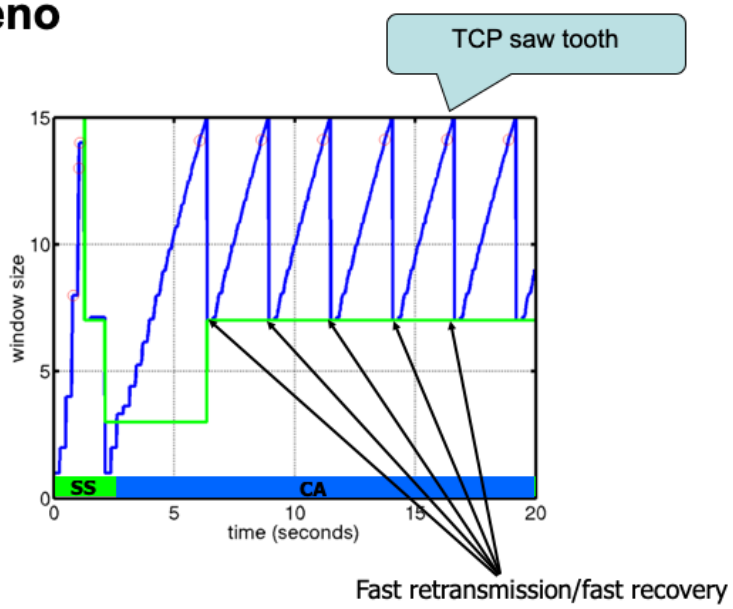
Flavors of TCP Congestion Control

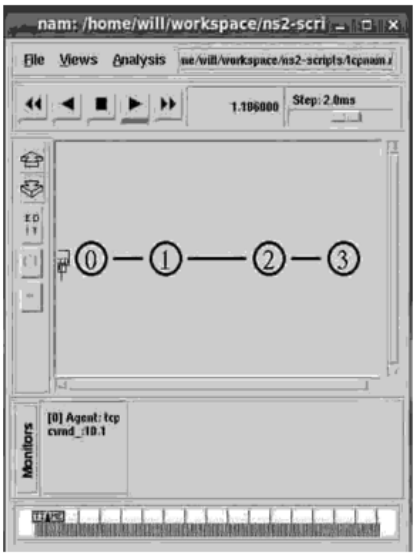
- **TCP Tahoe** (1988, FreeBSD 4.3 Tahoe)
  - Slow Start
  - Congestion Avoidance
  - Fast Retransmit
- **TCP Reno** (1990, FreeBSD 4.3 Reno)
  - Fast Recovery
  - Modern TCP implementation
- **New Reno** (1996)
- **SACK** (1996)

TCP Tahoe



TCP Reno


TCP saw tooth
window size
time (seconds)
SS
CA
0
5
10
15
20
Fast retransmission/fast recovery

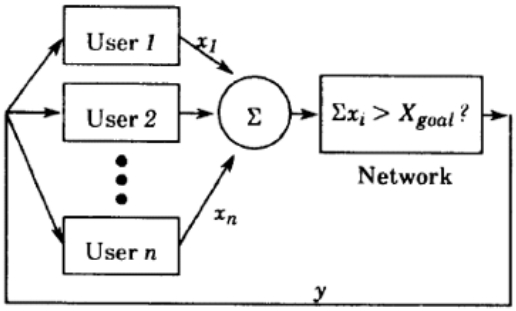

nam: /home/will/workspace/ns2-scri
File
Views
Analysis
1.196000
Step: 2.0ms
0
1
2
3
Monitors
[0] Agent: tcp
cwnd_:10.1

TCP summary

- Connection management
- Flow control
- When to transmit a segment
- Adaptive retransmission
- TCP options
- Modern extensions
- Congestion Control

Theory: why does it work?

Why does it work? [Chiu-Jain]



- A feedback control system
- The network uses feedback y to adjust users' load ∑x_i

Goals of Congestion Avoidance

- Efficiency: the closeness of the total load on the resource ot its knee
- Fairness:

$$F(x) = \frac{(\Sigma x_i)^2}{n(\Sigma x_i^2)}.$$

  - When all x_i's are equal, F(x) = 1
  - When all x_i's are zero but x_j = 1, F(x) = 1/n

- Distributedness
  - A centralized scheme requires complete knowledge of the state of the system
- Convergence
  - The system approach the goal state from any starting state

Metrics to measure convergence

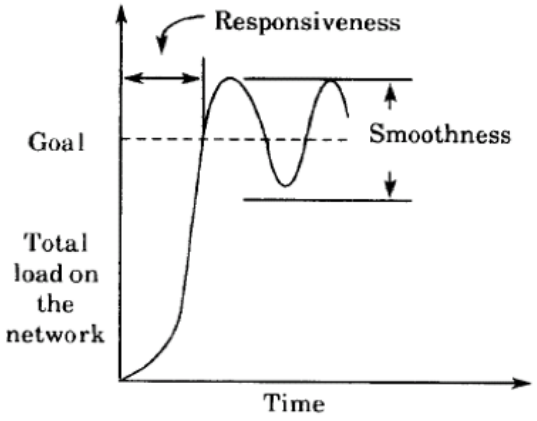


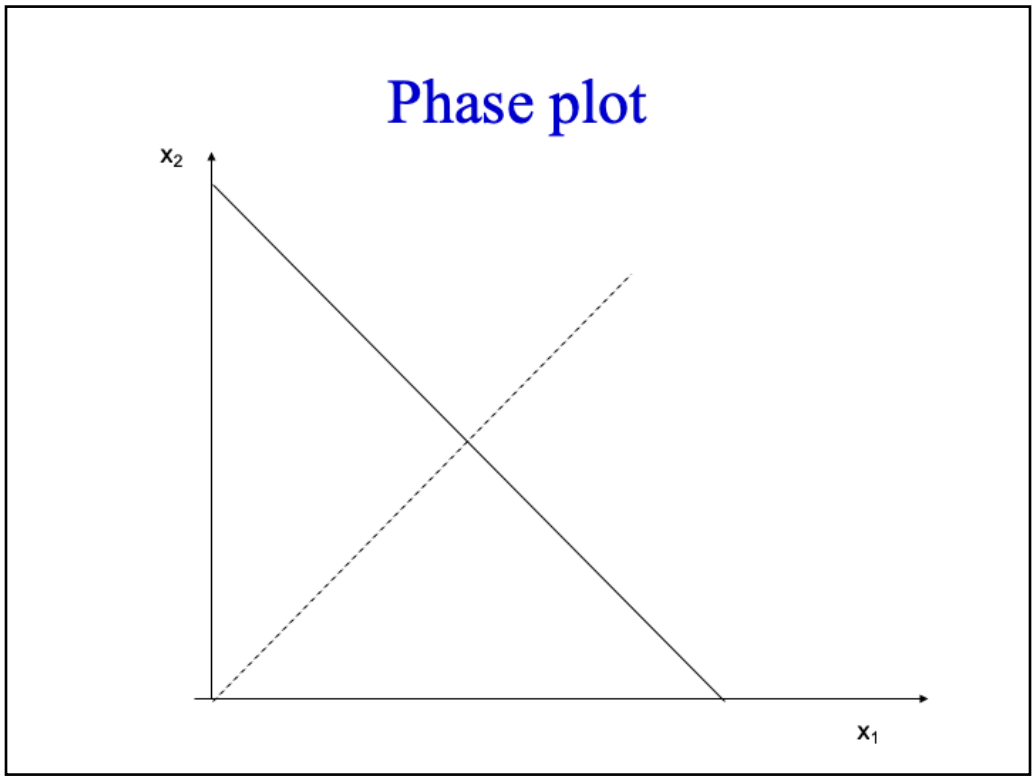
Fig. 3. Responsiveness and smoothness.

- Responsiveness
- Smoothness

Model the system as a linear control system

$$x_i(t+1) = \begin{cases} a_I + b_I x_i(t) & \text{if } y(t) = 0 \Rightarrow \text{Increase,} \\ a_D + b_D x_i(t) & \text{if } y(t) = 1 \Rightarrow \text{Decrease.} \end{cases}$$

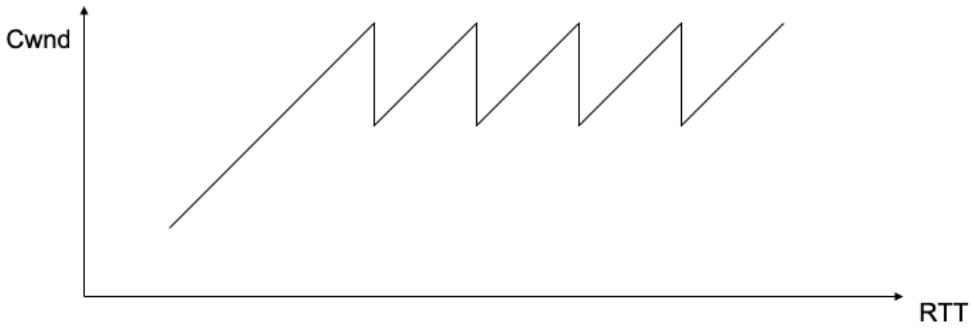
- Four sample types of controls
- AIAD, AIMD, MIAD, MIMD
  - A: additive
  - M: multiplicative
  - I: increase
  - D: decrease



1. efficiency line
2. fairness line

AIMD

The Sawtooth behavior of TCP



- For every ACK received
  - Cwnd += 1/cwnd *MSS
- For every packet lost
  - Cwnd /= 2

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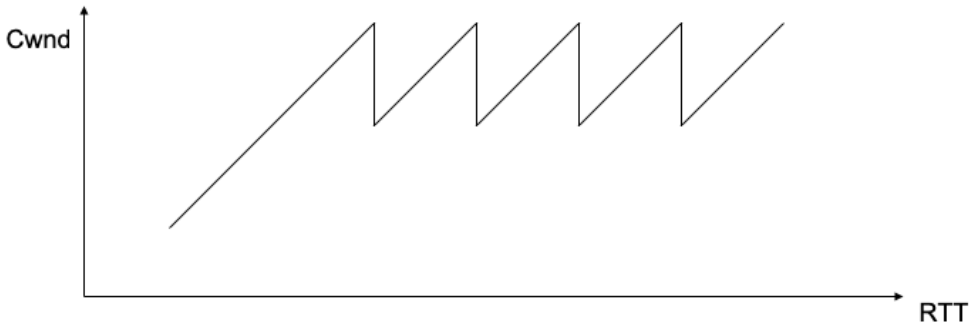
TCP congestion control is AIMD



- Problems:
  - Each source has to probe for its bandwidth
  - Congestion occurs first before TCP backs off
  - Unfair: long RTT flows obtain smaller bandwidth shares

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Macroscopic behavior of TCP

- Throughput is inversely proportional to RTT:

$$\frac{\sqrt{1.5} \bullet MSS}{RTT \bullet \sqrt{p}}$$

- In a steady state, total packets sent in one sawtooth cycle:
  - $S = w + (w+1) + \ldots (w+w) = 3/2\ w^2$
- the maximum window size is determined by the loss rate
  - $1/S = p$
  - $w = \frac{1}{\sqrt{1.5p}}$
- The length of one cycle: w * RTT
- Average throughput: 3/2 w * MSS / RTT

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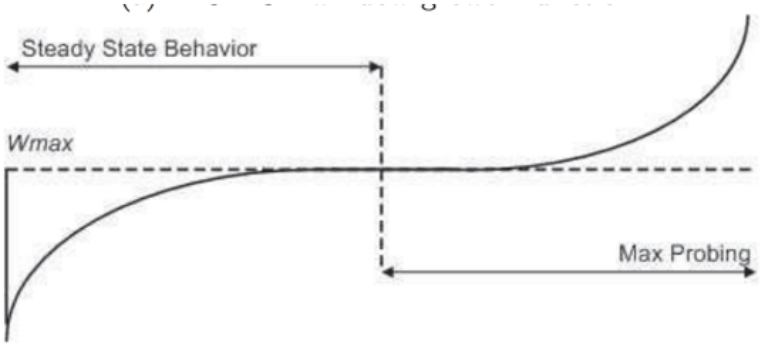
TCP Cubic



(b) CUBIC window growth function.

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

- CUBIC: a new TCP-friendly high-speed TCP variant by S. HaNorth, I. Rhee, and L. Xu
- Implemented in Linux kernel and Windows 10

http://delivery.acm.org/10.1145/1410000/1400105/p64-ha.pdf?ip=152.3.43.28&id=1400105&acc=ACTIVE%20SERVICE&key=7777116298C9657D%2E18C4EEC63BFE39A6%2E4D4702B0C3E38B35%2E4D4702B0C3E38B35&__acm__=1522697537_aad5e7bd094a3054060 5e9f018561443

https://tools.ietf.org/id/draft-ietf-tcpm-cubic-04.html

Summary

- TCP congestion control
- Why it works?
- The macroscopic behavior of TCP
- TCP Cubic