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Can the Linux networking stack be used with very high speed applications?

SEPTEMBER 2022

Introduction

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Set out to answer a fundamental question:

How does the Linux networking stack scale as the line rate increases?

Stated another way: **When 400G and 800G become common, will the S/W be ready?**

- Get out in front on what is needed and start working on solutions
- Changes to Linux take time - way too much time (e.g., XDP H/W hints)

Scale "**up**" (pushing a single flow to line rate) is as important as scale "**out**" (multiple flows to reach line rate)

- e.g, Machine Learning apps

Created a custom setup to investigate what is needed to scale S/W to higher line rates

- Able to push a single flow to over ~~670~~ 782 Gbps and more than 31M pps

Test Setup

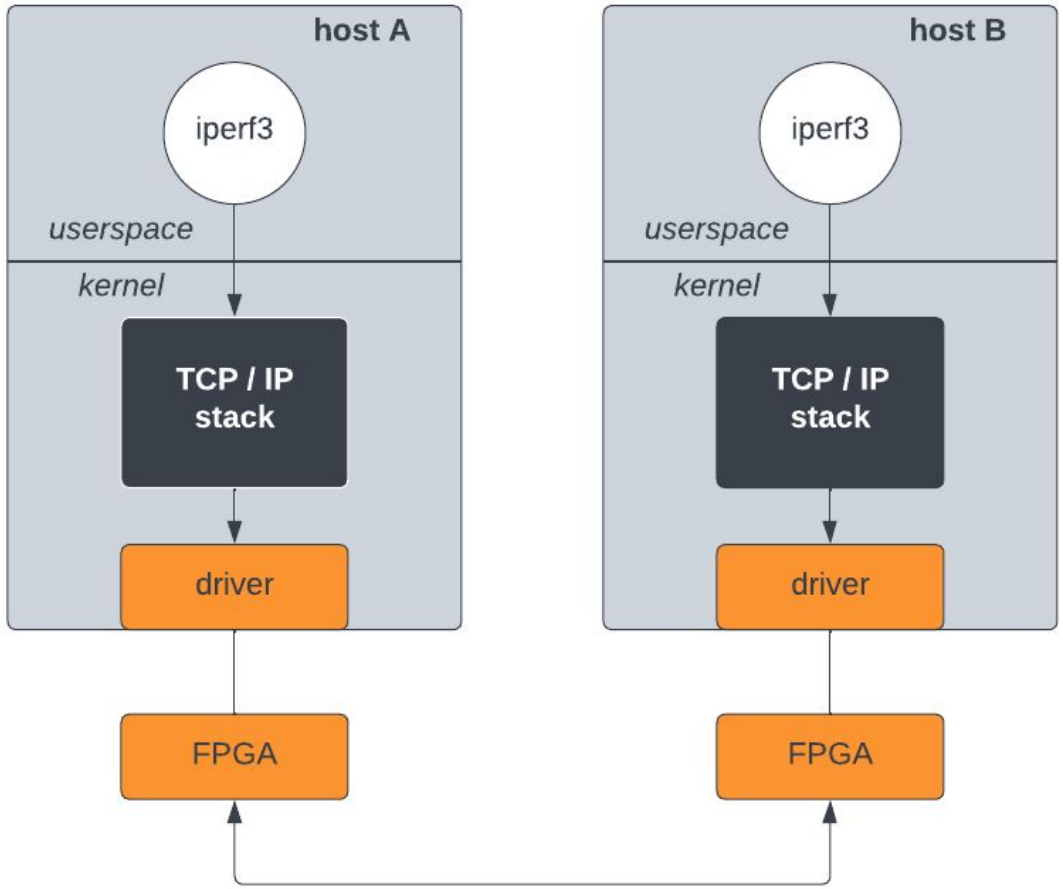
Off-the-shelf servers

Ryzen 9 Zen 3 cpu (5950x 16-core), 5GHz
128GB, DDR4, 3200 MT/s

Ubuntu 20.04 OS

Unmodified 5.13.19 kernel

Xilinx FPGA - VCU1525



Getting Around Current Physical Limits

PCI gen3 x16 (128 Gbps cap)

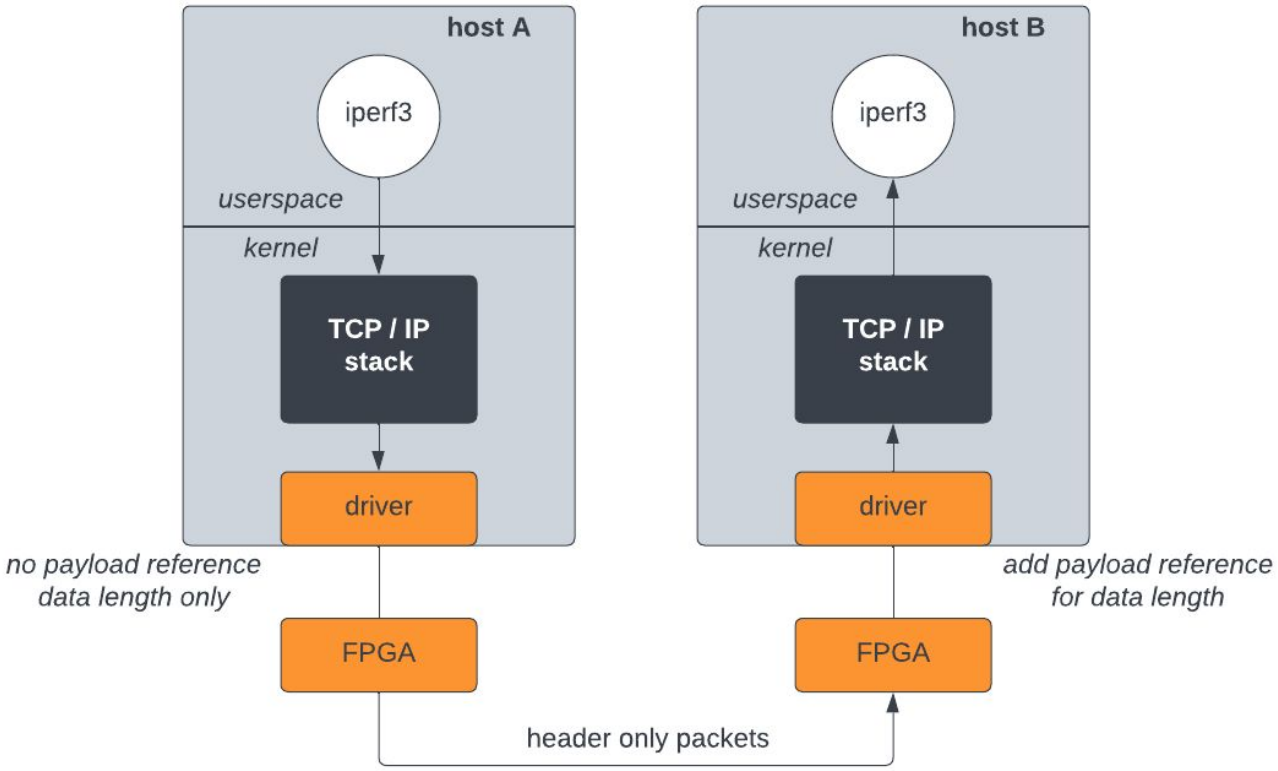
2 QSFP28 100Gbps interfaces

Idea: Payload in benchmark app is meaningless. Why send it?

- Drop payload over the wire

Key Point: **Software stack sees actual packet size and rate that TCP wants to send**

No modification to kernel. Payload games confined to driver and FPGA user logic



Zerocopy / Direct Data Placement

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memcpy - never going to happen

- Speed limited to ~30Gbps with memcpy
- ZC / DDP type scheme is a requirement for high speed networking

Existing Linux Zerocopy APIs

- **Tx**: fairly easy to use, but has its overhead
  get_user_pages (and variants) plus reaping completions (recvmsg syscalls)

- **Rx**: very limited and tricky to use
  Requires a specific MTU size and header split such that payloads are exactly PAGE_SIZE
  Side band with memcpy for data less than PAGE_SIZE

Key Point: **Modern workloads need hardware to land data in application buffers**

Modified iperf3 to avoid memcpy

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TX: Added support for ZC API (--zc_api option)

- Good enough for these tests to show intent - avoiding memcpy from userspace
- Extra CPU cycles for page pinning and completions is a factor, but not limiting one

Rx ZC API is too limiting and not usable for generic testing

Mimic **intent** of ZC API on Rx by dropping data

- --rx_drop option to iperf3 to use MSG_TRUNC with recvmsg
- Packets and data traverse networking stack as usual, attach to socket, process wakeup
- MSG_TRUNC drops payload to avoid memcpy to userspace

Net result is avoiding memcpy while still using existing socket APIs

Memory Management

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400G at 4096 L2 MTU = 12+M pages per second

- Actual number depends on MTU and how S/W and H/W handle posted buffers

FPGA driver managed pages for packets similar to other high speed NIC drivers

- Page per packet to keep it simple across MTUs
- Max pps in tests 31+M pps means 31+M pages per second handled by driver
- Even split page for 1500 MTU means 16.5M pages per second

Avoid system page allocators

- Page pool infrastructure as the base layer
- Driver managed per-cpu cache on top (preferred allocation if available)

skb recycling via napi cache

- Use napi_build_skb over build_skb

Key Point: **Current buffer management scheme has too much overhead**

Reducing Packet Rate Handled by S/W

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Amortize S/W stack overhead with more data per packet

- FIB lookup, socket lookup, tc and netfilter hooks, etc

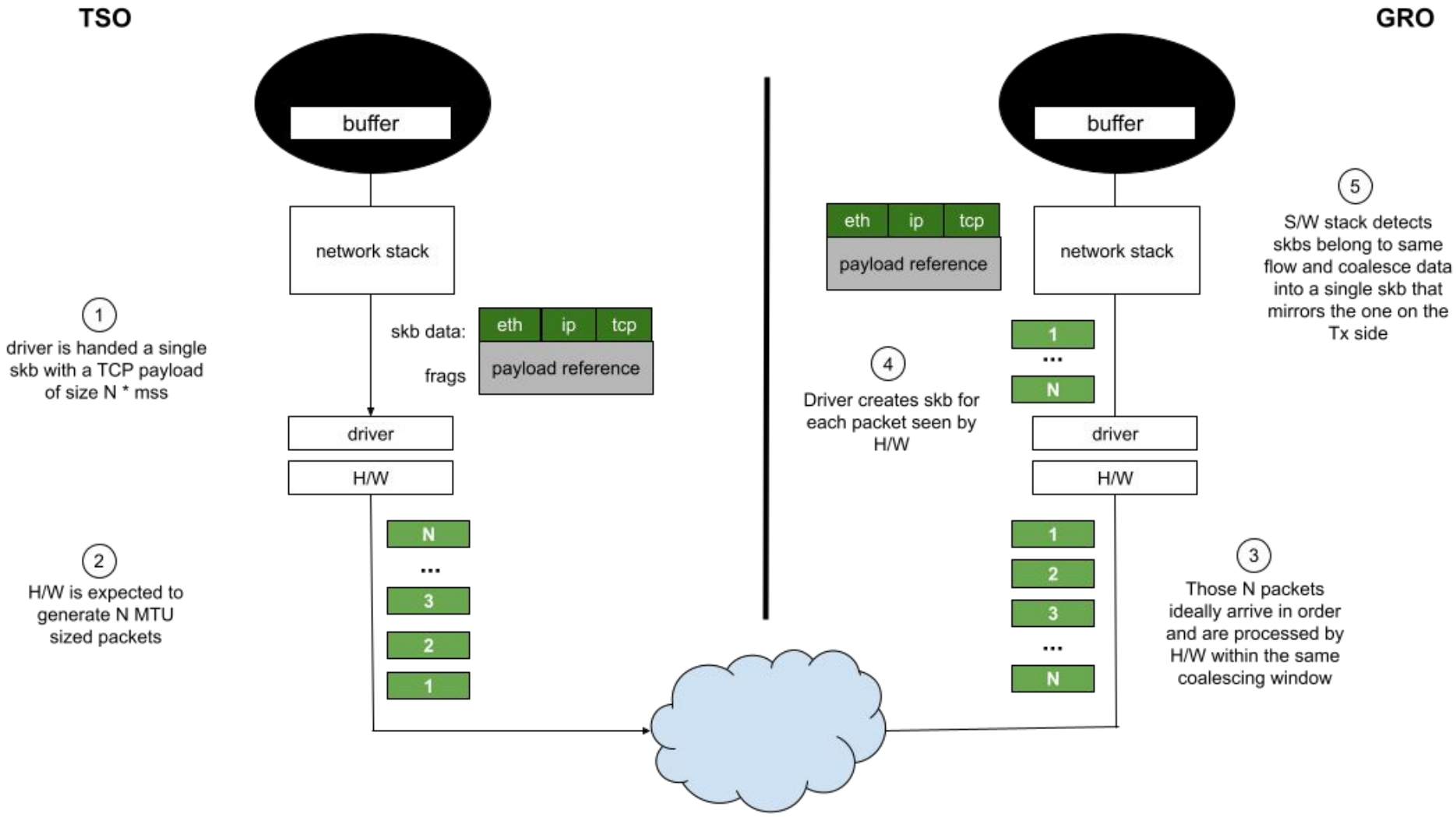
MTU

- More payload per packet on the wire

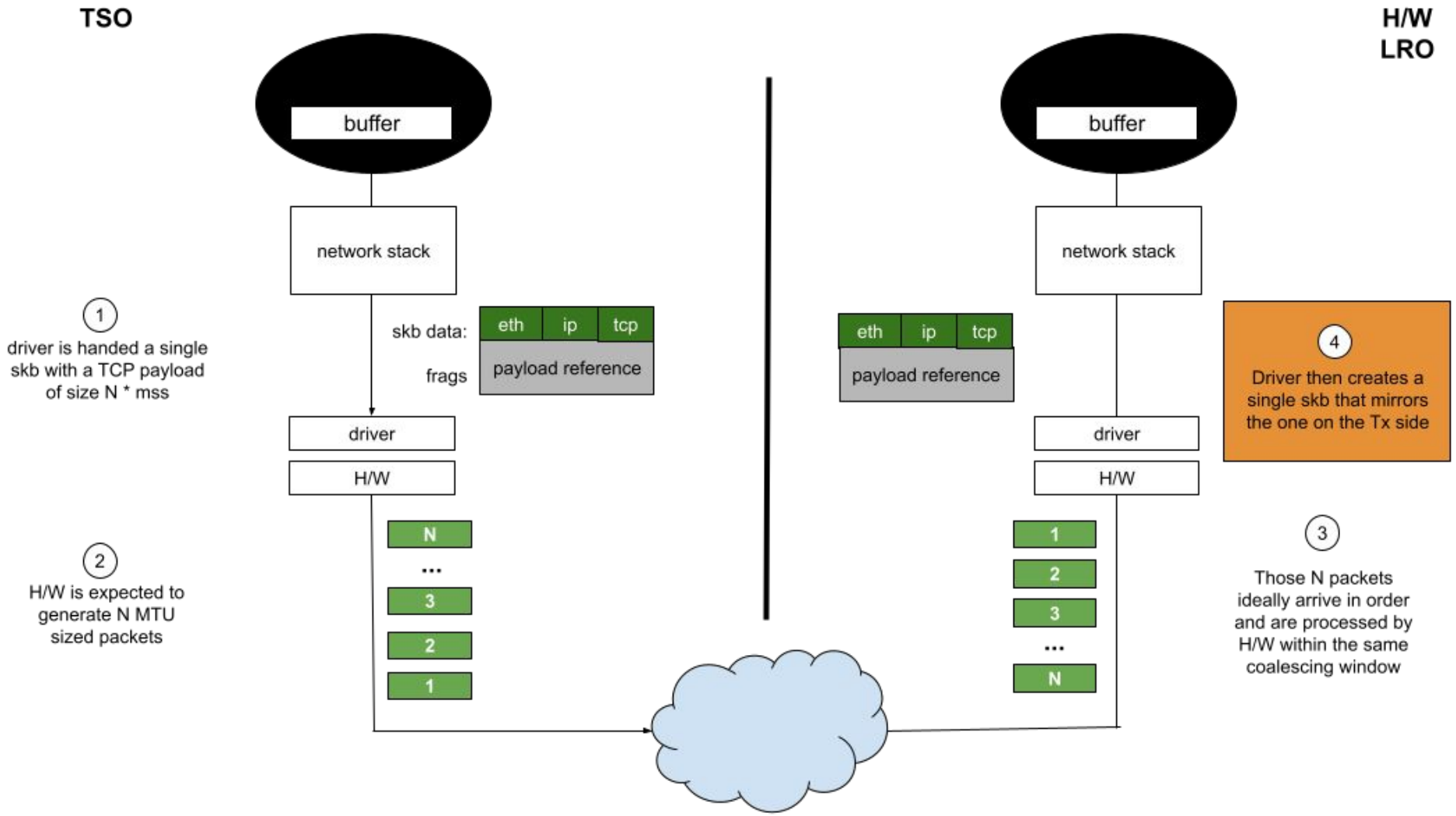
TSO into S/W GRO or H/W LRO

- Goal is pushing effective MTU seen by S/W up to 64kB

TSO -> S/W GRO



TSO -> H/W LRO



Data Rates on the Wire with TSO/*RO

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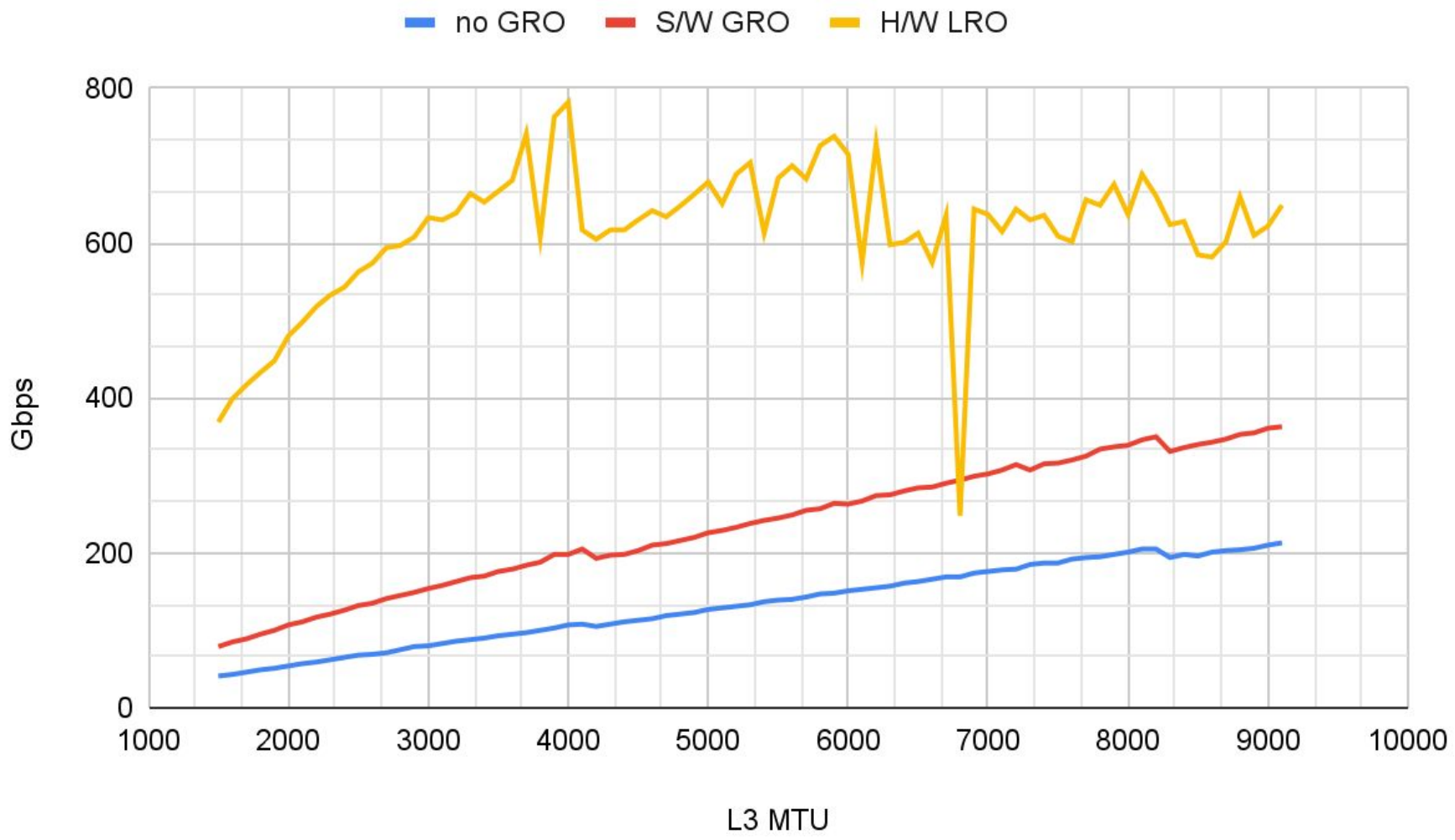
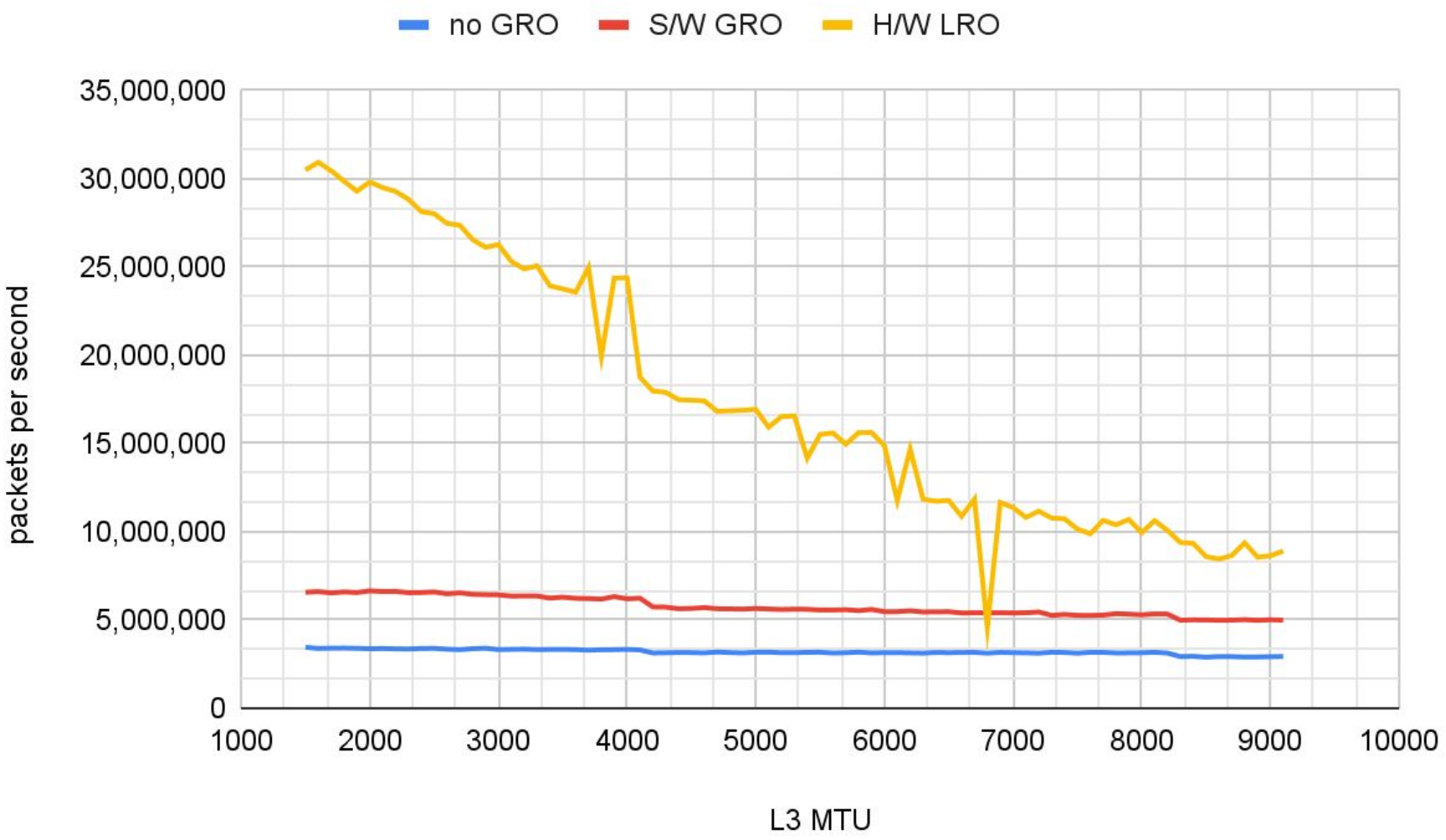
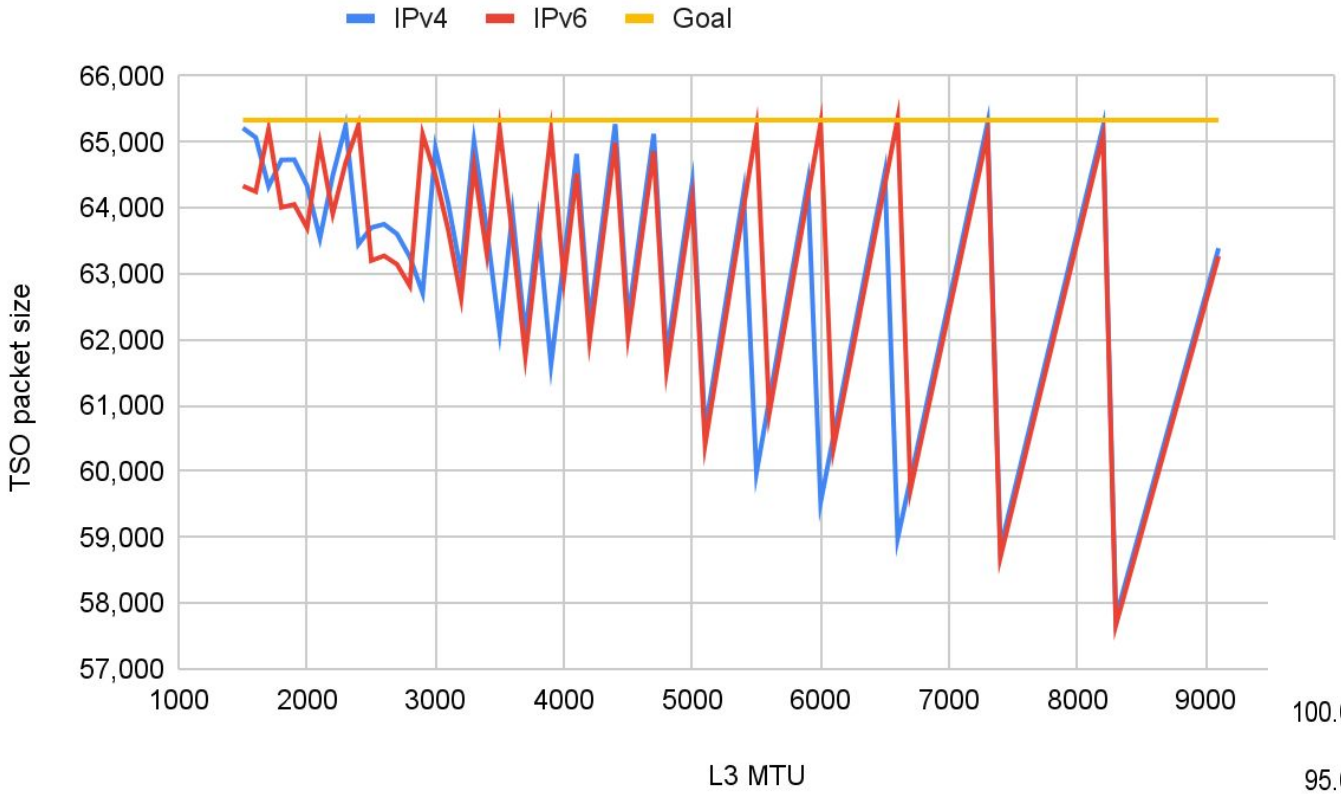
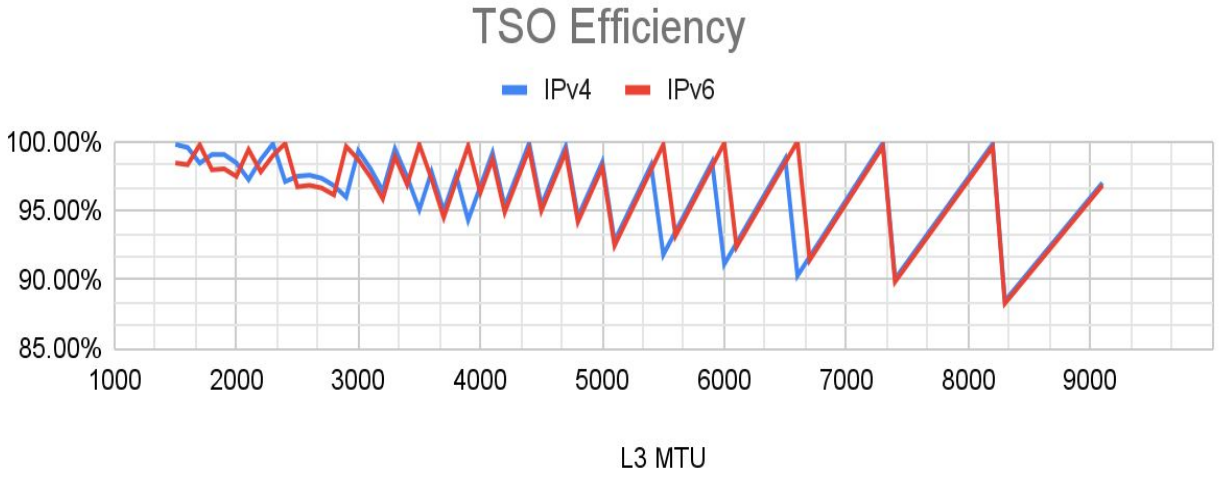


Packet Rate on the Wire with TSO/*RO



MTU / TSO Trade-off





Reducing Packet Rate Handled by S/W

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non-GRO/LRO case shows maximum pps for S/W stack: ~3M pps

- increasing MTU alone is insufficient

MTU affects TSO goal which affects S/W packet rate

GRO helps but S/W analysis of packet headers wastes CPU cycles

LRO:

- @1500 MTU: 31.7M pps on the wire -> 720k pps into software stack
- @9100 MTU: 8.3M pps on the wire -> 1.2M pps into software stack

Key Point: **Need a solid, robust H/W based LRO scheme to scale up**

Socket Buffers and Syscalls

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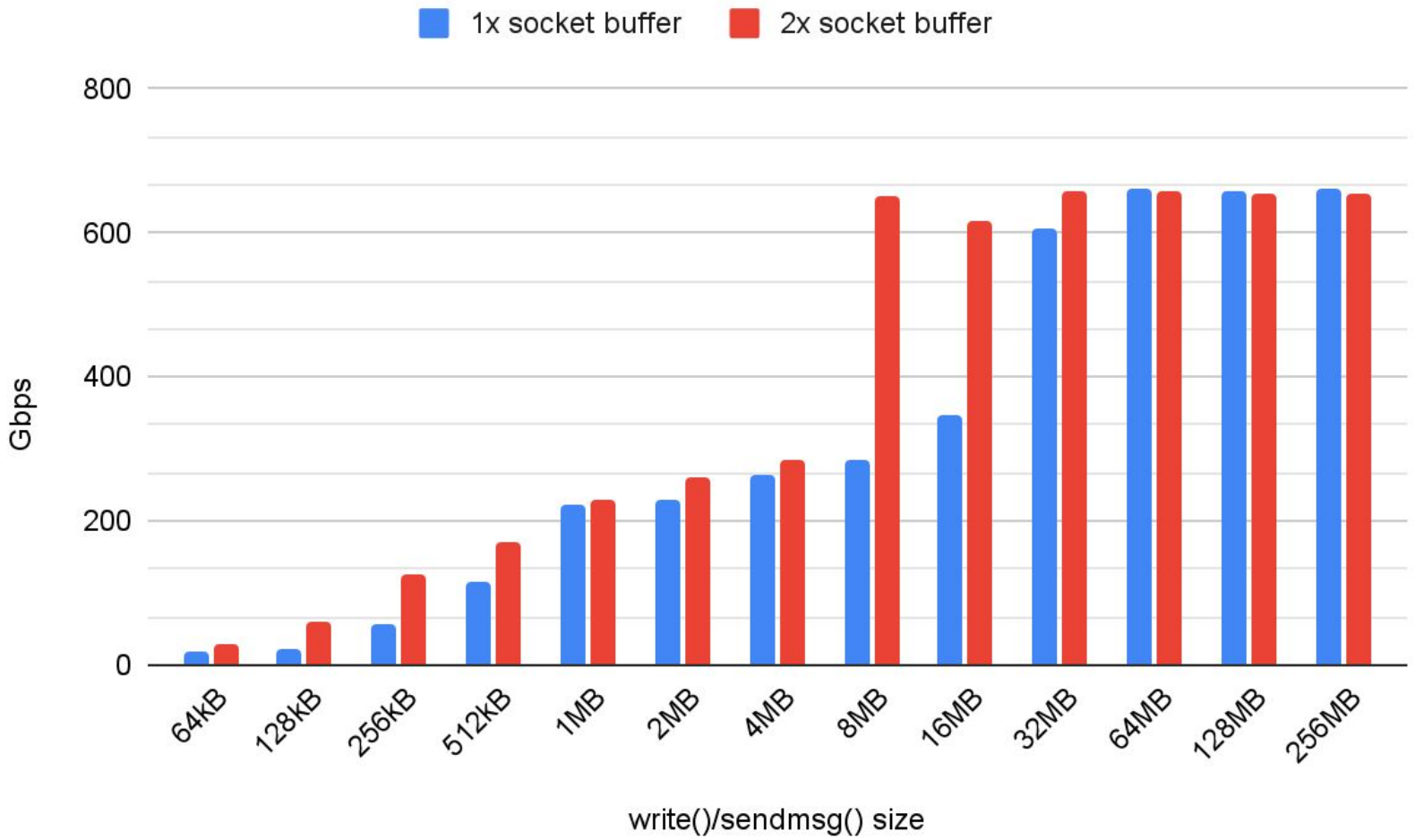
Keep the Tx pipeline primed

Reduce the overhead of using sockets to get data to/from H/W

More data per recvmsg /sendmsg syscall

More data queued up in socket buffers

-l and -w args to iperf3



Socket Buffers and Syscalls

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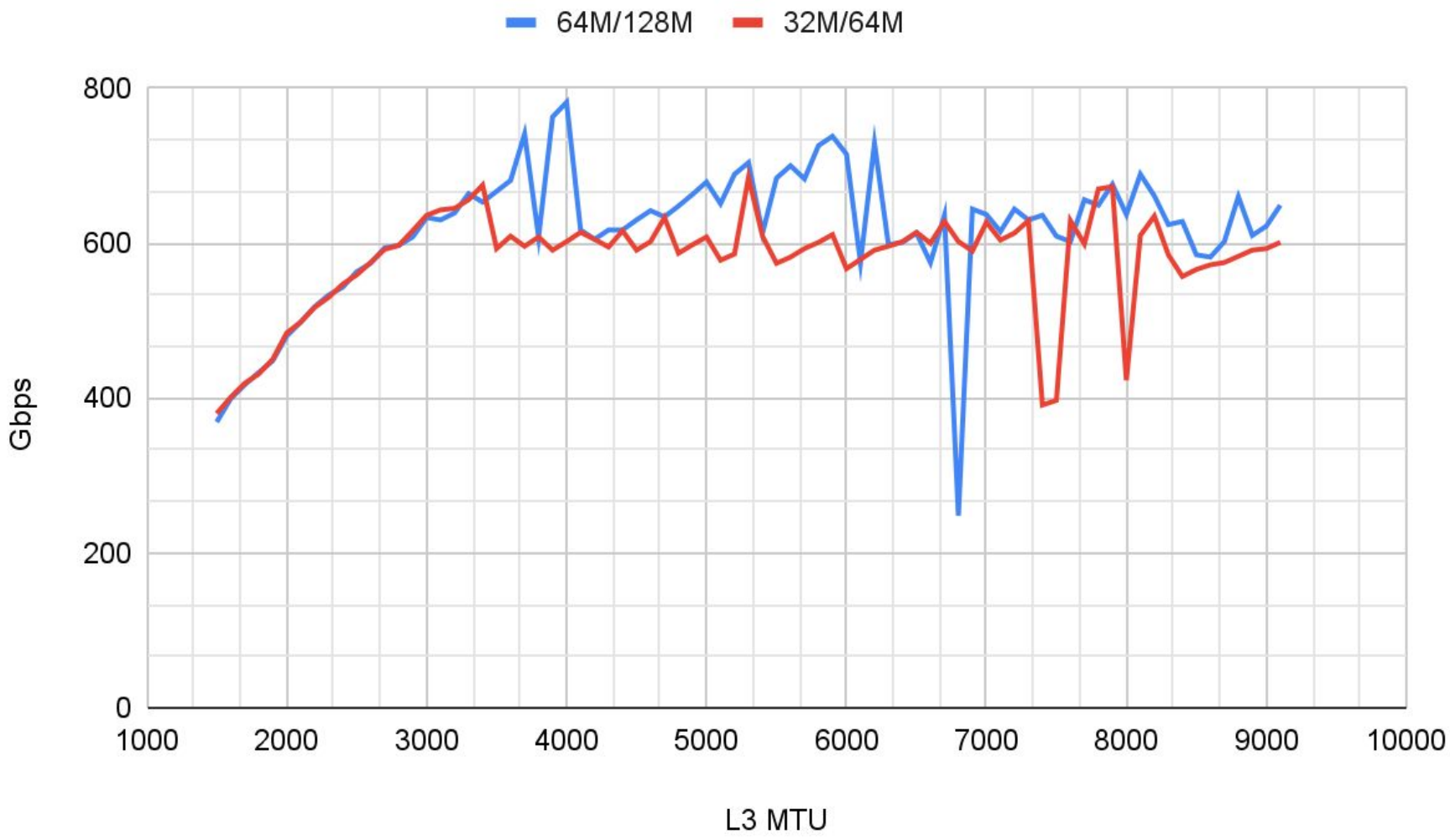
Comparison of 64M per read/write, 128M socket buffer vs 32M per read/write, 64M socket buffer

Key Point: **Need to manage datapath without system calls**

- io_uring does this via user-kernel queues, but it too is not sufficient



Hugepages

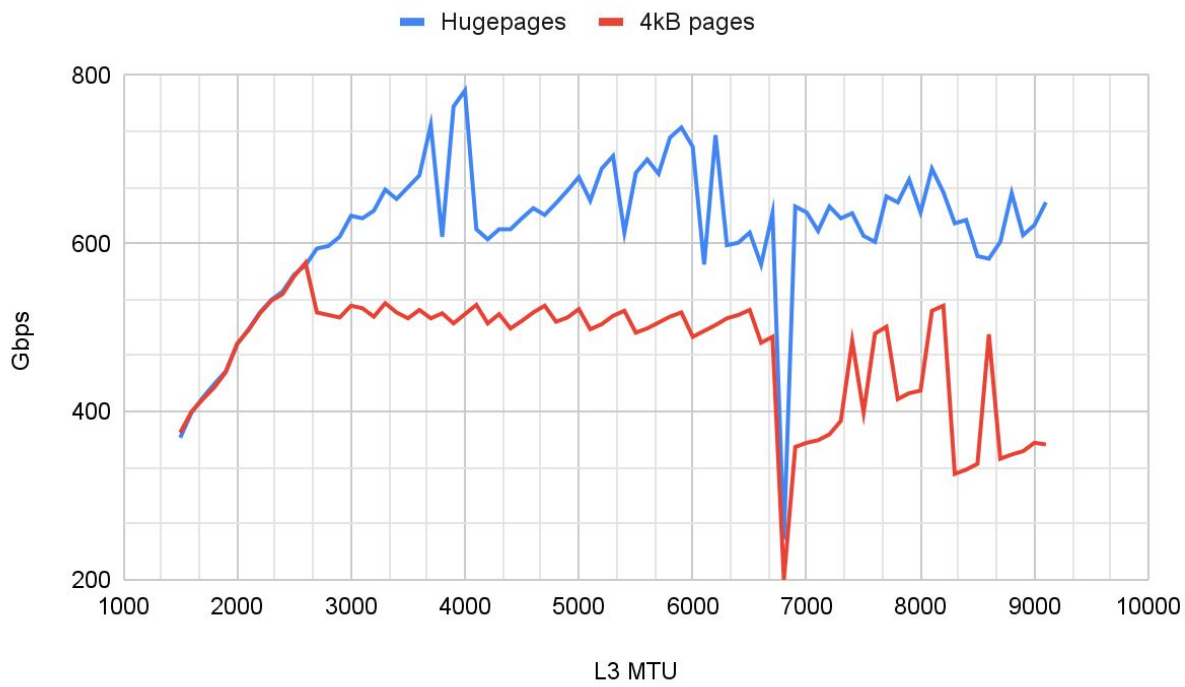
Tx ZC API iov is passed to driver and then H/W

- 4kB page size = 17 fragments per TSO skb
- 2MB hugepage = 2-3 fragments per skb
- non-ZC path for TCP has 2-3 fragments per skb

More fragments per skb == more overhead

- internal_get_user_pages_fast and skb_release_data become prominent in perf profiles

Key Point: **Reduce the overhead of the buffer representation going through the networking stack.**



Congestion Control Algorithm

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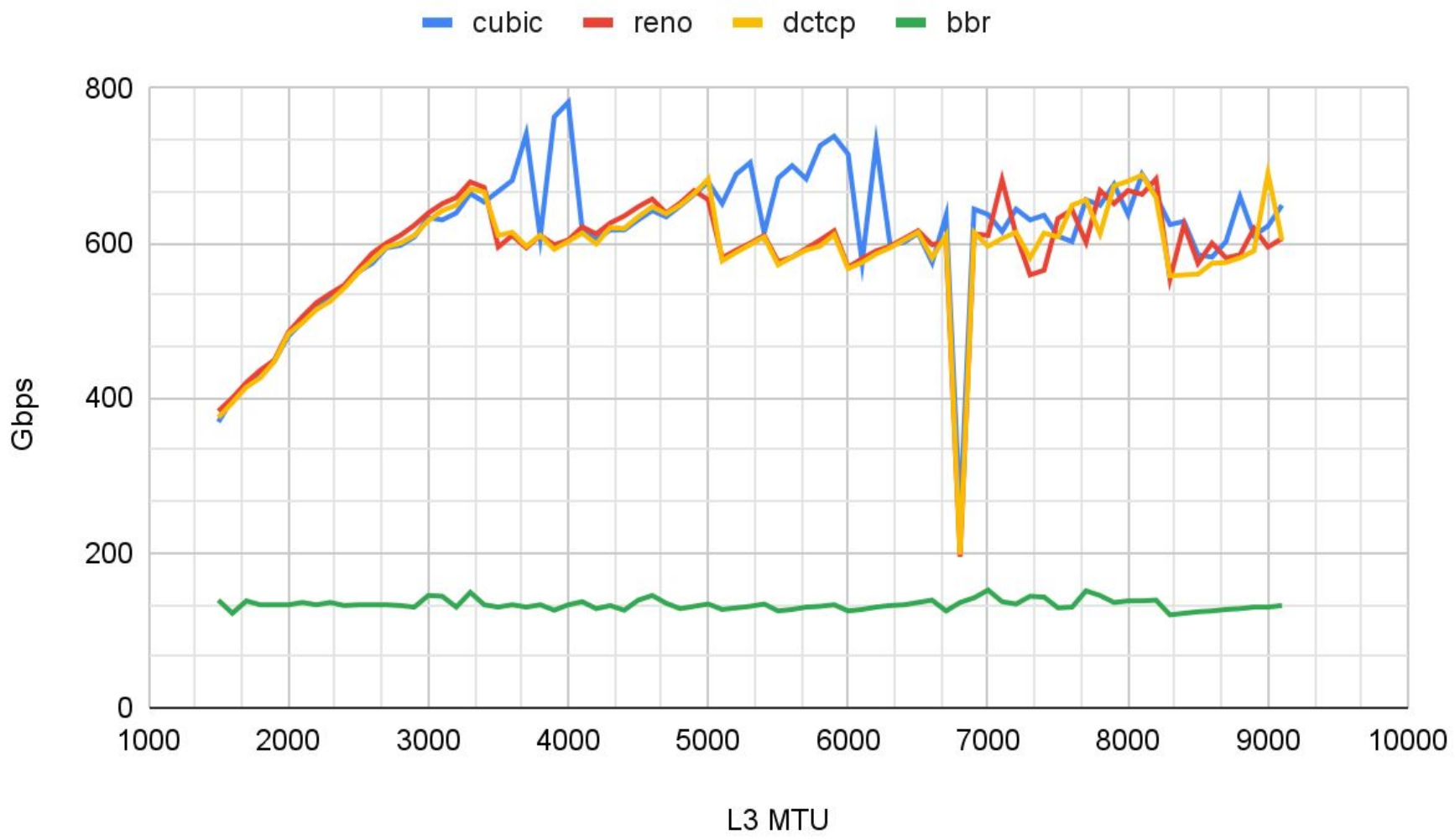

Hardware Considerations - CPU

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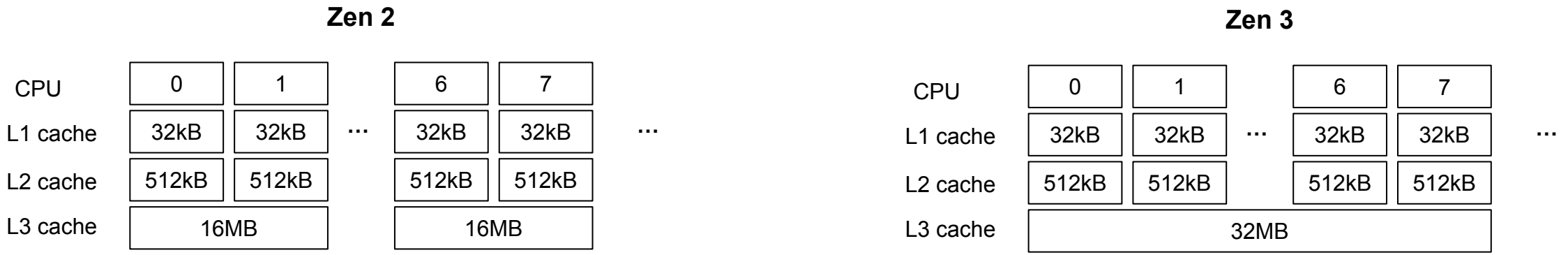
Speed is important

- CPU bound processing packets

L3 cache and task placement

- packet processing and application need to share L3 cache
- pinning means disabling irqbalance (static configuration)
- some CPU architectures make that more difficult



Hardware Considerations

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Memory Speed

- Epyc based servers with memory speed from 2400 MT/s to 3200 MT/s
- Ryzen servers with 3200 MT/s
- Populate ALL slots

NIC - bumped ring size of 8192

- irq driven system - too many packets land before irq handler runs
- See drops today with 200G nics and 4096 ring size

Scale Out

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VCU 1525 has 2 MACs

Isolated resources - task placement, device queues

- 700+ Gbps for each of 2 streams (750G on one, 750G on the other) at 4000 MTU

Kernel Regressions

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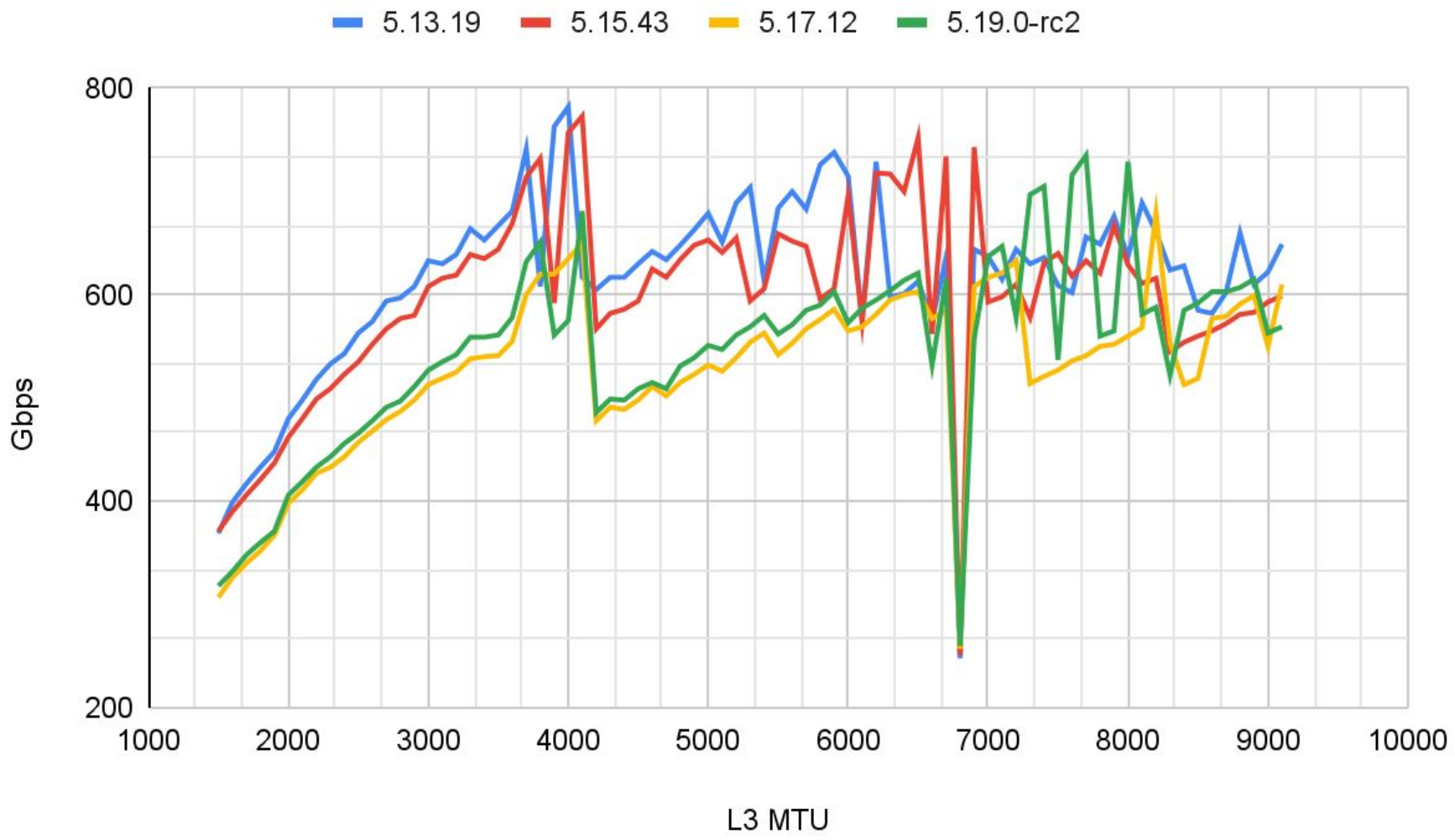

Misc. Tidbits

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Ubuntu based systems: Disable CONFIG_INIT_ON_ALLOC_DEFAULT_ON

- page clearing on alloc is cpu intensive (i.e., performance killer)

Be weary of SMIs

Any packet socket running on the system kills performance

- e.g., tcpdump, lldpd
- all packets are cloned

Key Point: **Application wanting high performance can be impacted by random events**

Summary

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Linux TCP stack can scale to high bit rates, but bottlenecks with socket API need to be removed

Must have a scheme where hardware places packet payload directly in application buffers

Better memory / buffer management scheme

Must have a solid LRO scheme from H/W - S/W GRO will not cut it

Reduce / Eliminate system calls

Simpler representation of application memory in skb as it traverses the networking stack

Resource isolation allows scale out and up

Followup

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Be sure to catch the next talk at netdev 0x16

Thank You

Results with ConnectX-6

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