How Bad is TCP?

(And What Are the Alternatives?)

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MLE Mission: “From Software to Silicon!”

High-Performance (Embedded) Compute & Connected Systems-of-Systems need “Offload Engines” for better performance, lower and deterministic latency and improved energy efficiency.

Focus on standards such as PCIe, NVMe, Ethernet, TCP/UDP/IP, TSN.

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intel partner Gold

FPGA MICROCHIP DESIGN PARTNER

trenz electronic GmbH

PCI SIG

Fraunhofer Heinrich-Hertz-Institut

Fraunhofer IPMS

ELEMASTER

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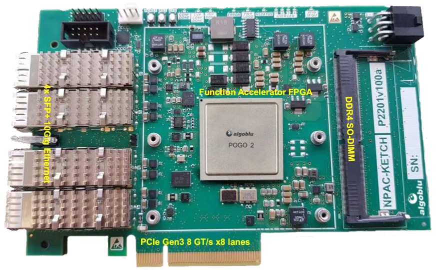
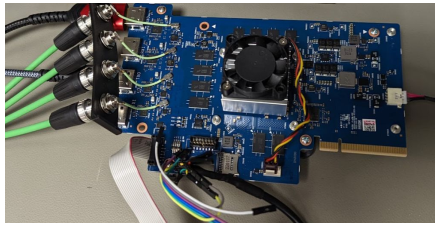
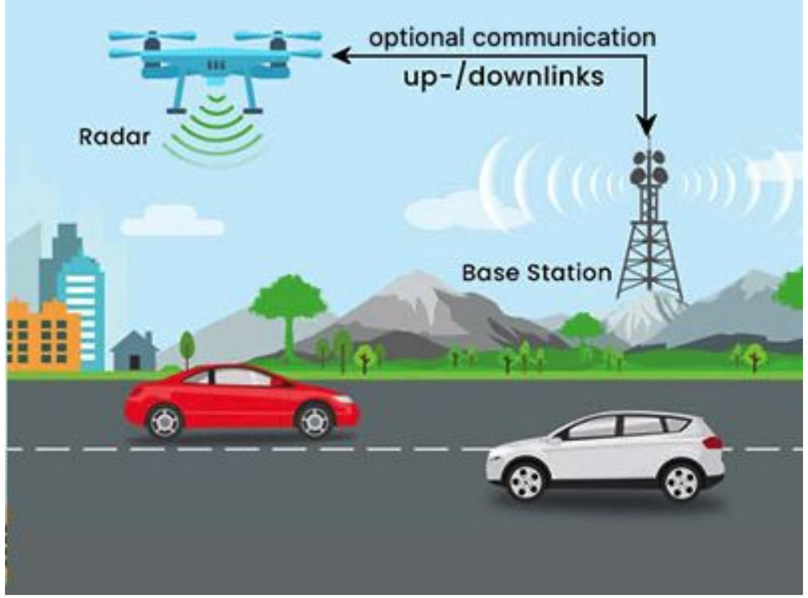




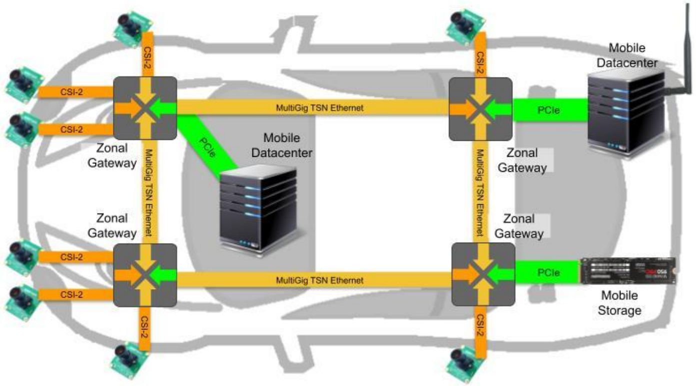
SDC 23

Multi-Gigabit Real-Time Networking Market & Technology Forces

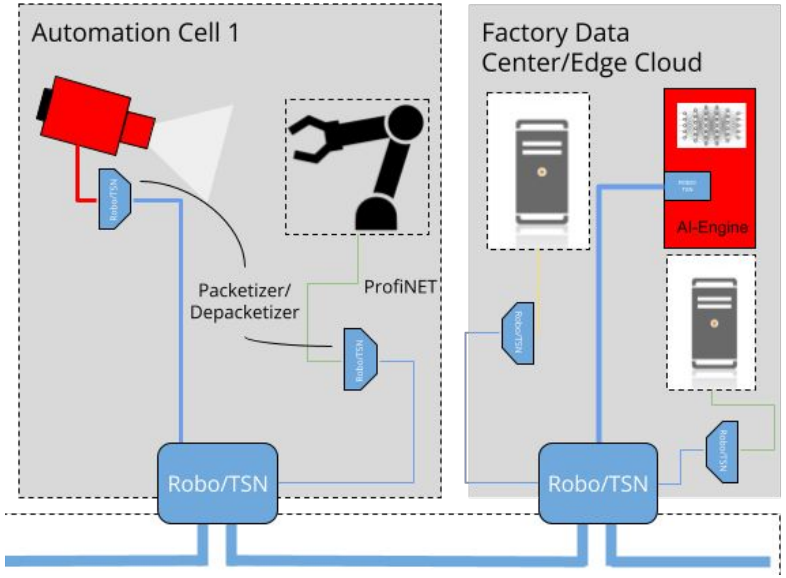
6G Radio Integrated Communication and Sensing (ICAS)



Zone-Based In-Vehicle Networking (Auto/TSN)



100G Real-time Backbone for Virtualized PLC (Robo/TSN)



Work Motivation

Systems-of-systems
- Tightly-coupled: i.e. distributed processing with microservices
- Loosely-connected via networks (which continuously are the bottleneck)

Need to optimize
- for power / energy efficiency
- for throughput
- for (deterministic) latency and real-time delivery

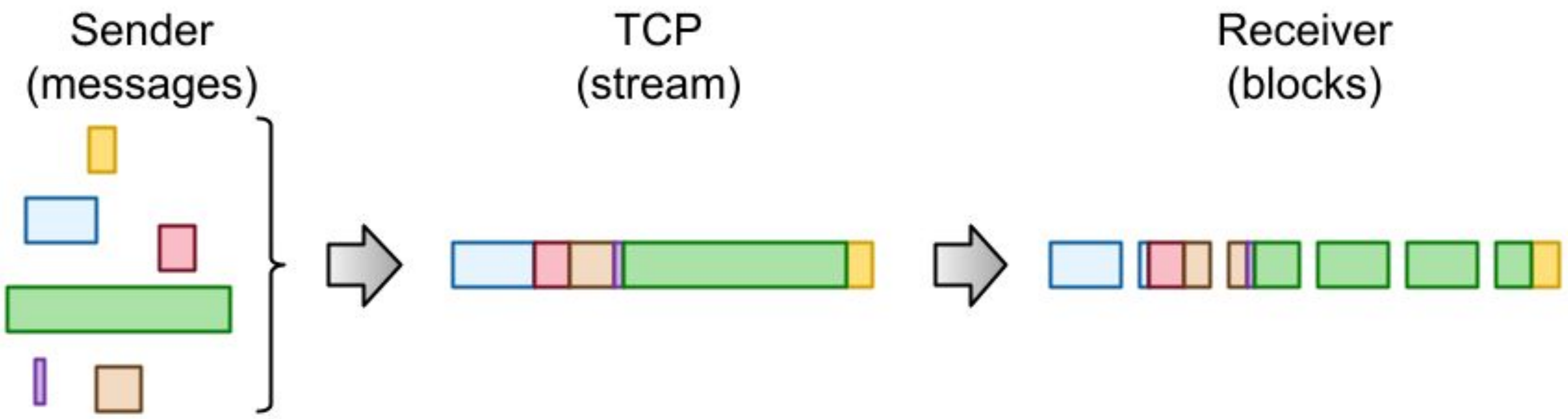
Domain-Specific Architectures:
- “Offload” (protocol) processing software onto silicon
  but adhere to (defacto) standards and APIs
- Make networks more deterministic and Time-Sensitive

Presentation Outline

- How Bad is TCP?
  - Computational Burden
  - Tail-end Latencies
- What Are the Alternatives?
  - Homa from John Ousterhout's team at Stanford University
  - QRP (Quad R P) - a Hardware Accelerated Version of Homa

Courtesy of John Ousterhout, Stanford University

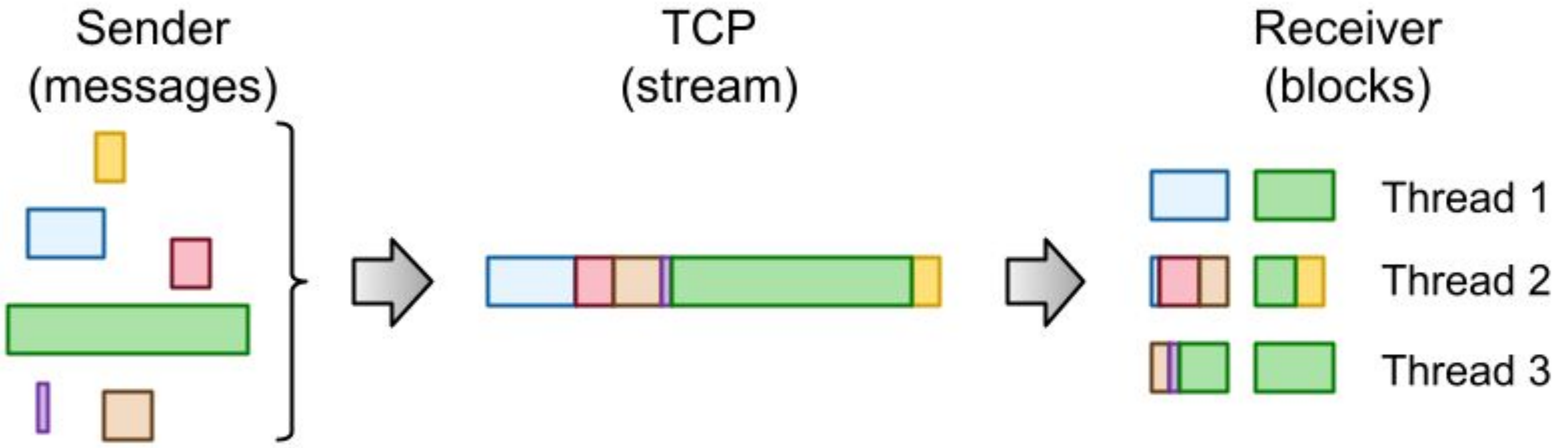
1. TCP Data Model: Byte Stream



- Applications care about **messages**, but TCP drops boundary info
- Extra complexity/overhead for message reassembly

Courtesy of John Ousterhout, Stanford University

1. TCP Byte Streams, cont'd

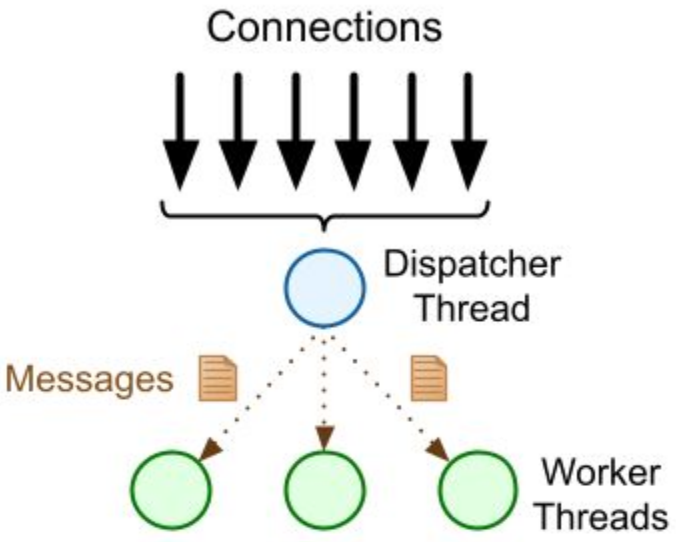


- **Disastrous for load balancing**
  - Can't share one stream among multiple threads
  - Can't offload dispatching to NIC

Courtesy of John Ousterhout, Stanford University

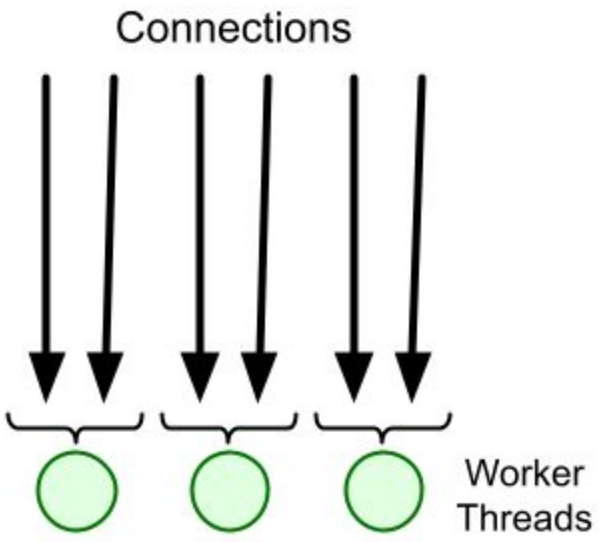
Load Balancing Choices

Choice #1: dispatcher thread



- **Extra latency for worker handoff**
- **Dispatcher is throughput bottleneck (~1M msgs/sec)**

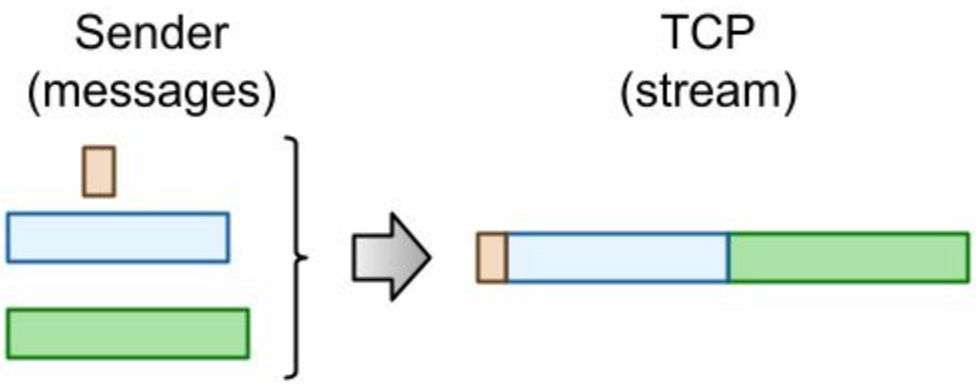
Choice #2: partition connections



- **Static load balancing: prone to hot spots**

Courtesy of John Ousterhout, Stanford University

1. TCP Byte Streams, cont'd

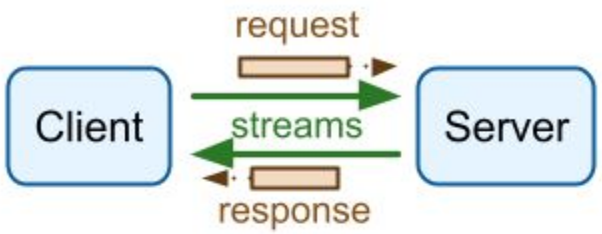


- **Head-of-line blocking:**
  - Short messages can get stuck behind long ones
  - High tail latency

Courtesy of John Ousterhout, Stanford University

Stream-Level Reliability Inadequate

- **Clients want round-trip guarantees:**
  - Deliver request
  - Ensure it is processed
  - Deliver response
  - Or, notify of error
- **Stream guarantees are weaker:**
  - Best-effort delivery of request or response
  - No notification if server machine crashes
- **Clients must implement additional timeout mechanisms**
  - Even though TCP already implements timers



Courtesy of John Ousterhout, Stanford University

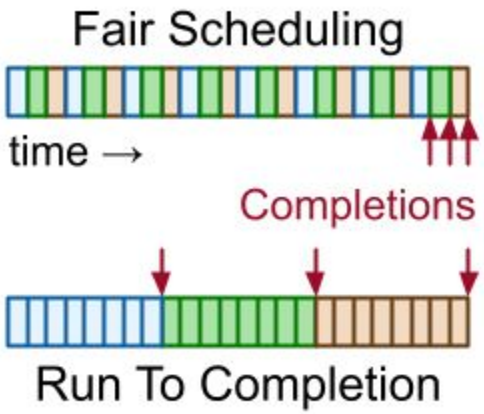
2. TCP is Connection-Oriented

- **Requires long-lived state for each stream**
  - ~2000 bytes per connection in Linux, not including packet buffers
  - Individual datacenter apps can have thousands of connections
  - Mitigate with connection pooling/proxies (e.g. Facebook)? Adds overhead
  - Challenging for NIC offloading (e.g. Infiniband): thrashing in connection caches
- **Before sending any data, must pay round-trip for connection setup**
  - Problematic in serverless environments: can't amortize setup cost
- **Motivation for connections:**
  - Enable reliable delivery, flow control, congestion control
  - But, all these can be achieved without connections

Courtesy of John Ousterhout, Stanford University

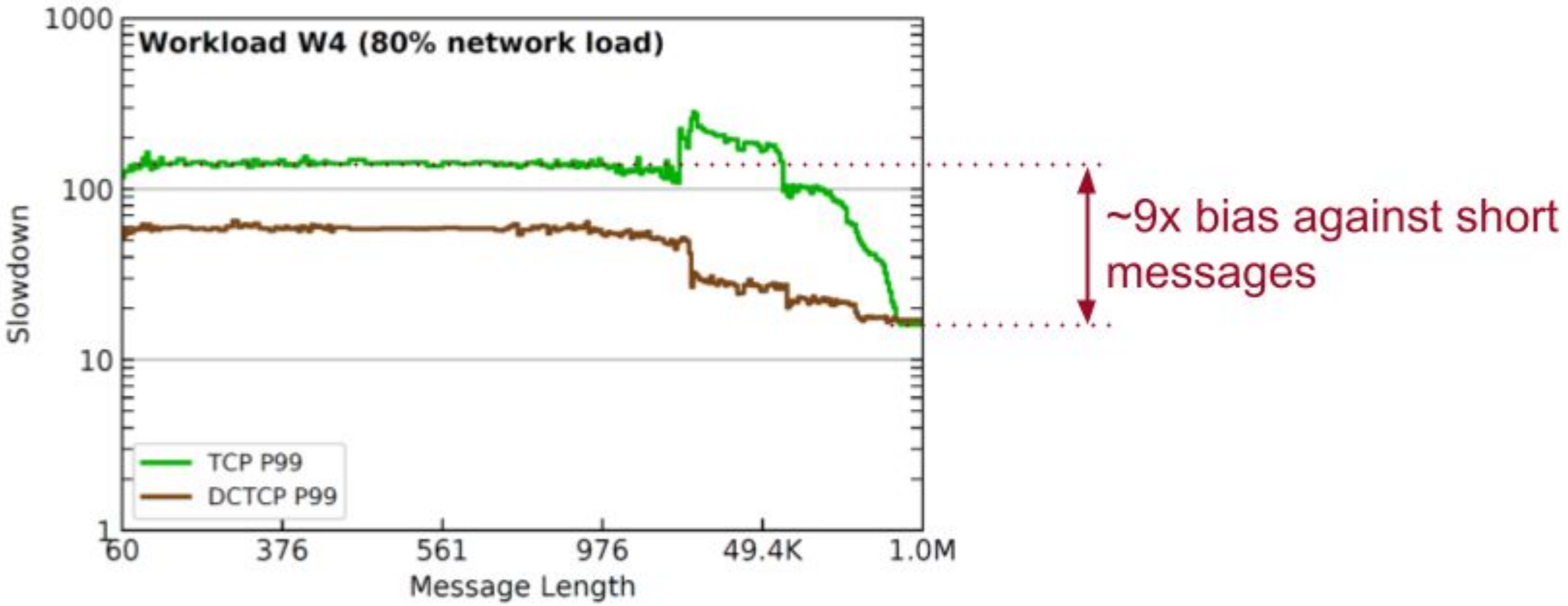
3. TCP Uses Fair Scheduling

- **When loaded, share bandwidth equally among active connections**
- **Well-known to perform poorly: everyone finishes slowly**
- **Run-to-completion approaches (e.g. SRPT) are better**
  - But requires message sizes



Courtesy of John Ousterhout, Stanford University

TCP Isn't Actually Fair!



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Courtesy of John Ousterhout, Stanford University

4. TCP: Sender-Driven Congestion Control

- **Senders responsible for scaling back transmission rates when needed**
  - But, they have no direct knowledge of congestion
- **Congestion signals based on buffer occupancy:**
  - Packets dropped if queues overflow
  - Congestion notifications based on queue length
- **Problems:**
  - Significant buffer occupancy when system is loaded
  - Queuing causes delays, especially for short messages

The Computational Burden of TCP

Benchmark TCP Point-to-Point with Netperf 2.6

- TCP_STREAM (and TCP_MAERTS) for throughput in Gbps
- CPU Load on Tx and Rx side
- TCP_RTT for Round-Trip-Time
- Efficiency = Throughput / CPU Load

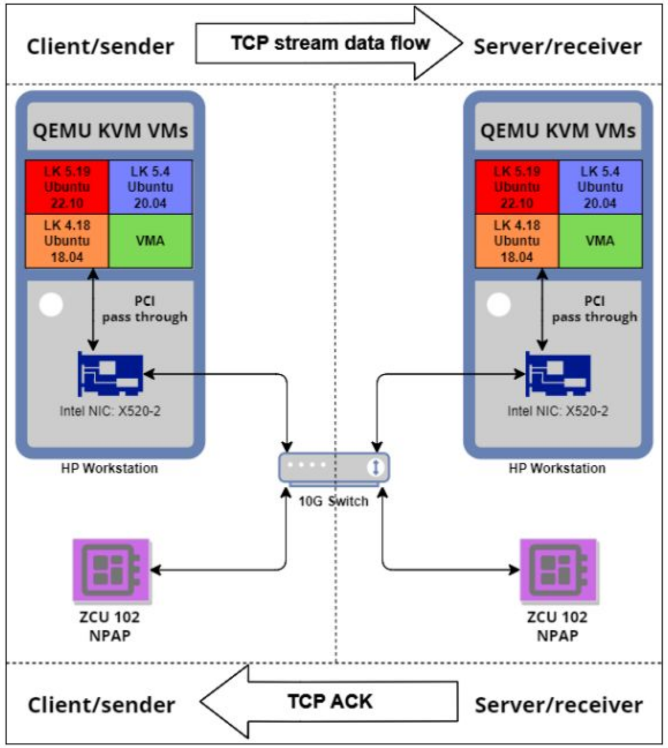
System Setup

- AMD FPGA w/ NPAP-25G
  (Fraunhofer HHI's TCP/UDP/IP Full Accelerator)
- 25 GigE NIC: Mellanox ConnectX-4 LX
- CPU: Intel(R) Xeon(R) e5-1620 v0 @ 3.60GHz
  1 socket, 4 cores, 1 thread per core
  RAM: 32G (4x8G) (Samsung, DDR3, 1600 MT/s, syn reg)

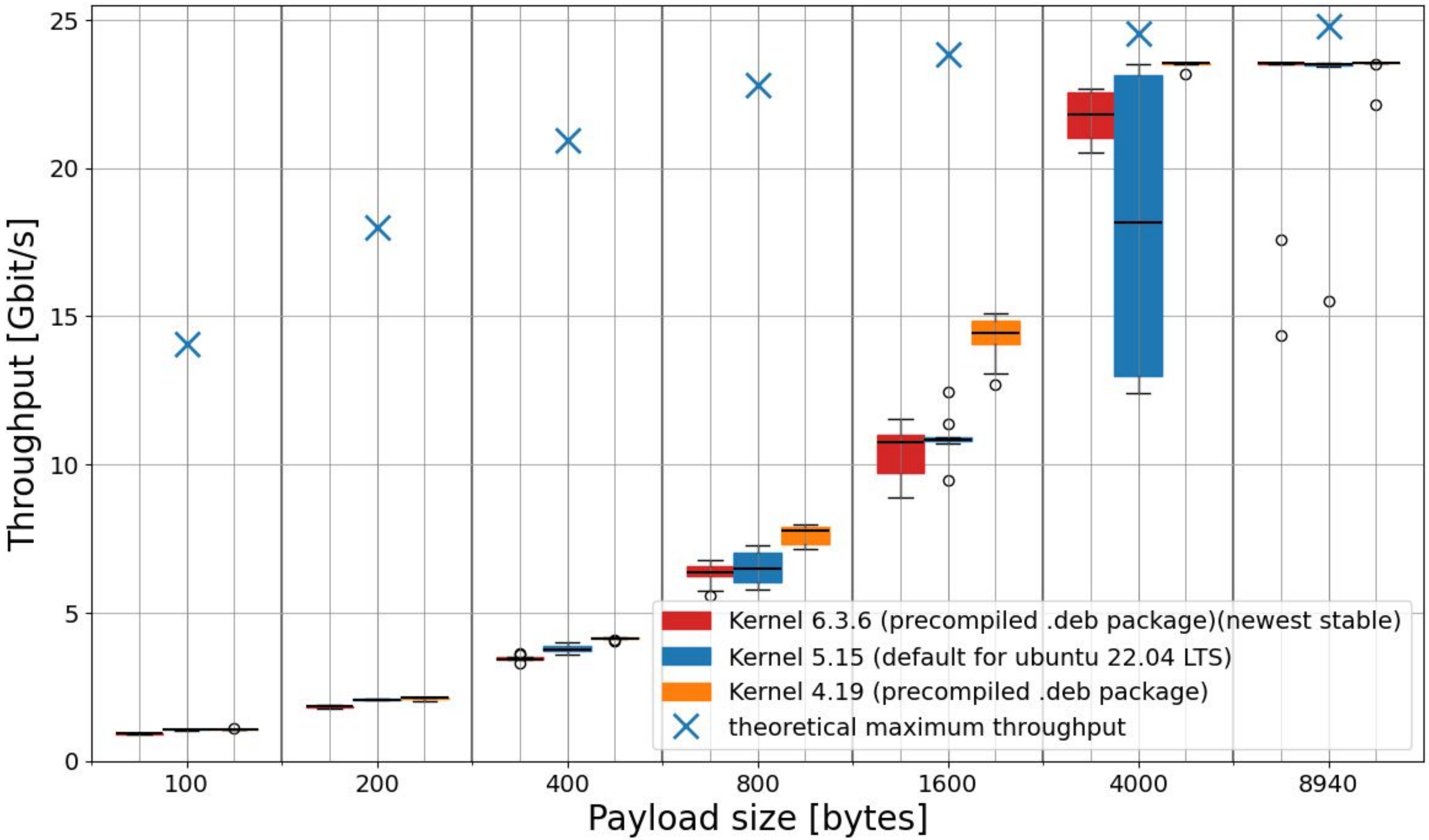
Effects of different Linux kernels

- Vanilla 4.19 vs vanilla 5.15. vs vanilla 6.3.6
- Vanilla 4.19 vs Centos 4.18

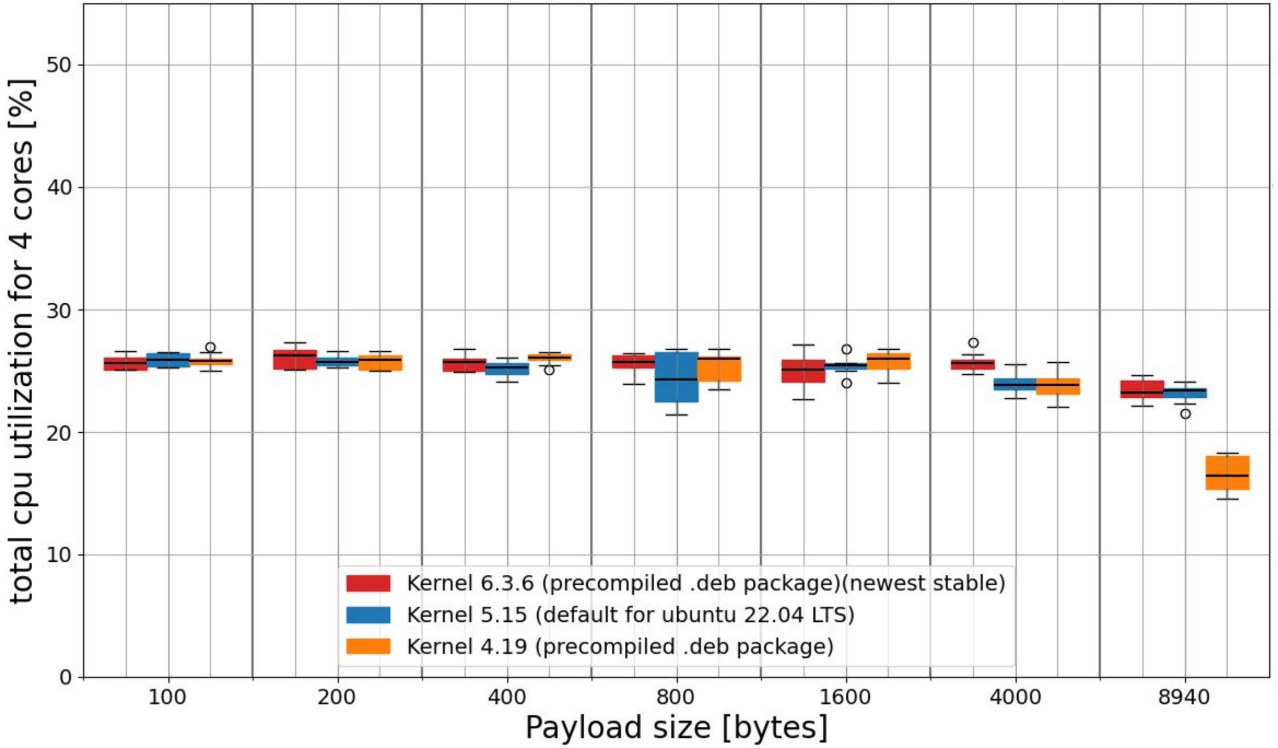
Experimental Setup



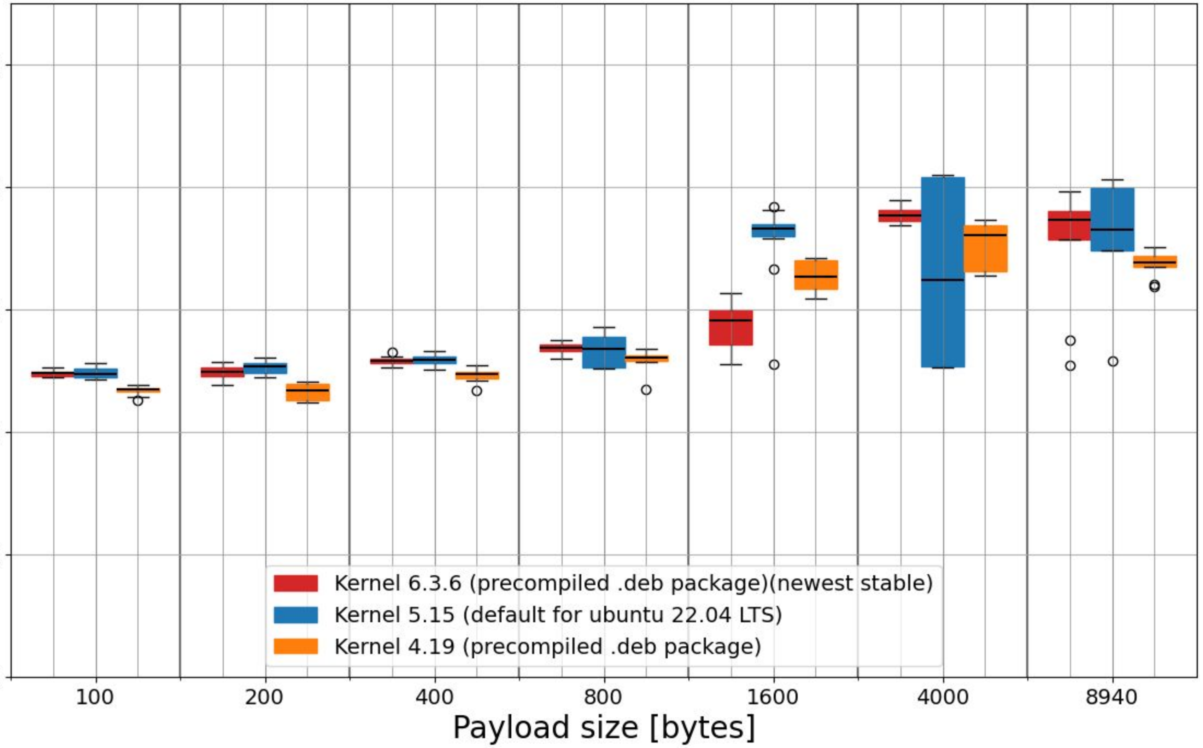
TCP_STREAM Results for Different Linux kernels



TCP_STREAM Results for Different Linux kernels

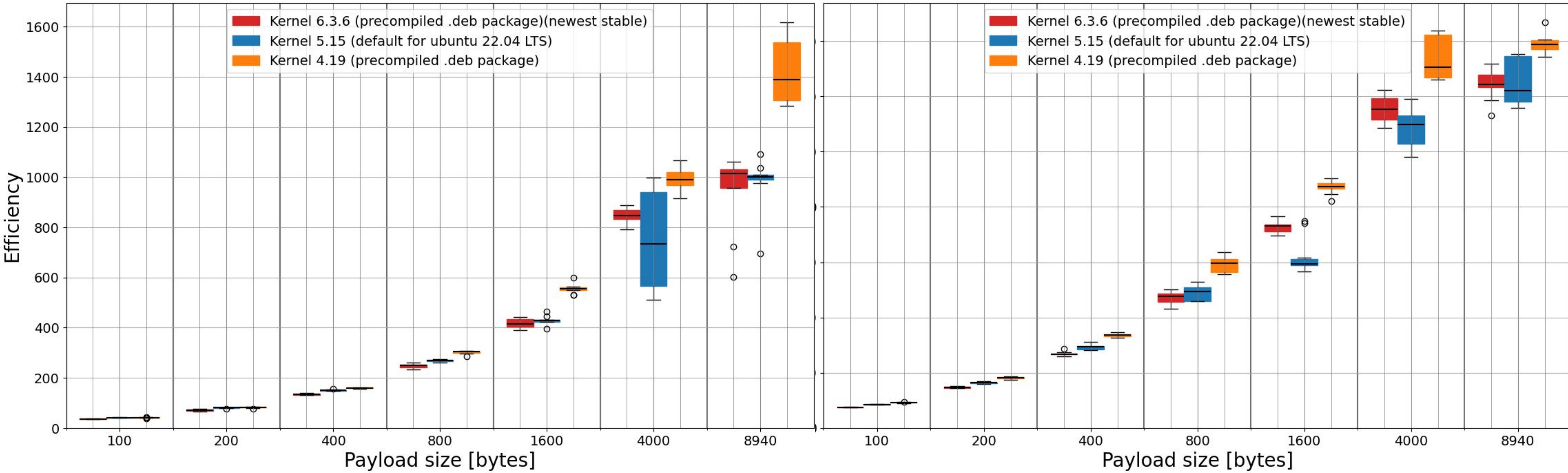


Tx Side



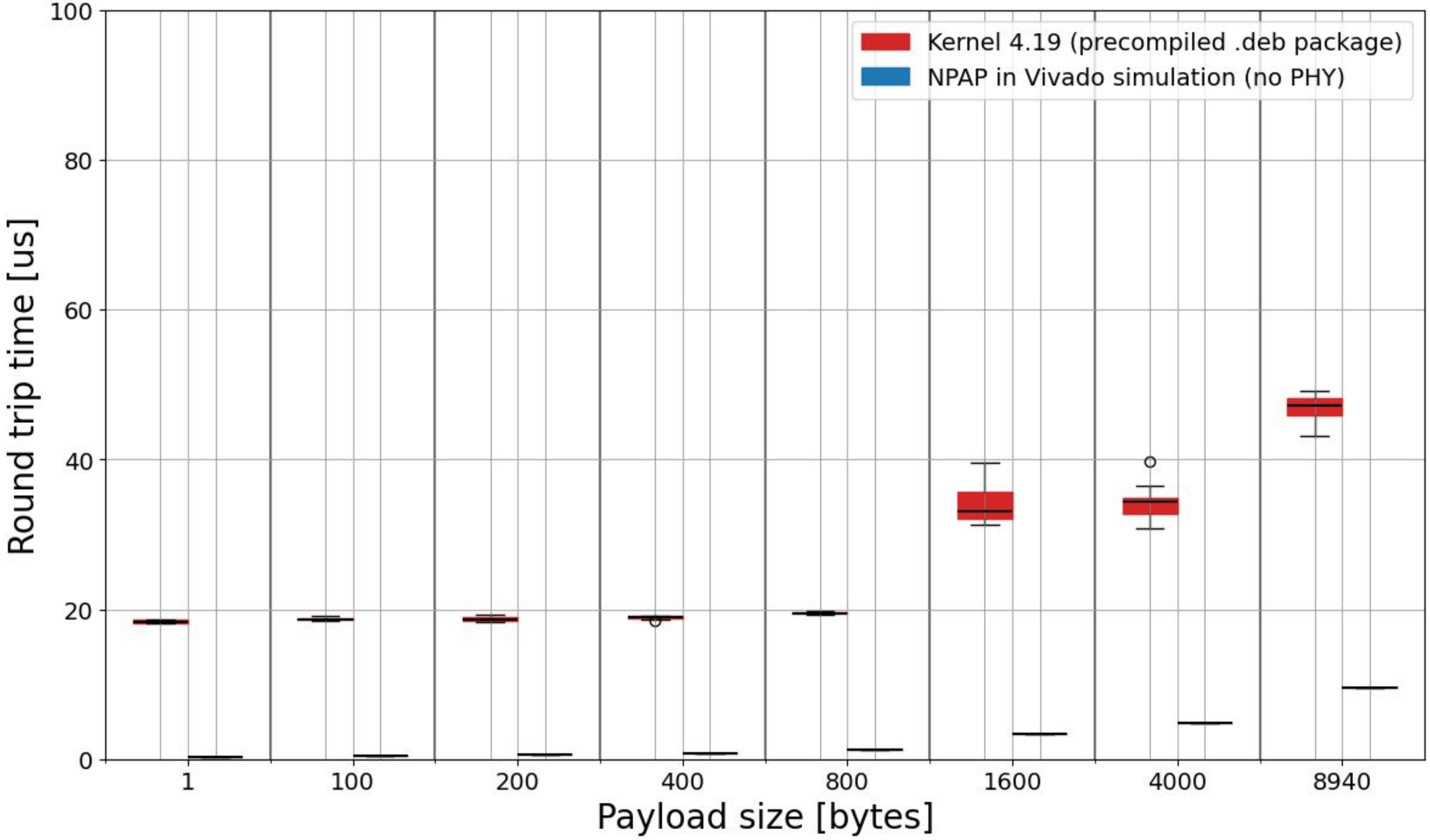
Rx Side

TCP_STREAM Results for Different Linux kernels



Tx Side Rx Side

TCP_RR Results for Different Linux kernels



Average RTT of FPGA Full Accelerator clearly outperforms (Linux) software

Courtesy of John Ousterhout, Stanford University

1. Homa is Message-Based

- **Dispatchable units are explicit in the protocol**
- **Enables efficient load balancing**
  - Multiple threads can safely read from a single socket
  - Future NICs can dispatch messages directly to threads
- **Enables run-to-completion (e.g. SRPT)**

Courtesy of John Ousterhout, Stanford University

2. Homa is Connectionless

- **Fundamental unit is a remote procedure call (RPC)**
  - Request message
  - Response message
  - RPCs are independent
- **No long-lived connection state**
  - (But there is long-lived per-peer state: ~200 bytes)
- **No connection setup overhead**
  - Use one socket to communicate with many peers
- **Homa ensures end-to-end RPC reliability**
  - No need for application-level timers

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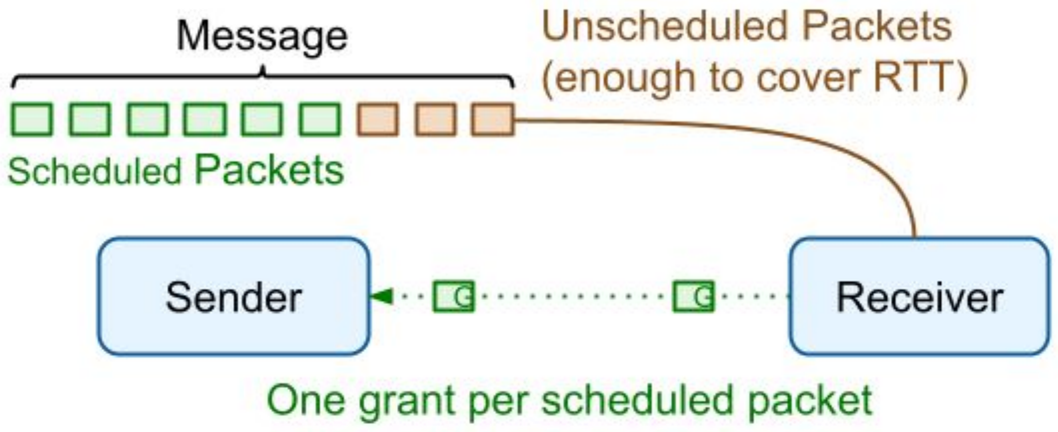
Courtesy of John Ousterhout, Stanford University

3. Homa: Receiver-Driven Congestion Control



- **Receiver can delay grants to:**
  - Reduce congestion in TOR
  - Prioritize shorter messages
- **Message sizes allow receivers to predict the future:**
  - Faster, more accurate response to congestion

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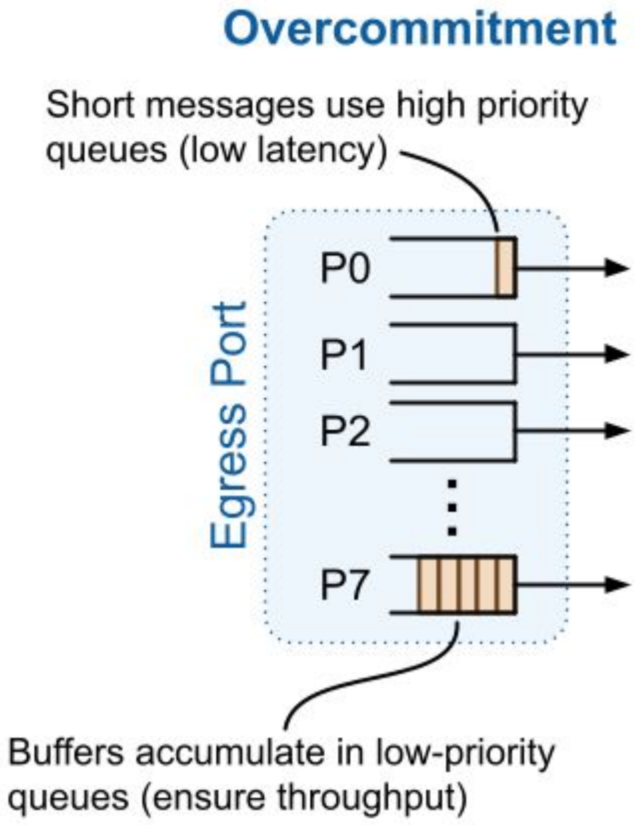
Courtesy of John Ousterhout, Stanford University

Homa Uses Priority Queues

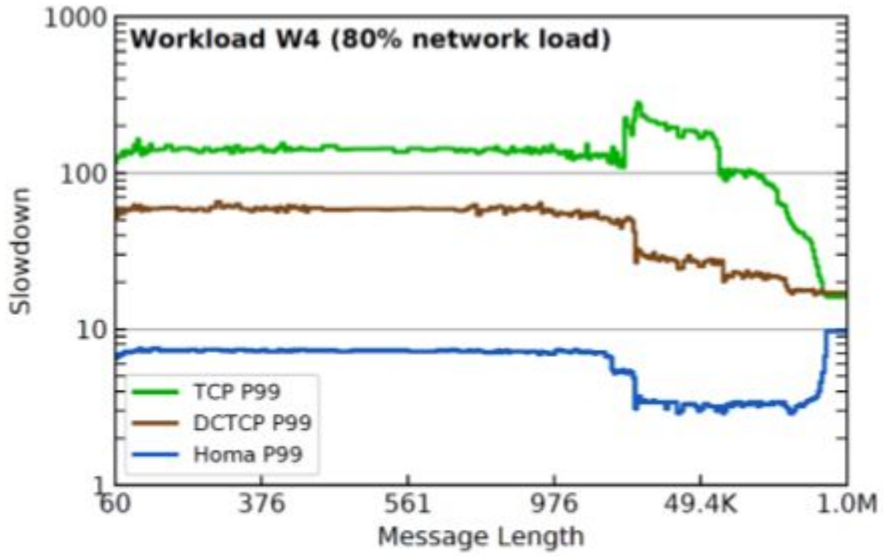
- **Modern switches: 8–16 priority queues per egress port**
- **Homa receivers select priorities for SRPT:**
  - Favor shorter messages
- **Achieve both high throughput and low latency**
  - Need buffering to maintain throughput (e.g. if sender doesn't respond to grant)
  - But buffers can result in delays
  - Solution: overcommitment:
    - Grant to multiple messages
    - Different priority for each message



Courtesy of John Ousterhout, Stanford University

4. Homa: SRPT

- **Combination of grants, priorities**
- **Run-to-completion improves performance for every message length!**
- **Starvation risk for longest messages?**
  - Use 5-10% of bandwidth for oldest message



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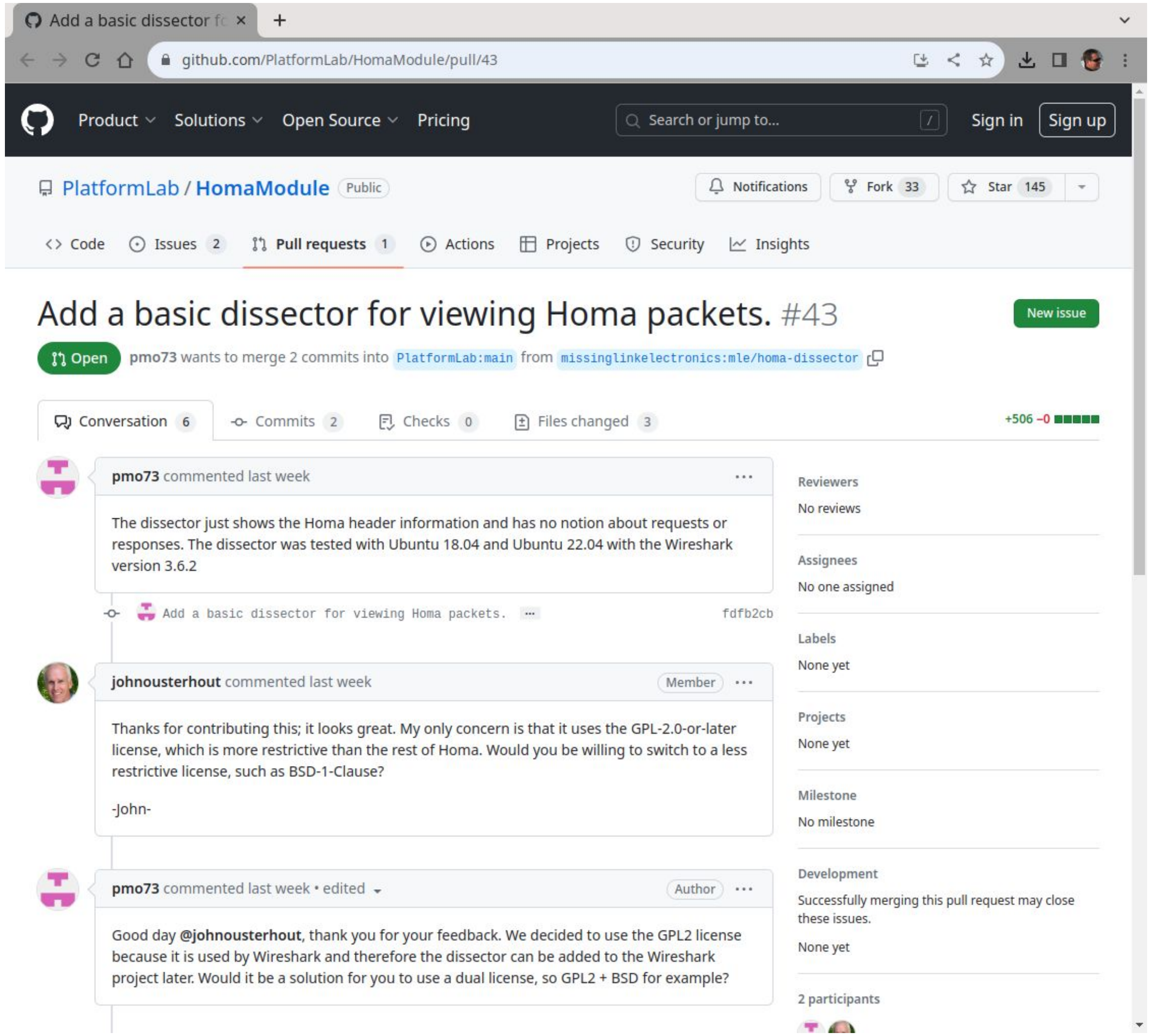
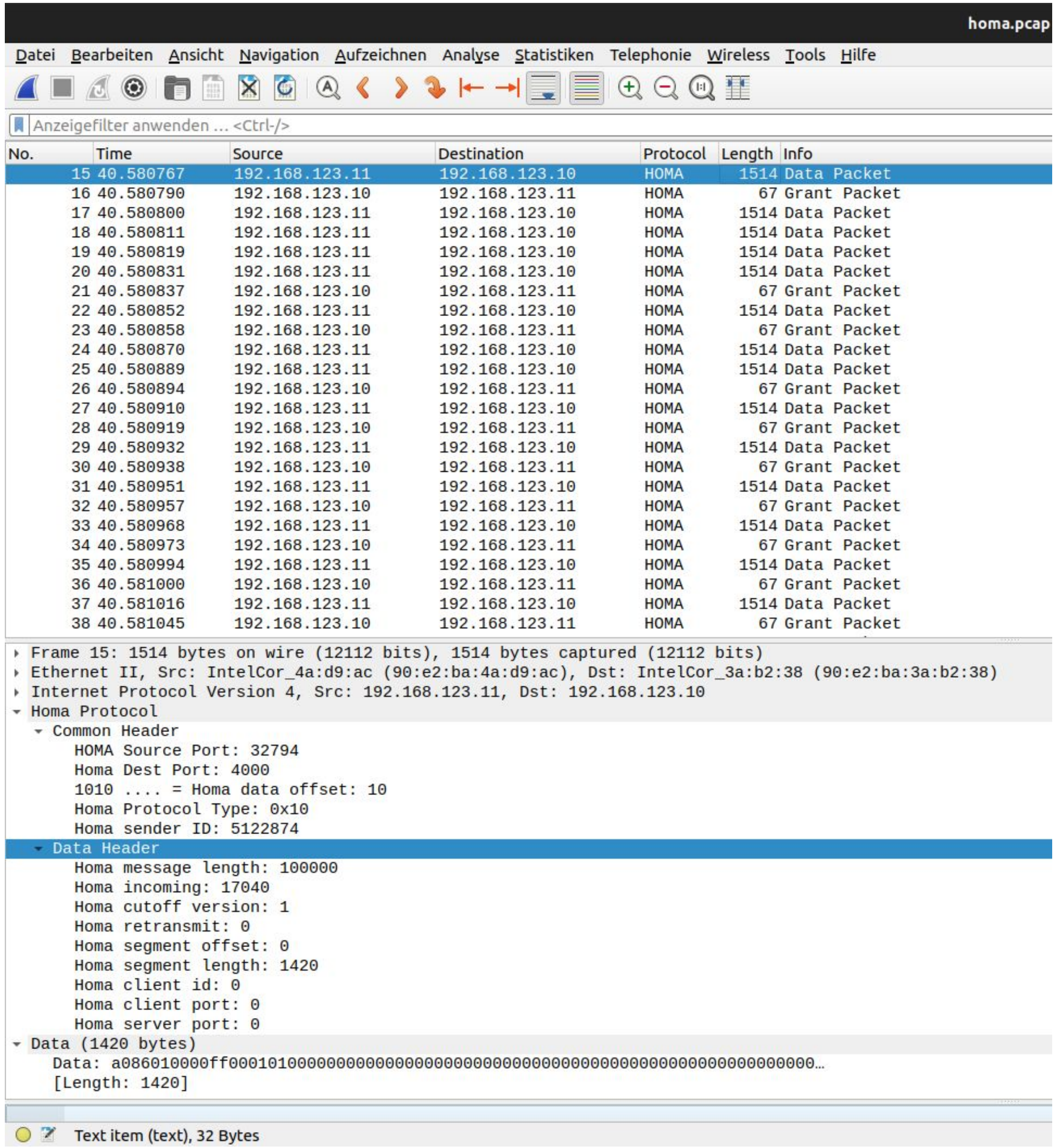
Courtesy of John Ousterhout, Stanford University

5. Homa: No Order Requirement

- **Can use packet spraying in datacenter networks**
  - Hypothesis: will eliminate core congestion (unless core fabric systemically overloaded)
- **Better load balancing across CPU cores**

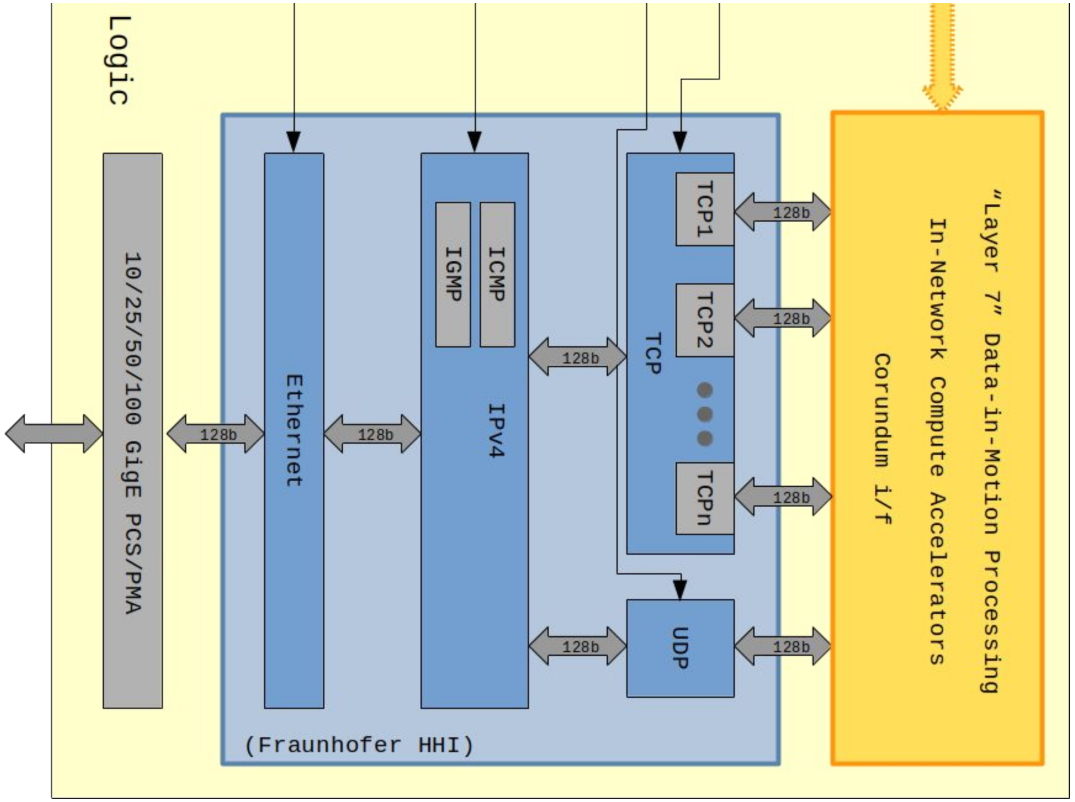
Wireshark Dissector for Homa





NPAP - Network Protocol Accelerator Platform

- Full Accelerator = no CPUs, no software
- Standard IEEE Ethernet PHYs with RMII, GMII, XGMII, etc via PCS/PMA via ASIC/FPGA Ethernet Subsystem
- Ethernet, ARP, IPv4, ICMPv4, IGMPv4, UDP & TCP, DHCP
- Optional TSN, optional TLS
- Datapath via AXI4-Stream 128-bit
- Complete stack uses generic VHDL code
- In production use for automotive, aero & defense, industrial test & measurement, telco applications

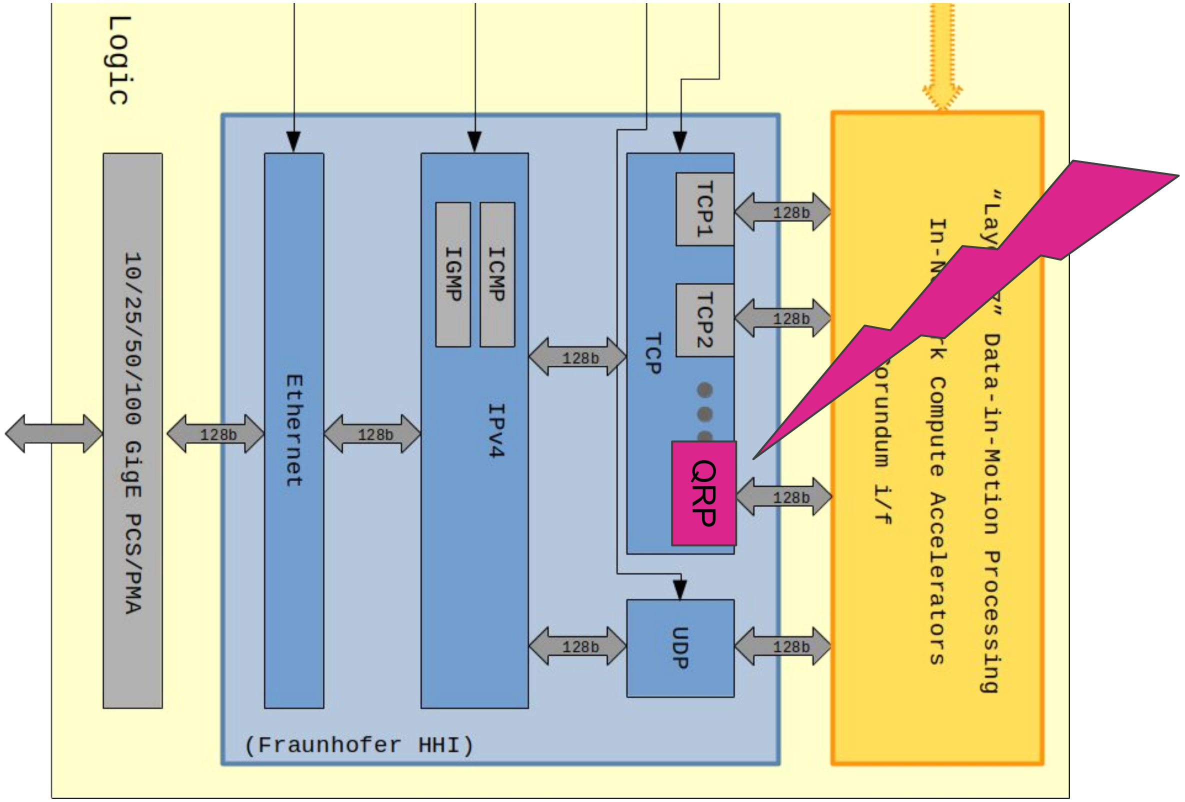


QuadRP - Reliable, Rapid Request-Response Protocol

- Based on Homa
- Implemented within NPAP
  Tested and proven Ethernet and IPv4
- Complements TCP/IP and UDP/IP

⇒ Best of both worlds:

- No CPU load
- Very low, deterministic latency
- Option for handling messages in
  - Programmable Logic, or
  - in Linux software

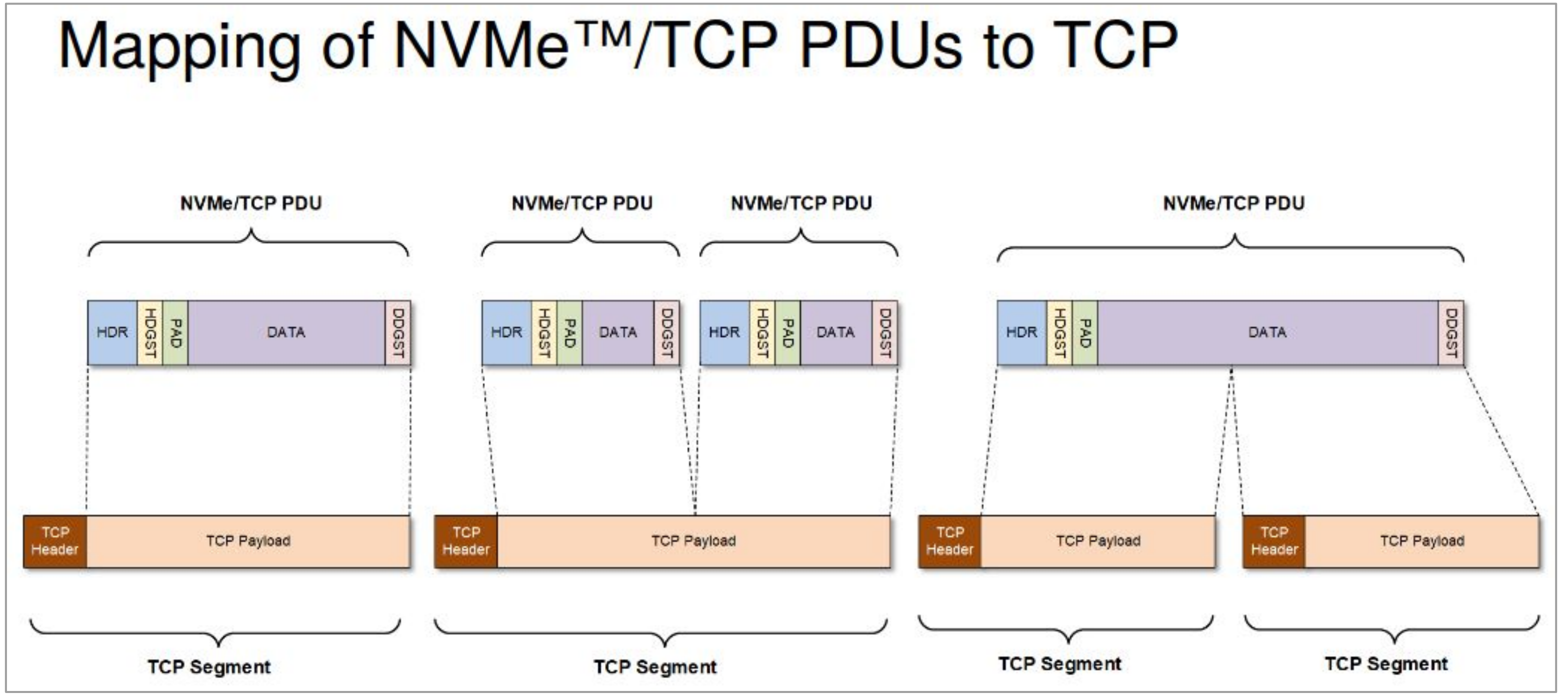


Homa's Benefits for NVMe-over-Fabric

LAN is the bottleneck already, with now additional burden from heavy SAN traffic.
Homa latencies can be 100x faster that TCP and promises to put less load on the network.
NVMe eliminated the legacy software overhead and uses fast PCIe Posted Writes for better response times and IOPS.

So, is TCP then the proper foundation for NVMe-over-Fabric?

NVMe-over-Homa can be a drop-in replacement or an add-on, achieving storage latencies close to DAS performance, with less overhead on network and servers.



HOMA References

[1] John Ousterhout, Stanford University: https://web.stanford.edu/~ouster/cgi-bin/papers/replaceTcp.pdf

[2] John Ousterhout's presentation at USENIX ATC'21 (15 minutes)
https://www.usenix.org/conference/atc21/presentation/ousterhout

[3] Montazeri's presentation at SIGCOMM18 (starts at 1:22)
https://www.youtube.com/watch?v=o_sg1nnN2bQ&t=4927s
https://conferences.sigcomm.org/sigcomm/2018/files/slides/paper_4.4.pptx

[4] Homa Linux kernel module implementation
https://github.com/PlatformLab/HomaModule

[5] Montazeri's PhD dissertation
http://purl.stanford.edu/sp122ms2496

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