Internet Congestion Control Research Group
Internet-Draft
Intended status: Experimental
Expires: January 4, 2018

N. Cardwell
Y. Cheng
S. Hassas Yeganeh
V. Jacobson
Google, Inc
July 03, 2017

BBR Congestion Control

draft-cardwell-iccrg-bbr-congestion-control-00

Abstract

This document specifies the BBR congestion control algorithm. BBR uses recent measurements of a transport connection's delivery rate and round-trip time to build an explicit model that includes both the maximum recent bandwidth available to that connection, and its minimum recent round-trip delay. BBR then uses this model to control both how fast it sends data and the maximum amount of data it allows in flight in the network at any time. Relative to loss-based congestion control algorithms such as Reno [RFC5681] or CUBIC [draft-ietf-tcpm-cubic], BBR offers substantially higher throughput for bottlenecks with shallow buffers or random losses, and substantially lower queueing delays for bottlenecks with deep buffers (avoiding "bufferbloat"). This algorithm can be implemented in any transport protocol that supports packet-delivery acknowledgment (thus far, open source implementations are available for TCP [RFC793] and QUIC [draft-ietf-quic-transport-00]).

Status of This Memo

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

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1. Introduction

The Internet has largely used loss-based congestion control algorithms like Reno ([Jac88], [Jac90], [WS95] [RFC5681]) and CUBIC ([HRX08], [draft-ietf-tcpm-cubic]), which assume that packet loss is equivalent to congestion. These algorithms worked well for many years, not due to first principles but rather because Internet switches' and routers' queues were generally well-matched to the bandwidth of Internet links. As a result, queues tended to fill up and drop excess packets close to the moment when senders had really begun sending data too fast.

But packet loss is not equivalent to congestion. Congestion can be thought of as a condition that occurs when a network path operates on a sustained basis with more data in flight than the bandwidth-delay product (BDP) of the path. As the Internet has evolved, loss-based congestion control is increasingly problematic because packet loss increasingly happens at moments that are divorced from the onset of congestion:

1. Shallow buffers: in shallow buffers, packet loss happens before congestion. With today's high-speed, long-haul links employing commodity switches with shallow buffers, loss-based congestion control can result in abysmal throughput because it overreacts, multiplicatively decreasing the sending rate upon packet loss, even if the packet loss comes from transient traffic bursts (this kind of packet loss can be quite frequent even when the link is mostly idle). Because of this dynamic, it is difficult to achieve full utilization with loss-based congestion control in practice: sustaining 10Gbps over 100ms RTT needs a packet loss rate below 0.000003%, and over a 100ms RTT path a more feasible loss rate like 1% can only sustain at most 3 Mbps (no matter what the bottleneck link is capable of) [draft-ietf-tcpm-cubic].
2. Deep buffers: at bottleneck links with deep buffers, congestion happens before packet loss. At the edge of today's Internet, loss-based congestion control causes the "bufferbloat" problem, by repeatedly filling the deep buffers in many last-mile links and causing up to seconds of needless queuing delay.

The BBR congestion control algorithm takes a different approach: rather than assuming that packet loss is equivalent to congestion, BBR builds a model of the network path in order to avoid and respond to actual congestion.

The BBR algorithm has been described previously at a high level [CCGHJ16][CCGHJ17], and active work on the BBR algorithm is continuing. This document describes the current BBR algorithm in detail.

This document is organized as follows. Section 2 provides various definitions that will be used throughout this document. Section 3 provides an overview of the design of the BBR algorithm, and section 4 describes the BBR algorithm in detail, including BBR's network path model, control parameters, and state machine. Section 5 describes the implementation status, section 6 describes security considerations, section 7 notes that there are no IANA considerations, and section 8 closes with Acknowledgments.

2. Terminology

This document defines the following state variables and constants for the BBR algorithm:

BBR.pacing_rate: The current pacing rate for a BBR flow, which controls inter-packet spacing.

BBR.send_quantum: The maximum size of a data aggregate scheduled and transmitted together.

cwnd: The transport sender's congestion window, which limits the amount of data in flight.

BBR.BtlBw: BBR's estimated bottleneck bandwidth available to the transport flow, estimated from the maximum delivery rate sample in a sliding window.

BBR.BtlBwFilter: The max filter used to estimate BBR.BtlBw.

BtlBwFilterLen: A constant specifying the length of the BBR.BtlBw max filter window for BBR.BtlBwFilter, BtlBwFilterLen is 10 packet-timed round trips.

BBR.RTprop: BBR's estimated two-way round-trip propagation delay of the path, estimated from the windowed minimum recent round-trip delay sample.

BBR.rtprop_stamp: The wall clock time at which the current BBR.RTProp sample was obtained.

BBR.rtprop_expired: A boolean recording whether the BBR.RTprop has expired and is due for a refresh with an application idle period or a transition into ProbeRTT state.

RTpropFilterLen: A constant specifying the length of the RTProp min filter window, RTpropFilterLen is 10 secs.

BBR.pacing_gain: The dynamic gain factor used to scale BBR.BtlBw to produce BBR.pacing_rate.

BBR.cwnd_gain: The dynamic gain factor used to scale the estimated BDP to produce a congestion window (cwnd).

BBRHighGain: A constant specifying the minimum gain value that will allow the sending rate to double each round (2/ln(2) ~= 2.89), used in Startup mode for both BBR.pacing_gain and BBR.cwnd_gain.

BBR.filled_pipe: A boolean that records whether BBR estimates that it has ever fully utilized its available bandwidth ("filled the pipe").

BBRMinPipeCwnd: The minimal cwnd value BBR tries to target using: 4 packets, or 4 * SMSS

BBR.round_count: Count of packet-timed round trips.

BBR.round_start: A boolean that BBR sets to true once per packet-timed round trip, on ACKs that advance BBR.round_count.

BBR.next_round_delivered: packet.delivered value denoting the end of a packet-timed round trip.

BBRGainCycleLen: the number of phases in the BBR ProbeBW gain cycle: 8.

ProbeRTTInterval: A constant specifying the minimum time interval between ProbeRTT states: 10 secs.

ProbeRTTDuration: A constant specifying the minimum duration for which ProbeRTT state holds inflight to BBRMinPipeCwnd or fewer packets: 200 ms.

SMSS: The Sender Maximum Segment Size.

The variables starting with C, P, or rs are defined in [draft-cheng-iccrg-delivery-rate-estimation].

The keywords "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119].

3. Design Overview

3.1. Network Path Model

BBR is a model-based congestion control algorithm: its behavior is based on an explicit model of the network path over which a transport flow travels. BBR's model includes explicit estimates of two parameters:

1. BBR.BtlBw: the estimated bottleneck bandwidth available to the transport flow, estimated from the maximum delivery rate sample from a moving window.
2. BBR.RTprop: the estimated two-way round-trip propagation delay of the path, estimated from the the minimum round-trip delay sample from a moving window.

3.2. Target Operating Point

BBR uses its model to seek an operating point with high throughput and low delay. To operate near the optimal operating point, the point with maximum throughput and minimum delay [K79] [GK81], the system needs to maintain two conditions:

1. Rate balance: the bottleneck packet arrival rate equals the bottleneck bandwidth available to the transport flow.
2. Full pipe: the total data in in fight along the path is equal to the BDP.

BBR uses its model to maintain an estimate of the optimal operating point for the connection. To aim for rate balance BBR paces packets at or near BBR.BtlBw, and to aim for a full pipe it modulates the pacing rate to maintain an amount of data in flight near the estimated bandwidth-delay product (BDP) of the path, or BBR.BtlBw * BBR.RTprop.

3.3. Control Parameters

BBR uses its model to control the connection's sending behavior, to keep it near the target operating point. Rather than using a single control parameter, like the cwnd parameter that limits the volume of in-flight data in the Reno and CUBIC congestion control algorithms, BBR uses three distinct control parameters:

1. pacing rate: the rate at which BBR sends data.
2. send quantum: the maximum size of any aggregate that the transport sender implementation may need to transmit in order to amortize per-packet transmission overheads.
3. cwnd: the maximum volume of data BBR allows in-flight in the network at any time.

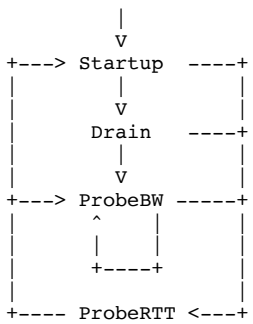
3.4. State Machine Design Overview

BBR varies its three control parameters with a simple state machine. The state machine aims for high throughput, low latency, and an approximately fair sharing of bandwidth by alternating sequentially between probing first for BBR.BtlBw and then for BBR.RTprop.

A BBR flow starts in the Startup state, and ramps up its sending rate quickly. When it estimates the pipe is full, it enters the Drain state to drain the queue. In steady state a BBR flow only uses the ProbeBW state, to periodically briefly raise inflight to probe for higher BBR.BtlBw samples, and (if needed) the ProbeRTT state, to briefly lower inflight to probe for lower BBR.RTprop samples.

3.4.1. State Transition Diagram

The following state transition diagram summarizes the flow of control and the relationship between the different states:



3.5. Algorithm Organization

The BBR algorithm executes steps upon connection initialization, upon each ACK, and upon each transmission. All of the sub-steps invoked referenced below are described below.

3.5.1. Initialization

Upon transport connection initialization, BBR executes its initialization steps:

```
BBROnConnectionInit():
  BBRInit()
```

3.5.2. Per-ACK Steps

On every ACK, the BBR algorithm executes the following BBRUpdateOnACK() steps in order to update its network path model, update its state machine, and adjust its control parameters to adapt to the updated model:

```
BBRUpdateOnACK():
  BBRUpdateModelAndState()
  BBRUpdateControlParameters()

BBRUpdateModelAndState():
  BBRUpdateBtlBw()
  BBRCheckCyclePhase()
  BBRCheckFullPipe()
  BBRCheckDrain()
  BBRUpdateRTprop()
```

```
  BBRCheckProbeRTT()

BBRUpdateControlParameters()
  BBRSetPacingRate()
  BBRSetSendQuantum()
  BBRSetCwnd()
```

3.5.3. Per-Transmit Steps

When transmitting, BBR merely needs to check for the case where the flow is restarting from idle:

```
BBROnTransmit():
  BBRHandleRestartFromIdle()
```

3.6. Environment and Usage

BBR is a congestion control algorithm that is agnostic to transport-layer and link-layer technologies, requires only sender-side changes, and does not require changes in the network. Open source implementations of BBR are available for the TCP [RFC793] and QUIC [draft-ietf-quic-transport-00] transport protocols, and these implementations have been used in production for a large volume of Internet traffic.

4. Detailed Algorithm

4.1. Maintaining the Network Path Model

As noted above, BBR is a model-based congestion control algorithm: it is based on an explicit model of the network path over which a transport flow travels. This model includes two estimated parameters: BBR.BtlBw, and BBR.RTprop.

4.1.1. BBR.BtlBw

BBR.BtlBw is BBR's estimate of the bottleneck bandwidth available to data transmissions for the transport flow. At any time, a transport connection's data transmissions experience exactly one slowest link or bottleneck. The bottleneck's delivery rate determines the connection's maximum data-delivery rate. BBR tries to closely match its sending rate to this bottleneck delivery rate to help seek "rate balance", where the flow's packet arrival rate at the bottleneck equals BBR.BtlBw. The bottleneck rate varies over the life of a connection, so BBR continually estimates BBR.BtlBw using recent delivery rate samples.

4.1.1.1. Delivery Rate Samples for Estimating BBR.BtlBw

Since calculating delivery rate samples is subtle, and the samples are useful independent of congestion control, the approach BBR uses for measuring each single delivery rate sample is specified in a separate Internet Draft [draft-cheng-iccrg-delivery-rate-estimation].

4.1.1.2. BBR.BtlBw Max Filter

Delivery rate samples tend to be below the bottleneck bandwidth available to the flow, due to "noise" introduced by random variation in physical transmission processes (e.g. radio link layer noise) or queues along the network path. Thus to filter out these effects BBR uses a max filter: BBR estimates BBR.BtlBw using the windowed maximum recent delivery rate sample seen by the connection over that past BtlBwFilterLen round trips.

The length of the BBR.BtlBw max filter window is BtlBwFilterLen = 10 round trips. This length is driven by trade-offs among several considerations:

- The BtlBwFilterLen is long enough to cover an entire ProbeBW gain cycle (see the "ProbeBW" section below). This ensures that the window contains at least some delivery rate samples that are the result of data transmitted with a super-unity pacing_gain (a pacing_gain larger than 1.0). Such super-unity delivery rate samples are instrumental in revealing the path's underlying available bandwidth even when there is noise from delivery rate shortfalls due to aggregation delays, queuing delays from cross-traffic, lossy link layers with uncorrected losses, or non-congestive buffer drops (e.g., brief coincident bursts in a shallow buffer).
- The BtlBwFilterLen aims to be long enough to cover short-term fluctuations in the network's delivery rate due to the aforementioned sources of noise. In particular, the delivery rate for radio link layers (e.g., wifi and cellular technologies) can be highly variable, and the filter window needs to be long enough to remember "good" delivery rate samples in order to be robust to such variations.
- The BtlBwFilterLen aims to be short enough to respond in a timely manner to real reductions in the bandwidth available to a flow, whether because new flows have started sharing the bottleneck, or the bottleneck link service rate has reduced due to physical changes, policy changes, or routing changes. In any of these cases, existing BBR flows traversing the bottleneck should, in a timely manner, reduce their BBR.BtlBw estimates and thus pacing rate and in-flight data, in order to match the sending behavior to the new available bandwidth.

4.1.1.3. Tracking Time for the BBR.BtlBw Max Filter

BBR tracks time for the BBR.BtlBw filter window using a virtual (non-wall-clock) time tracked by BBR.round_count, a count of "packet-timed" round-trips. BBR uses this virtual BBR.round_count because it is more robust than using wall clock time. In particular, arbitrary intervals of wall clock time can elapse due to variations in RTTs or timer delays for retransmission timeouts, causing wall-clock-timed bandwidth estimates to "time out" too quickly.

The BBR.round_count counts packet-timed round trips by recording state about a sentinel packet, and waiting for an ACK of any data packet that was sent after that sentinel packet, using the following pseudocode:

Upon connection initialization:

```
BBRInitRoundCounting():
  BBR.next_round_delivered = 0
  BBR.round_start = false
  BBR.round_count = 0
```

Upon sending each packet transmission:

```
packet.delivered = BBR.delivered
```

Upon receiving an ACK for a given data packet:

```
BBRUpdateRound():
  BBR.delivered += packet.size
  if (packet.delivered >= BBR.next_round_delivered)
    BBR.next_round_delivered = BBR.delivered
    BBR.round_count++
    BBR.round_start = true
  else
    BBR.round_start = false
```

4.1.1.4. BBR.BtlBw and Application-limited Delivery Rate Samples

Transmissions can be application-limited, meaning the transmission rate is limited by the application rather than the congestion control algorithm. This is quite common because of request/response traffic. When there is a transmission opportunity but no data to send, the delivery rate sampler marks the corresponding bandwidth sample(s) as application-limited [draft-cheng-iccrg-delivery-rate-estimation]. The BBR.BtlBw estimator carefully decides which samples to include in the bandwidth model to ensure that BBR.BtlBw reflects network limits, not application limits. By default, the estimator discards application-limited samples, since by definition they reflect application limits. However, the estimator does use application-limited samples if the measured delivery rate happens to be larger than the current BBR.BtlBw estimate, since this indicates the current BBR.BtlBw estimate is too low.

4.1.1.5. Updating the BBR.BtlBw Max Filter

For every ACK that acknowledges some data packets as delivered, BBR invokes BBRUpdateBtlBw() to update the BBR.BtlBw estimator as follows (here packet.delivery_rate is the delivery rate sample obtained from the "packet" that has just been ACKed, as specified in [draft-cheng-iccrg-delivery-rate-estimation]):

```
BBRUpdateBtlBw()
  BBRUpdateRound()
  if (rs.delivery_rate >= BBR.BtlBw || ! rs.is_app_limited)
      BBR.BtlBw = update_windowed_max_filter(
                    filter=BBR.BtlBwFilter,
                    value=rs.delivery_rate,
                    time=BBR.round_count,
                    window_length=BtlBwFilterLen)
```

4.1.2. BBR.RTprop

BBR.RTprop is BBR's estimate of the round-trip propagation delay of the path over which a transport connection is sending. The path's round-trip propagation delay determines the minimum amount of time over which the connection must be willing to sustain transmissions at the BBR.BtlBw rate, and thus the minimum amount of data needed in-flight, for the connection to reach full utilization (a "Full Pipe"). The round-trip propagation delay can vary over the life of a connection, so BBR continually estimates RTProp using recent round-trip delay samples.

4.1.2.1. Round-Trip Time Samples for Estimating BBR.RTprop

For every data packet a connection sends, BBR calculates an RTT sample that measures the time interval from sending a data packet until that packet is acknowledged.

For the most part, the same considerations and mechanisms that apply to RTT estimation for the purposes of retransmission timeout calculations [RFC6298] apply to BBR RTT samples. Namely, BBR does not use RTT samples based on the transmission time of retransmitted packets, since these are ambiguous, and thus unreliable. Also, BBR calculates RTT samples using both cumulative and selective acknowledgments (if the transport supports [RFC2018] SACK options or an equivalent mechanism), or transport-layer timestamps (if the transport supports [RFC7323] TCP timestamps or an equivalent mechanism).

The only divergence from RTT estimation for retransmission timeouts is in the case where a given acknowledgment ACKs more than one data packet. In order to be conservative and schedule long timeouts to avoid spurious retransmissions, the maximum among such potential RTT samples is typically used for computing retransmission timeouts; i.e., SRTT is typically calculated using the data packet with the earliest transmission time. By contrast, in order for BBR to try to reach the minimum amount of data in flight to fill the pipe, BBR uses the minimum among such potential RTT samples; i.e., BBR calculates the RTT using the data packet with the latest transmission time.

4.1.2.2. BBR.RTprop Min Filter

RTT samples tend to be above the round-trip propagation delay of the path, due to "noise" introduced by random variation in physical transmission processes (e.g. radio link layer noise), queues along the network path, the receiver's delayed ack strategy, ack aggregation, etc. Thus to filter out these effects BBR uses a min filter: BBR estimates BBR.RTprop using the minimum recent RTT sample seen by the connection over that past RTpropFilterLen seconds. (Many of the same network effects that can decrease delivery rate measurements can increase RTT samples, which is why BBR's min-filtering approach for RTTs is the complement of its max-filtering approach for delivery rates.)

The length of the RTProp min filter window is RTpropFilterLen = 10 secs. This is driven by trade-offs among several considerations:

- The RTpropFilterLen is longer than ProbeRTTInterval, so that it covers an entire ProbeRTT cycle (see the "ProbeRTT" section below). This helps ensure that the window can contain RTT samples that are the result of data transmitted with inflight below the estimated BDP of the flow. Such RTT samples are important for helping to reveal the path's underlying two-way propagation delay even when the aforementioned "noise" effects can often obscure it.
- The RTpropFilterLen aims to be long enough to avoid needing to cut in-flight and throughput often. Measuring two-way propagation delay requires in-flight to be at or below BDP, which risks some amount of underutilization, so BBR uses a filter window long enough that such underutilization events can be rare.
- The RTpropFilterLen aims to be long enough that many applications have a "natural" moment of silence or low utilization that can cut in-flight below BDP and naturally serve to refresh the BBR.RTprop, without requiring BBR to force an artificial cut in in-flight. This applies to many popular applications, including Web, RPC, chunked audio or video traffic.
- The RTpropFilterLen aims to be short enough to respond in a timely manner to real increases in the two-way propagation delay of the path, e.g. due to route changes, which are expected to typically happen on time scales of 30 seconds or longer.

4.1.2.3. Updating the BBR.RTprop Min Filter

Upon transmitting each packet, BBR (or the associated transport protocol) stores in per-packet data the wall-clock transmission time of the packet (Now() returns the current wall-clock time):

```
packet.send_time = Now()
```

For every ACK that acknowledges some data packets as delivered, BBR (or the associated transport protocol) calculates an RTT sample "rtt" as follows:

```
packet.rtt = Now() - packet.send_time
```

A BBR implementation MAY use a generic windowed min filter to track BBR.RTprop. However, a significant savings in space can be achieved by using the same state to track BBR.RTprop and ProbeRTT timing, so this document describes this combined approach. With this approach, on every ACK that provides an RTT sample BBR updates the BBR.RTprop estimator as follows:

```
BBRUpdateRTprop()
  BBR.rtprop_expired =
    Now() > BBR.rtprop_stamp + RTpropFilterLen
  if (packet.rtt >= 0 and
     (packet.rtt <= BBR.RTprop or BBR.rtprop_expired))
    BBR.RTprop = packet.rtt
    BBR.rtprop_stamp = Now()
```

Here BBR.rtprop_expired is a boolean recording whether the BBR.RTprop has expired and is due for a refresh, via either an application idle period or a transition into ProbeRTT state.

4.2. BBR Control Parameters

BBR uses three distinct but interrelated control parameters: pacing rate, send quantum, and congestion window (cwnd).

4.2.1. Pacing Rate

To help match the packet-arrival rate to the bottleneck link's departure rate, BBR paces data packets. Pacing enforces a maximum rate at which BBR schedules packets for transmission. Pacing is the primary mechanism that BBR uses to control its sending behavior; BBR implementations MUST implement pacing.

The sending host implements pacing by maintaining inter-packet spacing at the time each packet is scheduled for transmission, calculating the next transmission time for a packet for a given flow (here "next_send_time") as a function of the most recent packet size and the current pacing rate, as follows:

```
next_send_time = Now() + packet.size / pacing_rate
```

To adapt to the bottleneck, in general BBR sets the pacing rate to be proportional to BBR.BtlBw, with a dynamic gain, or scaling factor of proportionality, called pacing_gain.

When a BBR flow starts it has no BBR.BtlBw estimate. So in this case it sets an initial pacing rate based on the transport sender implementation's initial congestion window ("InitialCwnd", e.g. from [RFC6298]), the initial SRTT (smoothed round-trip time) after the first non-zero RTT sample, and the initial pacing_gain:

```
BBRInitPacingRate():
  nominal_bandwidth = InitialCwnd / (SRTT ? SRTT : 1ms)
  BBR.pacing_rate =  BBR.pacing_gain * nominal_bandwidth
```

After initialization, on each data ACK BBR updates its pacing rate to be proportional to BBR.BtlBw, as long as it estimates that it has filled the pipe (BBR.filled_pipe is true; see the "Startup" section below for details), or doing so increases the pacing rate. Limiting the pacing rate updates in this way helps the connection probe robustly for bandwidth until it estimates it has reached its full available bandwidth ("filled the pipe"). In particular, this prevents the pacing rate from being reduced when the connection has only seen application-limited samples. BBR updates the pacing rate on each ACK by executing the BBRSetPacingRate() step as follows:

```
BBRSetPacingRateWithGain(pacing_gain):
  rate = pacing_gain * BBR.BtlBw
  if (BBR.filled_pipe || rate > BBR.pacing_rate)
    BBR.pacing_rate = rate

BBRSetPacingRate():
  BBRSetPacingRateWithGain(BBR.pacing_gain)
```

4.2.2. Send Quantum

In order to amortize per-packet host overheads involved in the sending process, high-performance transport sender implementations often schedule an aggregate containing multiple packets (multiple MSS) worth of data as a single quantum (using TSO, GSO, or other offload mechanisms [DC13]). The BBR congestion control algorithm makes this control decision explicitly, dynamically calculating a BBR.send_quantum control parameter that specifies the maximum size of these transmission aggregates. This decision is based on a trade-off: a smaller BBR.send_quantum is preferred a lower data rates because it results in shorter packet bursts, shorter queues, lower queueing delays, and lower rates of packet loss; a bigger BBR.send_quantum can be required at higher data rates because it results in lower CPU overheads at the sending and receiving hosts, who can ship larger amounts of data with a single trip through the networking stack.

On each ACK, BBR runs BBRSetSendQuantum() to update BBR.send_quantum as follows:

```
BBRSetSendQuantum():
  if (BBR.pacing_rate < 1.2 Mbps)
    BBR.send_quantum = 1 * MSS
  else if (BBR.pacing_rate < 24 Mbps)
    BBR.send_quantum  = 2 * MSS
  else
    BBR.send_quantum  = min(BBR.pacing_rate * 1ms, 64KBytes)
```

A BBR implementation MAY use alternate approaches to select a BBR.send_quantum, as appropriate for the CPU overheads anticipated for senders and receivers, and buffering considerations anticipated in the network path. However, for the sake of the network and other users, a BBR implementation SHOULD attempt to use the smallest feasible quanta.

4.2.3. Congestion Window

The congestion window, or cwnd, controls the maximum volume of data BBR allows in flight in the network at any time. BBR's adapts the cwnd based on its model of the network path and the state machine's decisions about how to probe that path.

By default, BBR grows its cwnd to meet its target cwnd, BBR.target_cwnd, which is scaled to adapt to the estimated BDP computed from its path model. But BBR's selection of cwnd is designed to explicitly trade off among competing considerations that dynamically adapt to various conditions. So in loss recovery BBR more conservatively adjusts its sending behavior based on more recent delivery samples, and if BBR needs to re-probe the current BBR.RTprop of the path then it cuts its cwnd accordingly. The following sections describe the various considerations that impact cwnd.

4.2.3.1. Initial cwnd

At its core, BBR is about using measurements to build a model of the network path and then adapting control decisions to the path based on that model. As such, the selection of the initial cwnd is considered to be outside the scope of the BBR algorithm, since at initialization there are no measurements yet upon which BBR can operate. Thus, at initialization, BBR uses the transport sender implementation's initial congestion window (e.g. from [RFC6298] for TCP).

4.2.3.2. Target cwnd

The BBR BBR.target_cwnd is the upper bound on the volume of data BBR allows in flight. This bound is always in place, and dominates when all other considerations have been satisfied: the flow is not in loss recovery, does not need to probe BBR.RTprop, and has accumulated confidence in its model parameters by receiving enough ACKs to gradually grow the current cwnd to meet the BBR.target_cwnd.

On each ACK, BBR calculates the BBR.target_cwnd as follows:

```
BBRInflight(gain):
  if (BBR.RTprop == Inf)
    return InitialCwnd /* no valid RTT samples yet */
  quanta = 3*BBR.send_quantum
  estimated_bdp = BBR.BtlBw * BBR.RTprop
  return gain * estimated_bdp + quanta
```

```
BBRUpdateTargetCwnd():
  BBR.target_cwnd = BBRInflight(BBR.cwnd_gain)
```

The "estimated_bdp" term allows enough packets in flight to fully utilize the estimated BDP of the path, by allowing the flow to send at BBR.BtlBw for a duration of BBR.RTprop. Scaling up the BDP by cwnd_gain, selected by the BBR state machine to be above 1.0 at all times, bounds in-flight data to a small multiple of the BDP, in order to handle common network and receiver pathologies, such as delayed, stretched, or aggregated ACKs [A15]. The "quanta" term allows enough quanta in flight on the sending and receiving hosts to reach full utilization even in high-throughput environments using offloading mechanisms.

4.2.3.3. Minimum cwnd for Pipelining

Normally (except in the immediate aftermath of entering loss recovery), BBR imposes a floor of BBRMinPipeCwnd (4 packets, i.e. 4 * MSSS). This floor helps ensure that even at very low BDPs, and with a transport like TCP where a receiver may ACK only every alternate MSS of data, there are enough packets in flight to maintain full pipelining. In particular BBR tries to allow at least 2 data packets in flight and ACKs for at least 2 data packets on the path from receiver to sender.

4.2.3.4. Modulating cwnd in Loss Recovery

BBR interprets loss as a hint that there may be recent changes in path behavior that are not yet fully reflected in its model of the path, and thus it needs to be more conservative.

Upon a retransmission timeout, meaning the sender thinks all in-flight packets are lost, BBR conservatively reduces cwnd to one packet (1 MSS) and sends a single packet. Then BBR gradually increases cwnd using the normal approach outlined below in "Core cwnd Adjustment Mechanism".

When a BBR sender detects packet loss but there are still packets in flight, on the first round of the loss-repair process BBR temporarily reduces the cwnd to match the current delivery rate as ACKs arrive. On second and later rounds of loss repair, it ensures the sending rate never exceeds twice the current delivery rate as ACKs arrive.

When BBR exits loss recovery it restores the cwnd to the "last known good" value that cwnd held before entering recovery. This applies equally whether the flow exits loss recovery because it finishes repairing all losses or because it executes an "undo" event after inferring that a loss recovery event was spurious.

There are several ways to implement this high-level design for updating cwnd in loss recovery. One is as follows:

Upon retransmission timeout (RTO):

```
BBR.prior_cwnd = BBRSaveCwnd()
cwnd = 1
```

Upon entering Fast Recovery, set cwnd to the number of packets still in flight (allowing at least one for a fast retransmit):

```
BBR.prior_cwnd = BBRSaveCwnd()
cwnd = packets_in_flight + max(packets_delivered, 1)
BBR.packet_conservation = true
```

Upon every ACK in Fast Recovery, run the following BBRModulateCwndForRecovery() steps, which help ensure packet conservation on the first round of recovery, and sending at no more than twice the current delivery rate on later rounds of recovery (given that "packets_delivered" packets were newly marked ACKed or SACKed and "packets_lost" were newly marked lost):

```
BBRModulateCwndForRecovery():
  if (packets_lost > 0)
    cwnd = max(cwnd - packets_lost, 1)
  if (BBR.packet_conservation)
    cwnd = max(cwnd, packets_in_flight + packets_delivered)
```

After one round-trip in Fast Recovery:

```
BBR.packet_conservation = false
```

Upon exiting loss recovery (RTO recovery or Fast Recovery), either by repairing all losses or undoing recovery, BBR restores the best-known cwnd value we had upon entering loss recovery:

```
BBR.packet_conservation = false
BBRRestoreCwnd()
```

The BBRSaveCwnd() and BBRRestoreCwnd() helpers help remember and restore the last-known good cwnd (the latest cwnd unmodulated by loss recovery or ProbeRTT), and is defined as follows:

```
BBRSaveCwnd():
  if (not InLossRecovery() and BBR.state != ProbeRTT)
    return cwnd
  else
    return max(BBR.prior_cwnd, cwnd)

BBRRestoreCwnd():
  cwnd = max(cwnd, BBR.prior_cwnd)
```

4.2.3.5. Modulating cwnd in ProbeRTT

If BBR decides it needs to enter the ProbeRTT state (see the "ProbeRTT" section below), its goal is to quickly reduce the volume of in-flight data and drain the bottleneck queue, thereby allowing measurement of BBR.RTprop. To implement this mode, BBR bounds the cwnd to BBRMinPipeCwnd, the minimal value that allows pipelining (see the "Minimum cwnd for Pipelining" section, above):

```
BBRModulateCwndForProbeRTT():
  if (BBR.state == ProbeRTT)
    cwnd = min(cwnd, BBRMinPipeCwnd)
```

4.2.3.6. Core cwnd Adjustment Mechanism

The network path and traffic traveling over it can make sudden dramatic changes. To adapt to these changes smoothly and robustly, and reduce packet losses in such cases, BBR uses a conservative strategy. When cwnd is above the BBR.target_cwnd derived from BBR's path model, BBR cuts the cwnd immediately to the target. When cwnd is below BBR.target_cwnd, BBR raises the cwnd gradually and cautiously, increasing cwnd by no more than the amount of data acknowledged (cumulatively or selectively) upon each ACK.

Specifically, on each ACK that acknowledges "packets_delivered" packets as newly ACKed or SACKed, BBR runs the following BBRSetCwnd() steps to update cwnd:

```
BBRSetCwnd():
  BBRUpdateTargetCwnd()
  BBRModulateCwndForRecovery()
  if (not BBR.packet_conservation) {
    if (BBR.filled_pipe)
      cwnd = min(cwnd + packets_delivered, BBR.target_cwnd)
    else if (cwnd < BBR.target_cwnd || BBR.delivered < InitialCwnd)
      cwnd = cwnd + packets_delivered
    cwnd = max(cwnd, BBRMinPipeCwnd)
  }
  BBRModulateCwndForProbeRTT()
```

There are several considerations here. If BBR has measured enough samples to achieve confidence that it has filled the pipe (see the description of BBR.filled_pipe in the "Startup" section below), then it increases its cwnd based on the number of packets delivered, while bounding its cwnd to be no larger than the BBR.target_cwnd adapted to the estimated BDP. Otherwise, if the cwnd is below the target, or the sender has marked so little data delivered (less than InitialCwnd) that it does not yet judge its BBR.BtlBw estimate and BBR.target_cwnd as useful, then it increases cwnd without bounding it to be below the target. Finally, BBR imposes a floor of BBRMinPipeCwnd in order to allow pipelining even with small BDPs (see the "Minimum cwnd for Pipelining" section, above).

4.3. State Machine

BBR implements a simple state machine that uses the network path model described above to guide its decisions, and the control parameters described above to enact its decisions. At startup, BBR probes to build a model of the network path; to adapt to later changes to the path or its traffic, BBR must continue to probe to update its model. If the available bottleneck bandwidth increases, BBR must send faster to discover this. Likewise, if the actual round-trip propagation delay changes, this changes the BDP, and thus BBR must send slower to get inflight below the new BDP in order to measure the new BBR.RTprop. Thus, BBR's state machine runs periodic, sequential experiments, sending faster to check for BBR.BtlBw increases or sending slower to check for BBR.RTprop decreases. The frequency, magnitude, duration, and structure of these experiments differ depending on what's already known (startup or steady-state) and sending application behavior (intermittent or continuous).

This state machine has several goals:

- Achieve high throughput by efficiently utilizing available bandwidth.
- Achieve low latency by keeping queues bounded and small.
- Periodically send multiplicatively faster to probe the network to quickly discover newly-available bandwidth (in time proportional to the logarithm of the newly-available bandwidth).
- If needed, send slower in order to drain the bottleneck queue and probe the network to try to estimate the network's two-way propagation delay.
- Share bandwidth with other flows in an approximately fair manner.
- Feed samples to the BBR.BtlBw and BBR.RTprop estimators to refresh and update the model.

BBR's state machine uses two control mechanisms. First and foremost, it uses the pacing_gain (see the "Pacing Rate" section), which controls how fast packets are sent relative to BBR.BtlBw and is thus key to BBR's ability to learn. A pacing_gain > 1 decreases inter-packet time time and increases inflight. A pacing_gain < 1 has the opposite effect, increasing inter-packet time and generally decreasing inflight. Second, if the state machine needs to quickly reduce inflight to a particular absolute value, it uses the cwnd.

The following sections describe each state in turn.

4.3.1. Initialization Steps

Upon transport connection initialization, BBR executes the following steps:

```
BBRInit():
  init_windowed_max_filter(filter=BBR.BtlBwFilter, value=0, time=0)
  BBR.rtprop = SRTT ? SRTT : Inf
  BBR.rtprop_stamp = Now()
```

```
  BBR.probe_rtt_done_stamp = 0
  BBR.probe_rtt_round_done = false
  BBR.packet_conservation = false
  BBR.prior_cwnd = 0
  BBR.idle_restart = false
  BBRInitRoundCounting()
  BBRInitFullPipe()
  BBRInitPacingRate()
  BBREnterStartup()
```

4.3.2. Startup

4.3.2.1. Startup Dynamics

When a BBR flow starts up, it performs its first (and most rapid) sequential probe/drain process. Network link bandwidths currently span a range of at least 11 orders of magnitude, from a few bps to 100 Gbps. To quickly learn BBR.BtlBw, given this huge range to explore, BBR's Startup state does an exponential search of the rate space, doubling the sending rate each round. This finds BBR.BtlBw in O(log_2(BDP)) round trips.

To achieve this rapid probing in the smoothest possible fashion, upon entry into Startup state BBR sets BBR.pacing_gain and BBR.cwnd_gain to BBRHighGain = 2/ln(2) ~= 2.89, the minimum gain value that will allow the sending rate to double each round. Hence, when initializing a connection, or upon any later entry into Startup mode, BBR executes the following BBREnterStartup() steps:

```
BBREnterStartup():
  BBR.state = Startup
  BBR.pacing_gain = BBRHighGain
  BBR.cwnd_gain = BBRHighGain
```

As BBR grows its sending rate rapidly, it obtains higher delivery rate samples, BBR.BtlBw increases, and the pacing rate and cwnd both adapt by smoothly growing in proportion. Once the pipe is full, a queue generally forms, but the cwnd_gain bounds any queue to (cwnd_gain - 1) * BDP, and the immediately following Drain state is designed to quickly drain that queue.

4.3.2.2. Estimating When Startup has Filled the Pipe

During Startup, BBR estimates whether the pipe is full by looking for a plateau in the BBR.BtlBw estimate. The output of this "full pipe" estimator is tracked in BBR.filled_pipe, a boolean that records whether BBR estimates that it has ever fully utilized its available bandwidth ("filled the pipe"). If BBR notices that there are several (three) rounds where attempts to double the delivery rate actually result in little increase (less than 25 percent), then it estimates that it has reached BBR.BtlBw, sets BBR.filled_pipe to true, exits Startup and enters Drain.

Upon connection initialization the full pipe estimator runs:

```
BBRInitFullPipe():
  BBR.filled_pipe = false
  BBR.full_bw = 0
  BBR.full_bw_count = 0
```

Once per round trip, upon an ACK that acknowledges new data, and when the delivery rate sample is not application-limited (see [draft-cheng-iccrg-delivery-rate-estimation]), BBR runs the "full pipe" estimator, if needed:

```
BBRCheckFullPipe():
  if BBR.filled_pipe or
     not BBR.round_start or rs.is_app_limited
    return  // no need to check for a full pipe now
  if (BBR.BtlBw >= BBR.full_bw * 1.25)  // BBR.BtlBw still growing?
    BBR.full_bw = BBR.BtlBw    // record new baseline level
    BBR.full_bw_count = 0
    return
  BBR.full_bw_count++ // another round w/o much growth
  if (BBR.full_bw_count >= 3)
    BBR.filled_pipe = true
```

BBR waits three rounds in order to have solid evidence that the sender is not detecting a delivery-rate plateau that was temporarily imposed by the receive window. Allowing three rounds provides time for the receiver's receive-window autotuning to open up the receive window and for the BBR sender to realize that BBR.BtlBw should be higher: in the first round the receive-window autotuning algorithm grows the receive window; in the second round the sender fills the higher receive window; in the third round the sender gets higher delivery-rate samples. This three-round threshold was validated by YouTube experimental data.

4.3.3. Drain

In Startup, when the BBR "full pipe" estimator estimates that BBR has filled the pipe, BBR switches to its Drain state. In Drain, BBR aims to quickly drain any queue created in Startup by switching to a pacing_gain well below 1.0; specifically, it uses a pacing_gain that is the inverse of the value used during Startup, which drains the queue in one round:

```
BBREnterDrain():
  BBR.state = Drain
  BBR.pacing_gain = 1/BBRHighGain  // pace slowly
  BBR.cwnd_gain = bbr_high_gain    // maintain cwnd
```

In Drain, when the number of packets in flight matches the estimated BDP, meaning BBR estimates that the queue has been fully drained but the pipe is still full, then BBR leaves Drain and enters ProbeBW. To implement this, upon every ACK BBR executes:

```
BBRCheckDrain():
  if (BBR.state == Startup and BBR.filled_pipe)
    BBREnterDrain()
  if (BBR.state == Drain and packets_in_flight <= BBRInflight(1.0))
    BBREnterProbeBW()  // we estimate queue is drained
```

4.3.4. ProbeBW

4.3.4.1. Gain Cycling Dynamics

BBR flows spend the vast majority of their time in ProbeBW state, probing for bandwidth using an approach called gain cycling, which helps BBR flows reach high throughput, low queuing delay, and convergence to a fair share of bandwidth. With gain cycling, BBR cycles through a sequence of values for the pacing_gain. It uses an eight-phase cycle with the following pacing_gain values: 5/4, 3/4, 1, 1, 1, 1, 1, 1. Each phase normally lasts for roughly BBR.RTprop.

In phase 0 of the gain cycle, BBR probes for more bandwidth by using a pacing_gain of 5/4, which gradually raises inflight. It does this until the elapsed time in the phase has been at least BBR.RTprop and either inflight has reached 5/4 * estimated_BDP (which may take longer than BBR.RTprop if BBR.RTprop is low) or some packets have been lost (suggesting that perhaps the path cannot actually hold 5/4 * estimated_BDP in flight).

Next, phase 1 of the gain cycle is designed to drain any queue at the bottleneck (the likely outcome of phase 0 if the pipe was full) by using a pacing_gain of 3/4, chosen to be the same distance below 1 that 5/4 is above 1. This phase lasts until either a full BBR.RTprop has elapsed or inflight drops below estimated_BDP (suggesting that the queue has drained earlier than expected, perhaps because of application-limited behavior).

Finally, phases 2 through 7 of the gain cycle are designed to cruise with a short queue and full utilization by using a pacing_gain of 1.0. Each of these phases lasts for the BBR.RTprop.

The average gain across all phases is 1.0 because ProbeBW aims for its average pacing rate to equal BBR.BtlBw, the estimated available bandwidth, and thus maintain high utilization, while maintaining a small, well-bounded queue.

Note that while gain cycling varies the pacing_gain value, during ProbeBW the cwnd_gain stays constant at two, since delayed, stretched, or aggregated acks can strike at any time (see the "Target cwnd" section).

4.3.4.2. Gain Cycling Randomization

To improve mixing and fairness, and to reduce queues when multiple BBR flows share a bottleneck, BBR randomizes the phases of ProbeBW gain cycling by randomly picking an initial phase, from among all but the 3/4 phase, when entering ProbeBW.

Why not start cycling with 3/4? The main advantage of the 3/4 pacing_gain is to drain any queue that can be created by running a 5/4 pacing_gain when the pipe is already full. When exiting Drain or ProbeRTT and entering ProbeBW, there is typically no queue to drain, so the 3/4 gain does not provide that advantage. Using 3/4 in those contexts only has a cost: a link utilization for that round of 3/4 instead of 1. Since starting with 3/4 would have a cost but no benefit, and since entering ProbeBW happens at the start of any connection long enough to have a Drain, BBR uses this small optimization.

4.3.4.3. Gain Cycling Algorithm

BBR's ProbeBW gain cycling algorithm operates as follows.

Upon entering ProbeBW, BBR (re)starts gain cycling with the following:

```
BBREnterProbeBW():
  BBR.state = ProbeBW
  BBR.pacing_gain = 1
  BBR.cwnd_gain = 2
  BBR.cycle_index = BBRGainCycleLen - 1 - random_int_in_range(0..6)
  BBRAdvanceCyclePhase()
```

On each ACK BBR runs BBRCheckCyclePhase(), to see if it's time to advance to the next gain cycle phase:

```
BBRCheckCyclePhase():
  if (BBR.sate == ProbeBW and BBRIsNextCyclePhase()
    BBRAdvanceCyclePhase()

BBRAdvanceCyclePhase():
  BBR.cycle_stamp = Now()
  BBR.cycle_index = (BBR.cycle_index + 1) % BBRGainCycleLen
  pacing_gain_cycle = [5/4, 3/4, 1, 1, 1, 1, 1, 1]
  BBR.pacing_gain = pacing_gain_cycle[BBR.cycle_index]

BBRIsNextCyclePhase():
  is_full_length = (Now() - BBR.cycle_stamp) > BBR.RTprop
  if (BBR.pacing_gain == 1)
```

```
    return is_full_length
  if (BBR.pacing_gain > 1)
    return is_full_length and
              (packets_lost > 0 or
               prior_inflight >= BBRInflight(BBR.pacing_gain))
  else  //  (BBR.pacing_gain < 1)
    return is_full_length or
               prior_inflight <= BBRInflight(1)
```

Here, "prior_inflight" is the amount of data that was in flight before processing this ACK.

4.3.4.4. Restarting From Idle

When restarting from idle, BBR leaves its cwnd as-is and paces packets at exactly BBR.BtlBw, aiming to return as quickly as possible to its target operating point of rate balance and a full pipe. Specifically, if the flow's BBR.state is ProbeBW, and the flow is application-limited, and there are no packets in flight currently, then at the moment the flow sends one or more packets BBR sets BBR.pacing_rate to exactly BBR.BtlBw. More precisely, the BBR algorithm takes the following steps in BBRHandleRestartFromIdle() before sending a packet for a flow:

```
BBRHandleRestartFromIdle():
  if (packets_in_flight == 0 and C.app_limited)
    BBR.idle_start = true
    if (BBR.state == ProbeBW)
      BBRSetPacingRateWithGain(1)
```

The "Restarting Idle Connections" section of [RFC5681] suggests restarting from idle by slow-starting from the initial window. However, this approach was assuming a congestion control algorithm that had no estimate of the bottleneck bandwidth and no pacing, and thus resorted to relying on slow-starting driven by an ACK clock. The long (log_2(BDP)*RTT) delays required to reach full utilization with that "slow start after idle" approach caused many large deployments to disable this mechanism, resulting in a "BDP-scale line-rate burst" approach instead. Instead of these two approaches, BBR restarts by pacing at BBR.BtlBw, typically achieving approximate rate balance and a full pipe after only one BBR.RTprop has elapsed.

4.3.5. ProbeRTT

To help probe for BBR.RTprop, BBR flows cooperate to periodically drain the bottleneck queue using a state called ProbeRTT, when needed. In any state other than ProbeRTT itself, if the RTProp estimate has not been updated (i.e., by getting a lower RTT measurement) for more than ProbeRTTInterval = 10 seconds, then BBR enters ProbeRTT and reduces the cwnd to a minimal value, BBRMinPipeCwnd (four packets). After maintaining BBRMinPipeCwnd or fewer packets in flight for at least ProbeRTTDuration (200 ms) and one round trip, BBR leaves ProbeRTT and transitions to either Startup or ProbeBW, depending on whether it estimates the pipe was filled already.

BBR is designed to spend the vast majority of its time (about 98 percent) in ProbeBW and the rest in ProbeRTT, based on a set of tradeoffs. ProbeRTT lasts long enough (at least ProbeRTTDuration = 200 ms) to allow flows with different RTTs to have overlapping ProbeRTT states, while still being short enough to bound the throughput penalty of ProbeRTT's cwnd capping to roughly 2 percent (200 ms/10 seconds).

As discussed in the "BBR.RTprop Min Filter" section above, BBR's BBR.RTprop filter window, RTpropFilterLen, and time interval between ProbeRTT states, ProbeRTTInterval, work in concert. A BBR implementation MUST use a RTpropFilterLen equal to or longer than ProbeRTTInterval, and to allow coordination with other BBR flows MUST use the standard ProbeRTTInterval of 10 secs. It is RECOMMENDED to use 10 secs for both RTpropFilterLen and ProbeRTTInterval. An RTpropFilterLen of 10 secs is short enough to allow quick convergence if traffic levels or routes change, but long enough so that interactive applications (e.g., Web pages, remote procedure calls, video chunks) often have natural silences or low-rate periods within the window where the flow's rate is low enough or long enough to drain its queue in the bottleneck. Then the BBR.RTprop filter opportunistically picks up these BBR.RTprop measurements, and RTProp refreshes without requiring ProbeRTT. This way, flows typically need only pay the 2 percent throughput penalty if there are multiple bulk flows busy sending over the entire ProbeRTTInterval window.

On every ACK BBR executes BBRCheckProbeRTT() to handle the steps related to the ProbeRTT state as follows:

```
BBRCheckProbeRTT():
  if (BBR.state != ProbeRTT and
      BBR.rtprop_expired and
      not BBR.idle_restart)
    BBREnterProbeRTT()
    BBRSaveCwnd()
    BBR.probe_rtt_done_stamp = 0
  if (BBR.state == ProbeRTT)
    BBRHandleProbeRTT()
  BBR.idle_restart = false

BBREnterProbeRTT():
  BBR.state = ProbeRTT
  BBR.pacing_gain = 1
  BBR.cwnd_gain = 1

BBRHandleProbeRTT():
  /* Ignore low rate samples during ProbeRTT: */
  C.app_limited =
    (BW.delivered + packets_in_flight) ? : 1
  if (BBR.probe_rtt_done_stamp == 0 and
```

```
        packets_in_flight <= BBRMinPipeCwnd)
      BBR.probe_rtt_done_stamp =
        Now() + ProbeRTTDuration
      BBR.probe_rtt_round_done = false
      BBR.next_round_delivered = BBR.delivered
    else if (BBR.probe_rtt_done_stamp != 0)
      if (BBR.round_start)
        BBR.probe_rtt_round_done = true
      if (BBR.probe_rtt_round_done and
          Now() > BBR.probe_rtt_done_stamp)
        BBR.rtprop_stamp = Now()
        BBRRestoreCwnd()
        BBRExitProbeRTT()

BBRExitProbeRTT():
  if (BBR.filled_pipe)
    BBREnterProbeBW()
  else
    BBREnterStartup()
```

When restarting from idle (BBR.idle_restart is true) and finding that the BBR.RTprop has expired, BBR does not enter ProbeRTT; the idleness is deemed a sufficient attempt to coordinate to drain the queue.

The critical point is that before BBR raises its BBR.RTprop estimate (which will in turn raise its cwnd), it must first enter ProbeRTT to make a concerted and coordinated effort to drain the bottleneck queue and measure the BBR.RTprop. This allows the BBR.RTprop estimates of ensembles of BBR flows to stay well-anchored in reality, avoiding feedback loops of ever-increasing queues and RTT samples.

5. Implementation Status

This section records the status of known implementations of the algorithm defined by this specification at the time of posting of this Internet-Draft, and is based on a proposal described in [RFC7942]. The description of implementations in this section is intended to assist the IETF in its decision processes in progressing drafts to RFCs. Please note that the listing of any individual implementation here does not imply endorsement by the IETF. Furthermore, no effort has been spent to verify the information presented here that was supplied by IETF contributors. This is not intended as, and must not be construed to be, a catalog of available implementations or their features. Readers are advised to note that other implementations may exist.

According to [RFC7942], "this will allow reviewers and working groups to assign due consideration to documents that have the benefit of running code, which may serve as evidence of valuable experimentation and feedback that have made the implemented protocols more mature. It is up to the individual working groups to use this information as they see fit".

As of the time of writing, the following implementations of BBR have been publicly released:

- Linux TCP
  - Source code URL:
    - https://git.kernel.org/pub/scm/linux/kernel/git/torvalds/linux.git/tree/net/ipv4/tcp_bbr.c
  - Source: Google
  - Maturity: production
  - License: dual-licensed: GPLv2 / BSD
  - Contact: https://groups.google.com/d/forum/bbr-dev
  - Last updated: June 30, 2017
- QUIC
  - Source code URLs:
    - https://chromium.googlesource.com/chromium/src/net/+/master/quic/core/congestion_control/bbr_sender.cc
    - https://chromium.googlesource.com/chromium/src/net/+/master/quic/core/congestion_control/bbr_sender.h
  - Source: Google
  - Maturity: production
  - License: BSD-style
  - Contact: https://groups.google.com/d/forum/bbr-dev
  - Last updated: June 30, 2017

6. Security Considerations

This proposal makes no changes to the underlying security of transport protocols or congestion control algorithms. BBR shares the same security considerations as the existing standard congestion control algorithm [RFC5681].

7. IANA Considerations

This document has no IANA actions. Here we are using that phrase, suggested by [RFC5226], because BBR does not modify or extend the wire format of any network protocol, nor does it add new dependencies on assigned numbers. BBR involves only a change to the congestion control algorithm of a transport sender, and does not involve changes in the network, the receiver, or any network protocol.

Note to RFC Editor: this section may be removed on publication as an RFC.

8. Acknowledgments

The authors are grateful to Len Kleinrock for his work on the theory underlying congestion control. We are indebted to Larry Brakmo for pioneering work on the Vegas [BP95] and New Vegas [B15]

congestion control algorithms, which presaged many elements of BBR, and for Larry's advice and guidance during BBR's early development. The authors would also like to thank C. Stephen Gunn, Eric Dumazet, Ian Swett, Jana Iyengar, Victor Vasiliev, Nandita Dukkipati, Pawel Jurczyk, Biren Roy, David Wetherall, Amin Vahdat, Leonidas Kontothanassis, and the YouTube, google.com, Bandwidth Enforcer, and Google SRE teams for their invaluable help and support.

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Authors' Addresses

Neal Cardwell
Google, Inc
76 Ninth Avenue
New York, NY 10011
USA
EMail: ncardwell@google.com

Yuchung Cheng
Google, Inc
1600 Amphitheater Parkway
Mountain View, California 94043
USA
EMail: ycheng@google.com

Soheil Hassas Yeganeh
Google, Inc
76 Ninth Avenue
New York, NY 10011
USA
EMail: soheil@google.com

Van Jacobson
Google, Inc
1600 Amphitheater Parkway
Mountain View, California 94043
EMail: vanj@google.com