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Research Faculty Summit 2018

Systems | Fueling future disruptions

High Performance Data Center Communication with FlexNIC

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Data Center Application Trends

- **Small, frequent remote procedure calls**
  - Median RPC ~ 300 bytes across entire Google DC [Montazeri, SIGCOMM 18]
  - TCP semantics: reliable, in-order, congestion/flow control
  - Many to many

- Key-value store, database, distributed analytics …
- Pushing performance limits
  - More requests, larger data sets, real-time response, …
- Scale up to 1000s of machines
  - Need predictable tail latency behavior over multiplexed resources
- With NVM persistence now almost entirely a networking issue

…but software packet processing is too slow

- Recv+send TCP stack processing time (2.2 GHz)
  - Linux: 3.5μs
  - Kernel bypass: ~1μs

- **Single core performance has stalled**
- Parallelize? Assuming 1μs over 100Gb/s, ignoring Amdahl's Law:
  - 64B packets => 200 cores
  - 1KB packets => 14 cores

What About?

- Kernel bypass? (ex: MTCP)
  - Kernel overhead only part of the problem
  - No policy enforcement
- SmartNICs/NIC CPU array? (Cavium, Netronome, …)
  - Complex assignment of flows to CPU array
  - Limited per-flow performance
  - Relatively expensive
- RDMA?
  - RDMA API fine for some apps, but message passing is a better fit for small RPCs
  - Hardware bundles (poorly designed) flow/congestion control with API
- TCP Offload Engine?
  - Need protocol agility

Hardware Assist, OS Feature Set

- Multi-tenant policy compliance
  - VM/container security and access control
  - Shared network resource management (flow and congestion control)
- Protocol agility (across lifetime of the hardware)
  - API agnostic: both RDMA and message passing
  - Reconfigurable protocols vs. fixed function hardware
- Connection scalability: 100K+ active flows/server
- CPU efficiency for common case packet handling
  - From NIC through the application and back
- Performance predictability, esp tail latency with many flows
- Cost-efficient hardware: FPGA or micro-programmed VLSI

Hardware Assist Possible at Several Layers

- Virtual machine layer: Sambhrama
  - Deliver packets directly to the guest OS
  - With VM policy enforcement
- **Container OS layer: TCP packet handling**
  - Deliver packets directly to the application
  - With policy enforcement, flow/congestion control, …
- Application-specific processing: Simon Peter
- **Network switches: congestion and SLA management**

FlexNIC

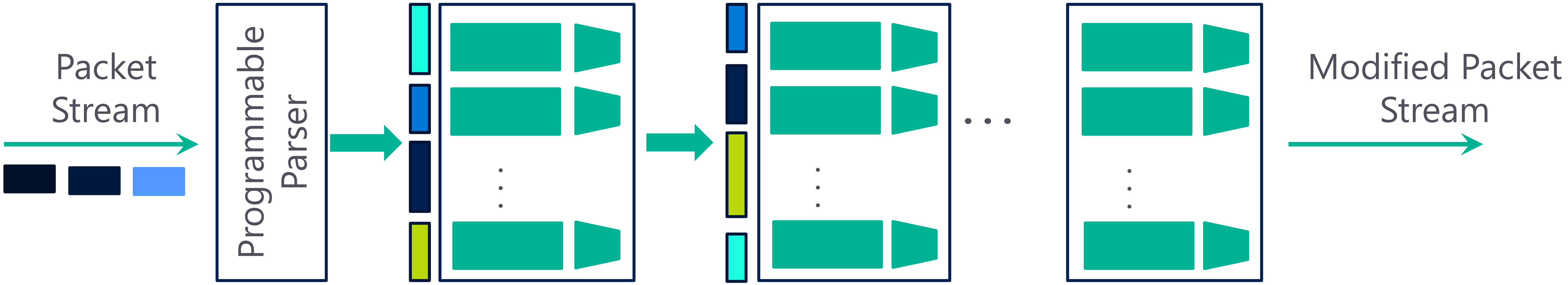
Approx Fair Queueing

Overarching Lesson

Common case packet handling is systolic (can be pipelined in hardware)

On both NICs and switches

FlexNIC: Reconfigurable Multi-stage Pipelines



- Reconfigurable packet processing pipelines
  - Protocol agnostic
  - Tbps implementations for a single pipeline (Barefoot)
  - Predictable performance
- Stages execute parallel

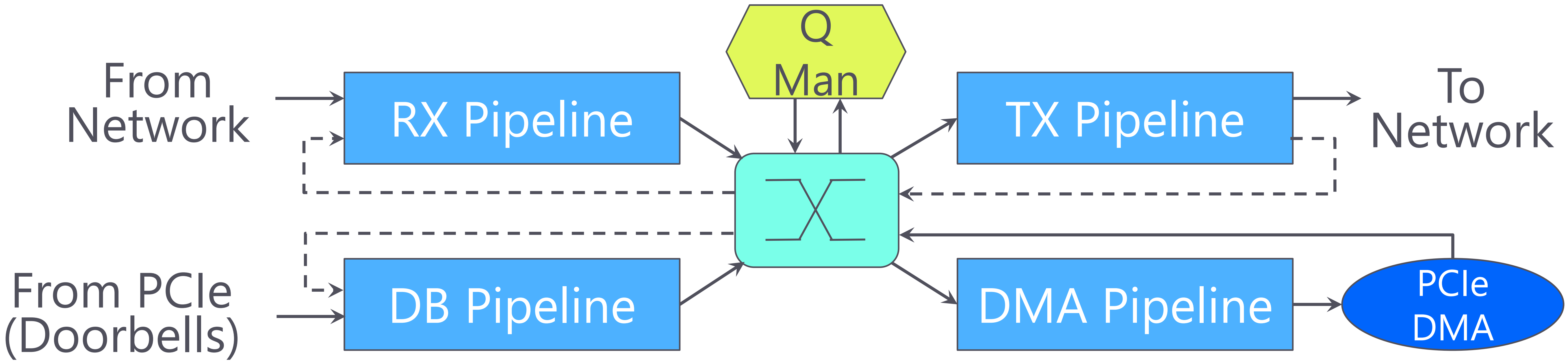
Match+Action Programs

Match:
IF udp.port == kvs
Action:
core = HASH(kvs.key) % 2
DMA hash, kvs **TO** Cores[core]

Supports:
- Steer packets
- Initiate DMA
- Trigger reply packet
- Modify/replicate packets
- Modest per-flow state

Does not support
- Loops
- Complex arithmetic
- Arbitrary state
- Arbitrary # of stages

FlexNIC Hardware Model



- Transform packets for efficient processing in SW
- DMA directly into and out of application data structures
- Send acknowledgements on NIC
- Queue manager implements rate limits
- Improve locality by steering to cores based on app criteria

Kernel

- Open/close connections

Per packet

- Socket API, locking
- IP routing, ARP
- Firewalling, traffic shaping
- Generate data segments
- Congestion control
- Flow control
- Process & send ACKs
- Re-transmission timeouts

Complex connection state spread over multiple data structures, multiple queues, pointer chasing, …

Application

- Socket API, locking

Fast Path: FlexNIC

Per packet: constant time operations

- Generate data segments
- Apply rate-limit
- Congestion statistics
- Flow control
- Process & send ACKs

Minimal Connection State: 100 bytes

Slow Path: Kernel

- Open/close connections
- IP routing, ARP
- Firewalling, traffic shaping
- Compute rate
- Re-transmission timeouts

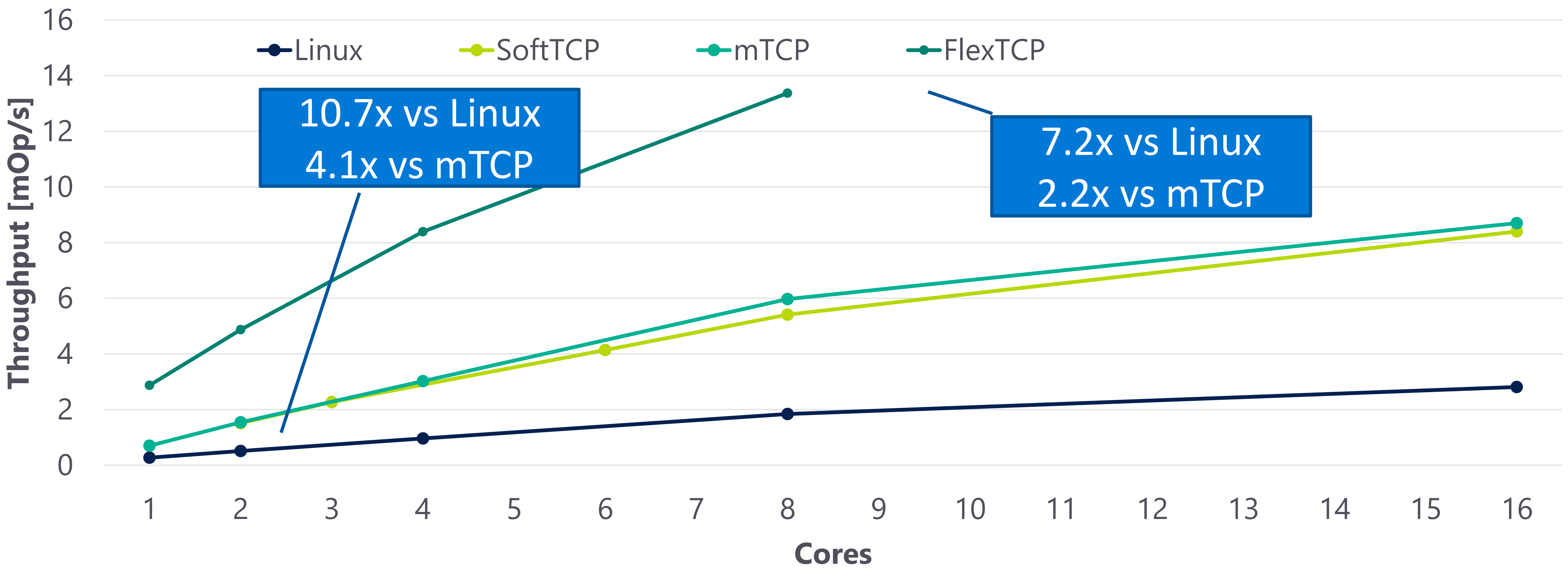
Periodic Congestion Control

- Linux TCP: per-packet congestion window calculation
  - Ack clocking triggers packet queuing for transmission
  - Liable to starvation as # of flows increases

- FlexTCP: per-RTT rate limit
  - FlexNIC: enforce rate-limit, collect CC statistics
  - Kernel software: Fetch CC statistics, update rate-limit
  - Congestion statistics: # ACKs, # ECN marks, # drops, RTT estimation

- Not specific to congestion algorithm
  - Implemented DCTCP, TIMELY, and Reno

FlexTCP Performance



- Latency: 7.8x better vs Linux
- FlexNIC per-flow isolation vs. Linux per-flow starvation

Fair Queueing: in-network enforcement

Enforce fair allocation and isolation at switches

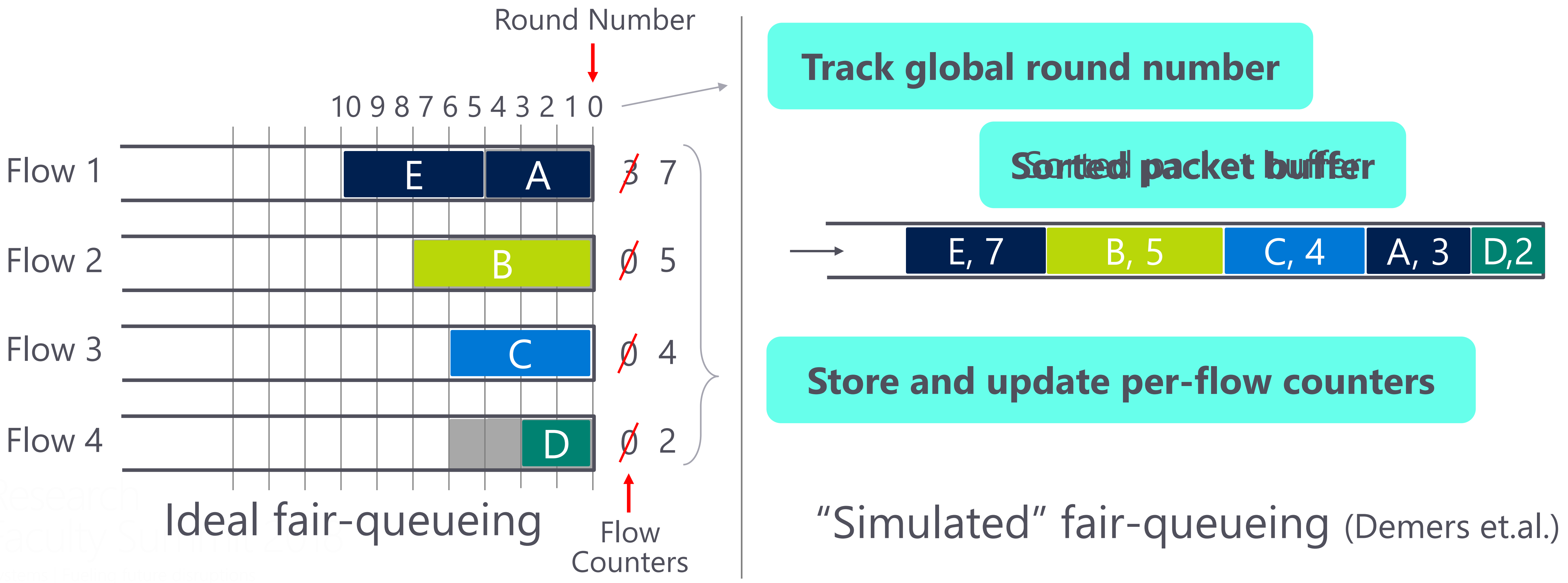
- Provide an illusion that every flow has its own queue
- Proven to have perfect isolation and fairness

+ Simplifies congestion control at the end-host
+ Protects against misbehaving traffic
+ Enables bounded delay guarantees

However, challenging to realize in high-speed switches.

Fair Queueing without per-flow queues

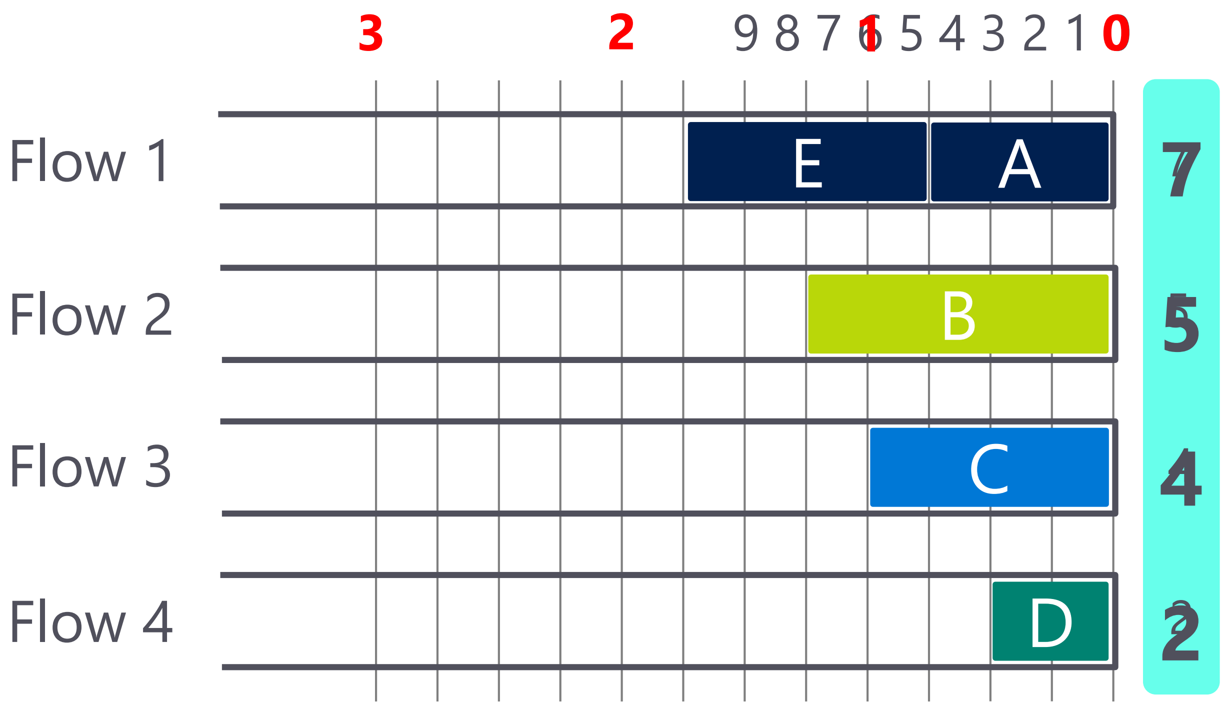
- *Simulates* an ideal round-robin scheme where each active flow transmits a single bit of data every round.



Our approach: Approximate Fair Queueing

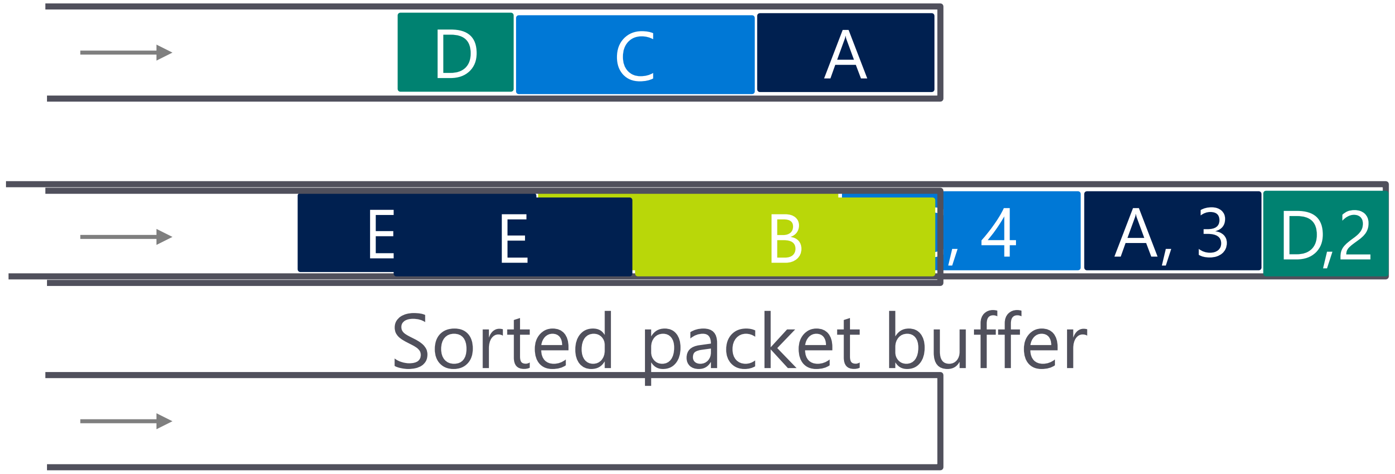
Simulate a bit-by-bit round robin scheme with key approximations

Coarse round numbers



Ideal fair-queueing

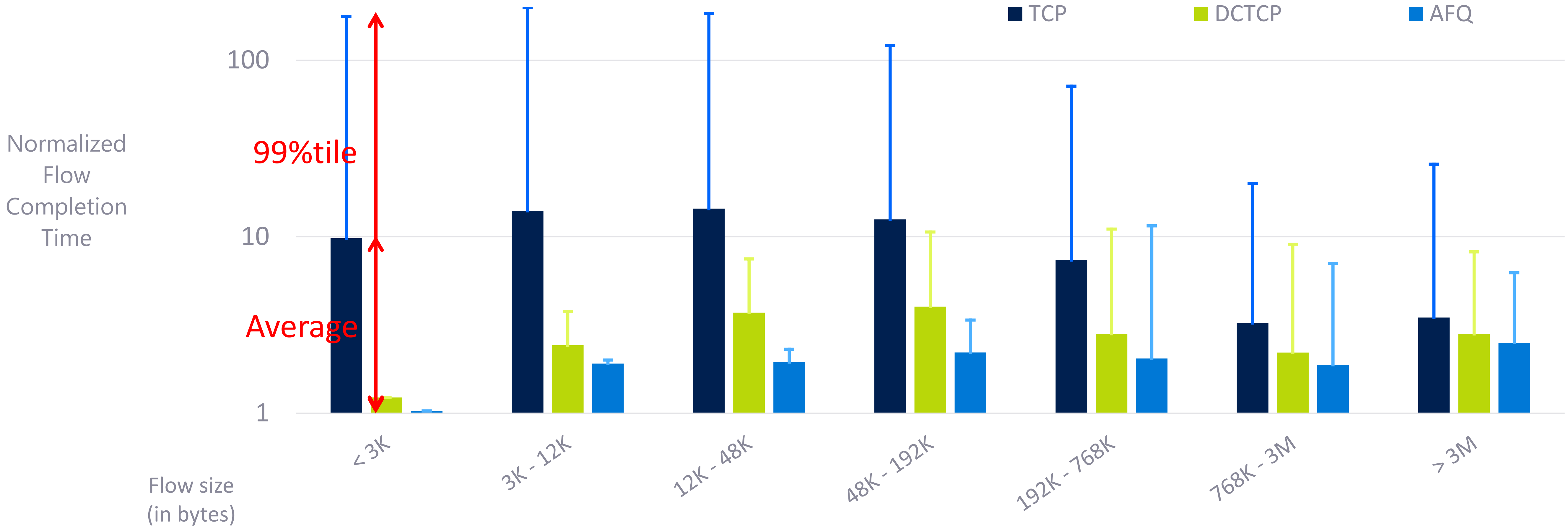
Limited # of FIFO queues with rotating priorities to approximate a sorted buffer



Store approximate per-flow counters using a variation of the count-min sketch

queueing

Testbed Results



- Compared to TCP, 4x better average FCT, 10x better tail latency
- Compared to DCTCP, 2x better average FCT, 4x better tail latency

Summary

- FlexNIC
  - Configurable, efficient, policy-compliant NIC packet handling
  - For VM, container, application
  - Key idea: common case behavior as match-action, kernel for exception handling

- Approximate fair queueing with switch match-action tables
  - Configurable, efficient, policy-compliant switch packet handling
  - Fair queueing provides performance isolation, network SLAs, QoS
  - Approximate with rotating priority queues, coarse-grained rounds, approx. per-flow counters

Thank you

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