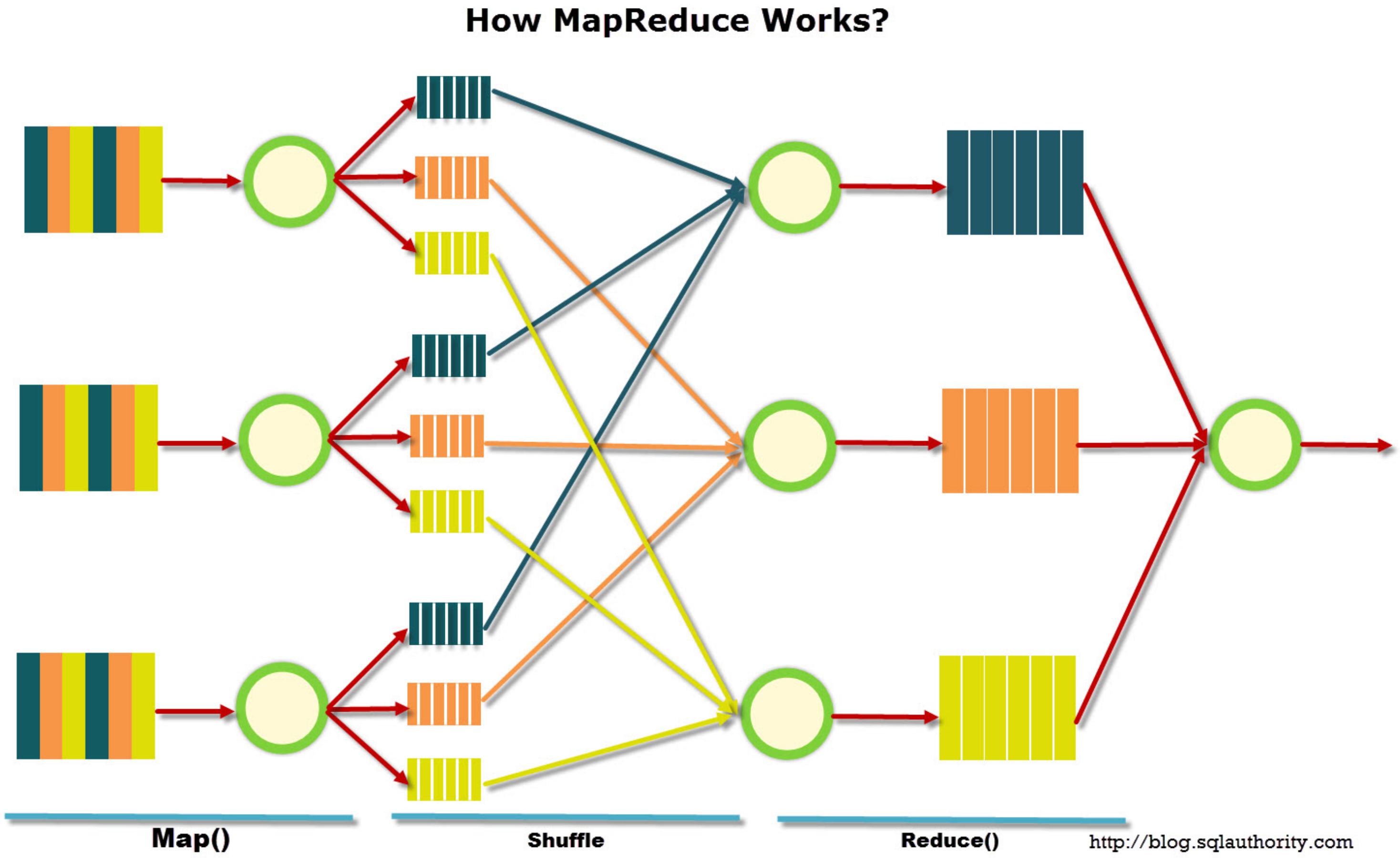
CS 4450
Network Fabric

Based on:

1. Jupiter Rising: A Decade of Clos Topologies and Centralized Control in Google’s Datacenter Network. Singh et al. SIGCOMM15.
2. Network Traffic Characteristics of Data Centers in the Wild. Benson et al. IMC10.
3. Benson’s original slide deck from IMC10.

Performance of distributed systems depends heavily on the datacenter interconnect

Example - MapReduce

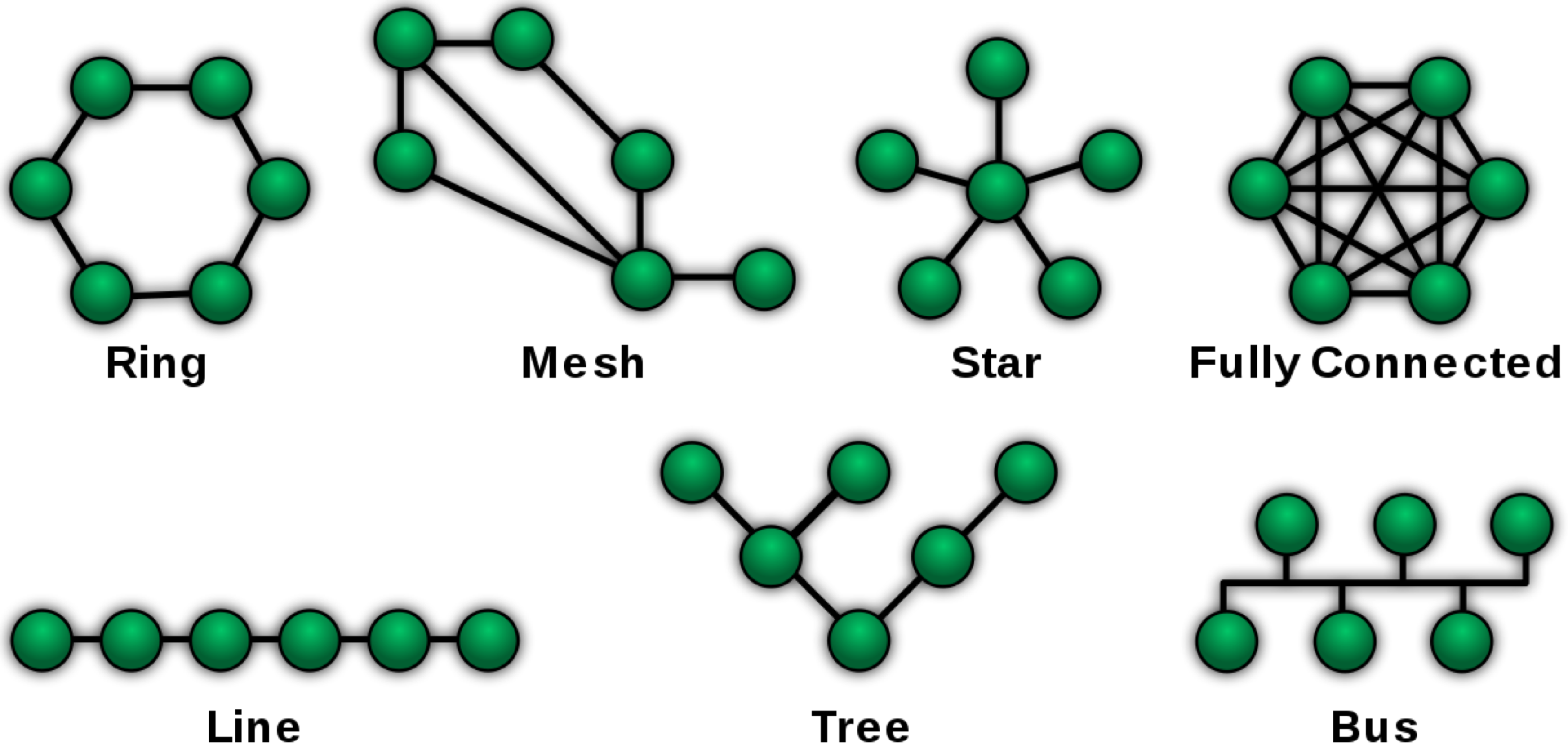


Source: https://blog.sqlauthority.com/2013/10/09/big-data-buzz-words-what-is-mapreduce-day-7-of-21/

Evaluation Metrics for Datacenter Topologies

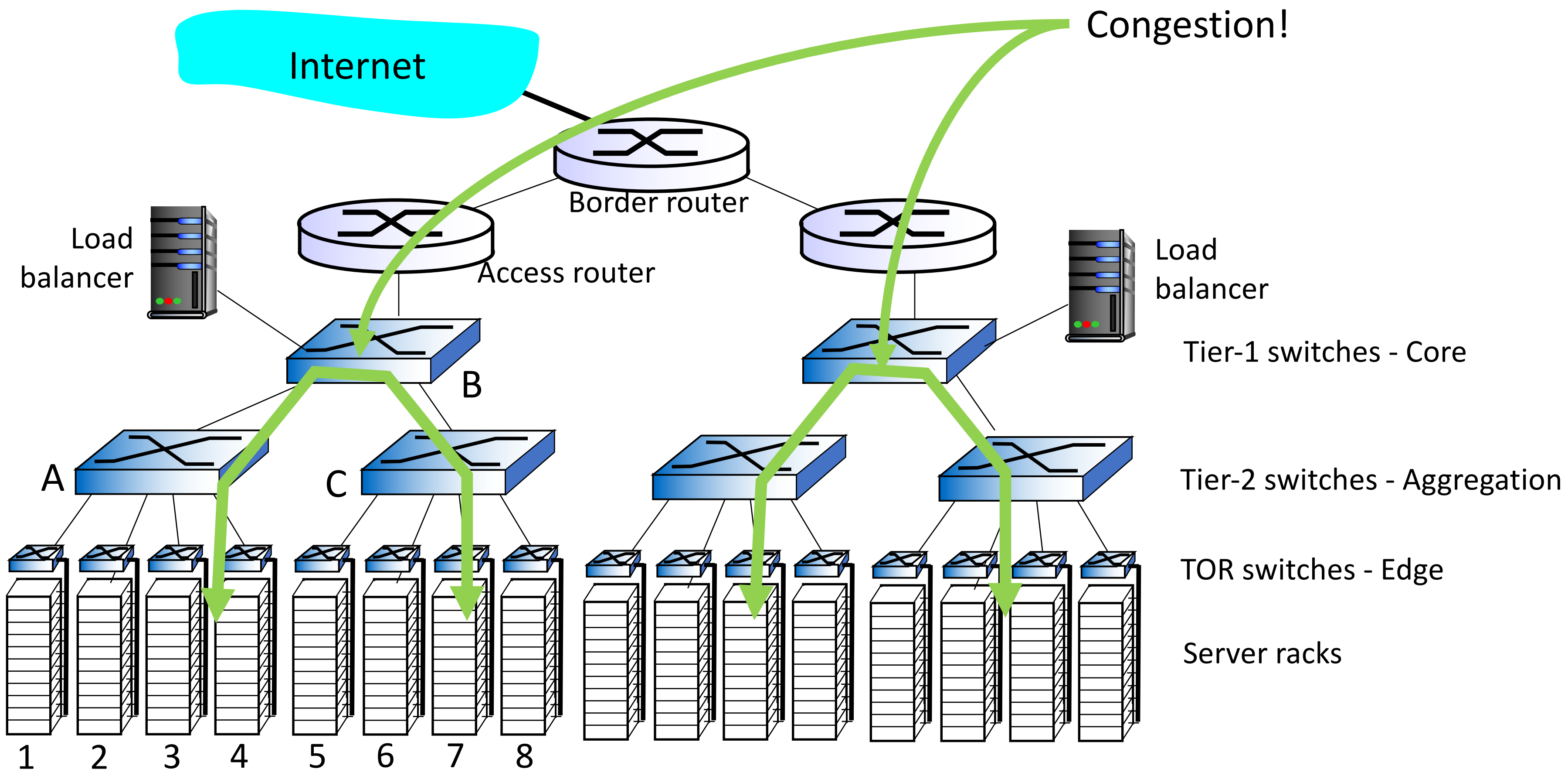
- Diameter – max #hops between any 2 nodes
  - Worst case latency
- Bisection Width – min #links cut to partition network into 2 equal halves
  - Fault tolerance
- Bisection Bandwidth – min bandwidth between any 2 equal halves of the network
  - Bottleneck
- Oversubscription – ratio of worst-case achievable aggregate bandwidth between end-hosts to total bisection bandwidth

Legacy Topologies



Source: http://pseudobit.blogspot.com/2014/07/network-classification-by-network.html

3-Tier Architecture



Source: CS 5413, Hakim Weatherspoon, Cornell University

Big-Switch Architecture

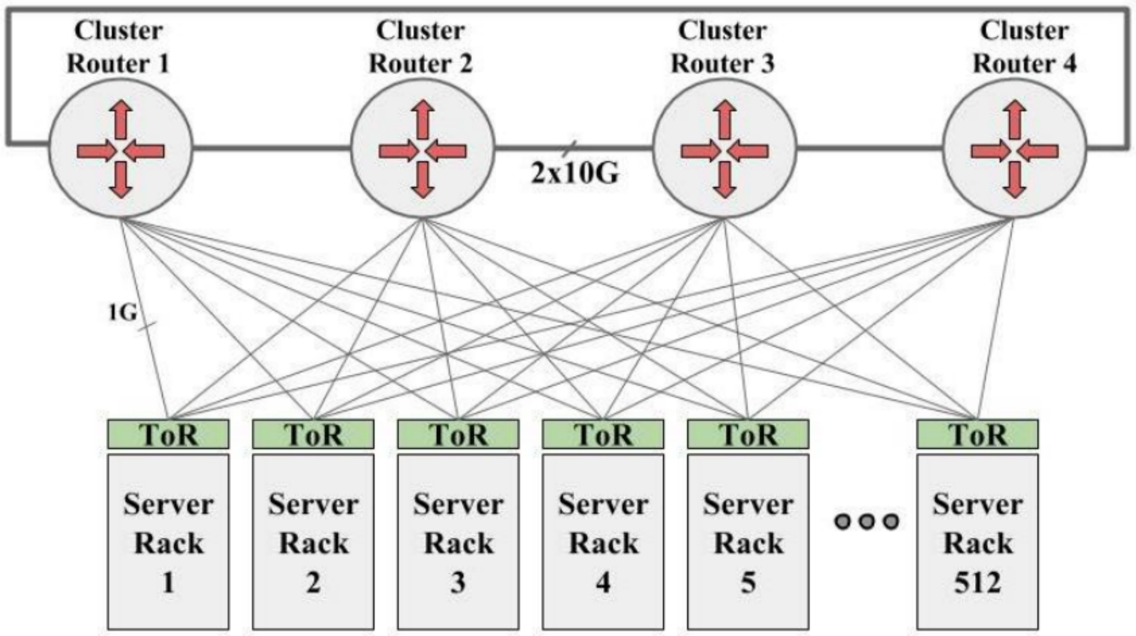


Figure 2: A traditional 2Tbps four-post cluster (2004). Top of Rack (ToR) switches serving 40 1G-connected servers were connected via 1G links to four 512 1G port Cluster Routers (CRs) connected with 10G sidelinks.

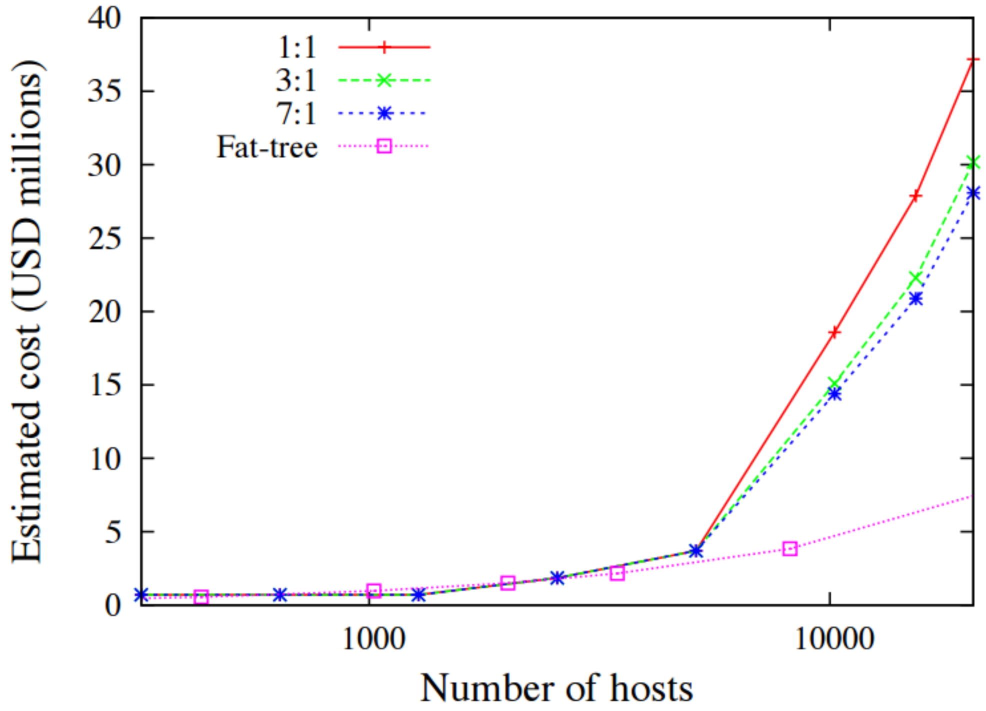
Cost \$O(100,000)!

Cost \$O(1,000)!

Source: Jupiter Rising, Google

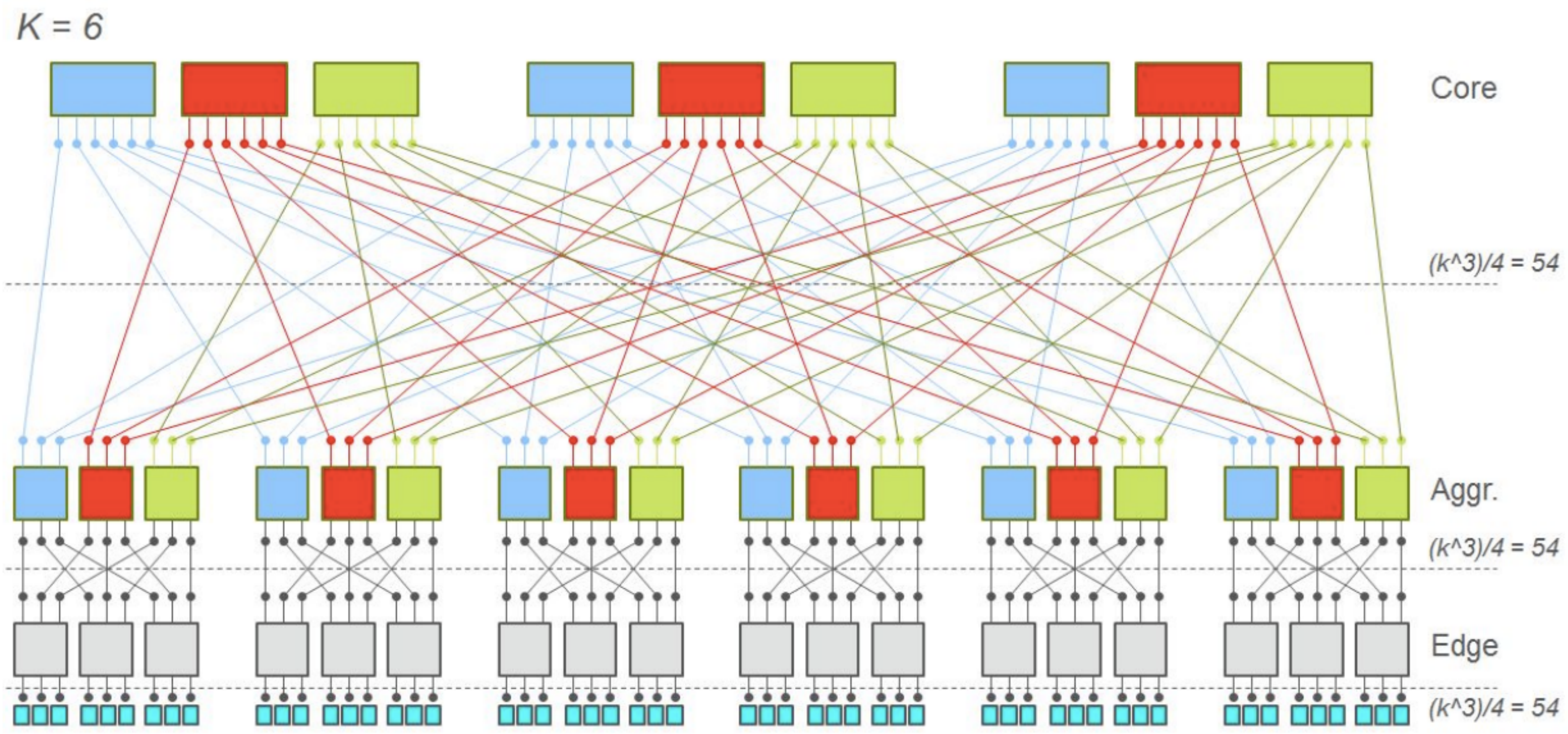
Goals for Datacenter Networks (circa 2008)

- 1:1 oversubscription ratio – all hosts can communicate with arbitrary other hosts at full bandwidth of their network interface
  - Google's Four-Post CRs offered only about 100Mbps
- Low cost – cheap off-the-shelf switches



Source: A Scalable, Commodity Data Center Network Architecture. Al-Fares et al.

Fat-Trees



Source: Francesco Celestino, https://www.systems.ethz.ch/sites/default/files/file/acn2016/slides/04-topology.pdf

Advantages of Fat-Tree Design

- Increased throughput between racks
- Low cost because of commodity switches
- Increased redundancy

Software Control

- Custom control plane
  - Existing protocols did not support multipath, equal-cost forwarding
  - Lack of high quality open source routing stacks
  - Protocol overhead of running broadcast-based algorithms on such large scale
  - Easier network manageability
- Treat the network as a single fabric with O(10,000) ports
- Anticipated some of the principles of Software Defined Networking

Issues – Congestion

High congestion as utilization approached 25%

- Bursty flows
- Limited buffer on commodity switches
- Intentional oversubscription for cost saving
- Imperfect flow hashing

Congestion – Solutions

- Configure switch hardware schedulers to drop packets based on QoS
- Tune host congestion window
- Link-level pause reduces over-running oversubscribed links
- Explicit Congestion Notification
- Provision bandwidth on-the-fly by repopulating
- Dynamic buffer sharing on merchant silicon to absorb bursts
- Carefully configure switch hashing to support ECMP load balancing

Insights Gained

- 75% of traffic stays within a rack (Clouds)
  - Applications are not uniformly placed
- Half packets are small (< 200B)
  - Keep alive integral in application design
- At most 25% of core links highly utilized
  - Effective routing algorithm to reduce utilization
  - Load balance across paths and migrate VMs
- Questioned popular assumptions
  - Do we need more bisection? No
  - Is centralization feasible? Yes

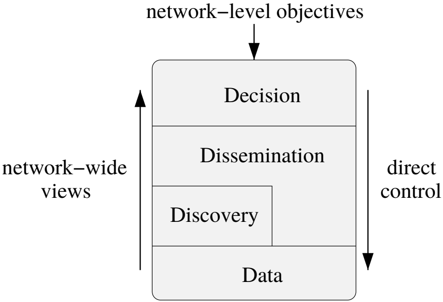
A Clean Slate 4D Approach to Network Control and Management

Complex Architecture of Networks

- Path-computation logic is bundled with packet handling.
  - In IP networks, path-computation logic is governed by distributed protocols such as OSPF, IS-IS, and EIGRP.
  - In Ethernet networks, path-computation logic is embedded in the Spanning Tree Protocol.
- Network-level objectives can be different from best-effort packet delivery.
- Incremental changes of the control-plane only leads to complex and fragile networks.

A Clean Slate Approach

- Redesign the network via the 4D approach: decision, dissemination, discovery, and data.



A Clean Slate Approach

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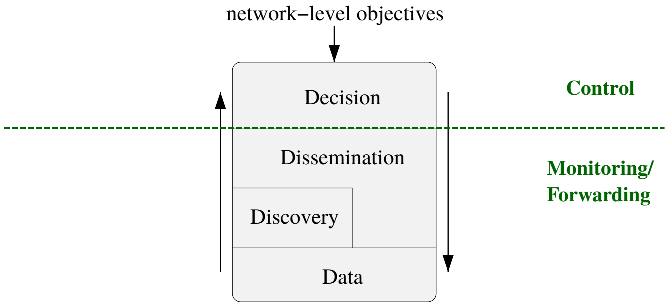


Advantages of the 4D Architecture

- Separate networking logic from distributed system issues.
- Higher robustness.
- Better security.
- Accommodating heterogeneity.
- Enabling of innovation and network evolution.

Challenges of the 4D Architecture

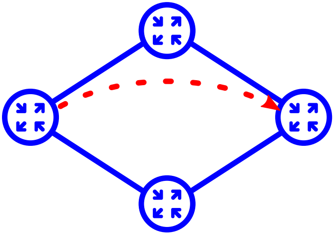
- Complexity apocalypse.
- Stability failures.
- Scalability problems.
- Response time.
- Security vulnerabilities.

Next Steps

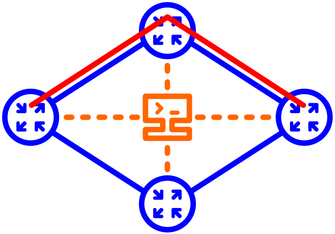
- Decision plane:
  - Satisfying network-level objectives.
  - Coordination between decision elements.
  - Hierarchy in the decision plane.
- Dissemination plane.
- Data plane.

Software-Defined Networking

- Separating the control logic (control plane) from the forwarding mechanism (data plane).



(a) Distributed protocol



(b) Software-defined networking

Software-Defined Networking

- Separate control plane and forwarding plane
- Common, open, agnostic vendor-agnostic interface
  - Control forwarding devices across different hardware/software devices
- OpenFlow
  - Proliferation of header fields complicates protocol
  - Multiple stages of rule tables
  - Difficult to scale due to lack of flexibility
- Goal: *tell the switch how to operate*

Abstract Forwarding Model

- Arriving packets are handled by the parser
  - No assumptions about headers' intent
- Header fields passed to the match-action tables
  - Ingress - modify packet, determine egress port and proper queue
  - Egress – modify packet, prepare for operations (e.g. multicast)

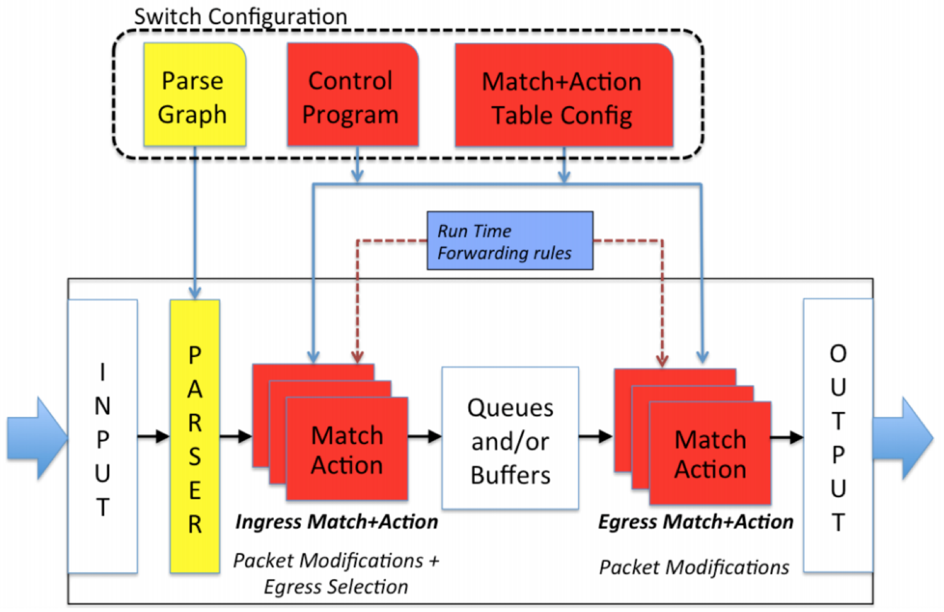


Figure 1: Abstract Forwarding Model

P4: Programming Protocol-Independent Packet Processors

P4: A Solution

- Raise the level of abstraction for programming the network
- General interface between the controller and switches
- Reconfigurability
  - Controller can redefine the packet parsing and processing
- Protocol Independence
  - Switch is decoupled from specific packet formats
  - Controller specified packet parser and match-action tables
- Target Independence
  - Compiler handles switch capabilities, *not* the controller programmer

Next Steps

- Control plane programming: NOX, Gude et al., 2008.
- SD-Internet Exchange Points: iSDX, Gupta et al., 2016
- Separating the edge and fabric control: Fabric, Casado et al., 2012.

Datacenter Congestion Control: DCTCP

TCP in the Datacenter context

- TCP in the context of Datacenters is not optimal
- TCP’s demands on limited buffer space in data center switches are too high
- Queues at switches become too congested, and impacts performance of “foreground” traffic

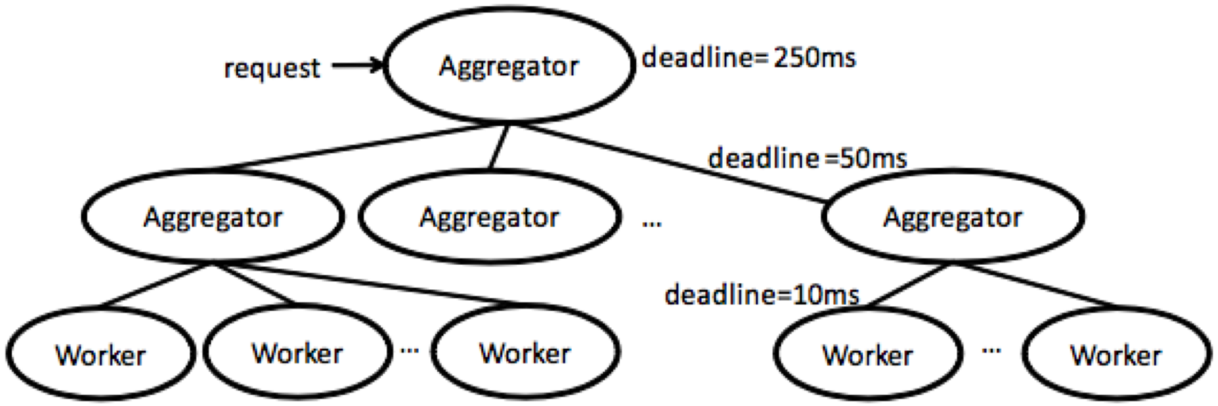
What we need:

- Low latency for short flows and high burst tolerance
  - many applications use a Partition/Aggregate workflow pattern
  - requirements for low latency directly impact the quality of application results
- High utilization for large flows
  - Need to continuously update internal data structures in applications and the data inside these data structures

Main Insights and Contributions

Partition/Aggregate Design pattern

- Used in many large scale web-applications
- Latency is key metric
- Network delays play a big role in application design
- Meeting deadlines with TCP is very difficult, so some developers resort to a



Workload Characterization

- Three types of workloads presented:
  - Query traffic
  - Short message traffic – coordinates cluster activities
  - Background traffic – ingests and organizes data

Query Traffic

- Follow Partition/Aggregate pattern
- consists of very short, latency-critical flows
- High Level Aggregators (HLA) partition queries to a large number of Mid Level Aggregators (MLA) and workers
- Servers act as an aggregator for some queries while also acting as worker for other queries

Background Traffic

- Runs concurrent to query traffic
- Consists of large and small flows
- Most flows are small, but most bytes are a part of large flows
- Update flows – update data to workers
- Short message flows – update control state of workers

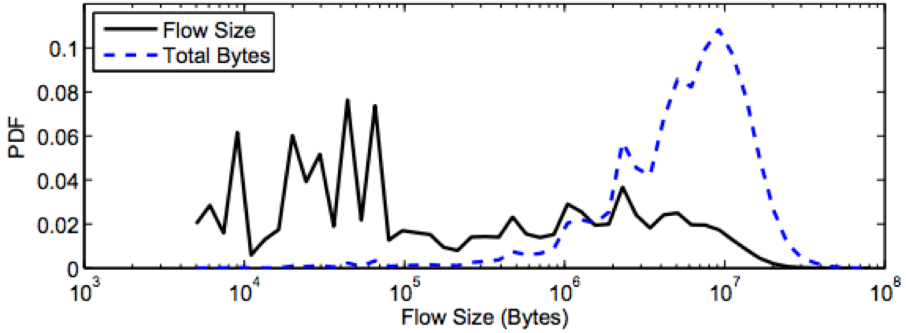


Figure 4: PDF of flow size distribution for background traffic.

Flow Concurrency and Size

- Median number of concurrent flows: 36
- In summary: large flows, small flows, and bursty query flows coexist in a datacenter

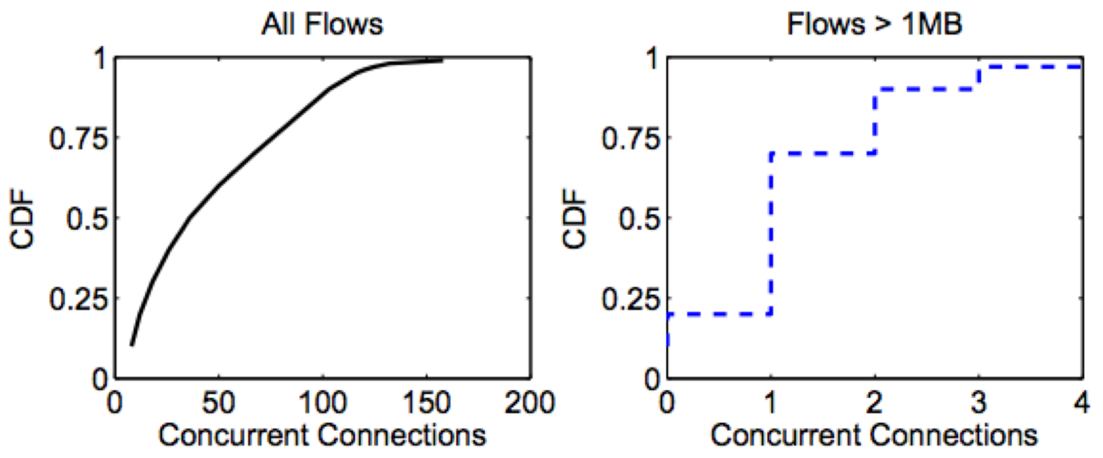
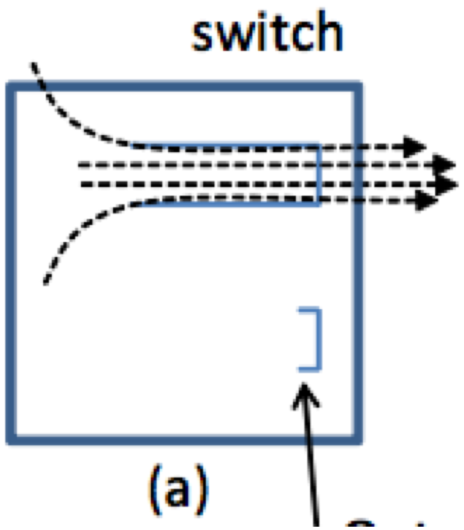


Figure 5: Distribution of number of concurrent connections.

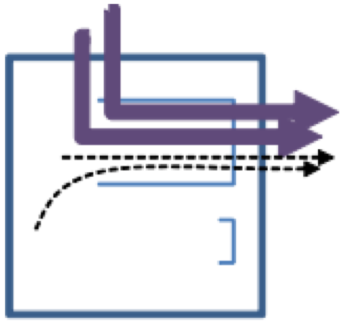
Incast

- Can occur even if flow sizes are small
- a response that causes incast will usually miss aggregator deadline
- current solution: jittering



Queue Buildup

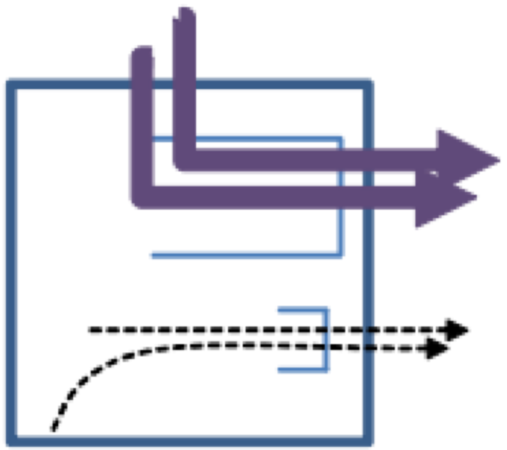
- Caused by long-lived greedy TCP flows and when long/short flows both traverse same queue
- packet loss on short flows cause incast
- short flows experience increased latency
- Since latency is caused by queueing, the only solution is to shrink queues



(b)

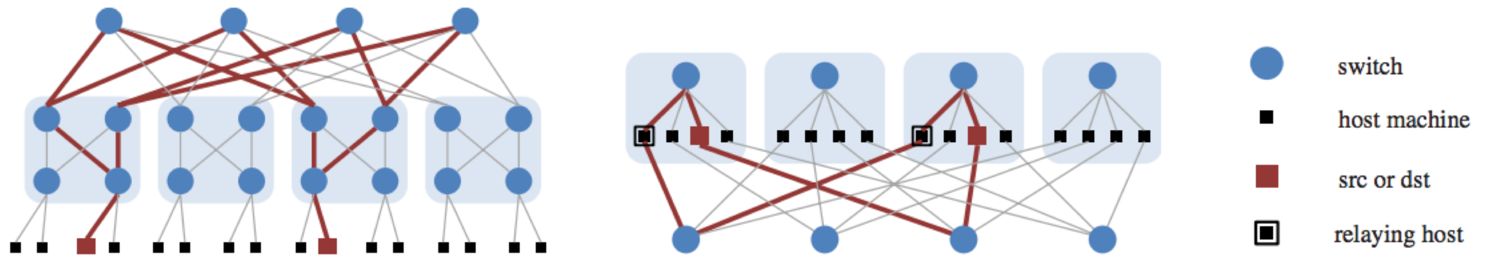
Buffer Pressure

- buffer space is a shared resource
- Results in packet loss and timeouts


(c)

Multipath TCP (MPTCP)

- Enables topologies that single path TCP cannot utilize
- Searches for multiple paths simultaneously
- links congestion response of subflows on different paths to move traffic away from congestion



(a) FatTree (b) BCube

MPTCP Cont’d.

- Extends TCP so that a single connection can be striped across multiple paths
- Can explicitly move traffic off more congested paths and place it on less congested ones
- Chooses paths randomly
- Additional TCP operations reconstruct the received data

pFabric

- Transport Protocol based on the idea that flow scheduling should be decoupled from rate control
- Goal: Design the simplest transport protocol that provides near optimal Flow Completition Time (FCT)
- Downsides: Requires specialized hardware, potentially expensive to deploy in real networks

pFabric Implementation

- Switch Design
  - Priority scheduling: if a port is idle, packet with the highest priority buffered is dequeued and sent out
  - Priority Dropping: drops lowest priority packet in buffer to make room
- Data structures
  - Queue of actual packets
  - Queue of packet metadata

Packet Scheduling and Rate Control

- Starvation Prevention: Dequeue earliest packet from the flow that has highest priority packet in the queue
- Rate Control: because of scheduling algorithm, need for rate control is minimal
- Exception: When a packet traverses multiple hops only to be dropped at a downstream link

Rate Control Policy

- Flows start at line rate
- Use SACKS, additive increase for every ACK
- Packet drops are detected by timeouts
- If a certain number of timeouts occur, flow enters “probe mode” where it periodically retransmits minimum sized packets and re-enters slow start after receiving an ACK

pHost

- Similar design principles as pFabric, but aims to rely only on commodity network hardware
- Allows programmers to customize the packet scheduling algorithm to achieve different policy goals
- Especially useful when datacenters are shared by multiple users/applications
- Paper is co-authored by Rachit!

Basic Transport Mechanism

- Built around a host-based scheduling mechanism
- Uses requests-to-send (RTS), per-packet token assignment, and receiver-based selection of pending flows
- Scheduling at destination, scheduling at source, priority level of each packet, and number of free tokens per source allow for different performance goals without network modification

Solution: Data Center TCP (DCTCP)

- TCP-like protocol
- Uses Explicit Congestion Notification (ECN) for congestion detection
- Implicit rate control by keeping queues small/empty
- Provides high burst tolerance and low latency for short flows
- Allows applications to handle much more background traffic without interrupting foreground traffic
- Increasing Foreground traffic does not cause timeouts

DCTCP Algorithm

- Goal: Achieve high burst-tolerance, low latency, and high throughput, with commodity shallow buffered switches
- Achieves these goals primarily by reacting to congestion in proportion to extent of congestion
- DCTCP source reacts by reducing window by a factor that depends on the fraction of marked packets

DCTCP Algorithm (Cont'd)

- Simple marking at switch
  - arriving packet will be marked if the queue has more than k elements. Otherwise, not marked.
- ECN Echo at receiver
  - uses delayed ACKS, otherwise similar to TCP receivers
- Controller at the Sender
  - sender maintains an estimate of fraction of packets that are marked, called alpha, which is updated once for every window of data

DCTCP Algorithm (Cont'd)

$$\alpha \leftarrow (1 - g) \times \alpha + g \times F,$$

- Where F is the fraction of packets that were marked in the last window of data
- g is the weight given to new samples
- if alpha close to 0, low congestion, if alpha close to 1, high congestion

Benefits

- Solves three problems:
  - Queue Buildup
    - DCTCP senders start to react as soon as queues have > K elements in them
    - reduces queuing delays on congested ports
    - allows for more headroom to absorb bursts
  - Buffer Pressure
    - a congested port’s queue length does not grow exceedingly large
  - Incast
    - incast scenario: large number of synchronized small flows hit the same queue
    - early/aggressive marking allows DCTCP to tame the size of follow up bursts

Evaluation Summary

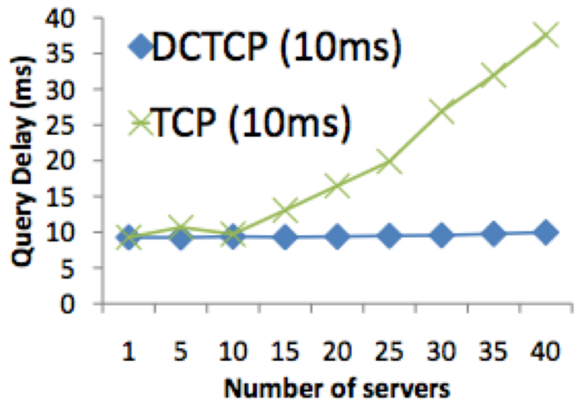
- pHost and pFabric seem to do better than DCTCP with websearch and data mining, but DCTCP does the best for total request completion times in Incast traffic patterns
- unclear how MPTCP does against DCTCP,
- all of these options are better than TCP

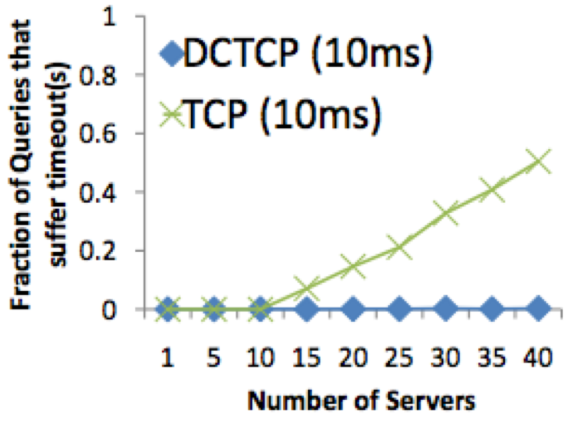
Evaluation (Cont'd)

95th percentile of query completion time

	Without background traffic	With background traffic
TCP	9.87ms	46.94ms
DCTCP	9.17ms	9.09ms

With Dynamic Buffering in DCTCP:





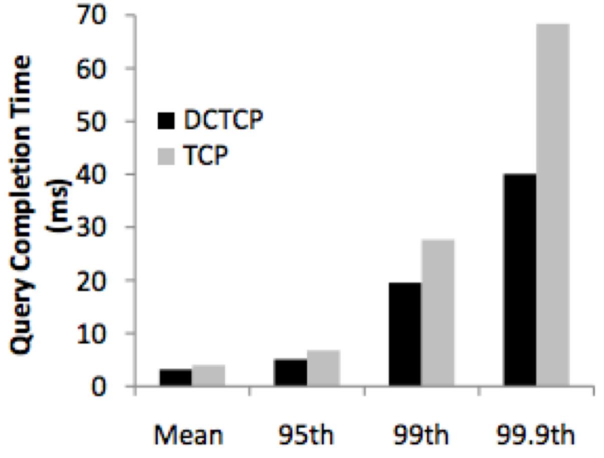


Figure 23: Completion time: query traffic

Evaluation compared to pFabric

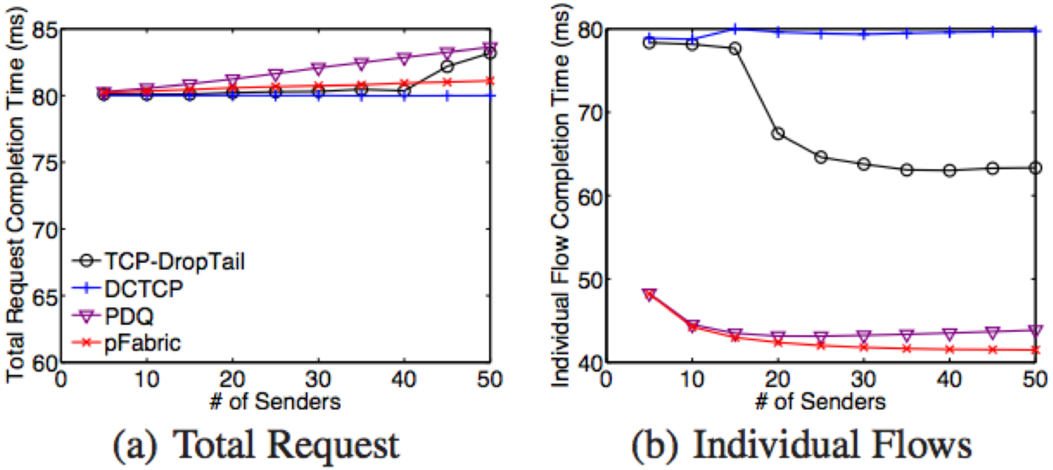


Figure 6: Total request and individual flow completion times in Incast scenario. Note that the range of the y-axis is different for the two plots.

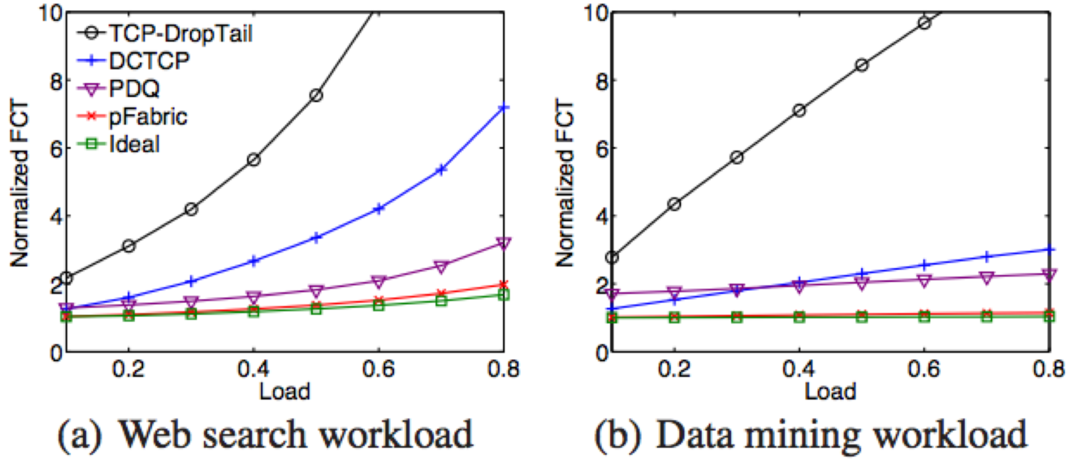
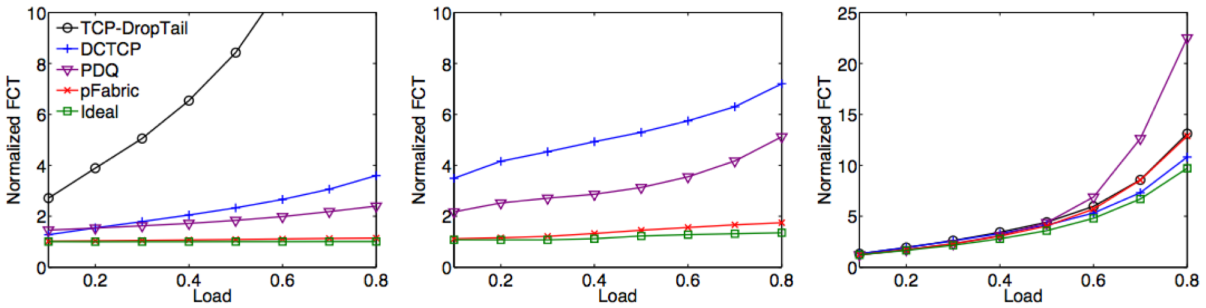


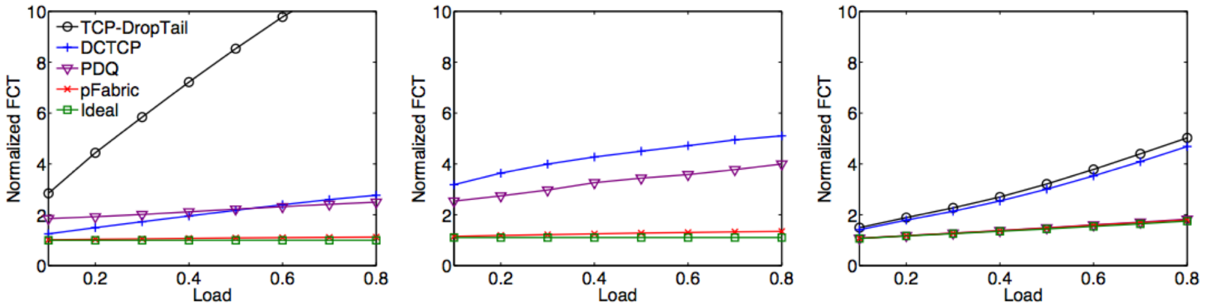
Figure 7: Overall average normalized flow completion time for the two workloads at various loads.

Evaluation compared to pFabric



(a) (0, 100KB]: Avg (b) (0, 100KB]: 99th prctile (c) (10MB, ∞): Avg

Figure 8: Web search workload: Normalized FCT statistics across different flow sizes. Note that TCP-DropTail does not appear in part (b) because its performance is outside the plotted range and the y-axis for part (c) has a different range than the other plots.



(a) (0, 100KB]: Avg (b) (0, 100KB]: 99th prctile (c) (10MB, ∞): Avg

Figure 9: Data mining workload: Normalized FCT statistics across different flow sizes. Note that TCP-DropTail does not appear in part (b) because its performance is outside the plotted range.

Future Work and Discussion Questions

Discussion Questions

- Why is today's class centered around DCTCP instead of more efficient transport protocols like pHost and pFabric?
- Is it worthwhile to continue looking into transport protocols similar to TCP, or should we look into different concepts like decoupling rate control from packet scheduling, like pFabric and pHost?