Slow Start (TCP Additive Increase)

TCP congestion control overview

Sender uses congestion window (cwnd)

- Sending rate (≈cwnd/RTT)

Sender uses loss as network congestion signal

Follow AIMD control law for a good allocation

- Goal is efficient and (roughly) fair allocation

TCP “Slow Start” Problem

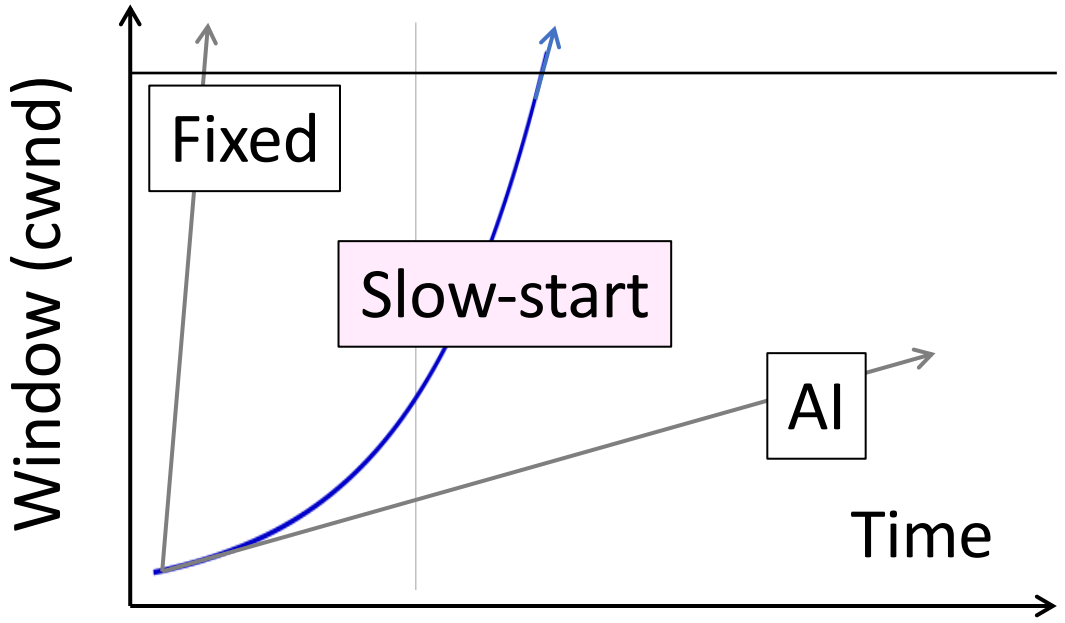
We want to quickly get to the right cwnd but it varies

- Fixed window can be too inefficient or too aggressive
- Additive Increase adapts cwnd gently, but might take a long time to become efficient

Slow-Start Solution

Start by doubling cwnd every RTT

- Exponential growth (1, 2, 4, 8, 16, …)
- Start slow, quickly reach large values



Slow-Start Solution (2)

Eventually packet loss will occur when the network is congested

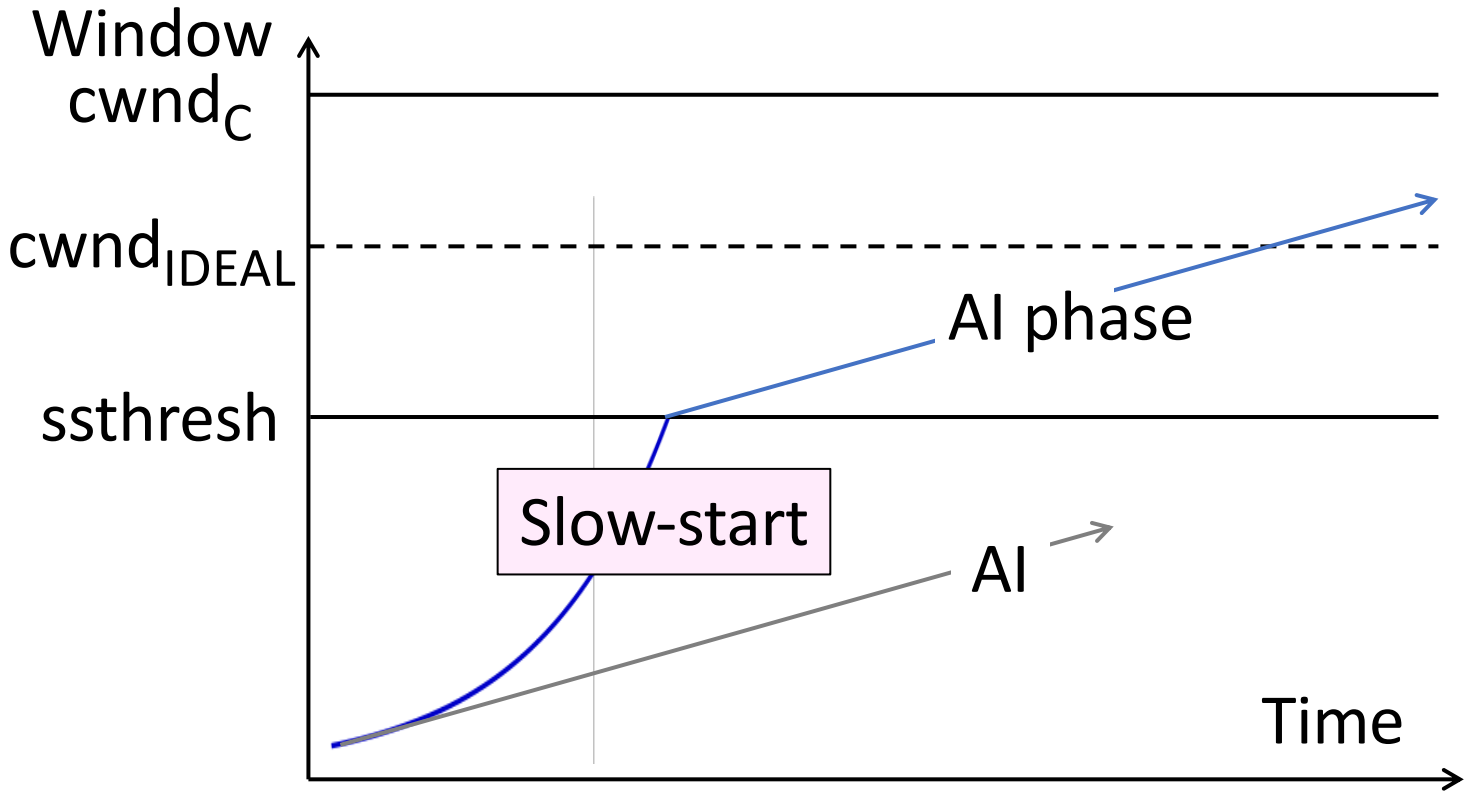
- Loss timeout tells us cwnd is too large
- Next time, switch to AI beforehand
- Slowly adapt cwnd near right value

In terms of cwnd:

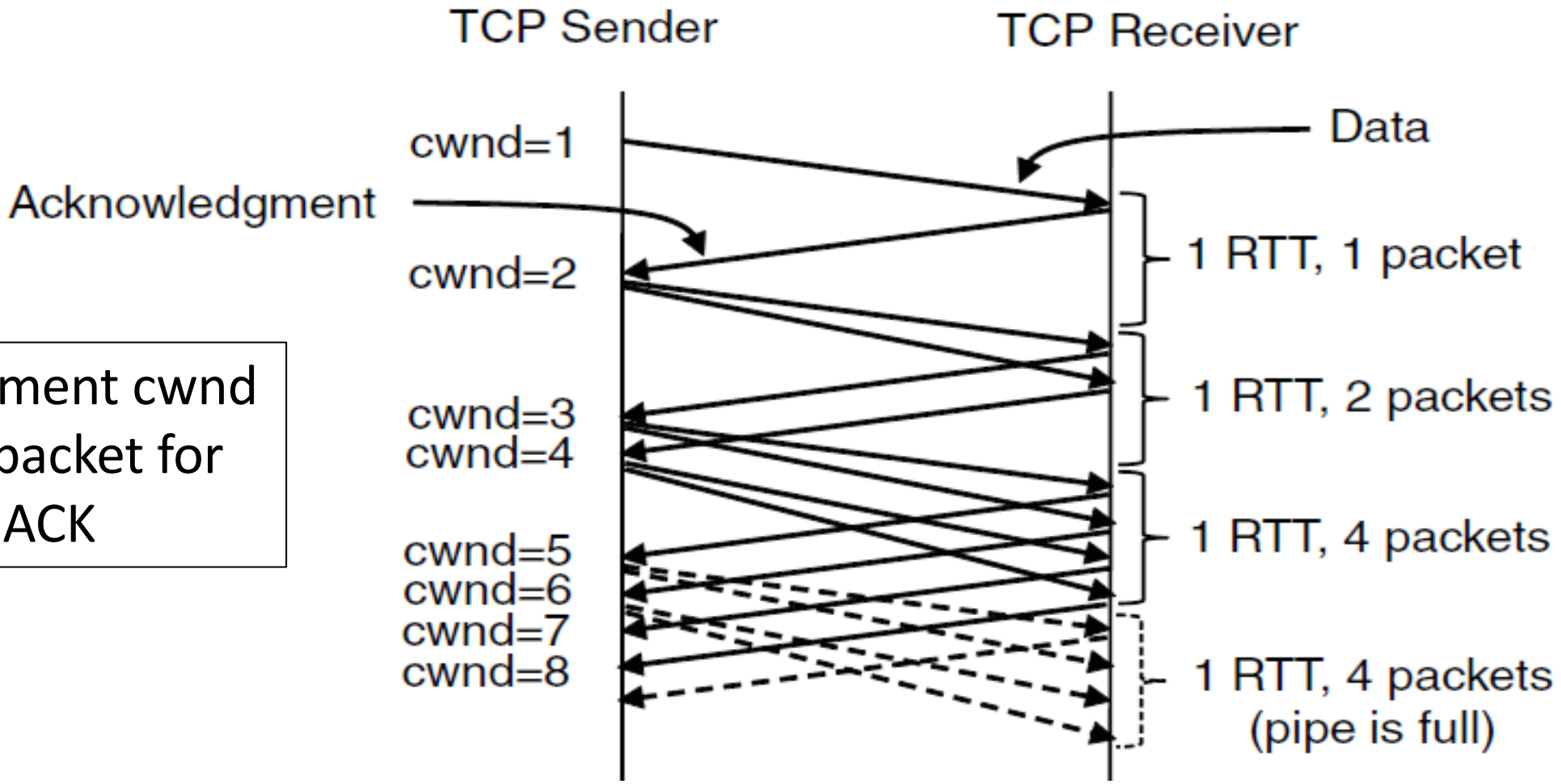
- Expect loss for $cwnd_C \approx 2BD+queue$
- Use ssthresh = $cwnd_C/2$ to switch to AI

Slow-Start Solution (3)

- Combined behavior, **after first time**
  - Most time spent near right value

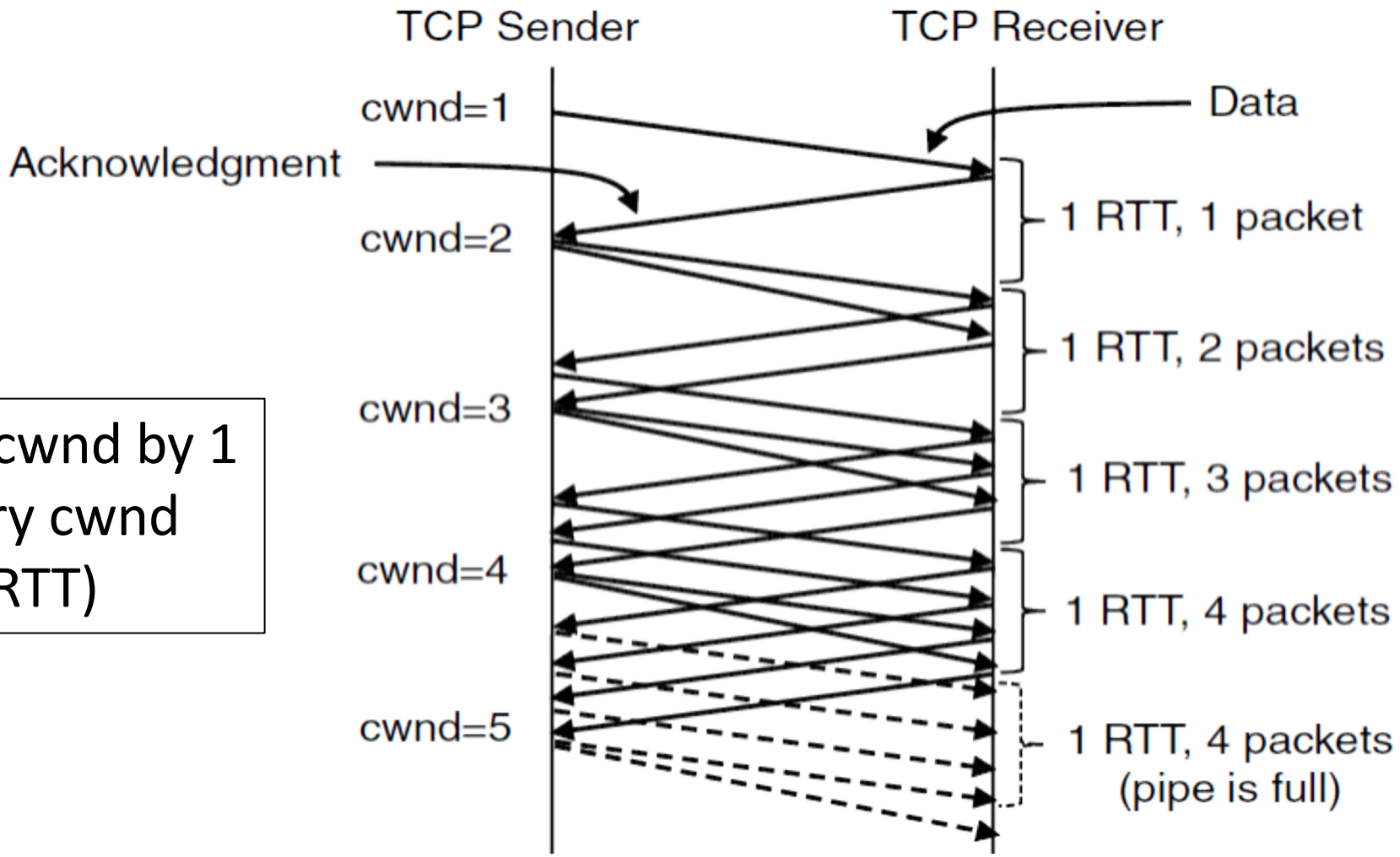


Slow-Start (Doubling) Timeline



Increment cwnd by 1 packet for each ACK

Additive Increase Timeline



Increment cwnd by 1 packet every cwnd ACKs (or 1 RTT)

TCP Tahoe (Implementation)

Initial slow-start (doubling) phase

- Start with cwnd = 1 (or small value)
- cwnd += 1 packet per ACK

Later Additive Increase phase

- cwnd += 1/cwnd packets per ACK
- Roughly adds 1 packet per RTT

Switching threshold (initially infinity)

- Switch to AI when cwnd > ssthresh
- Set ssthresh = cwnd/2 after loss
- Begin with slow-start after timeout

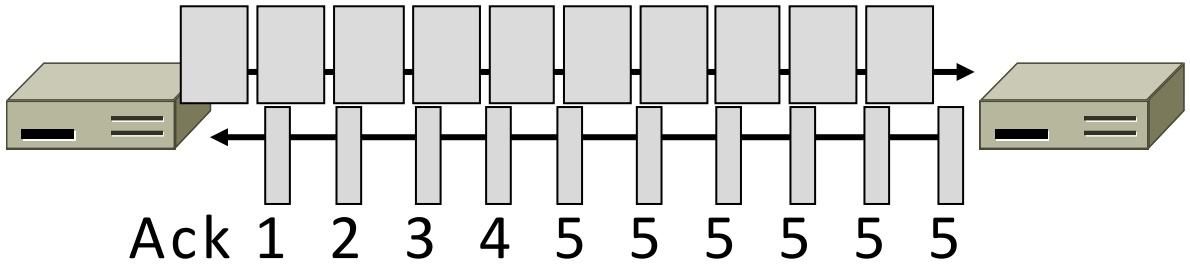
Fast Recovery
(TCP Multiplicative Decrease)

Inferring Loss from ACKs

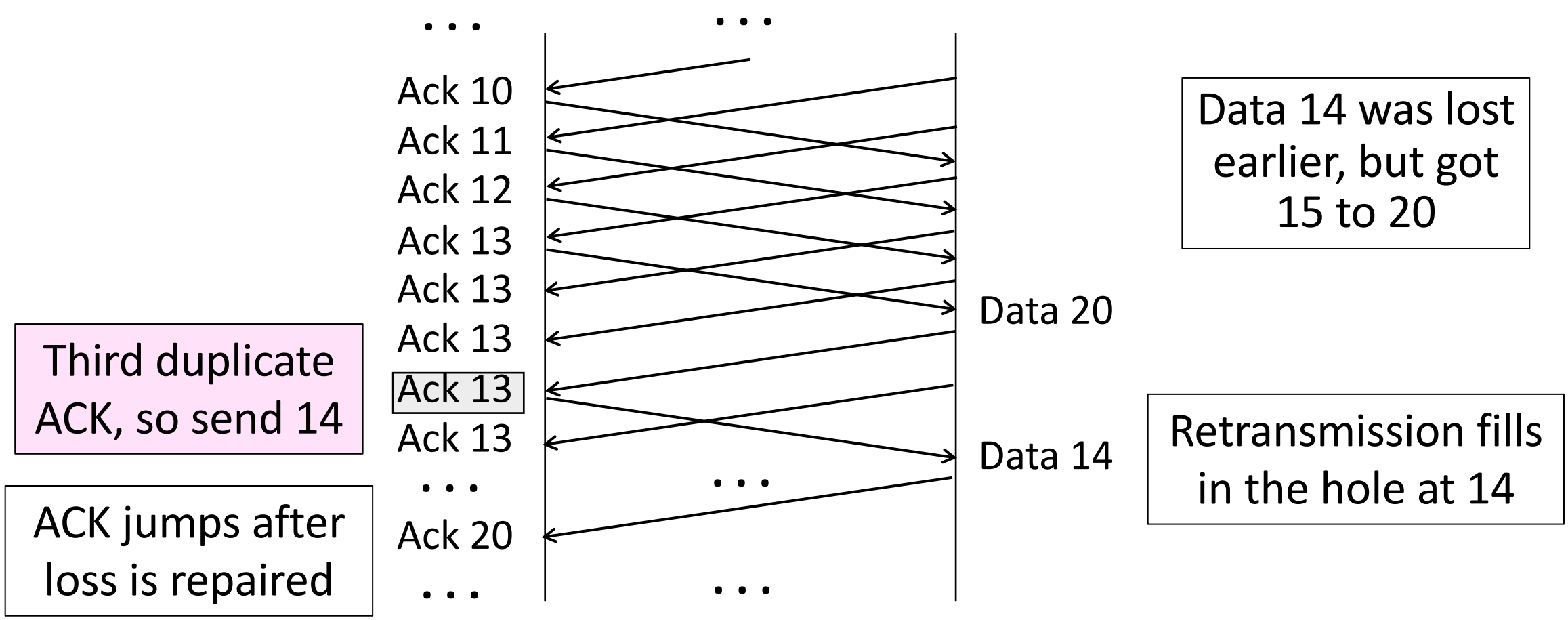
- TCP uses a cumulative ACK
  - Carries highest in-order seq. number
  - Normally a steady advance
- Duplicate ACKs give us hints about what data hasn't arrived
  - Tell us some new data did arrive, but it was not next segment
  - Thus the next segment may be lost

Fast Retransmit

- Treat three duplicate ACKs as a loss
  - Retransmit next expected segment
  - Some repetition allows for reordering, but still detects loss quickly



Fast Retransmit (2)



Fast Retransmit (3)

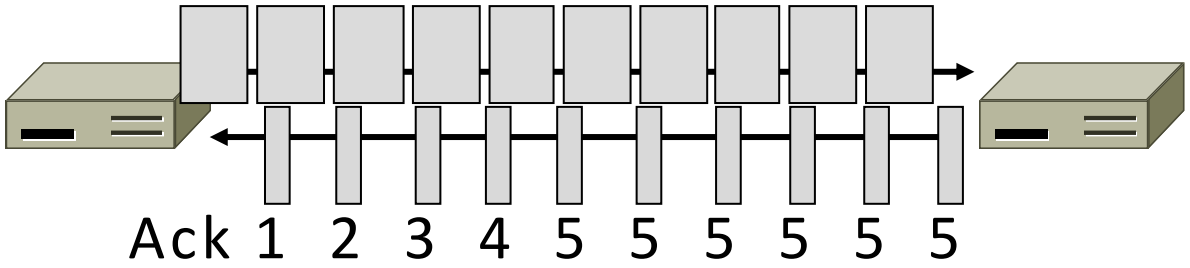
- It can repair single segment loss quickly, typically before a timeout
- However, we have quiet time at the sender/receiver while waiting for the ACK to jump
- And we still need to MD cwnd …

Inferring Non-Loss from ACKs

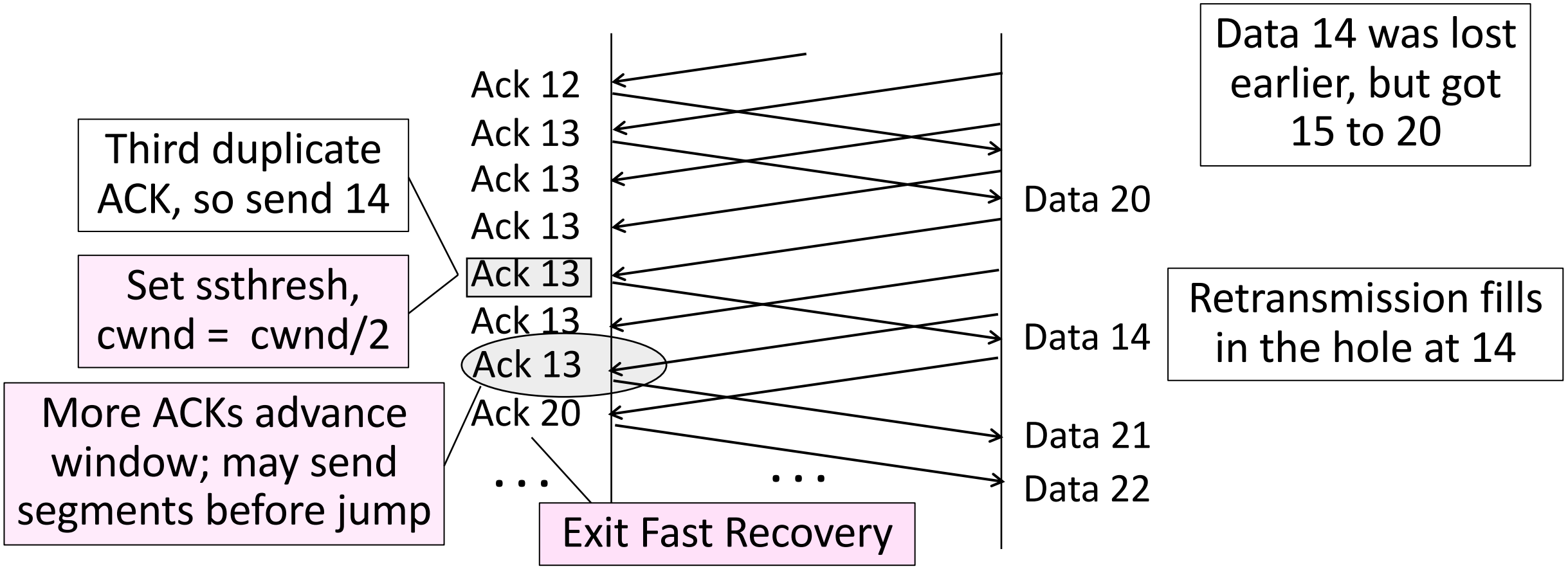
- Duplicate ACKs also give us hints about what data has arrived
  - Each new duplicate ACK means that some new segment has arrived
  - It will be the segments after the loss
  - Thus advancing the sliding window will not increase the number of segments stored in the network

Fast Recovery

- First fast retransmit, and MD cwnd
- Then pretend further duplicate ACKs are the expected ACKs
  - Lets new segments be sent for ACKs
  - Reconcile views when the ACK jumps



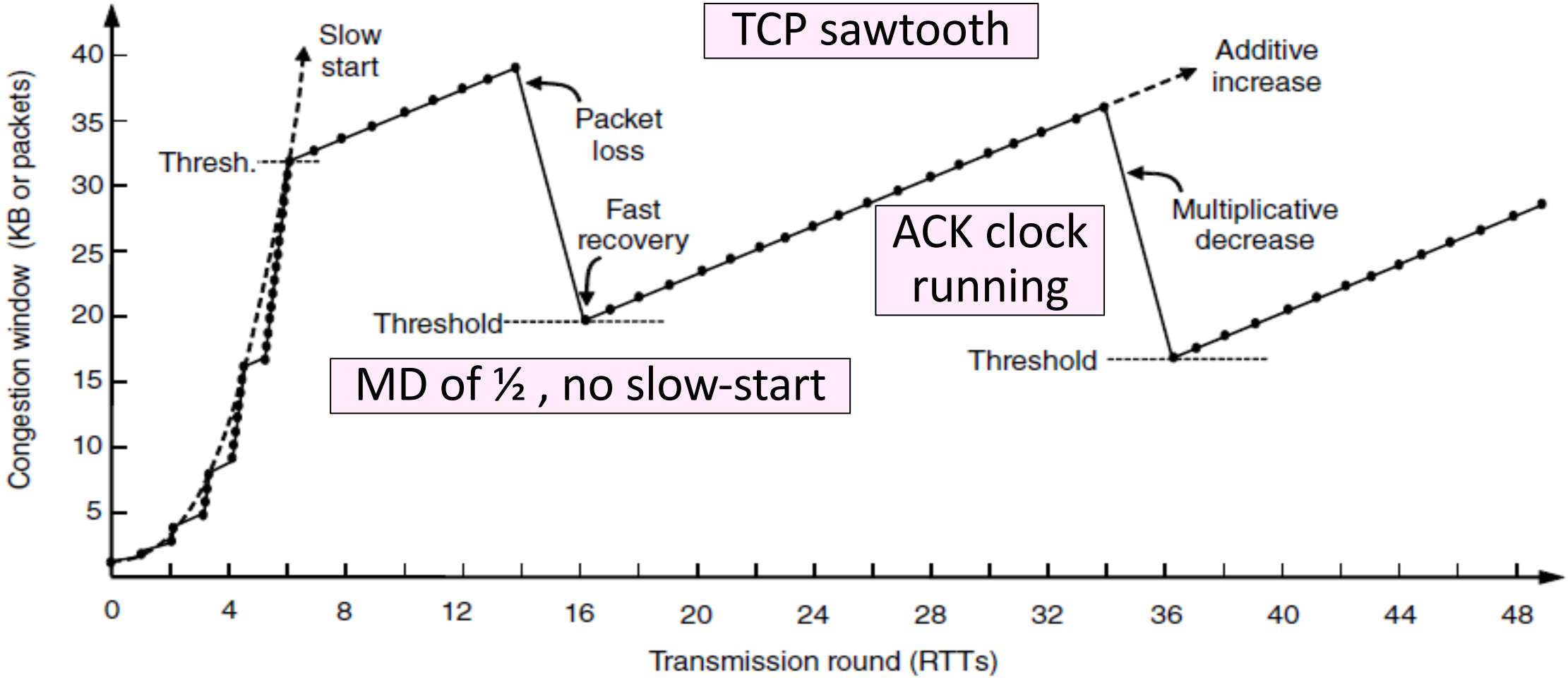
Fast Recovery (2)



Fast Recovery (3)

- With fast retransmit, it repairs a single segment loss quickly and keeps the ACK clock running
- This allows us to realize AIMD
  - No timeouts or slow-start after loss, just continue with a smaller cwnd
- TCP Reno combines slow-start, fast retransmit and fast recovery
  - Multiplicative Decrease is ½

TCP Reno


TCP sawtooth
Slow start
Thresh.
Packet loss
Fast recovery
Threshold
Additive increase
Multiplicative decrease
Threshold
ACK clock running
MD of ½ , no slow-start
Congestion window (KB or packets)
Transmission round (RTTs)
0
4
8
12
16
20
24
28
32
36
40
44
48
5
10
15
20
25
30
35
40

TCP Reno, NewReno, and SACK

- Reno can repair one loss per RTT
  - Multiple losses cause a timeout
- NewReno further refines ACK heuristics
  - Repairs multiple losses without timeout
- Selective ACK (SACK) is a better idea
  - Receiver sends ACK ranges so sender can retransmit without guesswork

Network-Assisted Congestion Control

Congestion Avoidance vs. Control

- Classic TCP drives the network into congestion and then recovers
  - Needs to see loss to slow down
- Would be better to use the network but avoid congestion altogether!
  - Reduces loss and delay
- But how can we do this?

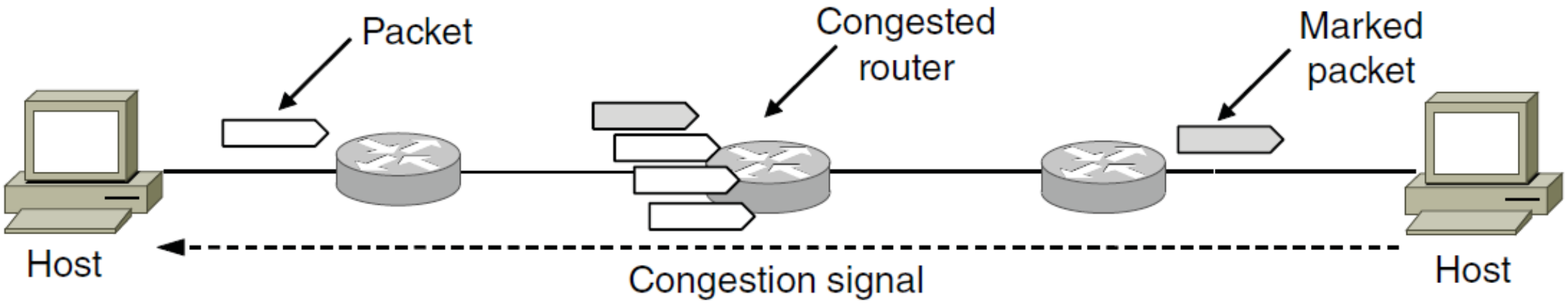
Feedback Signals

- Delay and router signals can let us avoid congestion

Signal	Example Protocol	Pros / Cons
Packet loss	Classic TCP Cubic TCP (Linux)	Hard to get wrong Hear about congestion late Other events can cause loss
Packet delay	Compound TCP (Windows)	Hear about congestion early Need to infer congestion
Router indication	TCPs with Explicit Congestion Notification	Hear about congestion early Require router support

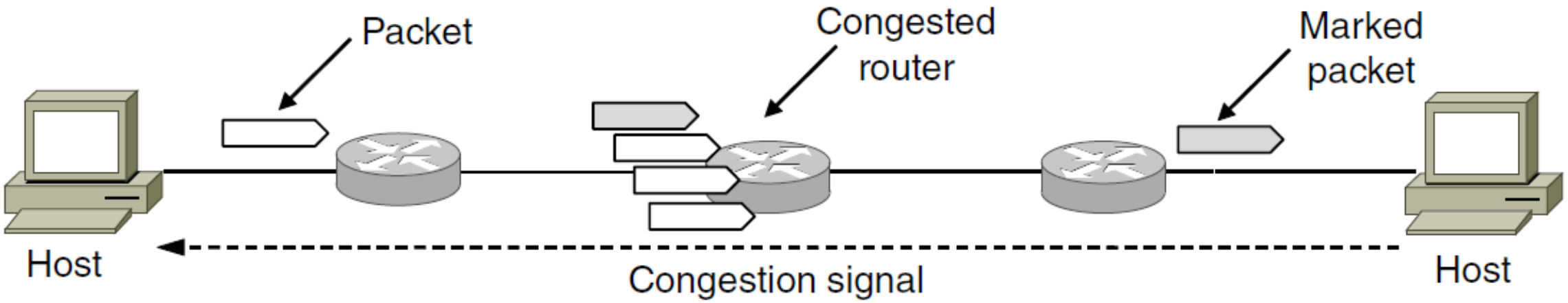
ECN (Explicit Congestion Notification)

- Router detects the onset of congestion via its queue
  - When congested, it marks affected packets (IP header)



ECN (2)

- Marked packets arrive at receiver
  - TCP receiver informs TCP sender of the congestion



ECN (3)

- Advantages:
  - Routers deliver clear signal to hosts
  - Congestion is detected early, no loss
  - No extra packets need to be sent
- Disadvantages:
  - Routers and hosts must be upgraded

What’s new in transport protocols?

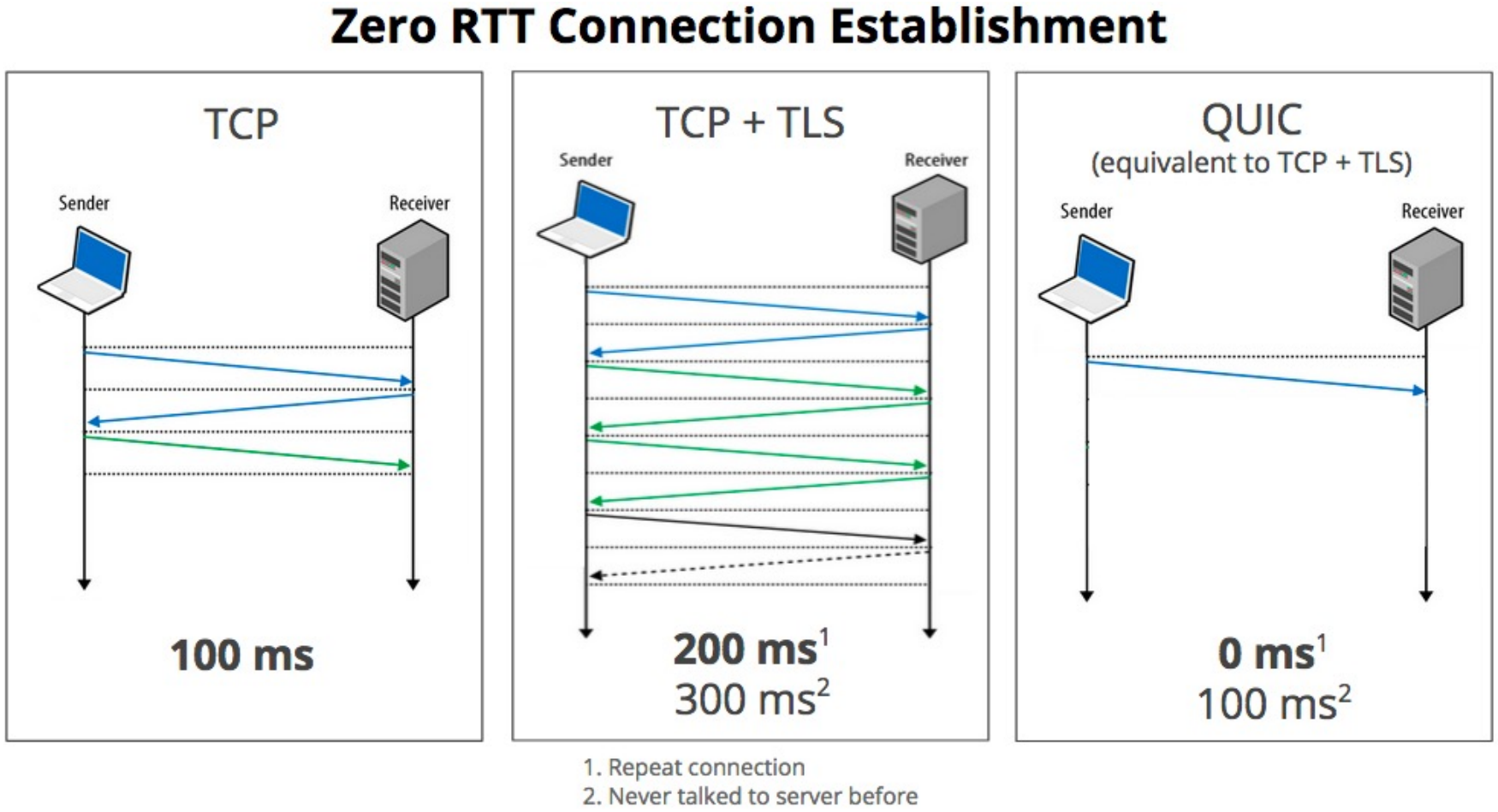
QUIC

MPTCP

BBR

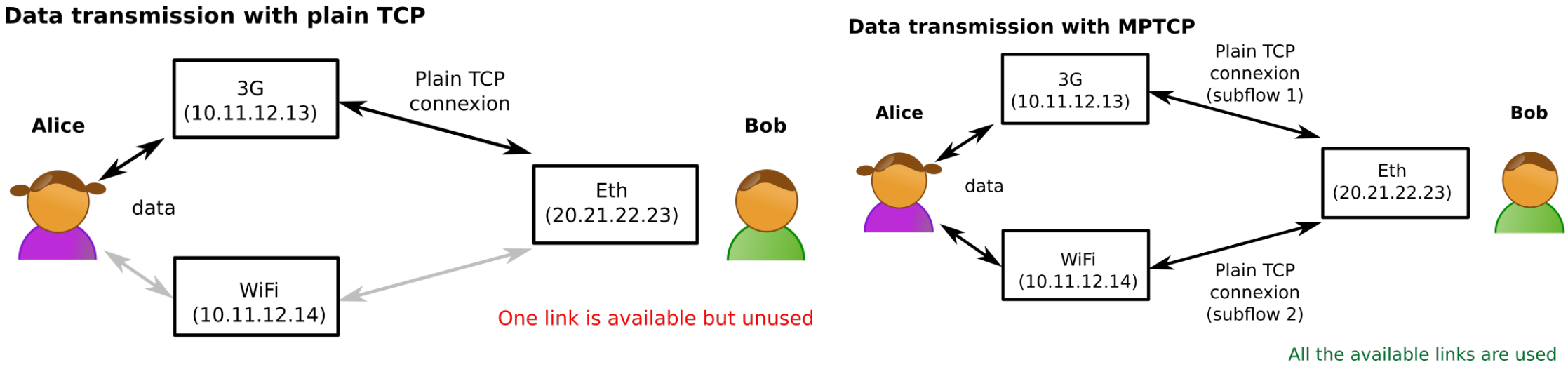
DCTCP

QUIC

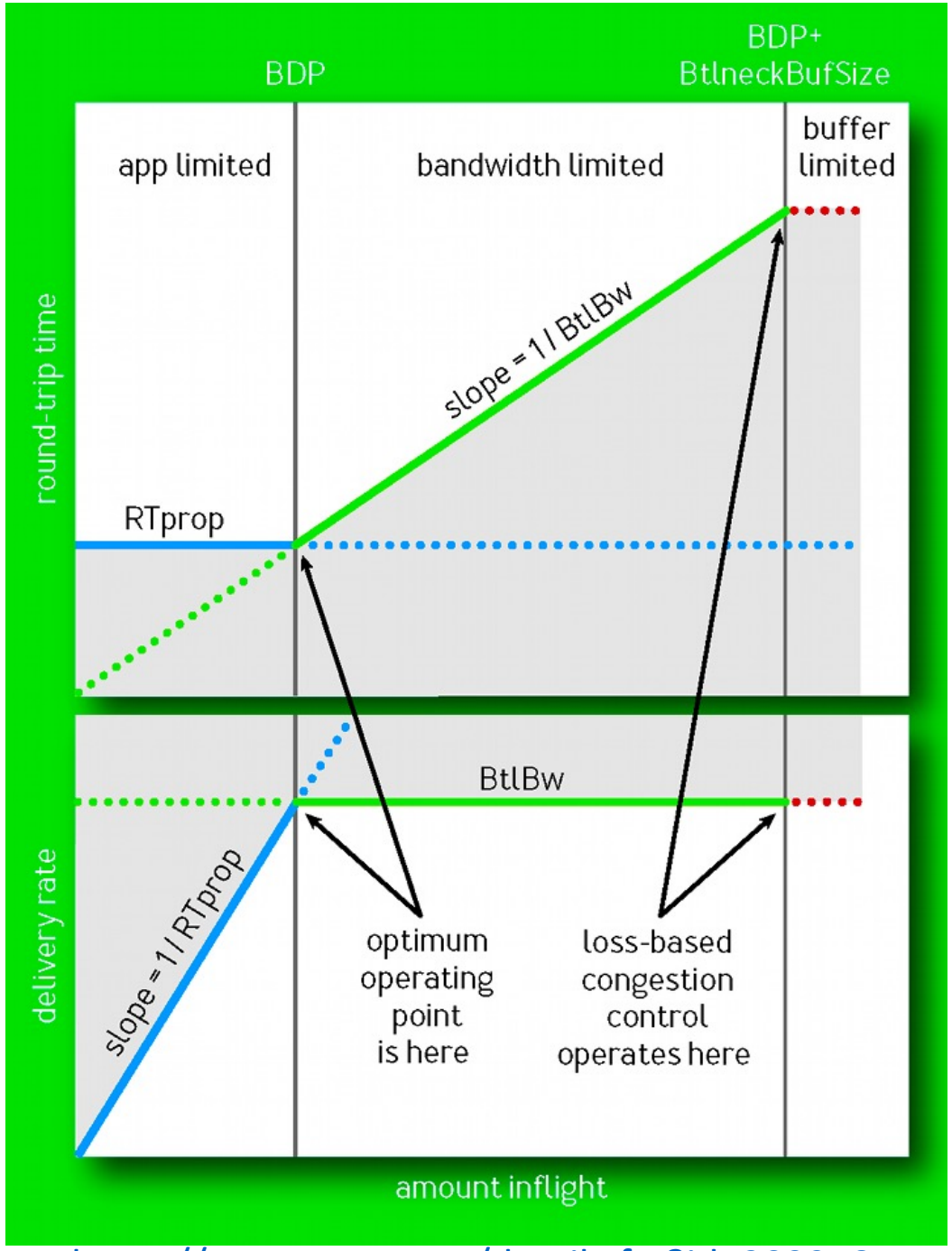


https://blog.chromium.org/2015/04/a-quic-update-on-googles-experimental.html

MPTCP: Multipath TCP

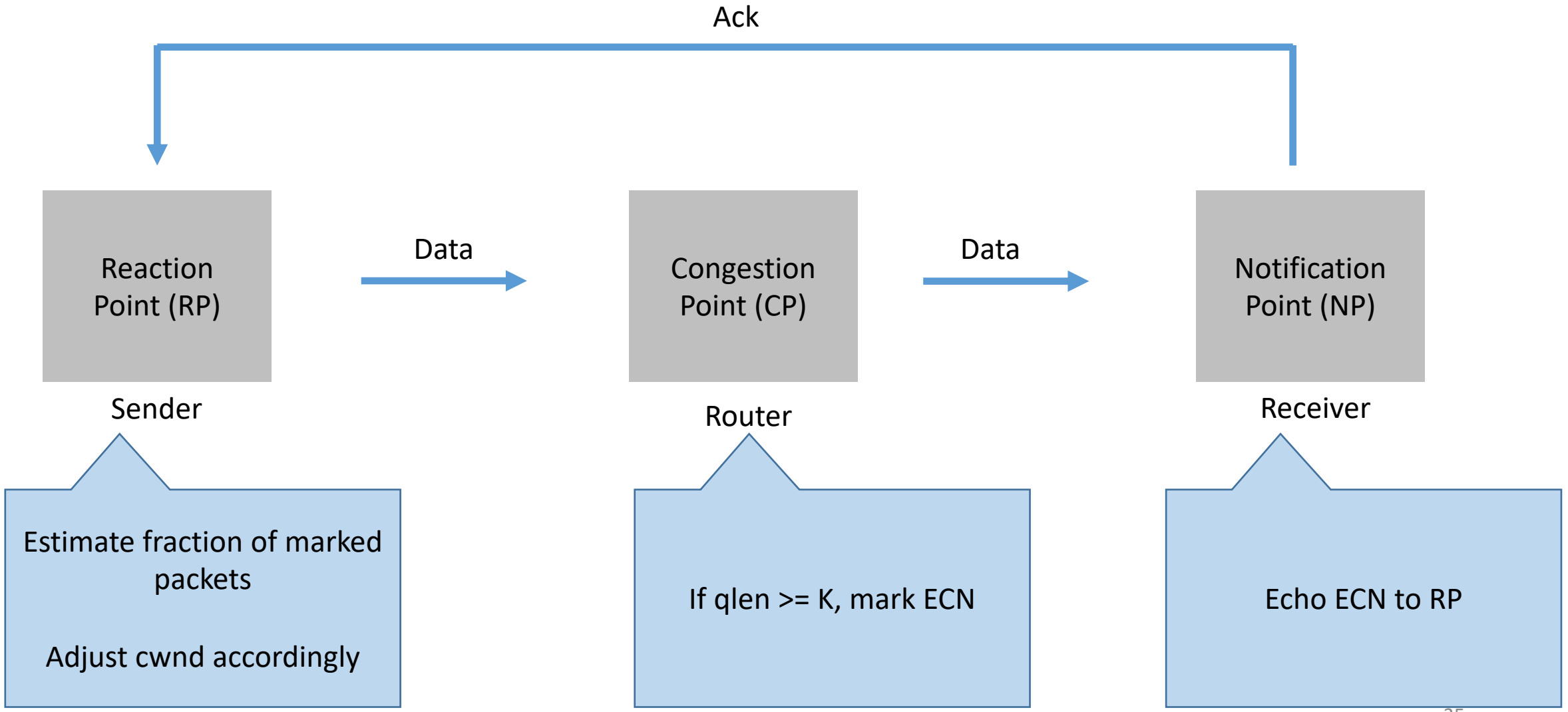


BBR:
Bottleneck Bandwidth and Round trip propagation



https://queue.acm.org/detail.cfm?id=3022184

DCTCP at a glance



Recap: Transport protocols

Goal: Provide end-to-end message delivery to applications

- Reliable (or not), messages vs streams

Challenges:

- Dealing with packet losses
- Dealing with slow receivers (flow control) and network (congestion control)
- Adapting to network conditions
  - Determine the right sending rate for yourself
  - Individual behaviors resulting in efficient and fair resource use

Toolbox

- Timeouts/retransmissions, sliding windows, max-min fairness, AIMD, ….