# TCP CUBIC versus BBR on the Highway

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# Background

# LTE Network Performance Challenges

**TCP is the major traffic source in the market.**

**Most TCP flows use AIMD-on-loss Congestion Control Algorithms (CCA).**

**AIMD-on-loss CCA is not LTE friendly.**

- Packet loss is not a good congestion indicator in LTE (bit errors and hand-off)
- AIMD not quickly adapt to available bandwidth change in LTE environment.
- Often induce large queuing delays at eNodeB

**Radio Access Network (RAN) performance challenges include:**

- Suboptimal radio link utilization efficiency due to smaller Tx block scheduling
- User-perceived RAN performance degradation.

# Performance Enhanced Proxy (PEP)

**Transparent TCP Proxy as an attractive RAN performance enhancement option**

- Transparently terminates an end-to-end TCP connection to two halves.
- Downlink performance enhancement by buffering L4 packets/data from servers and control transmission rate on the mobile side.

**RAN-friendly CCA on the mobile side to achieve:**

- Fast small object download time
- Maximize goodput for large object transfers
- Maintain low self-inflicted RTT

# Understanding TCP CCA Performance on LTE

**No winner TCP Congestion Control Algorithm (CCA) for LTE**

- Not very impressive LTE performance by existing CCAs
  - E.g., CUBIC, Westwood+ and etc. suffer from low link utilization
- Experimental TCP for wireless links implemented as UDP tunnels
  - E.g., TCP Sprout, TCP Verus, PCC does not yet support TCP.
- LTE performance NOT evaluated for new CCAs designed for data centers
  - E.g., BBR, NV and DCTCP.

**Less Knowledge on CCAs' Performance on High Mobility**

- No real measurement studies on High-Speed driving on LTE.
- No measurement studies to compare different CCAs performance.
- Difficult to model or simulate RF condition on highway.

# Evaluation

# Outline

- Methodology
- Radio Network Characteristics
- Compare CCAs’ Performance
- Discussions
- Conclusion

# Congestion Control Algorithms Compared

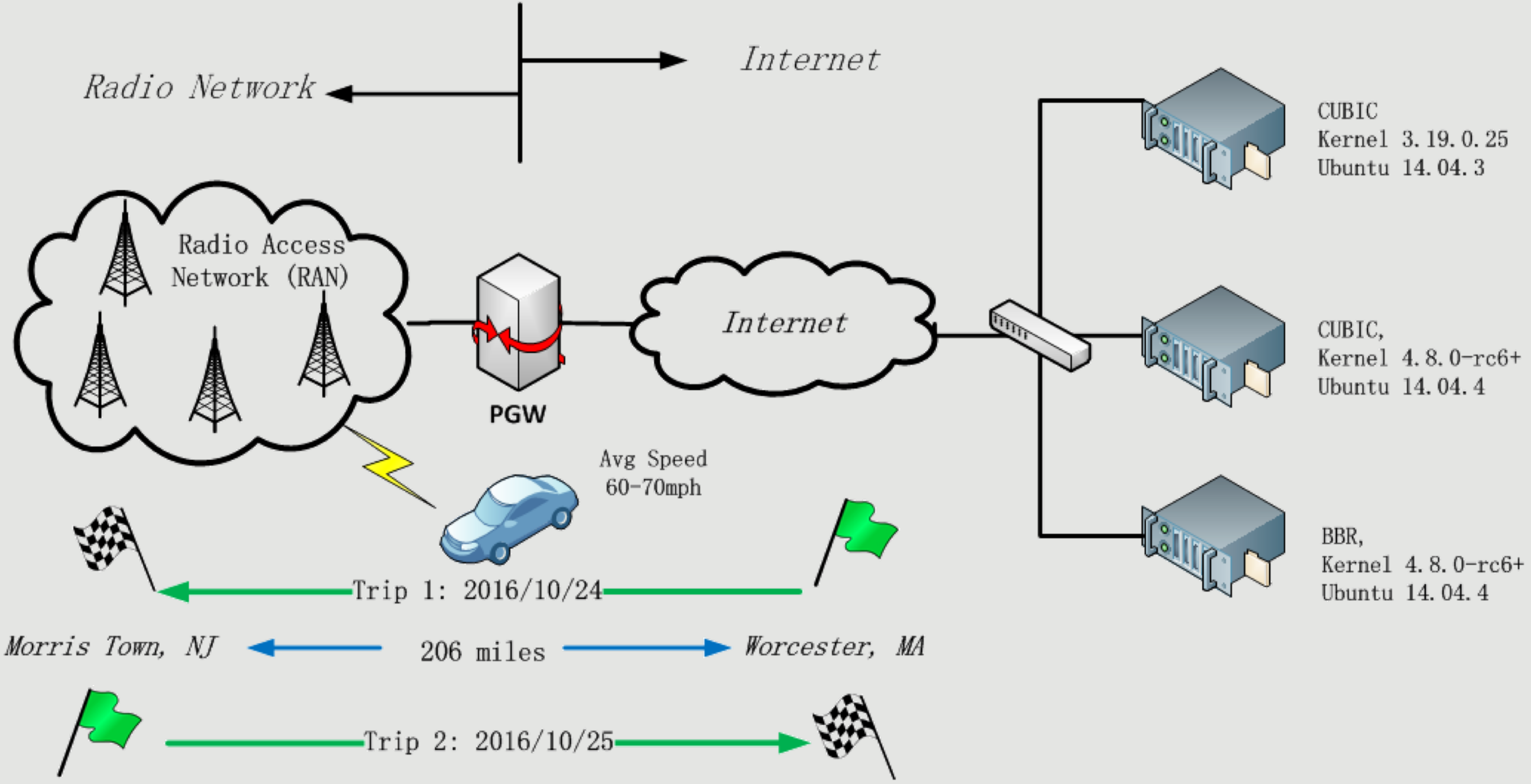
**BBR (Bottleneck Bandwidth and Round trip propagation time).**

- Developed by Google, originally for server to server communication.
- BBR was released with 4.8-rc6 kernel

**CUBICs**

- The current default CCA in Linux
- Two servers running 4.8-rc6 and 3.19 kernels.
  - CUBIC in 4.8 introduces a patch to keep cwnd growth to cubic curve after "application limited" long idle time (bictcp_cwnd_event()).

# Experimental Setup



# Driving Route


- Date:

2016/10/24 and 2016/10/25

- End Points

Worcester, MA
Morris Town, NJ

- Distance

410 miles+ round trip,

- Data Volume

15.0+ GB traffic as 720 20MB file downloading in 6 hours.

some “large scale” research only collect 90GB traffic in 8 months.

# Measurement Tools Used

**Commercial Tool (Qualipoc) on smart phone (LG G2 VS980)**

- Ping tool to measure propagation round trip time between server and phone.
- Throughput measurement tool.
- Physical and Link Layer statistics collected from device drivers.

**Three HP Proliant 460c Gen9 blade Servers**

- All run with Ubuntu 14.04: two with 4.8.0-rc6 kernel, and two with 3.19.0.25 kernel.
- Same kernel settings and Ethernet (NIC) settings, except default congestion control algorithm.
- Apache 2.4.7 Web server with PHP 5.0, dynamically generating  file to avoid caching.
- Tcpdump running as a service in background,
- Dedicated performance study servers, light load (< 1% CPU usage).

# 700MHz Radio Spectrum

**700MHz (Band XIII)**

- Verizon provide 700MHz and 1700/1900MHz (AWS) radio spectrum.
- AWS only provide extra capacity in urban area.
- None of US carrier provides national wide AWS coverage.

**Lock phone on 700MHz spectrum.**

- Lost GPS location and velocity in test, could only estimate average speed through checkpoints.

**Efforts to Reduce Random Variables**

- Same route, Same Driver, Same Car
- Identical Servers, except default congestion control algorithm.

## Band XIII Radio Spectrum

| Metric | Value |
|---|---|
| Band Number | Band XIII (13) |
| UP Link Freq. | 777-787 MHz |
| Down Link Freq. | 746-750 MHz |
| Channel Width | 10MHz |
| Modulation | **QPSK, 16QAM, 64QAM** |
| Theoretic TCP Throughput | 45 – 50 Mbps (maximum) |

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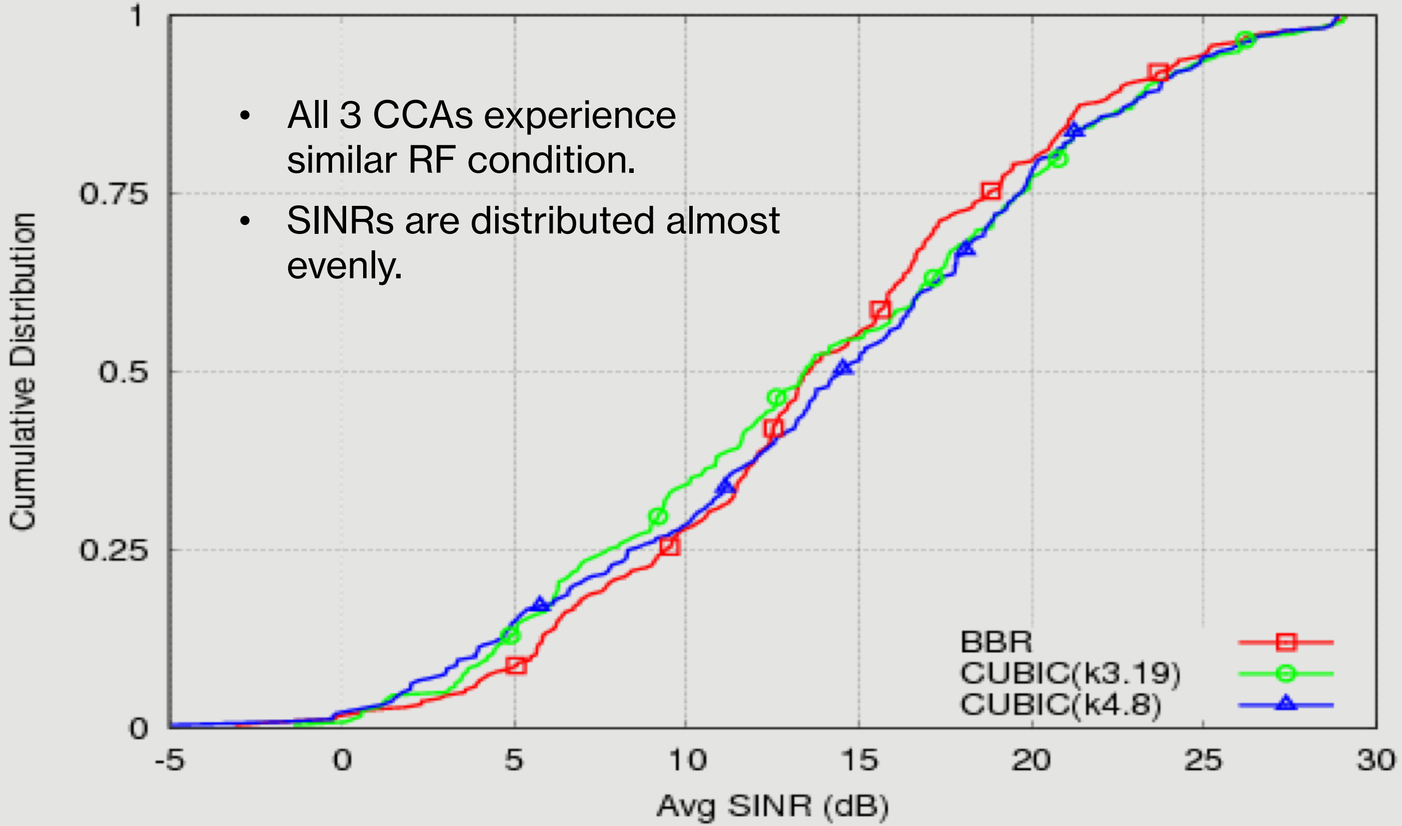
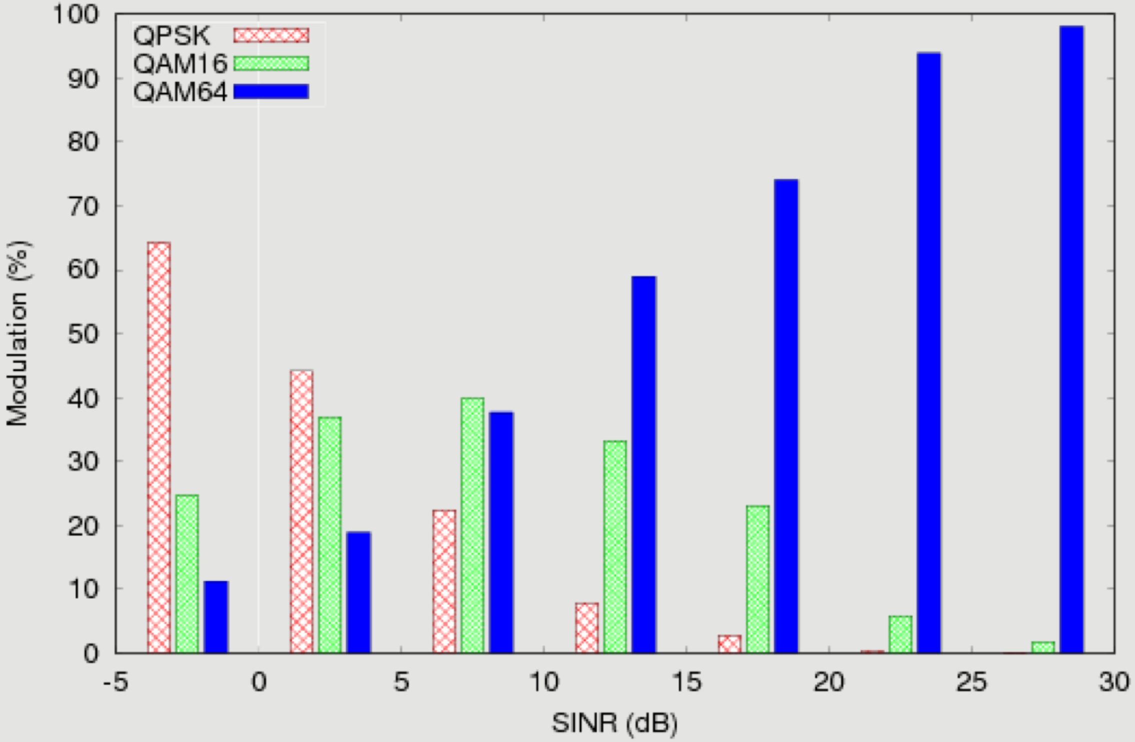
# Radio Condition (SINR) on Highway

- All 3 CCAs experience similar RF condition.
- SINRs are distributed almost evenly.



# Modulation / Rate Adaption

Fig. Modulation on Highway




| Theoretical Max PHY Throughput | 10MHz |
|---|---|
| QPSK | 17 Mbps |
| 16QAM | 25 Mbps |
| 64QAM | 50 Mbps |

- Modulation/Rate Adaption changes would impact bandwidth estimation algorithm, for example BBR.
- Rate drop suddenly increase the RLP queuing layer delay that cause eNodeB AQM drops.

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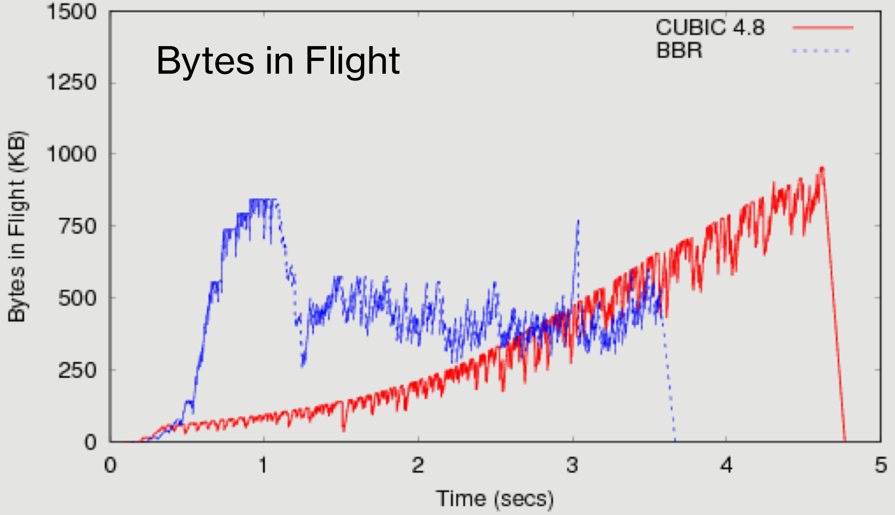
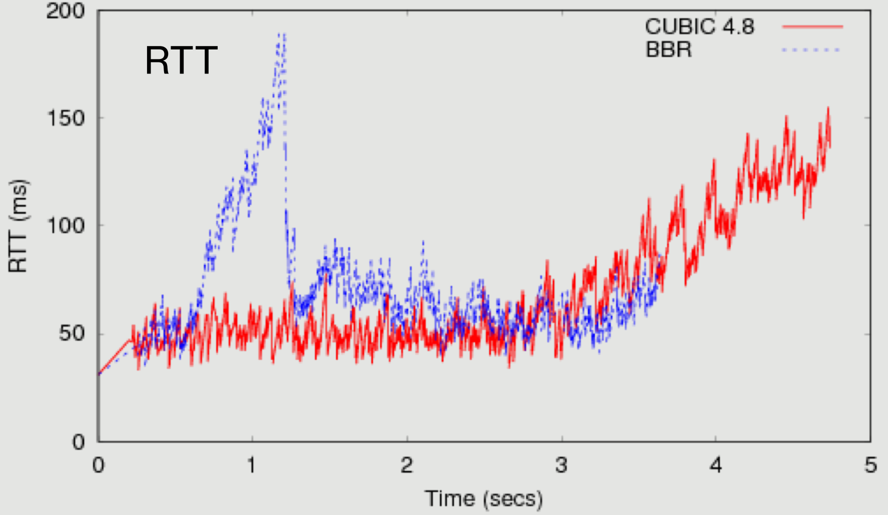
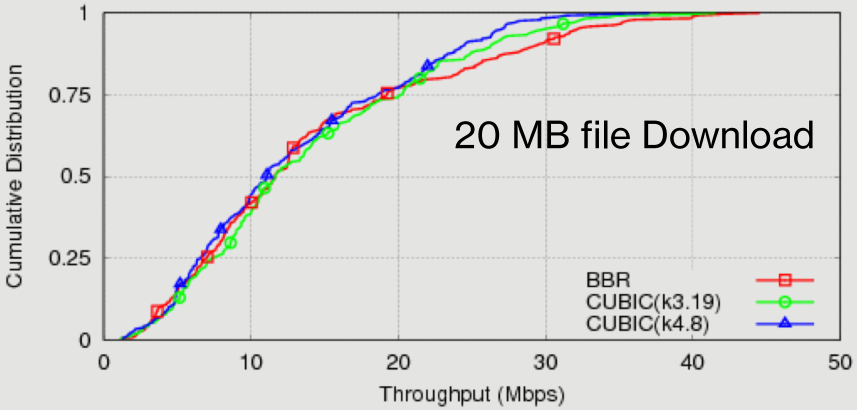
# Case Study: Single BBR and CUBIC (k4.8) Flow Comparison




- BBR transmits aggressively during its initial probing phase
- After probing phase, BBR maintains an RTT under 80ms.
- CUBIC exits from slow start early with a small congestion window.
- CUBIC unlikely fully utilize the radio link resources for the duration.

# Compare Throughputs of CCAs on Highway



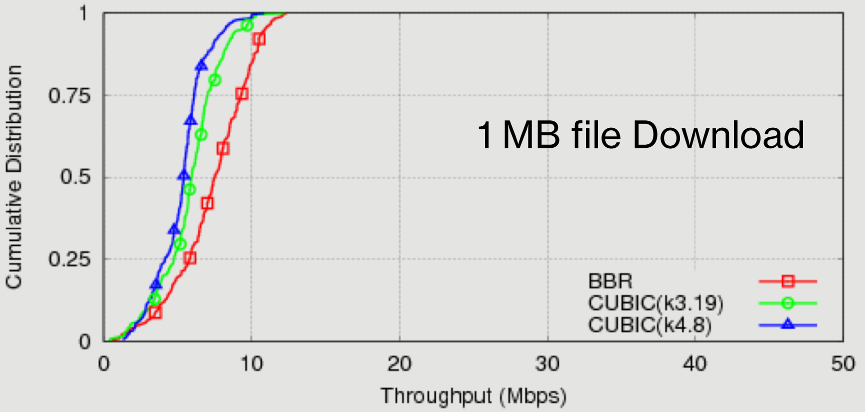
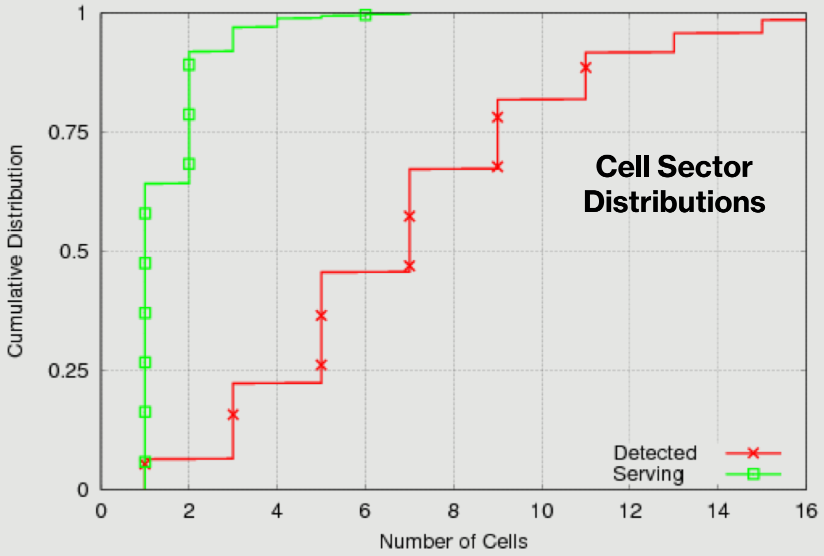



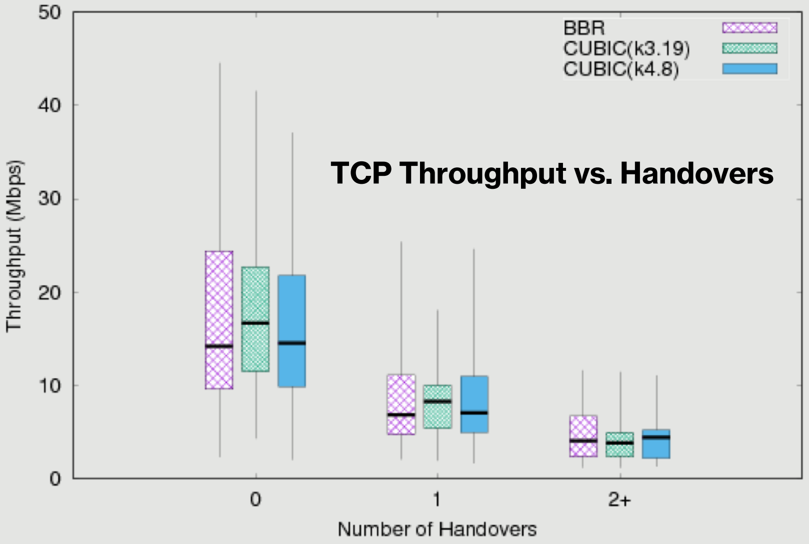

**Table Overall Throughputs**

| CCAs | Mean | Median |
|---|---|---|
| BBR | 14.1 ± 9.5 | 11.6 |
| CUBIC(k3.19) | 14.0 ± 8.4 | 11.6 |
| CUBIC(k4.8) | 13.0 ± 7.8 | 11.1 |

- All three CCAs achieve similar throughput distribution.
- BBR achieves the highest throughput as 44 Mbps, close to theoretical maximum download throughput on a 10Mhz channel.
- In first 1MB downloading, BBR's probing phase results in higher throughput.

# Hand-over Between eNodeBs

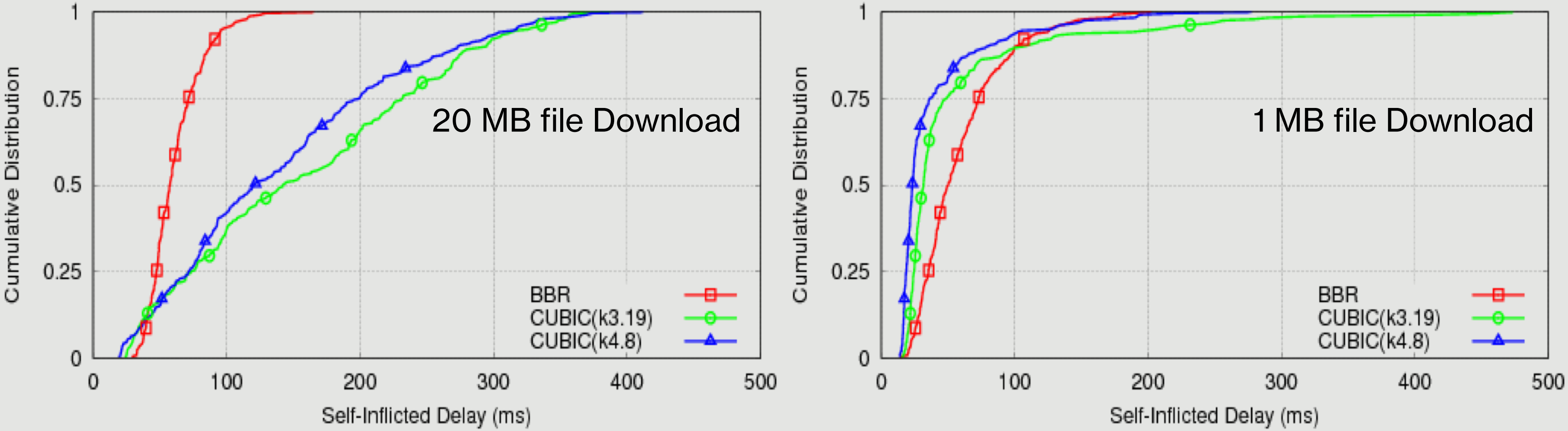



- Hand-over are not as frequent as we throughput, 65%+ does not have handovers.
- 700MHz eNB serves a large area (up to 4000 meters in radius), and car speed is only 30 m/s.
- Flows on LTE are “mice” and “dragonflies”

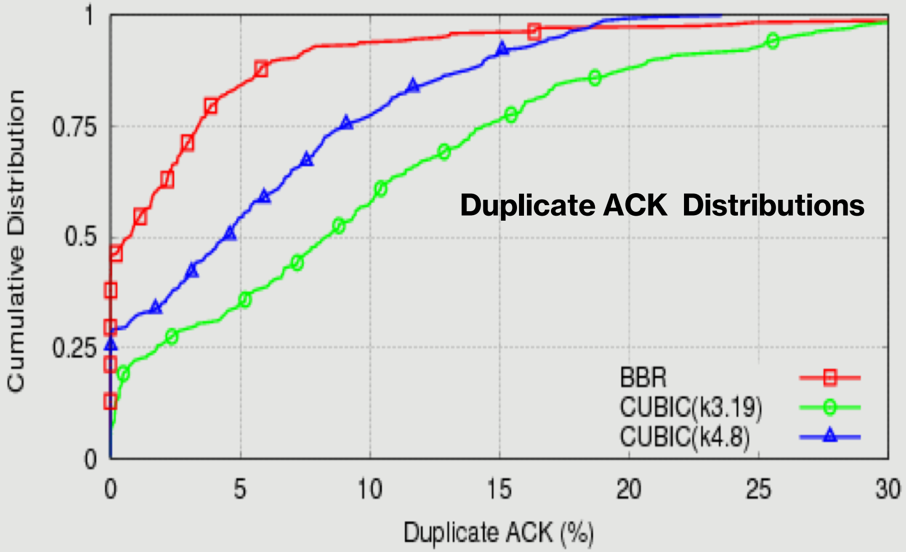
- On average, multiple hand-over would lower the throughput.
- Long Live video flows would be victim of Hand-over

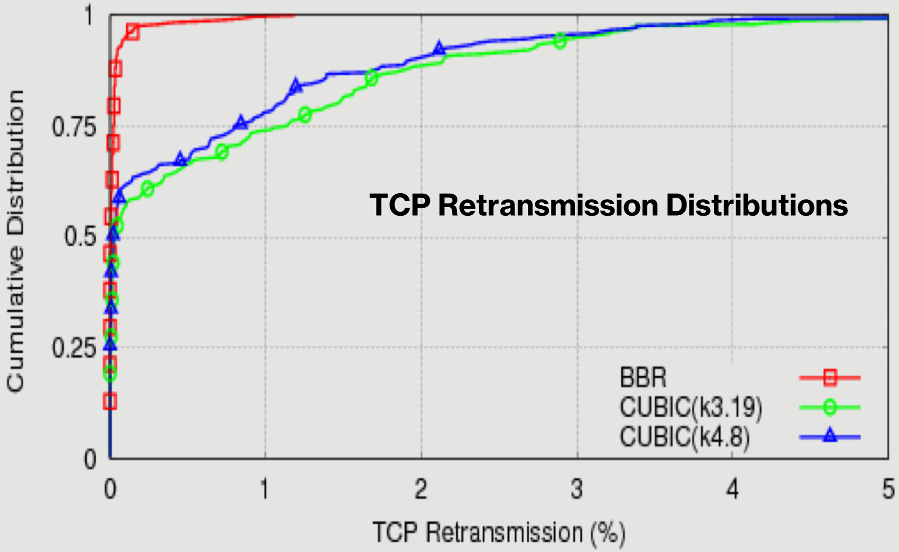
# Self-Inflicted Delay




- In full 20 MB file downloading, BBR has lower self-inflicted delays than CUBICs.
- During the first 1MB downloading, BBR has a slightly higher median delay.

# Retransmissions

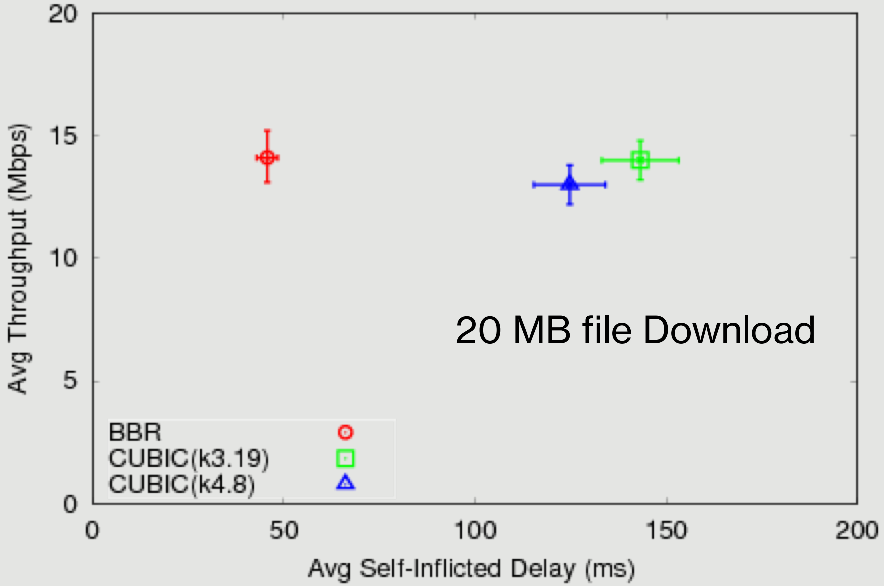


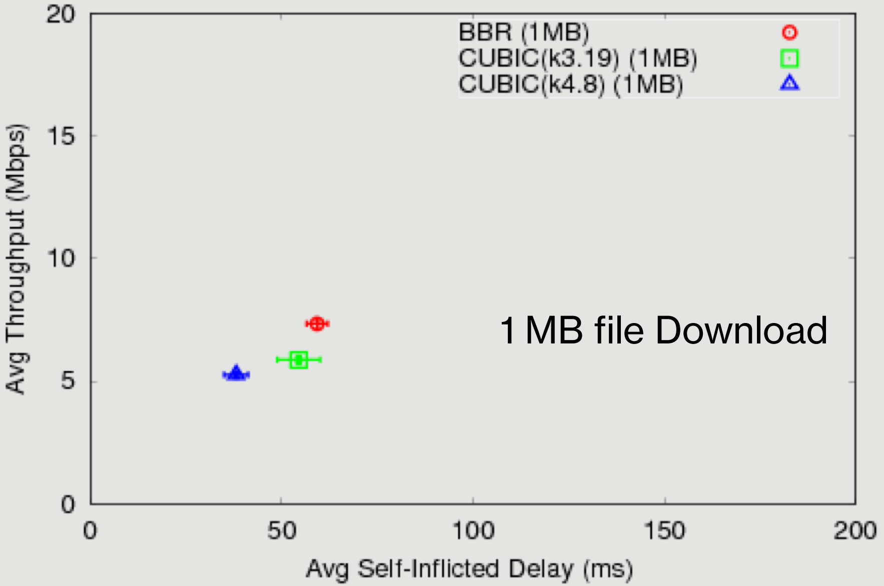




BBR attempts to have a low RTT with smaller CWND, and its benefits are:

- Fewer duplicate ACKs than either version of CUBIC
- Low retransmission rate

# Summary




- BBR balances the RTT and Throughput, (winner on Highway.)
- Different design principle of BBR and CUBIC

# Congestion Control Algorithm over Mobile Network

- eNodeB's are bottle-neck devices over mobile network, and "buffer bloat" is the main reason for TCP performance degradation.
- Reducing maximum RWND on UEs to avoid "buffer bloat" is not practical.
- Large buffer inside eNodeB is a double-edged sword to performance, and large buffer may increase RTT.
- Fairness may not be an important metric for CCA over LTE, because eNodeB supports per-device queue.

# Conclusions

**Cross Layer and Comprehensive Measurement Study on Highway.**

- Results as input to model and simulation in future.

**CUBIC with hystart may not preform well on LTE.**

- Long ramp up time to its maximum CWND causing a low link utilization

**BBR balances RTT and Throughput on LTE (tested w/ single flow per device)**

- BBR can achieve a high throughput with low self-inflicted RTT.
- BBR seems to be a good CCA candidate for LTE PEP in the first look.

**Future Works**

- Multiple BBR flows per device
- Evaluation of RTT based CCAs.

# Questions?