## TCP congestion control

Recall:

$$\texttt{EffectiveWindow} = \texttt{MaxWindow} - (\texttt{LastByteSent} - \texttt{LastByteAcked})$$

where

$$\texttt{MaxWindow} = \min\{\,\texttt{AdvertisedWindow}, \texttt{CongestionWindow}\,\}$$

Key question: how to set `CongestionWindow` which, in turn, affects ARQ's sending rate?

$\longrightarrow$ linear increase/exponential decrease

$\longrightarrow$ AIMD

TCP congestion control components:

(i) Congestion avoidance

$\longrightarrow$ linear increase/exponential decrease

$\longrightarrow$ additive increase/exponential decrease (AIMD)

As in Method B, increase `CongestionWindow` linearly, but decrease exponentially

Upon receiving ACK:

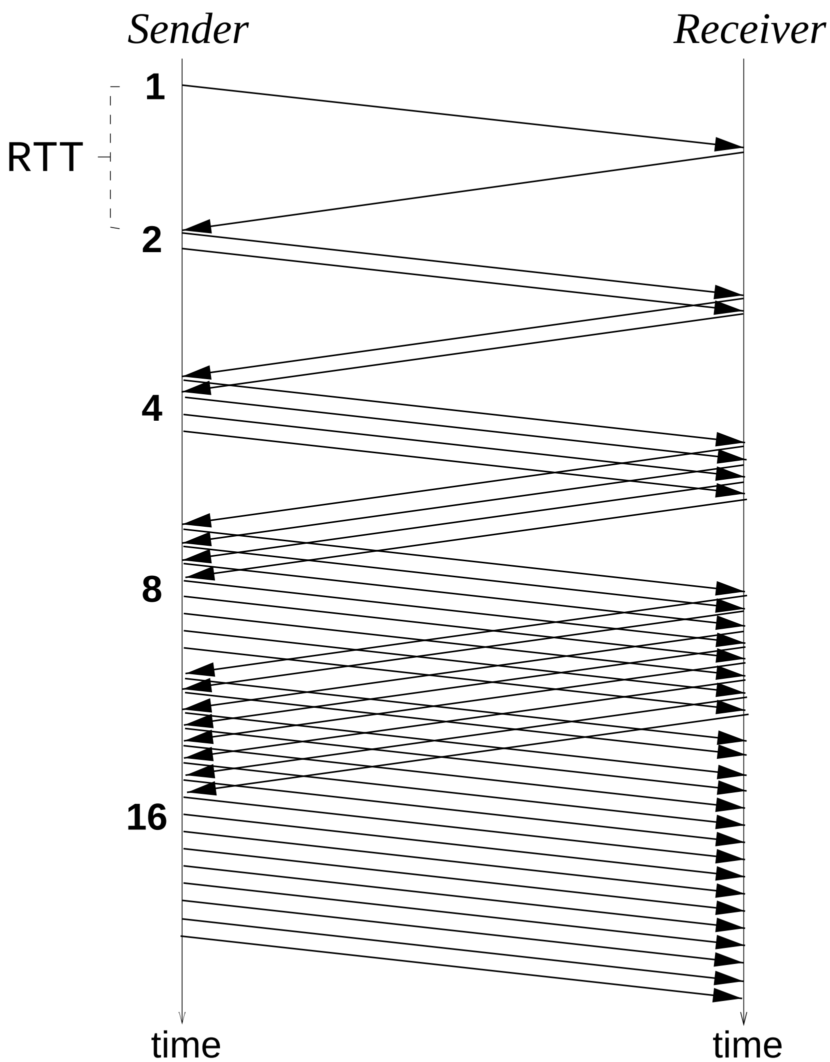
$$\texttt{CongestionWindow} \leftarrow \texttt{CongestionWindow} + 1$$

Upon timeout:

$$\texttt{CongestionWindow} \leftarrow \texttt{CongestionWindow} \,/\, 2$$

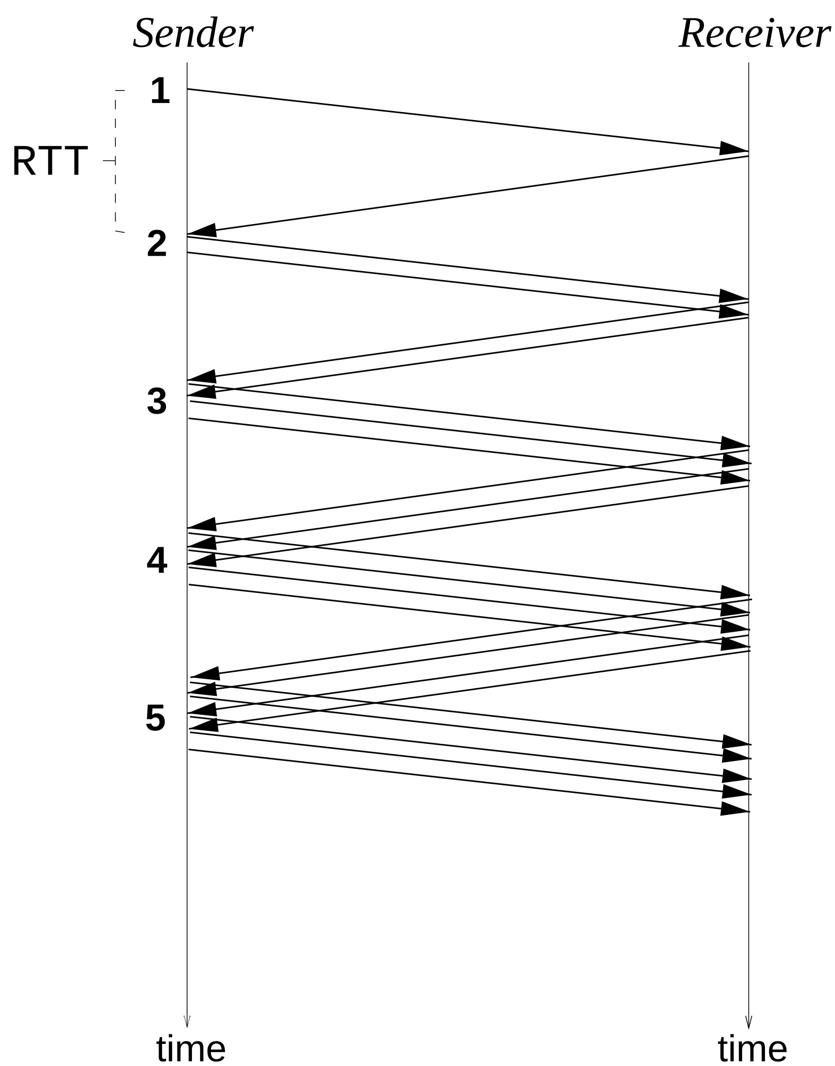
But is it correct. . .

"Linear increase" time diagram:




$\longrightarrow$ results in exponential increase

What we want:




$\longrightarrow$ increase by 1 every window

Thus, linear increase update:

$$\texttt{CongestionWindow} \leftarrow \texttt{CongestionWindow} + (1 \,/\, \texttt{CongestionWindow})$$

Upon timeout and exponential backoff,

$$\texttt{SlowStartThreshold} \leftarrow \texttt{CongestionWindow} \,/\, 2$$

(ii) Slow Start

Reset `CongestionWindow` to 1

Perform exponential increase

$$\texttt{CongestionWindow} \leftarrow \texttt{CongestionWindow} + 1$$

- Until timeout at start of connection

  $\rightarrow$ rapidly probe for available bandwidth

- Until `CongestionWindow` hits `SlowStartThreshold` following Congestion Avoidance

  $\rightarrow$ rapidly climb to safe level

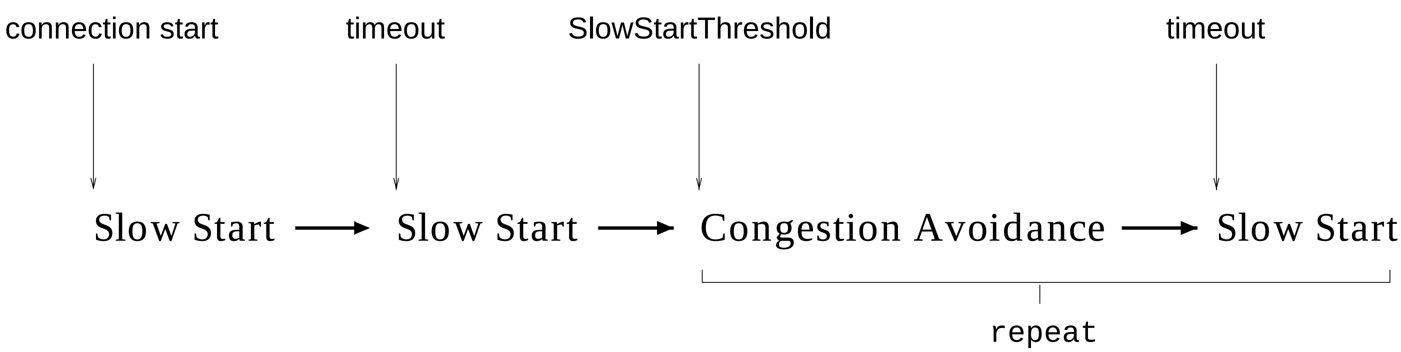
$\longrightarrow$ "slow" is a misnomer

$\longrightarrow$ exponential increase is super-fast

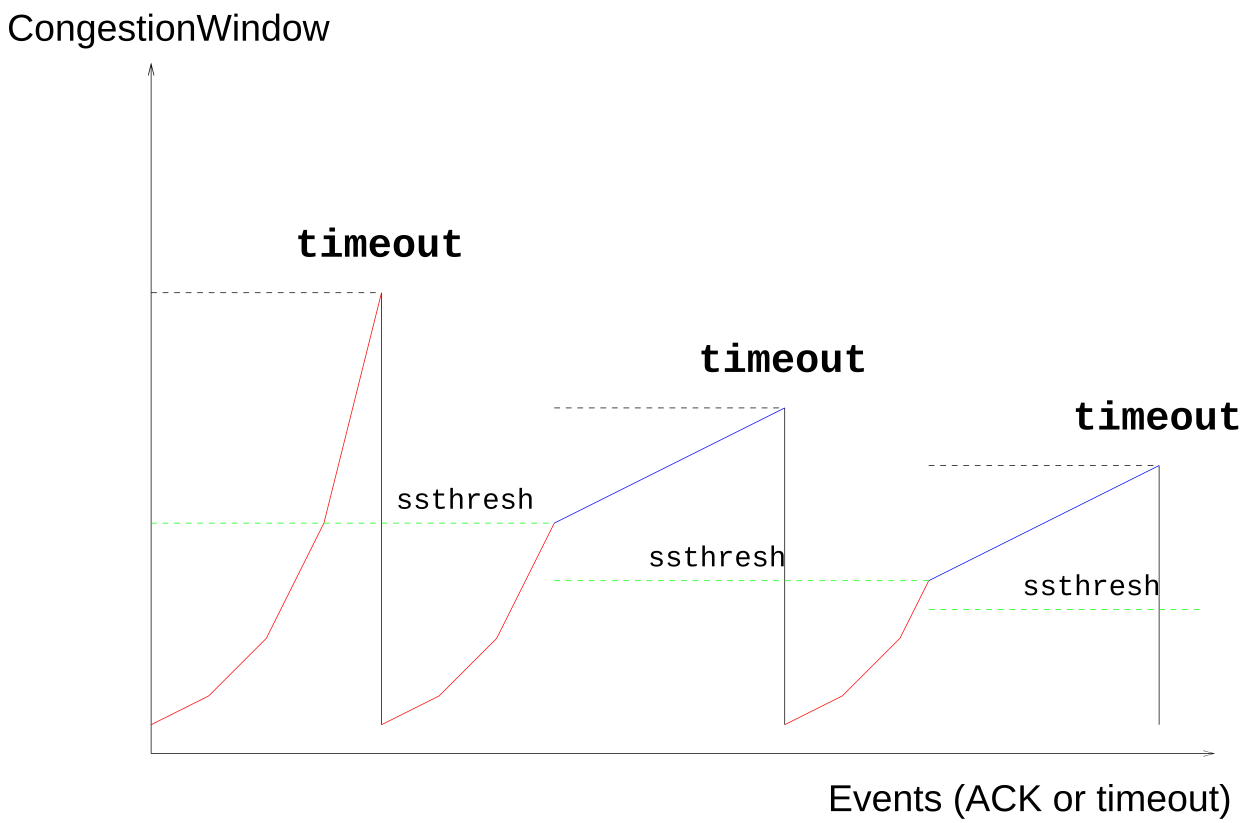
Basic dynamics:

$\longrightarrow$ after connection set-up

$\longrightarrow$ before connection tear-down



`CongestionWindow` evolution:



(iii) Exponential timer backoff

$$\texttt{TimeOut} \leftarrow 2 \cdot \texttt{TimeOut} \qquad \text{if retransmit}$$

(iv) Fast Retransmit

Upon receiving three duplicate ACKs:

- Transmit next expected segment

  $\rightarrow$ segment indicated by ACK value

- Perform exponential backoff and commence Slow Start

  $\longrightarrow$ three duplicate ACKs: likely segment is lost

  $\longrightarrow$ react before timeout occurs

TCP Tahoe: features (i)-(iv)

(v) Fast Recovery

Upon Fast Retransmit:

- Skip Slow Start and commence Congestion Avoidance

  $\rightarrow$ dup ACKs: likely spurious loss

- Insert "inflationary" phase just before Congestion Avoidance

Given sawtooth behavior of TCP's linear increase/exponential backoff:

Why use exponential backoff and not Method D?

- For multimedia streaming (e.g., pseudo real-time), AIMD (Method B) is not appropriate

  $\longrightarrow$ use Method D

- For unimodal case—throughput decreases when system load is excessive—story is more complicated

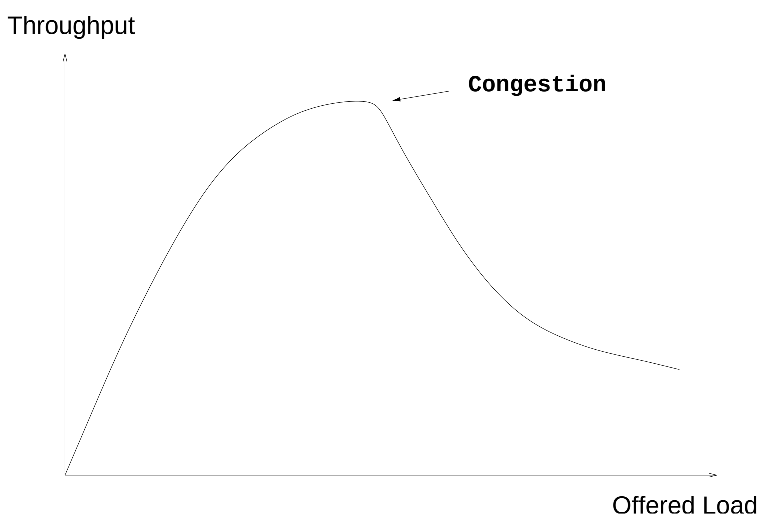
  $\longrightarrow$ asymmetry in control law needed for stability

## Congestion control and selfishness

$\longrightarrow$ to be or not to be selfish . . .

$\longrightarrow$ John von Neumann, John Nash, . . .

Ex.: "tragedy of commons," Garrett Hardin, '68




- if everyone acts selfishly, no one wins

  $\rightarrow$ in fact, everyone loses

- can this be prevented?

Ex.: Prisoner's Dilemma game

$\longrightarrow$ formalized by Tucker in 1950

$\longrightarrow$ "cold war"

- both cooperate (i.e., stay mum): 1 year each
- both selfish (i.e., rat on the other): 5 years each
- one cooperative/one selfish: 9 vs. 0 years

| | | *Bob* | |
|---|---|---|---|
| | | C | N |
| *Alice* | C | 5, 5 | 1, 9 |
| | N | 9, 1 | 3, 3 |

$\longrightarrow$ payoff matrix

$\longrightarrow$ what would "rational" prisoners do?

When cast as congestion control game:

| | | *Bob* | |
|---|---|---|---|
| | | C | N |
| *Alice* | C | 5, 5 | 1, 9 |
| | N | 9, 1 | 3, 3 |

$\longrightarrow$ Alice and Bob share network bandwidth

$\longrightarrow$ $(a, b)$: throughput (Mbps) achieved by Alice/Bob

$\longrightarrow$ upon congestion: back off or escalate?

$\longrightarrow$ equivalent to Prisoner's dilemma

Rational: in the sense of seeking selfish gain

$\longrightarrow$ both choose strategy "N"

$\longrightarrow$ called Nash equilibrium

$\longrightarrow$ why: strategy "N" dominates strategy "C"

Dominance: suppose Alice chooses "C"; from Bob's perspective, choosing "N" yields 9 Mbps whereas "C" yields only 5 Mbps. Similarly if Alice were to choose "N."

$\longrightarrow$ for Bob: "N" dominates "C"

$\longrightarrow$ a "no brainer" for Bob

$\longrightarrow$ by symmetry, the same logic applies to Alice

Ex.: von Neumann argued for first-strike policy based on this reasoning.

$\longrightarrow$ luckily "MAD" prevailed

$\longrightarrow$ MAD: mutually assured destruction

$\longrightarrow$ sometimes "delay" is good!

In a selfish environment, the system tends to converge to a Nash equilibrium.

A Nash equilibrium is a system state where no player has an incentive to make a **unilateral** move.

$\longrightarrow$ unilateral: only one player makes a move

$\longrightarrow$ e.g.: (N,C) is not a Nash equilibrium

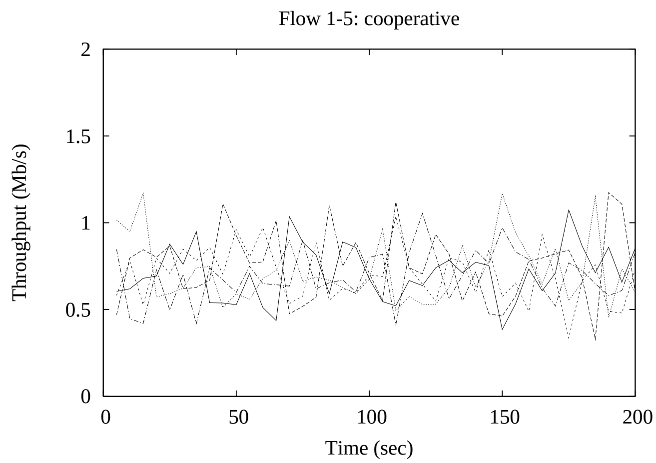
$\longrightarrow$ Bob gains by switching from "C" to "N"

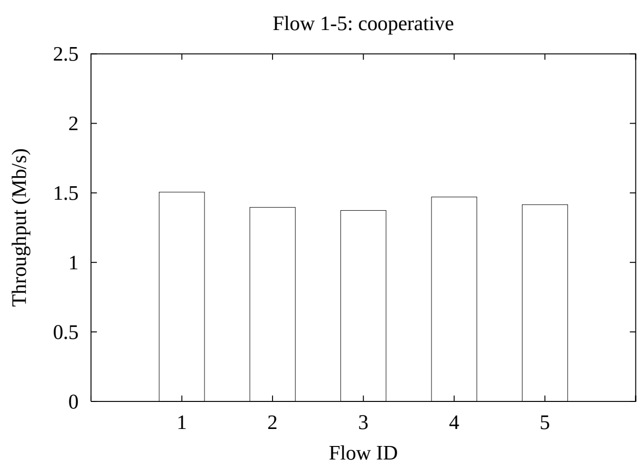
$\longrightarrow$ Bob's payoff increases from 1 to 3

$\longrightarrow$ Nash equilibrium is a stable state: impasse

5 regular (cooperative) TCP flows:

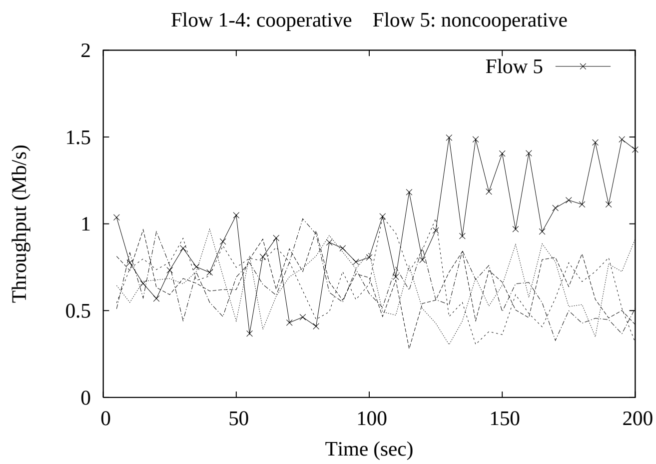
$\longrightarrow$ share 11 Mbps WLAN bottleneck link

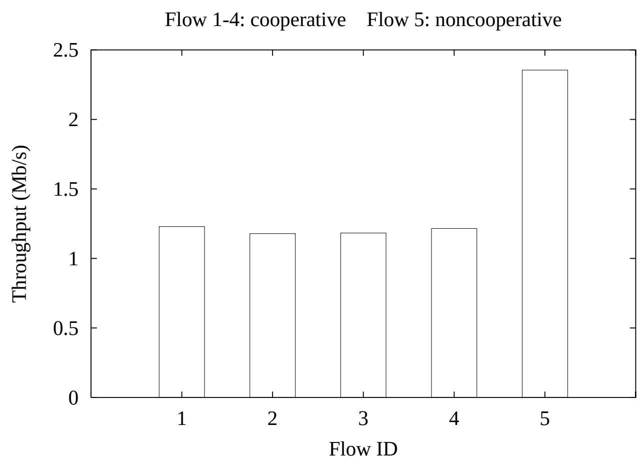


4 regular (cooperative) TCP flows and 1 noncooperative TCP flow:

$\longrightarrow$ same benchmark set-up



Remarks:

- a Nash equilibrium need not exist

  $\longrightarrow$ system subject to oscillation

  $\longrightarrow$ circular "chain reaction"

- Nash's main result (game theory): finite noncooperative games with **mixed** strategies—choose action probabilistically—always possess equilibrium

  $\longrightarrow$ vs. **pure** strategy (more in tune with reality)

  $\longrightarrow$ pure strategy games: hard problem

- congestion pricing

  $\longrightarrow$ penalize those who congest: e.g., usage pricing

  $\longrightarrow$ in the States: flat pricing (dominant)

  $\longrightarrow$ not skimpy like the rest of the world!

- repeated/evolutionary games
  - → e.g.: iterated Prisoner's Dilemma
  - → rob bank/get caught, again and again ...
  - → what should the prisoners do then?
  - → "grim trigger" policy: don't forgive
  - → "tit-for-tat" policy: conditionally forgive
  - → both are optimal (in a certain sense)
  - → most relevant for "greedy" TCP