Are we heading towards a BBR-dominant Internet?

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The promise of higher bandwidths!

Google, Dropbox, and Spotify are reporting **higher throughput** and **lower delay jitter** after switching to BBR.
BBR’s Rapid adoption

<table>
<thead>
<tr>
<th>Variant</th>
<th>Websites</th>
<th>Proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUBIC [15]</td>
<td>6,139</td>
<td>30.70%</td>
</tr>
<tr>
<td>BBR [4]</td>
<td>3,550</td>
<td>17.75%</td>
</tr>
<tr>
<td>BBR G1.1</td>
<td>167</td>
<td>0.84%</td>
</tr>
<tr>
<td>YeAH [2]</td>
<td>1,162</td>
<td>5.81%</td>
</tr>
<tr>
<td>CTCP [34]/Illinois[22]</td>
<td>1,148</td>
<td>5.74%</td>
</tr>
<tr>
<td>Vegas [3]/Veno [13]</td>
<td>564</td>
<td>2.82%</td>
</tr>
<tr>
<td>HTCP [21]</td>
<td>560</td>
<td>2.80%</td>
</tr>
<tr>
<td>BIC [37]</td>
<td>181</td>
<td>0.90%</td>
</tr>
<tr>
<td>New Reno [28]/HSTCP [12]</td>
<td>160</td>
<td>0.80%</td>
</tr>
<tr>
<td>Scalable [20]</td>
<td>39</td>
<td>0.20%</td>
</tr>
<tr>
<td>Westwood [7]</td>
<td>0</td>
<td>0.00%</td>
</tr>
<tr>
<td>Unknown</td>
<td>3,535</td>
<td>17.67%</td>
</tr>
<tr>
<td>Short flows</td>
<td>1,493</td>
<td>7.46%</td>
</tr>
<tr>
<td>Unresponsive websites</td>
<td>1,302</td>
<td>6.51%</td>
</tr>
<tr>
<td>Total</td>
<td>20,000</td>
<td>100%</td>
</tr>
</tbody>
</table>

(Mishra et al, SIGMETRICS 2020)
BBR’s Rapid adoption

In three short years, BBR already accounted for 18% of the top 20,000 websites on the Internet.

Traffic share estimated around 40%

(Mishra et al, SIGMETRICS 2020)
If you run a website and care about **throughput**, it is natural to consider switching from CUBIC to BBR.

Are we heading towards an **all-BBR Internet** then?
Are we heading towards an all-BBR Internet then?

#1 How will BBR’s throughput gains over CUBIC evolve as more people switch to BBR?
#1 How will BBR’s throughput gains over more people switch to BBR?

Game Theory

#2 How will these evolving throughput gains dictate the future CCA landscape?

Are we heading towards an all-BBR Internet then?
A primer on CUBIC

Cwnd-based congestion control algorithm

Treats packet loss as a congestion signal.

Reduces cwnd by 30% when it sees a packet loss.

Considered a buffer filler
A primer on BBR

Rate-based congestion control algorithm. Uses $\text{RTT}_{\text{min}}$ and bandwidth estimates to infer congestion.

Becomes \textbf{cwnd-limited} when it competes with CUBIC*. $\text{cwnd} = 2 \text{ BDP}$

Backs off every 10 sec to measure $\text{RTT}_{\text{min}}$

*according to Ware et al, IMC 2019
$RTT_{\text{min}}$ overestimation

BBR wants to empty the buffer every 10 sec

: BBR Packets
RTT\textsubscript{min} overestimation

But BBR can’t empty the buffer every 10 seconds because of CUBIC’s packets!
But BBR can’t empty the buffer every 10 seconds because of CUBIC’s packets!

This leads to $\text{RTT}_{\text{min}}$ overestimation for BBR
Basic 2-flow model

5 key assumptions
1. All competing flows have the same RTT
2. The buffer is at least 1 BDP and the link is always utilized
3. BBR always has 2 BDP packets in flight
4. Packets are uniformly distributed and the buffer is droptail
5. BBR’s reduction in bandwidth while probing for RTT_{min} is negligible
Basic 2-flow model

1. BBR’s throughput is cwnd divided by delay
   \[ \lambda_b \leftarrow \frac{2\lambda_b RTT^+}{RTT + Q_d} \]

2. Where RTT^+ is BBR’s over estimated RTT because of CUBIC
   \[ RTT^+ = RTT + b_{cmin} \]

3. Extent of this overestimation is based on CUBIC’s back off:
   \[ b_{cmin} = (0.7W_{max}) - (\lambda_{cmin}RTT) \]
Basic 2-flow model

1. BBR’s throughput is cwnd divided by delay
   \[ \lambda_b \leftrightarrow \frac{2\lambda_b RTT^+}{RTT^+ + \frac{b_{cmin}}{C}} \]

2. Extent of this overestimation is based on CUBIC’s back off:
   \[ b_{cmin} = (0.7W_{max}) - (\lambda_{cmin}RTT) \]
Basic 2-flow model

CUBIC’s throughput

\[ \lambda_c = \frac{2b_{cmin} + C \cdot RTT - B_b}{RTT + \frac{2b_{cmin}}{C}} \]

BBR’s throughput

\[ \lambda_b = C - \lambda_c \]
Validating the 2-flow model

Ran a CUBIC and a BBR flow through a 50 Mbps link with 40 ms RTT
Plotted the empirical and predicted throughput across buffer sizes

Bandwidth (Mbps)
Buffer size (BDP)

Reasonable accuracy with a very simple model!
True for other n/w too (see paper)
Extending the model to multiple flows

Basic 2-flow model:

Extent of this overestimation is based on CUBIC’s back off behavior

$$b_{c_{\min}} = (0.7W_{max}) - (\lambda_{c_{\min}}RTT)$$

No longer true for multiple CUBIC flows!

RTT overestimation now also depends on the degree of synchronization between the CUBIC flows.
Extending the model to multiple flows

**Basic 2-flow model:**

Extent of this overestimation is based on CUBIC’s back off behavior

\[ b_{cmin} = (0.7W_{max}) - (\lambda_{cmin}RTT) \]

**Solution:**

Predict the upper and lower bounds instead

**Sync bound**

\[ \hat{b}_{cmin} = (0.7\hat{W}_{max}) - (\hat{\lambda}_{cmin}RTT) \]

**De-sync bound**

\[ \hat{b}_{cmin} = \left( \frac{(N_c - 0.3)}{N_c} \hat{W}_{max} \right) - (\hat{\lambda}_{cmin}RTT) \]

Solve again!
Validating the multiple flow model

Launched 5 CUBIC and 5 BBR flows through a 100 Mbps 40 ms link
Plotted the empirical and predicted throughput across buffer sizes

Actual throughput is within predicted bounds
True for other n/w too (see paper)
Are we heading towards an all-BBR Internet then?

#1 How will BBR’s throughput gains over CUBIC evolve as more people switch to BBR?
BBR’s throughput as more flows run BBR

Ran 20 flows through a 100 Mbps 40 ms link
Progressively increased the number of BBR flows. All other flows ran CUBIC

Key trend:
As the number of BBR flows at the bottleneck increases, their per-flow average bandwidth decreases!
How low is too low?

Nash Equilibrium distribution of CUBIC and BBR

A given distribution of CUBIC and BBR flows in a network is the Nash Equilibrium (NE) if none of the flows can increase their throughput by changing algorithms.

If websites choose between CUBIC and BBR based on throughput, this is the distribution the Internet will move towards.
BBR’s diminishing returns and the NE

Distribution at which the BBR flows get a fairshare of the bandwidth.

BBR does better

CUBIC does better
BBR’s diminishing returns and the NE

BBR does better

CUBIC does better

BBR’s per-flow Bandwidth

Number of BBR flows

fairshare line

: current CCA distribution

BBR's diminishing returns and the NE

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BBR’s diminishing returns and the NE

If a CUBIC flow switches to BBR, it will do worse!

BBR does better
CUBIC does better

Number of BBR flows

BBR’s per-flow Bandwidth

: current CCA distribution

fairshare line
BBR’s diminishing returns and the NE

If a BBR flow switches to CUBIC, it will do worse!

BBR’s per-flow Bandwidth

Number of BBR flows

fairshare line

If a BBR flow switches to CUBIC, it will do worse!

BBR does better

CUBIC does better

: current CCA distribution
BBR’s diminishing returns and the NE

Nobody wants to switch algorithms at this distribution

It must be the Nash Equilibrium!

BBR’s per-flow Bandwidth

Number of BBR flows

: current CCA distribution

fairshare line
Verifying predicted Nash Equilibria

Ran 50 flows through a 50 Mbps 40 ms link

Tested all combinations of BBR and CUBIC to empirically calculate the NE distribution

Compared to model’s predictions

Empirically observed NE distributions exist within our model’s bounds.

Majority of NE distributions have CUBIC flows.

CUBIC is here to stay on the Internet!
Verifying predicted Nash Equilibria

Ran 50 flows through a 50 Mbps 40 ms link

Tested all combinations of BBR and CUBIC to empirically calculate the NE distribution

Compared to model’s predictions

Empirically observed NE distributions exist within our model’s bounds.

Majority of NE distributions have CUBIC flows.

CUBIC is here to stay on the Internet!

Unless the buffers are small (< 1 BDP)
NE in Multi-RTT scenarios

Tested the model’s assumption that all flows have the same RTT

NE exists for multi-RTT settings too

Shorter RTT flows opted for CUBIC, larger RTT flows opted for BBR at the NE
Nash Equilibria for BBRv2

Repeated experiments with BBRv2 instead of BBR
Empirically verified that mixed NE exist for BBRv2 as well

More CUBIC flows at NE when competing with BBRv2 when compared to BBRv1
Summary

We present a mathematical model for predicting the throughput shares of competing CUBIC and BBR flows.

As the number of BBR flows increases at the bottleneck, their throughput advantage will reduce.

Our game theoretic analysis shows that in most networks the Nash Equilibrium distribution of CUBIC and BBR flows will be mixed.
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ABSTRACT
Since its introduction in 2016, BBR has grown in popularity rapidly and likely already accounts for more than 60% of the Internet’s downstream traffic. In this paper, we investigate the following question given BBR’s performance benefits and rapid adoption, is ABR likely to completely replace CUBIC just like how CUBIC replaced New Reno?

We present a mathematical model that allows us to estimate BBR’s throughput to within a 5% error when competing with CUBIC flows. Using this model, we show that even though BBR currently has a throughput advantage over CUBIC, this advantage will be diminished as the proportion of BBR flows increases.

Therefore, if throughput is a key consideration, it is likely that the Internet will reach a stable mixed distribution of CUBIC and BBR flows. This mixed distribution is the No-Agile Equilibrium where none of the flows will have the performance incentive to switch between CUBIC and BBR. The question remains how BBR flows will switch to CUBIC flows in the long run.

This is an important question because the stability of the Internet depends on the competing flows interacting well with one another. We have not experienced a congestion collapse [17] for many years likely because the vast majority of flows have been well-understood AIMD/MIMD-window-based TCP flows [9]. The last major change in the Internet’s congestion landscape happened when CUBIC replaced New Reno [22, 18] and that transition was relatively incremental because both CUBIC and New Reno are loss-based and cwnd-based. Therefore, all existing network solutions, polling algorithms, and AQMs already deployed on the Internet could largely remain unchanged.

On the other hand, if BBR wins to replace CUBIC as the dominant congestion control algorithm for the Internet, it represents a fundamental paradigm shift. Many classic networking questions that have supposedly been solved would have to be re-evaluated. For example, it was said that router buffers ought to be sized inversely proportional to √N where N is the number of flows [19]. Later