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

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
### Application
- Socket API, locking

### Slow Path: Kernel
- Open/close connections
- IP routing, ARP
- Firewalling, traffic shaping
- Compute rate
- Re-transmission timeouts

### 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**
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.

```
10 9 8 7 6 5 4 3 2 1 0
Flow 1
Flow 2
Flow 3
Flow 4
```

```
E, 7
B, 5
C, 4
A, 3
D, 2
```

- Track global round number
- Sorted packet buffer
- Store and update per-flow counters

“Simulated” fair-queueing (Demers et.al.)
Our approach: Approximate Fair Queueing

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

**Coarse round numbers**

```
3 2 9 8 7 6 5 4 3 2 1 0
```

**Ideal fair-queueing**

```
Flow 1
```

```
Flow 2
```

```
Flow 3
```

```
Flow 4
```

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

```
D C A
```

```
E E B
```

```
A 3 D 2
```

**Sorted packet buffer**

```

```

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