CS 725/825 & IT 725

Lecture 14

Transport Layer

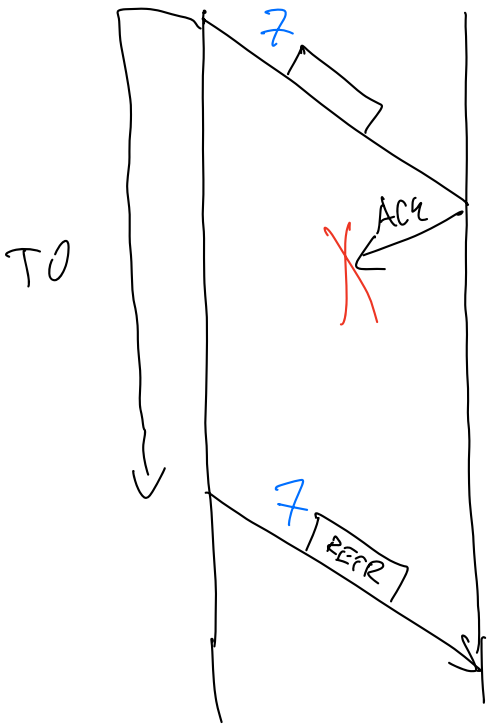
October 26, 2026

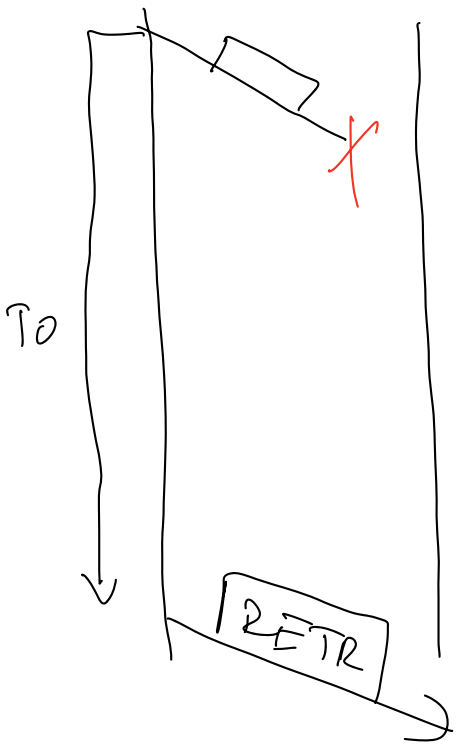
Principles of Reliable Transport

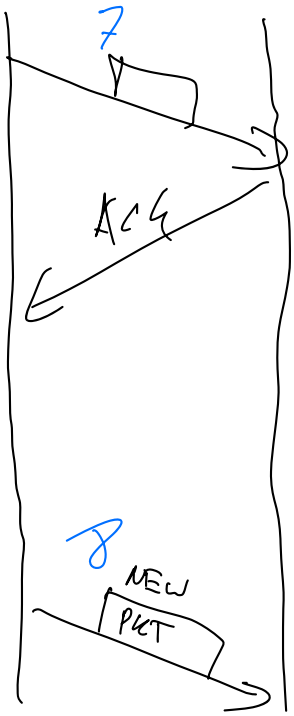
- **Goal**: deliver despite unreliability of the network layer or detect that delivery is not possible
- Automatic Repeat reQuest (ARQ):
  - acknowledgment
  - timeout
  - retransmission
  - give up after *k* retransmissions
  - sequence numbers on data packets
  - cumulative acknowledgment numbers

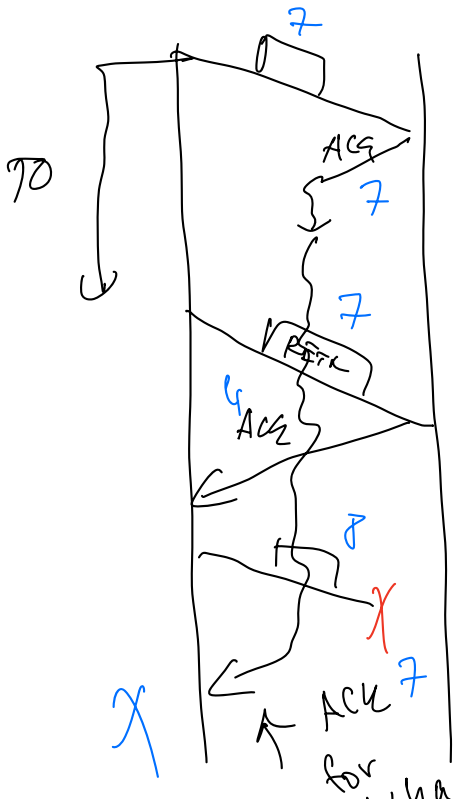
MOTIVATION:

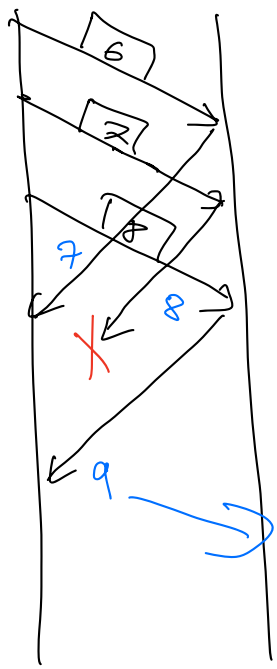
- SEQUENCE NUMBERS
- ACKNOWLEDGMENT NUMBERS

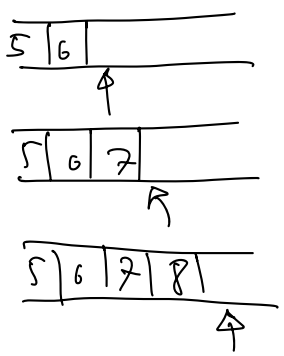










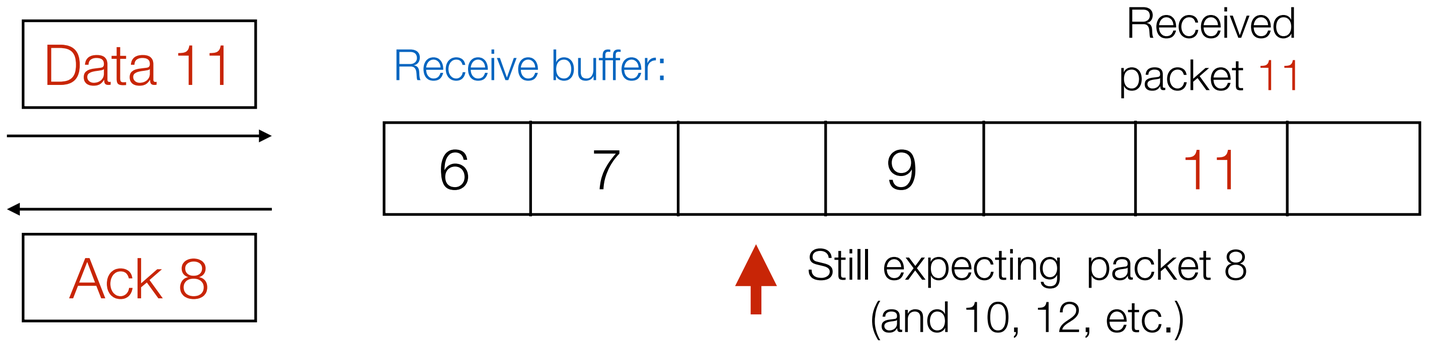


9 → 5, 6, 7, 8 rec'd

=!

Cumulative ACK numbers

- Method 1 (obvious but not used):
  - ACK carries the sequence number of the packet it acknowledges
- Method 2 (Cumulative ACK, used by TCP)
  - ACK carries the lowest sequence number of the packets that were not yet received (sequence number of the next expected packet)



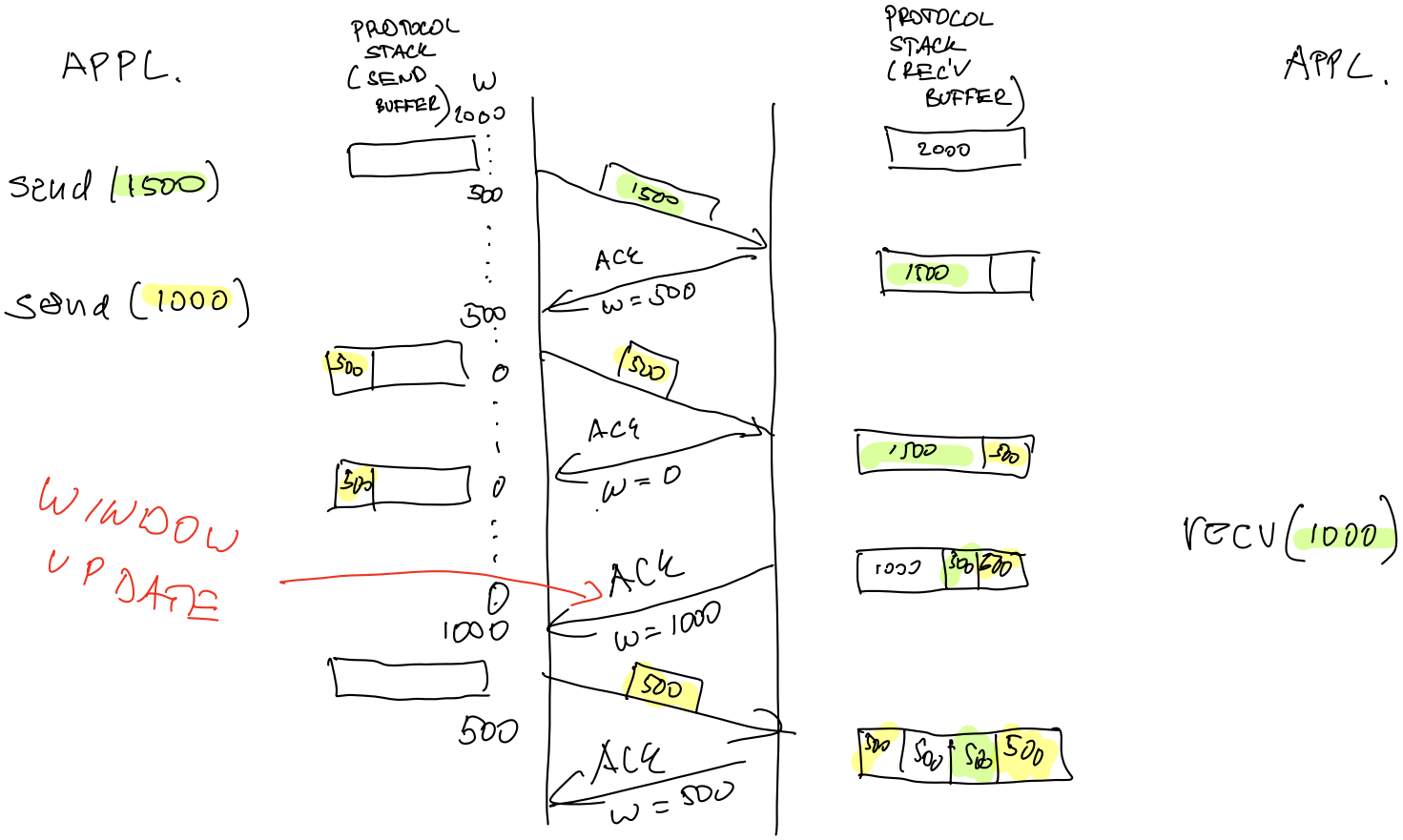
Filling the pipe…

- Stop and Wait protocol
  - wait for acknowledgment before sending the next packet
- Sliding Window protocols
  - send up to W (window size) packets/bytes before waiting for acknowledgment
  - when a packet is lost:
    - retransmit the packet (*Selective-Reject ARQ*)
    - retransmit all un-acknowledged packets (*Go-Back-N ARQ*)
- Measure: utilization (a.k.a. normalized throughput)
  - the ratio between *goodput* and *maximum theoretical capacity*

Two bottlenecks

- Receiver
  - receiver is unable to keep up with incoming data
  - addressed by flow control mechanisms
  - typically uses explicit feedback from receiver to sender
- Network
  - nodes or links of the network are overloaded
  - addressed by congestion control mechanism
  - explicit congestion notification (few technologies)
  - implicit congestion notification (Internet)

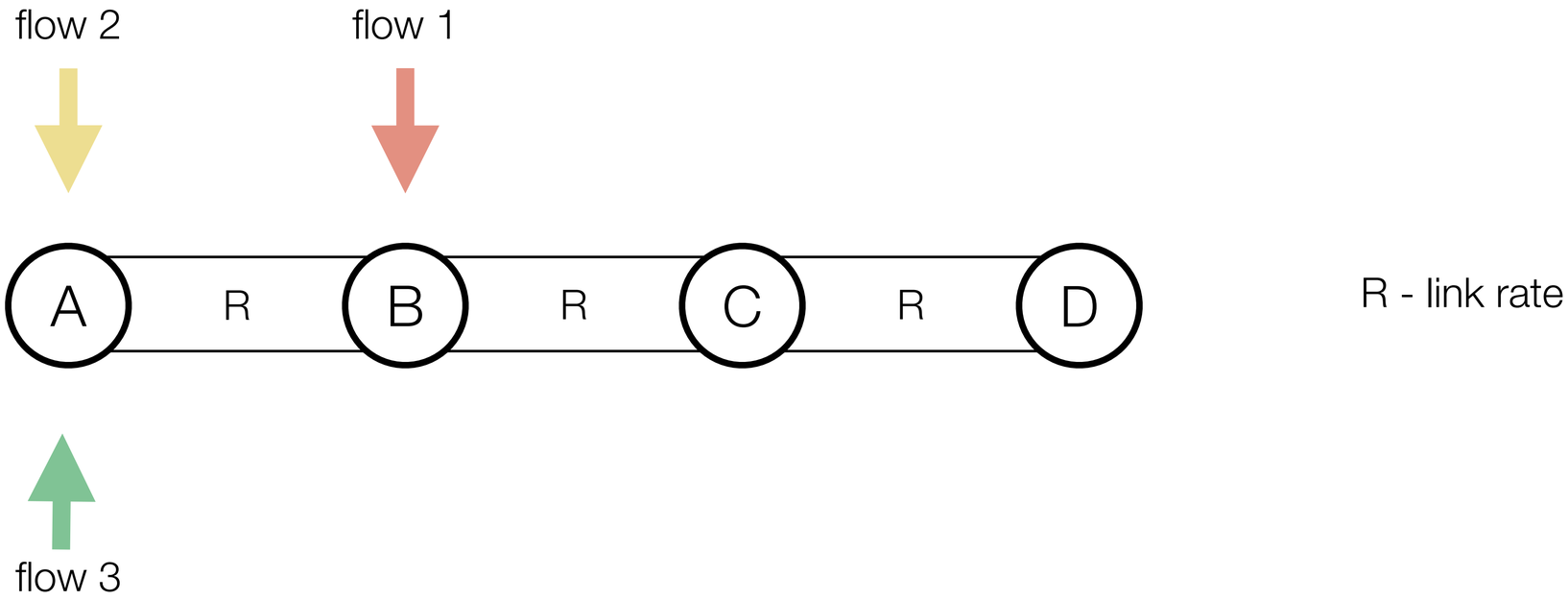
FLOW CONTROL



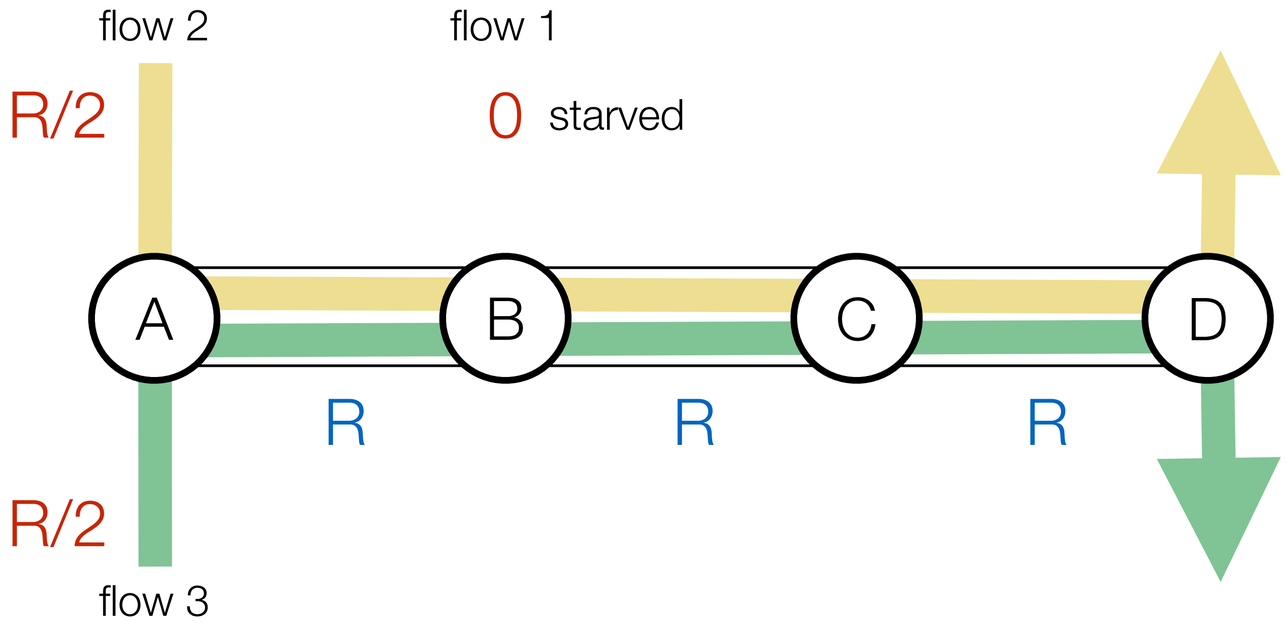
Congestion control

- Goal: Make the most effective use of the network capacity
  - avoid congestion
  - maximize utilization
  - maintain fairness (or deliver promised service level)
- Method: Controlling the rate with which traffic is injected into the network by the transmitter

Utilization vs fairness



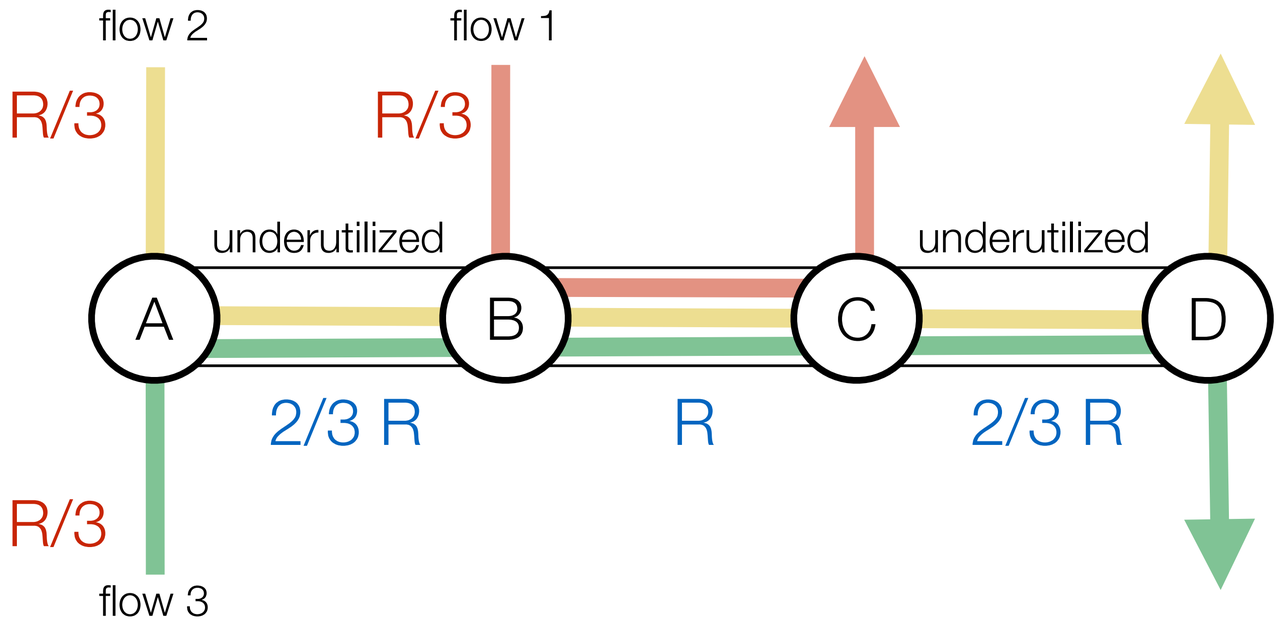
Max utilization



	Max utilization	Max fairness
flow 1	0	R/3
flow 2	R/2	R/3
flow 3	R/2	R/3

R - link rate

Max fairness



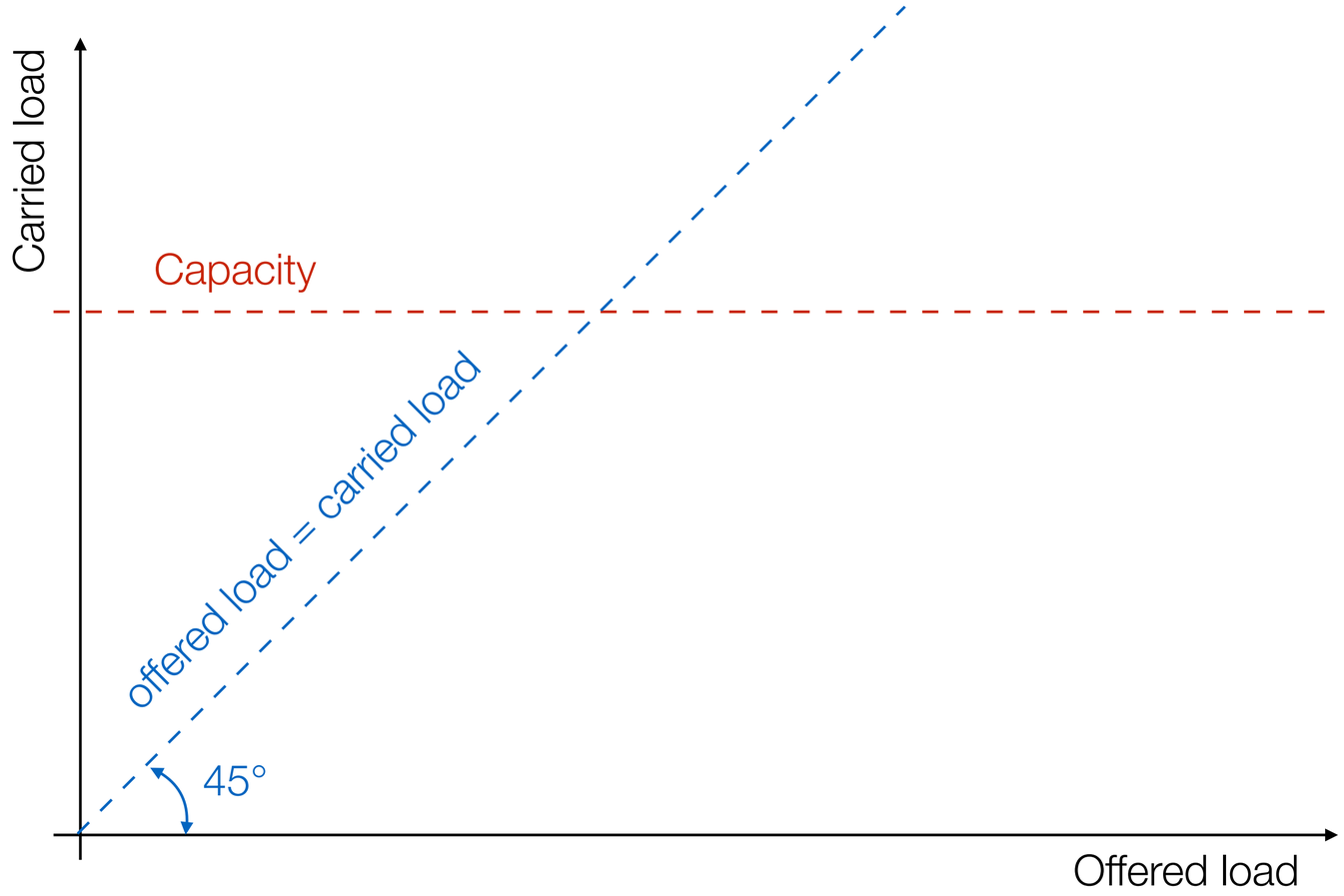
	Max utilization	Max fairness
flow 1	0	R/3
flow 2	R/2	R/3
flow 3	R/2	R/3

R - link rate

Network congestion control

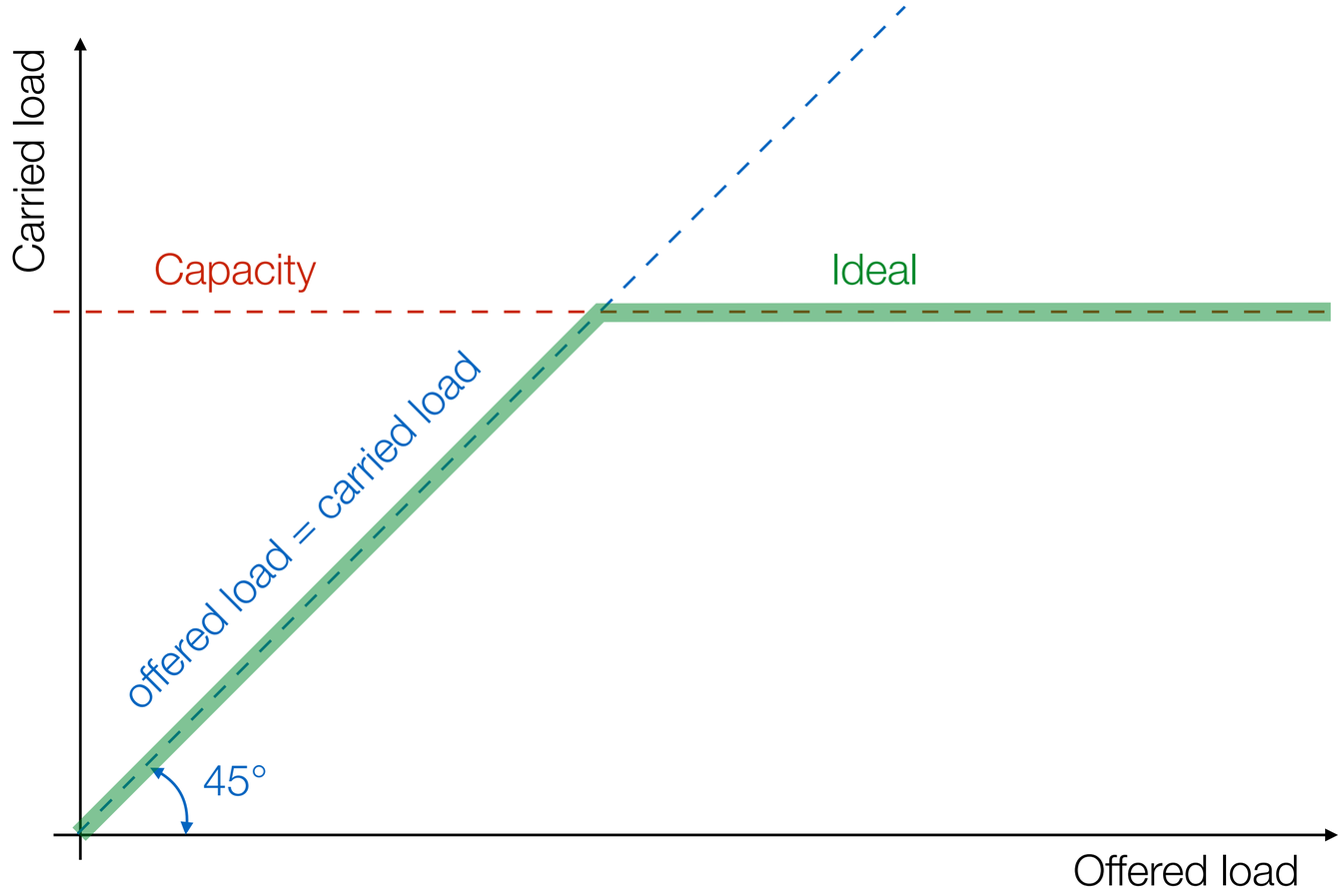
- Reasons why congestion control mechanisms are critical for the stable operation of the Internet [RFC 8085]:
- Prevention of congestion collapse
  - i.e., a state where an increase in network load results in a decrease in useful work done by the network
- Establishment of a degree of fairness
  - i.e., allowing multiple flows to share the capacity of a path reasonably equitably.

Impact of Congestion

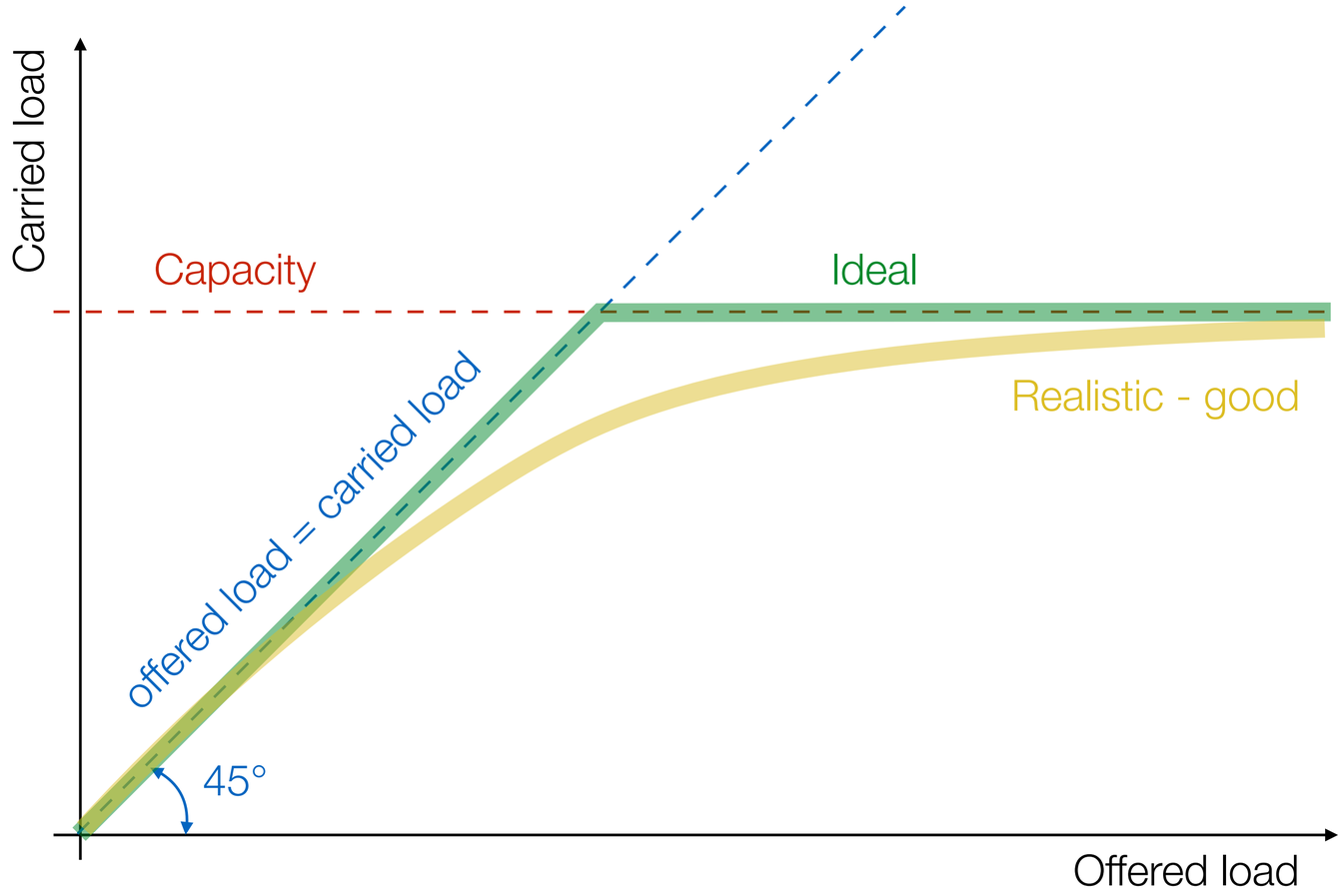


Offered vs carried load graph

Impact of Congestion



Impact of Congestion



Impact of Congestion

