TCP Self-clocking

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Eight Things

Eight things we know about TCP.

1. During slow start, cw grows exponentially.
2. When cw exceeds bdp, packets get dropped.
3. After a drop, the send rate decreases.
4. After slow start, cw grows linearly between drops.

Eight Things

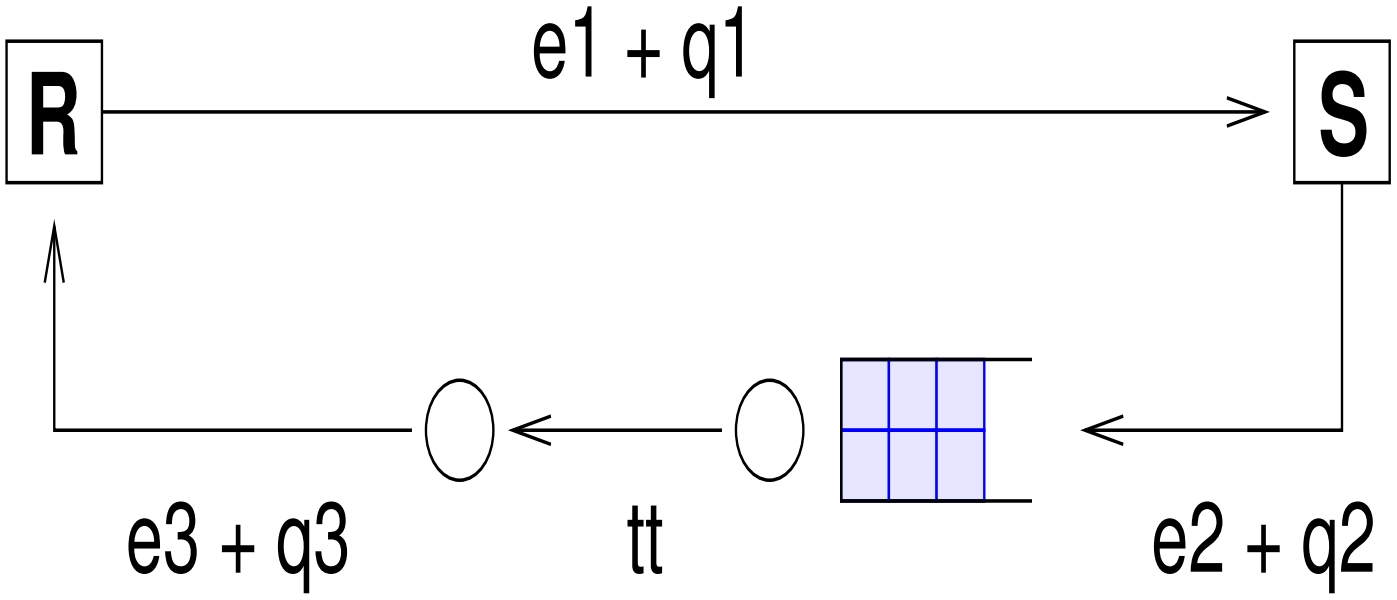
5. Steady-state behavior for long transfers is AIMD.
6. In steady state, $throughput \sim 1/\sqrt{p}$.
7. When connections share a bottleneck, $throughput \sim 1/rtt$.
8. TCP is slow to discover increased available capacity.

False!

- These claims are all false, when the buffer at the bottleneck $> bdp$.
- And it often is.
- Model first, then measurements...

Network Model

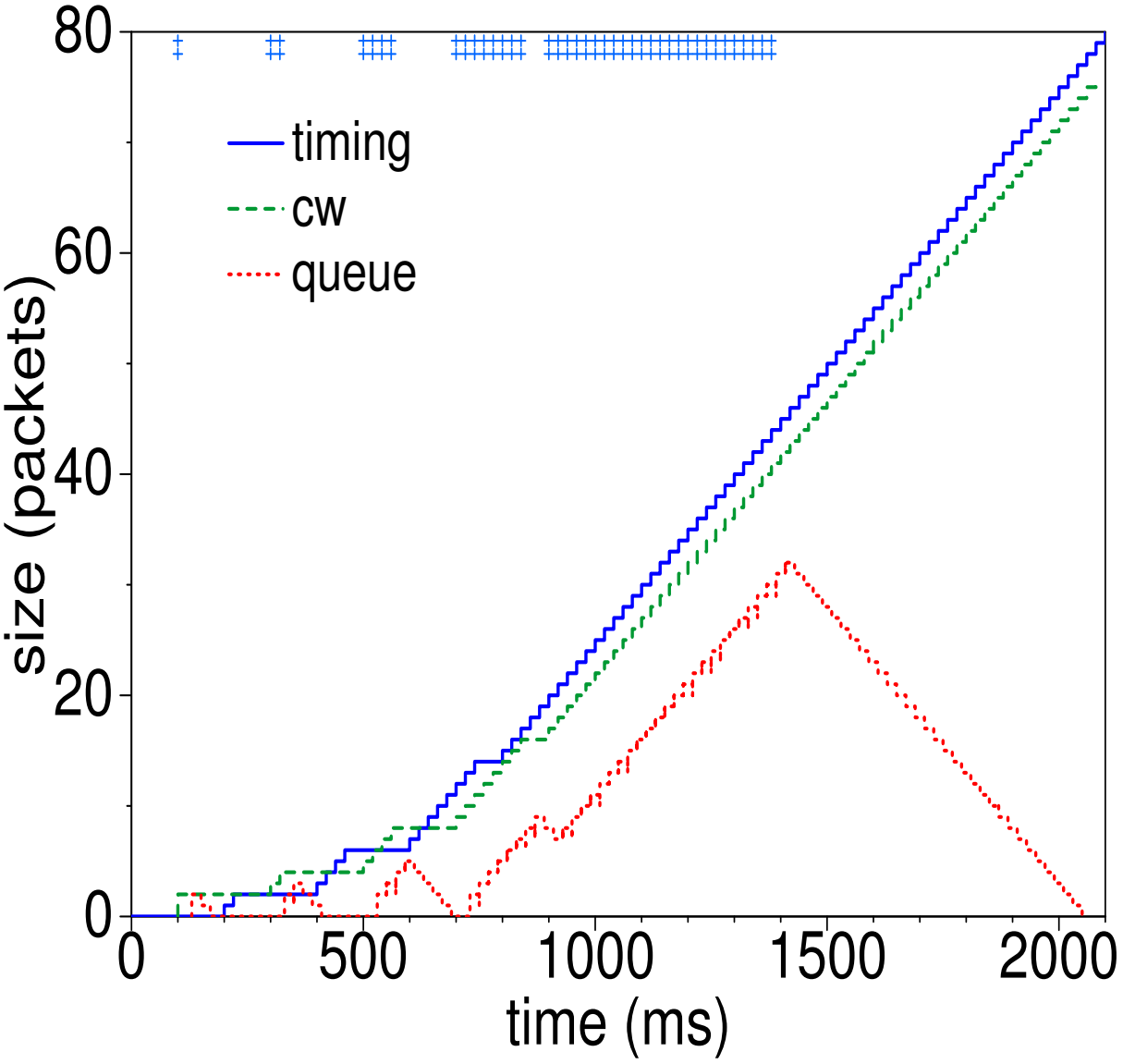
- Receiver sends request, gets reply.
- Then sends ACKs, gets packets.
- Explicit queue at bottleneck.
- Random queue delays before and after bottleneck.



Protocol Model

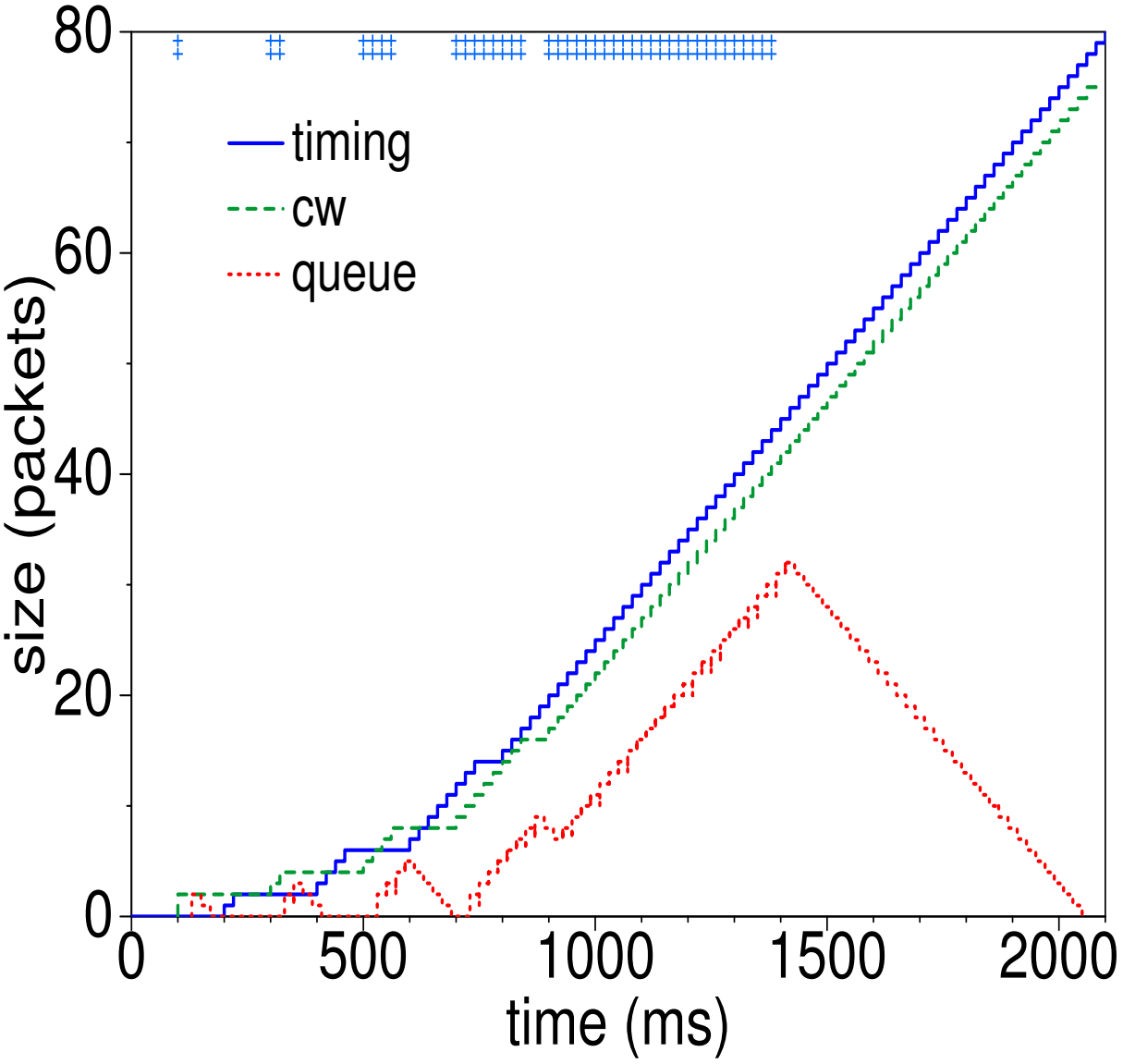
- In slow start, cw grows 1 packet per 1 ACK.
- Switch to CA when $cw > ssthresh$ or receive trip-dup.
- In CA, cw grows 1 packet per cw ACK.
- Model includes fast recovery.
- No timeouts, no delayed ACKs.

Model output



- $tt = 20$ms, $rtt = 200$ms, $bdp = 10$ packets.
- Timing chart shows total data received, cw, queue.
- Expect $cw = 2, 4, 8, 16,$ drop!

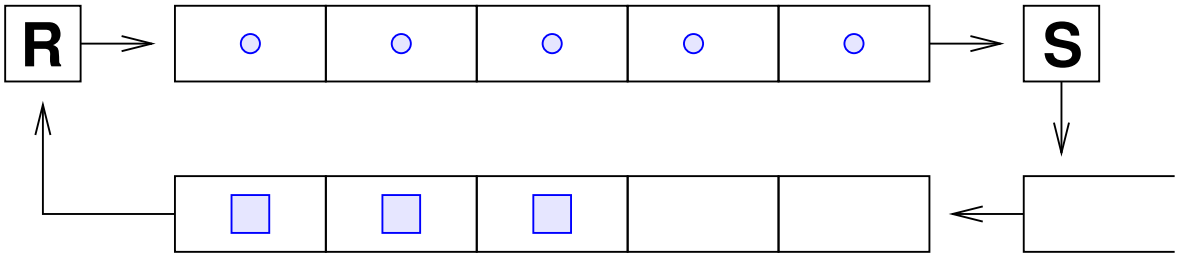
Self-clocking



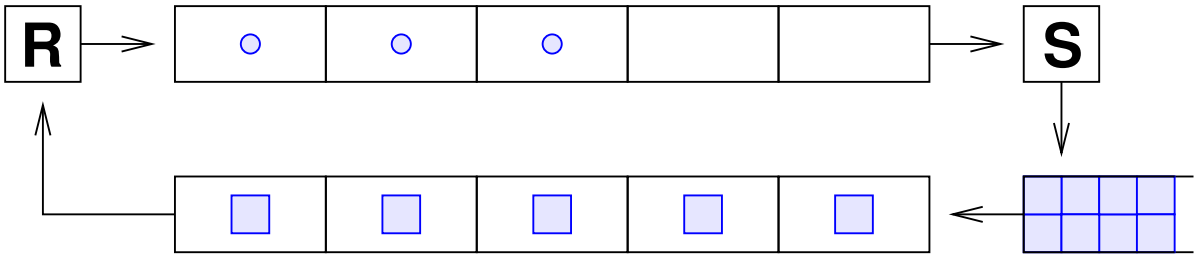
- After $cw > bdp$, cw grows linearly.
- Queue also grows linearly.
- Send rate $= 2bw$.

Transition to SC

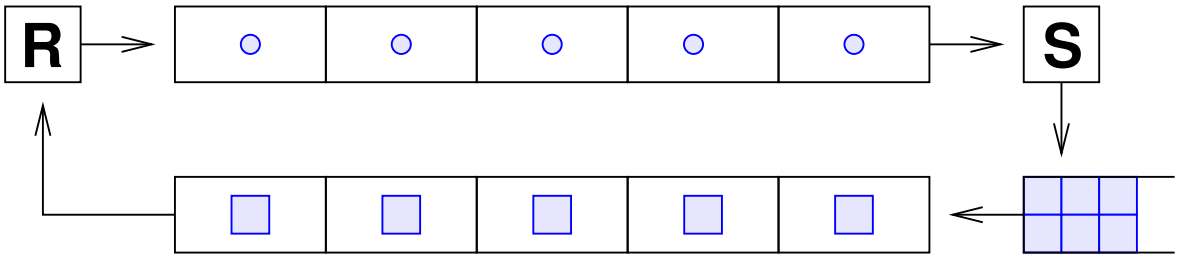
t = 0, cw = 8



t = 8, cw = 16



t = 10, cw = 16



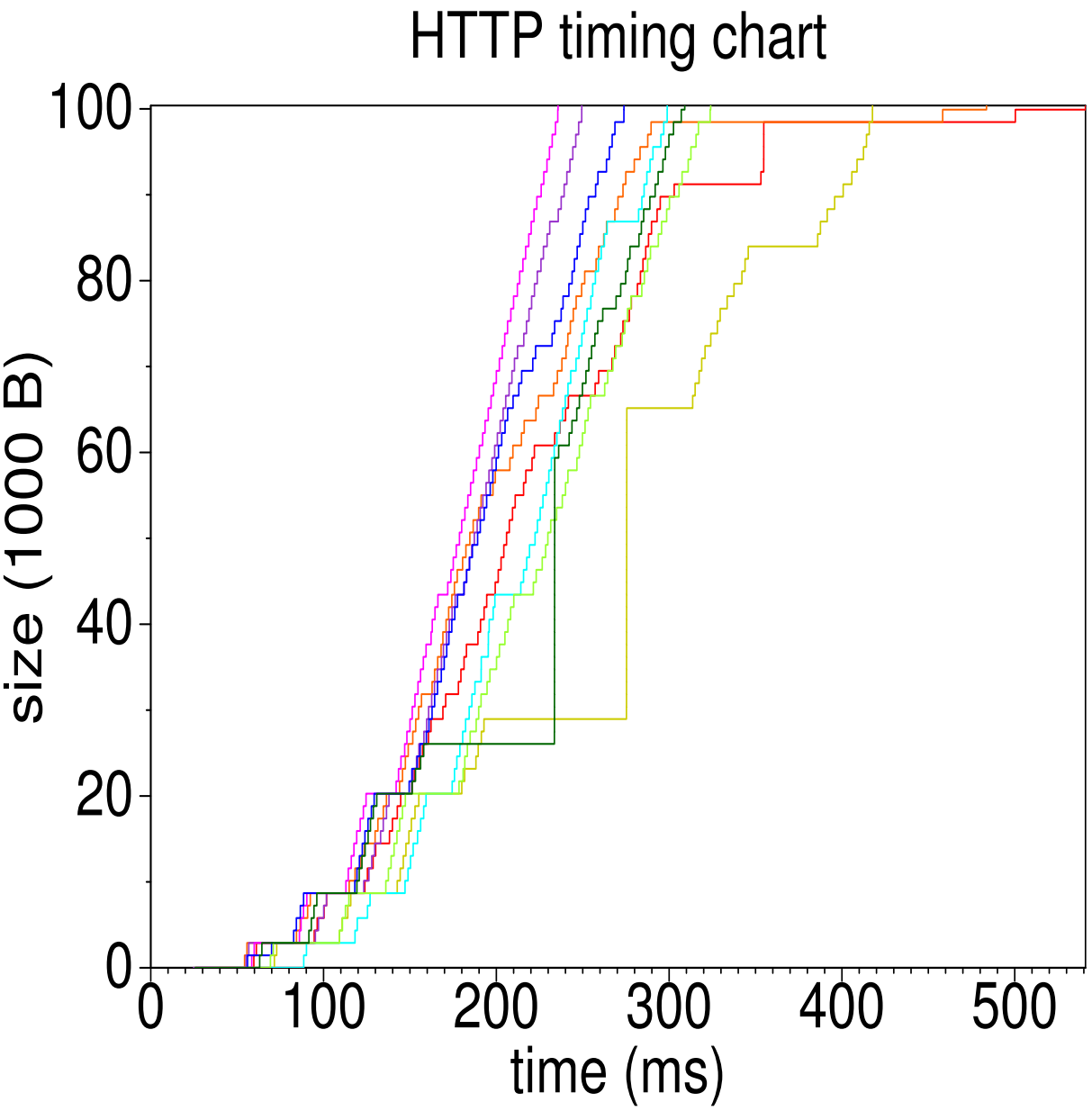
- Define $t = 0$ when $cw = 8$.
- Send 16 packets at $2bw$.
- At $t = 10$, $cw > bdp$, send rate $> bw$, no dropped packets.

Definition of SC

- SC = connection state where:
  - $cw \geq bdp$
  - send rate $\geq bw$
  - no endogenous drops.
- connection state $\neq$ sender state:

  Sender may be in slow start or congestion avoidance while connection is in SC.

Does this really happen?

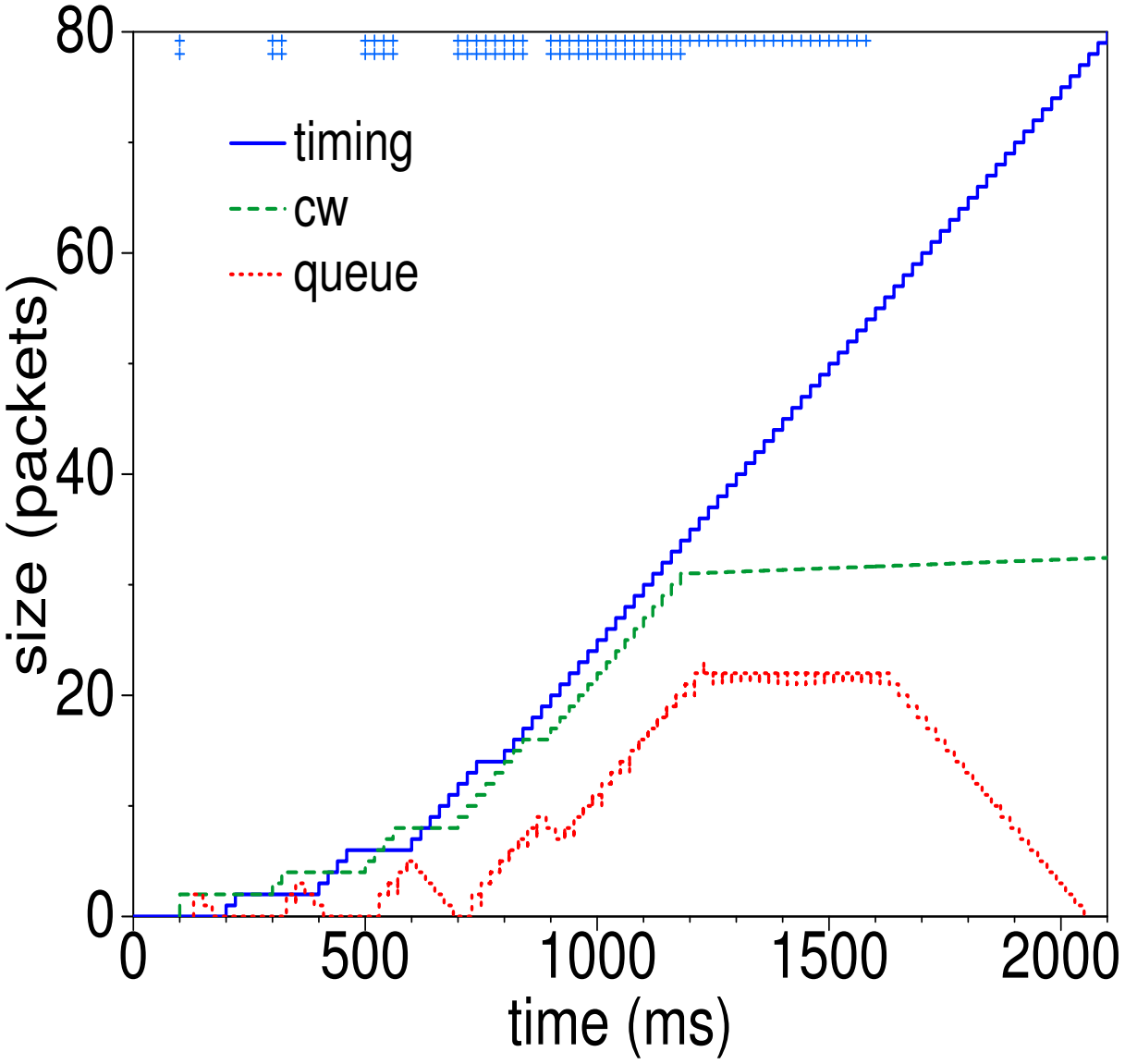


- Initiate long HTTP transfers.
- Record data arrivals.

Where are we?

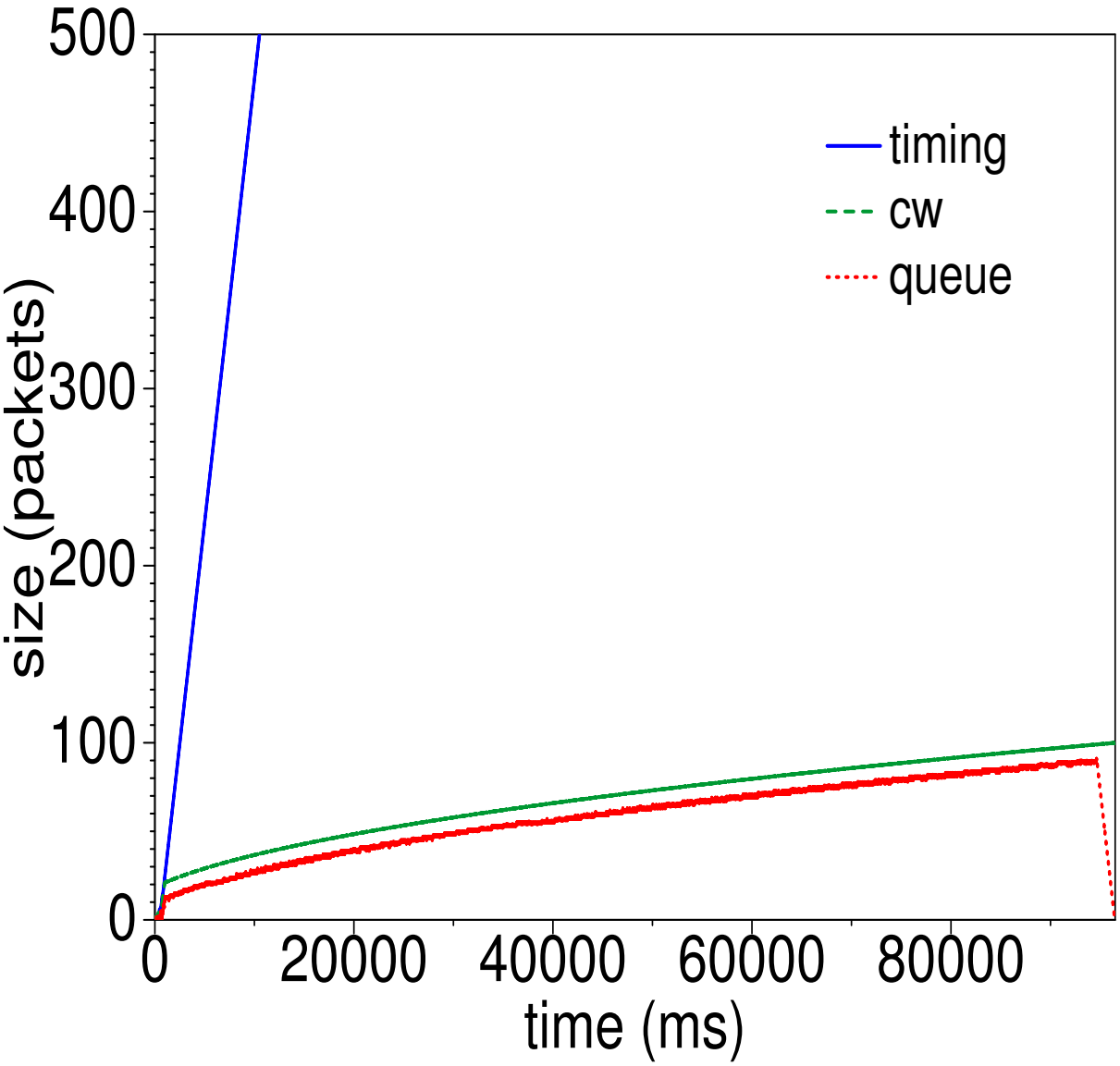
- Model explains transition from SS to SC.
- Measurements demonstrate existence of SC.
- Use model to explore the effect of:
  - $ssthresh$
  - Delays and dropped packets.
  - Bandwidth sharing.
- More measurements to verify results.

Slow start threshold



- When $cw > ssthresh$, sender switches to congestion avoidance.
- SC continues, but cw and queue grow as $\sqrt{t}$.

Slow start threshold

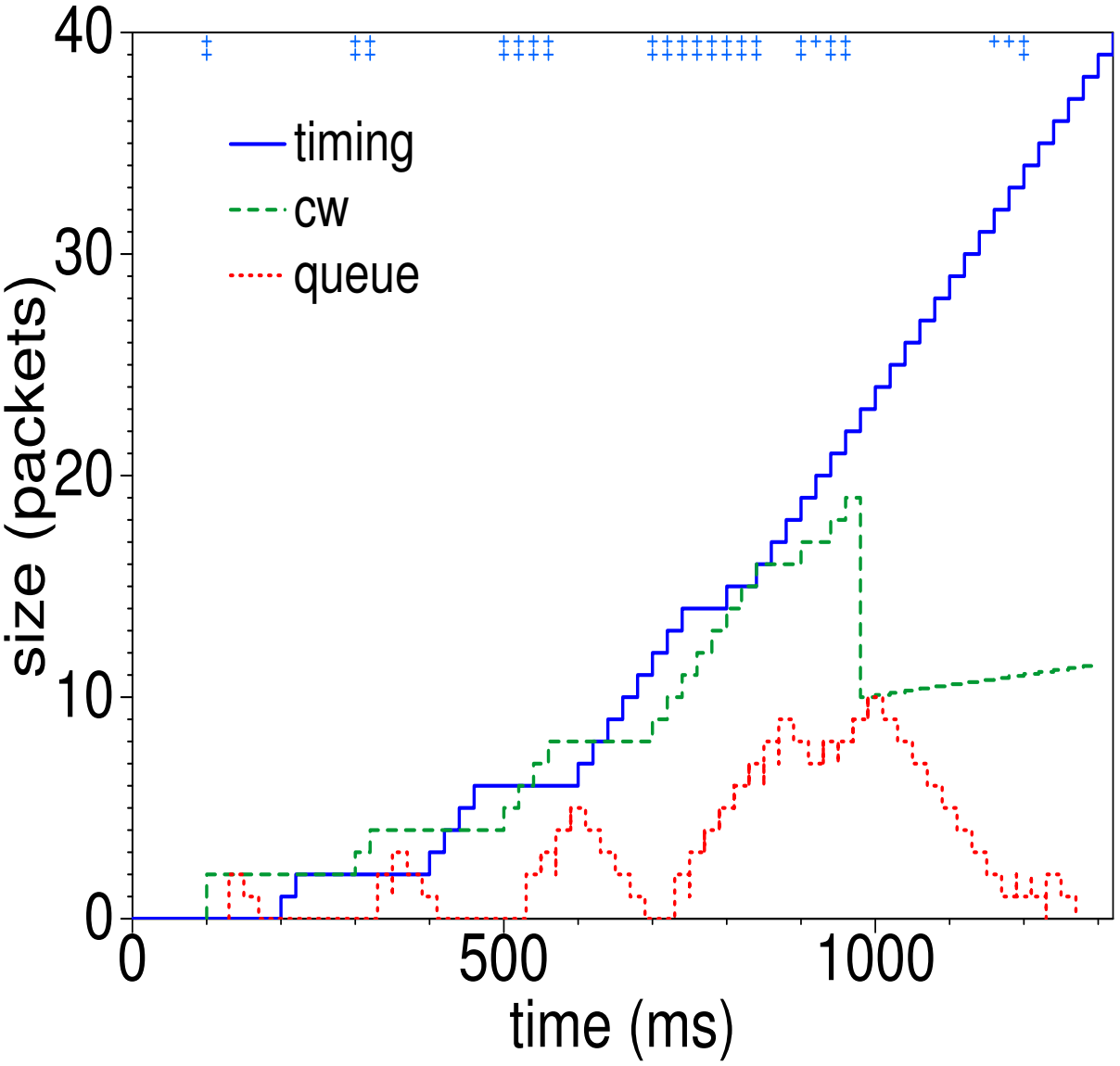


- If $ssthresh = 20$ and buffer $= 100$, we can send 4800 packets before overflow.

Capybara

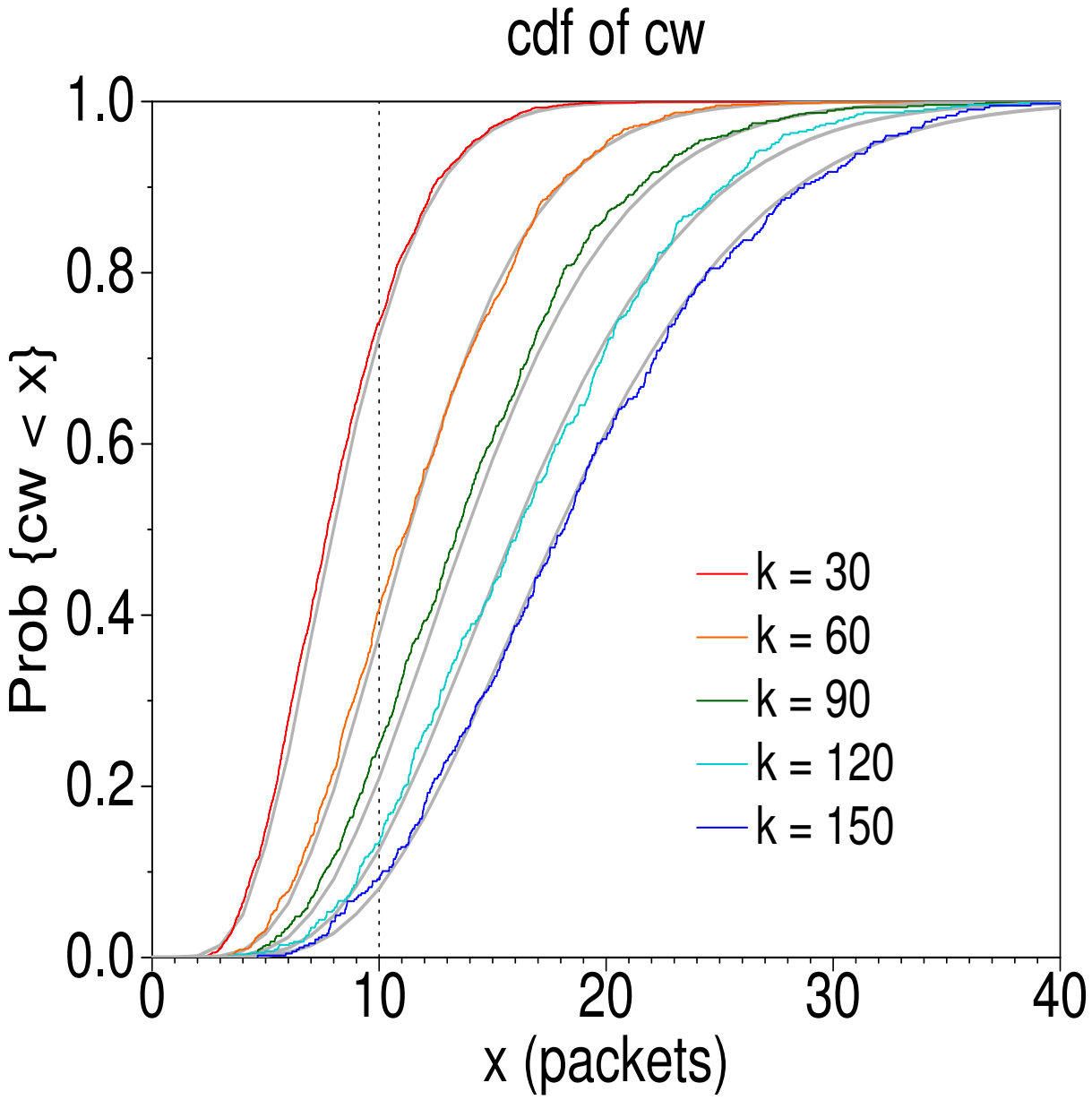
- mouse = short transfer in SS
- elephant = long transfer in AIMD
- capybara = long transfer in SC

Dropped packets



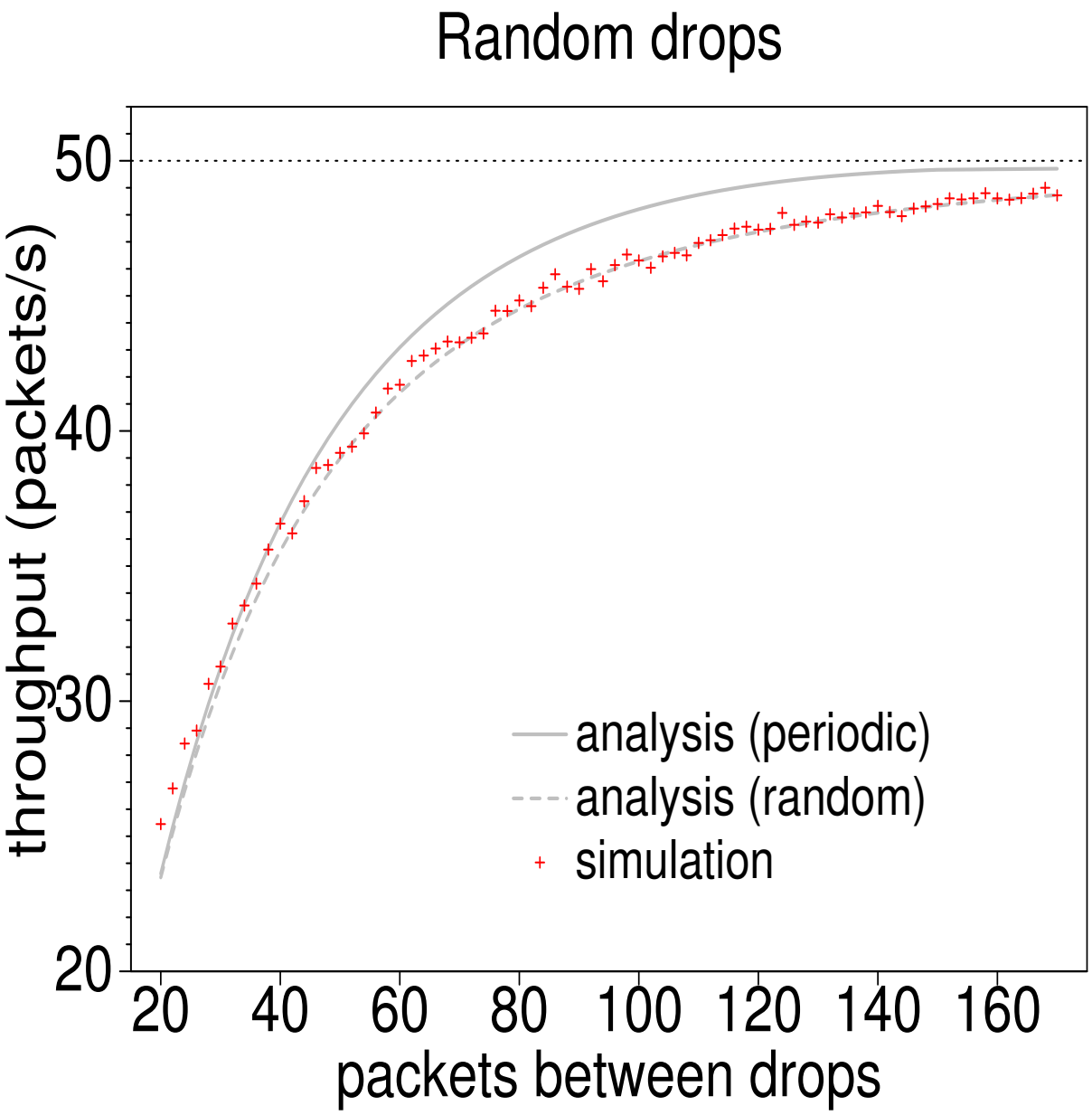
- Can SC survive a drop?
- Yes, if $cw \geq bdp$ before the queue drains.

Exogenous drops



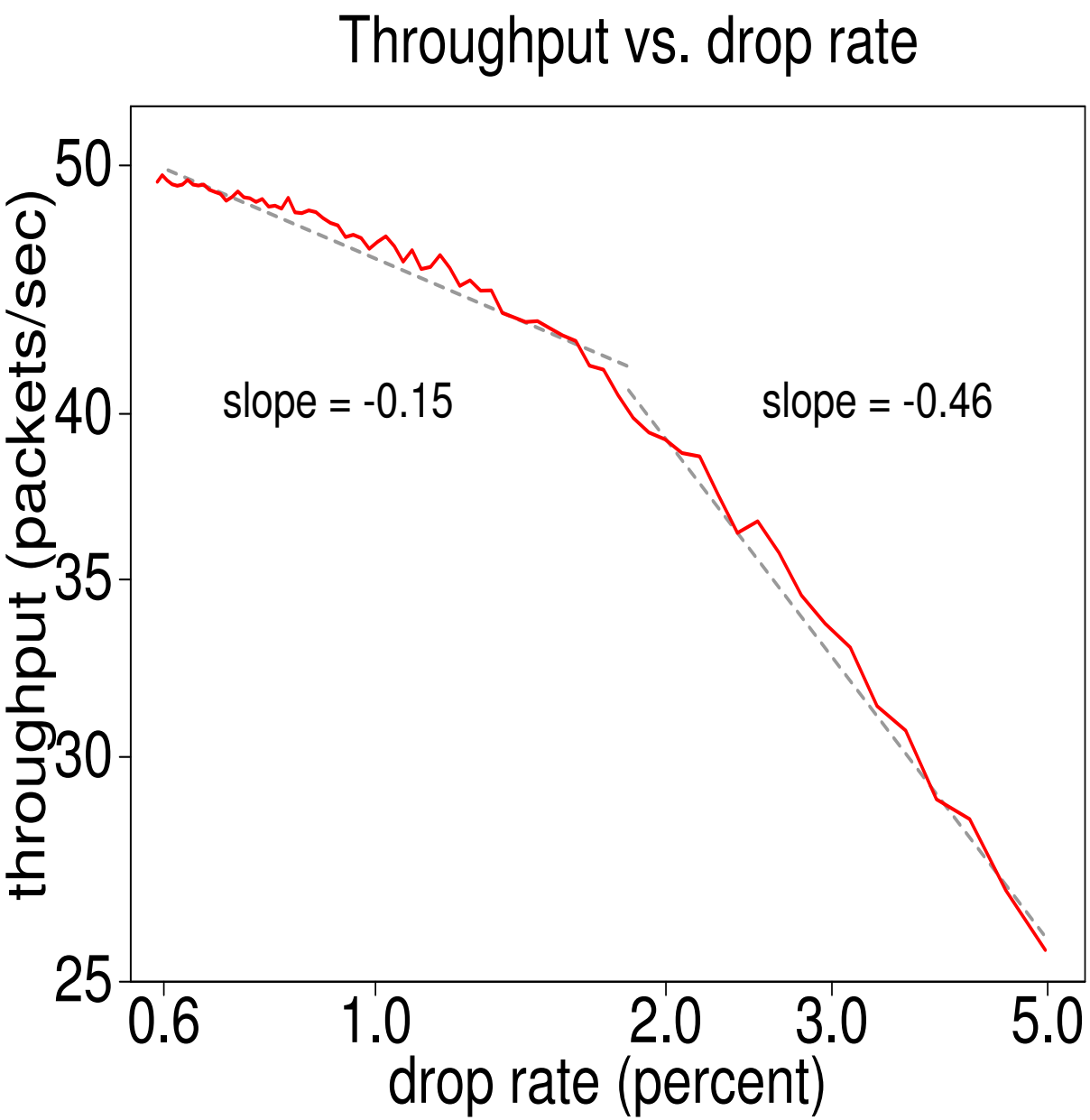
- $k = 1/p =$ average packets between drops.
- Large $k \Rightarrow$ large cw.
- Even with $k = 30$, $cw > bdp$ sometimes.

Throughput versus drop rate



- Low $k \Rightarrow$ high drop rate $\Rightarrow cw$-bound.
- High $k \Rightarrow$ low drop rate $\Rightarrow bw$-bound.

Throughput versus drop rate

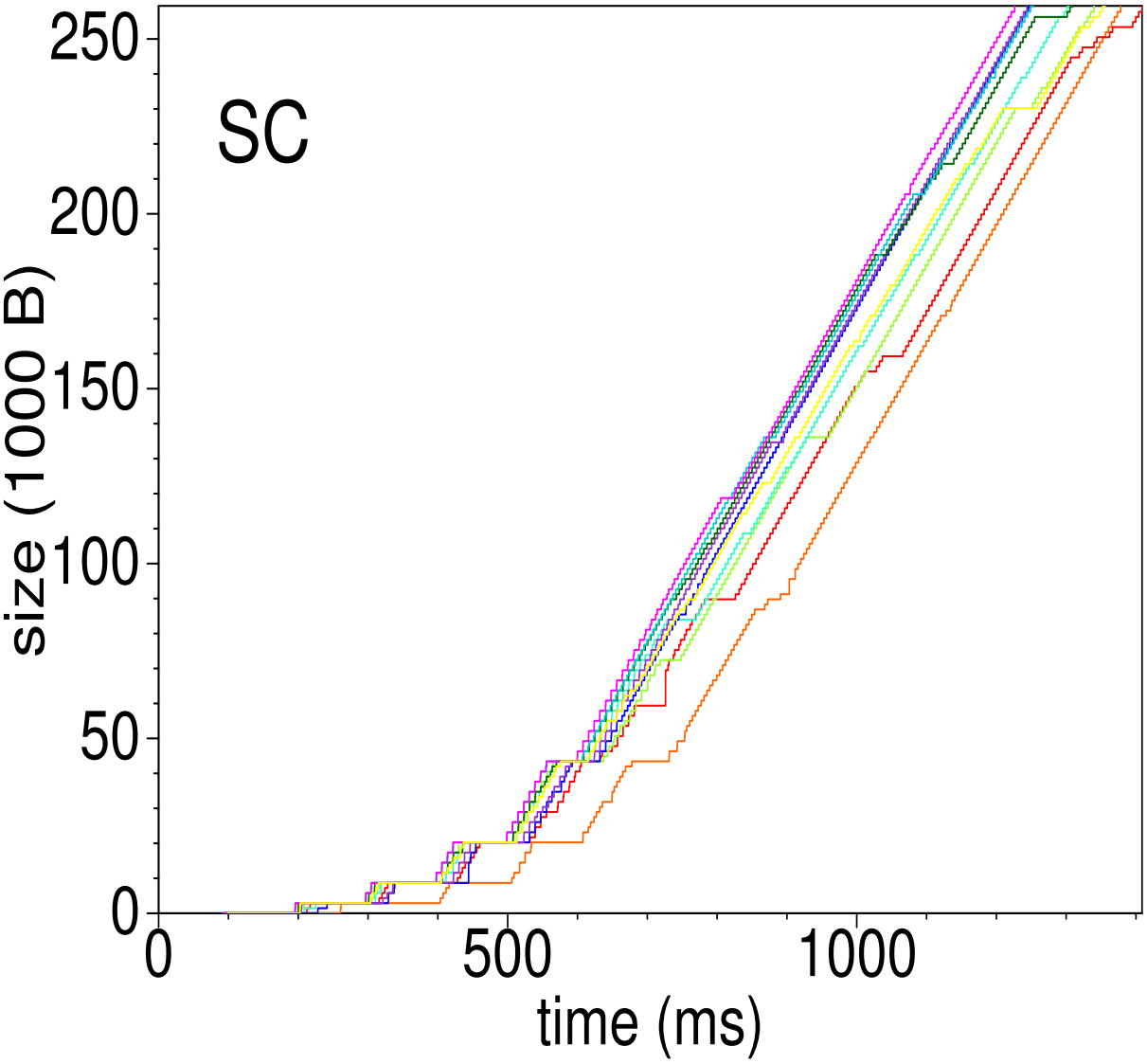


- Log-log scale.
- High drop rate, $th \sim p^{-0.46}$
- Low drop rate, no $1/\sqrt{p}$ rule.

Measurements

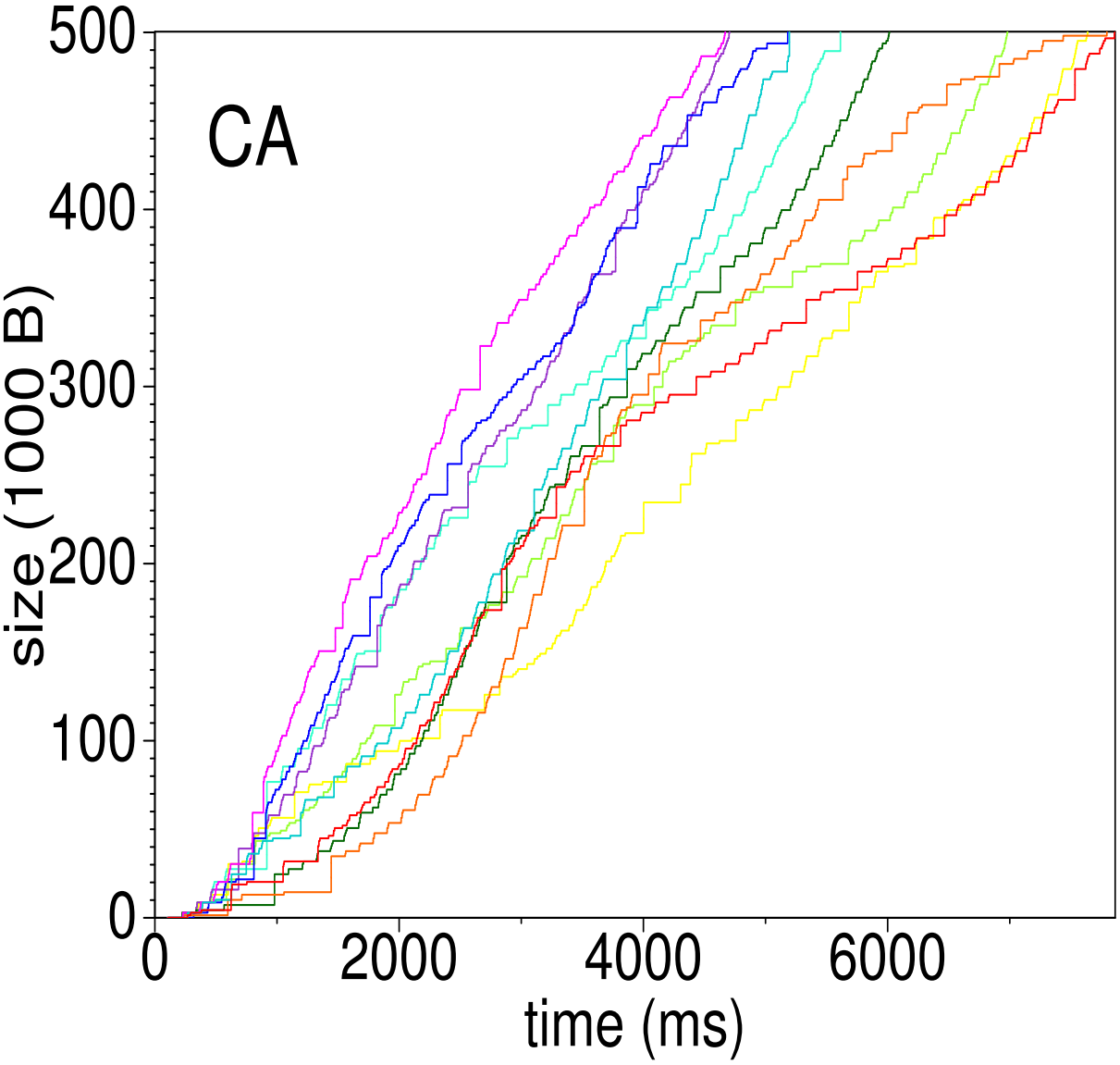
- Find 100 busy Web sites with large files (100–500 KB).
- Download 10 times.
- Classify timing charts (visual and statistical).

Self-clocking



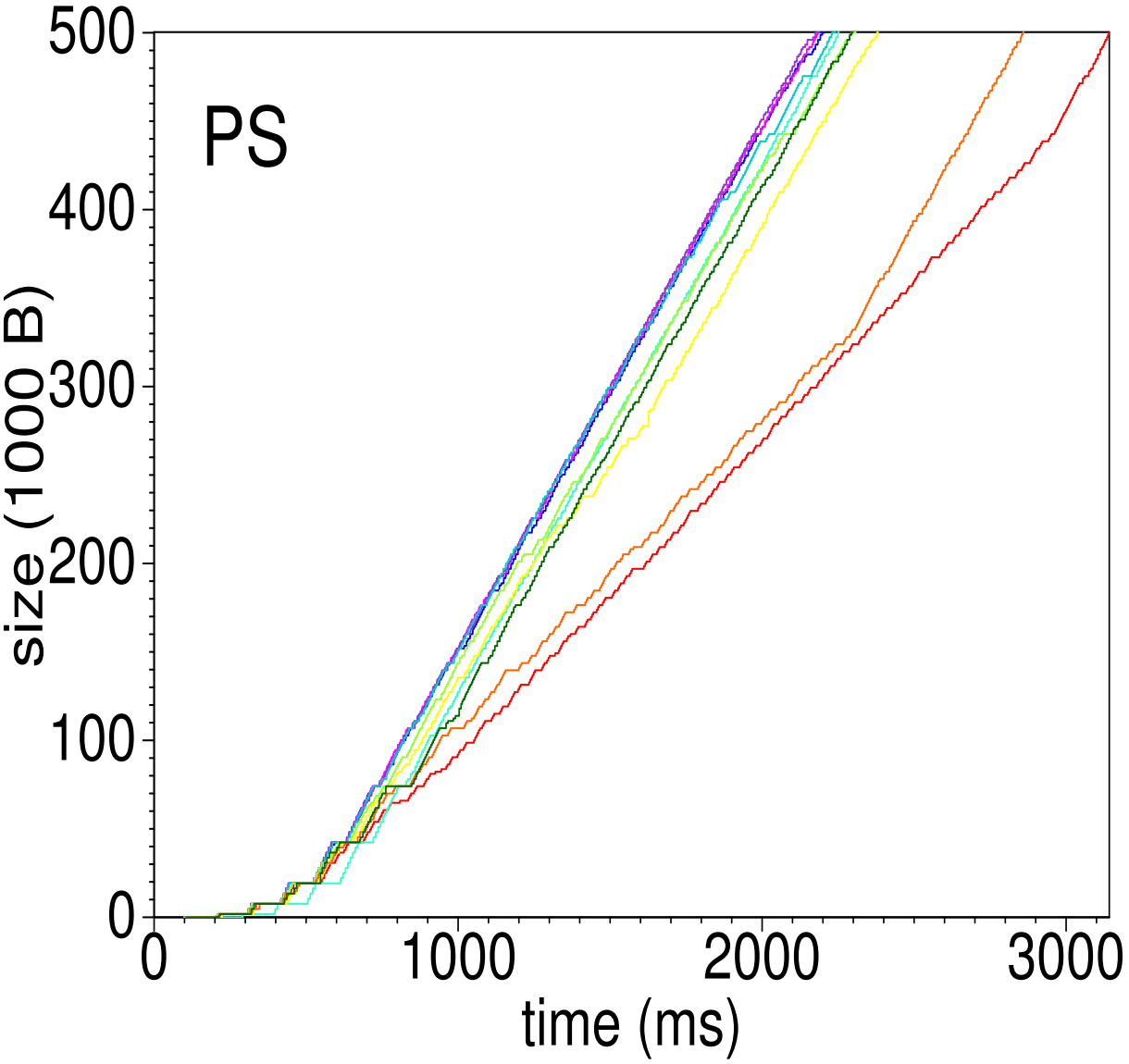
- 61 paths where SC is most common state.

Congestion avoidance



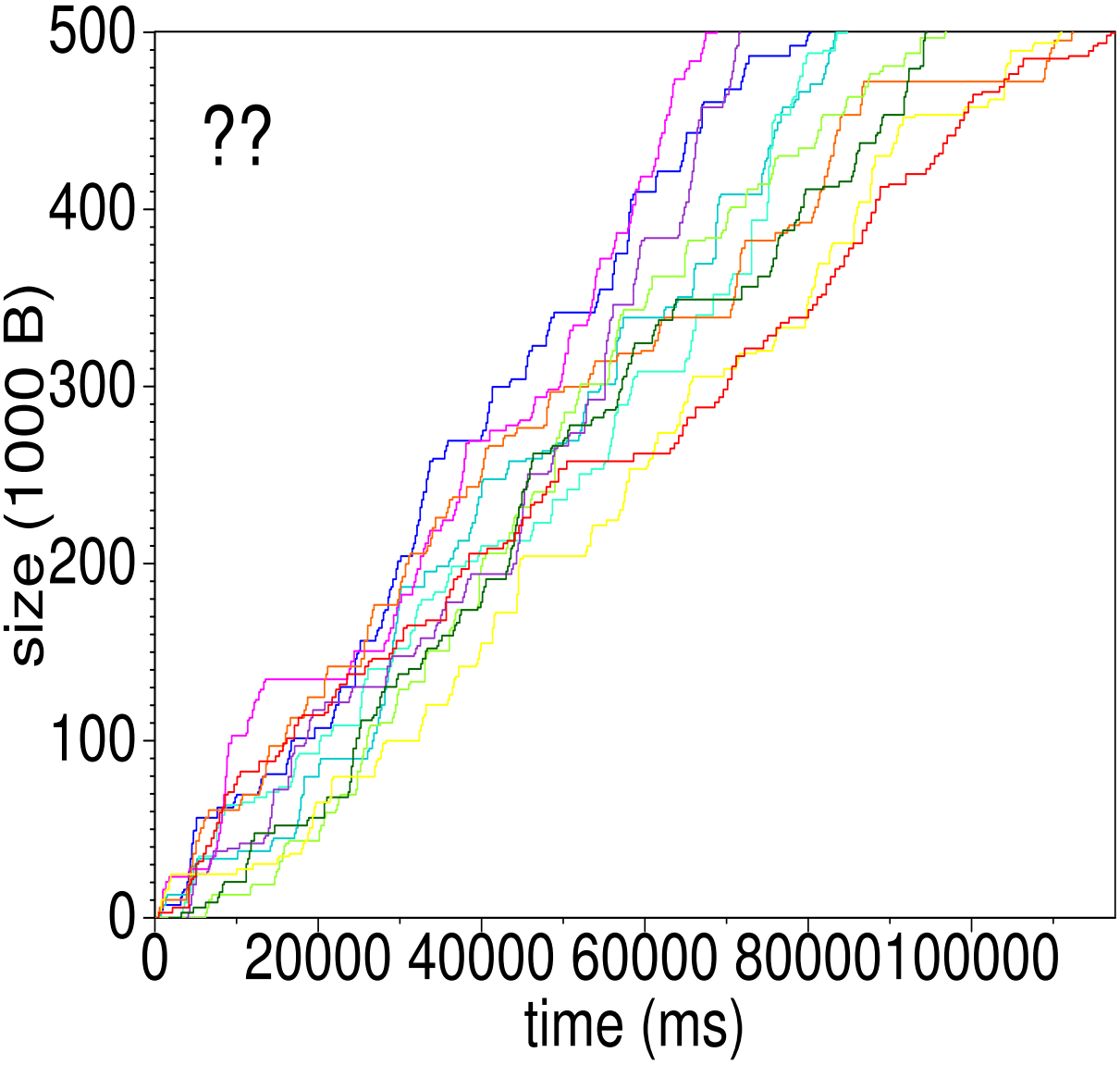
- 7 paths where AIMD is the most common state.

Bandwidth sharing



- Evidence of bandwidth sharing.

Who knows?



- 2 cases of who knows what.
- 10 buffer-limited.
- 2 opportunity-limited.
- 1 application-limited (thttpd).
- 17 file not available.

Summary

- 83 successful downloads.
- 61 paths (73%) where SC is common.
- Client on college campus, behind 2 T1s (2.8 Mbps), tends to see low bdp.

Client	SC	CA	BL	OL	??	AL	Total
1	61	7	10	2	2	1	83

Table 1: Path classifications.

More measurements

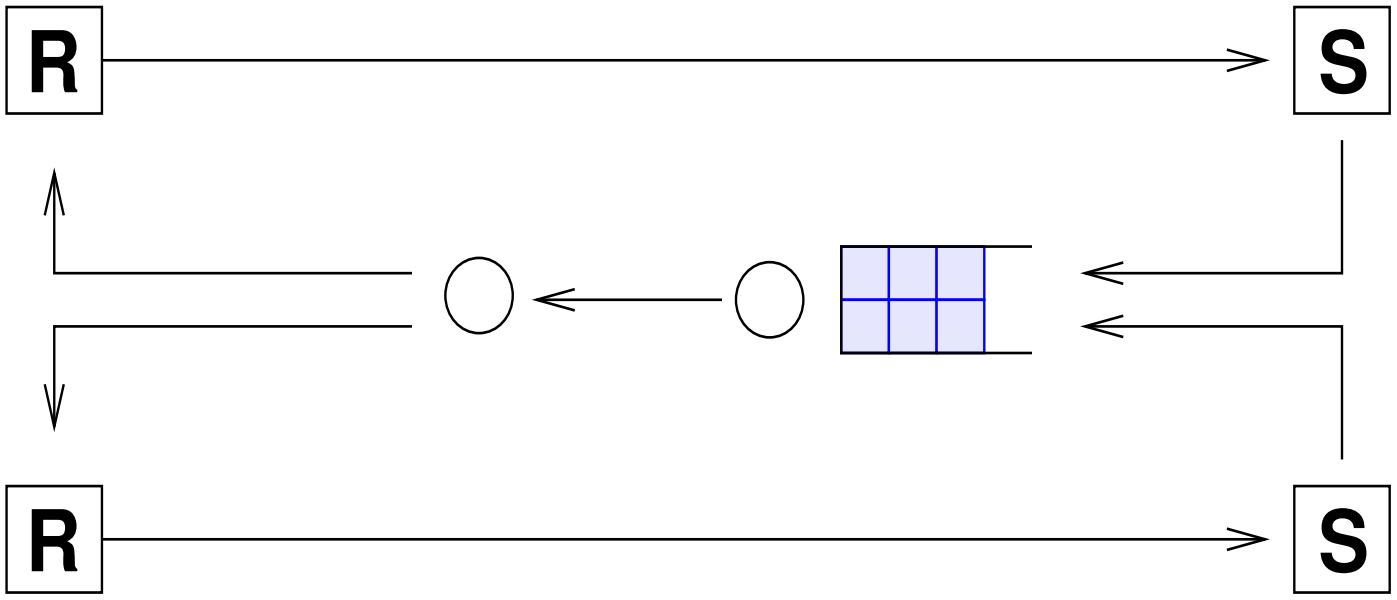
- Client 2, house with cable modem (almost 8 Mbps).
- Client 3, university (45 Mbps and 1 Gbps).

Client	SC	CA	BL	OL	??	AL	Total
1	61	7	10	2	2	1	83
2	54	6	11	9	7	1	88
3	24	24	44	17	24	0	133

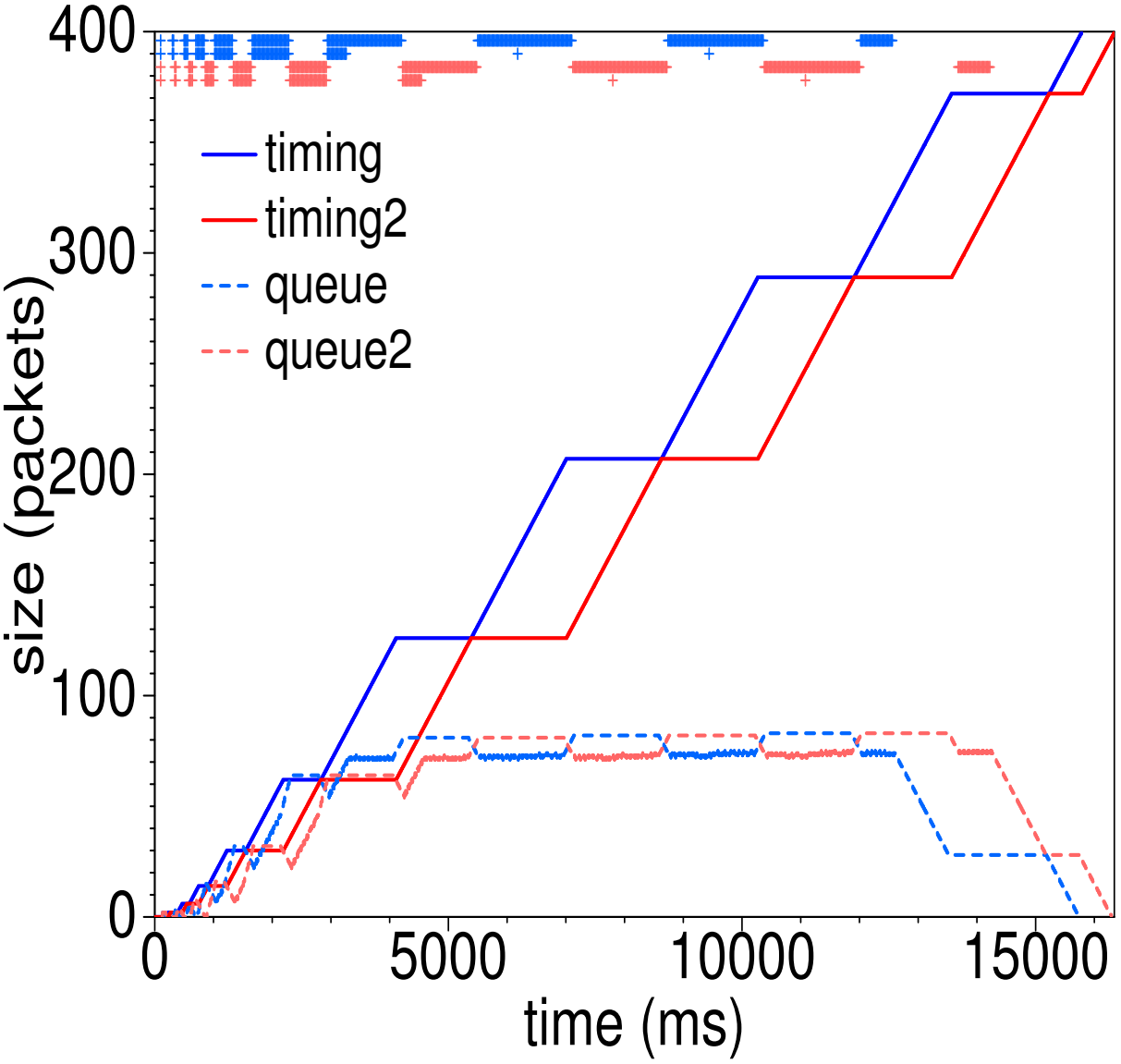
Table 2: Path classifications.

Bandwidth sharing

- Extend the model for n transfers sharing the bottleneck.
- Starting with $n = 2$:
  same rtt and ss, different rtt, different ss.

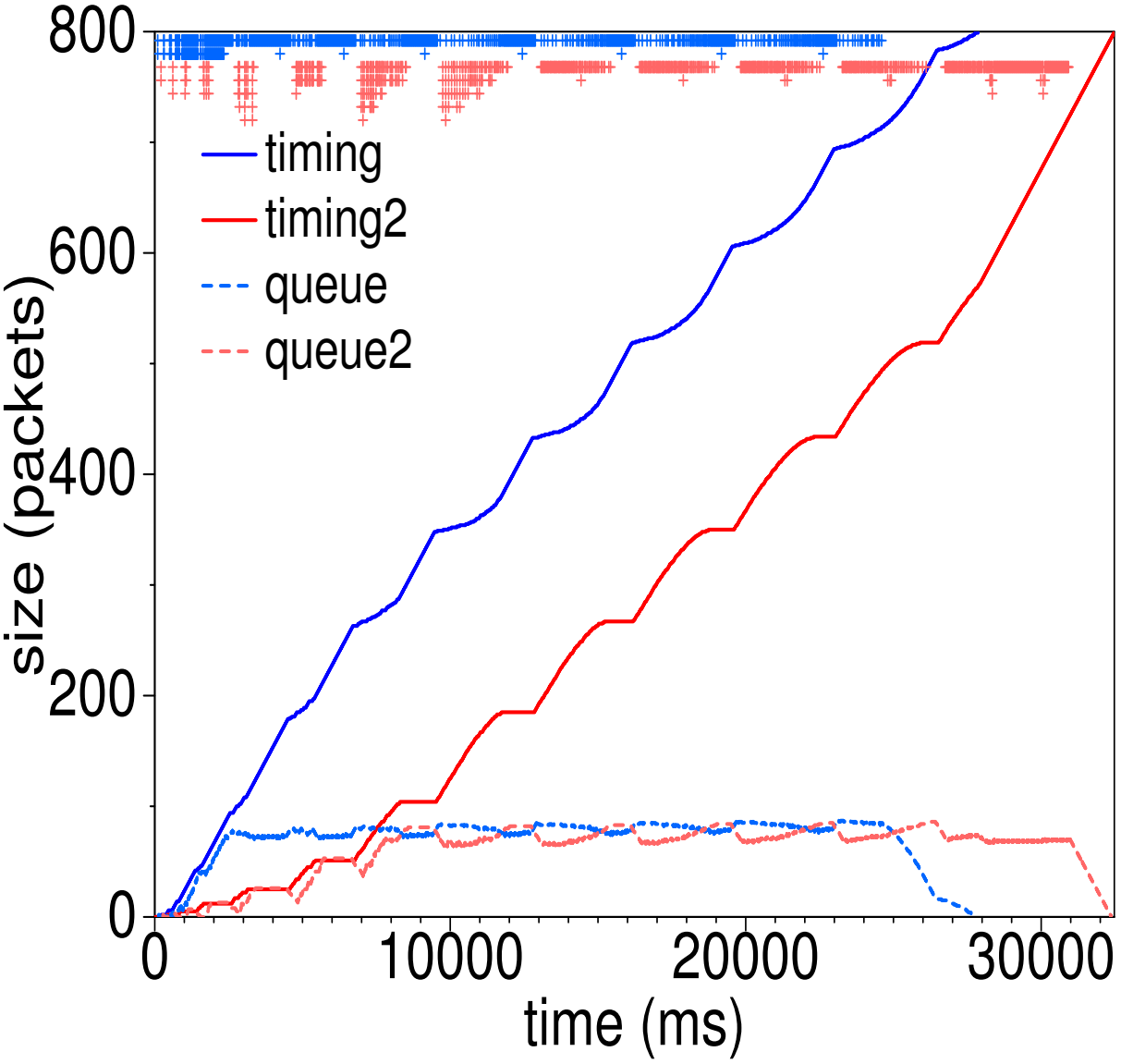


Periodic sharing



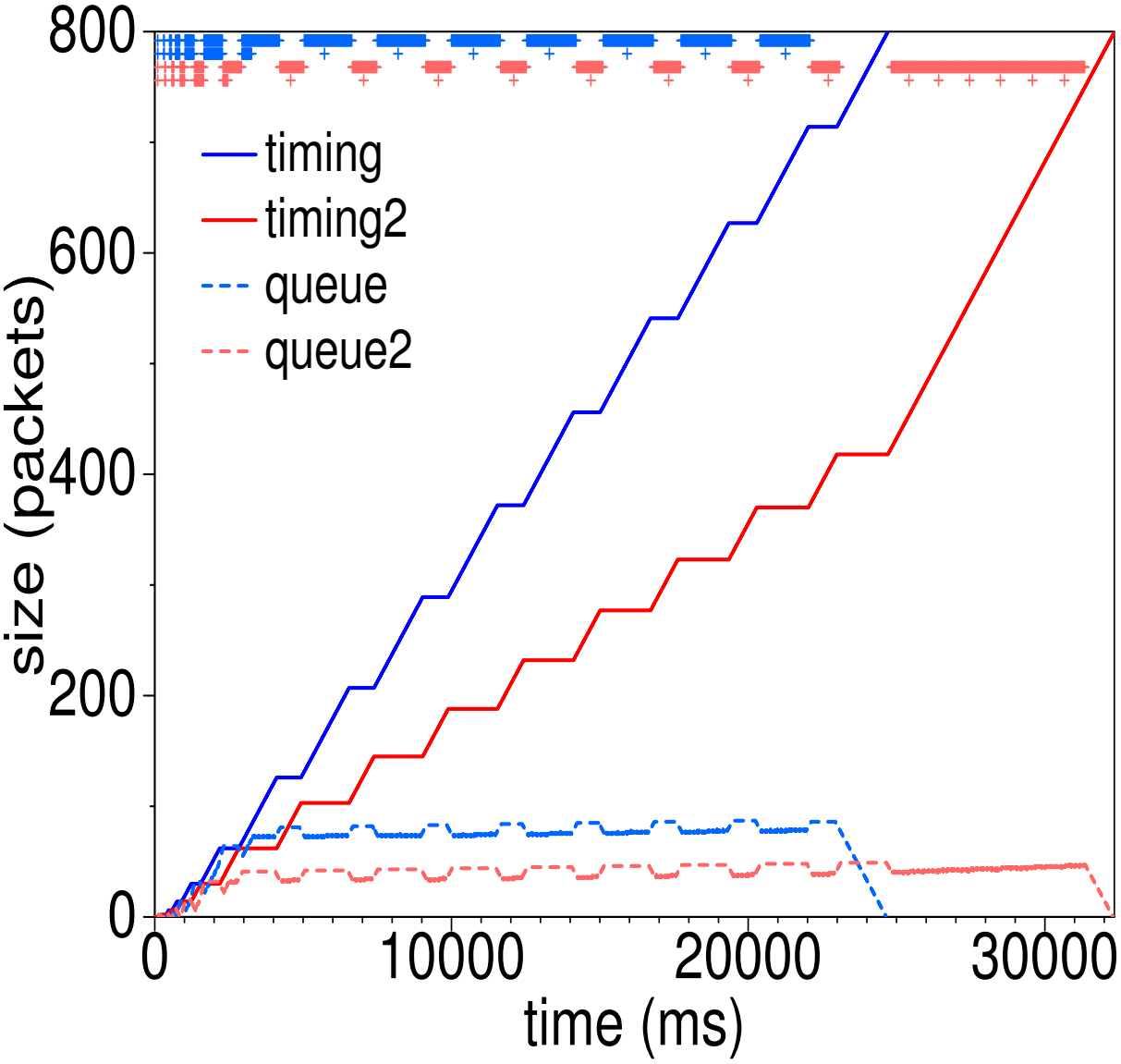
- $rtt_1 = rtt_2 = 200$ ms.
- $ss_1 = ss_2 = 80$ packets.
- Periodic sharing (PS).

Periodic sharing



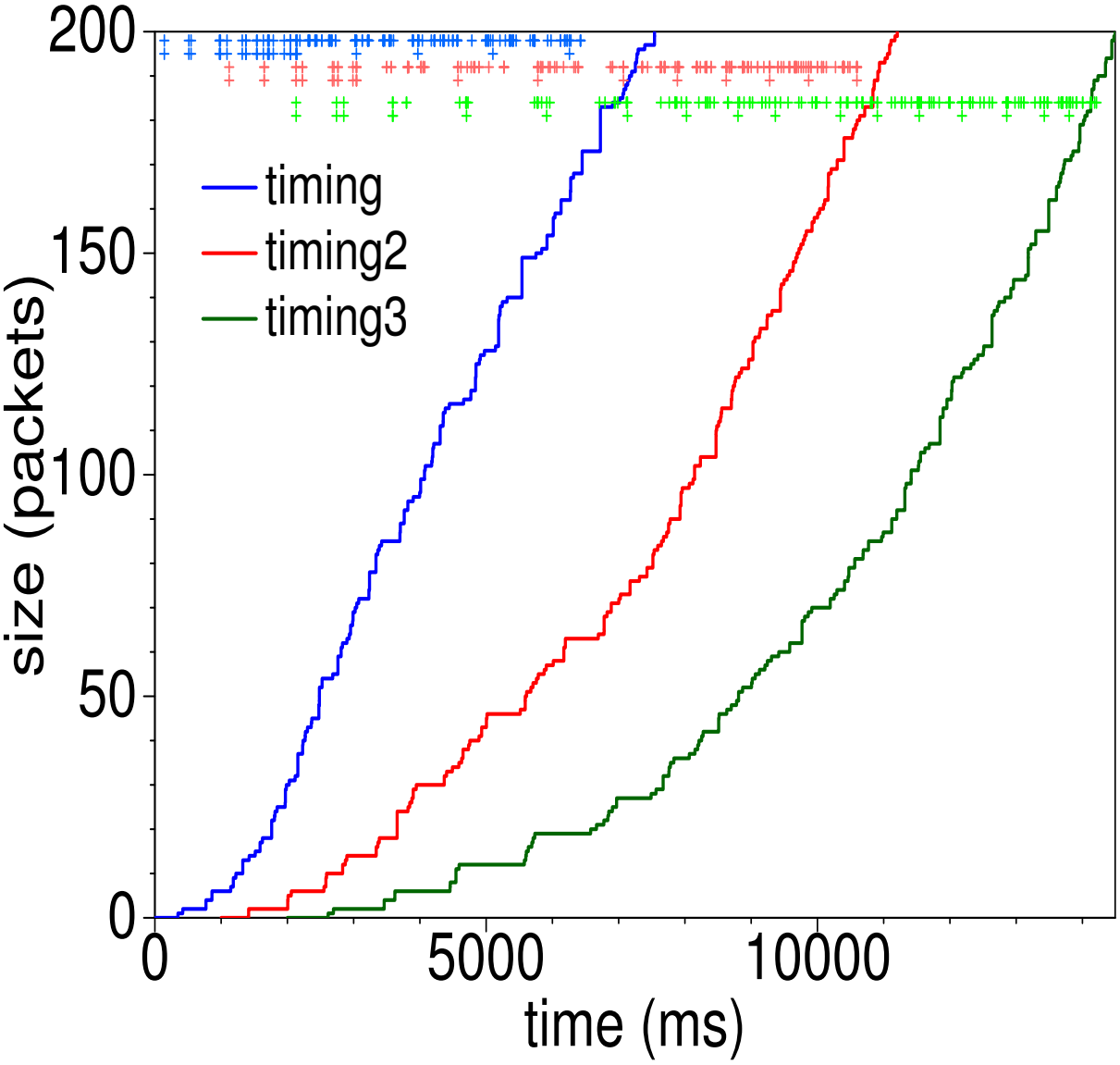
- $rtt_1 = 200$ ms.
- $rtt_2 = 400$ ms.
- $ss_1 = ss_2 = 80$ packets.
- Same throughput!
- Each connection sends cw_i per period.

Periodic sharing



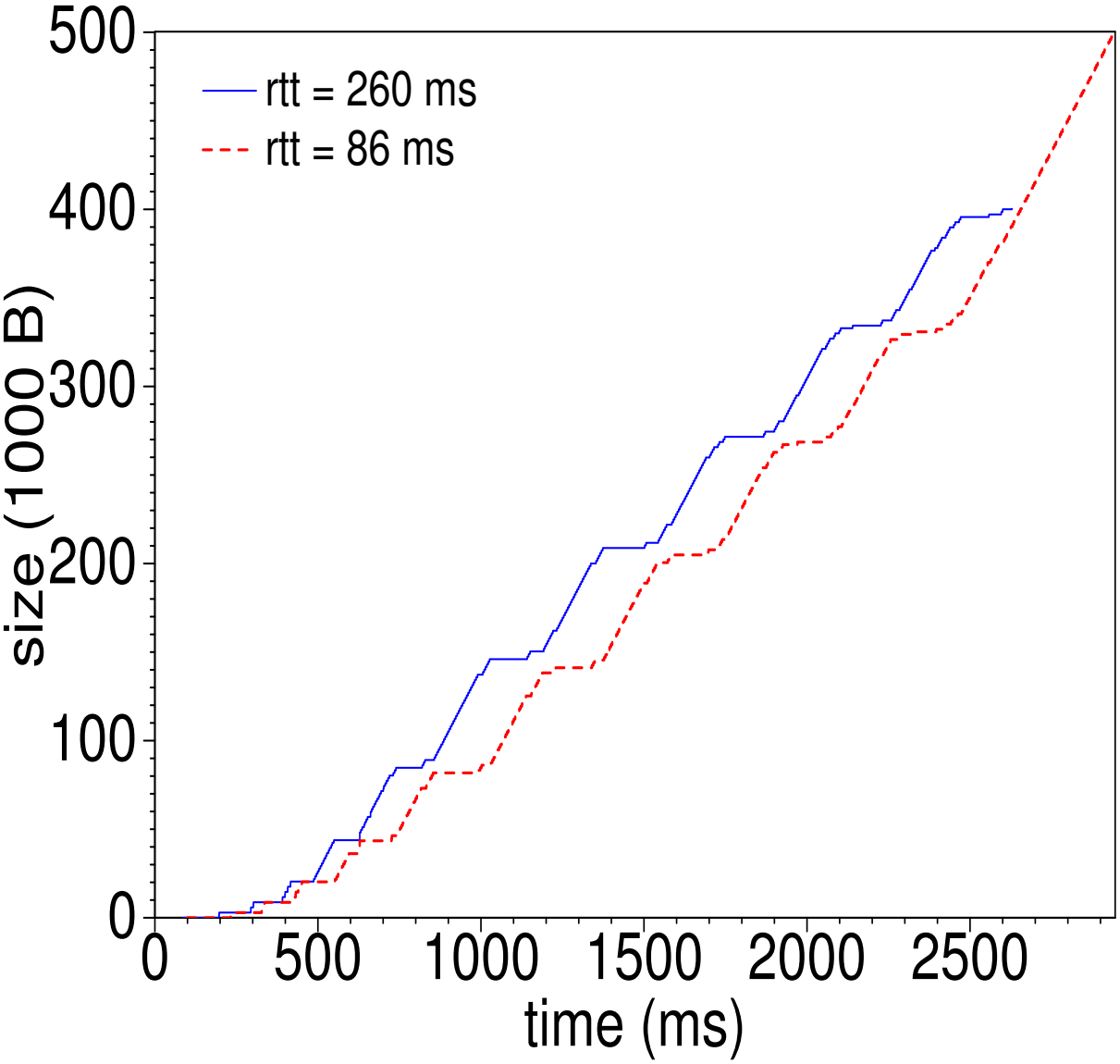
- $rtt_1 = rtt_2 = 200$ ms.
- $ss_1 = 80$.
- $ss_2 = 40$.
- $throughput \sim$ queue residency.
- When one ends, the other takes over.

Periodic sharing



- Random delays obscure periodic behavior.
- Hard to identify PS from measurements.

Periodic sharing

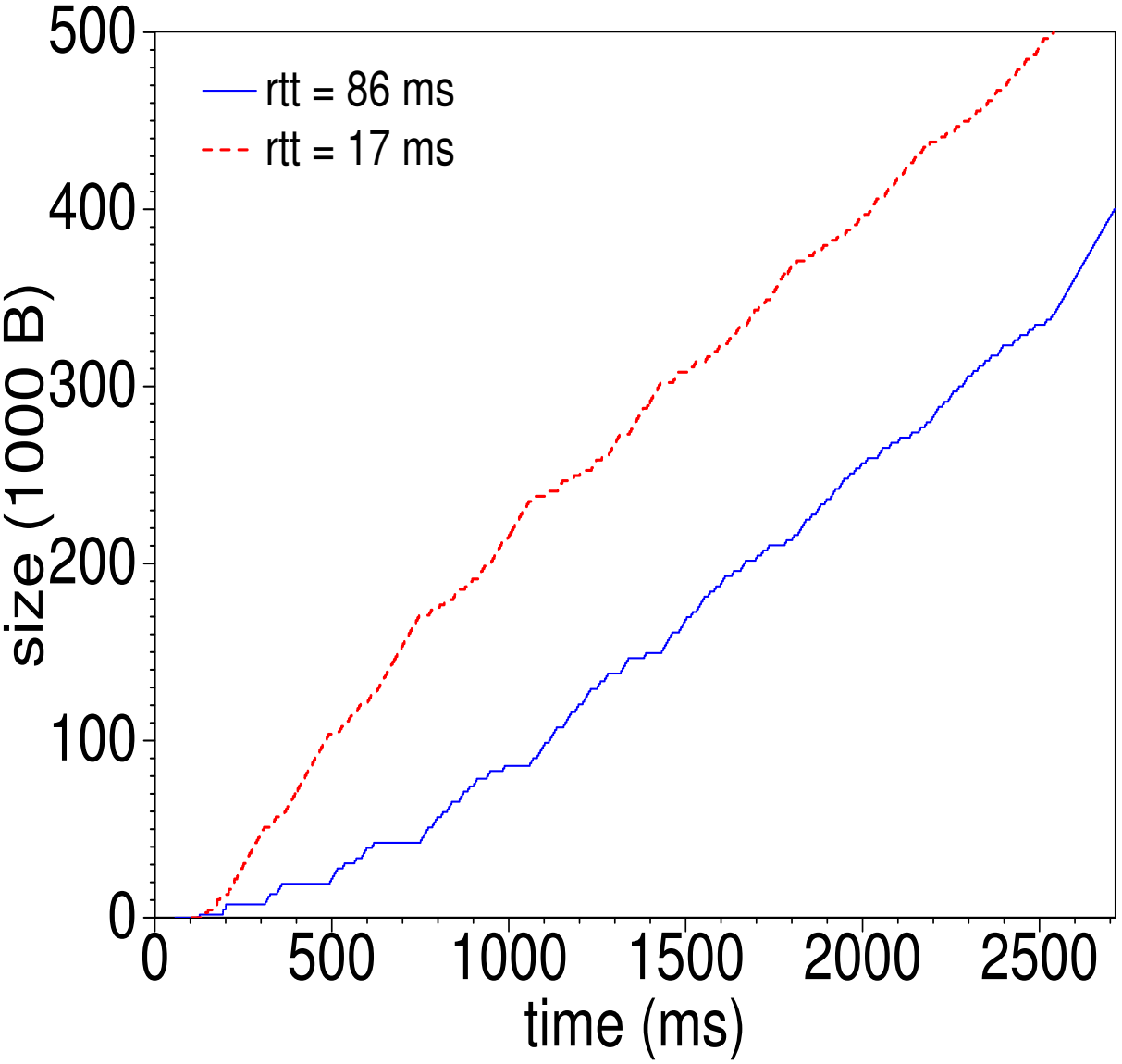


- But some measurements show unambiguous PS.
- Even with different rtt.

Measuring PS

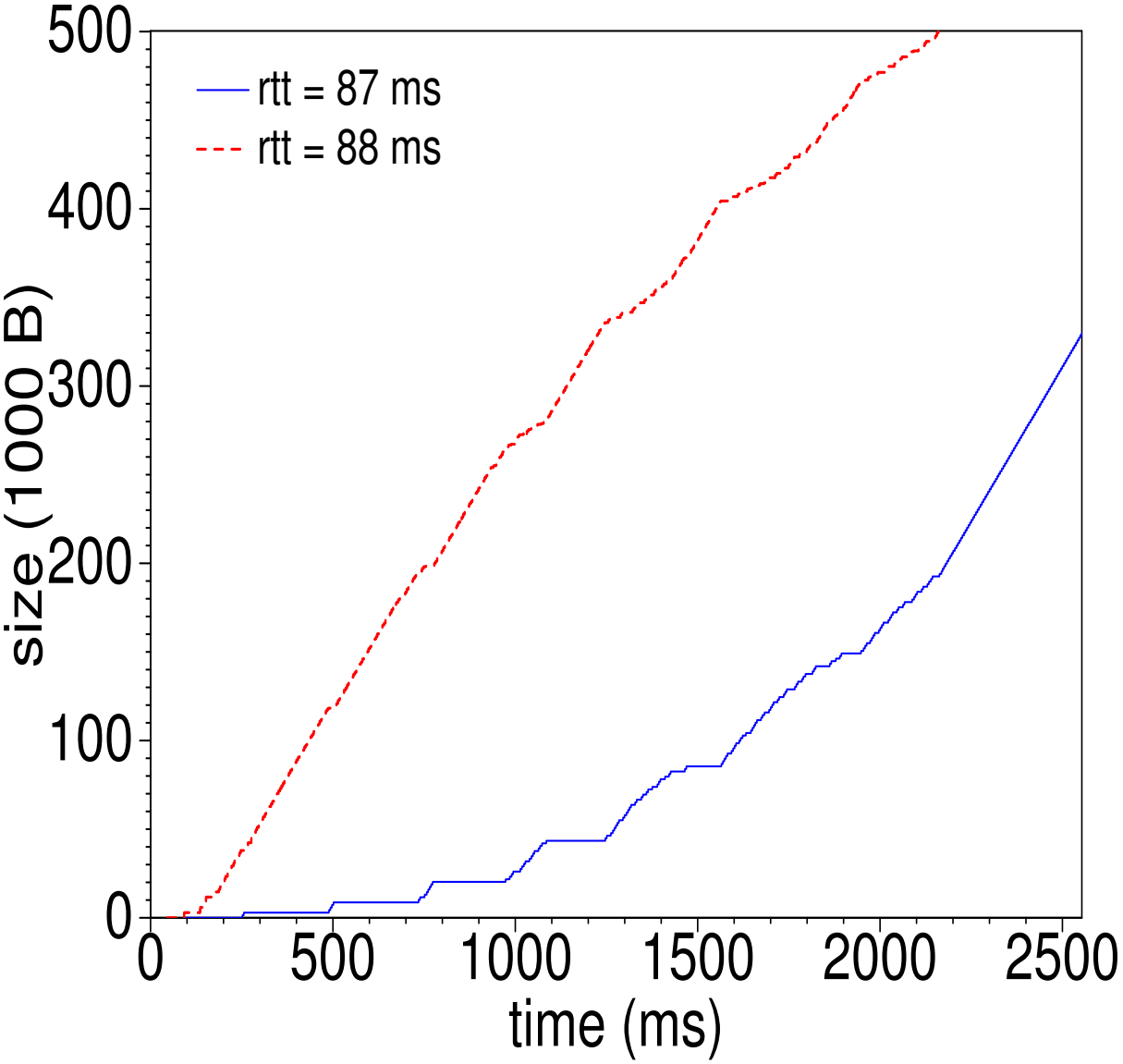
- Find 25 busy Web sites with very large files.
- Choose 2 at random and initiate simultaneous downloads.
- Run 100 pairs.
- Classify timing charts (visual and statistical).

Periodic sharing



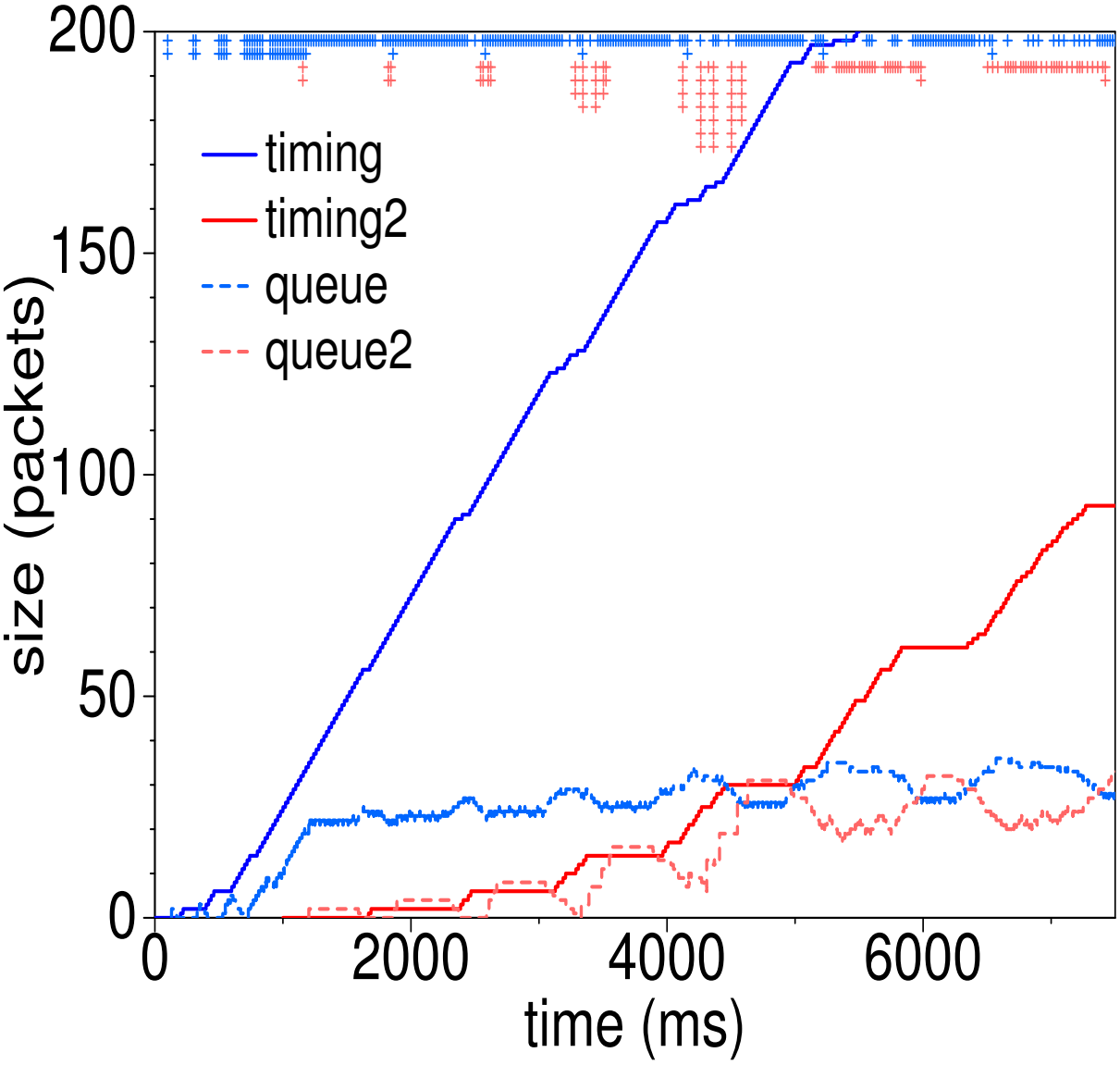
- Very different rtt.
- Same throughput.
- Characteristic scalloping.
- When one ends, the other takes over.

Periodic sharing



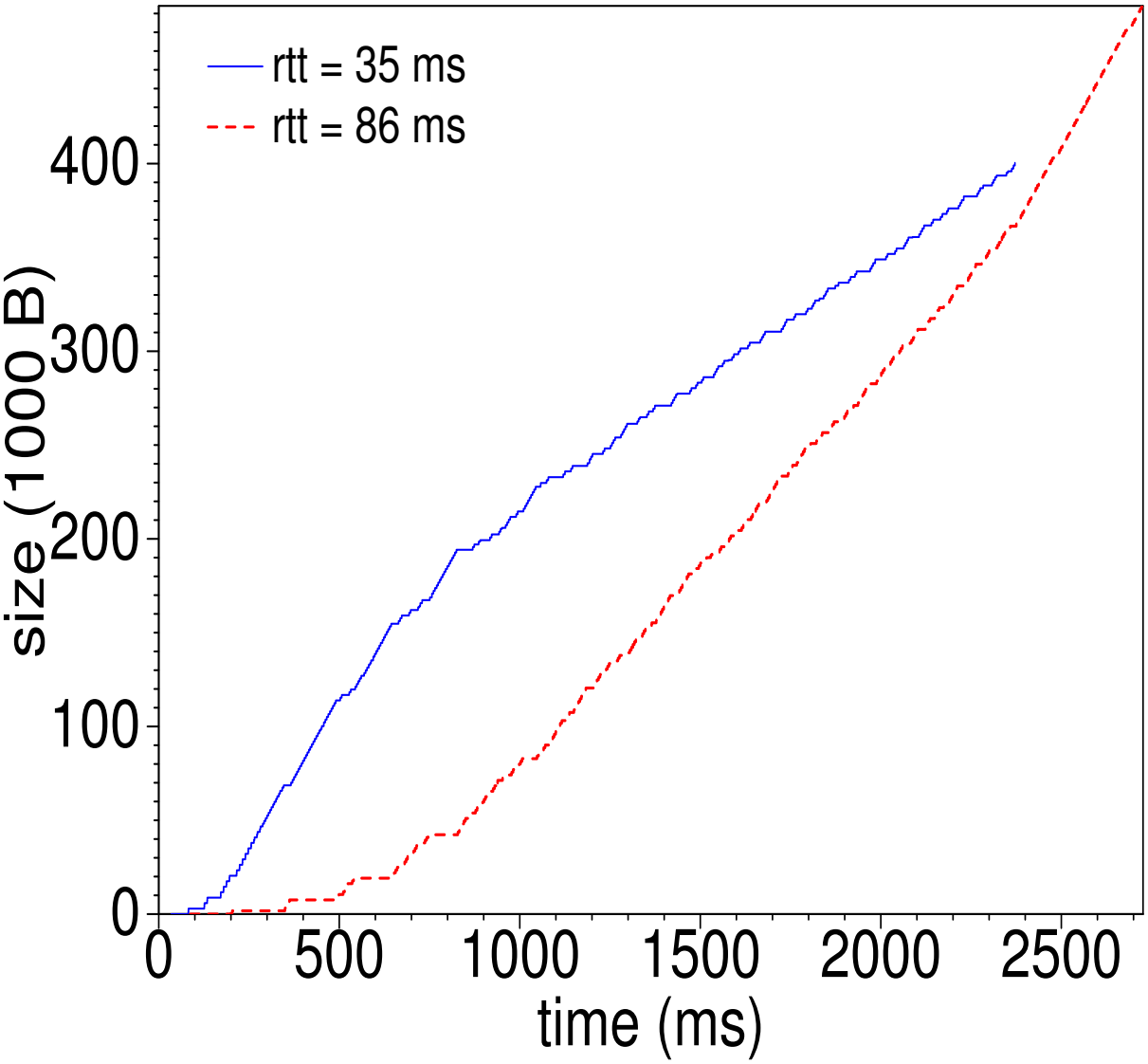
- Same rtt.
- Second transfer to start is delayed by the queue induced by the first...

Periodic sharing



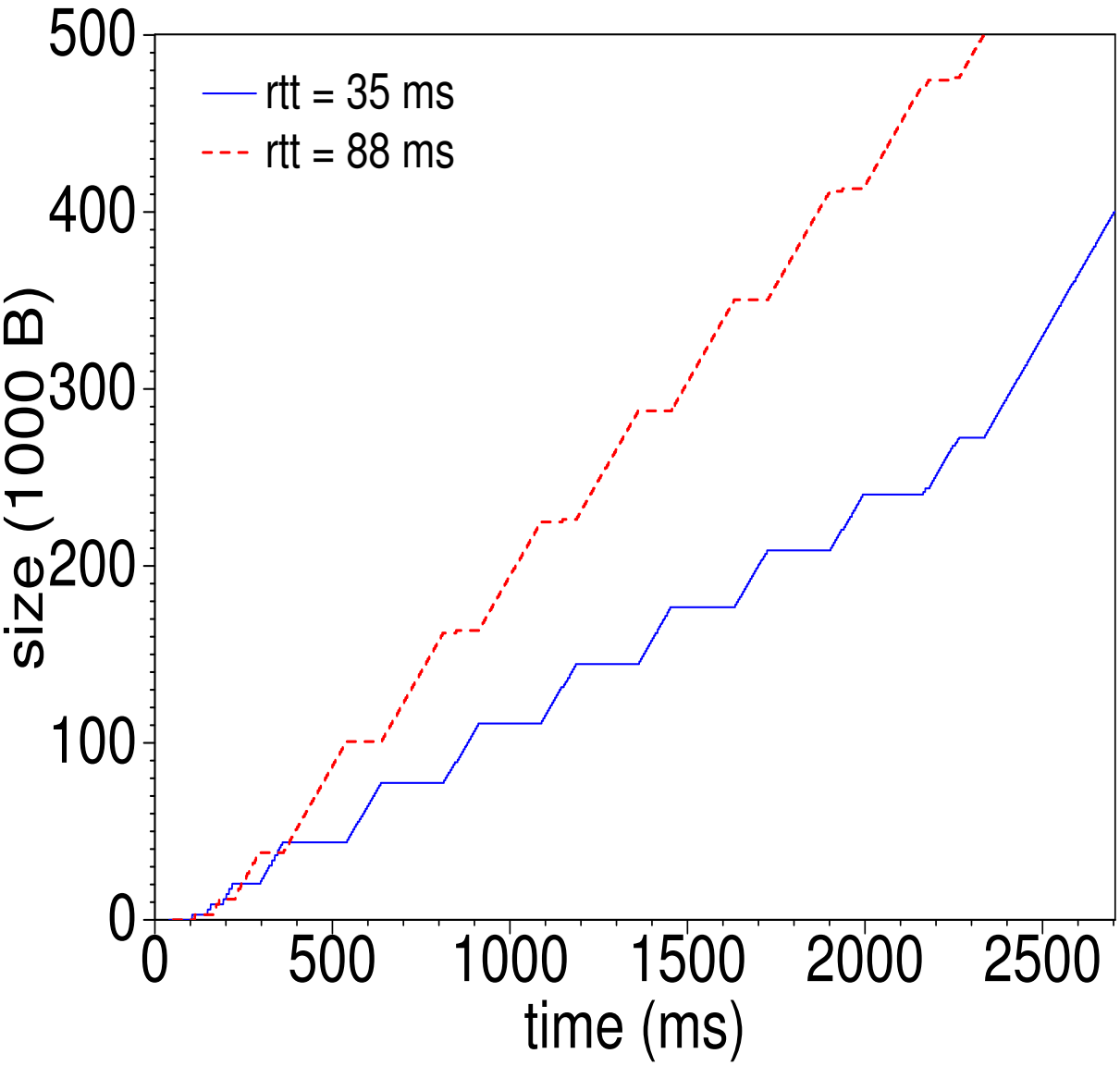
- ... as predicted by the model.
- Connections share the bottleneck bw in proportion to queue residency.

Periodic sharing



- Faster rtt, earlier start, lower throughput?

Periodic sharing



- Alone, both servers reach SC.
- In PS, their queue residency is limited by the send buffer.

Periodic sharing

- Of 100 pairs, 3 don't overlap and 6 don't share a bottleneck.
- 68 of the remaining 93 cases (75%) show clear PS.
- Another 11 cases show aperiodic queue sharing.
- In 12 cases, one of the connections is in CA.

Results

- For hosts behind slow links, SC is common.
- Even for well-connected hosts, SC happens.
- PS is a common mode of bandwidth sharing (at least for low bdp paths).

Eight Things

Eight things we know about TCP.

1. During slow start, cw grows exponentially.
   cw grows exponentially until $cw > bdp$,
   then it grows linearly until $cw > ssthresh$.

2. In steady state, cw grows linearly between drops.
   In SC, cw grows as $\sqrt{t}$.

Eight Things

3. When cw exceeds bdp, packets get dropped.
   cw can exceed bdp for a long time without overflowing the buffer at the bottleneck.

4. After a drop, TCP decreases the send rate.
   In SC the sender might pause, then resume at higher rate.

Eight Things

5. Steady-state behavior for long transfers is AIMD.
   On many paths, the most common steady-state behavior is SC, which is neither AI nor MD.

6. In steady state, $throughput \sim 1/\sqrt{p}$.
   For low drop rates, throughput is less sensitive to p.

Eight Things

7. When connections share a bottleneck, $throughput \sim 1/rtt$.
   In PS, connections share in proportion to queue residency, which depends on start time, $ssthresh$ and send/receive buffers.

8. TCP is slow to discover increased available capacity.
   By keeping excess packets in queue, connections absorb capacity instantly.

Discussion

Is self-clocking a good thing?

- SC does most of what TCP Vegas tries to do.
- Persistent queues make long transfers robust...
- ... but they are a disaster for latency.

Discussion

- $ssthresh$ affects bandwidth sharing!
- If $ssthresh = bdp$, then $throughput \sim rtt$.
- $ssthresh$ arms race?

Discussion

- Send and receive buffers affect bandwidth sharing!
- Buffer arms race?

Thanks

- Most of this work done at BU.
- Thanks to John Byers, Dhiman Barman and others.
- More at `allendowney.com/research/tcp`