# Data Center TCP (DCTCP)

# TCP in the Data Center

- We'll see TCP does not meet demands of apps.
  - Suffers from bursty packet drops, Incast [SIGCOMM '09], ...
  - Builds up large queues:
    - Adds significant latency.
    - Wastes precious buffers, esp. bad with shallow-buffered switches.

- Operators work around TCP problems.
  - Ad-hoc, inefficient, often expensive solutions
  - No solid understanding of consequences, tradeoffs

# Methodology

- What's really going on?
  - Interviews with developers and operators
  - Analysis of applications
  - Switches: shallow-buffered vs deep-buffered
  - Measurements

- A systematic study of transport in Microsoft's DCs
  - Identify **impairments**
  - Identify **requirements**

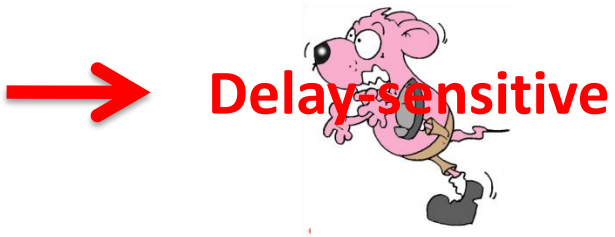
- Our solution: **Data Center TCP**

# Case Study: Microsoft Bing

- Measurements from 6000 server production cluster
- Instrumentation passively collects logs
  - Application-level
  - Socket-level
  - Selected packet-level
- More than **150TB** of compressed data over a month

# Workloads

- Partition/Aggregate
  **(Query)**



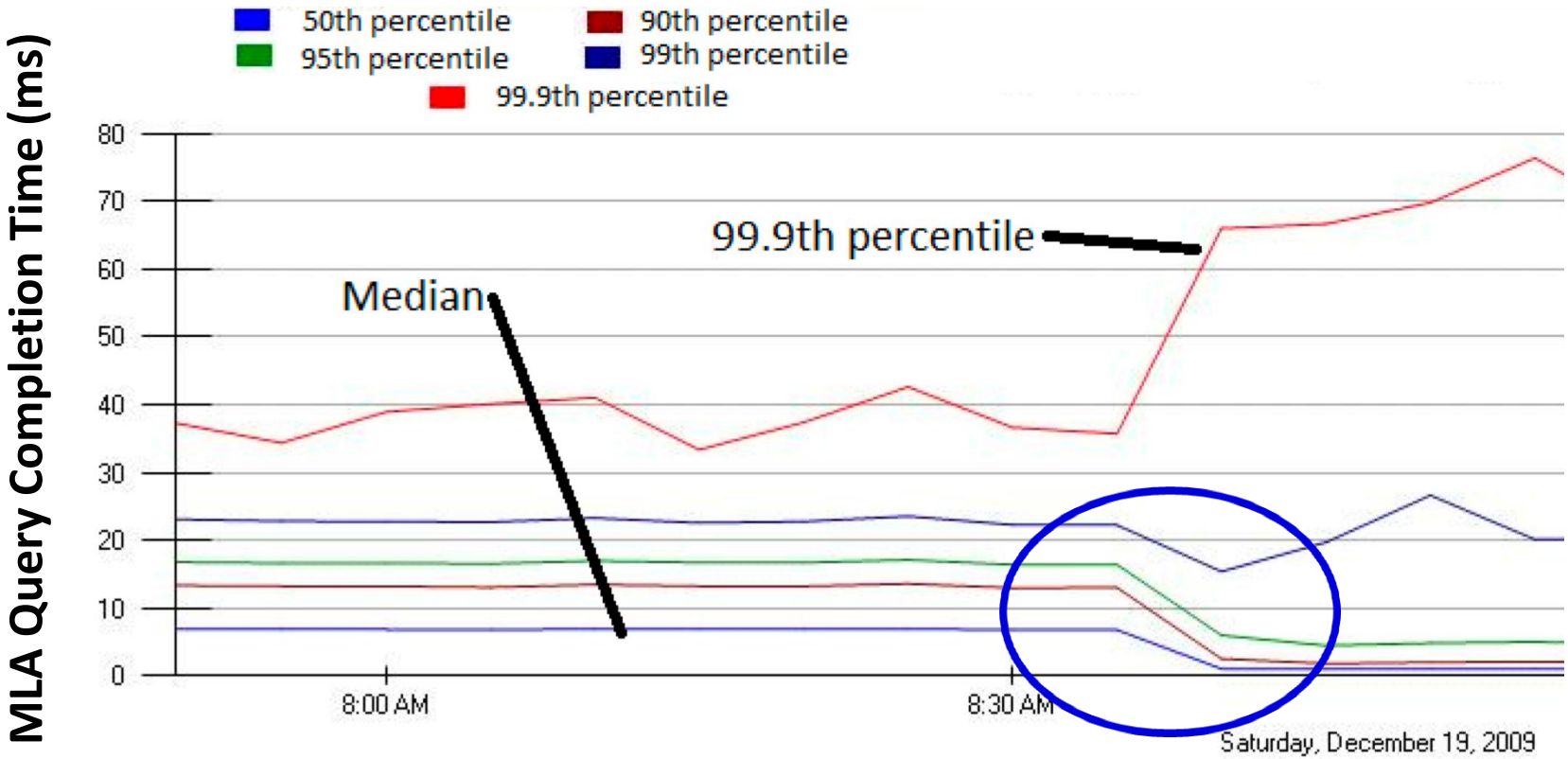

- Short messages [50KB-1MB]
  **(Coordination, Control state)**


- Large flows [1MB-50MB]
  **(Data update)**

# Impairments

- Incast
- Queue Buildup
- Buffer Pressure

# Incast Really Happens




Jittering

99.9th percentile is being tracked.

ntiles.

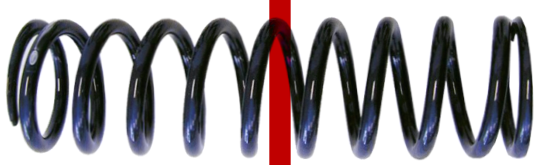
# Data Center Transport Requirements

1. **High Burst Tolerance**
   - Incast due to Partition/Aggregate is common.
2. **Low Latency**
   - Short flows, queries
3. **High Throughput**
   - Continuous data updates, large file transfers

**The challenge is to achieve these three together.**

# Tension Between Requirements

**High Throughput**
**High Burst Tolerance**



**Low Latency**

**Deep Buffers:**

- Qu
  Inc

**Shallow Buffers:**

- &

**Objective:**
**Low Queue Occupancy & High Throughput**

**Reduced $RTO_{min}$ (SIGCOMM '09)**

- Doesn't Help Latency

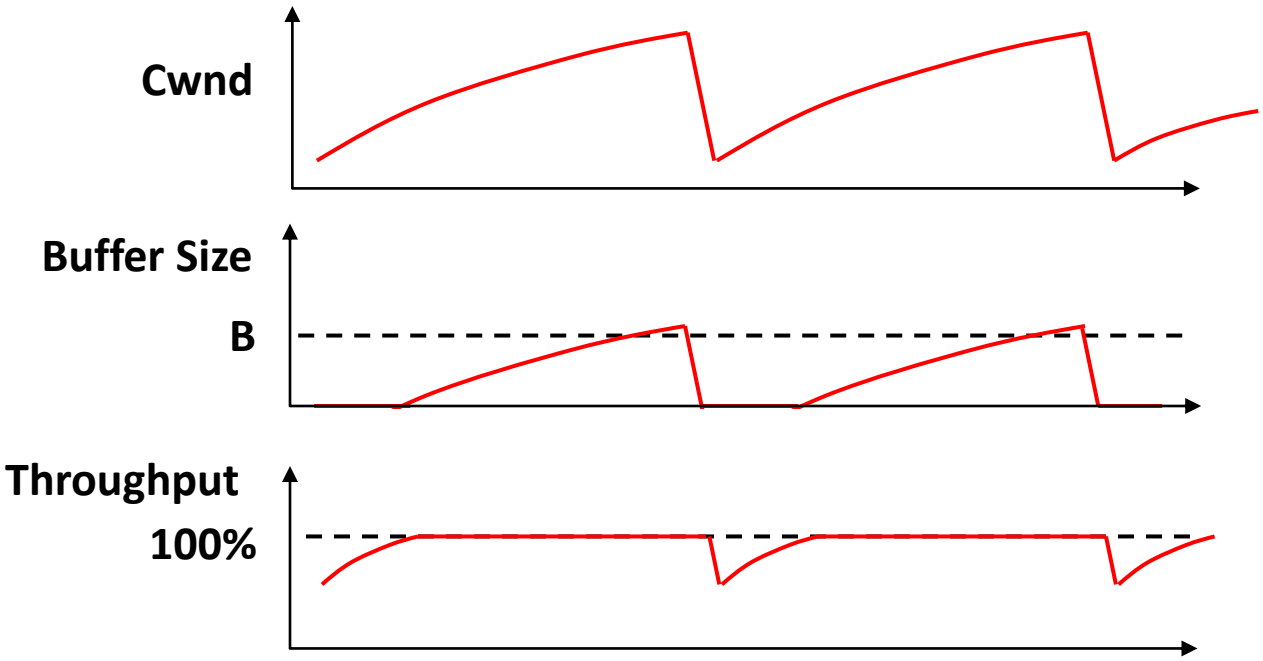
**AQM – RED:**

- Avg Queue Not Fast Enough for Incast

# The DCTCP Algorithm

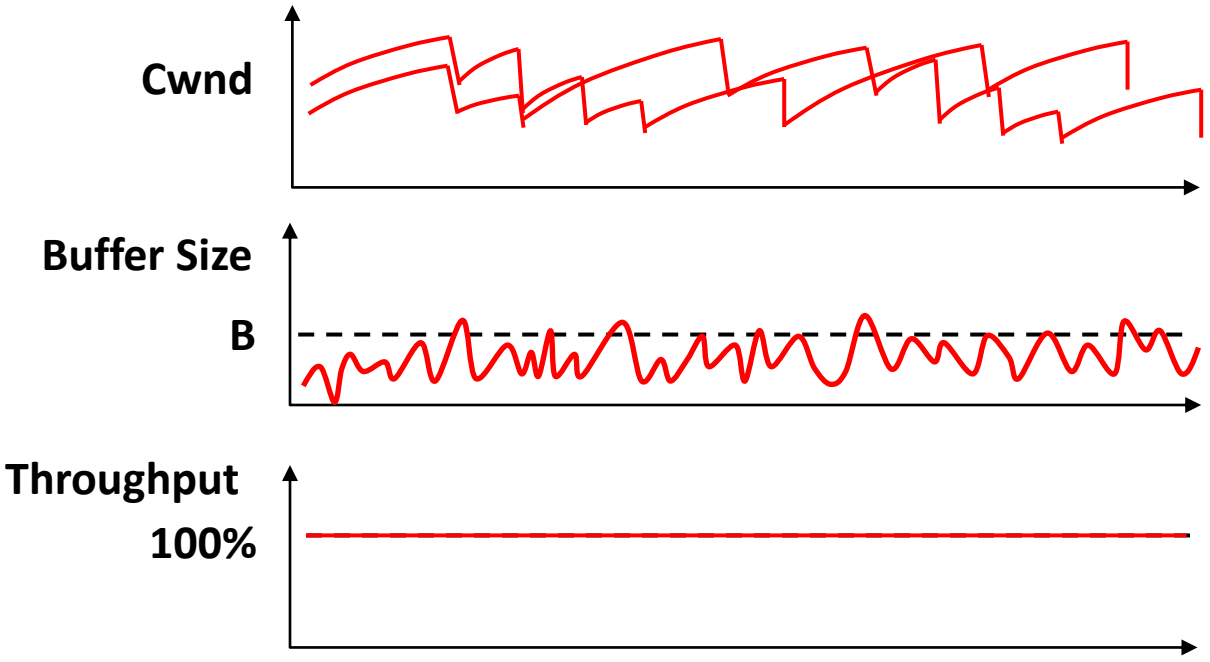
# Small Queues & TCP Throughput:
## The Buffer Sizing Story

- Bandwidth-delay product rule of thumb:
  - A single flow needs $C \times RTT$ buffers for **100% Throughput.**



# Small Queues & TCP Throughput:
## The Buffer Sizing Story

- Bandwidth-delay product rule of thumb:
  - A single flow needs $C \times RTT$ buffers for **100% Throughput.**
- Appenzeller rule of thumb (SIGCOMM '04):
  - Large # of flows: $C \times RTT/\sqrt{N}$ is enough.



# Small Queues & TCP Throughput:
## The Buffer Sizing Story

- Bandwidth-delay product rule of thumb:
  - A single flow needs $C \times RTT$ buffers for **100% Throughput.**
- Appenzeller rule of thumb (SIGCOMM '04):
  - Large # of flows: $C \times RTT/\sqrt{N}$ is enough.
- Can't rely on stat-mux benefit in the DC.
  - Measurements show **typically 1-2 big flows** at each server**, at most 4.**

# Small Queues & TCP Throughput:
## The Buffer Sizing Story

- Bandwidth-delay product rule of thumb:
  - A single flow needs $C \times RTT$ buffers for **100% Throughput.**
- Appenzeller rule of thumb (SIGCOMM '04):
  - Large # of flows: $C \times RTT/\sqrt{N}$ is enough.
- Can't rely on stat-mux benefit in the DC.
  - Measurements show **typically 1-2 big flows** at each server**, at most 4.**

**Real Rule of Thumb:**
**Low Variance in Sending Rate → Small Buffers Suffice**

# Two Key Ideas

1. React in proportion to the **extent** of congestion, not its **presence**.
   - ✓ Reduces **variance** in sending rates, lowering queuing requirements.

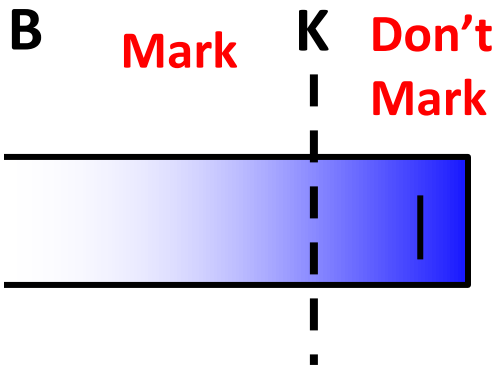
| ECN Marks | TCP | DCTCP |
|---|---|---|
| 1 0 1 1 1 1 0 1 1 1 | Cut window by 50% | Cut window by 40% |
| 0 0 0 0 0 0 0 0 0 1 | Cut window by 50% | Cut window by 5% |

2. Mark based on **instantaneous** queue length.
   - ✓ Fast feedback to better deal with bursts.

# Data Center TCP Algorithm

**Switch side:**

- Mark packets when **Queue Length > K.**




**Sender side:**

- Maintain running average of ***fraction*** of packets marked **($\alpha$)**.

**In each RTT:**

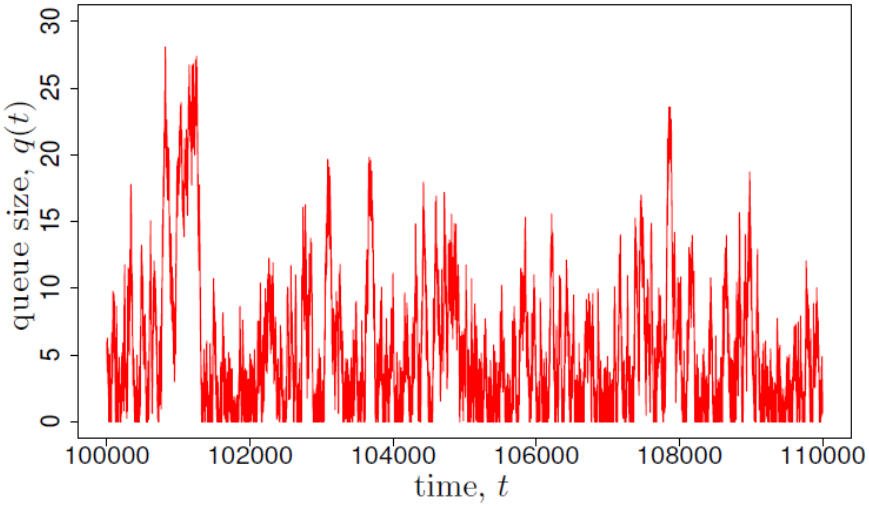
$$F = \frac{\#\ of\ marked\ ACKs}{Total\ \#\ of\ ACKs} \qquad \alpha \leftarrow (1-g)\alpha + gF$$

- **Adaptive window decreases:** $Cwnd \leftarrow (1 - \frac{\alpha}{2})Cwnd$
  - Note: decrease factor between 1 and 2.

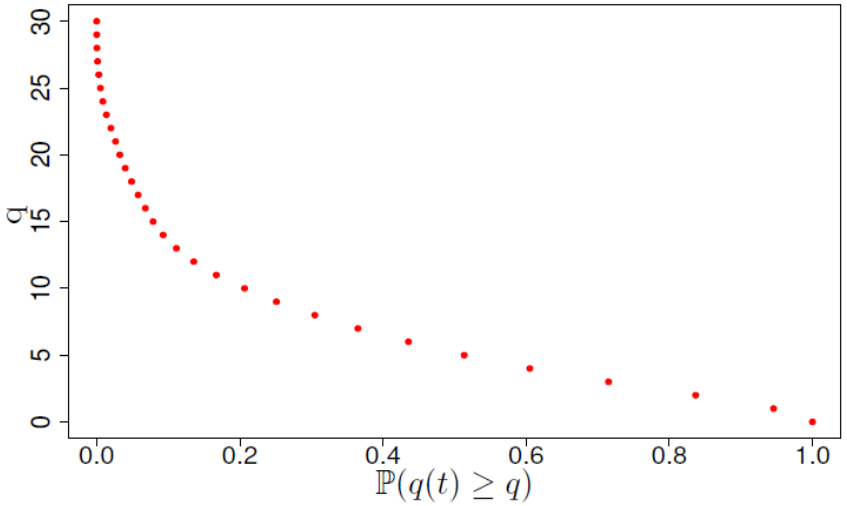
# Rate-based Feedback

- Sources estimate *fraction* of time queue size exceeds a threshold, $\alpha$.
  - a robust statistic, acting as a proxy to the load

Queue Size Sample Path

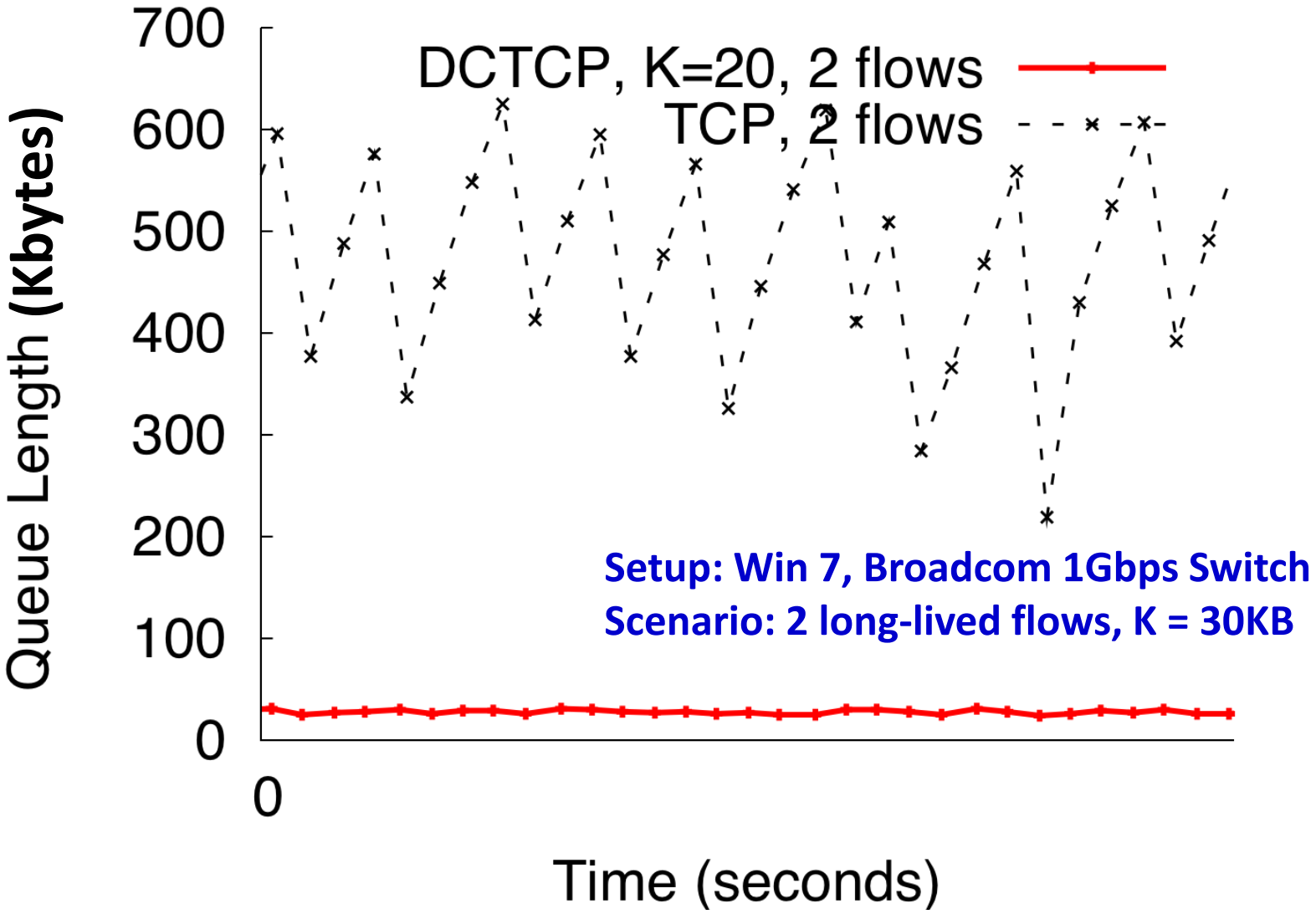



Queue Size Empirical Distribution




* Excerpted from Kelly et al., "Stability and fairness of explicit congestion control with small buffers", Computer Communication Review, 2008.

# DCTCP in Action



# Why it Works

## 1. High Burst Tolerance

- ✓ **Large buffer headroom →** bursts fit.
- ✓ **Aggressive marking →** sources react before packets are dropped.

## 2. Low Latency

- ✓ **Small buffer occupancies →** low queuing delay.

## 3. High Throughput

- ✓ **ECN averaging →** smooth rate adjustments, low variance.

# Analysis

- How low can DCTCP maintain queues without loss of throughput?
- How do we set the DCTCP parameters?
  - ➢ **Need to quantify queue size oscillations (Stability).**

$$K > \frac{1}{7} C \times RTT$$

**85% Less Buffer than TCP**

Detailed analysis @
http://www.stanford.edu/~balaji/papers/11analysisof.pdf

# Evaluation

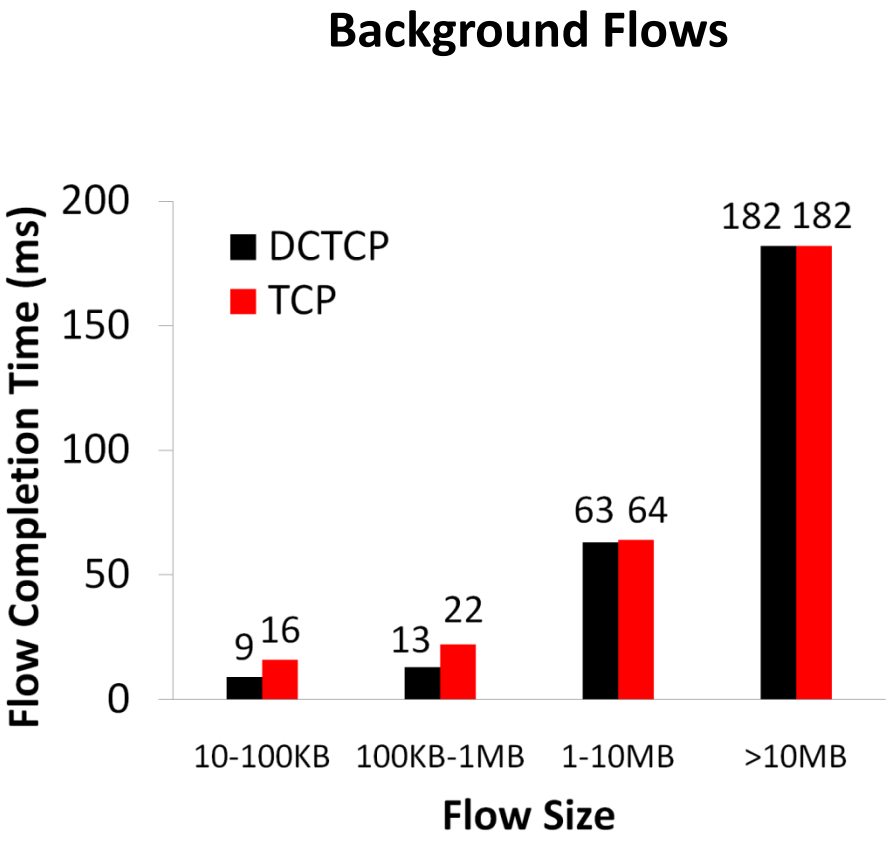
- Implemented in Windows stack.
- Real hardware, **1Gbps and 10Gbps** experiments
  - **90 server testbed**
  - **Broadcom Triumph** **48 1G ports – 4MB shared memory**
  - **Cisco Cat4948** **48 1G ports – 16MB shared memory**
  - **Broadcom Scorpion** **24 10G ports – 4MB shared memory**
- Numerous micro-benchmarks
  - **Throughput and Queue Length**
  - **Multi-hop**
  - **Queue Buildup**
  - **Buffer Pressure**
  - **Fairness and Convergence**
  - **Incast**
  - **Static vs Dynamic Buffer Mgmt**
- **Cluster traffic benchmark**

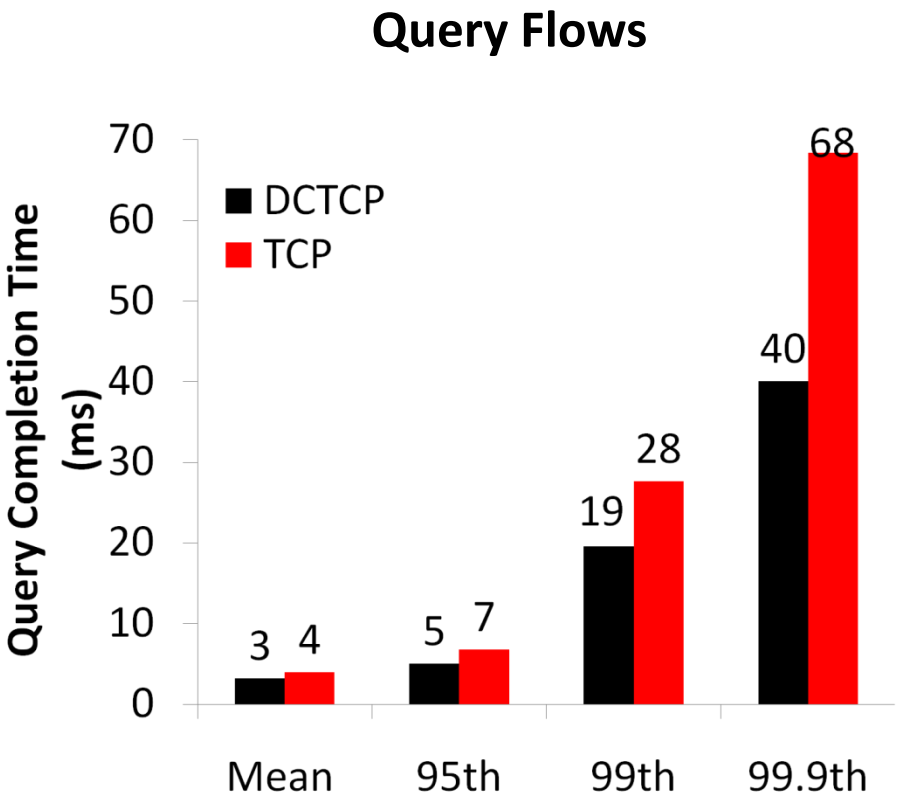
# Cluster Traffic Benchmark

- Emulate traffic within 1 Rack of Bing cluster
  - 45 1G servers, 10G server for external traffic
- Generate query, and background traffic
  - Flow sizes and arrival times follow distributions seen in Bing
- Metric:
  - Flow completion time for queries and background flows.

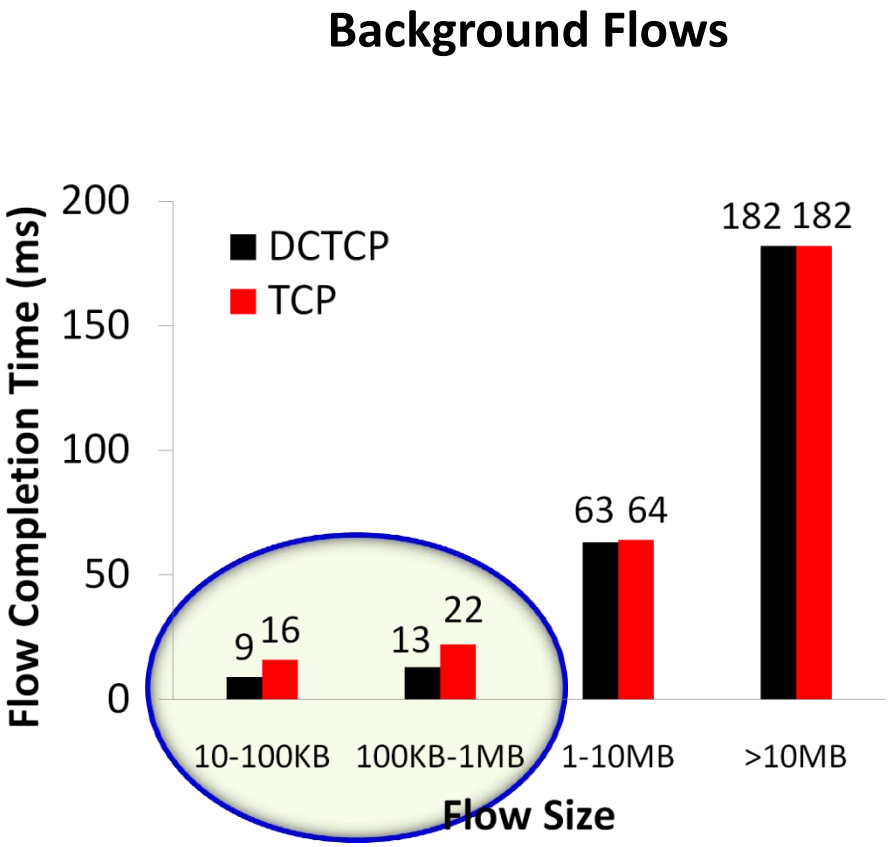
**We use $RTO_{min}$ = 10ms for both TCP & DCTCP.**

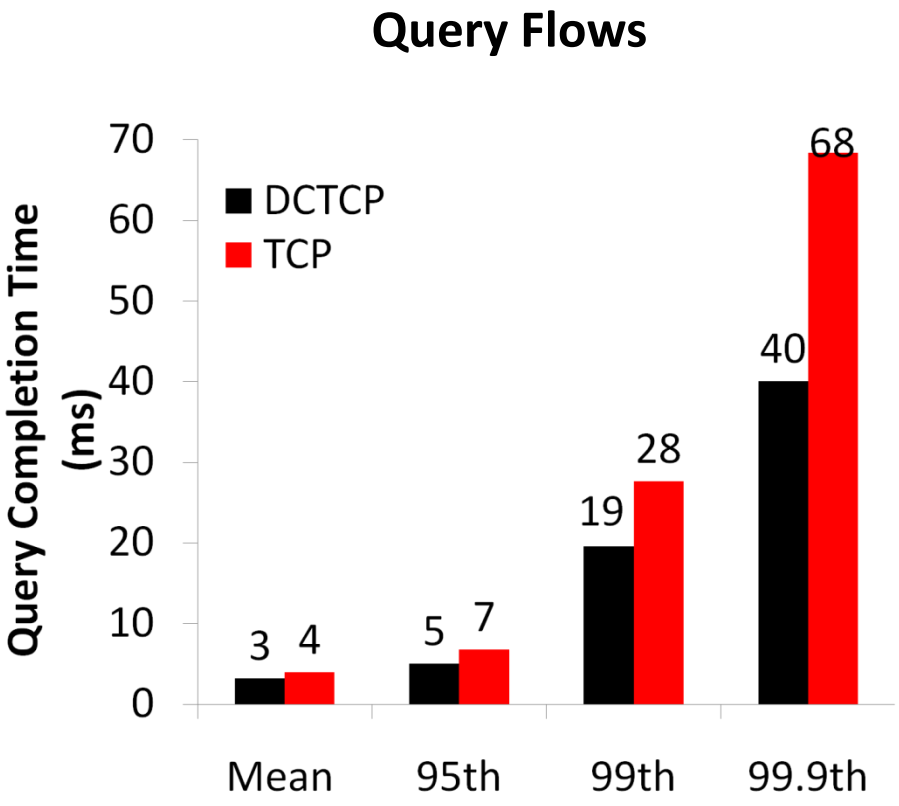
# Baseline


Background Flows
Flow Completion Time (ms)
200
150
100
50
0
DCTCP
TCP
9
16
13
22
63
64
182
182
10-100KB
100KB-1MB
1-10MB
>10MB
Flow Size


Query Flows
Query Completion Time (ms)
70
60
50
40
30
20
10
0
DCTCP
TCP
3
4
5
7
19
28
40
68
Mean
95th
99th
99.9th

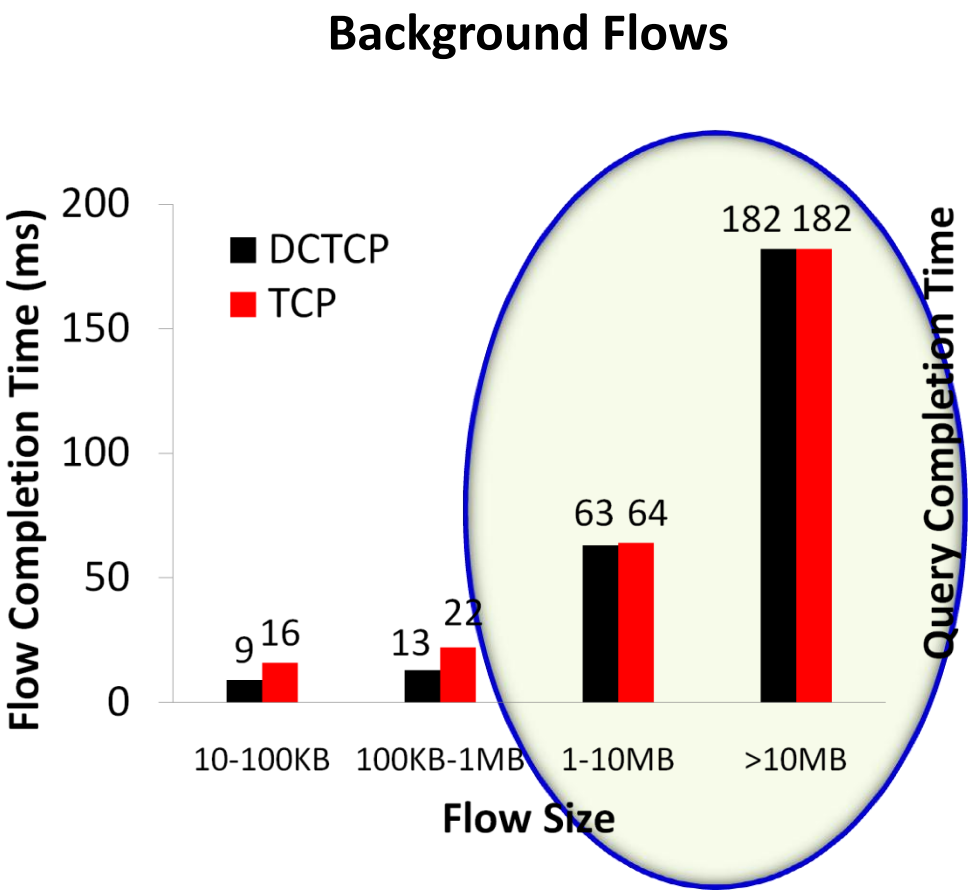
# Baseline

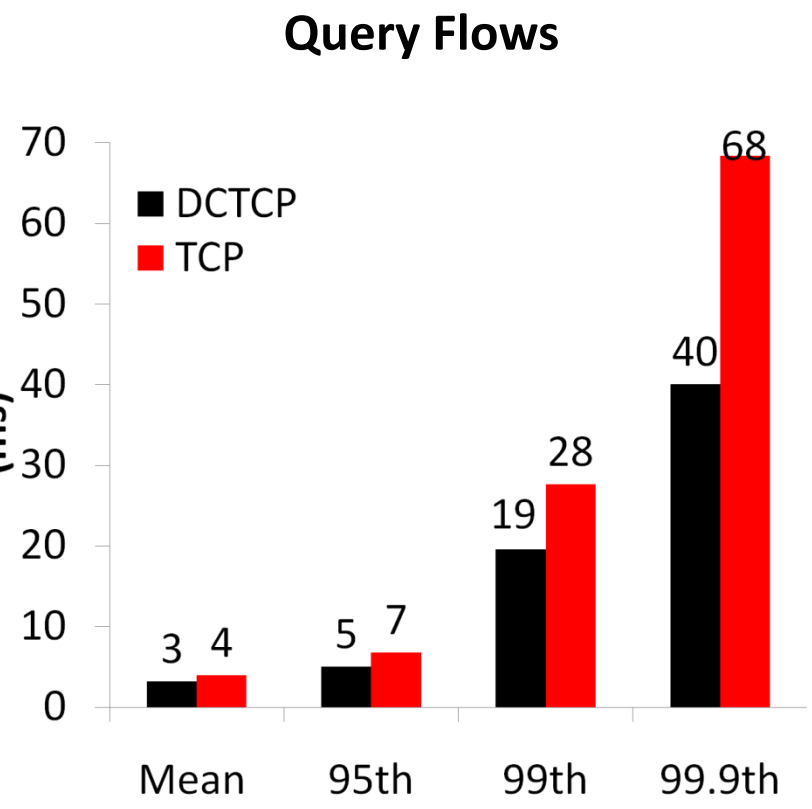



✓ Low latency for short flows.

# Baseline

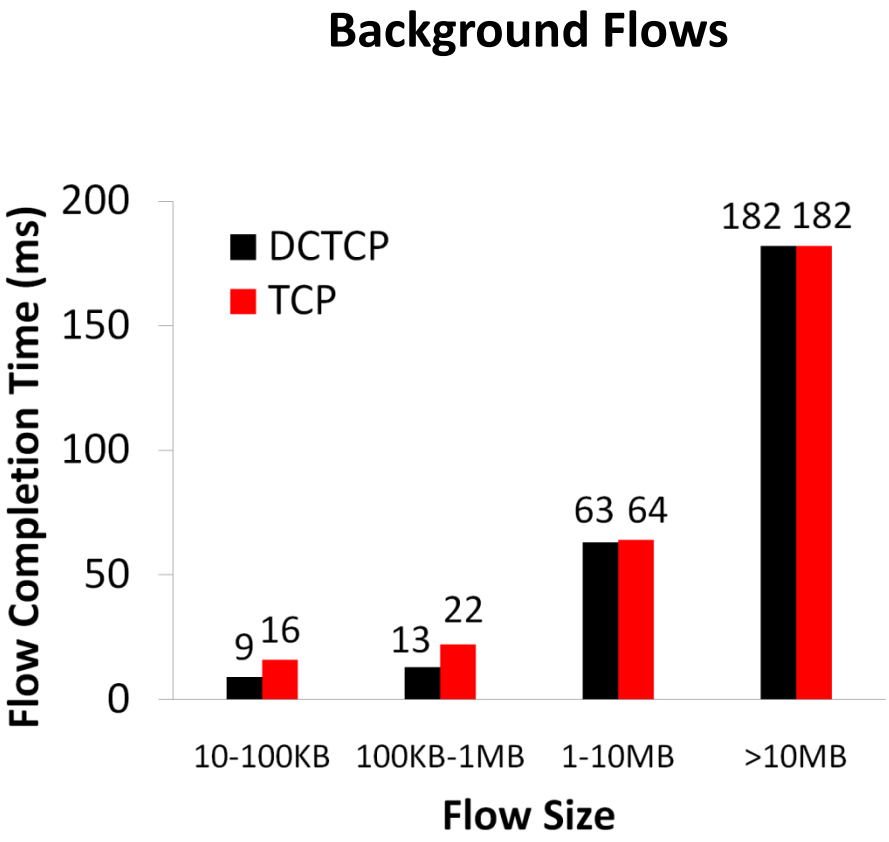


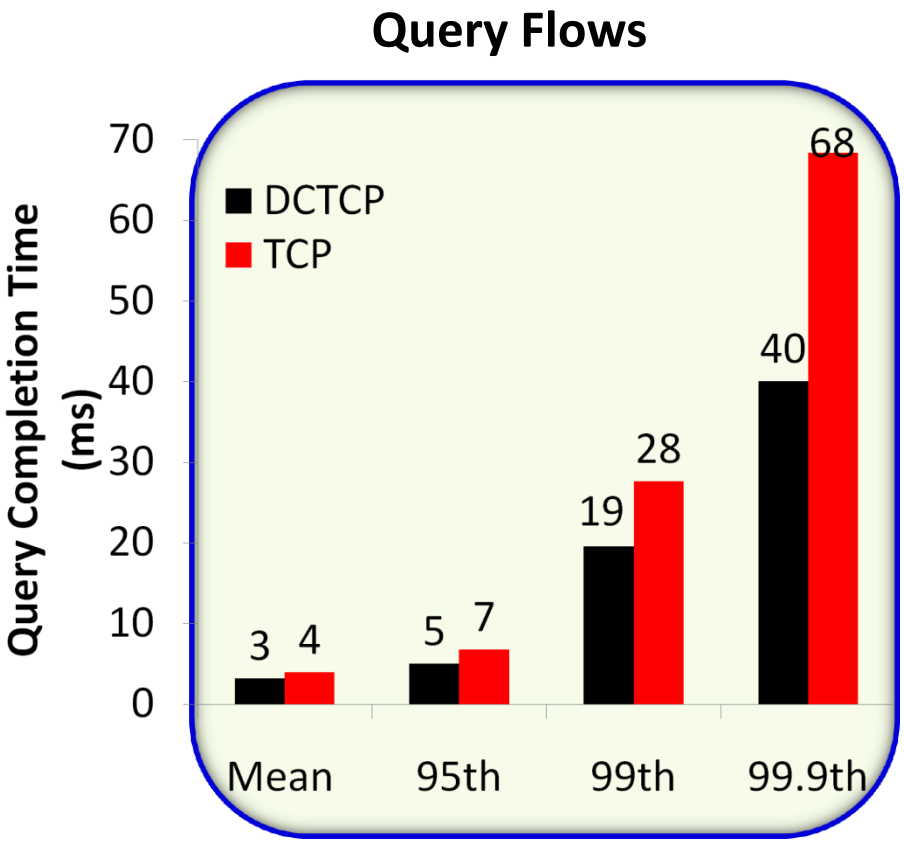




✓ Low latency for short flows.

✓ High throughput for long flows.

# Baseline

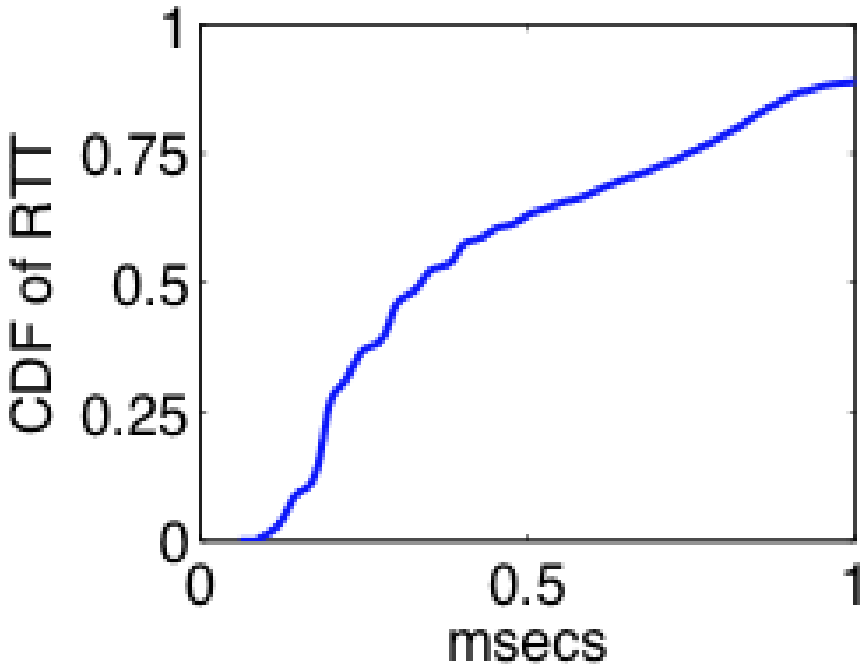


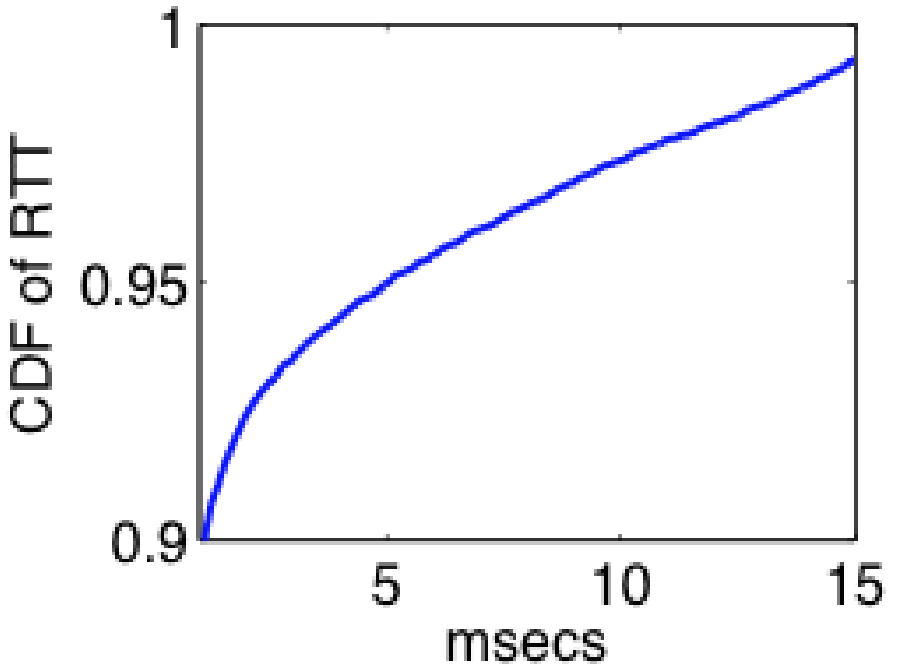




- ✓ Low latency for short flows.
- ✓ High throughput for long flows.
- ✓ High burst tolerance for query flows.

# Latency – Queuing Delay

**RTT to Aggregator**



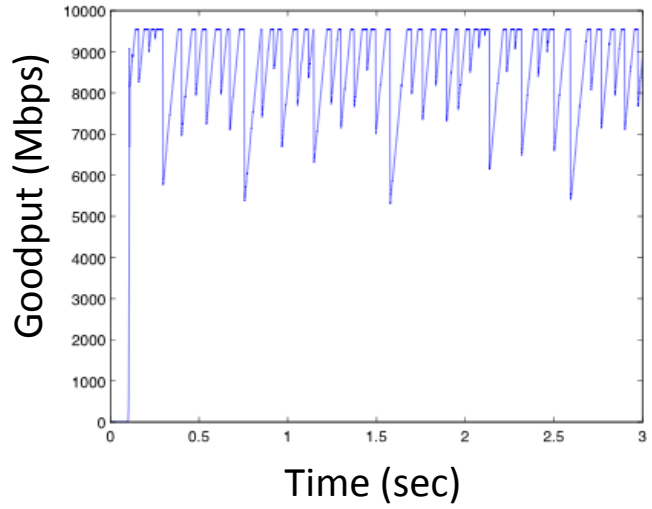




Long flows build up queues causing delay to short flows.

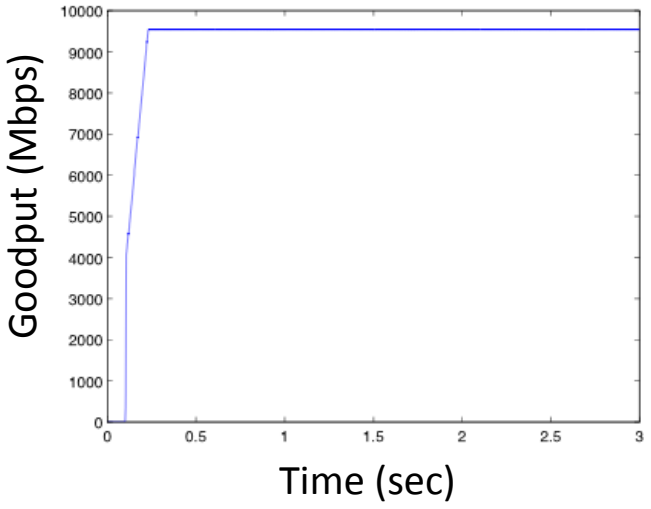
# AQM is not enough

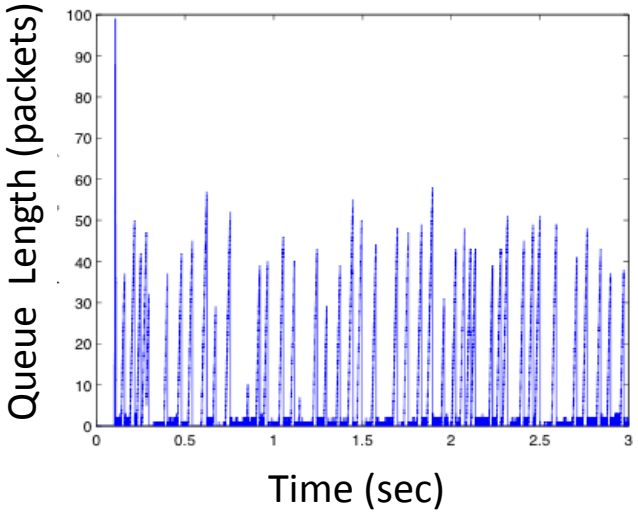
- C = 10Gbps, RTT = 500µs, 2 long-lived flows

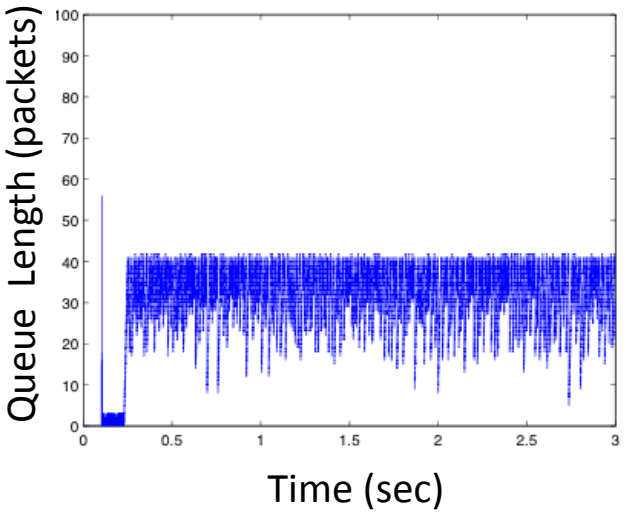
TCP/PI




DCTCP

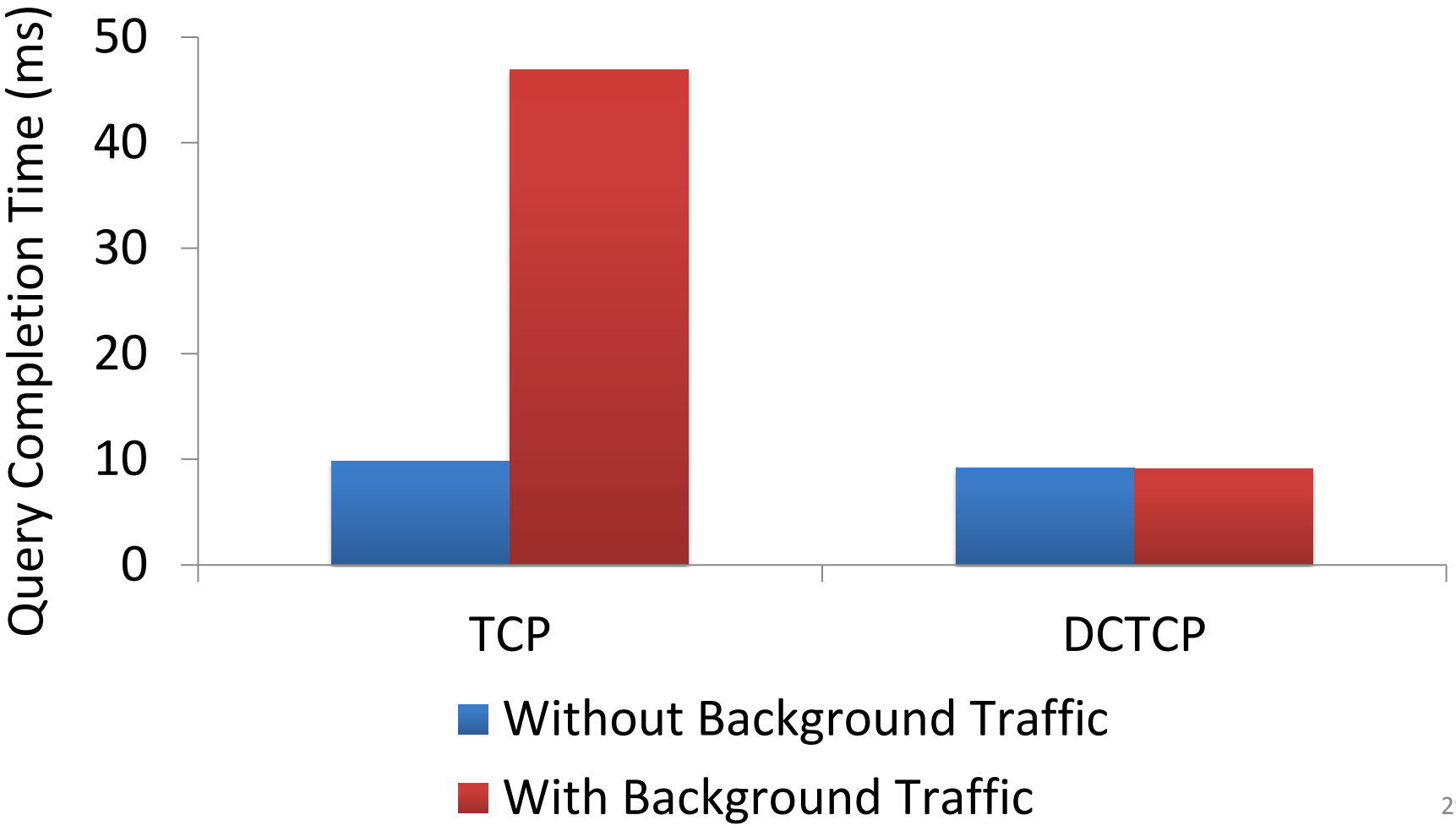


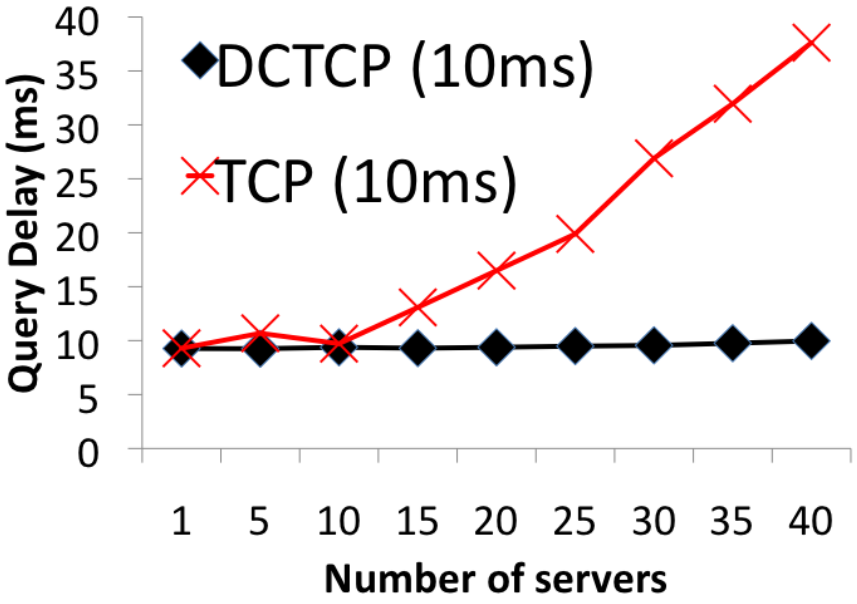
# Buffer Pressure

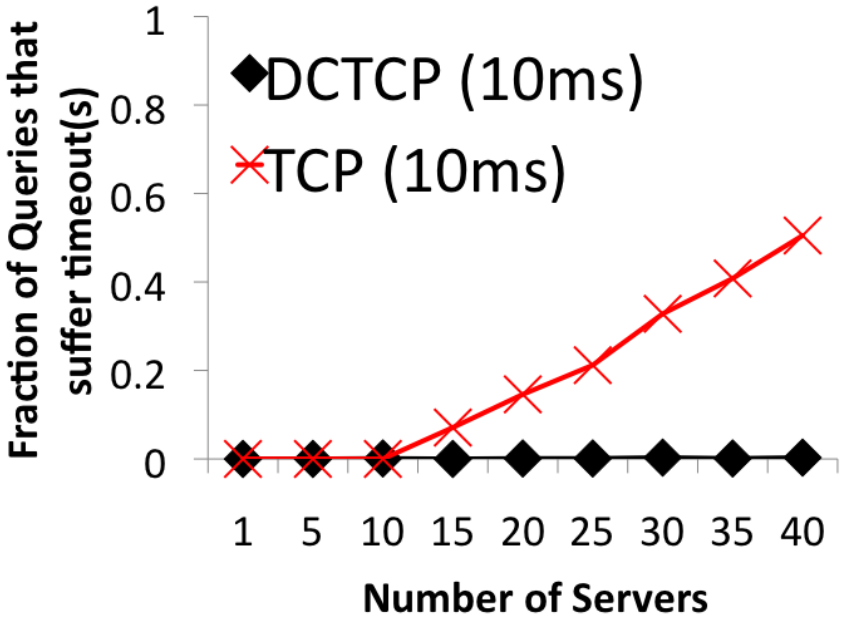
- 1 Rack: 10-to-1 Incast, Background traffic between other 30 servers.



# Incast
## many-to-one

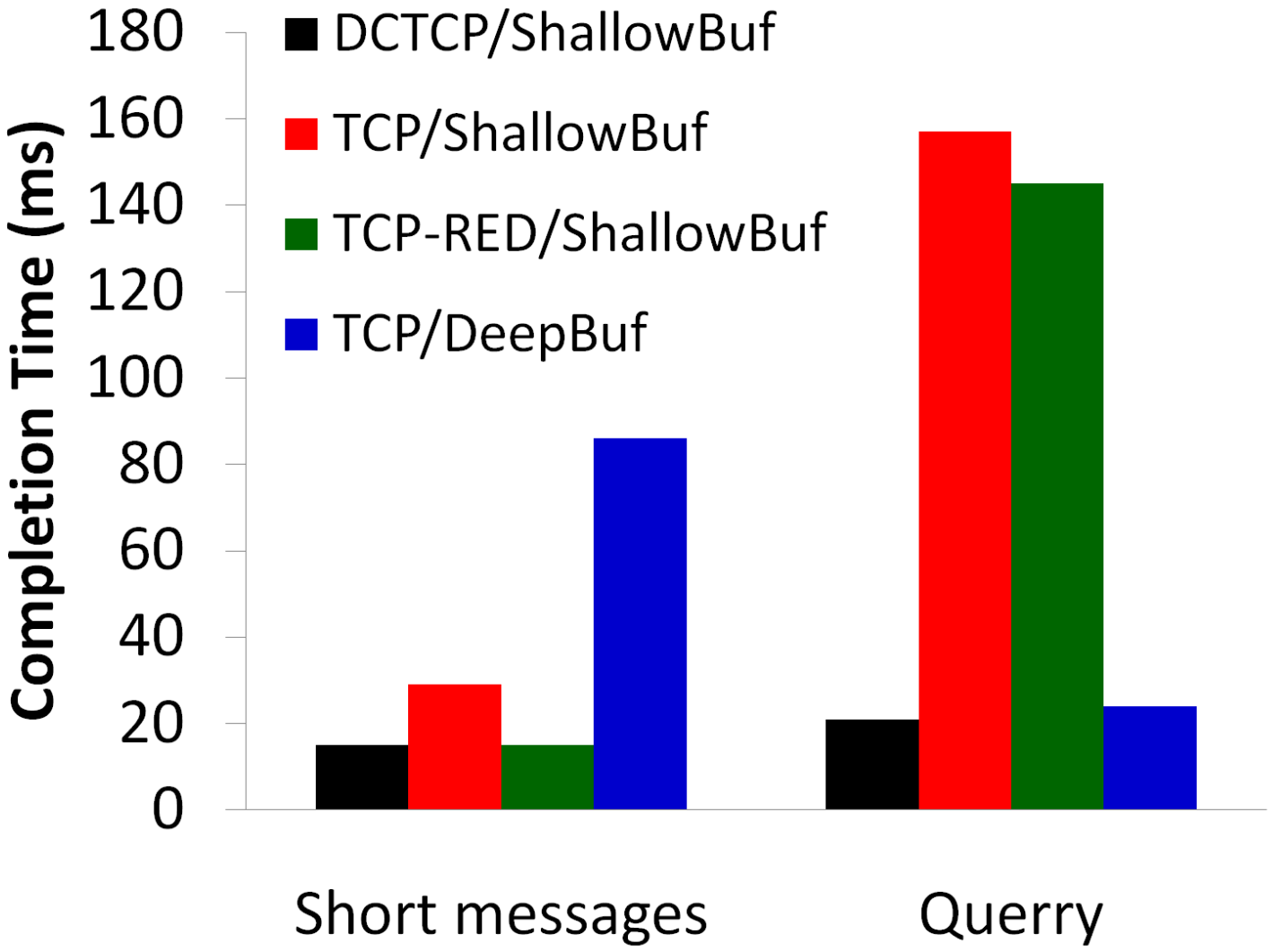
- Client requests 1MB file, striped across 40 servers (25KB each).



# Scaled Background & Query

## 10x Background, 10x Query



# Conclusions

- DCTCP satisfies all our requirements for Data Center packet transport.
  - ✓ **Handles bursts well**
  - ✓ **Keeps queuing delays low**
  - ✓ **Achieves high throughput**

- Features:
  - ✓ **Very simple change to TCP and a single switch parameter.**
  - ✓ **Based on mechanisms already available in Silicon.**