BBR v2: A Model-based Congestion Control Performance Optimizations

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

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● BBR v2 performance optimizations
● Status of the BBR v2 code and Google deployment
● Conclusion
BBR v2 performance optimizations
BBR v2 performance optimizations: goals

(1) Ensure BBRv2 is suitable as a general-purpose CC for LAN, WAN, datacenter, VM guest
   ○ And as a drop-in replacement for Reno, CUBIC, DCTCP...
     ■ Yields performance improvements across these environments
     ■ Has suitable coexistence behavior with Reno, CUBIC

(2) As a stepping stone to (1), deploy BBRv2 for all TCP/QUIC traffic at Google

(3) To prepare for (2), test BBRv2 host and network performance
   ○ Ensure it exceeds or approximately matches the preceding TCP/QUIC CC algorithms used at Google and widely deployed elsewhere:
     ■ e.g. Reno, CUBIC, DCTCP
BBR v2 optimizations: summary

- All Google production kernel changes, including BBRv2 internal deployments, must pass a suite of rigorous application benchmarks
  - Wide-ranging applications: search, databases, storage, etc.
  - Metrics: CPU usage, throughput, CPU/operation, median and tail RPC latency
  - Not just small/simple bulk transfer dumbbell tests, throughput, loss rate, fairness

- In the production deployments of congestion control algorithms, many details matter:
  - Host-side: CPU usage, interrupt rate, data packet rate, ACK rate, offload burst size
  - Workloads: Thousands of flows per sender, and/or sharing a tiny BDP, app-limited transfers

- To handle these, implemented performance improvements for BBRv2:

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<td>to match CPU usage for Reno/CUBIC/DCTCP</td>
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<td>2: Improved TSO autosizing</td>
<td>to match CPU usage for Reno/CUBIC/DCTCP</td>
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<td>3: Faster ACKs</td>
<td>to fix an issue uncovered with Linux TCP</td>
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<td>4: Reducing queues with many flows</td>
<td>to enhance BBRv2 beyond Reno/CUBIC/DCTCP</td>
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• Much real-world traffic is app-limited: web, RPC, adaptive bit-rate video
• CUBIC/Reno/DCTCP have a de-facto fast path when processing each ACK:
  ○ if (not cwnd_limited) then return;
• Problem: BBR CPU usage, throughput regressions on some app-limited workloads
  ○ Why? BBR prioritized simplicity, so ran the entire algorithm on every ACK:
    ■ Update entire model of the network path (max_bw, min_rtt, etc.)
    ■ Update probing state machine
    ■ Adjust all control parameters: pacing rate, offload chunk size, cwnd
  ○ Caused 2-5% CPU and throughput regression vs CUBIC/DCTCP in some tests
• Solution: a BBRv2 fast path:
  ○ Only run the portions of the algorithm that are strictly needed, based on each ACK
  ○ Resolved those CPU regressions, without sacrificing throughput or latency
Core Linux TCP stack uses a TSO autosizing algorithm to adapt offload chunk size:

\[
\text{pacing\_rate} = K_{\text{scale}} \times \text{cwnd} / \text{srtt} \quad \text{// } K_{\text{scale}} = 2 \text{ in slow start; else } 1.2
\]

\[
\text{size} = \text{pacing\_rate} \times 1\text{ms} \quad \text{// chunk size is proportional to pacing rate}
\]

\[
\text{size} = \max(2 \times \text{SND.MSS}, \text{size})
\]

\[
\text{size} = \min(0xFFFF, \text{size})
\]

If the sender host is bottleneck for many flows (e.g. thousands) there's no ECN or loss

○ Thus DCTCP/CUBIC/Reno cwnd, pacing rate, and TSO chunk size can be very large
○ Thus DCTCP/CUBIC/Reno CPU usage is low for such workloads

Problem: BBR CPU use from setting pacing rate purely based on flow's bandwidth share

○ With many flows, flow's fair share is tiny, so BBR offload chunks were tiny

Solution: for BBR, adapt offload chunk size based on min_rtt as well as pacing rate:

\[
r = \min_{\text{rtt}} \gg K_{\text{r}}
\]

\[
\text{size} += 0xFFFF \gg r
\]
Linux TCP delayed ACKs
  ○ DCTCP, BBRv2 emit an ACK when incoming CE bits change
    ■ But that mechanism does not trigger under continuous CE marking
  ○ Linux TCP "ACK per 2*RCV.MSS" logic only ACKed data immediately if both:
    ■ (1) > RCV.MSS bytes received since sending last ACK, **and**
    ■ (2) Next offered receive window ≥ previous offered receive window

Problem: If receive window stops growing, this causes sender to become cwnd-limited, waiting for app read to free receive buffer space and trigger ACK
  ○ Caused 2x higher p99 RPC latency with sustained congestion in some tests

Solution: remove check (2)
  ○ Resolved these RPC latency issues
    ■ Fix applies to any congestion control interacting with a Linux TCP receiver
Linux TCP ACKs delayed due to constant receive window: An example of the problem (before the fix)

Receive window (yellow) stops growing

ACKs released only by app reads
4: Reducing queues with many flows
Standing queues with many flows sharing small BDPs

- When there are many flows and a low BDP, thus far BBRv2 (like BBRv1, DCTCP, CUBIC, Reno...) runs window-limited, and has a standing queue at the bottleneck when:
  \[\text{number_of_flows} \times \text{min_cwnd} > \text{BDP}\]  
  [Morris, "TCP Behavior with Many Flows", '97]

- Problem: in these cases there is a standing queue that is roughly:
  \[\text{queue} = \text{number_of_flows} \times \text{min_cwnd} - \text{BDP}\]
  - BBRv2 min_cwnd (aside from RTO timeout recovery) is 4 MSS
    - To avoid stop-and-wait behavior with TCP's "ACK every other packet" policy
Solution: improve use of ECN/loss signal to adapt **pacing** rate to match available bandwidth:

- Multiplicatively decrease pacing rate and in-flight data in response to ECN
  - Quickly match available bandwidth, drain queue, allow convergence toward fair
- Additively increase when ACK suggests queue is low enough (CE=0)
  - Fairness is helped by an additive component to the flow dynamics (Chiu/Jain, '89)

[Also see: SIGCOMM 2015 "TIMELY" paper]

The goal:
TCP BBR v2: pacing to scale to num_flows > BDP

- At end of each round trip with ECN marks:
  
  ```
  // alpha: EWMA of ECN mark rate
  inflight_lo = (1 - alpha*ecn_factor) * inflight_lo
  bw_lo     = (1 - alpha*ecn_factor) * bw_lo  // <- NEW
  ```

- Experimental changes (this is work in progress):
  - Reduce bw_lo multiplicatively, in proportion to EWMA ECN mark rate
    - Use ECN to adjust both rate and volume, as with loss
  - Increase ecn_factor from 0.3 to 0.5 (similar to DCTCP)
  - Decouple bw_hi from max bw sample
    - Refine bw_hi to be the maximum bw that showed tolerable ECN mark rate
    - Multiplicative cut to bw_hi if no bw sample has ECN mark rate < ecn_thresh
  - Additive increase to rate and volume of inflight data when starting bw probing:
    ```
    inflight_hi += 1pkt
    bw_hi        += 1pkt / min_rtt
    ```
TCP BBR v2: experiments with scalability

- 2 sender machines, 1 receiver machine, on the same switch
- All 3 machines have 50 Gbit/s NIC
- Switch configured for DCTCP-style marking: CE iff instantaneous queue > 80 KBytes
- N 60-second bulk netper flows split across both sender machines, to single receiver
- Metrics collected using ss:
  - throughput
  - smoothed RTT, sampled every 100ms
  - retransmission rate
  - CE rate
  - Jain fairness index
- Comparing 3 congestion control variants:
  - DCTCP: latest Linux DCTCP as of 2019-11-10, up to and including 2874c5fd2842
  - bbr2_old: baseline bbr2
  - bbr2_new: bbr2 with the experimental changes
Many flows sharing small BDPs: Experiment results
• bbr2_new has a much lower retransmission rate than DCTCP, for num_flows $\geq 320$
average RTT

- bbr2_new has a lower average RTT, for num_flows $\geq 160$
- bbr2_new has a lower 95% RTT, for num_flows >= 160
All variants have similar throughputs
ECN mark rate

- DCTCP and bbr2_new avoid saturation of the congestion experienced (CE) signal
All three variants have reasonable, though not ideal, fairness.
Wrapping up...
Performance improvements #1-4 (and some fixes) pushed to "alpha/preview" release:
  ○ Linux TCP (dual GPLv2/BSD): github.com/google/bbr/blob/v2alpha/README.md

As noted at IETF 105, BBR v2 was released in July 2019 for QUIC:
  ○ Chromium QUIC (BSD): on chromium.org in bbr2_sender.{ cc, h }

BBR v2 release is ready for research experiments
  ○ We invite researchers to share...
    ■ Ideas for test cases and metrics to evaluate
    ■ Test results
    ■ Algorithm/code ideas
  ○ Always happy to see patches or look at packet traces...

BBR v2 algorithm was described at IETF 104 [ slides | video ]
BBR v2 open source release was described at IETF 105 [ slides | video ]
YouTube: deployed for a small percentage of users
  ○ Reduced queuing delays: RTTs lower than BBR v1 and CUBIC
  ○ Reduced packet loss: loss rates closer to CUBIC than BBR v1
Internal: continuing test pilot program between and within some Google data-centers
  ○ BBRv2 being deployed as default TCP congestion control for internal Google traffic
Continuing to iterate using production experiments and lab tests
Conclusion

- Actively working on BBR v2 at Google
  - Tuning performance to enable full-scale roll-out at Google
  - Improving the algorithm to scale to larger numbers of flows
  - We invite the community to share test results, issues, patches, or ideas
- Work under way for BBR in FreeBSD TCP @ Netflix as well
- Food for thought:
  - What should KPIs (key performance indicators) for congestion control look like?
    - How to tell if CC is "doing well" in a production environment...
      - ...given dynamic traffic, routing, and topologies?
https://groups.google.com/d/forum/bbr-dev

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

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Backup slides...
BBR v1 status: deployment, release, documentation

- BBR v1 used for TCP/QUIC on Google.com/YouTube, Google WAN backbone
  - Better performance than CUBIC for web, video, RPC traffic
- BBR v1 code open source in Linux TCP (dual GPLv2/BSD), Chromium QUIC (BSD)
- BBR v2 preview code available: Linux TCP (dual GPLv2/BSD), Chromium QUIC (BSD)
- Active BBR work under way for BBR in FreeBSD TCP @ Netflix
- BBR v1 Internet Drafts are out and ready for review/comments:
  - Delivery rate estimation: draft-cheng-iccrg-delivery-rate-estimation
  - BBR congestion control: draft-cardwell-iccrg-bbr-congestion-control
- IETF presentations: 97 | 98 | 99 | 100 | 101 | 102 | 104 (v2 design overview) | 105
- BBR v1 Overview in Feb 2017 CACM
## What's new in BBR v2: a summary

<table>
<thead>
<tr>
<th>Model parameters to the state machine</th>
<th>CUBIC</th>
<th>BBR v1</th>
<th>BBR v2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N/A</td>
<td>Throughput, RTT</td>
<td>Throughput, RTT, max aggregation, max inflight</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Loss</th>
<th>CUBIC</th>
<th>BBR v1</th>
<th>BBR v2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduce cwnd by 30% on window with any loss</td>
<td>N/A</td>
<td>Explicit loss rate target</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>ECN</th>
<th>CUBIC</th>
<th>BBR v1</th>
<th>BBR v2</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFC3168 (Classic ECN)</td>
<td>N/A</td>
<td>DCTCP-inspired ECN</td>
<td></td>
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</tbody>
</table>

<table>
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<tr>
<th>Startup</th>
<th>CUBIC</th>
<th>BBR v1</th>
<th>BBR v2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow-start until RTT rises (Hystart) or any loss</td>
<td>Slow-start until tput plateaus</td>
<td>Slow-start until tput plateaus or ECN/loss rate &gt; target</td>
<td></td>
</tr>
</tbody>
</table>
BBR congestion control: the big picture

Input: measurements from network traffic

throughput, delay, loss, ECN, ...

Network Path Model

State Machine

Model-based Congestion Control Algorithm

Output: Control parameters

Sender data

Sent Data Packets

rate, volume, quantum, ...

Sending Engine

Packets

Sent
max bw: bottleneck bandwidth available to this flow
min rtt: round-trip propagation delay
max inflight: max inflight data, based on loss/ECN
max aggregation: max measured aggregation level
BBR v2: 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 (as discussed at IETF 104 [slides | video]):
  - Improved coexistence when sharing bottleneck with Reno/CUBIC
  - Much lower loss rates for cases where bottleneck queue < 1.5*BDP
  - High throughput for paths with high degrees of aggregation (e.g. wifi)
  - Using 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