WPI

An In-depth Study of LTE: Effect of Network Protocol and Application Behavior on Performance

Authors: Junxian Huang, Feng Qian, Yihua Guo, Yuanyuan Zhou, Qiang Xu, Z. Morley Mao, Subhabrata Sen, Oliver Spatscheck

CS577

Brett Levasseur

Outline

WPI

- Introduction
- LTE Data And Local Testbed
- LTE Network Characteristics
- Abnormal TCP Behavior
- Bandwidth Estimation
- Network Applications in LTE
- Conclusions
- Questions

Introduction

WPI

- Previously observed LTE network characteristics
  - Higher bandwidths
  - Lower RTT
  - TCP underutilizes links
- This work examines
  - Measurements from real LTE network
  - TCP bandwidth estimation algorithm
  - Power management

LTE Network

WPI

- UE – User Equipment
- RAN – Radio Access Network
- CN – Core Network
- Monitor – Author's data collection point
- PEP – Performance Enhancing Proxy

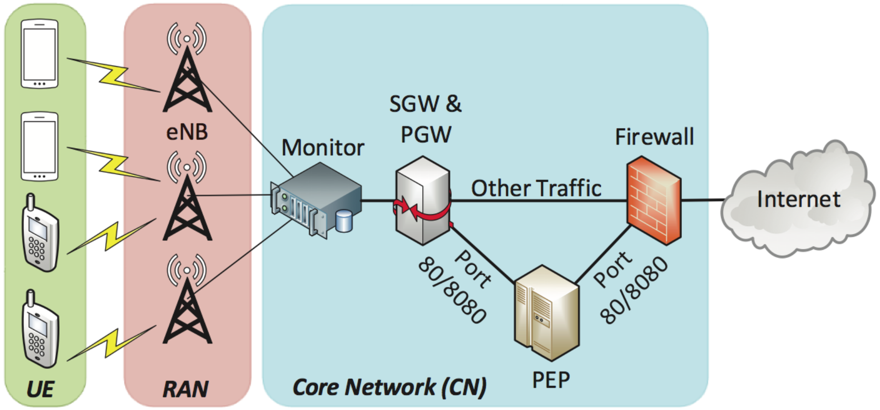
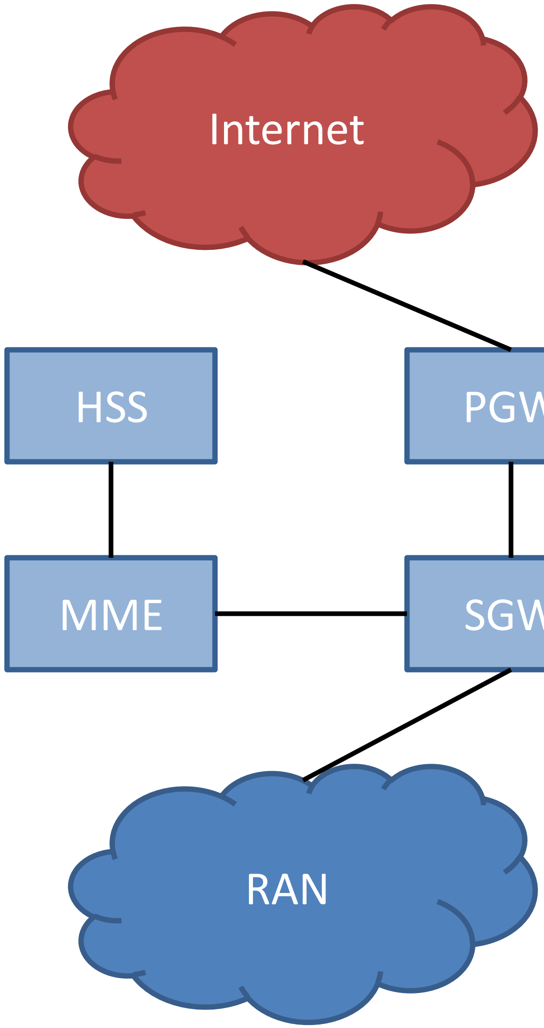


Figure 1: Simplified network topology of the large LTE carrier from which we obtained our measurement data.

LTE Network

WPI

- PEP – Not part of normal CN
- Intercepts TCP traffic on ports 80 and 8080
- Splits end to end TCP connection to two
  - UE to PEP
  - PEP to server
- Performs compression and caching



[Dahlman]

LTE Data

WPI

- Covered 22 eNBs in a US city
- Collection from 10/12/2012 - 10/22/2012
- Collected
  - IP and transport headers
  - 64 bit timestamps per packet
  - HTTP headers
  - 3.8 billion packets
  - 2.9 TB of traffic (324 GB of headers)

Local Test Bed

- UE
  - Samsung Galaxy S III
  - Android 4.0.4 / Linux Kernel 3.0.8
- Server
  - 2GB RAM / 2.4 GHz Intel Core 2 CPU
  - Ubuntu 12.04 / Linux Kernel 3.2.0-36-generic
  - TCP CUBIC
- Measured TCP throughput and RTT
- Used two different LTE networks

Outline

WPI

- Introduction
- LTE Data And Local Testbed
- LTE Network Characteristics
- Abnormal TCP Behavior
- Bandwidth Estimation
- Network Applications in LTE
- Conclusions
- Questions

Measurements

WPI

- Majority of traffic is TCP
- Majority of the remainder is UDP

TCP Flows (95.3 %)	HTTP (80/8080) 50.1%
	HTTPS (443) 42.1%
TCP Bytes (97.2%)	HTTP (80/8080) 76.6%
	HTTPS (443) 14.8%

TCP Flow Size

WPI

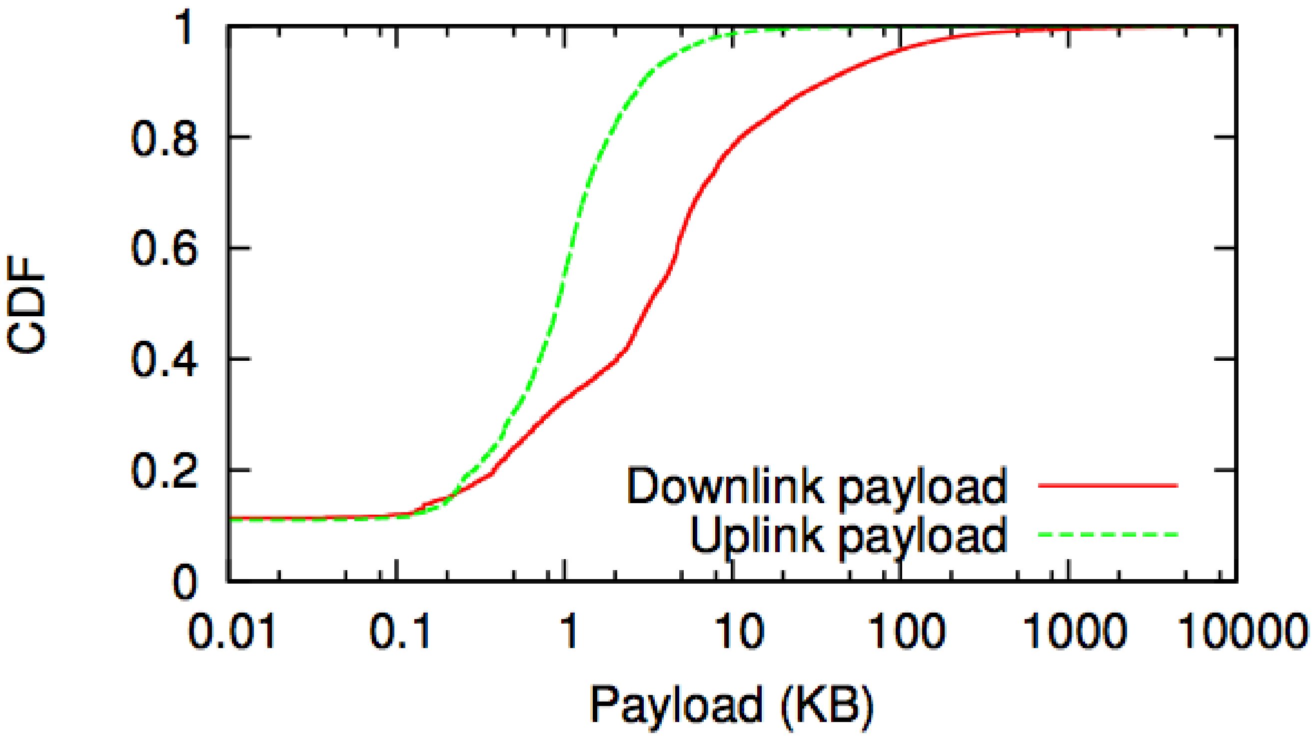


Figure 2: Distribution of TCP flow sizes.

TCP Flow Size

UL Flows	90%, less than 2.9 KB	
	10.9% have no uplink	
	Top 0.1% (by payload) account for 63.9% of total bytes	
	73.6% of the top flows are images	
DL Flows	90%, less than 35.9 KB	
	11.3% have no downlink	
	Top 0.6% (by payload) account for 61.7% of total bytes	
	Top 5% (by payload size)	Payload >= 85.9 KB
		80.3% use HTTP
		74.4% video or audio

TCP Flow Duration

WPI

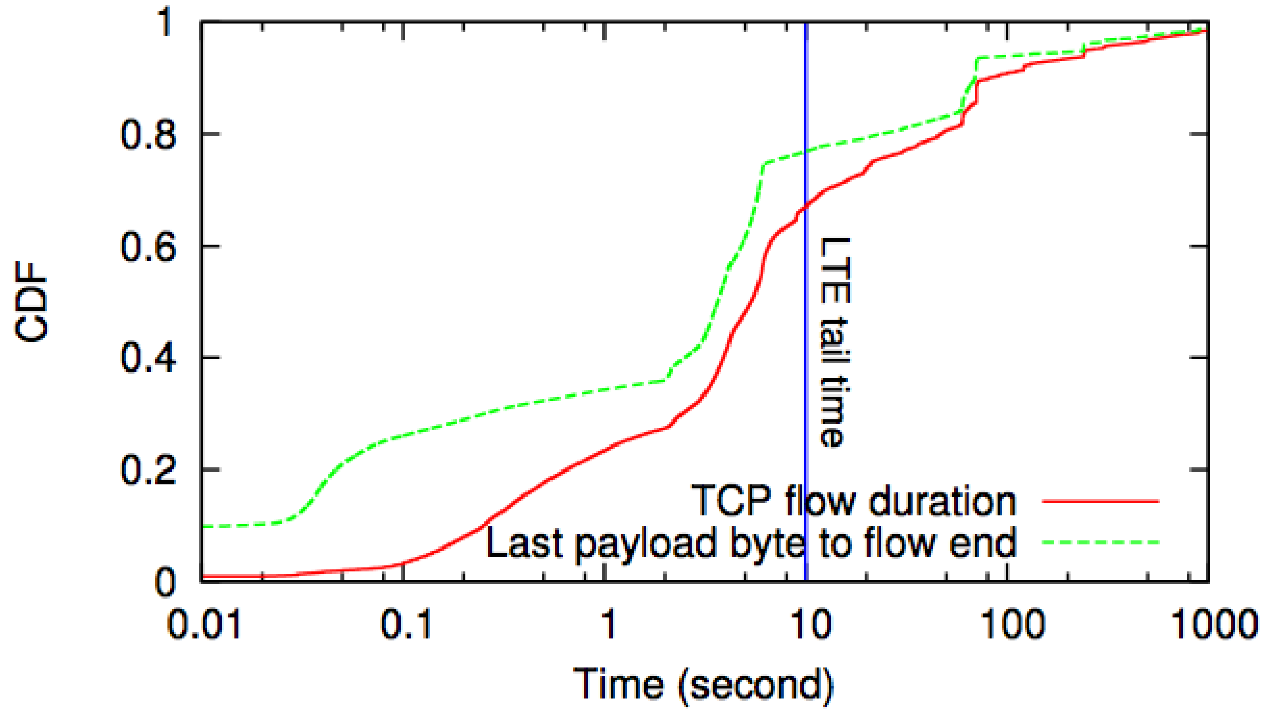


Figure 3: Distribution of flow duration and the duration between the last payload byte to the end of the flow.

TCP Flow Duration

WPI

Flows	Duration
48.1%	< 5 seconds
6.8%	>= 3 minutes
2.8%	>= 10 minutes

Flows	Termination
86.2%	TCP FIN
5.4%	TCP RESET
8.5%	TCP SYN (did not connect properly)

Tail Time

WPI

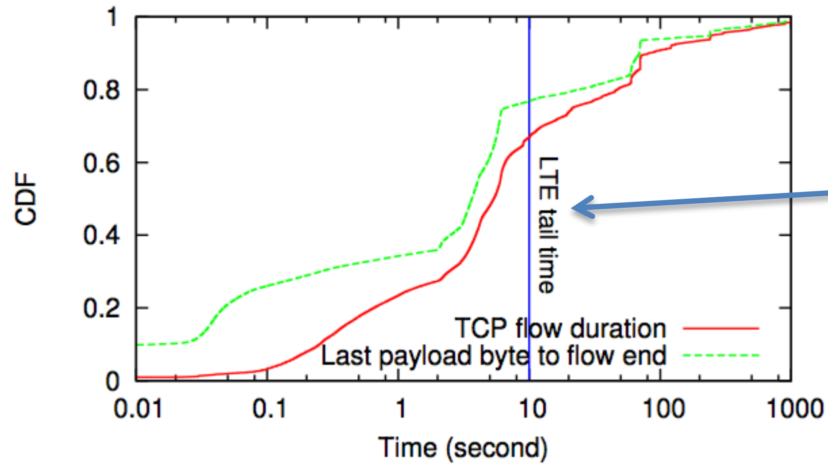


Figure 3: Distribution of flow duration and the duration between the last payload byte to the end of the flow.

10 seconds between last transmission and the UE radio being turned off

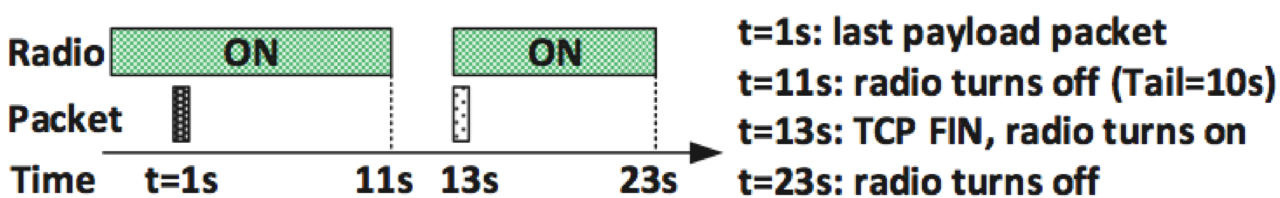
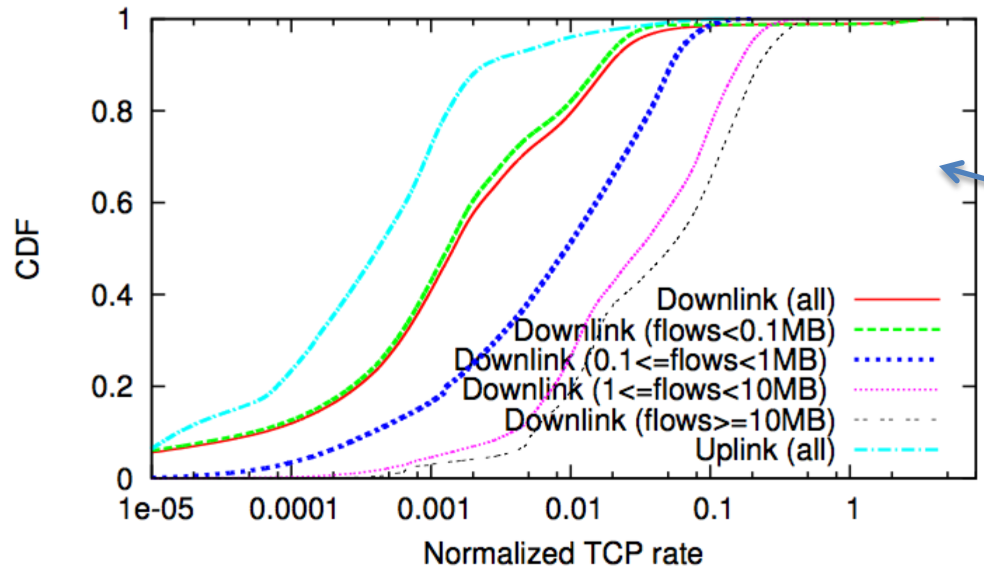


Figure 4: An example of delayed FIN packet and its impact on radio resource management.

TCP Flow Rate

WPI



Better flow rate

Figure 5: Distributions of normalized TCP flow rates.

- Larger flows send faster than smaller flows
- Flow duration and rate are more negatively correlated than on Internet backbone

TCP Concurrency

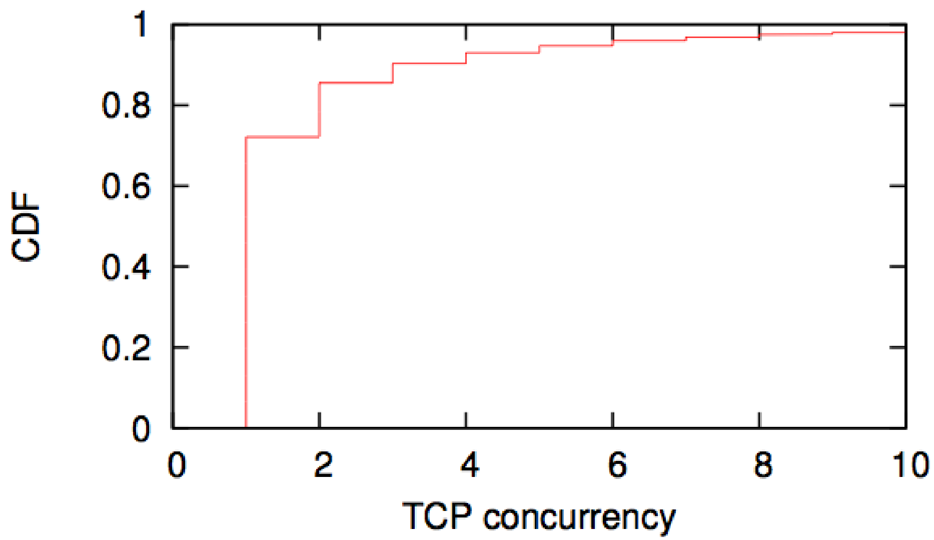


Figure 6: Concurrency for TCP flows per user uniformly sampled by time.

- 72.1% of the time there is only one active TCP flow
- Possibly higher for smartphones

RTT

WPI

Better RTT

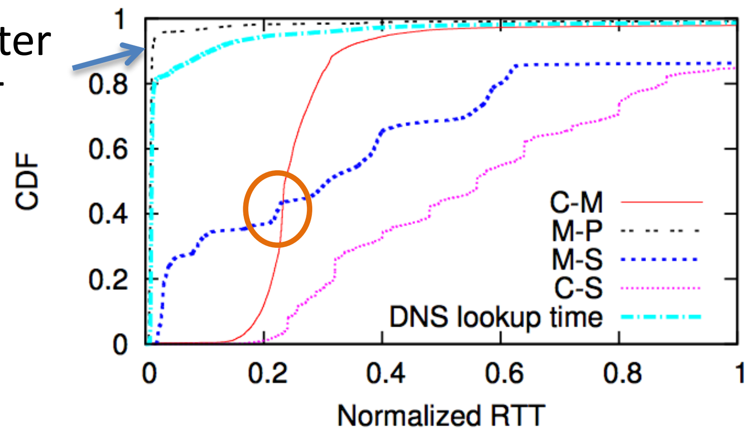


Figure 7: Distributions of normalized handshake RTT and DNS lookup time.

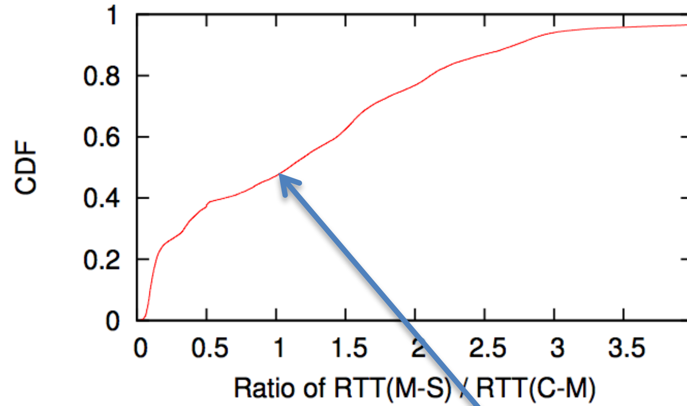


Figure 8: Distribution of the radio between uplink and down-link RTT (for non-PEP traffic).

RTT to M-S > C-M

C-M = Client to monitor
M-P = Monitor to PEP
M-S = Monitor to server
C-S = Client to server

- RTT Monitor to server > than client to monitor
- Indicates wireless link is not largest delay factor

LTE Promotion Delay

WPI

- Time to turn radio on
- $G(TS_b - TS_a)$ = RTT seen by UE
- G – Inverse ticking frequency of UE's clock

Percentile	Promotion Delay
25%	319ms
50%	435ms
75%	558ms

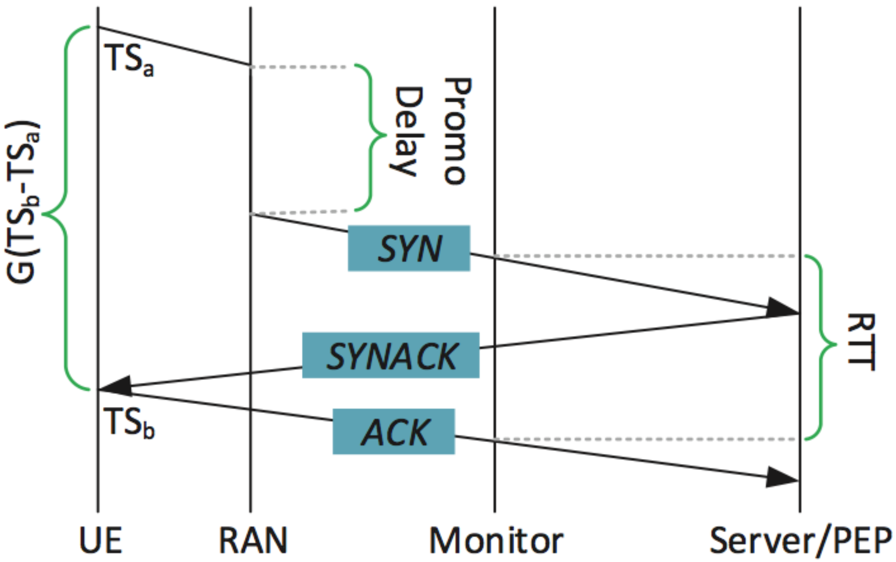


Figure 9: Estimating the promotion delay.

Queuing Delay

WPI

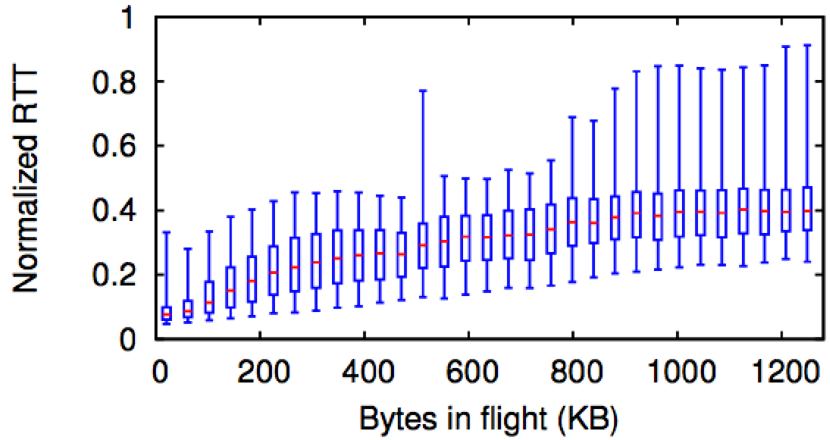


Figure 10: Downlink bytes in flight vs. downstream RTT.

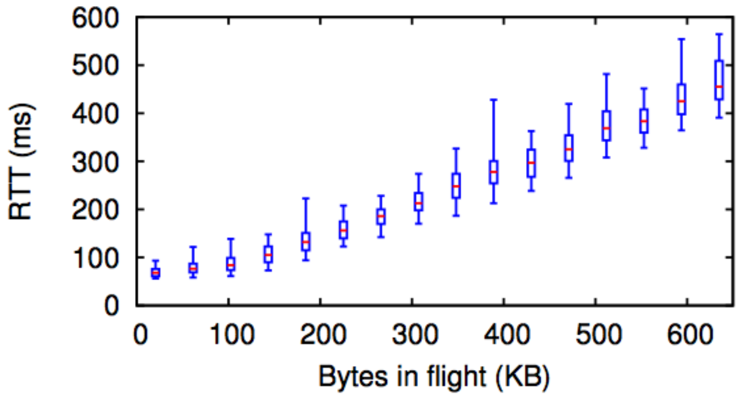


Figure 11: Downlink bytes in flight vs. downstream RTT (controlled lab experiments with LTE Carrier A).

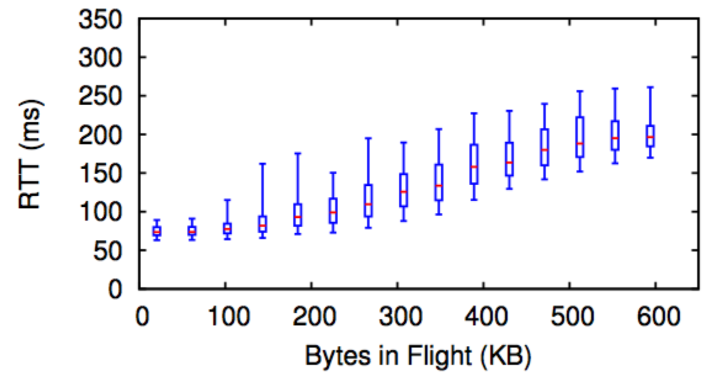


Figure 12: Downlink bytes in flight vs. downstream RTT (controlled lab experiments with LTE Carrier B).

Queuing Delay

WPI

- 10% of large flows have > 200 KB in-flight
- Leads to
  - Queue delay
  - Longer RTT
  - Created by long flows but impacts short flows

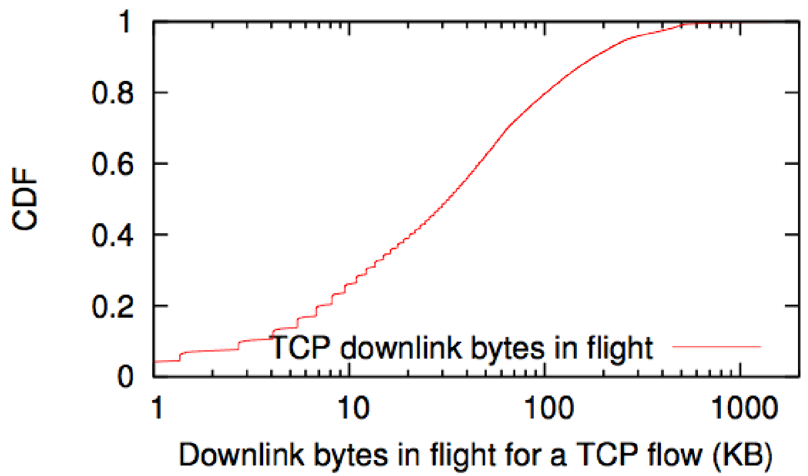


Figure 13: Distribution of downlink bytes in flight for large flows (> 1 MB).

TCP Retransmission Rate

WPI

- 38.1% of flows have no retransmission
- 0.06% is the median of flows with retransmission
- Physical/MAC layer retransmission reduced transport layer retransmission
- Study does not look at LTE RLC layer retransmissions

Measurement History

WPI

Table 1: Comparing with previous measurement studies

Study	Our Results	3GTest [14]	4GTest [13]		SpeedTest [31]					
Time	October 2012	Aug to Dec 2009	Oct to Dec 2011		February 21 2011 to June 5 2011 (15 weeks)					
Location	One US Metro Area	Across U.S.	Across U.S.		New York City		Madison WI, US		Manchester UK	
Type	LTE Only	Four 3G ISPs	LTE	WiMAX	Cellular	WiFi	Cellular	WiFi	Cellular	WiFi
5% TCP DL*	569	74 – 222**	2112	431	108	404	99	347	28	267
50% TCP DL	9185	556 – 970	12740	4670	1678	7040	895	5742	1077	4717
95% TCP DL	24229	1921 – 2943	30812	10344	12922	17617	3485	14173	3842	15635
5% TCP UL	38	24 – 52	387	172	52	177	55	168	25	180
50% TCP UL	2286	207 – 331	5640	1160	772	2020	478	1064	396	745
95% TCP UL	8361	434 – 664	19358	1595	5428	10094	1389	5251	1659	5589
5% HS RTT	30	125 – 182	37	89	68	21	99	24	98	34
50% HS RTT	70	160 – 200	70	125	159	54	184	69	221	92
95% HS RTT	467	645 – 809	127	213	786	336	773	343	912	313

* TCP DL: downlink throughput (kbps). TCP UL: uplink throughput (kbps). HS RTT: TCP handshake RTT (ms). 5%, 50%, 95% are percentiles.
** For a range $x - y$, x and y are the result of the worst and the best carriers, respectively, for that particular test.

- LTE outperforms 3G, WiMAX and WiFi
- 4GTest LTE is higher than measurements
  - Possibly due to rate limiting at remote server

Outline

WPI

- Introduction
- LTE Data And Local Testbed
- LTE Network Characteristics
- Abnormal TCP Behavior
- Bandwidth Estimation
- Network Applications in LTE
- Conclusions
- Questions

Duplicate ACKs

WPI

- Medians
  - 17 Dup ACKs
  - 2 out of order packets
- Over 29% of flows have > 100 Dup ACKs
- Ratio Dup ACK / out of order
  - 24.7% of flows over 25
  - Some up to 5,000
  - 1 out of order packet can cause many Dup ACKs

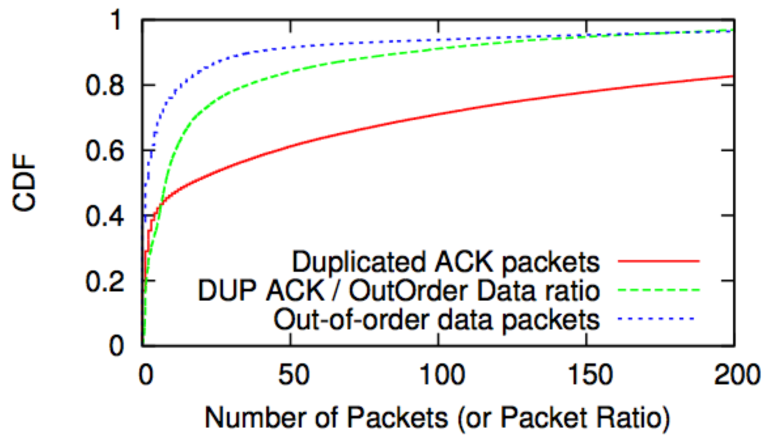


Figure 14: Observed duplicate ACKs and packet reordering in large TCP flows.

Undesired Slow Start

WPI

- Undesired Slow Start – Large RTT triggers RTO
- Author's measure undesired slow start with

$$R_{ss} = \frac{\theta_{[100,200]}}{\theta_{[0,100]}}$$

- Where $\theta_{[t_1,t_2]}$ is average downlink throughput from t_1 ms to t_2 ms after last Dup ACK
- R_{ss} > 1.5 in slow start
  - 20.1% of large flows have >= 1 lost packet
  - 12.3% of all large flows have >= 1 lost packet

Undesired Slow Start

WPI

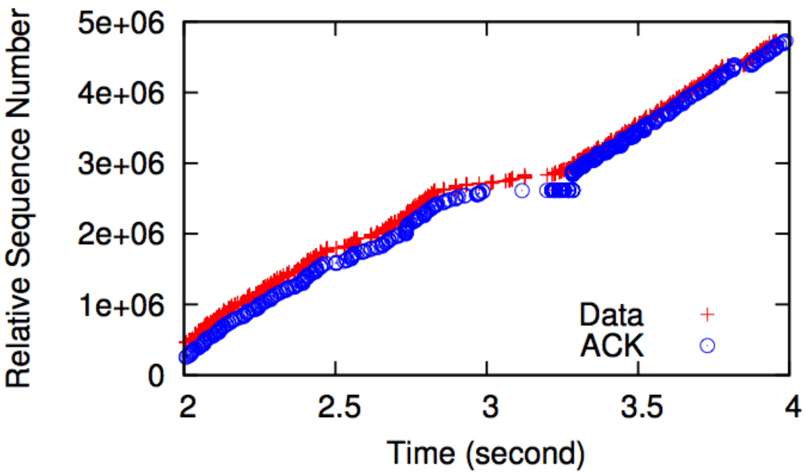


Figure 15: Duplicate ACKs not triggering a slow start.

R_{ss} = 1.0

R_{ss} = 3.5

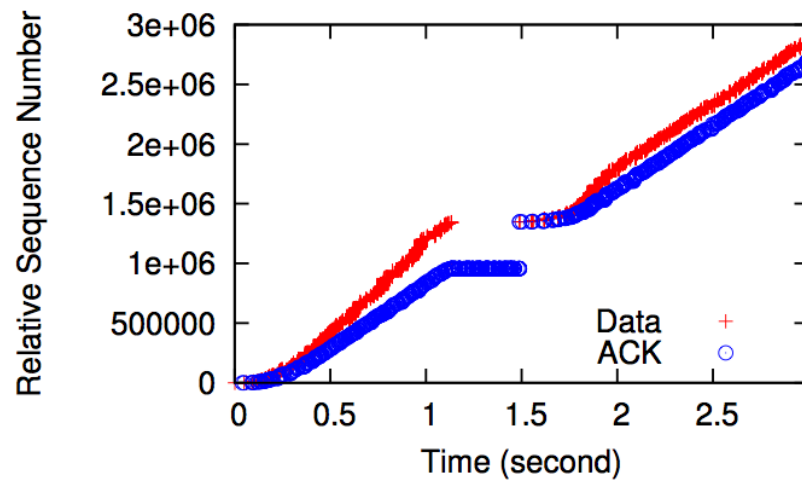


Figure 16: Duplicate ACKs triggering a slow start.

Mitigate Undesired Slow Start

WPI

- Update RTO from duplicate ACKs with SACK
  - Take difference between SACK window of two consecutive duplicate ACKs
  - 82.3% of flows used SACK in dataset
  - < 1% of flows had packet reordering
- Update RTO from duplicate ACKs without SACK
  - Assume duplicate ACKs in response to data packets in order
- Prevent > 95% of observed undesired slow starts

Outline

WPI

- Introduction
- LTE Data And Local Testbed
- LTE Network Characteristics
- Abnormal TCP Behavior
- Bandwidth Estimation
- Network Applications in LTE
- Conclusions
- Questions

TCP Transmission Rate

WPI

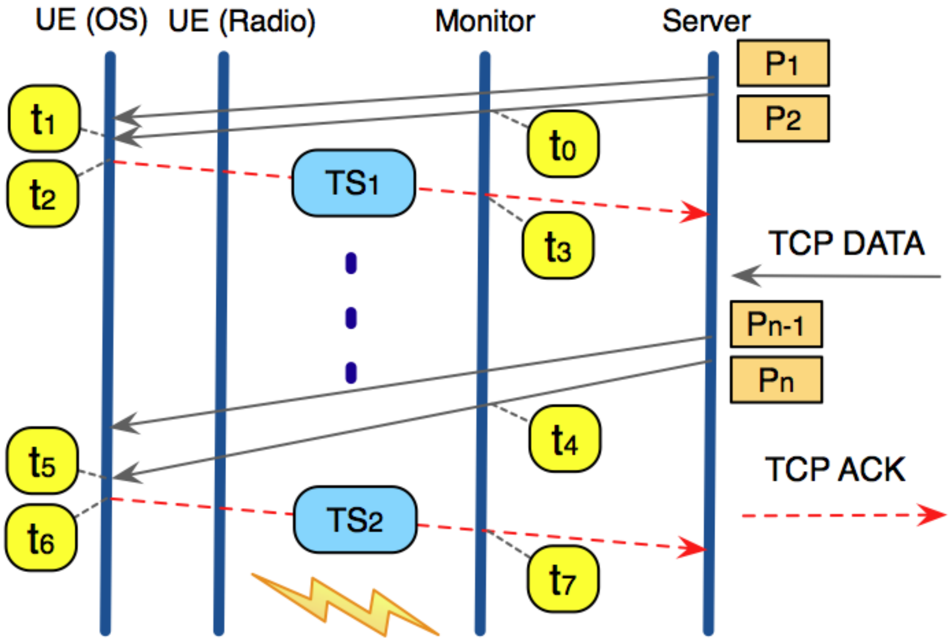


Figure 17: Typical TCP data transfer.

Sending Rate from Monitor

$$R_{snd} = \frac{S(n-2)}{t_4 - t_0}$$

Receive Rate at UE

$$R_{rcv} = \frac{S(n-2)}{t_5 - t_1}$$

TCP Timestamps

WPI

- Replace t_1 and t_5 with t_2 and t_6
- t_2 and t_6 originate at UE
- Replace t_2 and t_6 with TCP Timestamps
- Infer G

$$R_{rcv} \approx \frac{S(n-2)}{t_6 - t_2}$$

$$R_{rcv} \approx \frac{S(n-2)}{G(TS_2 - TS_1)}$$

$$G \approx \frac{TS_2 - TS_1}{t_7 - t_3}$$

Estimation Accuracy

WPI

- For accurate G
  $t_7 - t_3 > \delta_G$
- Error rate of G drops as δ_G grows
- At δ_G = 3 seconds error rate < 0.1%

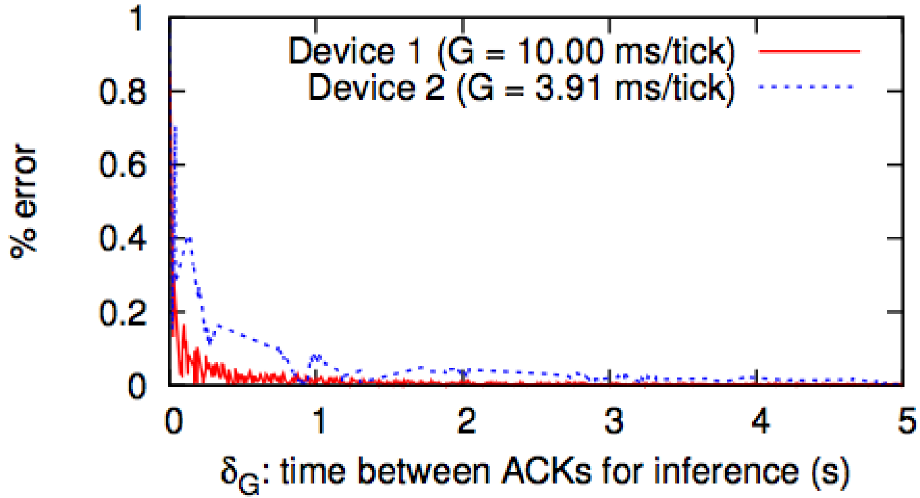


Figure 18: G **inference and the selection of** δ_G**.**

Estimation Accuracy

WPI

Flows	G
5.9%	NA
57.3%	1ms/tick
36.4%	10ms/tick
0.4%	100ms/tick

- With δ_G = 3 seconds the error rate of inferred G < 0.1% for the majority of flows
- If G is unknown it is estimated from its formula

Estimation Summary

WPI

- G is known or inferred
- Calculate R_{snd}
- If R_{snd} >= C AND packets in order AND no duplicates AND last packet is not delayed ACK
  - R_{rcv} calculated
- If C too small – underestimate
- If C too large – not enough samples
- C = 30Mbps

Validation

WPI

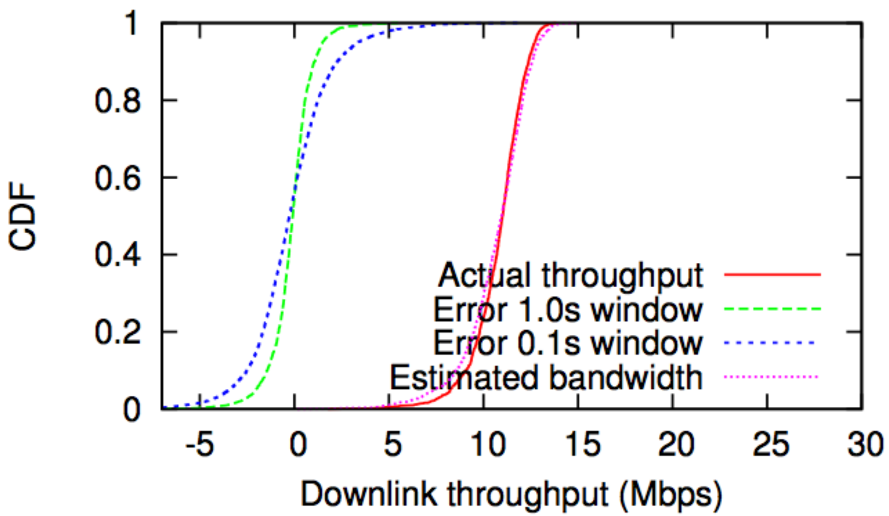


Figure 19: CDF of bandwidth estimation results for LTE network (controlled lab experiments with Carrier A).

- Compare server side estimate and UE trace
- 1 sec sample window average error rate is 7.9%
- 0.1 sec sample window average error rate has higher variation

Validation

WPI

- Actual throughput is UE perceived throughput
- Used 1 sec sample window
- Actual throughput varies around 10Mbps
- Error varies by +- 1 Mbps

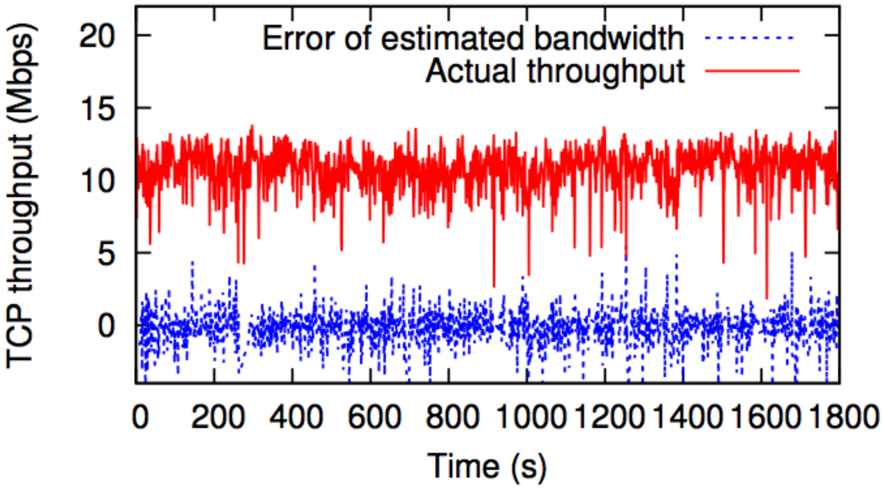


Figure 20: Time series of bandwidth estimation for LTE network (controlled lab experiments with Carrier A).

Large Flow Utilization

WPI

- Median ratio 19.8%
- 71.3% of large flows < 50% utilization
- 6.4% use more bandwidth than estimated
- Average ratio 34.6%
- Low utilization, flows last longer
  - Higher radio usage

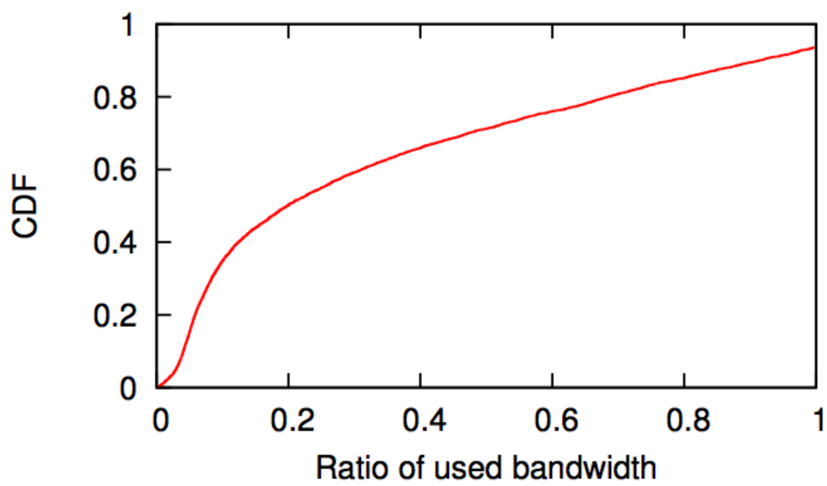


Figure 21: BW utilization ratio for large downlink TCP flows.

LTE Bandwidth Variation

WPI

- Two large flows
  - Two different users
  - Two different times
- Bandwidth varies over time
  - Condition of the wireless link
  - Movement
  - Resource scheduling

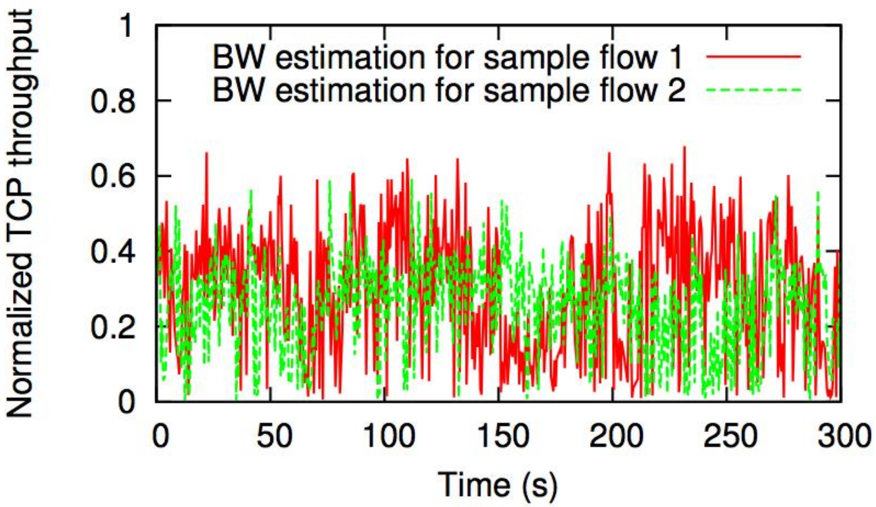


Figure 22: BW estimation timeline for two large TCP flows.

RTT & Throughput

WPI

- Experiments with modifiable RTT
  - Used iptables to redirect packets to scheduler
  - Scheduler changes available bandwidth similar to observed LTE
  - Scheduler injects delays to impact RTT
- Under small RTT TCP utilizes 95% of the bandwidth
- RTT > 400ms utilization drops below 50%

Outline

WPI

- Introduction
- LTE Data And Local Testbed
- LTE Network Characteristics
- Abnormal TCP Behavior
- Bandwidth Estimation
- Network Applications in LTE
- Conclusions
- Questions

HTTP Characterization

WPI

HTTP Content	% of traffic
Video	37.8%
Images	19.5%
Text	11.8%
Zip	8.3%
Audio	6.5%
Other	5.6%
Unknown	10.5%

- 12.9% of video content is octet-streams generated mostly by video players

TCP Receive Window

WPI

- Shazam app on iOS
- 30s, 1 MB audio
- 0s – 2s 3Mbps
- Recv window full
- 2s – 9s < 300 Kbps
- Download could have been done in 2.5s
- Connection not closed until 30s

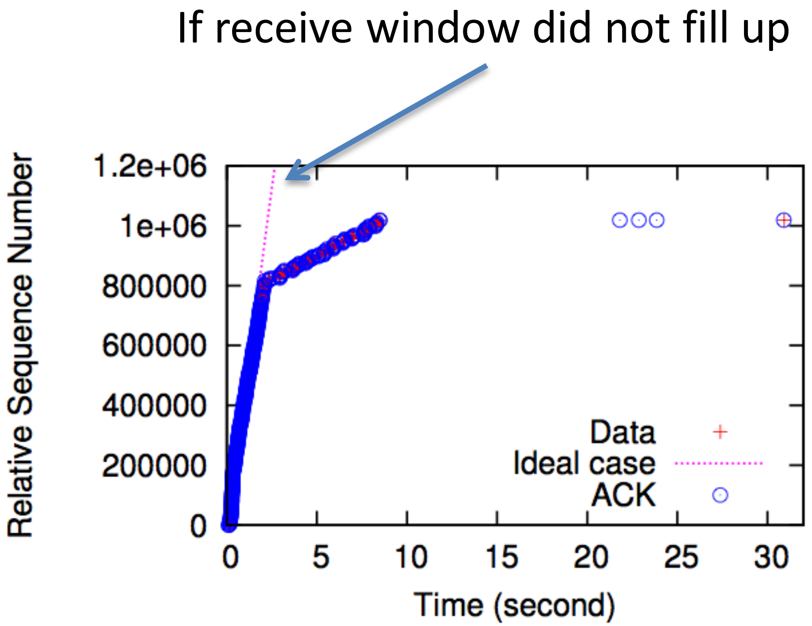


Figure 23: Full receive window slows Shazam player (a popular app) in downloading a 30-second music file.

TCP Receive Window

WPI

- Receive Window around 131,712 +- 600 bytes
  - True for > 90% of iOS, Android and Windows Phone flows
- Applications not reading from receive buffer quickly enough
- 52.6% of downlink TCP flows experience full receive window
  - 91.2% of these bottleneck happens in initial 10% of the flow duration

Application Design

WPI

- Netflix on iOS
- Multiple HTTP byte-range requests
- Many short HTTP responses
  - < 1s
  - 1 – 4MB
- Periodic requests leaves radio idle

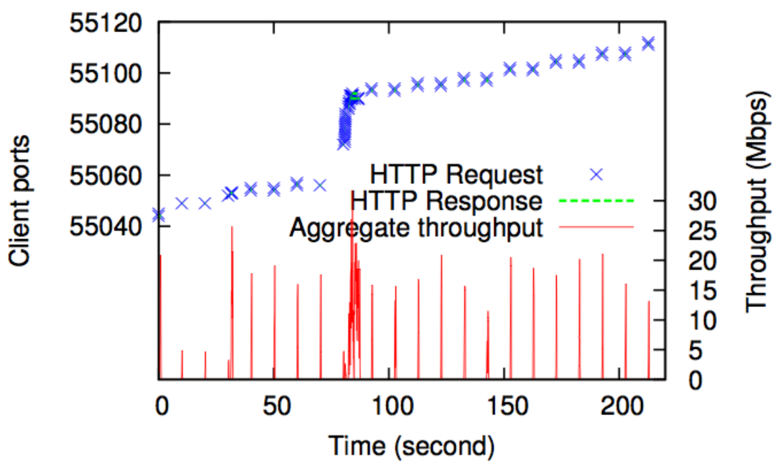


Figure 24: The periodic request behavior of Netflix player limiting its overall throughput.

Discussion

WPI

- Manufactures reduce TCP receive window
  - Decreases buffer bloat
  - Underutilizes network
- Use application buffers
  - Relieves TCP buffers
  - Allows radio interface to close sooner
- Increase amount downloaded per request, decrease number of requests

Conclusions

WPI

- Not updating RTT from Dup ACKs causes performance issues with single packet loss
- Bandwidth estimation algorithm
  - 71.3% of large flows have < 50% utilization
  - High variation of network bandwidth
  - cwnd too slow to adjust
- TCP receive window throttles 52.6% of downlink flows
- App design underutilizes bandwidth

Questions

WPI

References

- Huan J. et all, An In-depth Study of LTE: Effect of Network Protocol and Application Behavior on Performance. SIGCOMM 2013.
- Dahlman E. et all, 4G LTE/LTE-Advanced for Mobile Broadband. Academic Press, 2011.