Exploring the BBRv2 Congestion Control Algorithm for use on Data Transfer Nodes

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https://www.es.net
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TCP Congestion Control 40 year History

- 1981 Base specification [RFC 793]
- 1986: TCP Reno (First appeared in BSD4.3)
- 1988 Van Jacobson's landmark TCP paper
- 1996: "Mathis Equation" paper defining relationship between loss and bandwidth
- 1997: TCP Slow Start, Congestion Avoidance, Fast Retransmit, and Fast Recovery (RFC2001)
- 1999: New Reno (RFC 2582)
- 2004: Cubic TCP released
- 2005: Fast TCP and Hamilton TCP (H-TCP) released
- 2006: Cubic becomes the default in Linux
- 2013: ESnet's TCP slide motivation for a Science DMZ (next slide)
- 2013: FQ traffic shaper added to Linux
- 2016: BBRv1 (Bottleneck Bandwidth and Round-trip propagation time)
- 2019: BBRv2

See Matt Mathis's talk from March 2020 for excellent summary of TCP congestion control history
  – https://www.es.net/science-engagement/ci-engineering-lunch-and-learn-series

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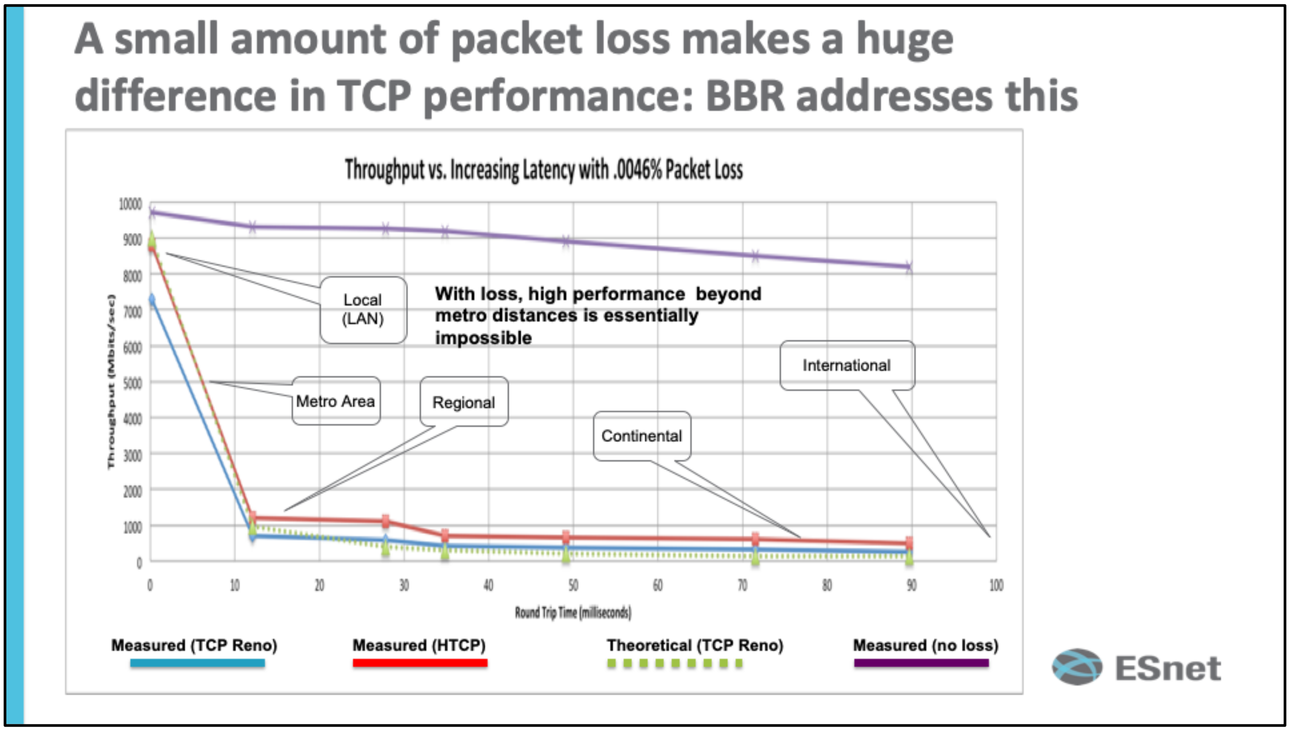
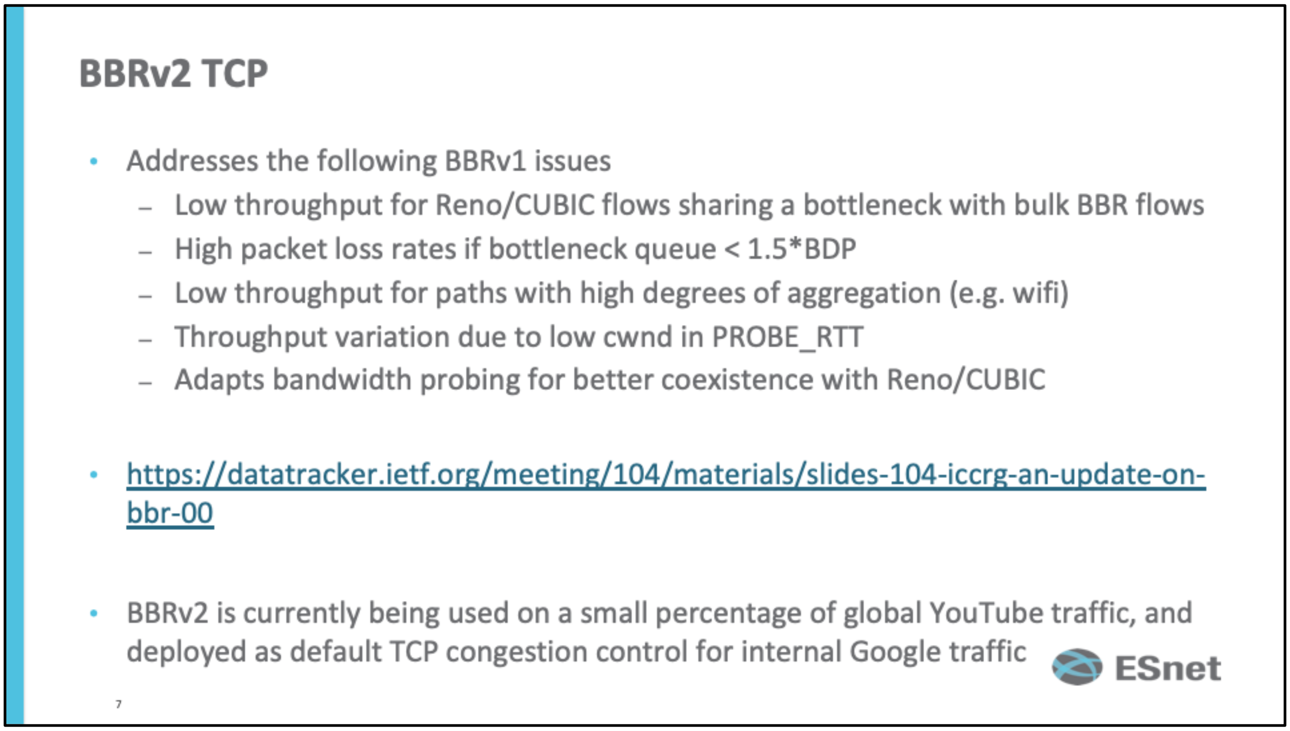


On a 10 Gb/s LAN path the impact of low packet loss rates is minimal
On a 10 Gb/s WAN path the impact of low packet loss rates is enormous

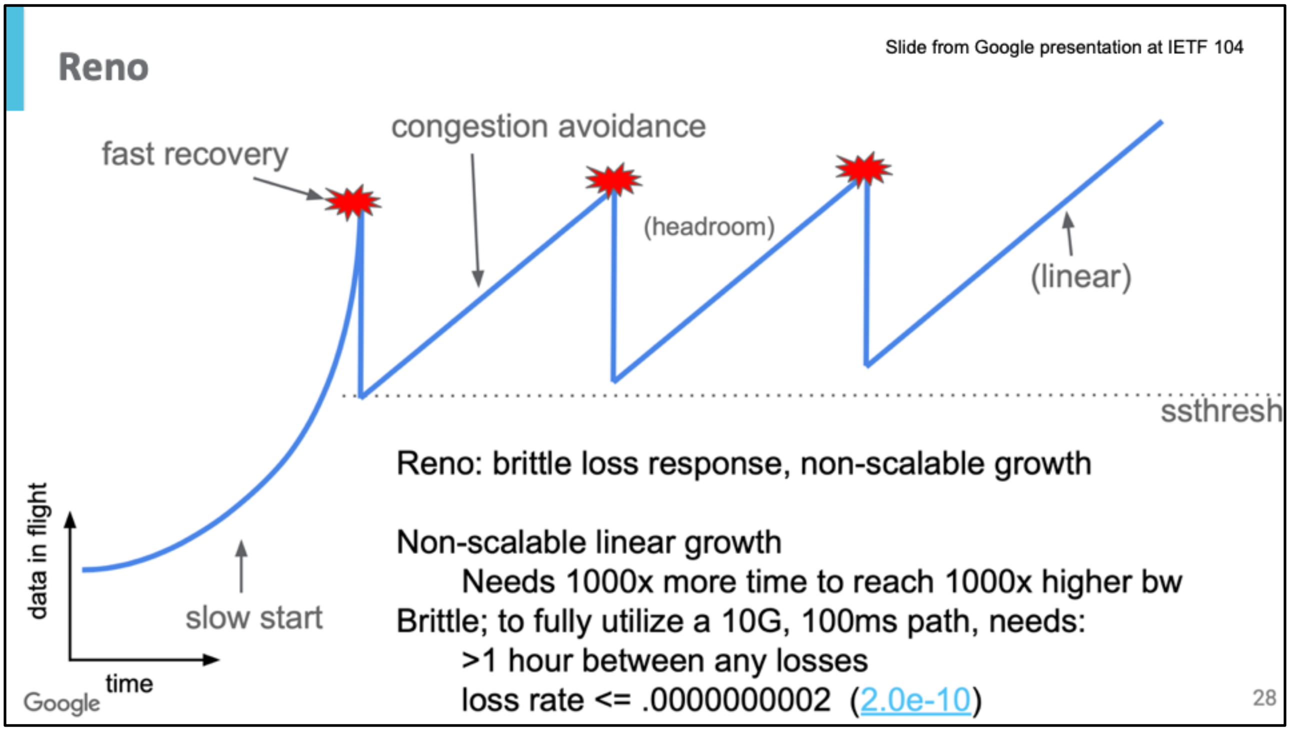
Beyond your metro area, zero loss is essentially required for performance
When global collaboration is the norm, nobody can afford to be a local-only resource

TCP Congestion Control

- Congestion Control Algorithms fall into 2 general categories:
  - Loss-based. (e.g.: Reno and Cubic)
    - Sender slows down if loss is detected
  - Delay-based (e.g.: Vegas and Fast)
    - Sender slows down if additional delay is detected
- The Internet has largely used loss-based congestion control algorithms
  - assumes that packet loss is equivalent to congestion
- But packet loss **is not** equivalent to congestion.
  - Congestion: network path has more data in flight than the bandwidth-delay product (BDP) of the path.
- Loss-based CC is increasing problematic due to:
  - Shallow buffers: in shallow buffers, packet loss happens before congestion
  - Deep buffers: at bottleneck links with deep buffers, congestion happens before packet loss.
- The BBR congestion control algorithm takes a different approach
  - *Does not assume that packet loss = congestion,*
  - BBR builds a model of the network path in order to avoid and respond to actual congestion.



https://datatracker.ietf.org/meeting/104/materials/slides-104-iccrg-an-update-on-bbr-00



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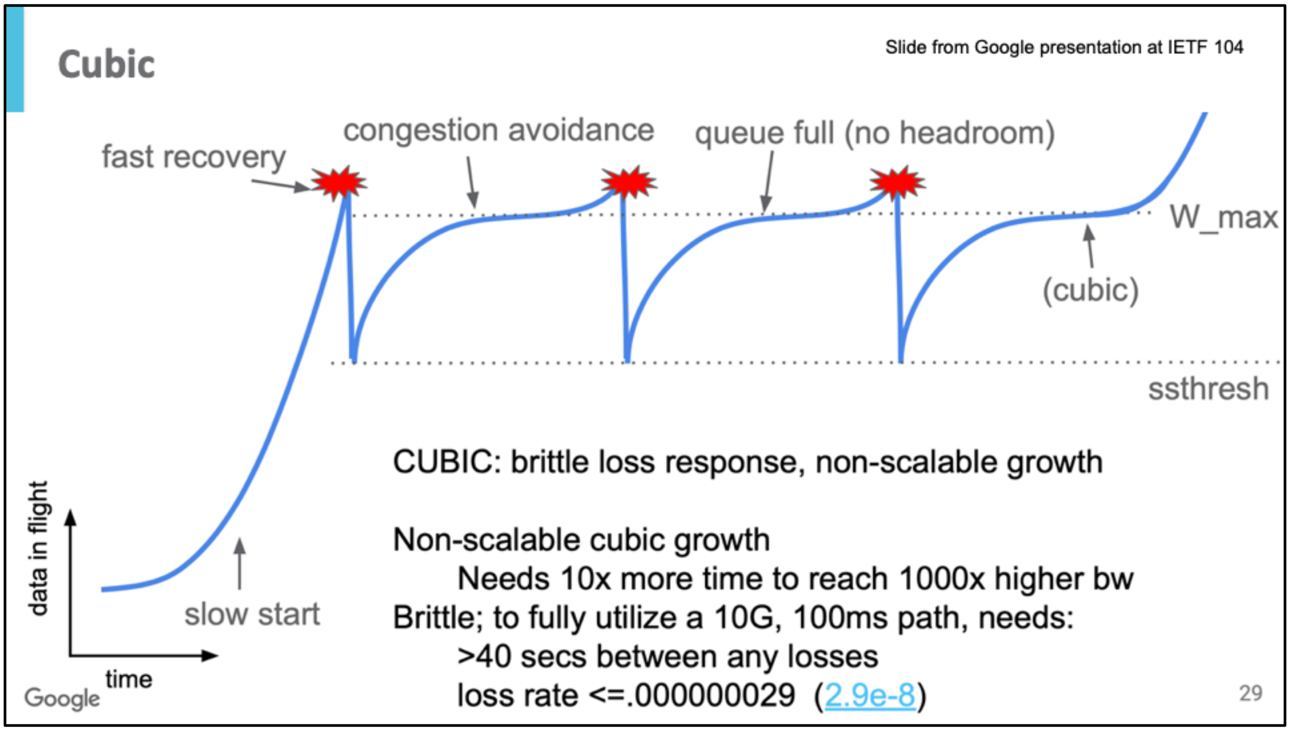
Cubic
Slide from Google presentation at IETF 104
fast recovery
congestion avoidance
queue full (no headroom)
W_max
(cubic)
ssthresh
data in flight
time
slow start
CUBIC: brittle loss response, non-scalable growth
Non-scalable cubic growth
Needs 10x more time to reach 1000x higher bw
Brittle; to fully utilize a 10G, 100ms path, needs:
>40 secs between any losses
loss rate <=.000000029 (2.9e-8)
Google
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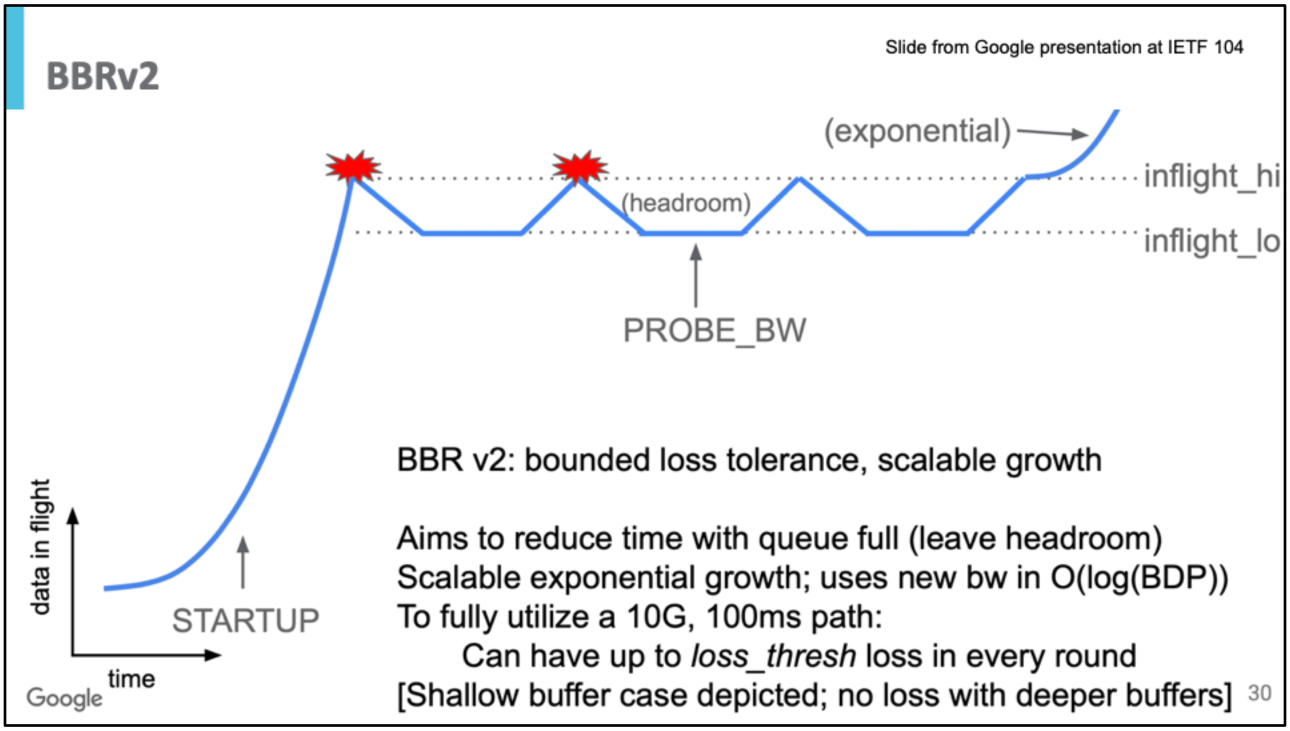
BBRv2
Slide from Google presentation at IETF 104
(exponential)
inflight_hi
(headroom)
inflight_lo
PROBE_BW
BBR v2: bounded loss tolerance, scalable growth
Aims to reduce time with queue full (leave headroom)
Scalable exponential growth; uses new bw in O(log(BDP))
To fully utilize a 10G, 100ms path:
Can have up to loss_thresh loss in every round
[Shallow buffer case depicted; no loss with deeper buffers]
data in flight
STARTUP
time
Google
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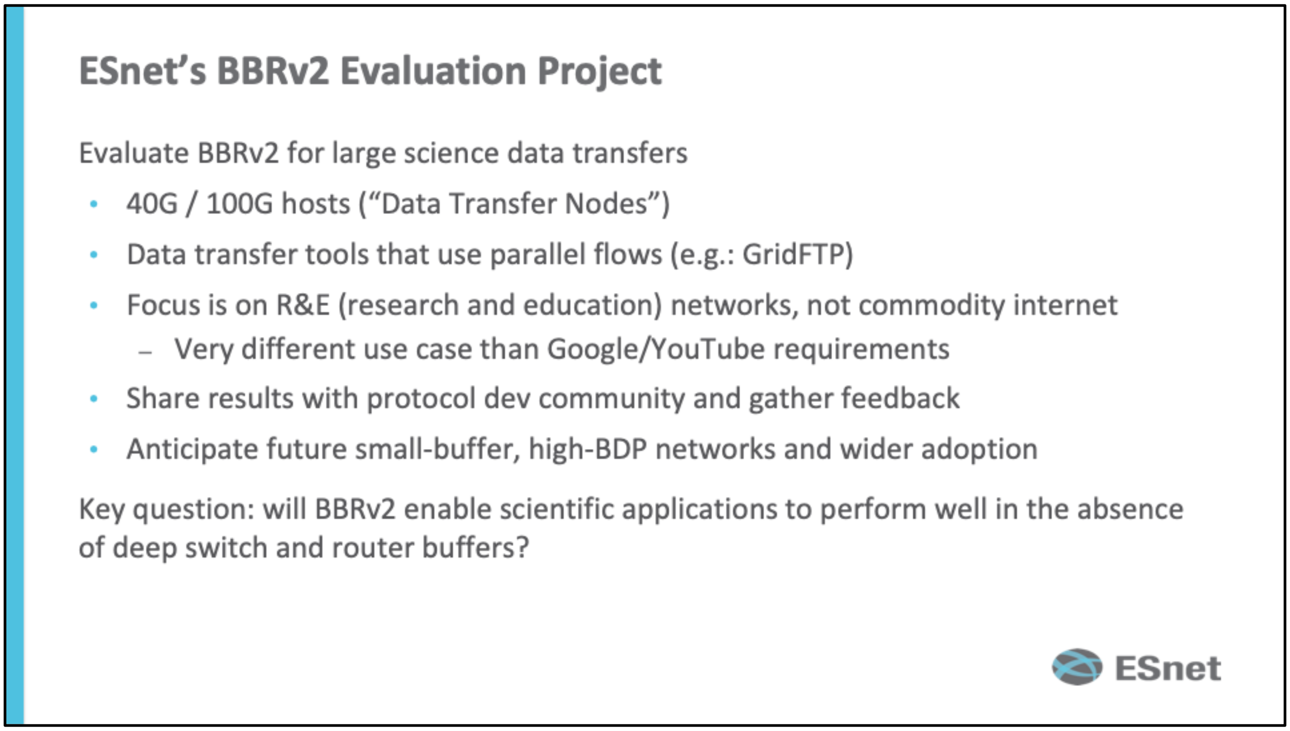

Several papers evaluating BBRv1 and v2 exist, but must use Mininet, not real networks

BBRv2 has some assumptions 'baked in'

Comment in the BBRv2 source code:

```
/*
 * We bound the Reno-coexistence inter-bw-probe time to be 62-63 round trips.
 * This is calculated to allow fairness with a 25Mbps, 30ms Reno flow,
 * (eg 4K video to a broadband user):
 *   BDP = 25Mbps * .030sec /(1514bytes) = 61.9 packets
 */
```

- Our use case is quite different
  - Incoming DTN transfers to a ScienceDMZ will be a mix of BBR and CUBIC while BBR catches on
- Does BBRv2 work well for the DTN use case? How well does it coexist with CUBIC flows?

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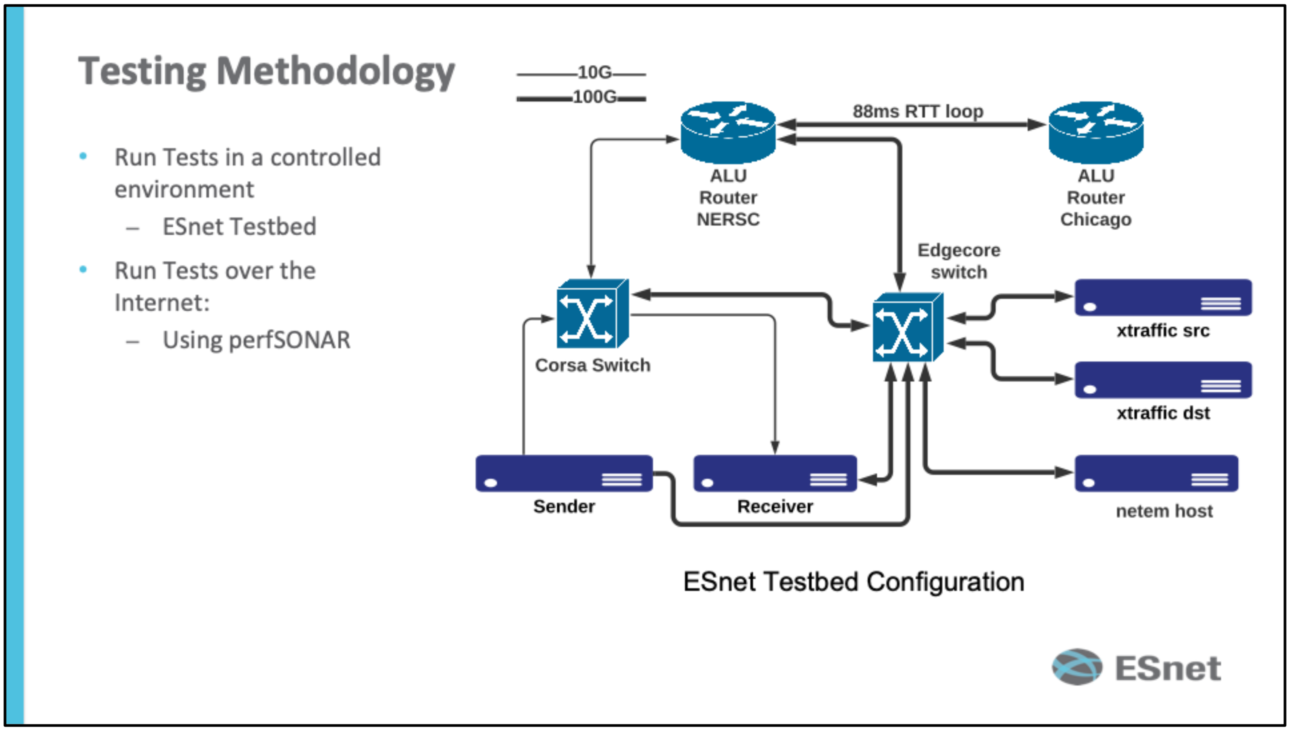
See: https://github.com/google/bbr



Host network settings (everything else is Ubuntu 20 system default)
net.core.rmem_max = 536870912
net.core.wmem_max = 536870912
net.ipv4.tcp_rmem = 4096 87380 268435456
net.ipv4.tcp_wmem = 4096 65536 268435456
net.core.default_qdisc = fq
net.ipv4.tcp_no_metrics_save = 1

‘real world’ Testing

Source Node:

- 40G host directly connected to ESnet backbone
- Ubuntu 20, 5.10.0 kernel with bbr2 patches
- perfSONAR *Testpoint* Docker container
  - https://docs.perfsonar.net/install_options.html
  - perfSONAR only allows 1 throughput test to be run at a time

Destination Nodes:

- There are roughly 2000 registered perfSONAR hosts worldwide
  - most of which allow testing from ESnet
  - many of which allow testing from anywhere
  - most restrict testing to 1 minute, but ESnet allows longer tests from other ESnet hosts.
- Tests are running on production networks, with no control over competing traffic
- We selected a variety of test hosts of various RTTs and various loss characteristics

Host network settings (everything else is Ubuntu 20 system default)
net.core.rmem_max = 536870912
net.core.wmem_max = 536870912
net.ipv4.tcp_rmem = 4096 87380 268435456
net.ipv4.tcp_wmem = 4096 65536 268435456
net.core.default_qdisc = fq
net.ipv4.tcp_no_metrics_save = 1

Test Harness

- Python program to facilitate running tests and collecting instrumentation data.
- Sample config file entry:

```
[pscheduler_bbr2_p16]
type = perfSONAR
enabled = true
iterations = 10
src = localhost
dst = 10.201.1.2
src-cmd = pscheduler task --format json throughput --congestion=bbr2 --
ip-version 4 --parallel 16 --duration PT5M --dest {dst}
pre-src-cmd = /usr/sbin/sysctl -w net.ipv4.tcp_congestion_control=bbr2
post-src-cmd = /usr/sbin/sysctl -w net.ipv4.tcp_congestion_control=cubic
tcpdump = true
tcpdump-filt = -s 128 -i ens2np0 "host {dst} and port 5201"
netem-loss = 0.001
lat-sweep = 2,5,10,20,30,50
pacing = 2.4gbit
```

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Raw Data

Our test harness has the ability to collect the following:

- iperf3 JSON output (as reported by pscheduler tool)
- ss (socket stats)
- tcpdump / tcptrace
- mpstat (CPU load)

The data used to generate these plots is available at:

- https://downloads.es.net/INDIS-2021/

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Testing / Plotting Methodology and Terminology

- Parallel Flow tests all use 16 flows
  - This is a common default for Globus and other DTN tools
- "non-overlapped" means a 16 flow CUBIC test, followed by a 16 flow BBRv2 test
- "overlapped" means 8 CUBIC flows and 8 BBRv2 flows, all at the same time
- Netem-based results have netem setting in the lower right of the plot

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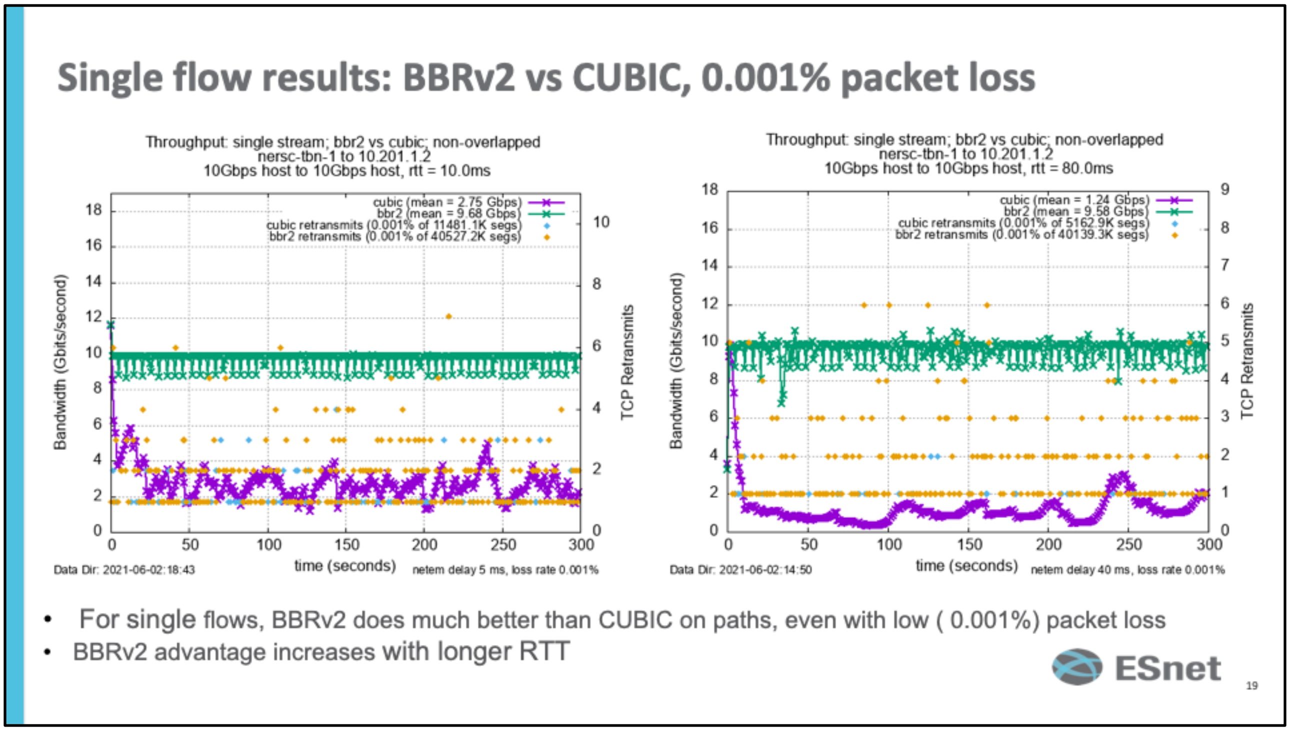


Fig 2 in paper
Single flow, non-overlapped, Higher RTT on the right

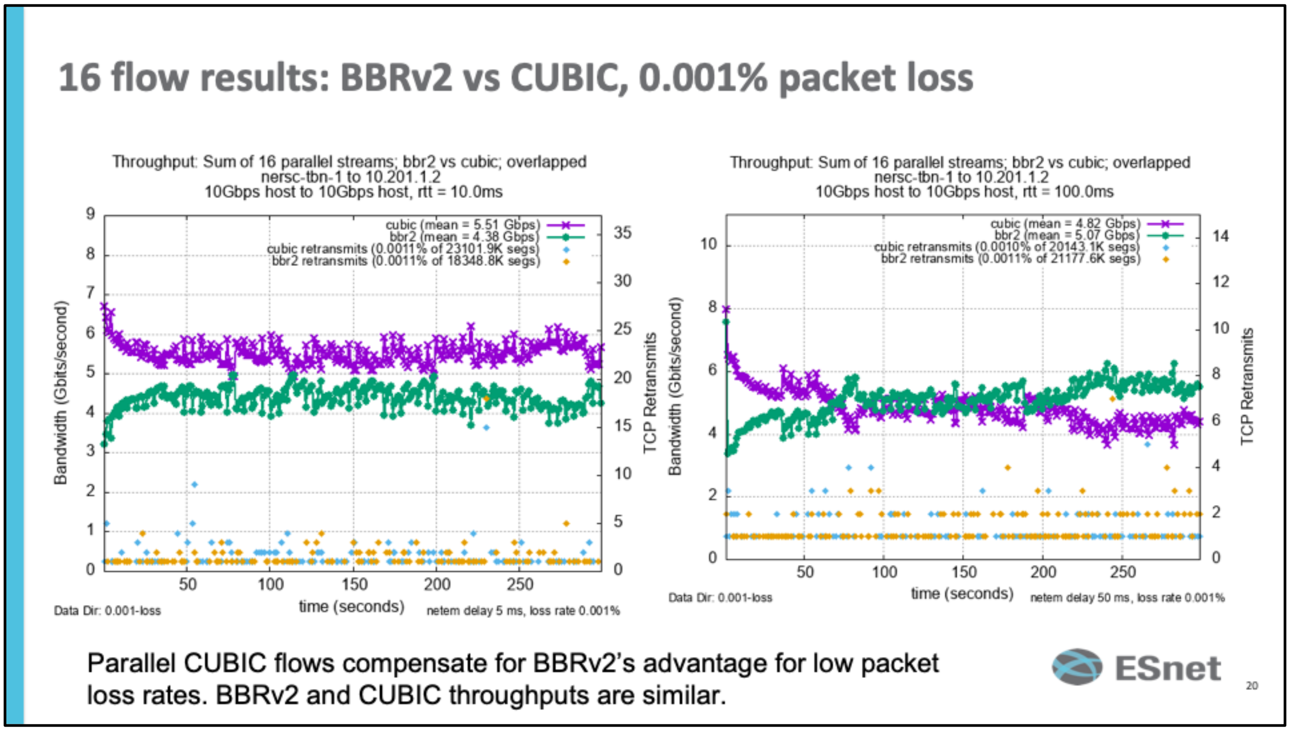
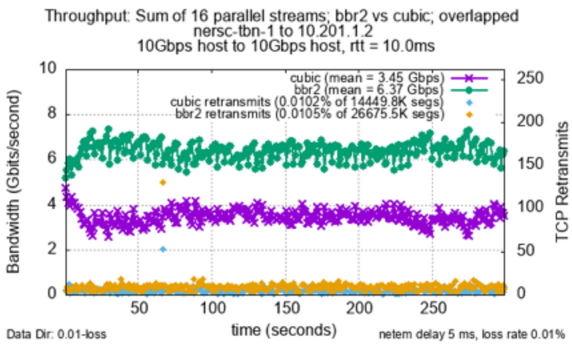
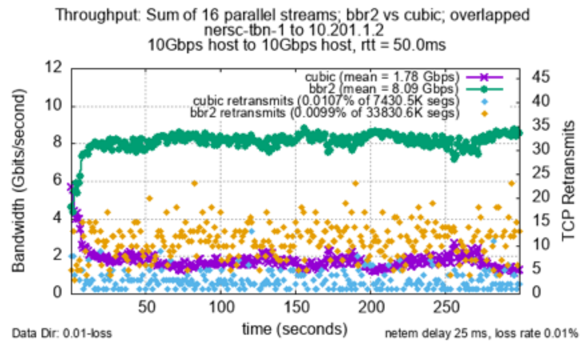


Figure 3 in paper
Parallel flows, Much higher RTT on right

16 flow results: BBRv2 vs CUBIC, 0.01% packet loss





With additional packet loss (0.01%) parallel BBRv2 starts to do much better than CUBIC, especially on long paths

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Figure 4 in paper
Higher RTT on right

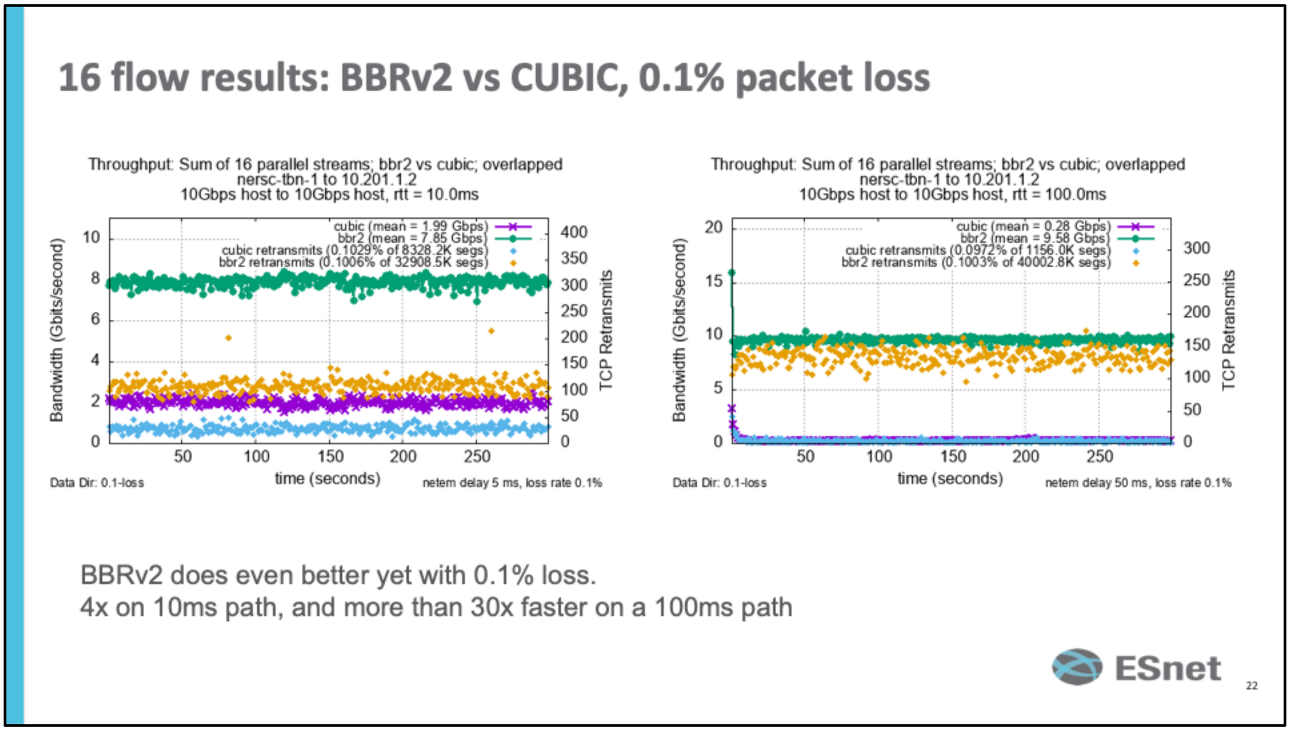
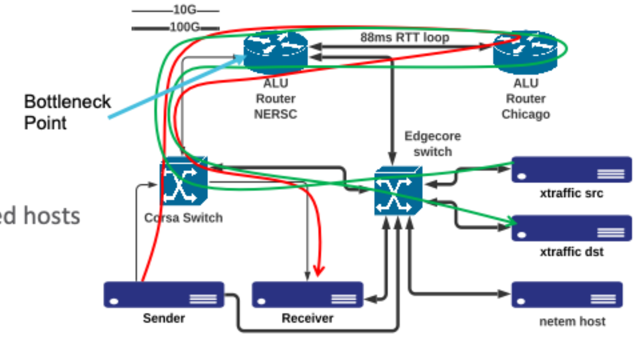


Figure 5 in paper
Much higher RTT on right

Buffer Size results

- TCP over 10G 88ms loop path (red line)
- Background 1 Gbps UDP stream between testbed hosts xtraffic src/dst to create congestion (green line)
- Adjusted buffer size on Corsa Switch



Buffer Size	CUBIC throughput	BBRv2 throughput
8 MB	0.4 Gbps	8.3 Gbps
12 MB	0.9 Gbps	8.0 Gbps
16 MB	1.8 Gbps	6.9 Gbps
32 MB	4.5 Gbps	4.3 Gbps
64 MB	4.6 Gbps	4.2 Gbps

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BBRv2 does much better with smaller buffers
CUBIC does slightly better with large buffers

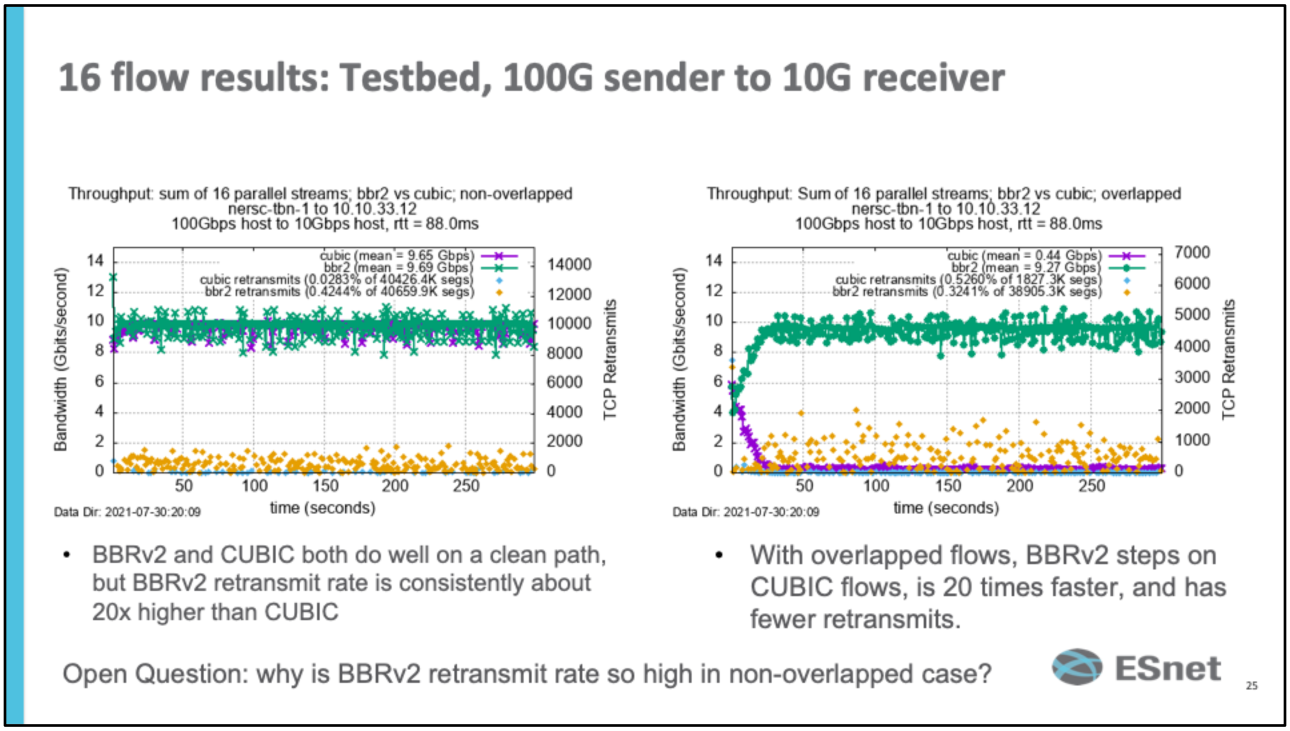


Figure 6 in paper
Non-overlapped on left, overlapped on right
Flows are paced to 2.4G, but that still significantly over-subscribes the receive host

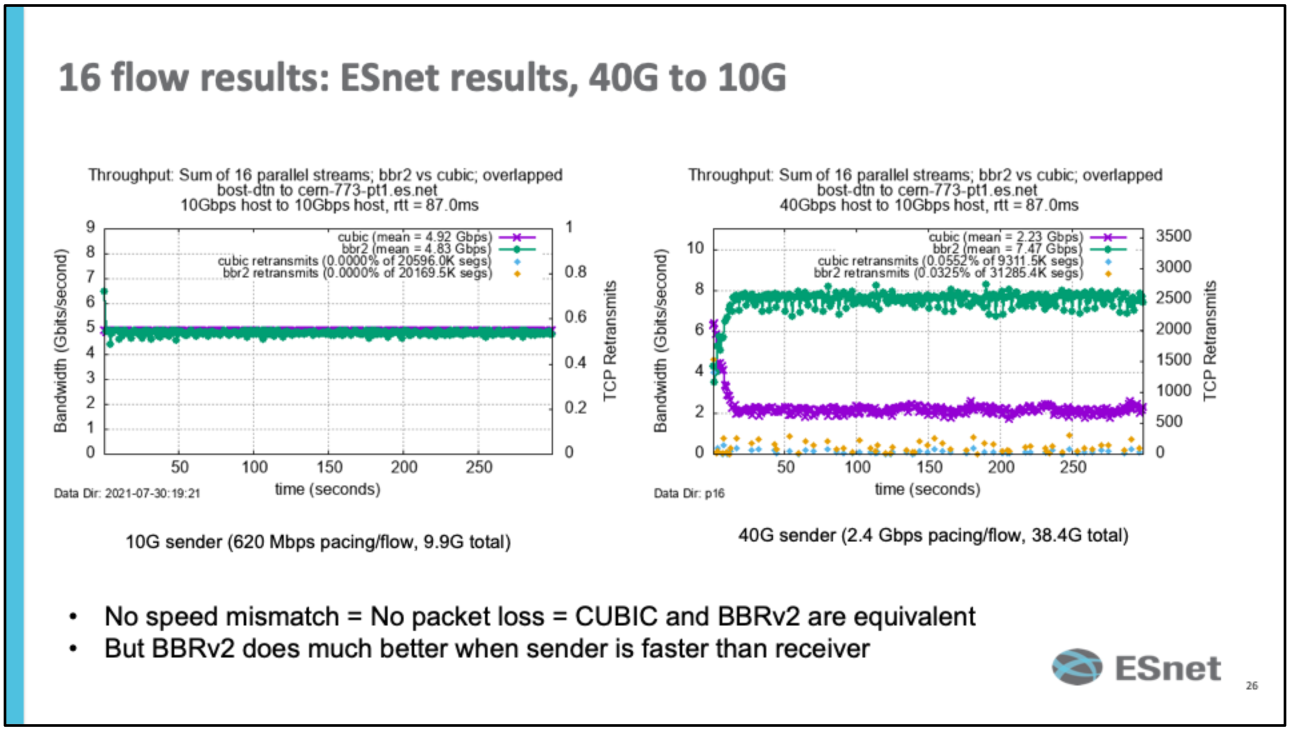
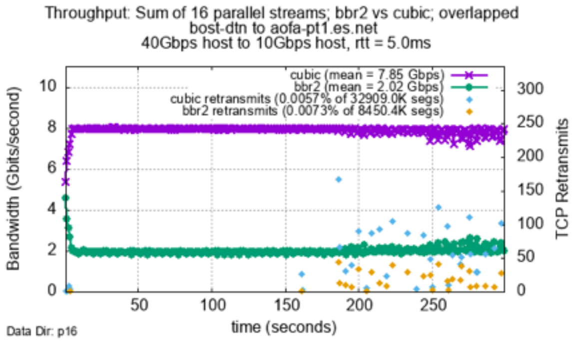


Figure 8 in paper

similar results from the testbed, but not quite as dramatic: 4x vs 20x, possibly due to more buffering

But, Sometimes CUBIC is faster



- Overlapped CUBIC and BBR2 flows
- 5ms RTT, low packet loss
- CUBIC is considerably faster
- Note: very deep buffers on this path

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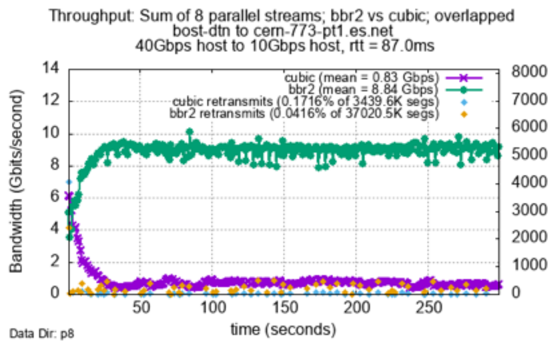
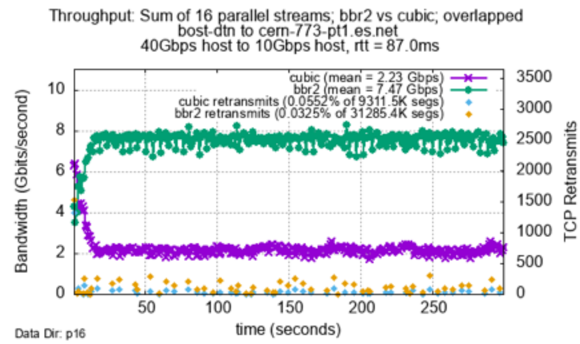
Figure 9 in paper

Paper by Cao et all in the related work section also shows CUBIC 4x faster than BBRv2 with very large buffers on Mininet

How many parallel flows?





- CUBIC benefits from additional flows, BBRv2 does not
- Initial testing shows that maximum BBRv2 throughput is achieved with 2-4 flows; more testing needed

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Figure 12 in paper
8 flows on the left, 16 on the right
For BBRv2, parallel flows help most with RTT > 80ms

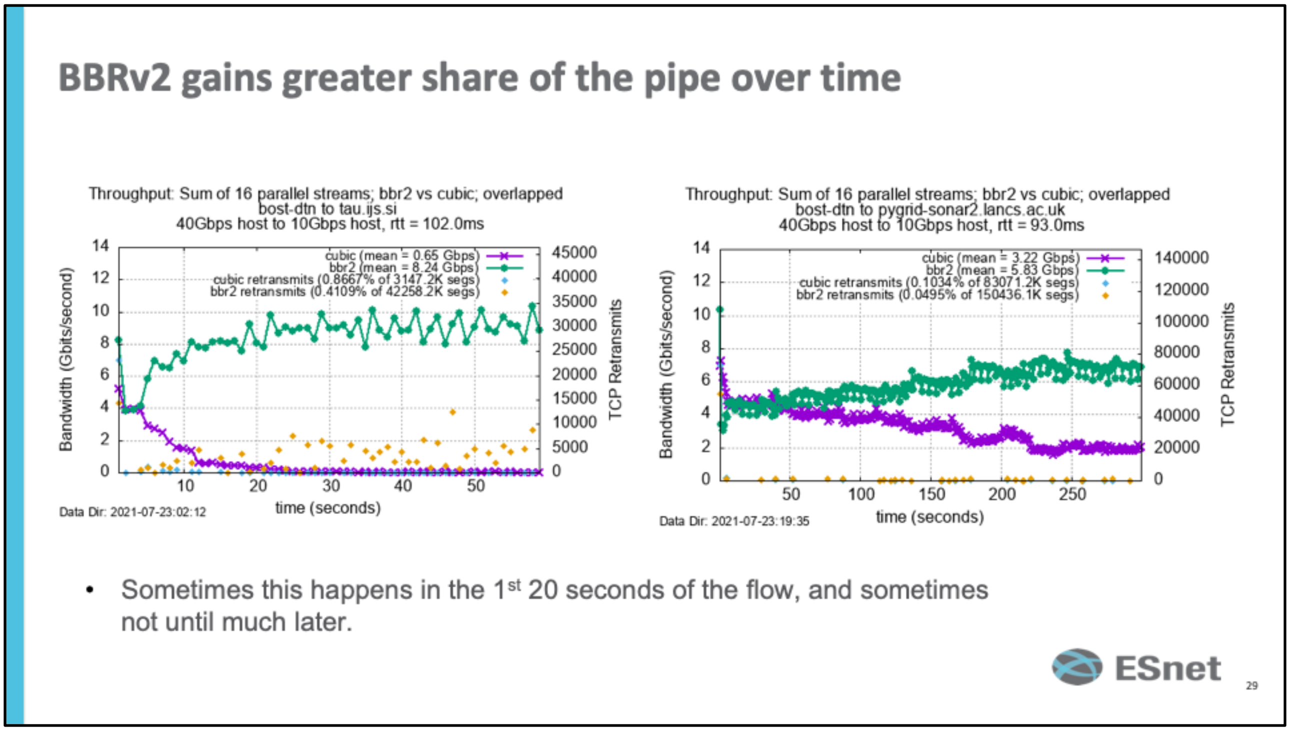
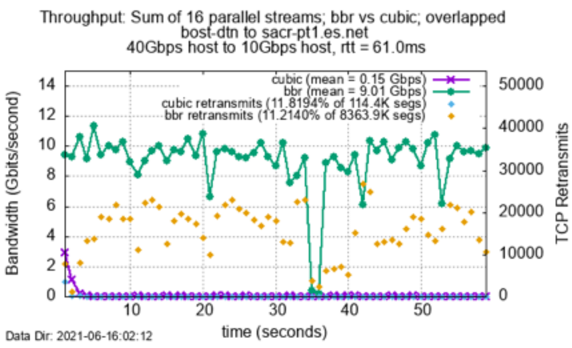
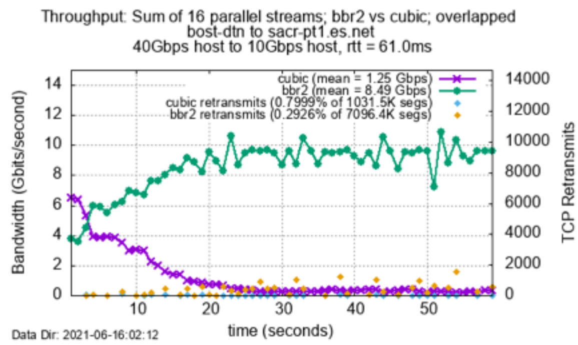


Figure 13 in paper

BBRv2 vs BBRv1





BBRv1 has way more retransmits and is way more unfriendly to CUBIC

- CUBIC only gets 0.15Gbps, vs 1.25Gbps with BBRv2
- Retransmits > 11% for BBRv1, and < 1% for BBRv2

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Figure 14 in paper

BBRv2 Tuning Parameters

- Lots of tuning knobs (/sys/module/tcp_bbr2/parameters/)

ack_epoch_acked_reset_thresh bw_probe_rand_us extra_acked_gain
inflight_headroom **probe_rtt_cwnd_gain** bw_probe_reno_gain
extra_acked_in_startup full_bw_cnt **loss_thresh** probe_rtt_mode_ms
usage_based_cwnd bw_probe_base_us cwnd_gain
ecn_factor extra_acked_max_us full_bw_thresh **min_rtt_win_sec**
probe_rtt_win_ms bw_probe_max_rounds cwnd_min_target
drain_gain ecn_max_rtt_us extra_acked_win_rtts
full_ecn_cnt min_tso_rate refill_add_inc
bw_probe_pif_gain cwnd_tso_bduget drain_to_target
ecn_reprobe_gain fast_ack_mode full_loss_cnt **pacing_gain**
startup_cwnd_gain bw_probe_rand_rounds cwnd_warn_val
ecn_alpha_gain ecn_thresh fast_path
high_gain precise_ece_ack tso_rtt_shift

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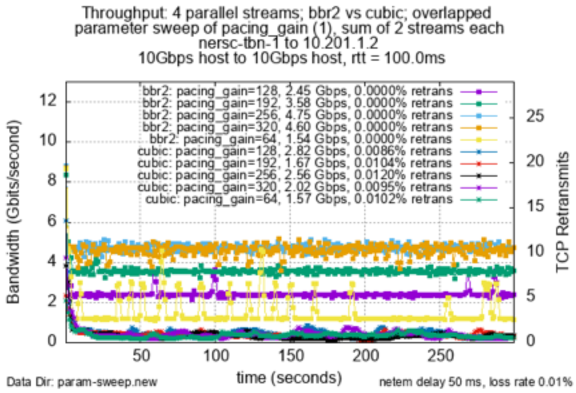
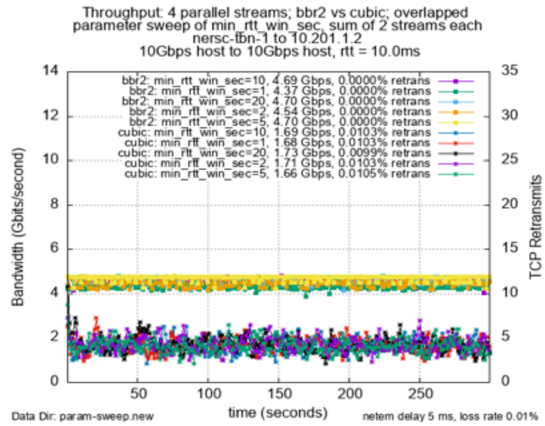
Tested the params in bold

Parameter Sweep Results





- Our test harness supports testing a range of BBRv2 parameters
- Results to date show that default settings appear optimal
- Much more testing is needed

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Figure 15 in paper

Test Variability

- We ran 10 runs of each experiment configuration, and computed the coefficient of variation (CV) of each
  - CV is defined as the ratio of the standard deviation to the mean.
  - The higher the coefficient of variation, the greater the level of dispersion around the mean.
- The CV for all experiments was < 1 (i.e.: reasonable)
- BBRv2 results were 4-5 times more stable than CUBIC based on the CV
- See the paper for more details

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Fairness to CUBIC

- Under some circumstances, BBRv2 is unfair to CUBIC
  - High-BDP paths with packet loss (e.g. from shallow buffer switch or congestion)
  - Speed mismatch (e.g. 100G host to 10G host)
- In theory, it is useful to study fairness, because it helps us understand protocols
- In practice, CUBIC requires very expensive engineering to be competitive with BBRv2
  - Very low packet loss requires deep buffers, significant human effort – especially for high-BDP environments (e.g. science/DTN workloads)
  - How should we account for the difference in cost to achieve "fairness?"
- Practical deployment concerns are likely to favor the adoption of BBRv2 and the phase-out of CUBIC over time

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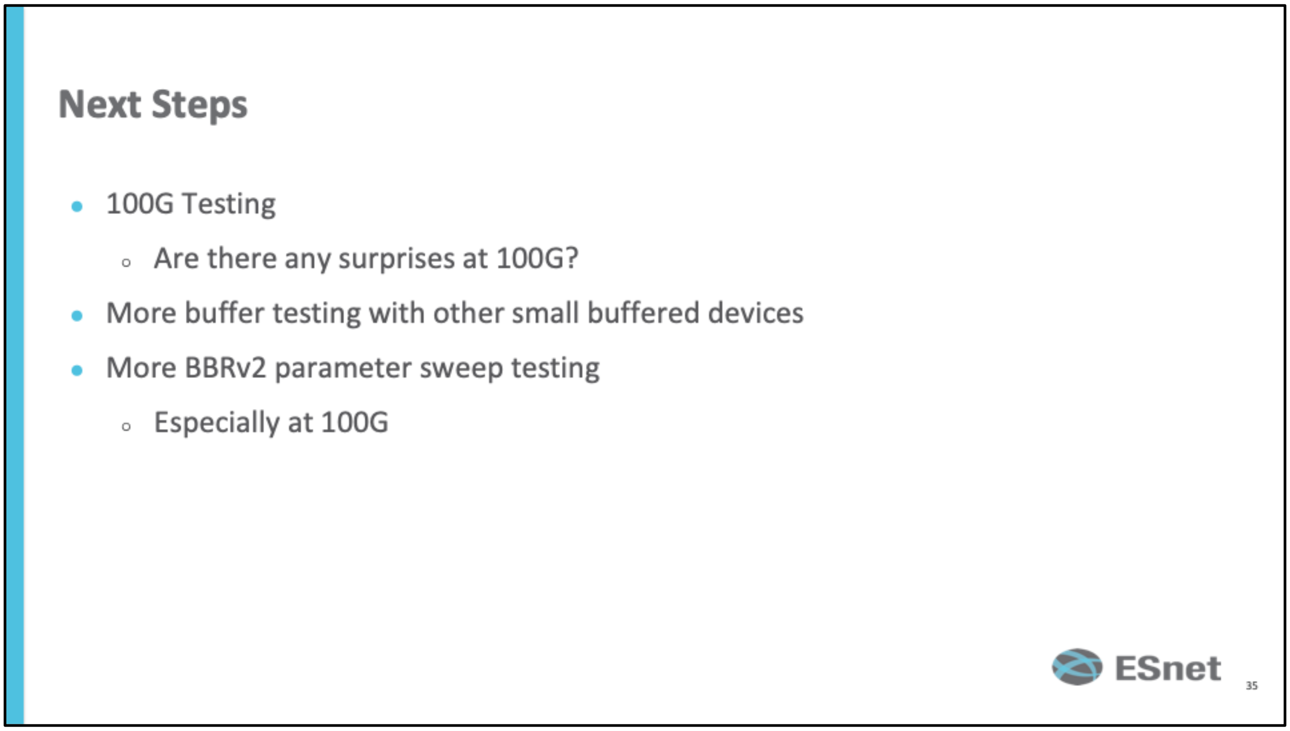
Next Steps
100G Testing
Are there any surprises at 100G?
More buffer testing with other small buffered devices
More BBRv2 parameter sweep testing
Especially at 100G
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Key Takeaways

- BBR (both v1 and v2) does much better than CUBIC on lossy paths
  - The higher the loss rate and RTT, the more BBR wins out.
- Faster hosts sending parallel flows to slower hosts leads to packet loss
  - BBR does much better than CUBIC in this situation.
- The BBRv1 retransmit rate is unacceptably high with parallel flows, and is very unfair to CUBIC
  - BBRv1 should not be used with parallel data transfer applications.
- BBR prefers smaller switch buffers, and CUBIC prefers larger buffers.
  - As network interface speed increases, larger and larger buffers are impractical (and thus more expensive)
  - Therefore BBR will be a better choice in the future.

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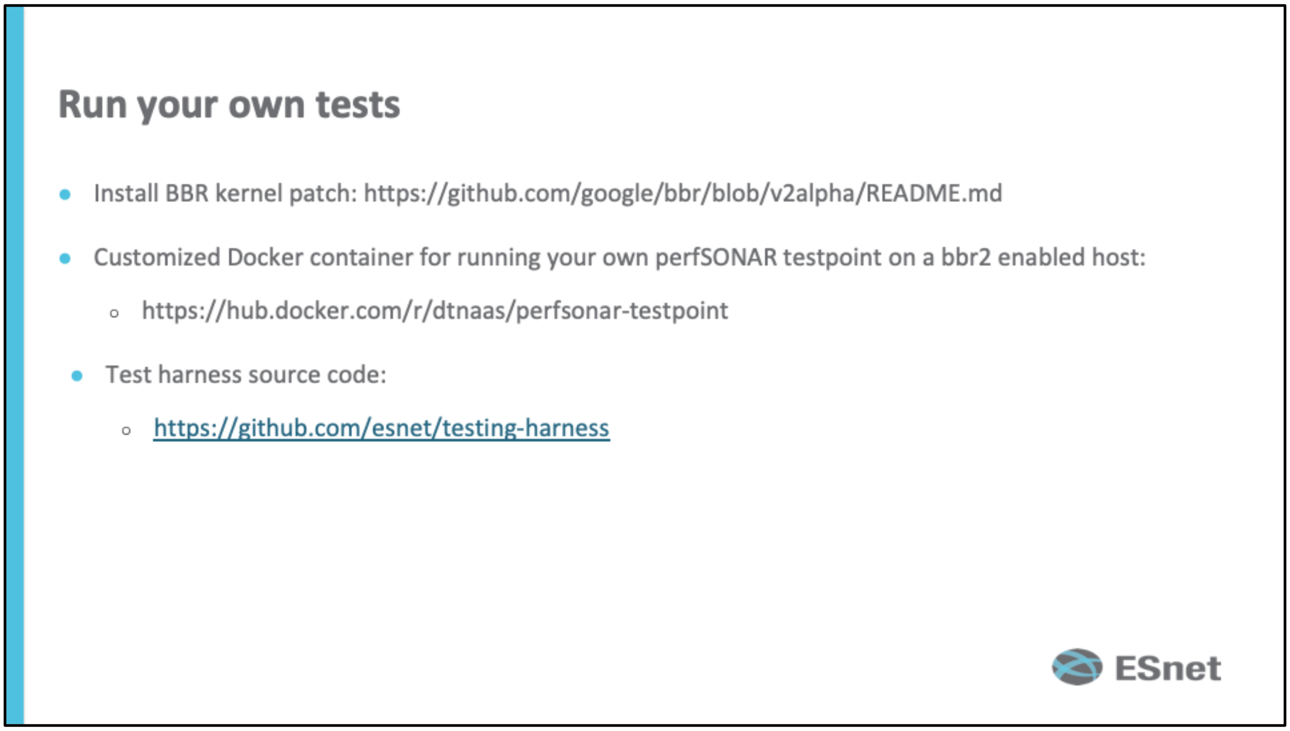

Our tests used this pscheduler command:
pscheduler task --priority 100 --format json throughput --ip-version 4 --parallel 4 --duration PT60S --dest hostname

For more options, run: pscheduler task throughput --help

For more information

- BBRv2:
  - https://groups.google.com/g/bbr-dev
  - Links to all of Google's BBR papers and talks can be found there.
- Relevant pages on FasterData:
  - https://fasterdata.es.net/science-dmz/DTN/tuning/
  - https://fasterdata.es.net/network-tuning/packet-pacing/
- All data collected for this paper are available at
  - *https://downloads.es.net/INDIS-2021/*.
  - This includes output from *iperf3* and *ss*, as well at the gnuplot files used to generate the plots in this paper.

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Extra Slides

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Variance

TABLE II: COMPARING MEAN (M) & COEF. OF VARIANCE (C.V) FOR ESNET TESTBED.

Test		RTT < 30ms				RTT ≥ 30ms			
		BBRv2		CUBIC		BBRv2		CUBIC	
		Mean	*C.V.*	*Mean*	*C.V.*	*Mean*	*C.V.*	*Mean*	*C.V.*
No loss	bbrv2/cubic - p1	9.6533	0.0030	9.8799	0.0024	9.4749	0.0080	9.8435	0.0019
	bbrv2/cubic - p16	9.7891	0.0064	9.8827	0.0007	9.8044	0.0039	9.8348	0.0029
	both - p16	3.1188	0.1834	6.7642	0.0849	3.3604	0.0627	6.4739	0.0334
0.001% loss	bbrv2/cubic - p1	9.6545	0.0021	3.3341	0.4694	9.4834	0.0073	1.2988	0.1541
	bbrv2/cubic - p16	9.7918	0.0061	9.8819	0.0008	9.7838	0.0041	9.7794	0.0071
	both - p16	4.2258	0.1360	5.6566	0.1026	4.9394	0.0390	4.8894	0.0435
0.01% loss	bbrv2/cubic - p1	2.3477	0.0017	1.0500	0.5585	2.3041	0.0018	0.2454	0.0722
	bbrv2/cubic - p16	9.7586	0.0053	9.0397	0.1325	9.8131	0.0017	3.9534	0.0205
	both - p16	6.1650	0.1954	3.6777	0.3352	8.0112	0.0068	1.7950	0.0276
0.1% loss	bbrv2/cubic - p1	8.8108	0.0788	0.3308	0.5180	8.7230	0.0746	0.0472	0.2533
	bbrv2/cubic - p16	9.7969	0.0037	5.1883	0.5058	9.7824	0.0038	0.7438	0.2552
	both - p16	7.5959	0.1542	2.2361	0.5284	9.4057	0.0068	0.3652	0.2545
100G-to-10G	bbrv2/cubic - p16	-	-	-	-	9.6275	0.0004	9.4377	0.0344
	both - p16	-	-	-	-	9.2094	0.0028	0.4254	0.0473

TABLE III: COMPARING M & C.V, BOST-DTN to ESNET & NON-ESNET HOSTS.

Test			RTT < 30ms				RTT ≥ 30ms			
			BBRv2		CUBIC		BBRv2		CUBIC	
			Mean	*C.V.*	*Mean*	*C.V.*	*Mean*	*C.V.*	*Mean*	*C.V.*
10G-to-10G	**ESNET**	both - p16	4.7750	0.0726	5.0057	0.1122	4.7733	0.0055	4.8860	0.0043
	NON-ESNET	both - p16	4.2526	0.0742	4.6333	0.0309	3.9346	0.2188	3.8361	0.2972
40G-to-10G	**ESNET**	both - p8	4.5768	0.2991	5.2852	0.2399	8.3485	0.0899	1.2883	0.6450
		both - p16	4.3490	0.2291	5.1557	0.1906	6.9421	0.1222	2.4023	0.3816
	NON-ESNET	both - p8	-	-	-	-	8.2697	0.0626	2.9697	0.2500
		both - p16	-	-	-	-	8.1870	0.1512	1.9163	0.6094

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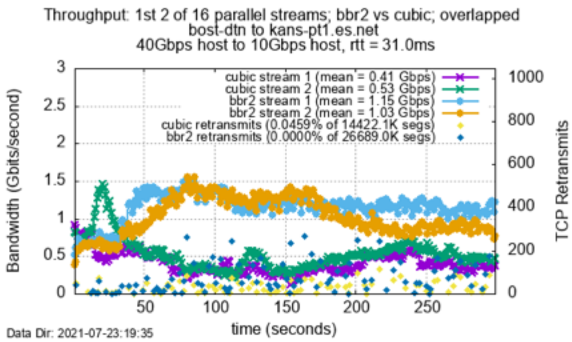
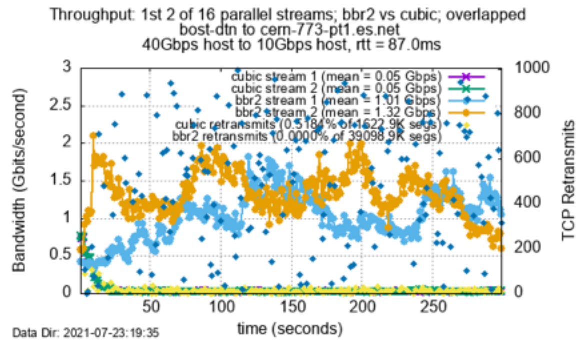
Parallel Stream Behavior





- BBRv2 performance not very stable in this environment

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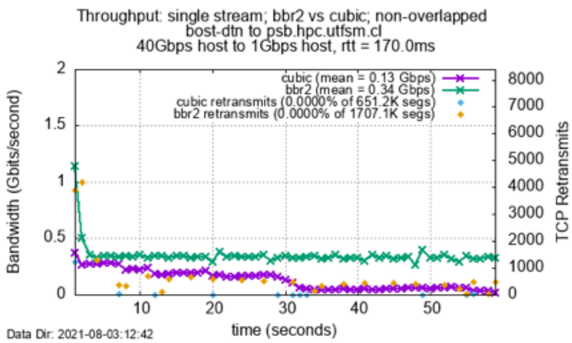
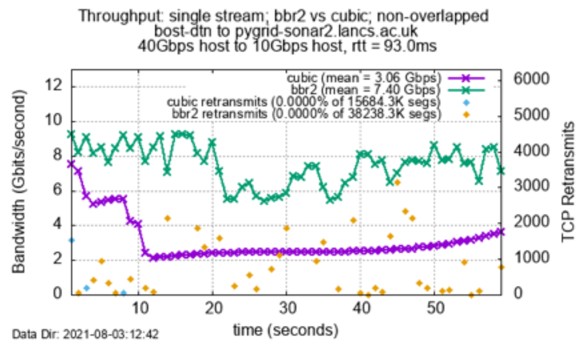
More Single Flow Examples





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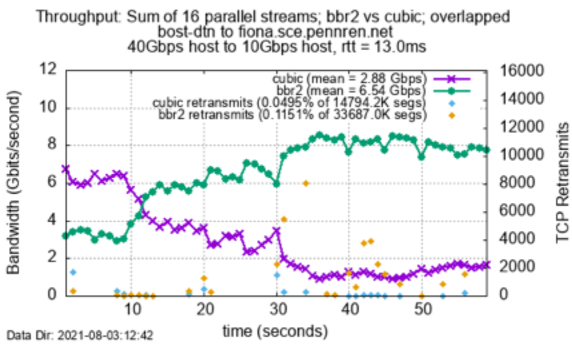
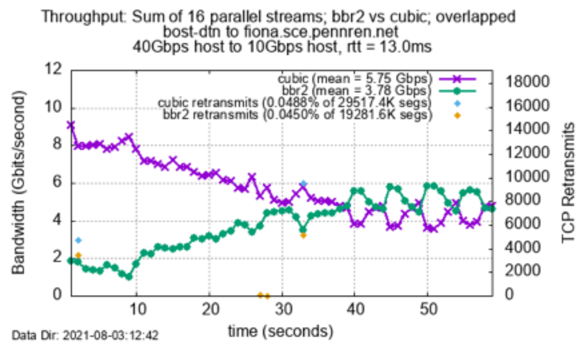
More 16-flow parallel examples: Some paths are odd..





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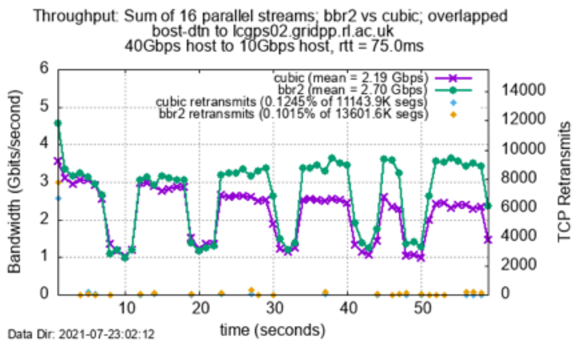
More 16-flow parallel examples: Some paths are odd..



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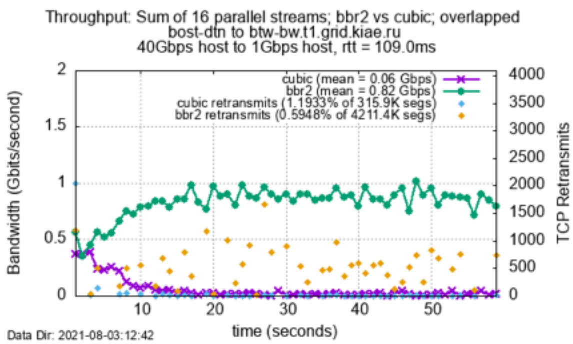
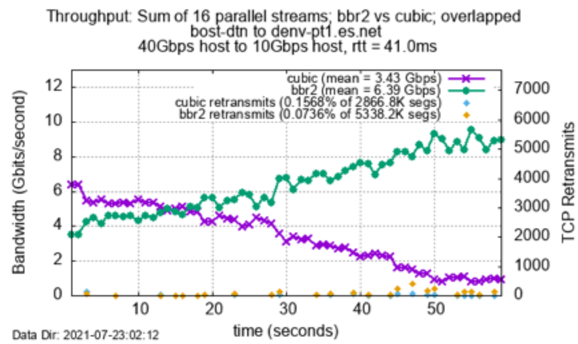
More 16-flow parallel examples





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