BBR Congestion Control: Fundamentals and Updates

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https://groups.google.com/d/forum/bbr-dev

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Google

Outline

- BBRv1
- BBRv2
- BBRv3
- Comparing Reno, CUBIC, BBRv3
- Links for further information
- Conclusion

BBRv1

Problems with loss-based congestion control

2011: many reported excessive buffering and delays on the Internet (a.k.a. bufferbloat)

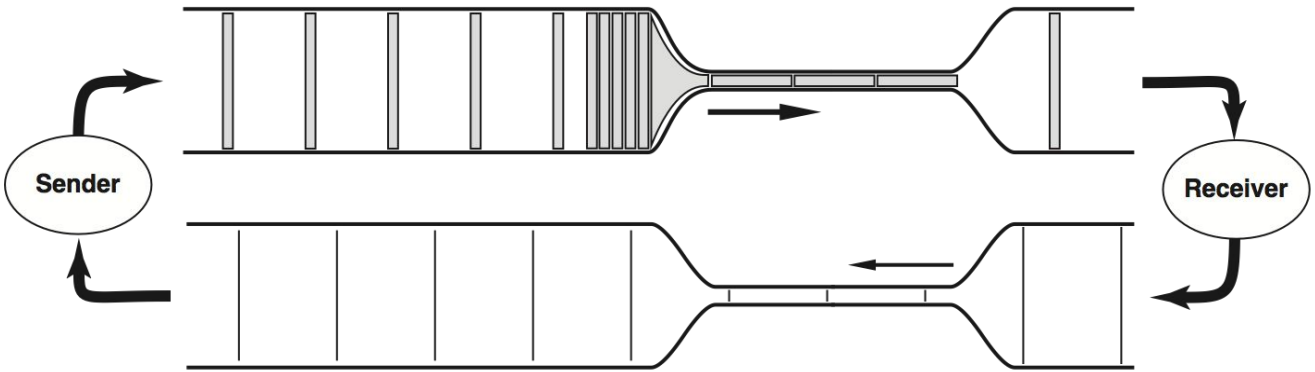
2012: single-connection HTTP/2 was much slower than multi-conn HTTP/1 on lossy links

2013: poor TCP throughput on WANs w/ commodity shallow-buffer switches

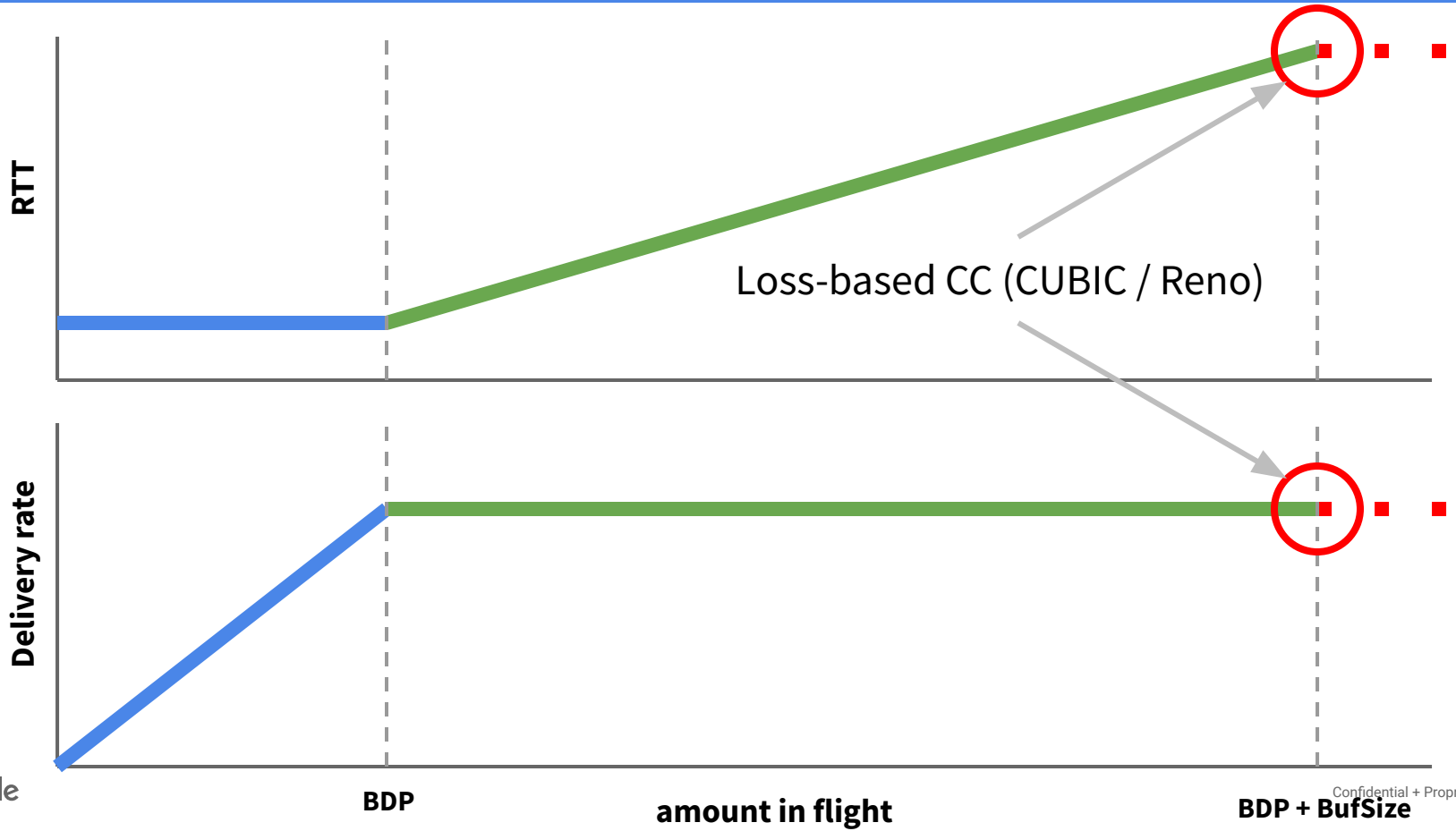
Culprit: loss-based congestion control (CC) (Reno, then CUBIC)

- Packet loss alone is **not** a good proxy to detect congestion
- Loss-based CC is overly sensitive to losses that come **before** congestion
  - 10Gbps over 100ms RTT needs <0.000003% packet loss (infeasible)
  - 1% loss (feasible) over 100ms RTT gets only 3Mbps
- Loss-based CC bloats buffers if loss comes **after** congestion

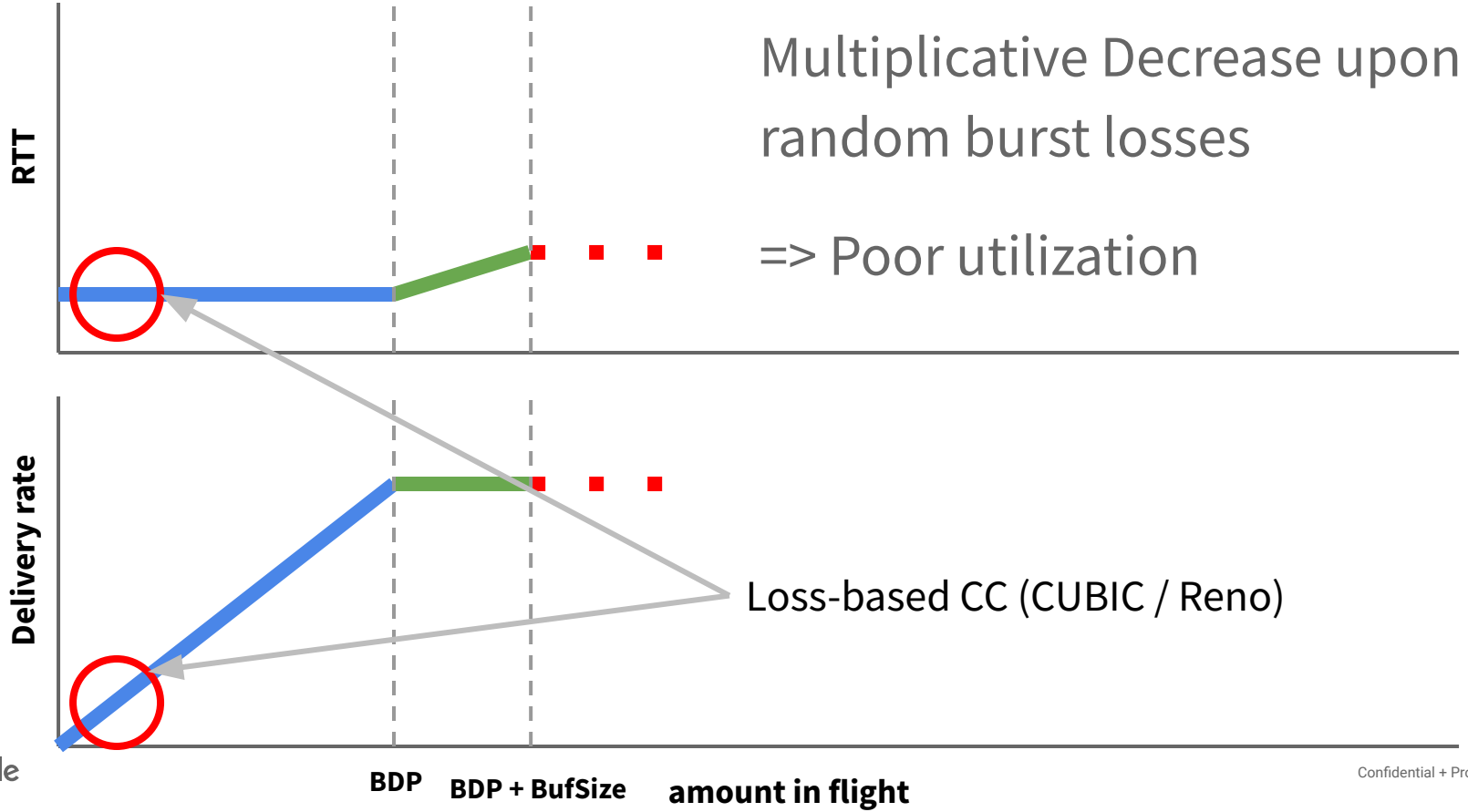
Network congestion and bottlenecks



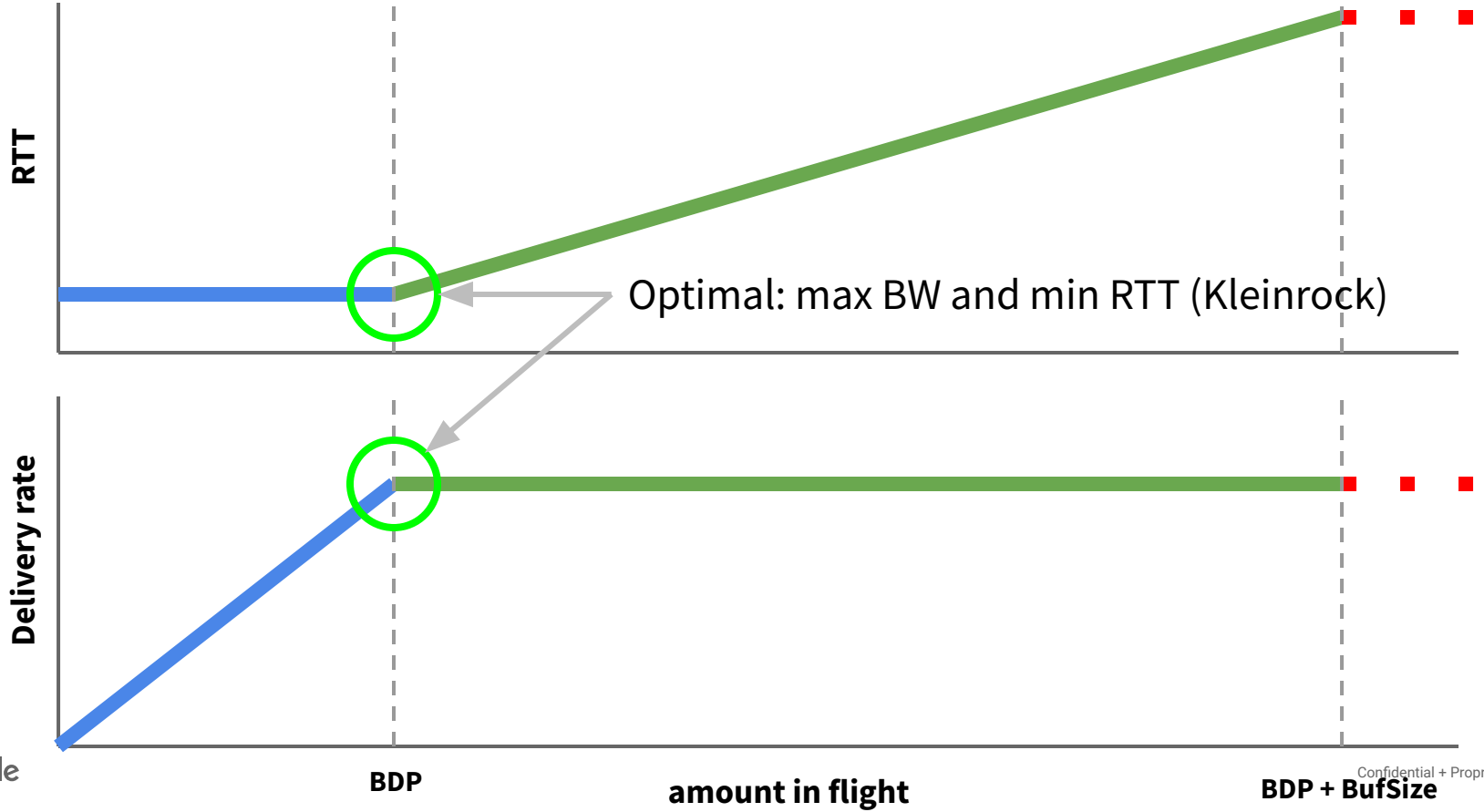
Loss-based congestion control in deep buffers



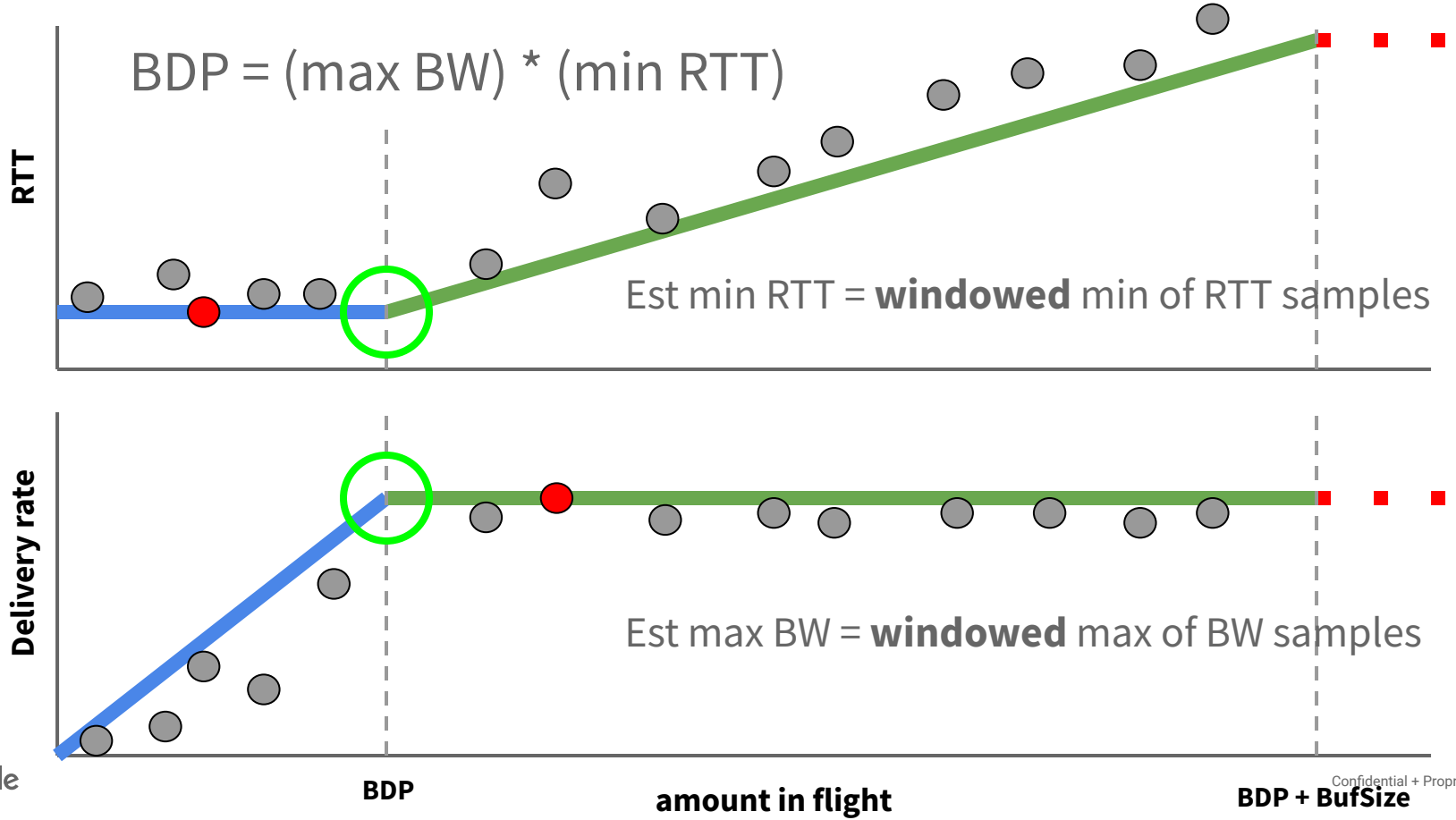
Loss-based congestion control in shallow buffers



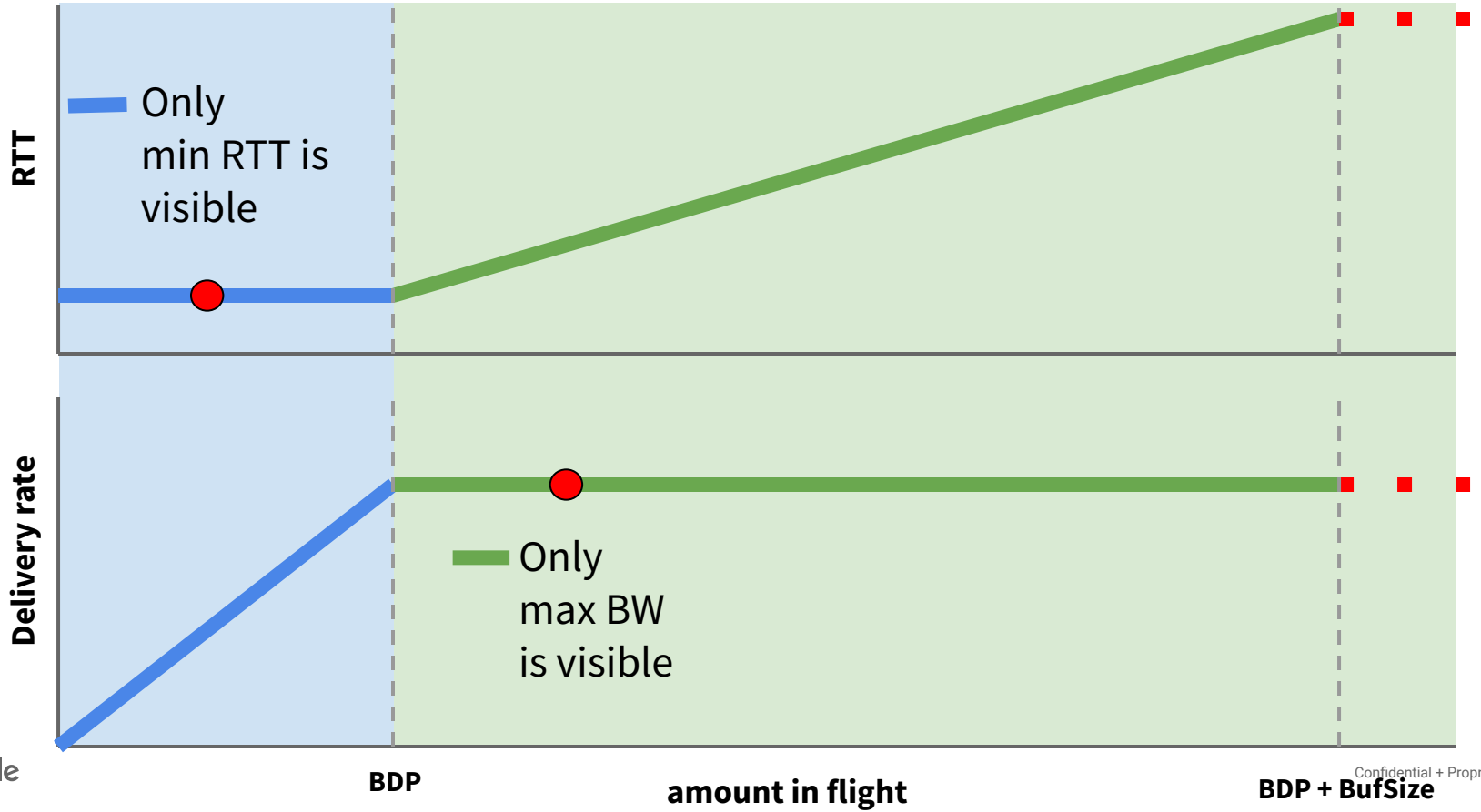
Optimal operating point



Estimating optimal point (max BW, min RTT)



To see max BW, min RTT: probe both sides of BDP



BBRv1: Design

BBR = **B**ottleneck **B**andwidth and **R**ound-trip propagation time

- Model network path
  - **Dynamically** estimate windowed max BW and min RTT on each ACK
- Control sending based on the model, to...
  - **Sequentially** probe max BW and min RTT, to feed the model samples
  - Pace near estimated BW
  - Vary pacing rate to keep inflight near BDP
- Seek high throughput with a small queue
  - Approaches maximum available throughput for random losses up to 15%
  - Maintains small queue independent of buffer depth

Evolution of BBR

BBR v2 [2019]: what's new?

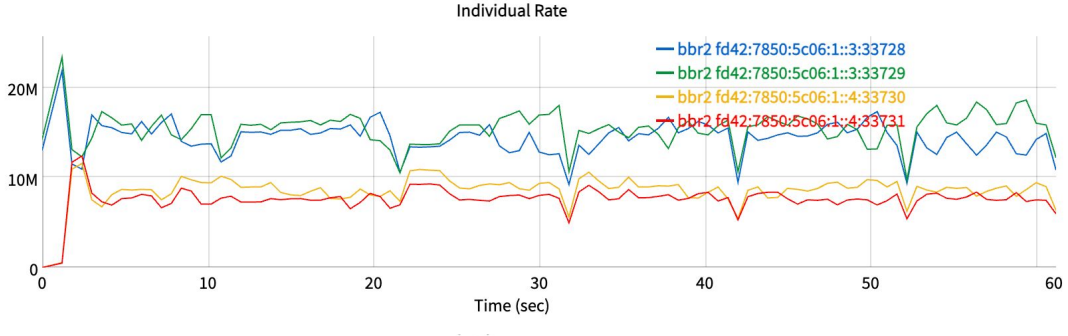
- Properties maintained between BBR v1 and BBR v2:
  - High throughput with a targeted level of random packet loss
  - Bounded queuing delay, despite bloated buffers
- Improvements from BBR v1 to BBR v2:
  - Improved coexistence when sharing bottleneck with Reno/CUBIC
  - Much lower loss rates for cases where bottleneck buffer < 1.5*BDP
  - High throughput for paths with high degrees of aggregation (e.g. wifi)
  - Responds to DCTCP/L4S-style ECN signals
  - Vastly reduced the throughput reduction in PROBE_RTT
- Following are a few tests, to illustrate the core properties maintained and improved...
  - Metrics we're evaluating in these:
    - throughput, queuing latency, retransmit rate, fairness

BBR v3 [2023]: what's new?

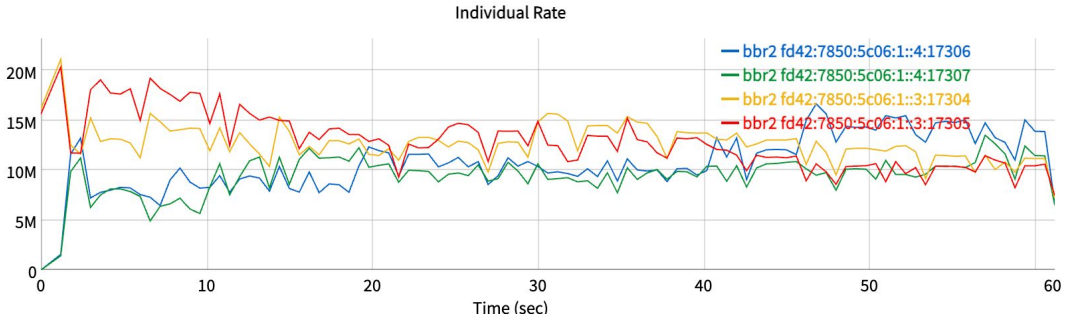
- BBR v3 is a minor evolution of BBR v2, with two areas of improvement:
  - 1: Bug fixes
    - Bandwidth convergence **with** loss and/or ECN marks
    - Bandwidth convergence **without** loss or ECN marks
  - 2: Performance tuning

BBR v3 bug fix 1: fix bw convergence *with* loss/ECN

Before bug fix 1:



After bug fix 1:



Example test results from:

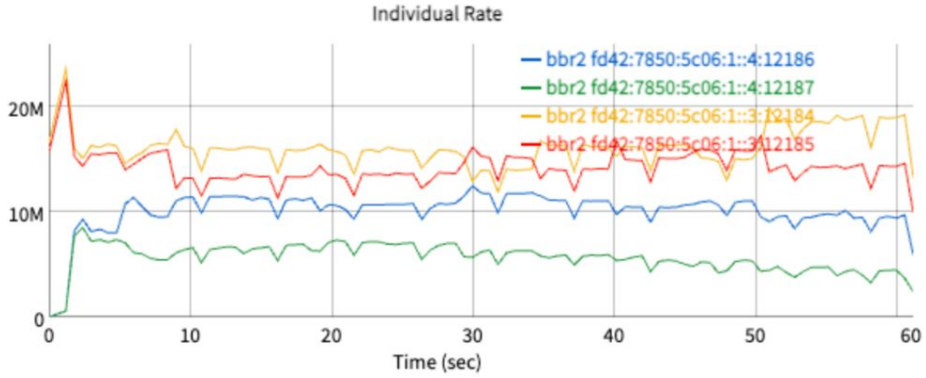
transperf bulk TCP transfer test with 4 TCP BBRv3 flows with

bottleneck_bw=50Mbps, min_rtt=40ms, **buffer=1*BDP**

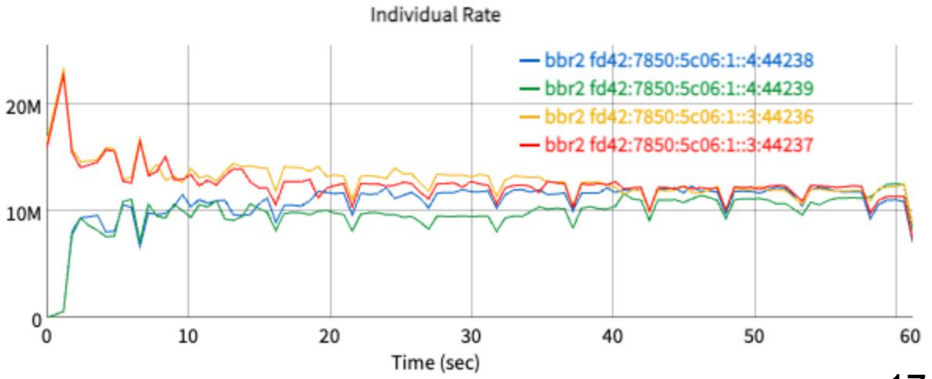
(at t=0s flows 0, 1 start; at t=1s flows 2, 3 start)

BBR v3 bug fix 2: fix bw convergence *without* loss/ECN

Before bug fix 2:



After bug fix 2:



Example test results from:

transperf bulk TCP transfer test with 4 TCP BBRv3 flows with

bottleneck_bw=50Mbps, min_rtt=40ms, **buffer=100*BDP**

(at t=0s flows 0, 1 start; at t=1s flows 2, 3 start)

BBR v3 performance tuning

- Performance tuning changes:
  - STARTUP cwnd gain: 2.89 => 2.0 [analytic derivation]
  - STARTUP pacing gain: 2.89 => 2.77 [analytic derivation]
  - When exiting STARTUP, set inflight_hi based on:
    - max(estimated BDP, max number of packets delivered in last round trip)
  - To trigger exit of STARTUP based on packet loss...
    - Require fewer loss events in a single round trip (6 rather than 8)
- Primary impact of these changes:
  - Lower queuing delays and packet loss rates during and shortly after STARTUP

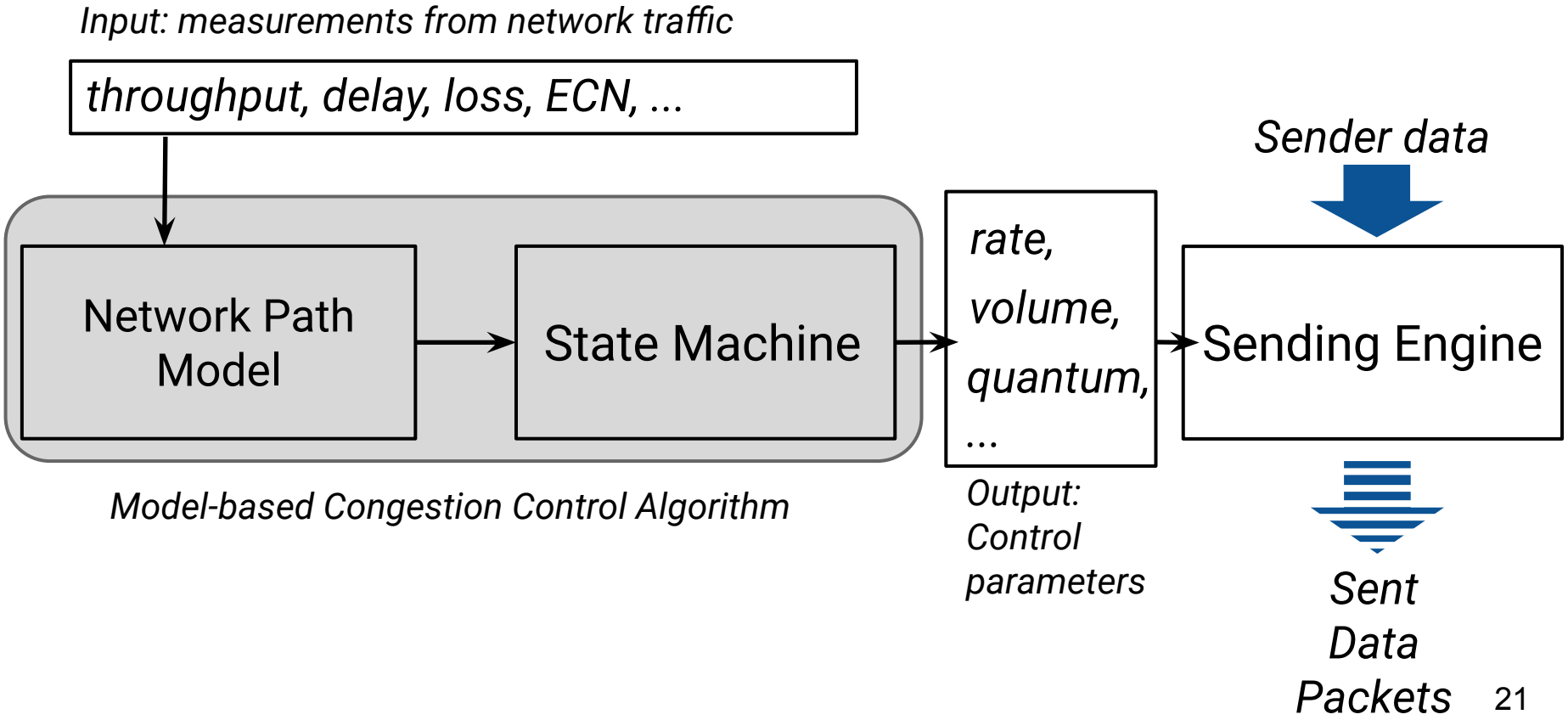
BBR v3 Properties

- BBR v3 properties:
  - Full throughput, with up to 1% random loss
  - Low queue delay, despite bloated buffers of any depth
  - Low queuing latency and loss using DCTCP/L4S-style ECN signals
  - Coexistence with usable throughput for CUBIC/Reno in the most common Internet and Datacenter scenarios

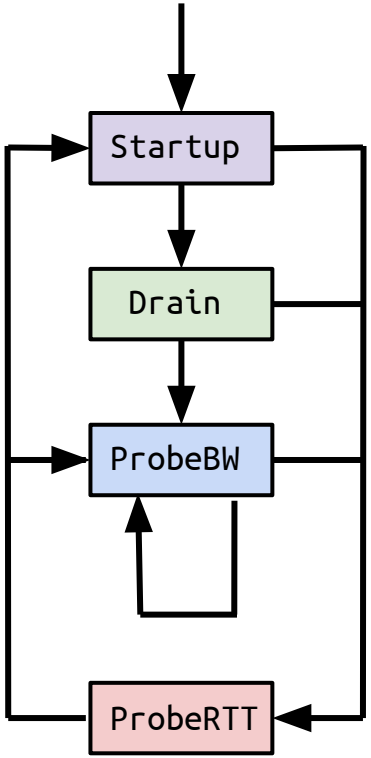
Evolution of BBR: a summary

	CUBIC	BBR v1	BBR v3
Model parameters to the state machine	N/A	Throughput, RTT	Throughput, RTT, max aggregation, max inflight
Loss	Reduce cwnd by 30% on window with any loss	N/A	Explicit loss rate ceiling of 2%
ECN	RFC3168 (Classic ECN)	N/A	DCTCP-inspired ECN
Startup	Slow-start until RTT rises (Hystart) or any loss	Slow-start until tput plateaus	Slow-start until throughput plateaus or ECN/loss rate > target

BBR v3 congestion control: the big picture

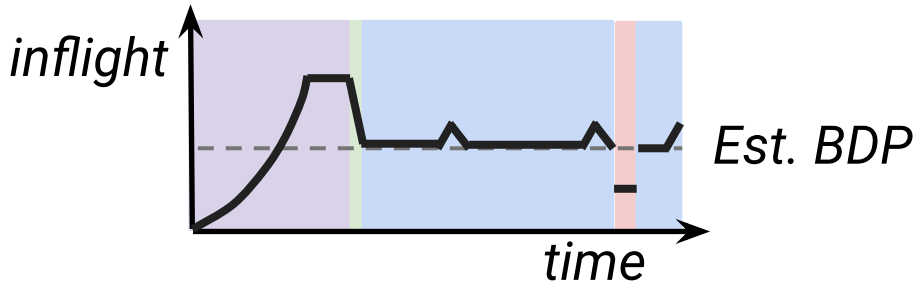


BBR: the state machine



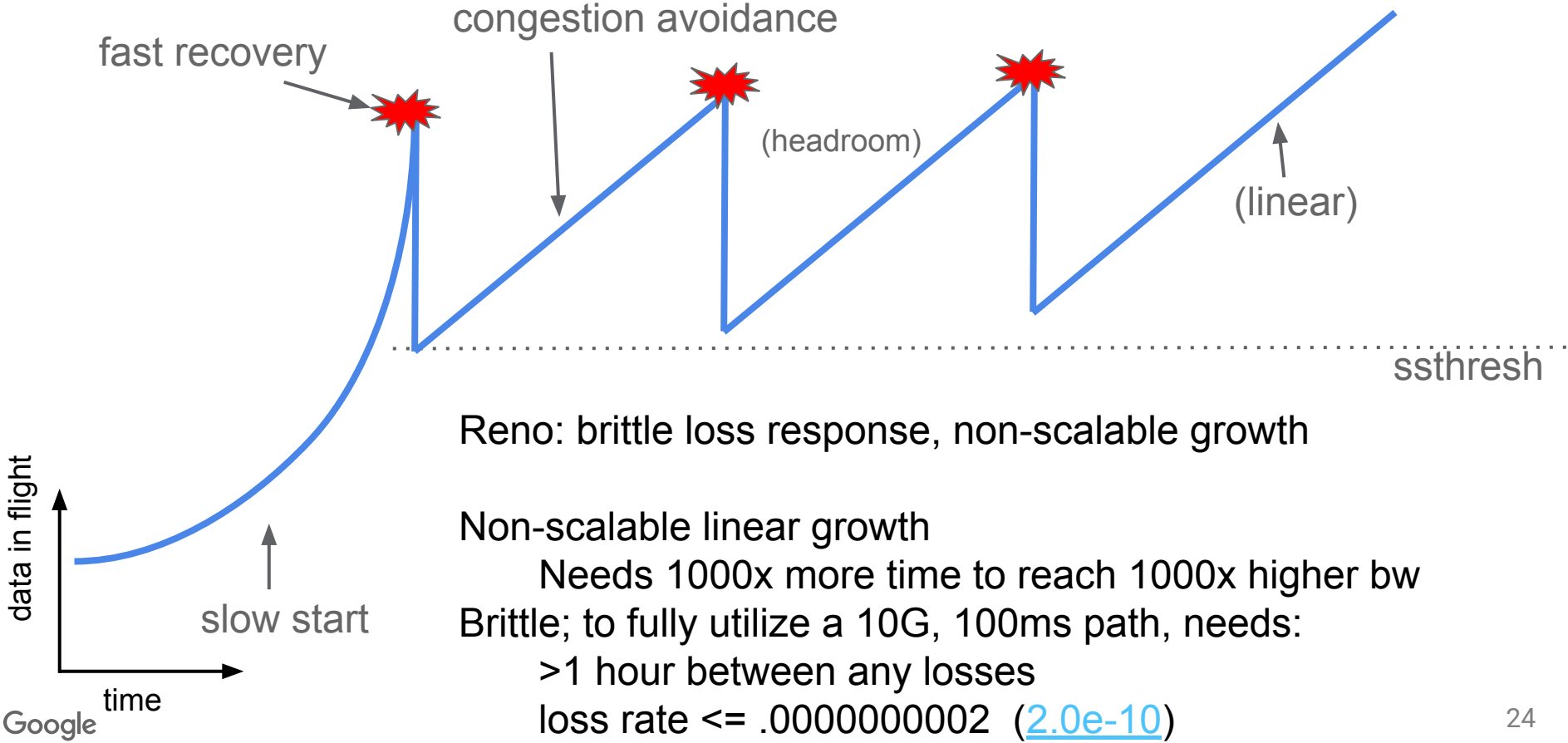
State machine uses 2-phase sequential probing of bw, RTT

- 1: raise inflight to probe BtlBw, get high throughput
- 2: lower inflight to probe RTprop, get low delay
- At two different time scales: warm-up, steady state...
- Warm-up:
  - Startup: ramp up quickly until we estimate pipe is full
  - Drain: drain the estimated queue from the bottleneck
- Steady-state:
  - ProbeBW: cycle pacing rate to vary inflight, probe BW
  - ProbeRTT: if needed, a coordinated dip to probe RTT



Congestion Control algorithms: a comparison

Reno



Reno: brittle loss response, non-scalable growth

Non-scalable linear growth

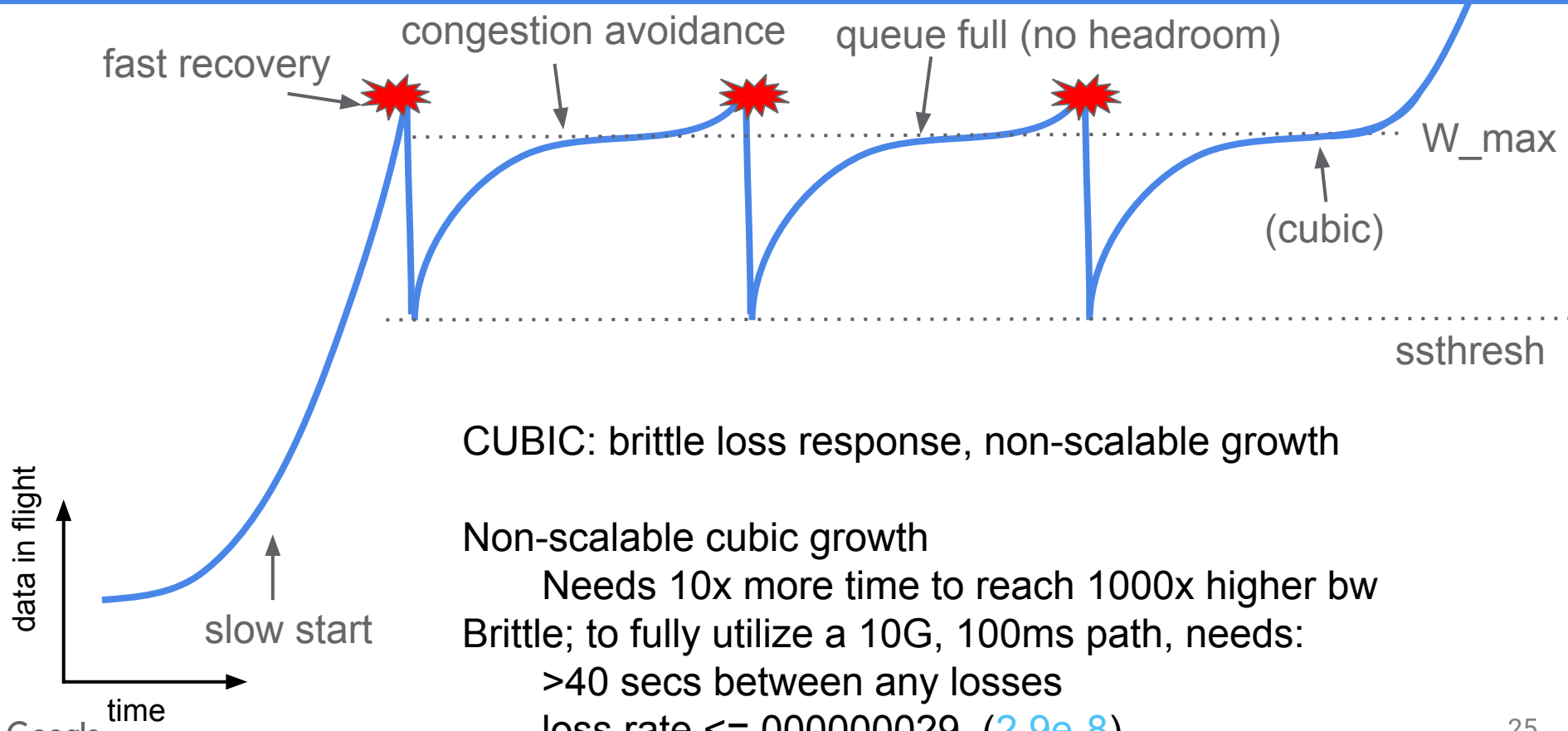
Needs 1000x more time to reach 1000x higher bw

Brittle; to fully utilize a 10G, 100ms path, needs:

>1 hour between any losses

loss rate <= .0000000002 (2.0e-10)

CUBIC



CUBIC: brittle loss response, non-scalable growth

Non-scalable cubic growth

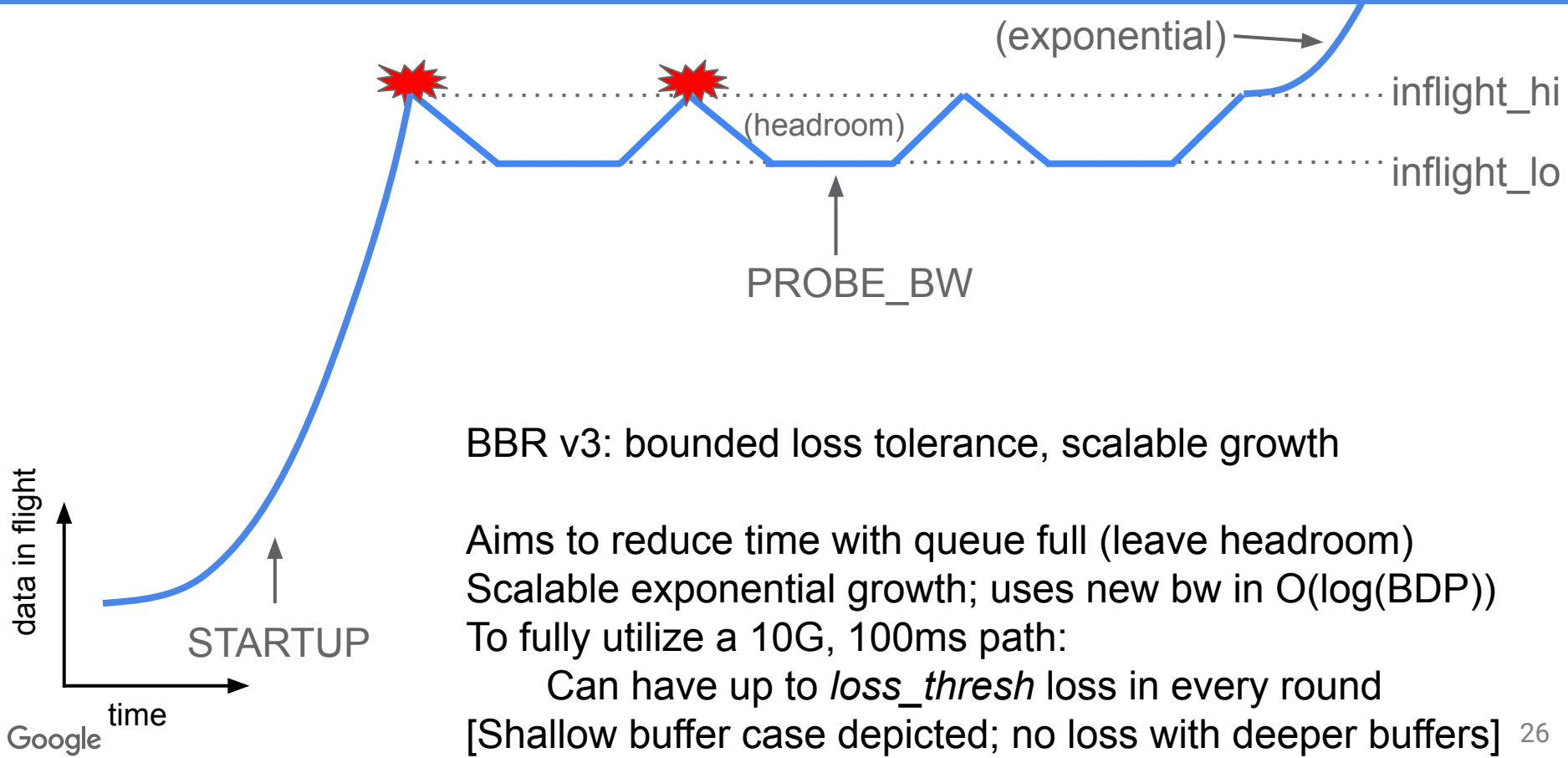
Needs 10x more time to reach 1000x higher bw

Brittle; to fully utilize a 10G, 100ms path, needs:

>40 secs between any losses

loss rate <=.000000029 (2.9e-8)

BBR v3



BBR v3: bounded loss tolerance, scalable growth

Aims to reduce time with queue full (leave headroom)
Scalable exponential growth; uses new bw in O(log(BDP))
To fully utilize a 10G, 100ms path:
Can have up to *loss_thresh* loss in every round
[Shallow buffer case depicted; no loss with deeper buffers]

Current Status of BBR

BBR deployment status at Google

- Google-internal traffic:
  - **BBRv3** is TCP congestion control for all internal **WAN traffic**
  - BBR.Swift is TCP congestion control used **within a datacenter**
- Google-external traffic:
  - **BBRv3** is TCP congestion control for all Google.com public Internet traffic
  - A/B experiments: BBRv3 vs BBRv1 for small % of users for:
    - TCP for YouTube
    - QUIC for google.com and YouTube

BBRv3 performance impact for public Internet traffic

- Impact of BBRv3 vs BBRv1 on Google.com and YouTube TCP public Internet traffic:
  - Lower retransmit rate (12% reduction)
  - Slight latency improvement (0.2% reduction) for:
    - Google.com web search
    - Starting YouTube video playback
  - Latency wins seem to be from lower loss rate (less/faster loss recovery)

BBR Open Source Code

- TCP BBRv3 release:
  - Linux TCP (dual GPLv2/BSD): github.com/google/bbr/blob/v3/README.md
  - Main updates: the bug fixes described earlier in this presentation
  - TCP BBR v3 release is open source (dual GPL/BSD), available for review/testing
  - Plan to email patches to propose inclusion in mainline Linux TCP
- BBRv1 code in Linux TCP "bbr" module will be upgraded to BBRv3
- Why upgrade BBRv1->BBRv3 in place rather than a separate module? BBRv3 has...
  - Better coexistence with Reno/CUBIC, vs v1
  - Lower loss rates, vs v1
  - Lower latency for short web requests (from google.com, YouTube data), vs v1
  - Throughput similar to v1 (within 1% of v1 on YouTube)

How to Experiment with Linux TCP BBR

- How to enable BBR:
  - To enable manually for one-shot experimentation:
    - `sysctl net.ipv4.tcp_congestion_control=bbr`
  - To enable every time a machine boots:
    - Add to /etc/sysctl.conf (Ubuntu, Debian, RedHat, CentOS):
      - `net.ipv4.tcp_congestion_control=bbr`
      - `net.core.default_qdisc=fq`
- BBRv1 for TCP:
  - In mainline Linux (since v4.9 in Dec 2016)
- BBRv3 for TCP:
  - On github: **github.com/google/bbr/blob/v3/README.md**
- Pacing options:
  - Preferred: **fq** qdisc: implements pacing and fair queuing
  - If **fq** is not present, BBR uses TCP-layer pacing (usable since v4.20 in Dec 2018)

Conclusion

- Summary:
  - Open sourced BBRv3 on github with significant bug fixes vs BBRv2
  - BBRv3 used for all TCP for Google.com public Internet and internal WAN traffic
  - BBRv3 under A/B testing for YouTube TCP, YouTube and Google.com QUIC
- Next:
  - Plan on submitting BBRv3 for inclusion in mainline Linux TCP
  - Will update BBR Internet Drafts to cover BBRv3:
    - Delivery rate estimation: draft-cheng-iccrg-delivery-rate-estimation
    - BBR Congestion control: draft-cardwell-iccrg-bbr-congestion-control
- We invite the community to share…
  - Feedback on the algorithm, code, or drafts
  - Test results, issues, patches, or ideas
- Thanks!

Q & A

https://groups.google.com/d/forum/bbr-dev

Internet Drafts, paper, code, mailing list, talks, etc.

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