Modeling BBR's Interactions With Loss-Based Congestion Control

Ranysha Ware
Carnegie Mellon University

Matthew K. Mukerjee
Nefeli Networks

Justine Sherry
Carnegie Mellon University

Srinivasan Seshan
Carnegie Mellon University

Is BBRv1 fair to legacy congestion control algorithms?

Prior work has tried to answer the fairness question with **measurement.**

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BBR is fair to Cubic in deep-buffered networks.

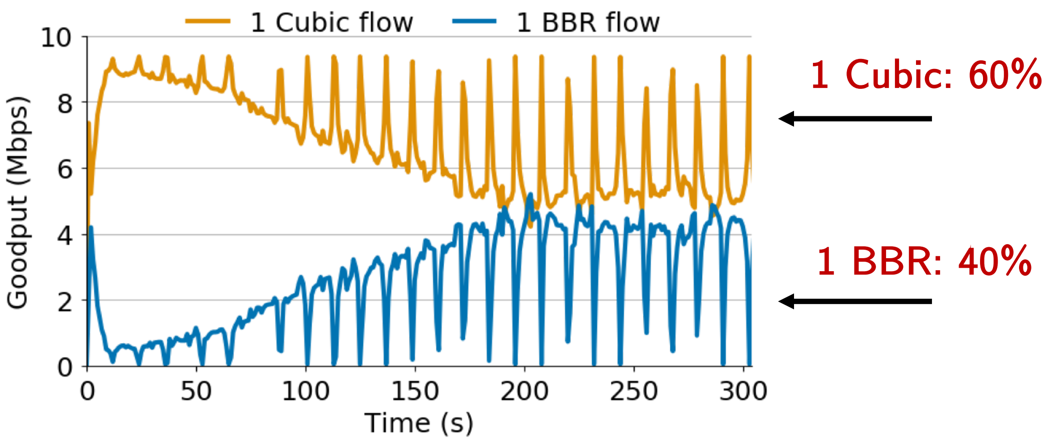

Figure: 1 BBR vs. 1 Cubic.
(10 Mbps network, 32 BDP queue)

Reference: N. Cardwell, et.al. 2016. BBR: Congestion control. In Presentation at IETF97
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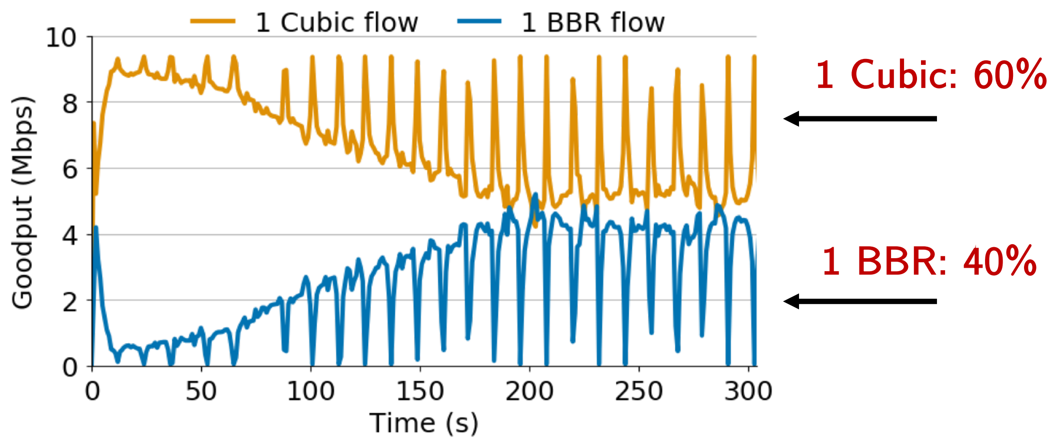

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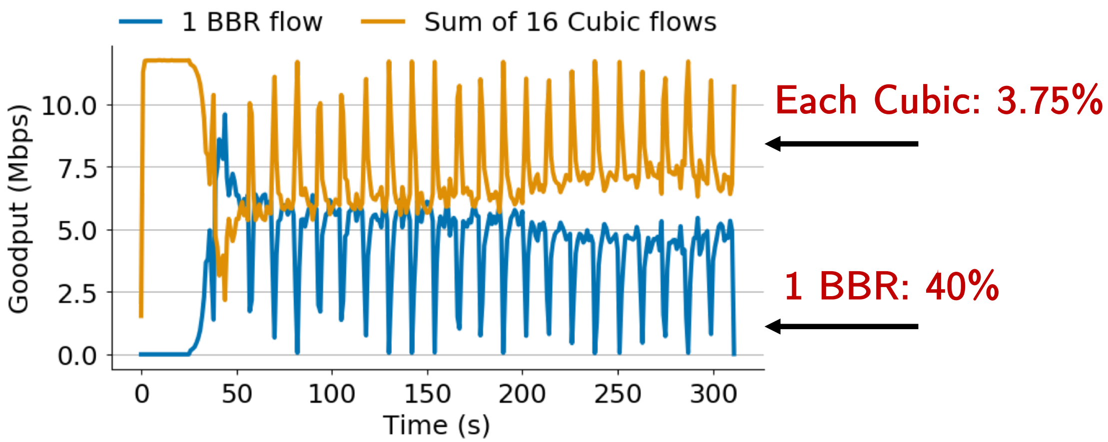


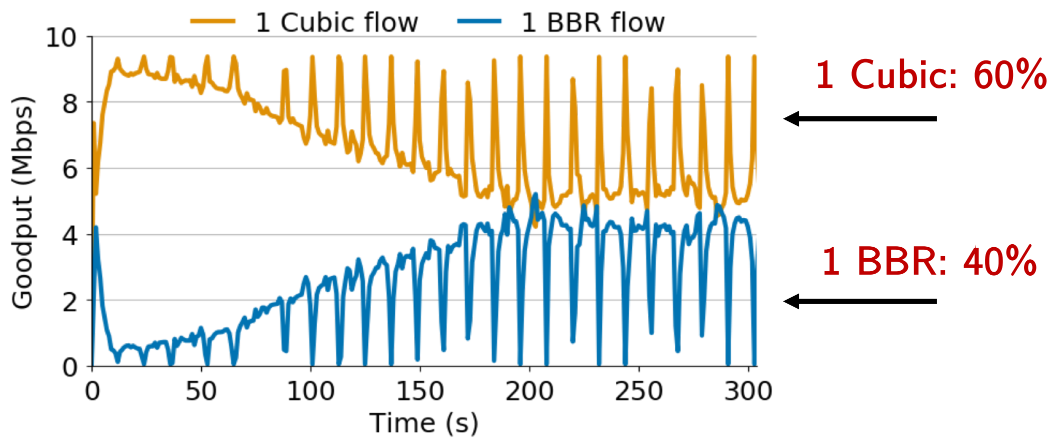
Figure: 1 BBR vs. 16 Cubic.
(10 Mbps network, 32 BDP queue)

Reference: Ware et. al. The Battle for Bandwidth: Fairness and Heterogenous Congestion Control. NSDI 2018.

Prior work does not explain why we see certain behavior.

BBR is <u>fair to Cubic</u> in deep-buffered networks.

BBR is <u>unfair to Cubic</u> in deep-buffered networks.



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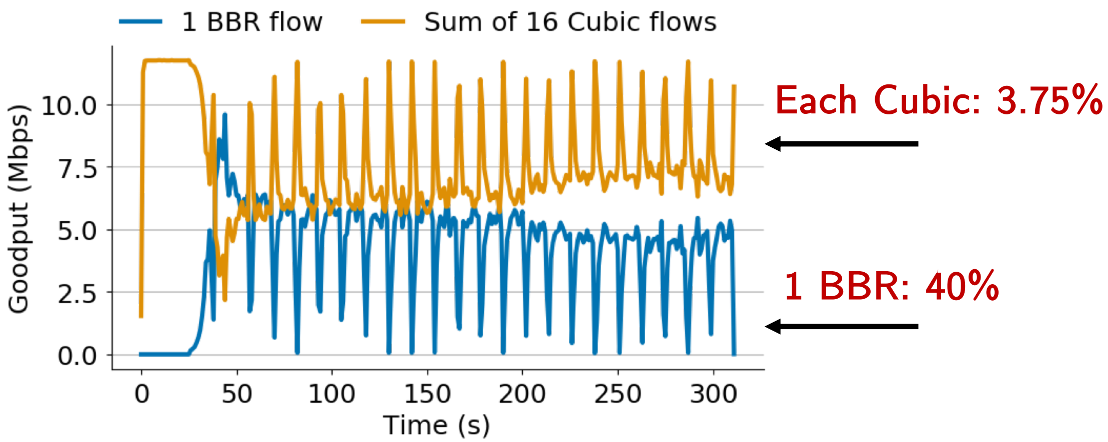

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How can we explain these results?

We can use modeling to understand an algorithm's behavior.

Mathis equation for TCP Reno's throughput

$$BW < \left(\frac{MSS}{RTT}\right) \frac{1}{\sqrt{p}}$$

Padhye equation for TCP Reno's throughput

$$B(p) \approx \min\left(\frac{W_{max}}{RTT}, \frac{1}{RTT\sqrt{\frac{2bp}{3}} + T_0 \min\left(1, 3\sqrt{\frac{3bp}{8}}\right) p(1+32p^2)}\right)$$

Can we build a model to understand BBR's interactions with loss-based algorithms?

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Can we build a model?

Can we build a model to understand BBR's interactions with loss-based algorithms? Yes!

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Our equation for BBR's throughput

$$BBR_{frac} = \left(1 - \frac{1}{2} + \frac{1}{2X} + \frac{4N}{q}\right) \times \left(1 - \left(\frac{q}{c} + .2 + l\right) \times \frac{1}{10}\right)$$

Our model shows BBR's throughput does not depend on the number of competing loss-based flows.

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None of these variables depend on the number of loss-based flows!

BBR is a **rate-based algorithm**.
How does BBR figure out sending rate?

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How does BBR figure out sending rate? **ProbeBW**

- Send at rate r - 6 RTTs
- Sent at rate 1.25r. - 1 RTT
- Reduce to new sending rate (Drain) - 1 RTT

BBR is a **rate-based algorithm**.

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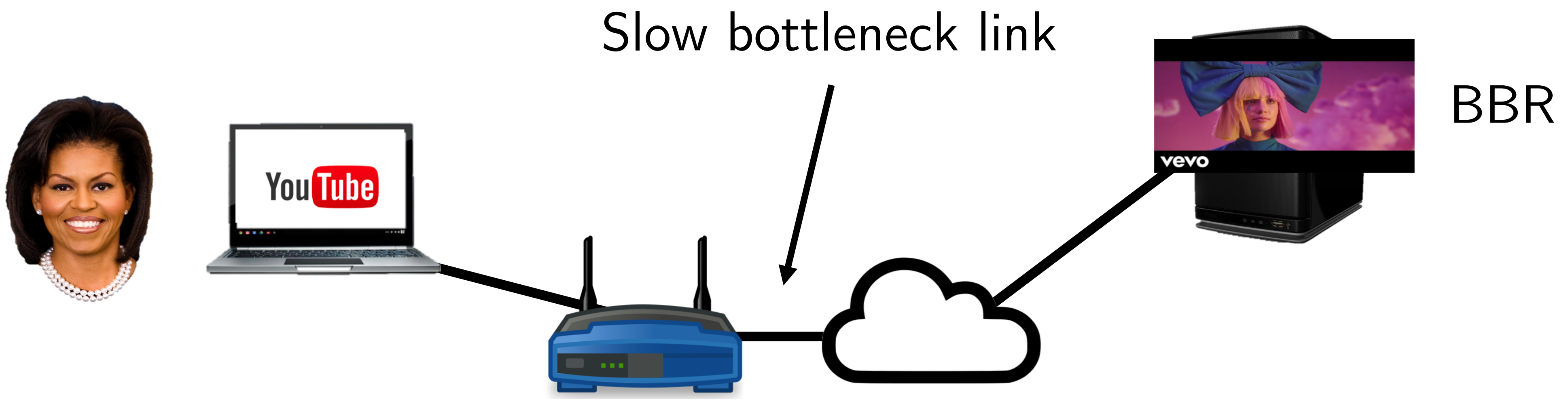
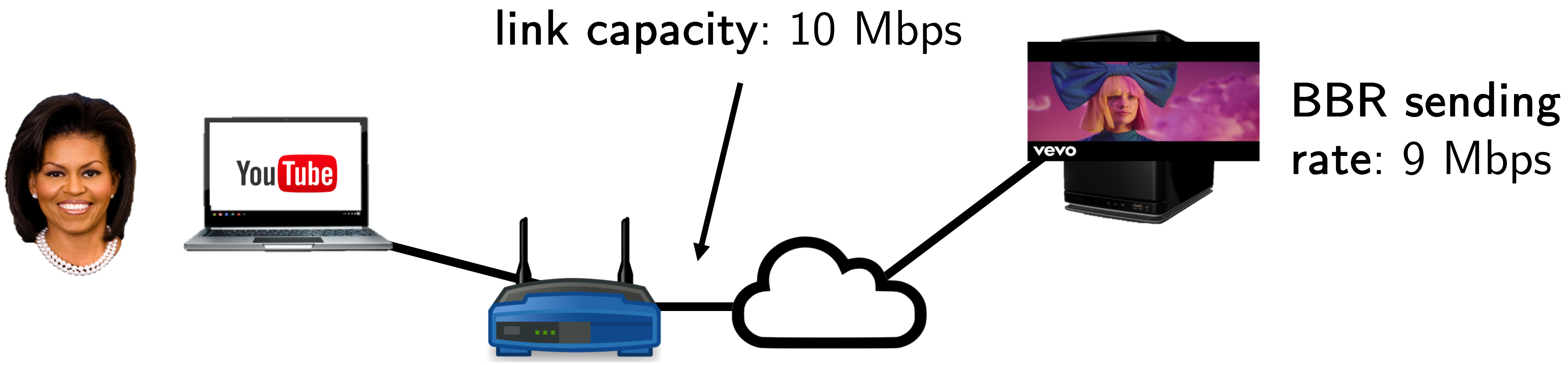
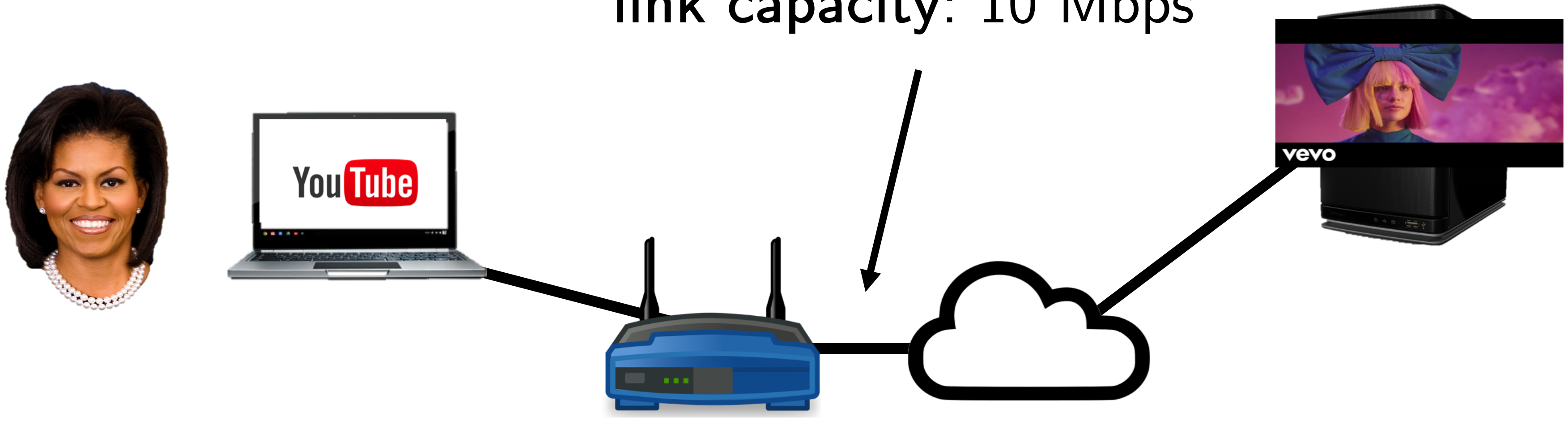


BBR bandwidth estimate is the largest throughput it has seen over an 8 RTT window.



During ProbeBW, BBR increases its sending rate by 25% to see if it can get more throughput.



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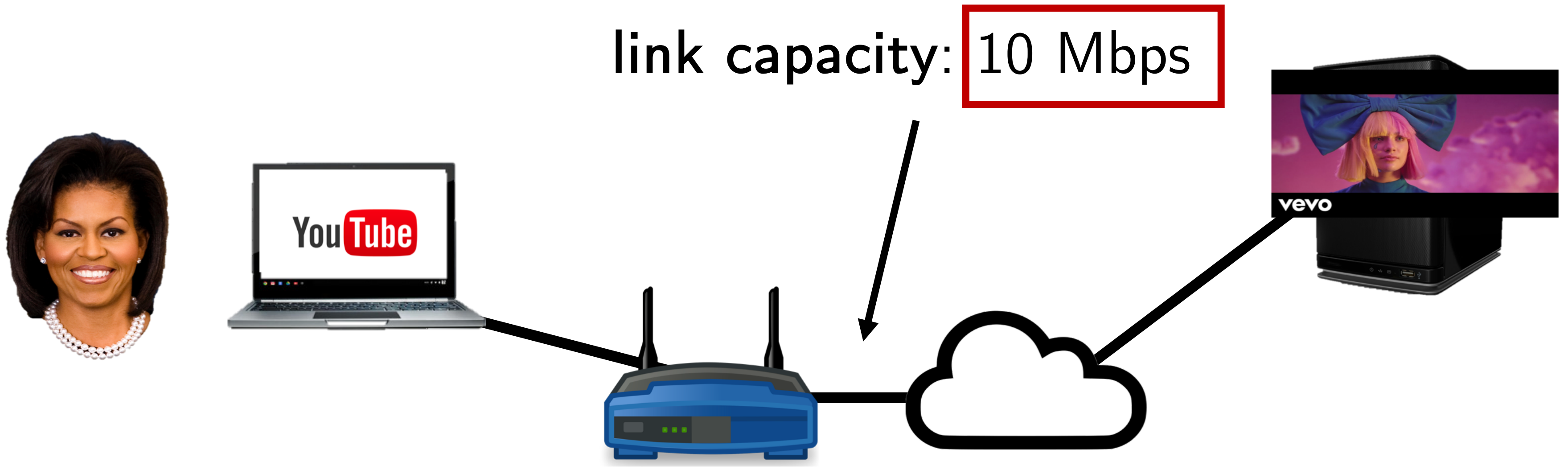
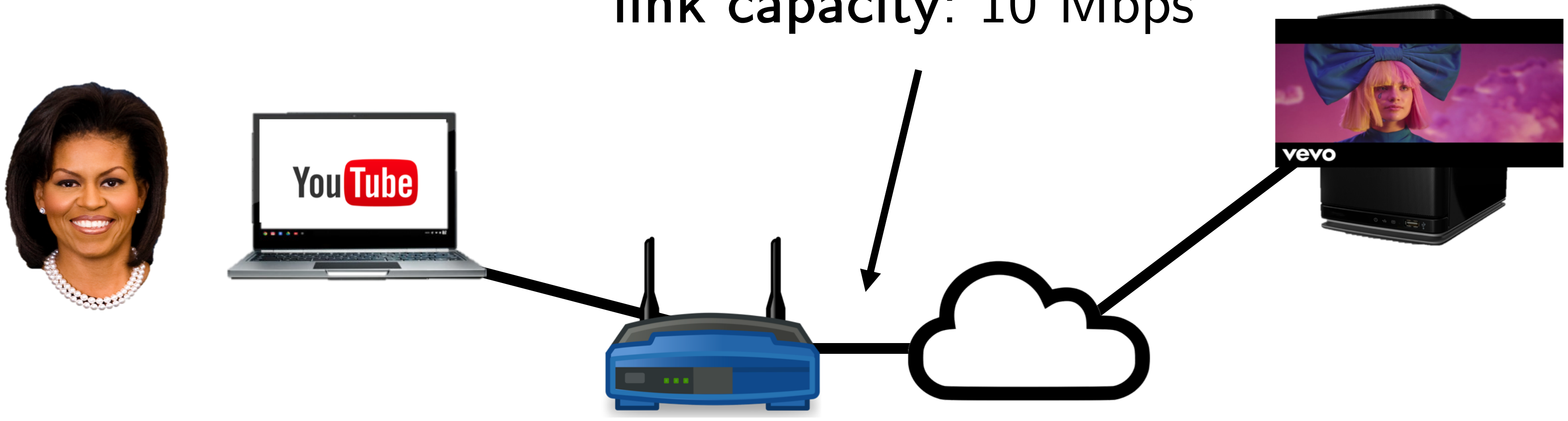


BBR sending rate: ~~9 Mbps~~
1.25 x 9 Mbps
= 11.25 Mbps

During ProbeBW, BBR increases its sending rate by 25% to see if it can get more throughput.

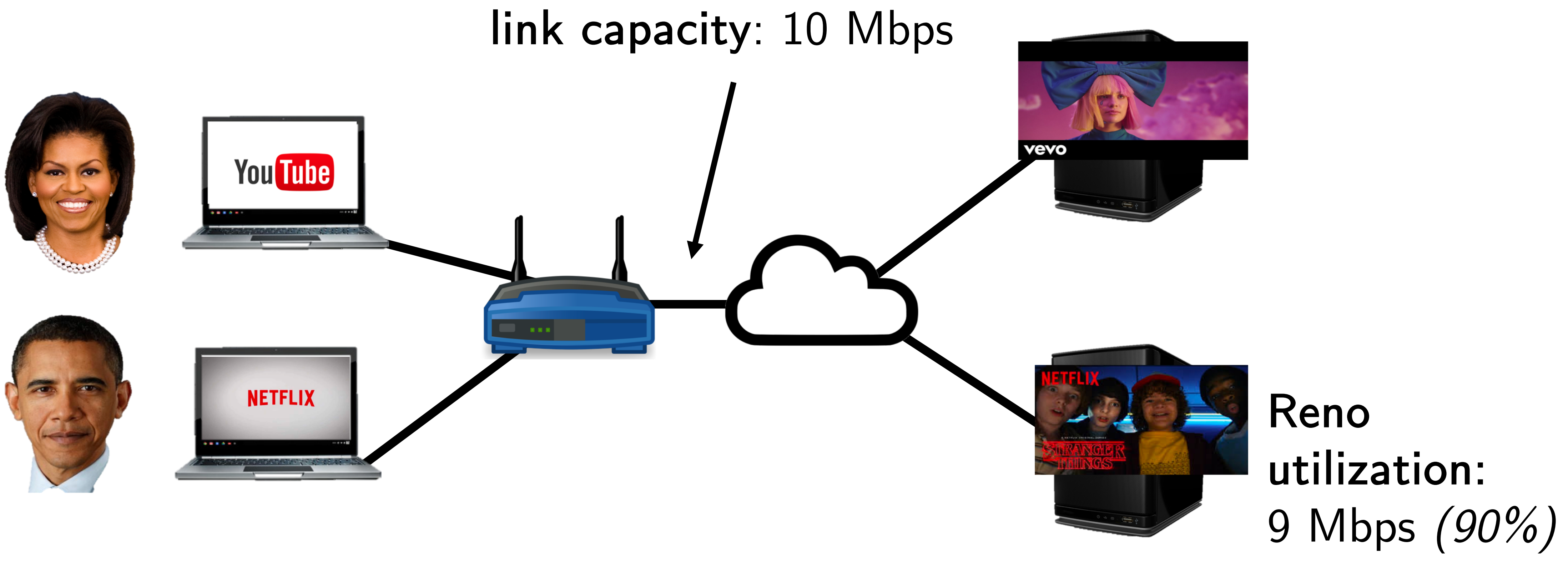
link capacity: 10 Mbps



BBR sending rate: ~~9 Mbps~~
~~1.25 x 9 Mbps~~
10 Mbps

Send at this new rate for 6 RTTs

What happens during ProbeBW when competing with Reno or Cubic?



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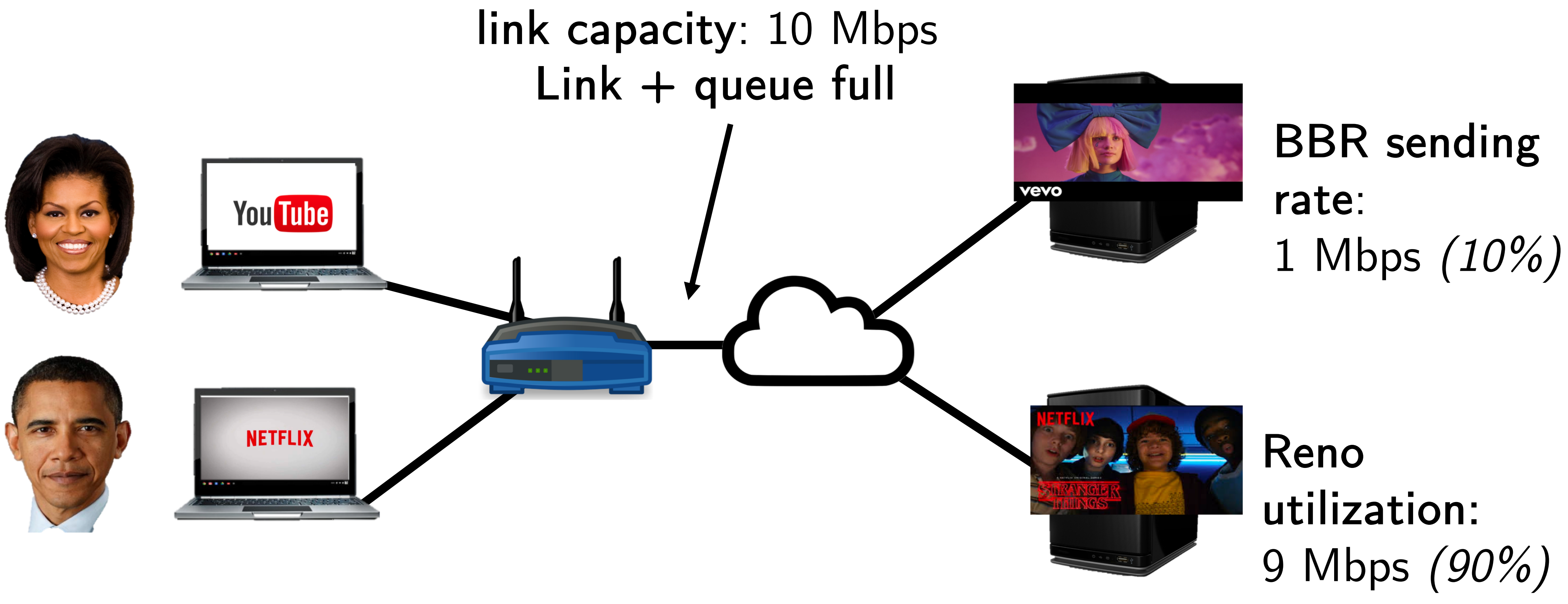
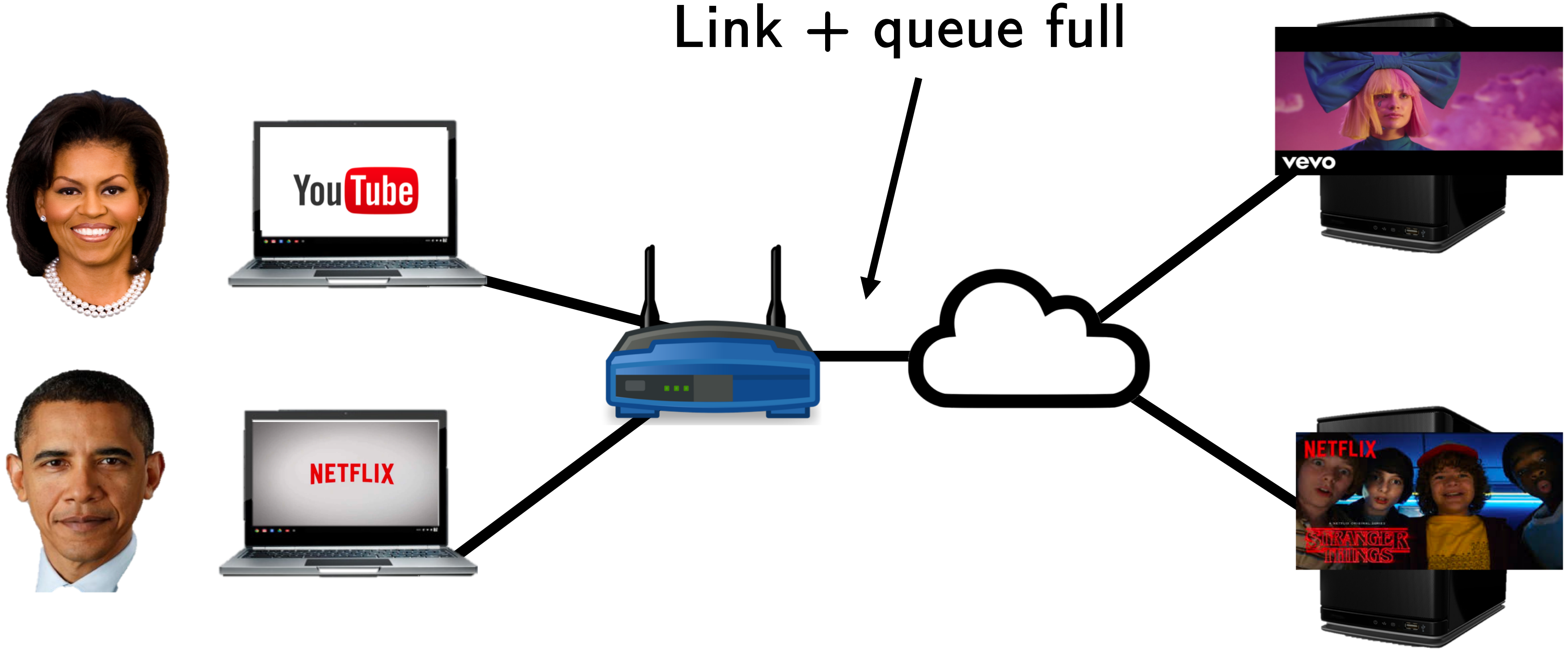


During ProbeBW, BBR will cause packet loss.



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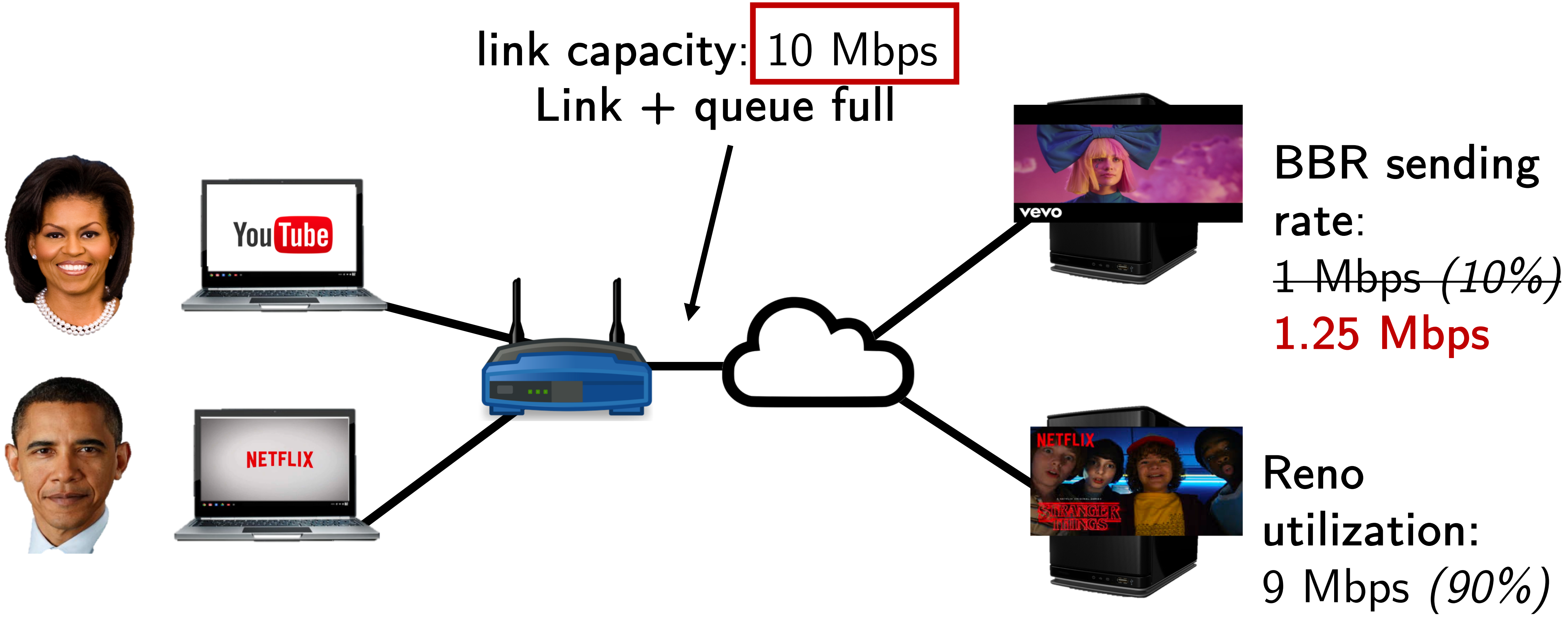
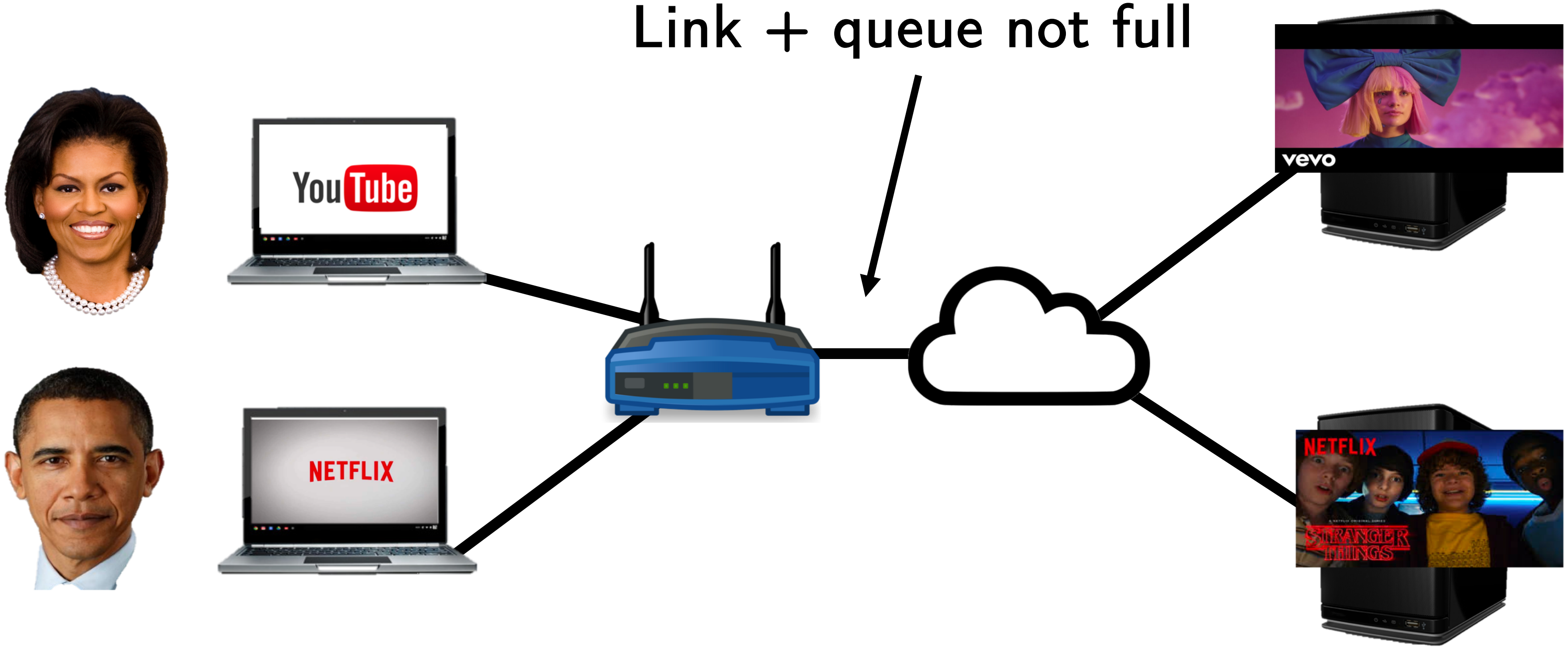


During ProbeBW, BBR will cause packet loss.

link capacity: 10 Mbps

Link + queue not full



BBR sending rate:

~~1 Mbps *(10%)*~~

~~1.25 Mbps~~

1.21 Mbps(12%)

Reno utilization:

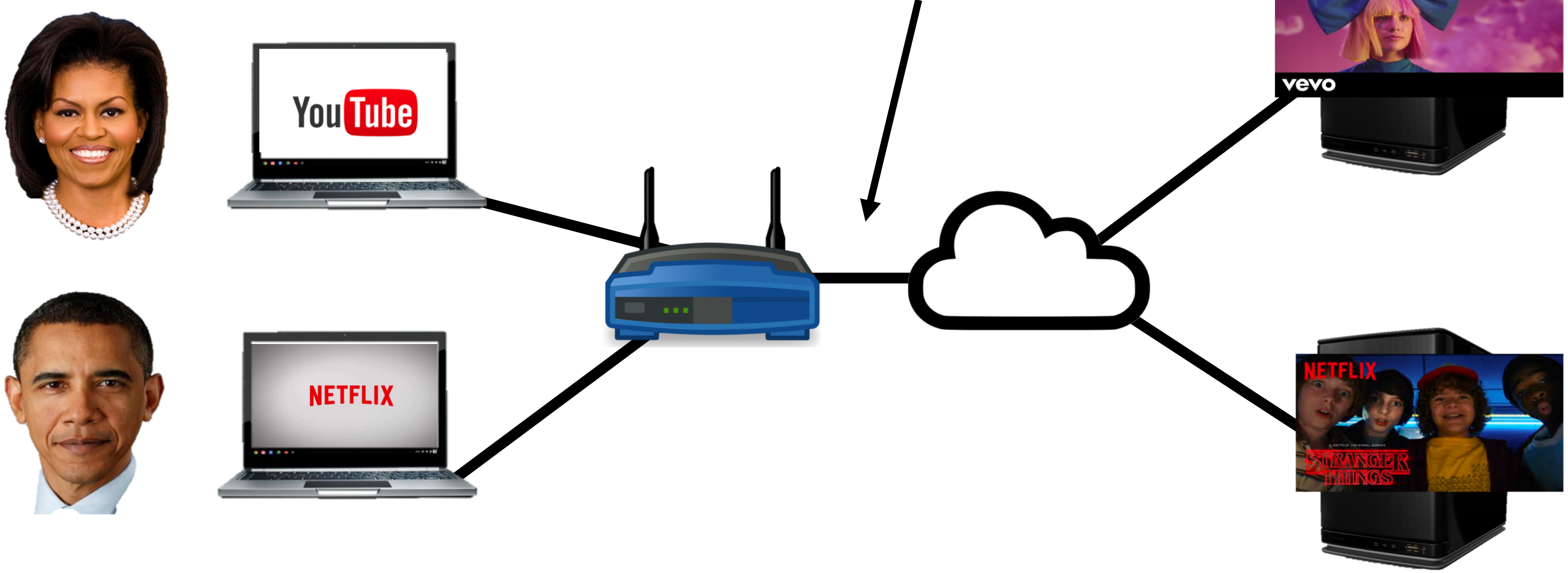
~~9 Mbps *(90%)*~~

4.5 Mbps (45%)

BBR will **increase** its steady-state sending rate while loss-based flows will back off.

link capacity: 10 Mbps

Link + queue not full



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1.21 Mbps(12%)

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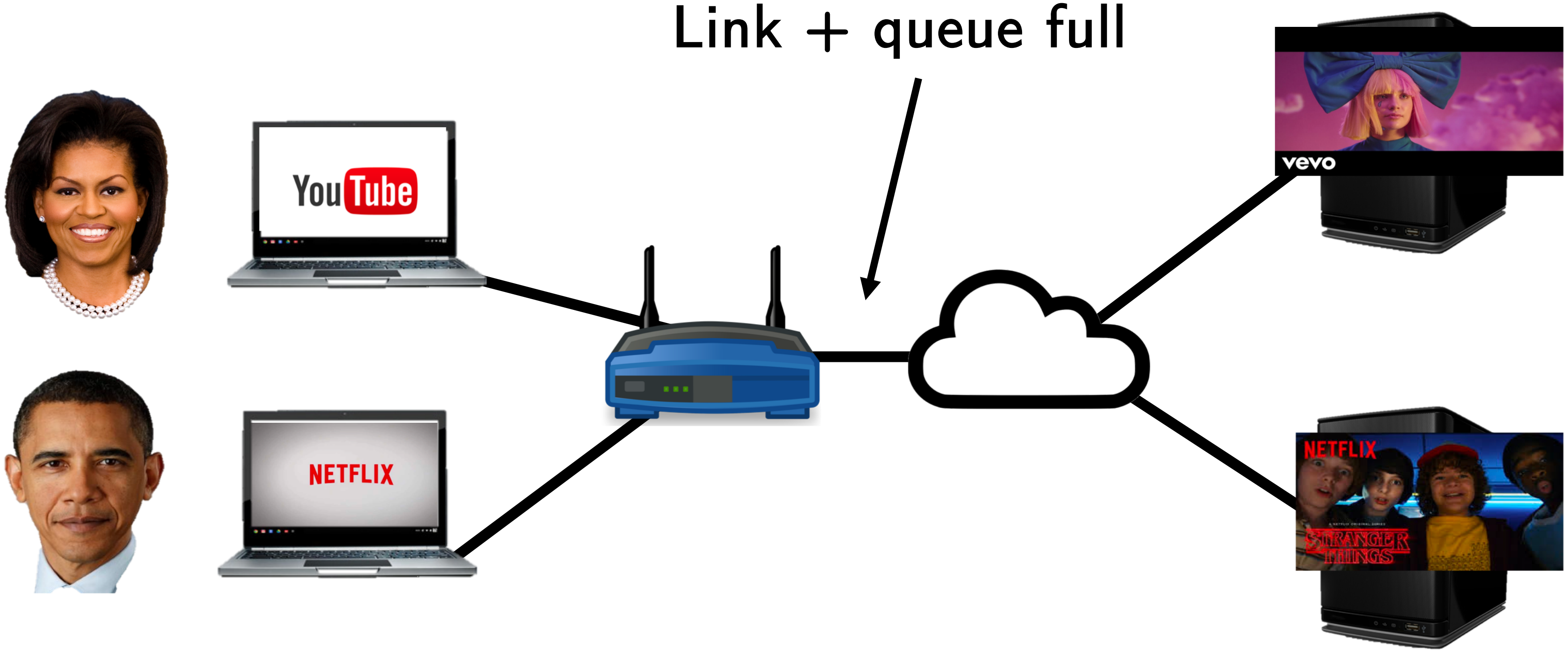
4.5 Mbps (45%)

BBR's new rate is 1.21 Mbps

Cubic and Reno cannot return to their former throughput.

link capacity: 10 Mbps
Link + queue full



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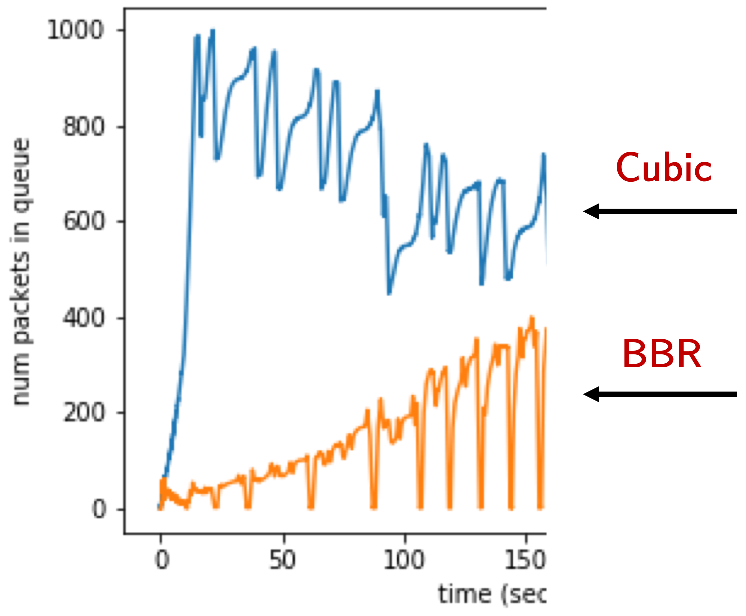
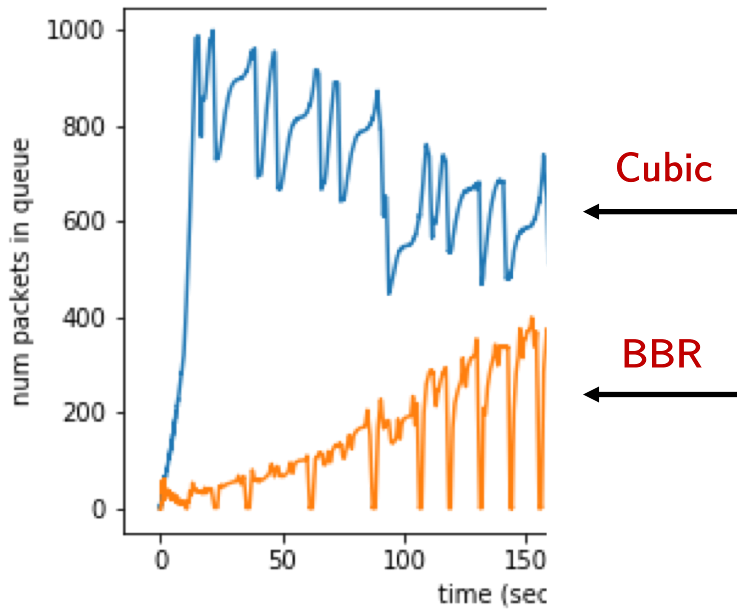
~~1 Mbps *(10%)*~~
~~1.25 Mbps~~
1.21 Mbps(12%)

Reno utilization:
~~9 Mbps *(90%)*~~
~~4.5 Mbps (45%)~~
8.79 Mbps (88%)



During ProbeBW, BBR will put more packets into the queue and will update its BW estimate.



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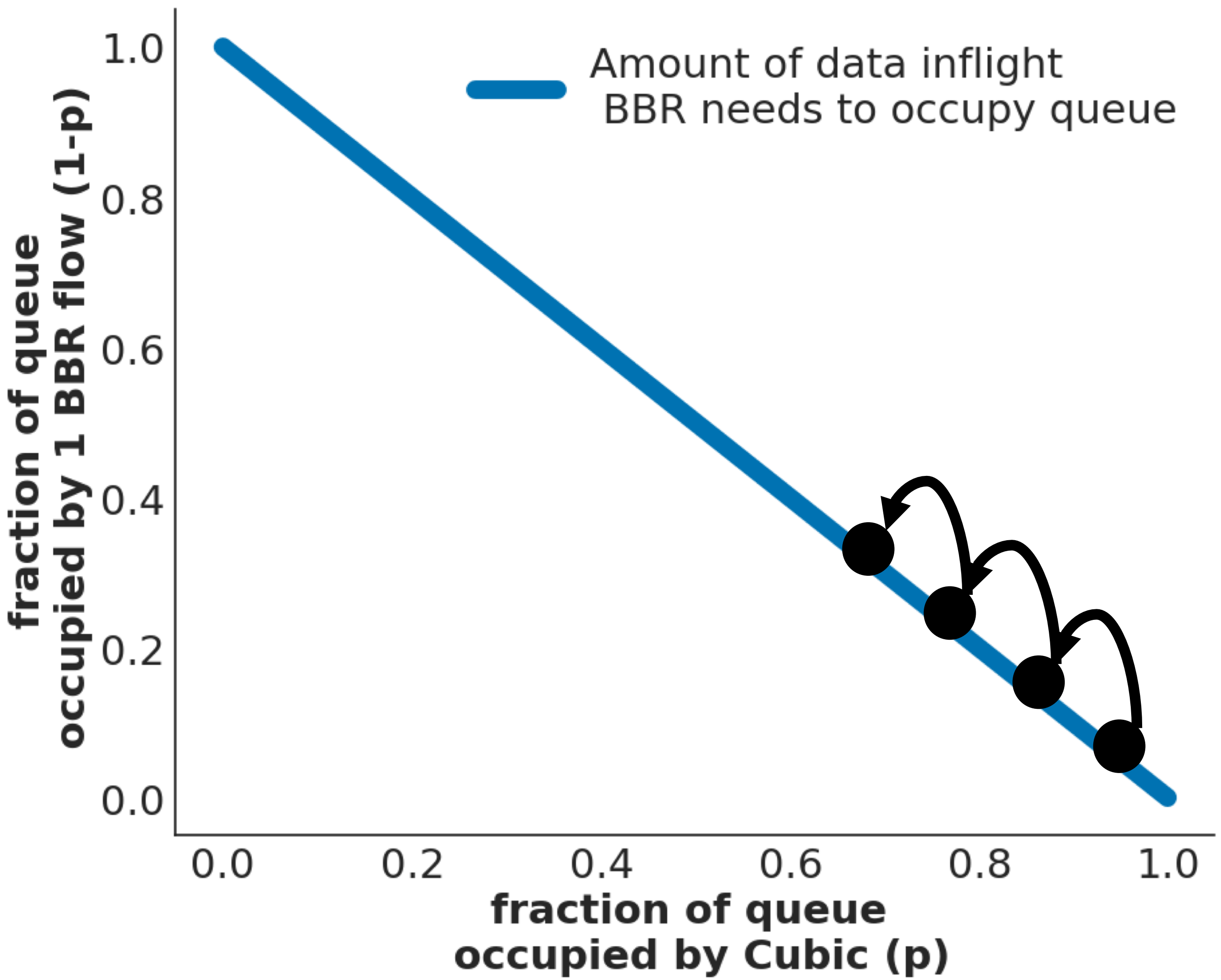
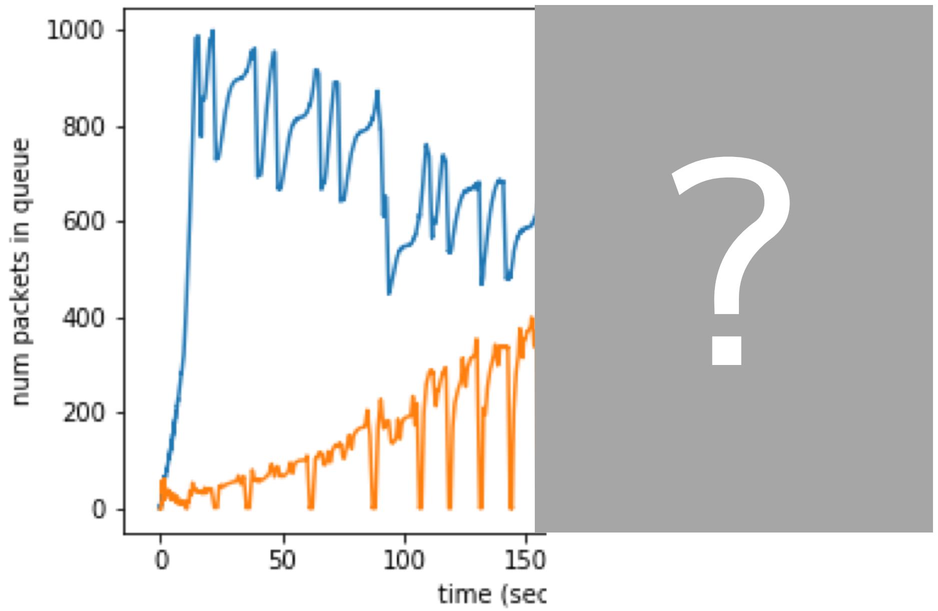
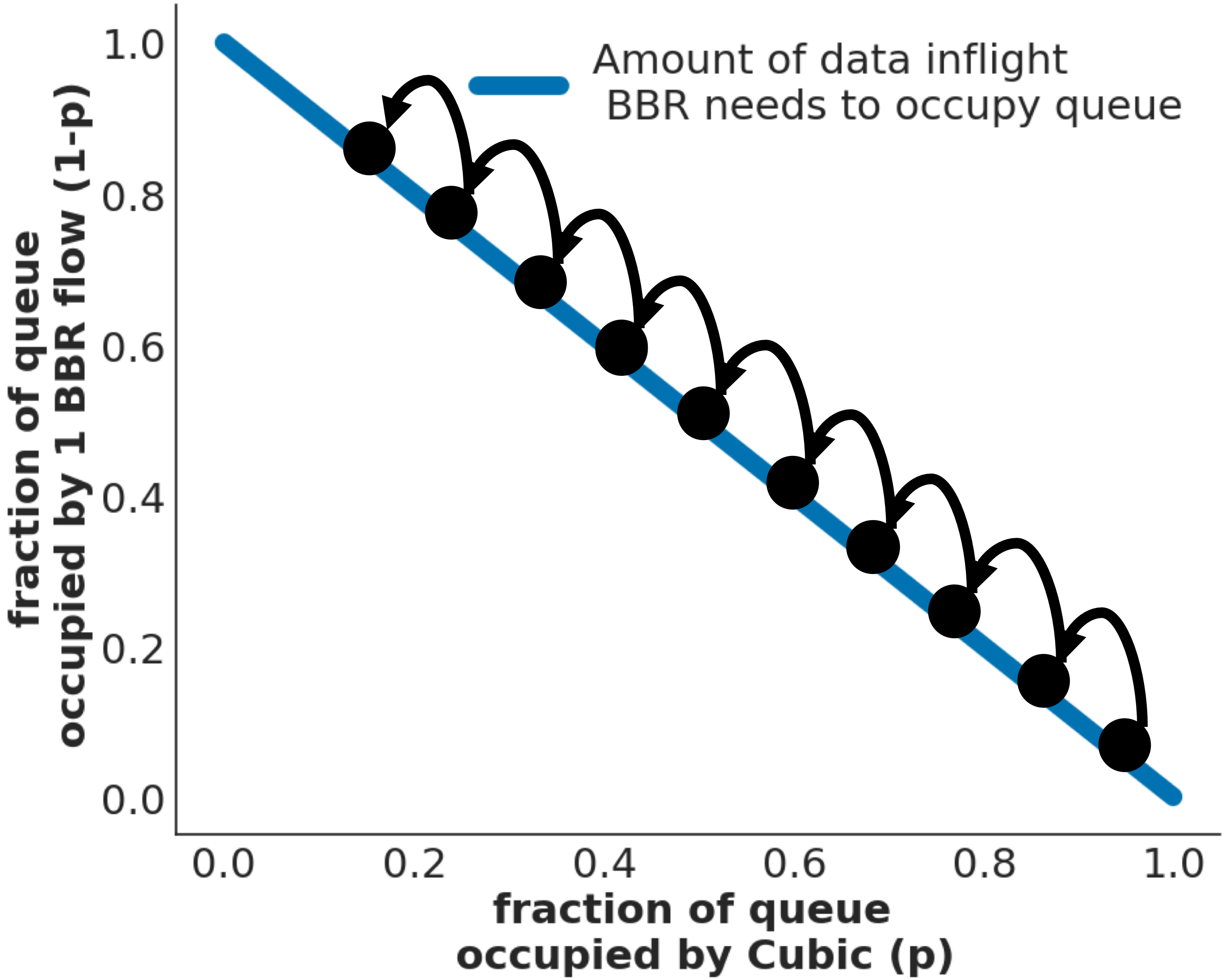
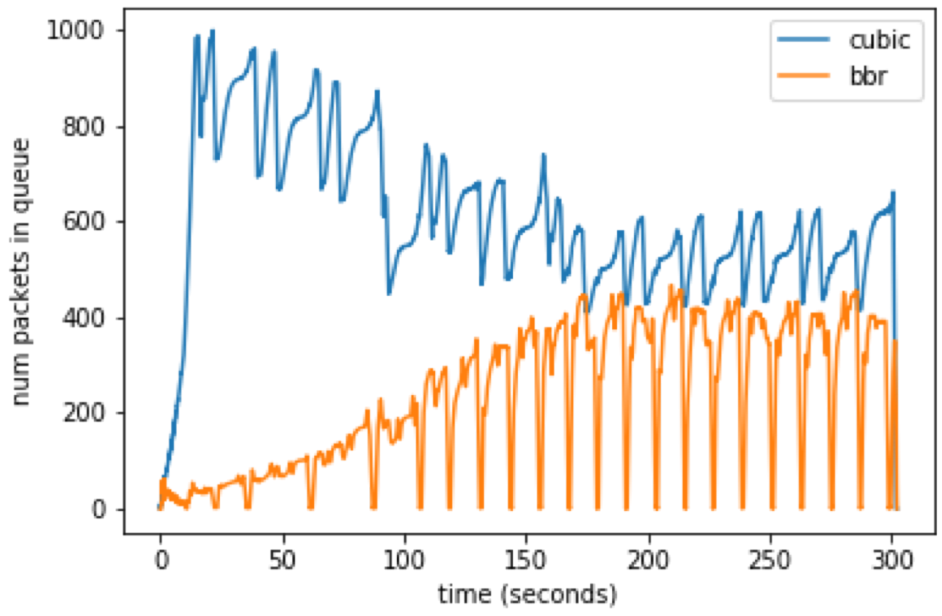


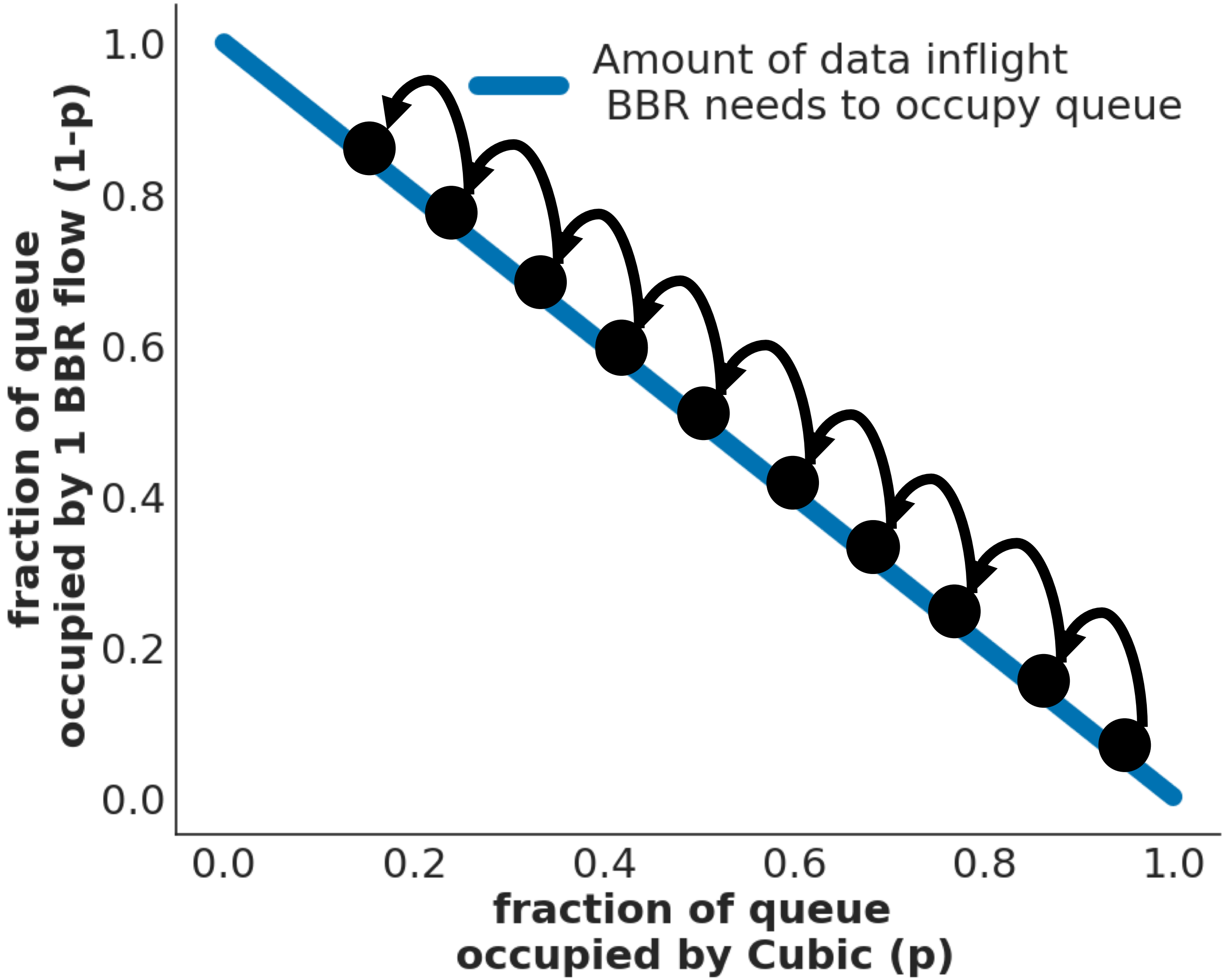


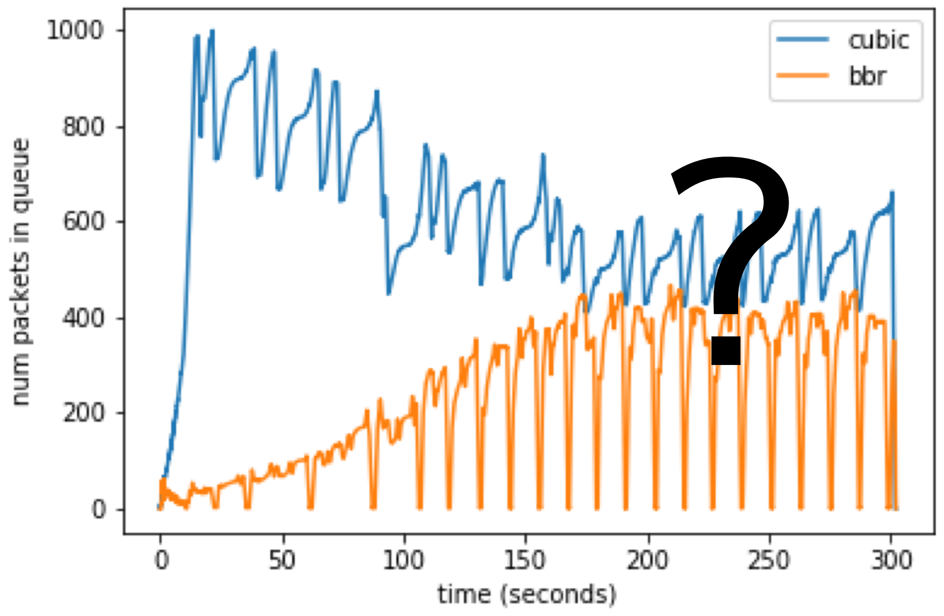
Shouldn't BBR just keep going into ProbeBW, putting more and more packets into the queue?





Why doesn't BBR keep putting more packets into the queue?





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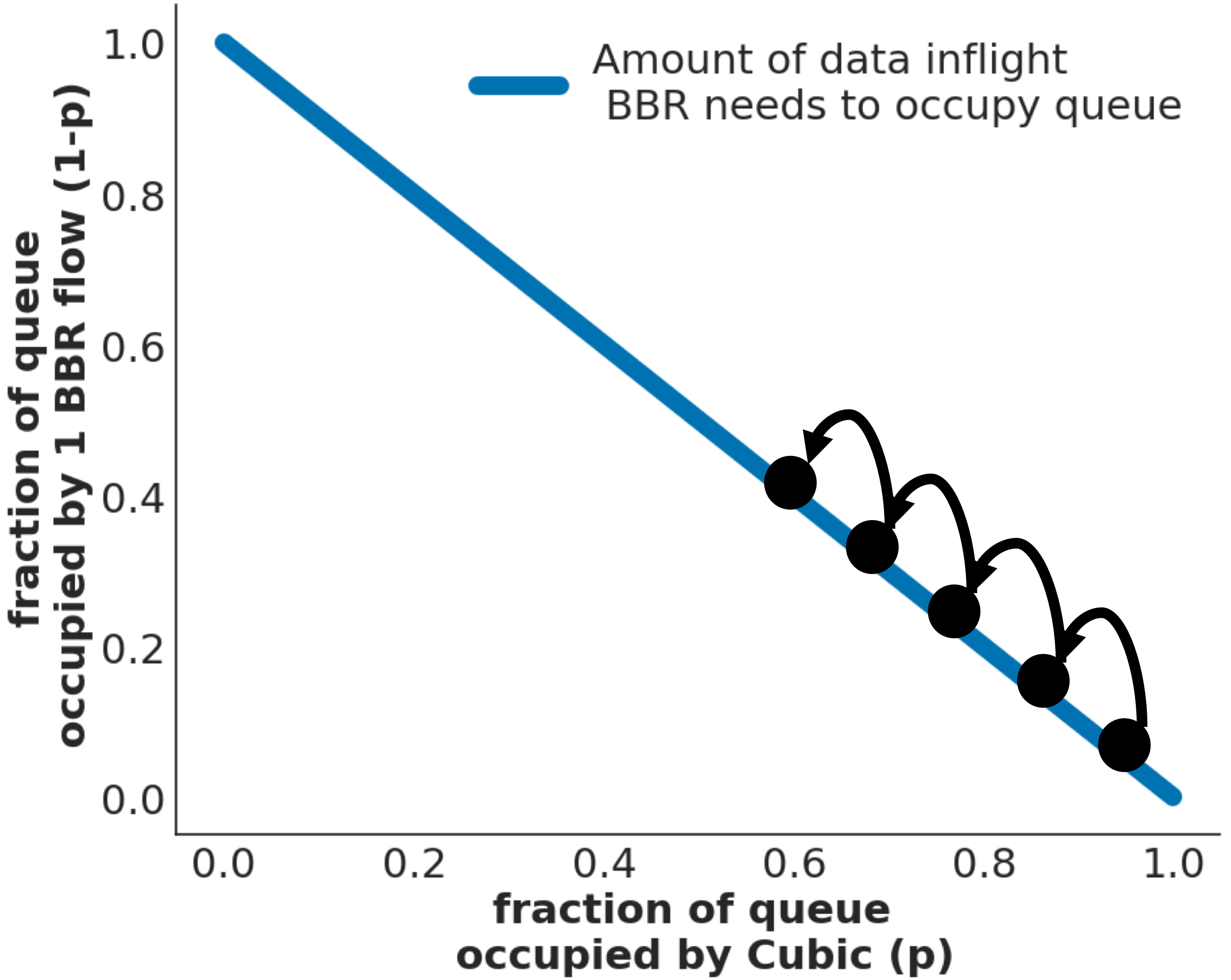

What is stopping ProbeBW from consuming the whole link?

One sentence in the BBR paper revealed the answer.

> DELAYED AND STRETCHED ACKS
>
> Cellular, Wi-Fi, and cable broadband networks often delay and aggregate ACKs.[1] When inflight is limited to one BDP, this results in throughput-reducing stalls. Raising ProbeBW's cwnd_gain to two allowed BBR to continue sending smoothly at the estimated delivery rate, even when ACKs are delayed by up to one RTT. This largely avoids stalls.

A safety mechanism dictates BBR's link fraction under competition.

Key Insight:
Under competition,
BBR is not rate-limited,
it is <u>window-limited</u>
due to the in-flight cap.

We need to model the **in-flight cap**.

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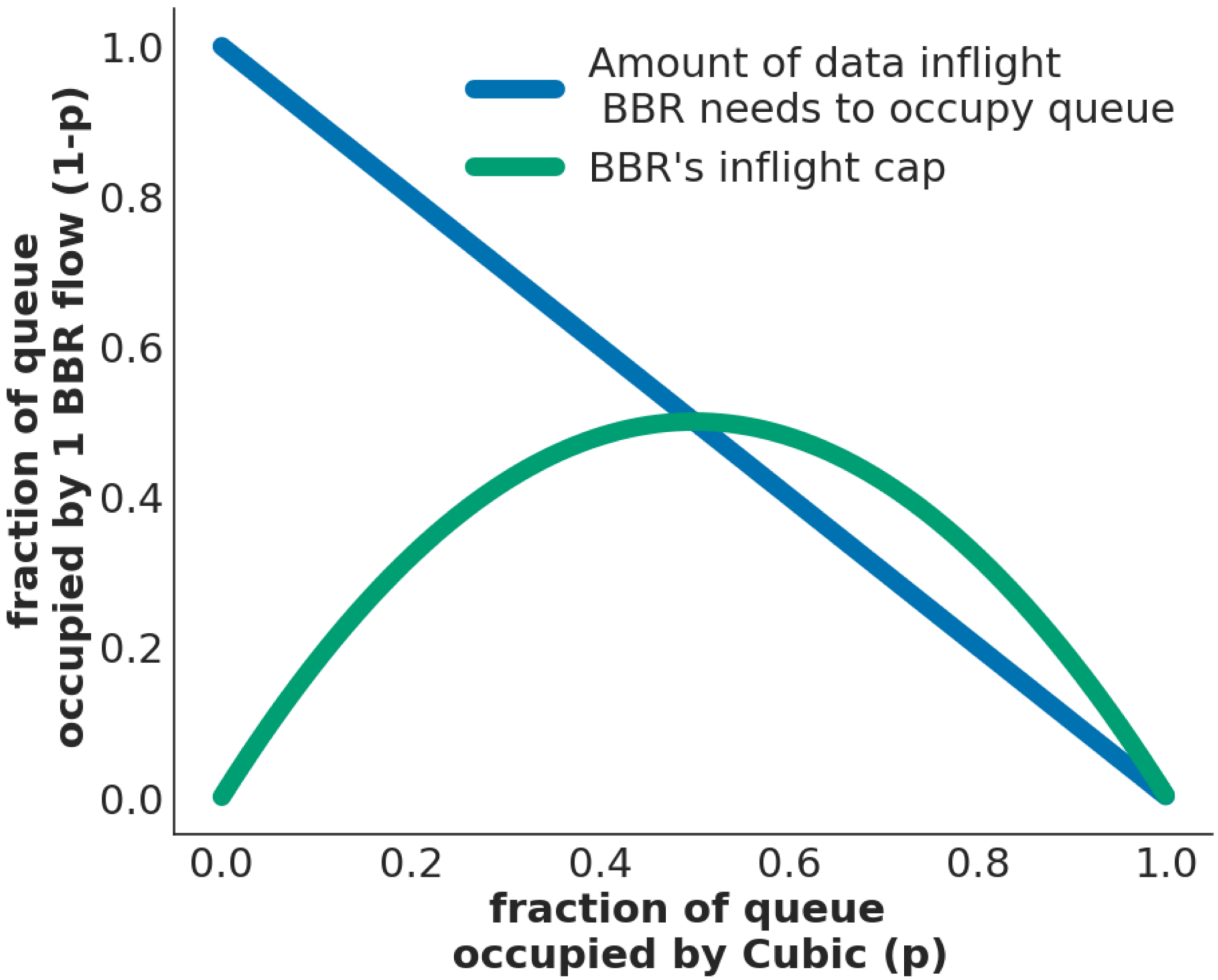


Assume that we have 1 BBR flow vs. 1 Cubic flow in a **deep-buffered network**.

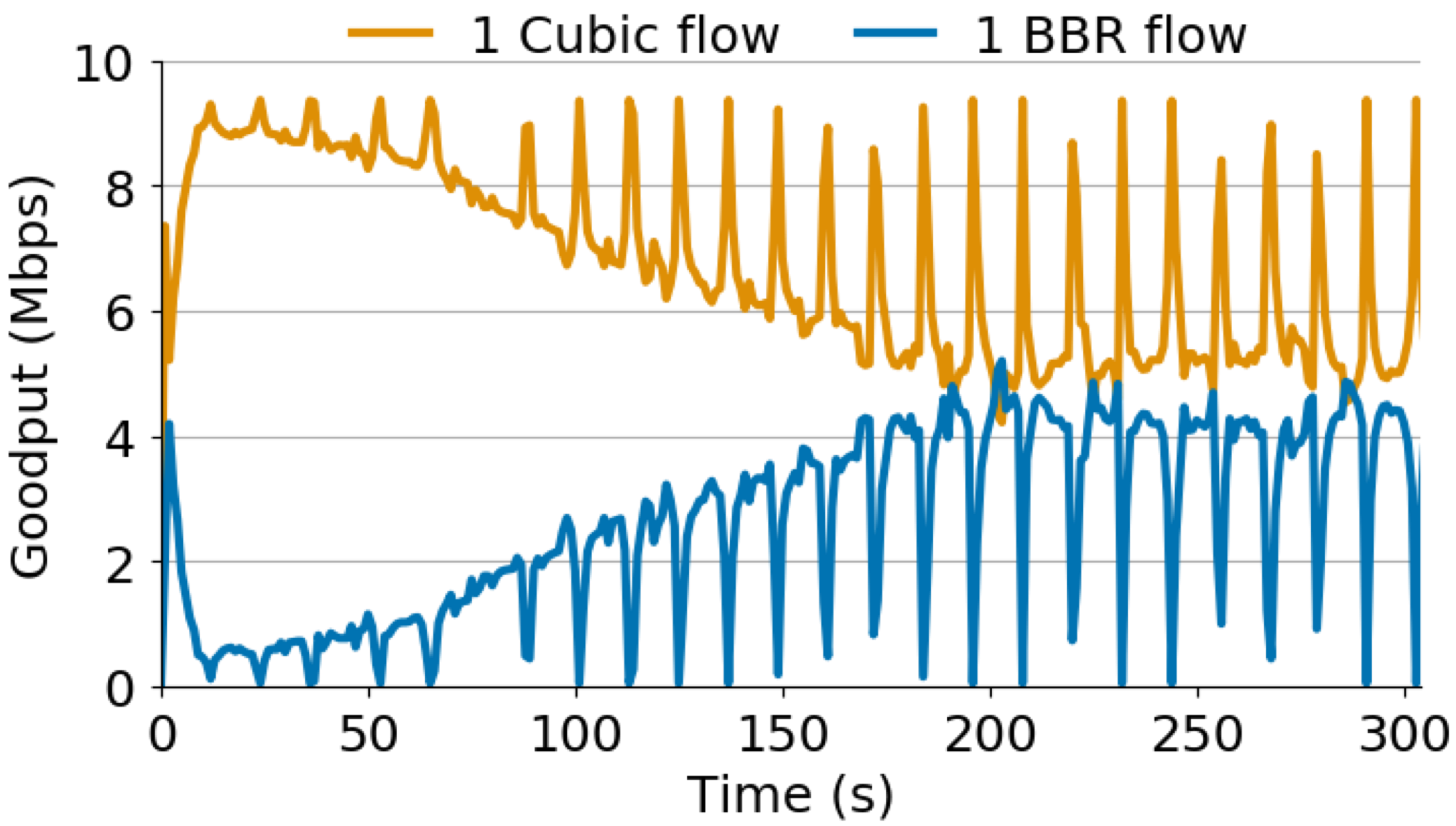
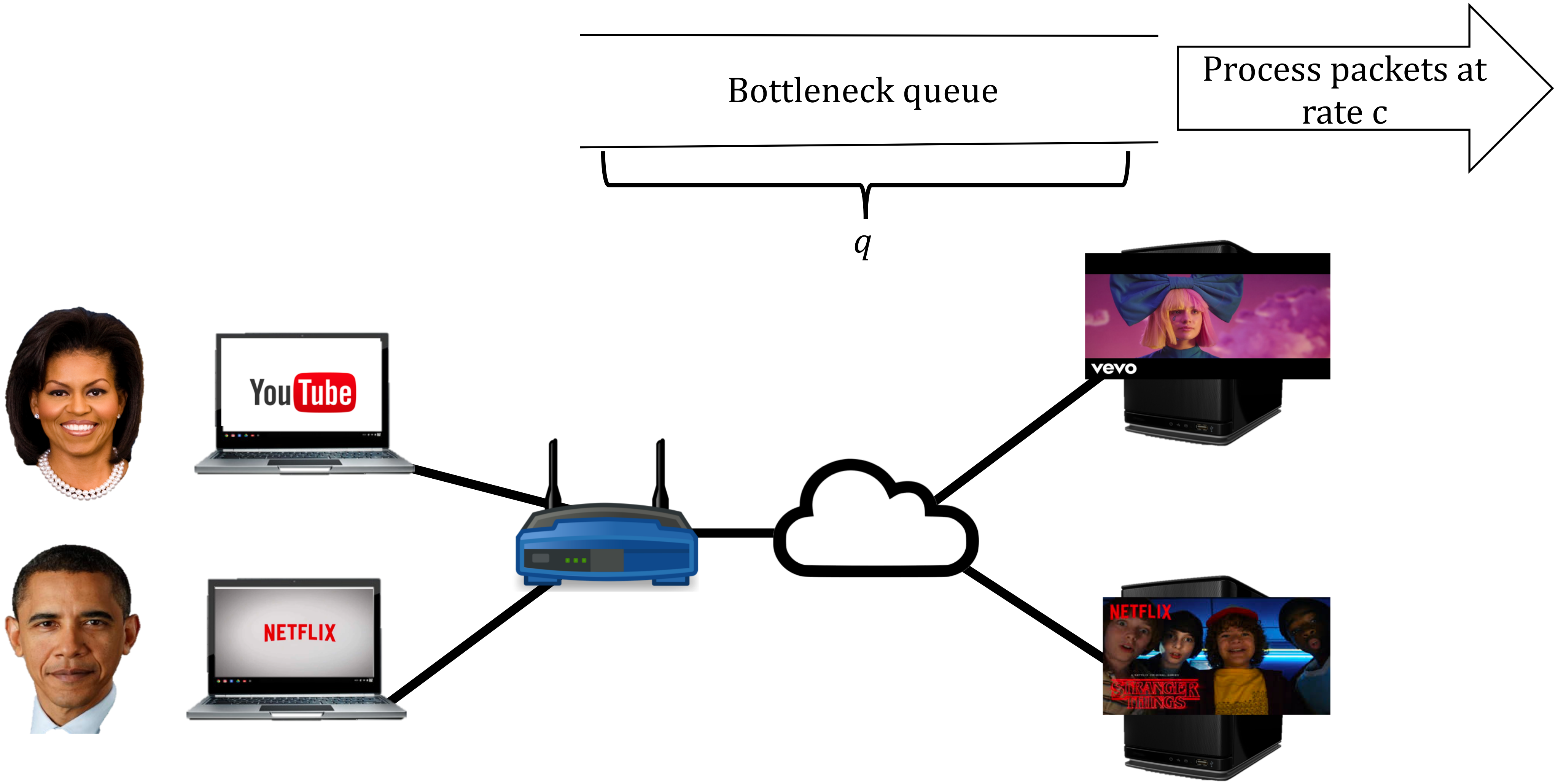


Figure: 1 BBR vs. 1 Cubic. (10 Mbps network, 32 BDP queue)

Assume:

c = btlnk link capacity

q = size of btlnk queue



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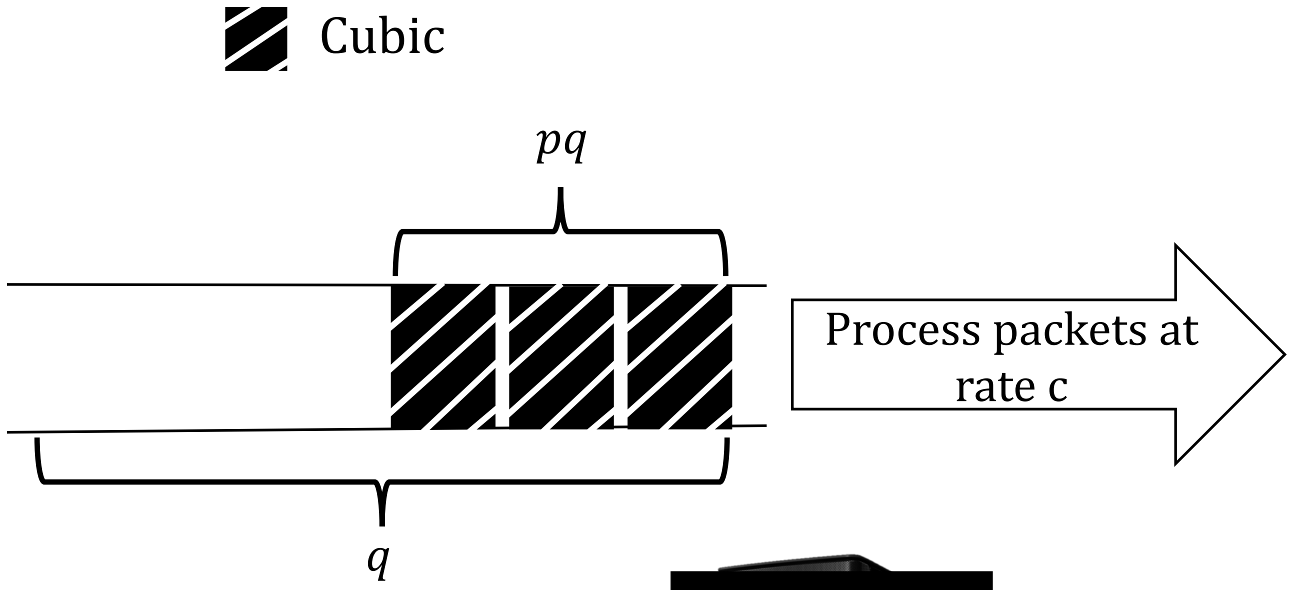

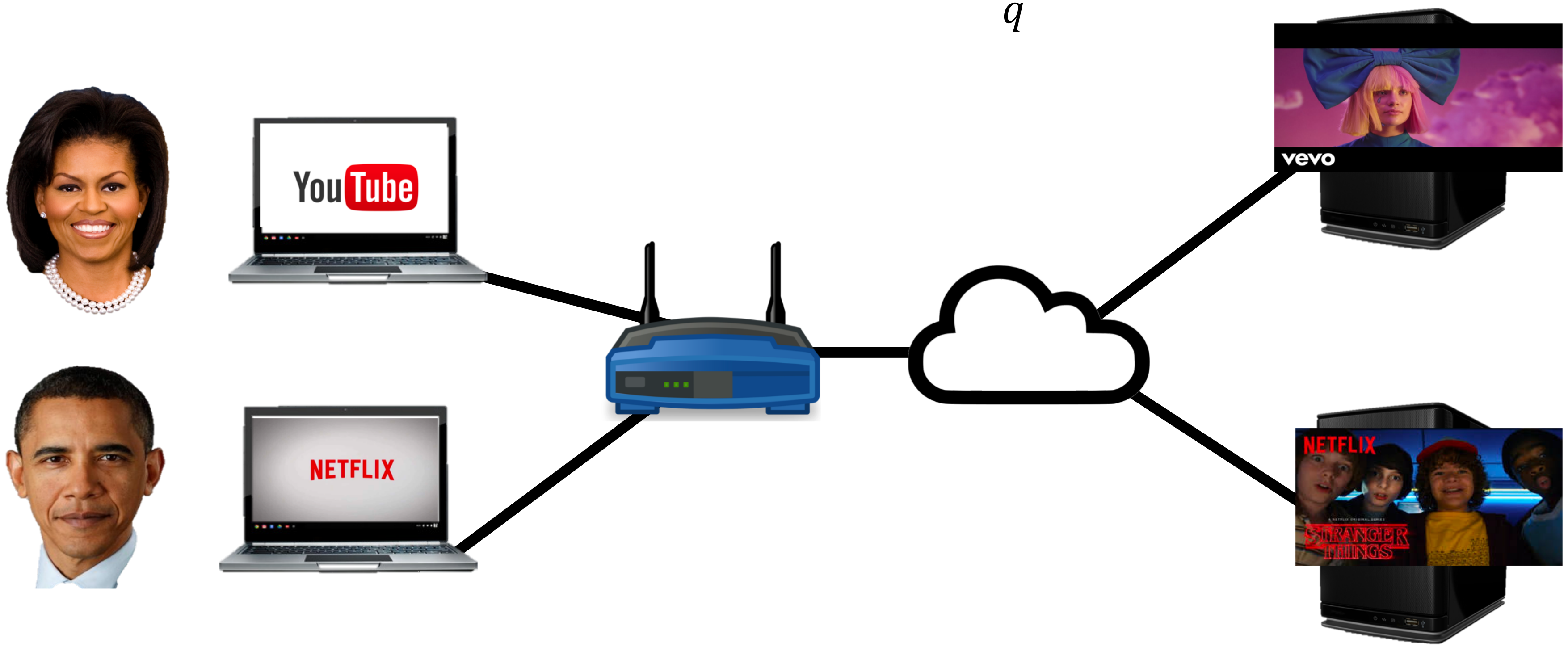

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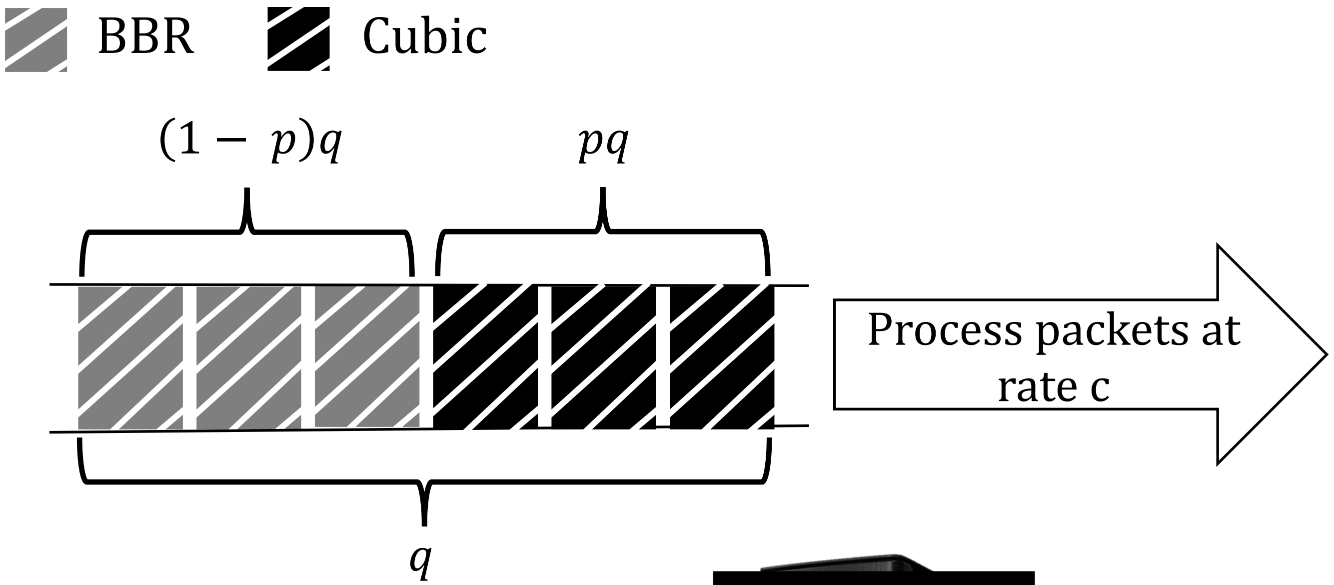

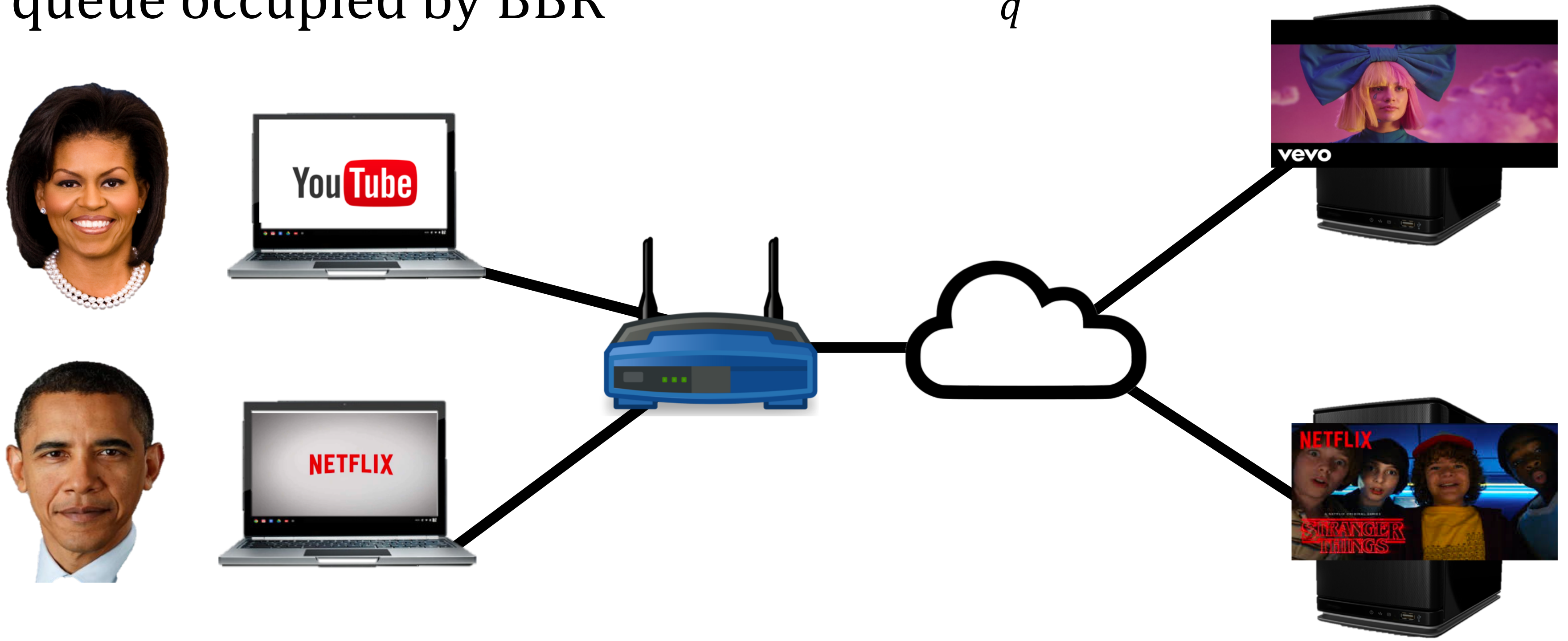

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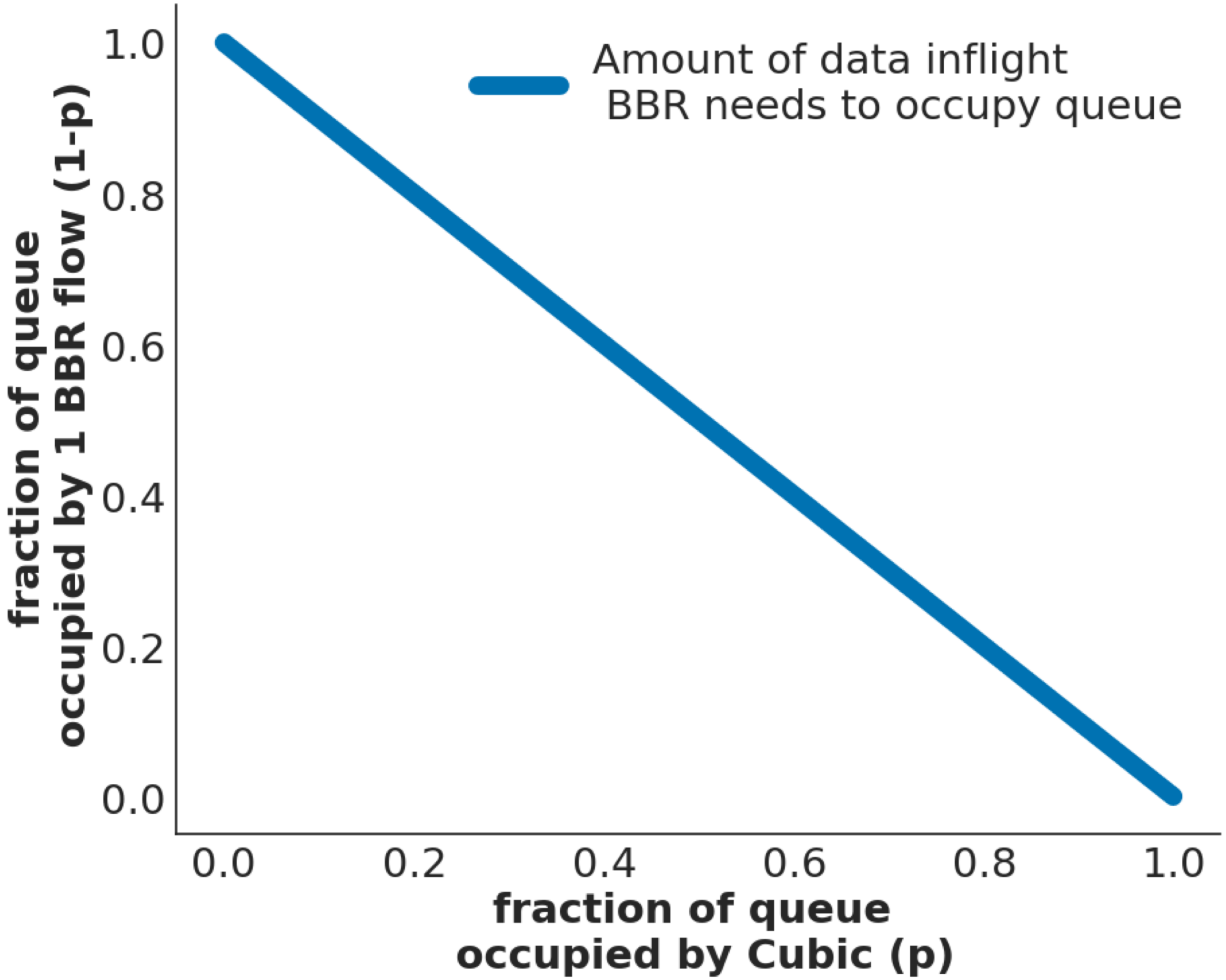

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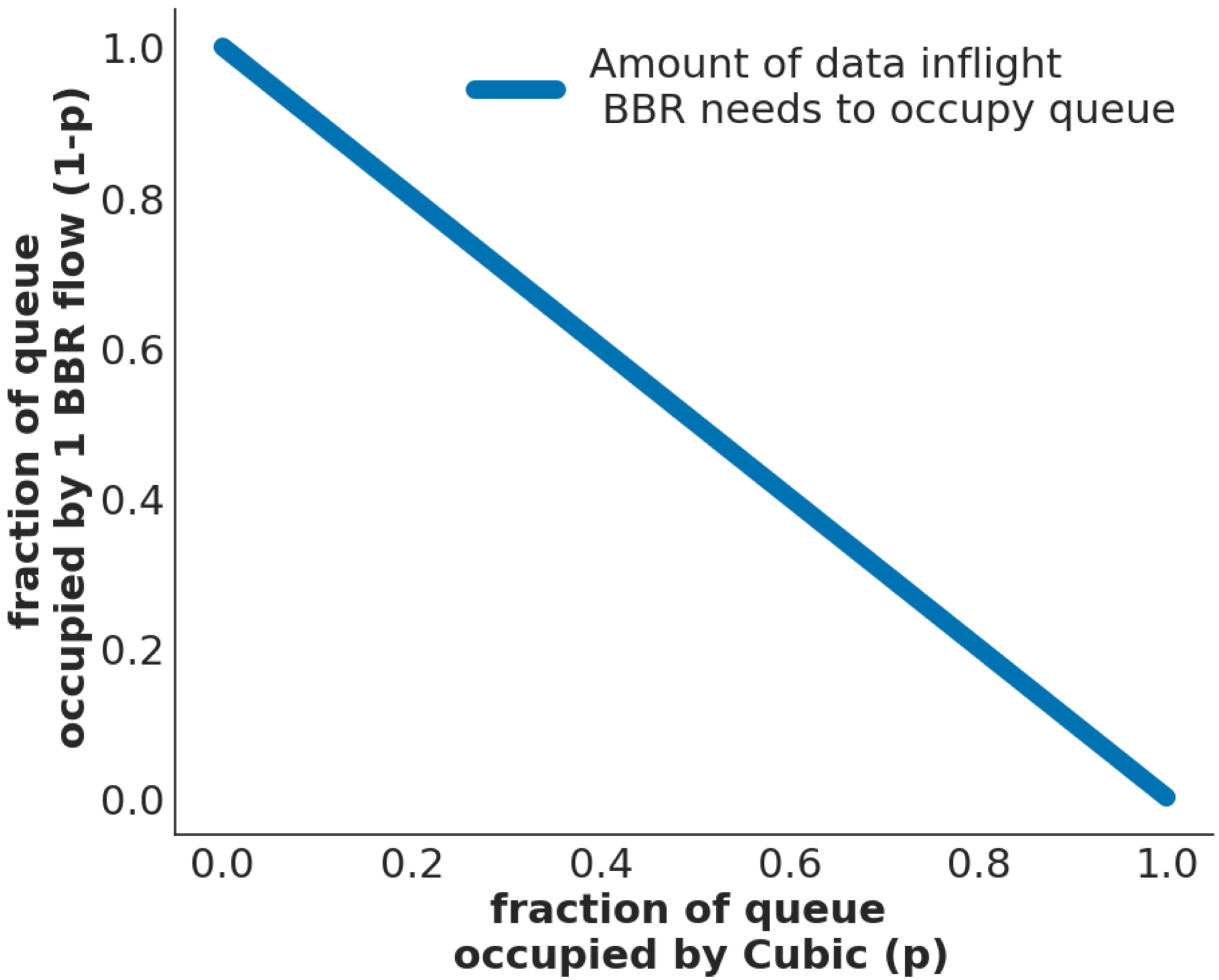
BBR inflight cap
$= 2 * BW * RTT$

$BW = (1 - \mathrm{p}) * \mathrm{c}$



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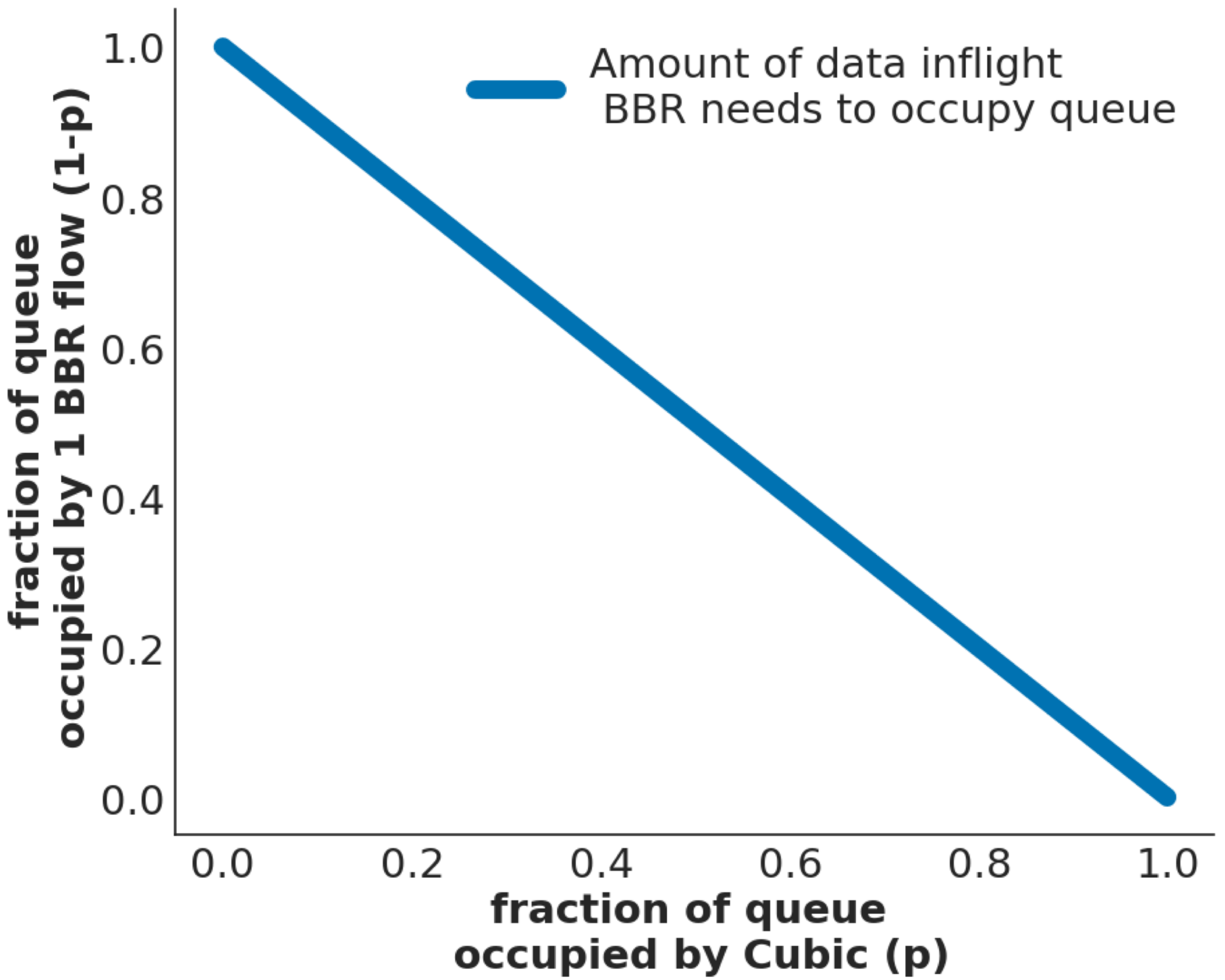

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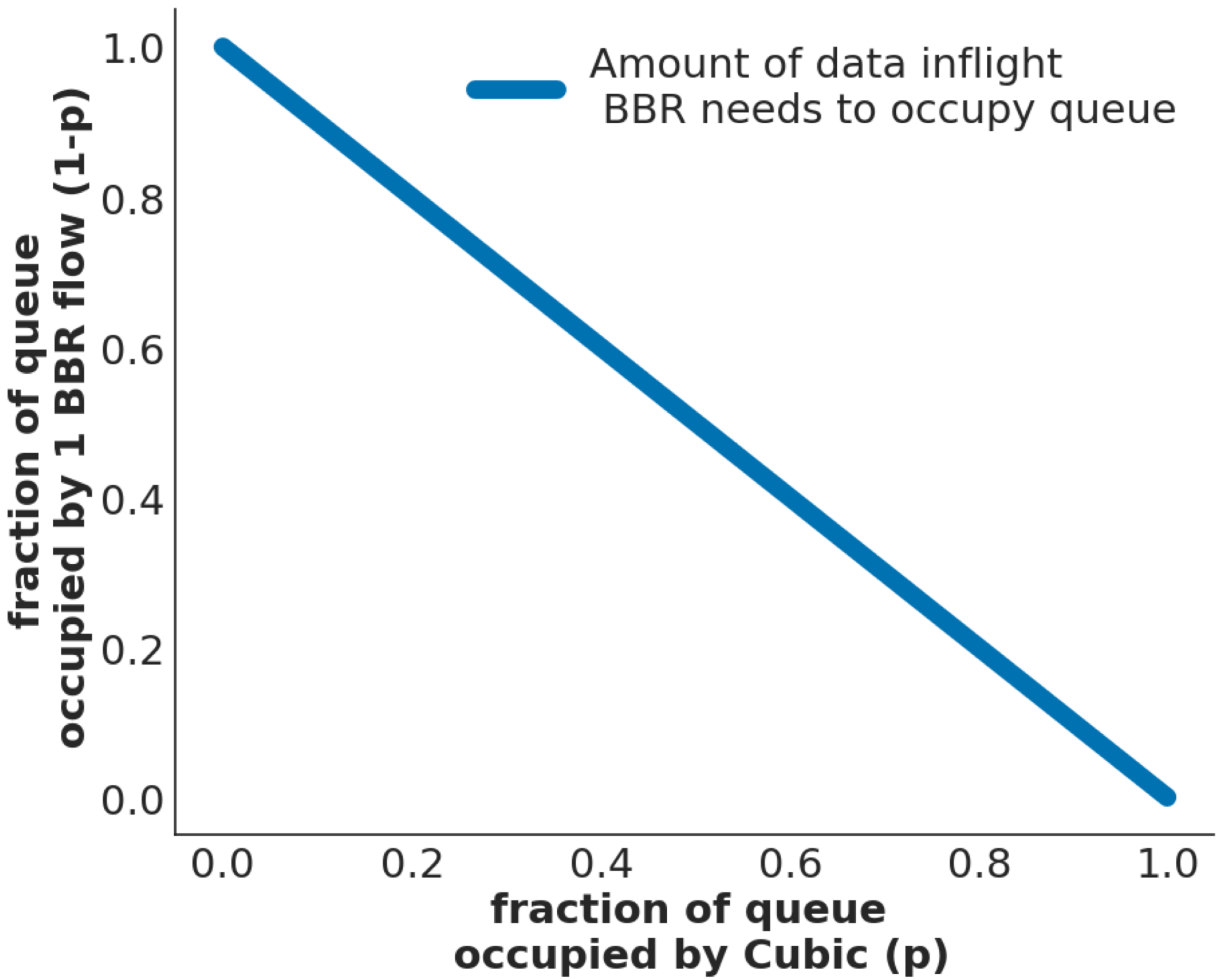

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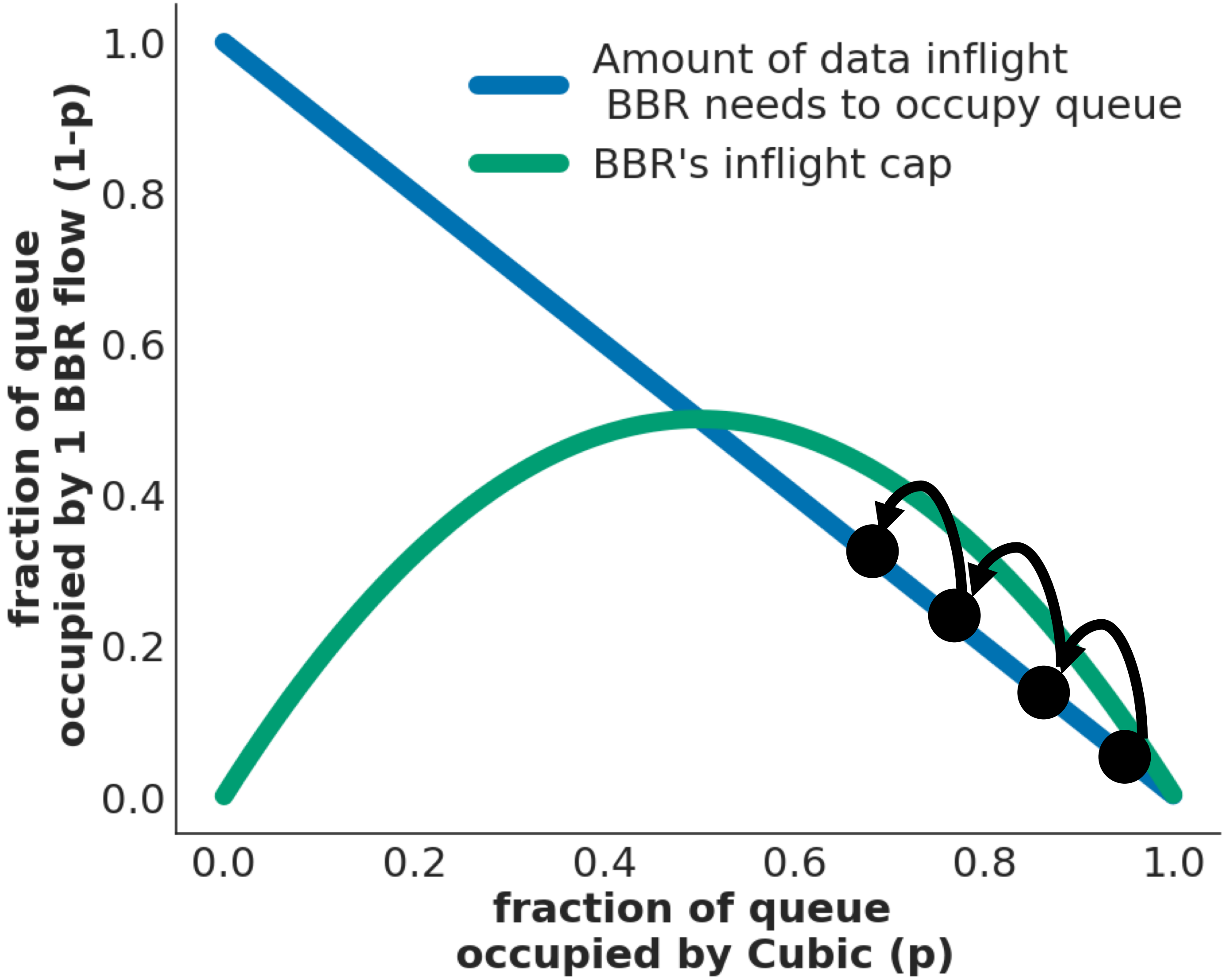

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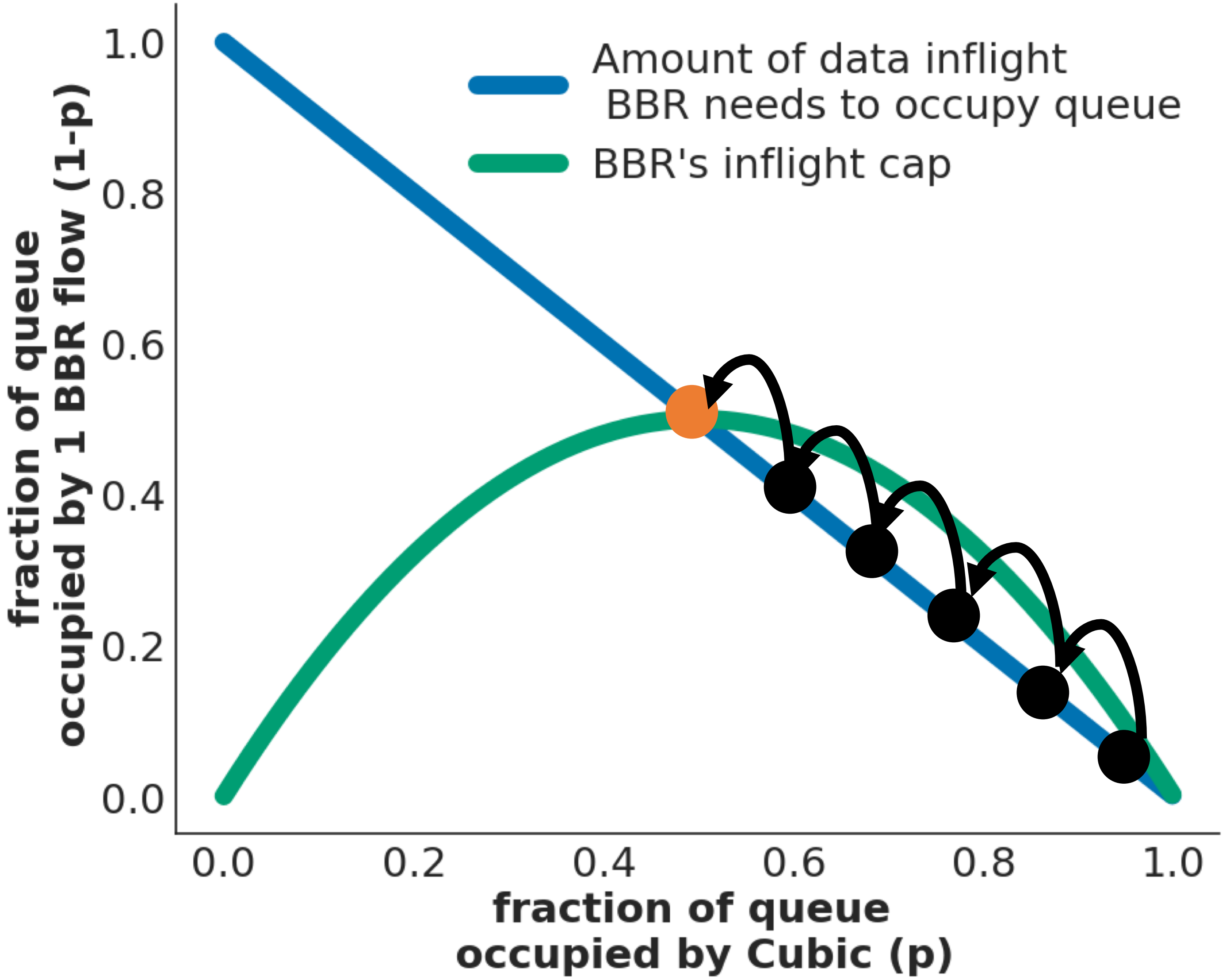

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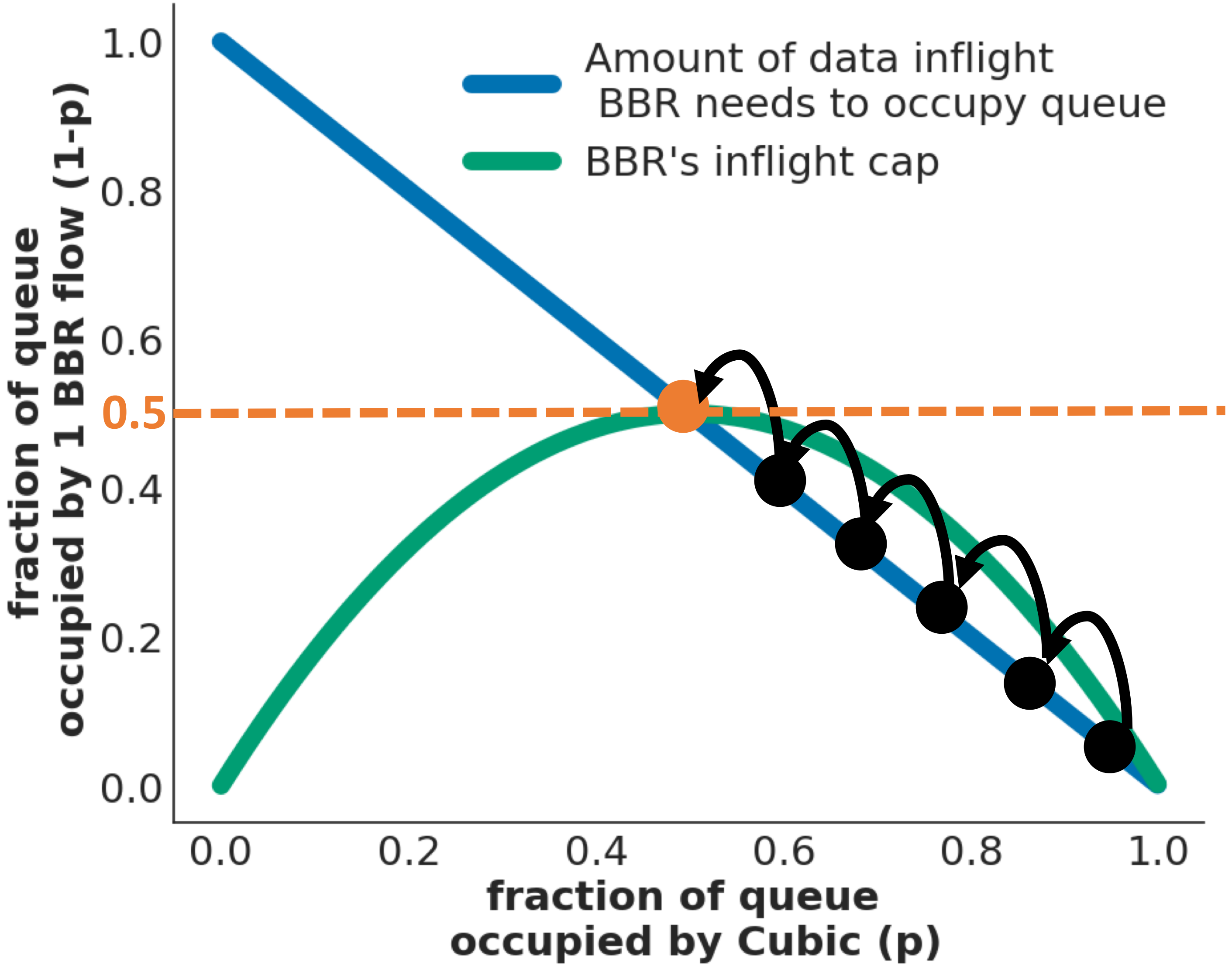

1 BBR flow gets **up to half the queue/link** with a 2 BDP in-flight cap.

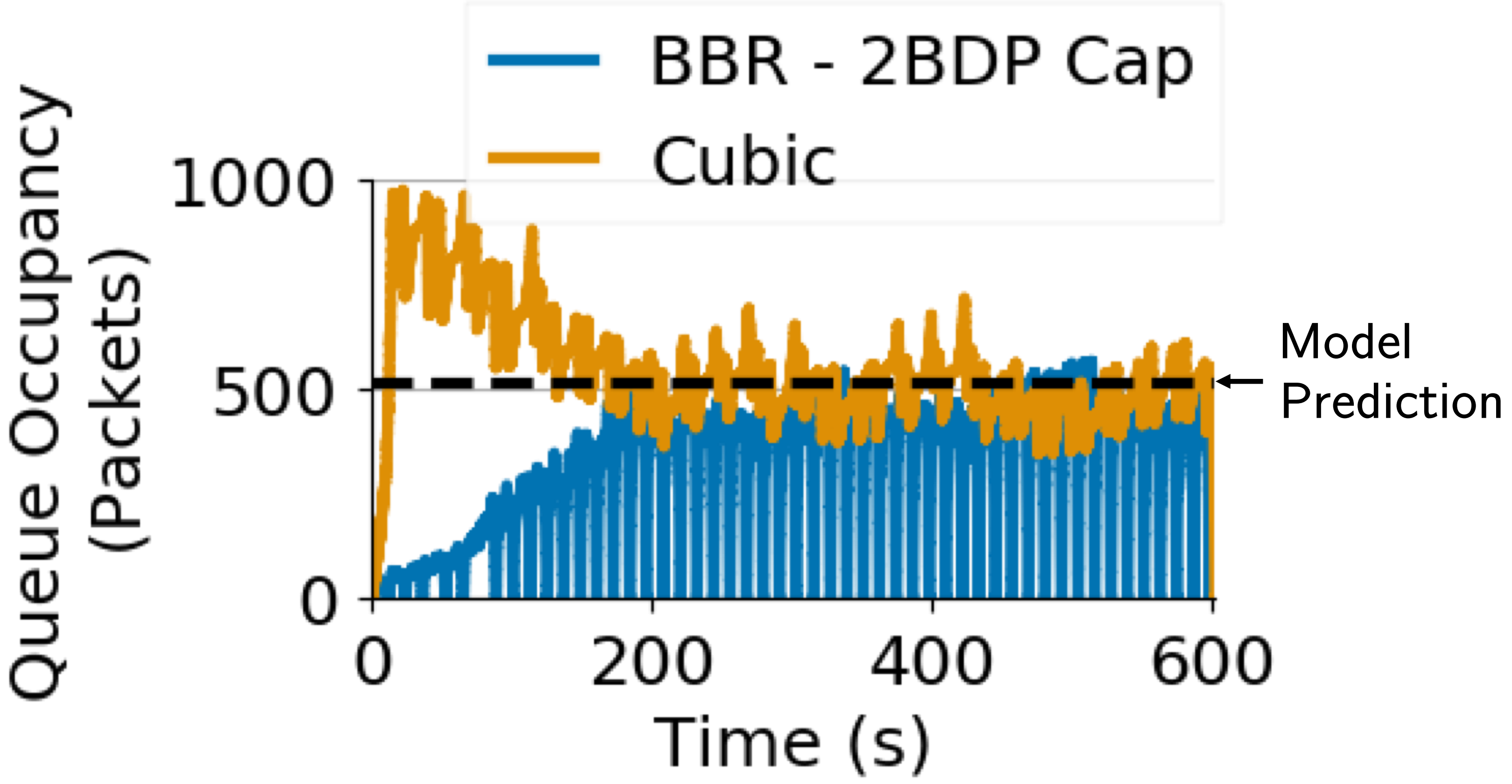

Figure: 1 BBR vs. 1 Cubic (32 BDP queue)

When we **change the in-flight cap**, we see BBR can get more of the queue.

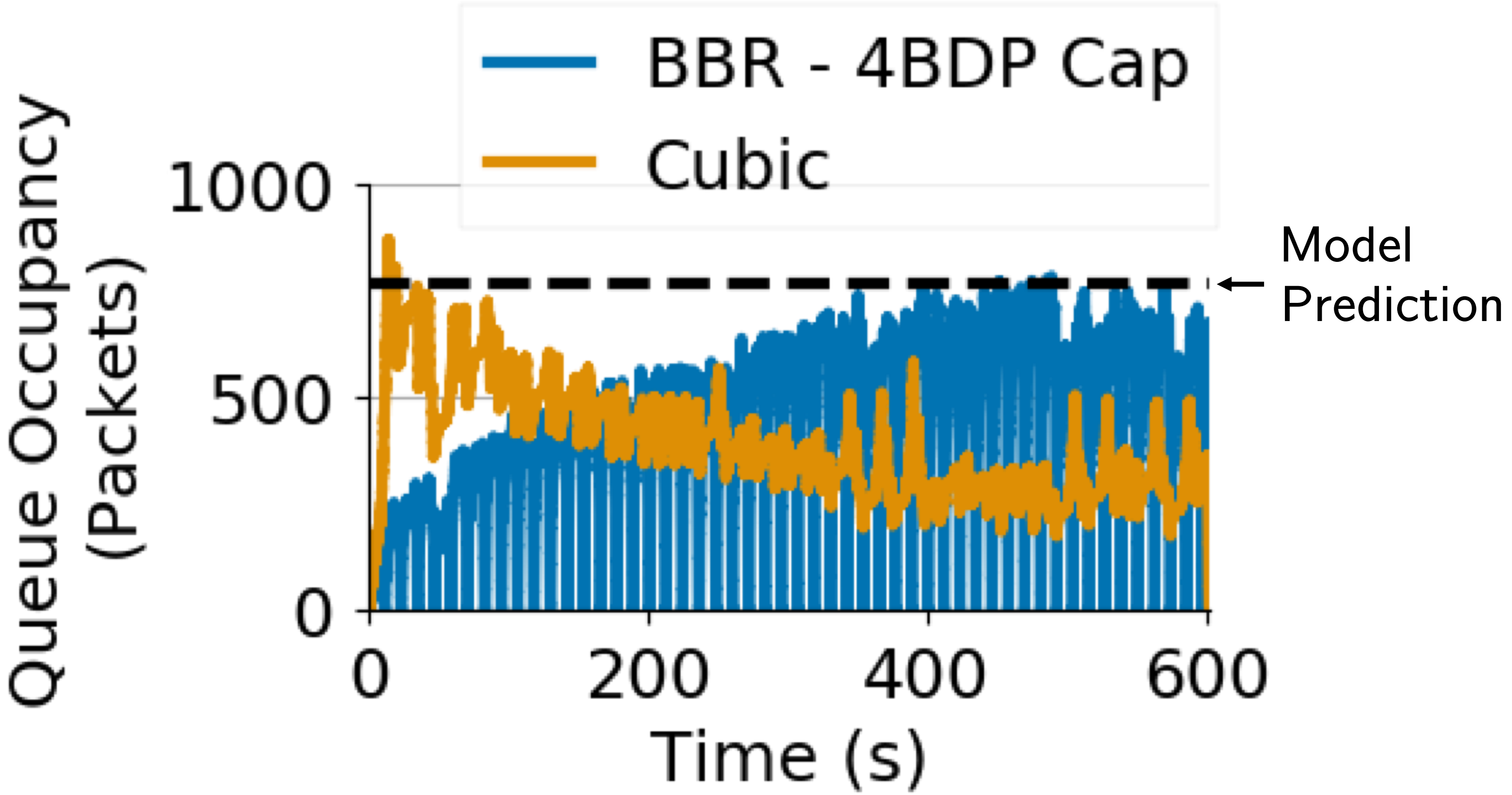

Figure: 1 BBR vs. 1 Cubic (32 BDP queue)

Our paper has a more **robust model** of BBR's in-flight cap.

4 Key Differences From Simple Model:

1. Propagation delay (l)
2. Queue size ($q = Xcl$)
3. # of BBR flows (N)
4. Probing overhead

$$BBR_{frac} = \left(1 - \frac{1}{2} + \frac{1}{2X} + \frac{4N}{q}\right) \times \left(1 - \left(\frac{q}{c} + .2 + l\right) \times \frac{1}{10}\right)$$

Our model predicts BBR's throughput when competing against Cubic flows with a median error of 5% (error is 8% for Reno).

4 Key Differences From Simple Model:

1. Propagation delay (l)
2. Queue size ($q = Xcl$)
3. # of BBR flows (N)
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See paper for details!

$$BBR_{frac} = \left(1 - \frac{1}{2} + \frac{1}{2X} + \frac{4N}{q}\right) \times \left(1 - \left(\frac{q}{c} + .2 + l\right) \times \frac{1}{10}\right)$$

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Takeaways:

When BBR competes with other traffic, it becomes window-limited, sending packets at a rate determined by its in-flight cap.

BBR's in-flight cap does not depend on the number of competing loss-based flows.

Ranysha Ware

rware@cs.cmu.edu
@ranyshaware