



Network stack challenges at increasing speeds

The 100Gbit/s challenge

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Overview

- **Understand** 100Gbit/s challenge and time budget
 - Measurements: understand the costs in the stack?
- **Recent** accepted changes
 - TX bulking, xmit_more and qdisc dequeue bulk
- **Future** work needed
 - RX, qdisc, MM-layer
- **Memory** allocator limitations
 - Qmempool: Lock-Free bulk alloc and free scheme
 - Extending SLUB with bulk API



Coming soon: 100 Gbit/s

- Increasing network speeds: 10G -> 40G -> 100G
 - challenge the network stack
- Rate increase, time between packets get smaller
 - Frame size 1538 bytes (MTU incl. Ethernet overhead)
 - at **10Gbit/s == 1230.4 ns** between packets (815Kpps)
 - at **40Gbit/s == 307.6 ns** between packets (3.26Mpps)
 - at **100Gbit/s == 123.0 ns** between packets (8.15Mpps)
- Time used in network stack
 - need to be smaller to keep up at these increasing rates



Pour-mans solution to 100Gbit/s

- Don't have 100Gbit/s NICs yet?
 - No problem: use 10Gbit/s NICs with smaller frames
- Smallest frame size 84 bytes (due to Ethernet overhead)
 - at 10Gbit/s == **67.2 ns** between packets (14.88Mpps)
- How much CPU budget is this?
 - Approx **201 CPU cycles** on a 3GHz CPU
 - Approx 269 CPU cycles on a 4GHz CPU



Is this possible with hardware?

- Out-of-tree network stack bypass solutions
 - Grown over recent years
 - Like netmap, PF_RING/DNA, DPDK, PacketShader, OpenOnload, RDMA/IBverbs etc.
- Have shown kernel is not using HW optimally
 - On same hardware platform
 - (With artificial network benchmarks)
 - Hardware can forward 10Gbit/s wirespeed smallest packet
 - On a **single CPU !!!**



Single core performance

- Linux kernel have been scaling with number of cores
 - hides regressions for per core efficiency
 - latency sensitive workloads have been affected
- We need to increase/improve efficiency per core
 - IP-forward test, single CPU only 1-2Mpps (1000-500ns)
 - Bypass alternatives handle 14.8Mpps per core (67ns)
 - although this is like comparing apples and bananas



Understand: nanosec time scale

- This time scale is crazy!
 - $67.2\text{ns} \Rightarrow 201$ cycles (@3GHz)
- Important to understand time scale
 - Relate this to other time measurements
- Next measurements done on
 - Intel CPU E5-2630
 - Unless explicitly stated otherwise



Time-scale: cache-misses

- A single cache-miss takes: **32 ns**
 - Two misses: $2 \times 32 = 64 \text{ ns}$
 - almost total 67.2 ns budget is gone
- Linux skb (sk_buff) is 4 cache-lines (on 64-bit)
 - writes zeros to these cache-lines, during alloc.
 - usually cache hot, so not full miss



Time-scale: cache-references

- Usually not a full cache-miss
 - memory usually available in L2 or L3 cache
 - SKB usually hot, but likely in L2 or L3 cache.
- CPU E5-xx can map packets directly into L3 cache
 - Intel calls this: Data Direct I/O (DDIO) or DCA
- Measured on E5-2630 (lmbench command "lat_mem_rd 1024 128")
 - L2 access costs **4.3ns**
 - L3 access costs **7.9ns**
 - This is a usable time scale



Time-scale: "LOCK" operation

- Assembler instructions "LOCK" prefix
 - for atomic operations like locks/cmpxchg/atomic_inc
 - some instructions implicit LOCK prefixed, like xchg
- Measured cost
 - atomic "LOCK" operation costs **8.23ns** (E5-2630)
 - Between **17-19 cycles** (3 different CPUs)
- Optimal spinlock usage lock+unlock (same single CPU)
 - Measured spinlock+unlock calls costs **16.1ns**
 - Between 34-39 cycles (3 different CPUs)



Time-scale: System call overhead

- Userspace syscall overhead is large
 - (Note measured on E5-2695v2)
 - Default with SELINUX/audit-syscall: 75.34 ns
 - Disabled audit-syscall: **41.85 ns**
- Large chunk of 67.2ns budget
- Some syscalls already exists to amortize cost
 - By sending several packet in a single syscall
 - See: [sendmmsg\(2\)](#) and [recvmmsg\(2\)](#) notice the extra "m"
 - See: [sendfile\(2\)](#) and [writev\(2\)](#)
 - See: [mmap\(2\)](#) tricks and [splice\(2\)](#)



Time-scale: Sync mechanisms

- Knowing the cost of basic sync mechanisms
 - Micro benchmark in tight loop
- **Measurements** on CPU E5-2695
 - `spin_{lock,unlock}`: 34 cycles(tsc) 13.943 ns
 - `local_BH_{disable,enable}`: 18 cycles(tsc) 7.410 ns
 - `local_IRQ_{disable,enable}`: 7 cycles(tsc) 2.860 ns
 - `local_IRQ_{save,restore}`: 37 cycles(tsc) 14.837 ns



Main tools of the trade

- Out-of-tree network stack bypass solutions
 - Like netmap, PF_RING/DNA, DPDK, PacketShader, OpenOnload, RDMA/Ibverbs, etc.
- How did others manage this in 67.2ns?
 - General tools of the trade is:
 - batching, preallocation, prefetching,
 - staying cpu/numa local, avoid locking,
 - shrink meta data to a minimum, reduce syscalls,
 - faster cache-optimal data structures
 - lower instruction-cache misses



Batching is a fundamental tool

- Challenge: Per packet processing cost overhead
 - Use batching/bulking opportunities
 - Where it makes sense
 - Possible at *many different levels*
- Simple example:
 - E.g. working on batch of packets amortize cost
 - Locking per packet, cost $2 \times 8\text{ns} = 16\text{ns}$
 - Batch processing while holding lock, amortize cost
 - Batch 16 packets amortized lock cost 1ns



Recent changes

What have been done recently



Unlocked Driver TX potential

- Pktgen 14.8Mpps single core (10G wirespeed)
 - Spinning same SKB (no mem allocs)
- Primary trick: *Bulking packet (descriptors) to HW*
- What is going on:
 - Defer tailptr write, which notifies HW
 - Very expensive write to non-cacheable mem
 - Hard to perf profile
 - Write to device
 - does not showup at MMIO point
 - Next LOCK op is likely “blamed”



API `skb->xmit_more`

- SKB extended with `xmit_more` indicator
 - Stack use this to indicate (to driver)
 - another packet will be given immediately
 - After/when `->ndo_start_xmit()` returns
- Driver usage
 - Unless TX queue filled
 - Simply add the packet to HW TX ring-queue
 - And defer the expensive indication to the HW



Challenge: Bulking without added latency

- Hard part:
 - **Use bulk API without adding latency**
- Principal: Only bulk when really needed
 - Based on solid indication from stack
- Do NOT speculative delay TX
 - Don't bet on packets arriving shortly
 - Hard to resist...
 - as benchmarking would look good



Use SKB lists for bulking

- Changed: Stack xmit layer
 - Adjusted to work with SKB lists
 - Simply use existing `skb->next` ptr
- E.g. See `dev_hard_start_xmit()`
 - `skb->next` ptr simply used as `xmit_more` indication
- Lock amortization
 - TXQ lock no-longer per packet cost
 - `dev_hard_start_xmit()` send entire SKB list
 - while holding TXQ lock (`HARD_TX_LOCK`)



Existing aggregation in stack GRO/GSO

- Stack already have packet aggregation facilities
 - GRO (Generic Receive Offload)
 - GSO (Generic Segmentation Offload)
 - TSO (TCP Segmentation Offload)
- Allowing bulking of these
 - Introduce no added latency
- Xmit layer adjustments allowed this
 - `validate_xmit_skb()` handles segmentation if needed



Qdisc layer bulk dequeue

- A queue in a qdisc
 - Very solid opportunity for bulking
 - Already delayed, easy to construct skb-list
- Rare case of reducing latency
 - Decreasing cost of dequeue (locks) and HW TX
 - Before: a per packet cost
 - Now: cost amortized over packets
- Qdisc locking have extra locking cost
 - Due to `__QDISC___STATE_RUNNING` state
 - Only single CPU run in dequeue (per qdisc)



Qdisc path overhead

- Qdisc code path takes 6 LOCK ops
 - LOCK cost on this arch: approx 8 ns
 - $8 \text{ ns} * 6 \text{ LOCK-ops} = 48 \text{ ns}$ pure lock overhead
- Measured qdisc overhead: between 58ns to 68ns
 - 58ns: via `trafgen -qdisc-path bypass` feature
 - 68ns: via `ifconfig txlength 0 qdisc NULL` hack
 - Thus, using between 70-82% on LOCK ops
- Dequeue side lock cost, now amortized
 - But only in-case of a queue
 - Empty queue, `direct_xmit` still see this cost
 - Enqueue still per packet locking



Qdisc locking is nasty

- Always **6 LOCK** operations ($6 * 8\text{ns} = 48\text{ns}$)
 - **Lock** qdisc(root_lock) (also for direct xmit case)
 - Enqueue + possible Dequeue
 - Enqueue can exit if other CPU is running deq
 - Dequeue takes `__QDISC__STATE_RUNNING`
 - **Unlock** qdisc(root_lock)
 - **Lock** TXQ
 - Xmit to HW
 - **Unlock** TXQ
 - **Lock** qdisc(root_lock) (can release STATE_RUNNING)
 - Check for more/newly enqueued pkts
 - Softirq reschedule (if quota or need_sched)
 - **Unlock** qdisc(root_lock)



Qdisc TX bulking require BQL

- Only support qdisc bulking for BQL drivers
 - *Implement BQL in your driver now!*
- Needed to avoid overshooting NIC capacity
 - Overshooting cause requeue of packets
- Current qdisc layer requeue cause
 - Head-of-Line blocking
 - Future: better requeue in individual qdiscs?
- Extensive experiments show
 - BQL is very good at limiting requeues



FIB lookup

- IP-forwarding route lookup
 - FIB lookup (were) most expensive component
 - Alex Duyck improved this recently!



Future work

- What need to be worked on?
- Taking advantage of TX capabilities
- Current stack limited by
 - Userspace syscall overhead (amortize)
 - Qdisc “baseline” overhead
 - RX performance/limitations (DMA or mem alloc limits?)
 - Memory allocator, hitting slowpath
 - Instruction cache misses, forward case



Future: Lockless qdisc

- Motivation for lockless qdisc (cmpxchg based)
 - 1) Direct xmit case (qdisc len==0) “fast-path”
 - Still requires taking all 6 locks!
 - 2) Enqueue cost reduced (qdisc len > 0)
 - from 16ns to 10ns
- Measurement show huge potential for saving
 - (lockless ring queue cmpxchg base implementation)
 - If TCQ_F_CAN_BYPASS saving 58ns
 - Difficult to implement 100% correct
 - Not allowing direct xmit case: saving 48ns



What about RX?

- TX looks good now
 - How do we fix RX?
- Experiments show
 - Forward test, single CPU only 1-2Mpps
 - Highly tuned setup RX max 6.5Mpps (Early drop)
- Alexie started optimizing the RX path
 - from 6.5 Mpps to 9.4 Mpps
 - via `build_skb()` and `skb->data` prefetch tuning
 - Early drop, don't show real mem alloc interaction



Instruction Cache misses

- Packet forward case
 - Too slow, when calc/add components
 - 2Mpps → 500ns
 - Profiling shows many inst-cache misses
 - Better fwd performance with new GCC compilers
 - Measured factor x10 reduced icache-misses
 - Code level icache optimizations
 - Driver bulking on RX
 - Small RX queue, before activating stack call loop



Memory Allocator limitations

- Artificial RX benchmarking
 - Drop packets early
 - Don't see limitations of mem alloc
- Real network stack usage, hurts allocator
 - 1) RX-poll alloc up-to 64 packets (SKBs)
 - 2) TX put packets into TX ring
 - 3) Wait for TX completion, free up-to 256 SKBs
- Cause IP-forward to hit “slowpath” for SLUB



Micro benchmark: kmem_cache

- Micro benchmarking code execution time
 - kmem_cache with SLUB allocator
- Fast reuse of same element with SLUB allocator
 - Hitting reuse, per CPU lockless fastpath
 - kmem_cache_alloc+kmem_cache_free = 19ns
 - **42-48 cycles(tsc)**
- Pattern of 256 alloc + 256 free (Based on ixgbe cleanup pattern)
 - Cost increase to: 40ns
 - **88-105 cycles**



MM: Derived MM-cost via pktgen

- Hack: Implemented SKB recycling in pktgen
 - But touch all usual data+skb areas, incl. zeroing
- Recycling only works for dummy0 device:
 - No recycling: 3,301,677 pkts/sec = 303 ns
 - With recycle: 4,424,828 pkts/sec = 226 ns
- Thus, the derived Memory Manager cost
 - alloc+free overhead is (303 - 226): **77ns**
 - Slower than expected, should have hit slub fast-path
 - SKB->data **page** is likely costing more than SLAB



MM: Memory Manager overhead

- SKB Memory Manager overhead
 - kmem_cache: between 19ns to 40ns
 - Between: 42-105 cycles
 - pktgen fastpath recycle derived: 77ns
 - $(77-19) = 58\text{ns}$ data/page + “touch” overhead?
 - Larger than our time budget: 67.2ns
- Thus, for our performance needs
 - Either, MM area needs improvements
 - Or need some alternative faster mempool



Qmempool: Faster caching of SKBs

- Last NFWS2014 qmempool was only an idea
- Implemented qmempool
 - Lock-Free bulk alloc and free scheme
 - Backed by `alf_queue`
- Practical network **measurements** show
 - saves 12 ns on "fast-path" drop in iptables "raw" table
 - saves 40 ns with IP-forwarding
 - Forwarding hits slower SLUB use-case



Qmempool: Micro benchmarking

- Micro benchmarked against SLUB
 - Cost of alloc+free (CPU i7-4790K @4GHz)
- Fast-path: reuse-same element in loop
 - kmem_cache(slub): 42 cycles(tsc)
 - qmempool in softirq: 31 cycles(tsc)
 - qmempool BH-disable: 44 cycles(tsc)
- Slower-path: alloc 256-pattern before free:
 - kmem_cache(slub): 105 cycles(tsc)
 - qmempool BH-disable: 58 cycles(tsc)



Qmempool what is the secret?

- Why is qmempool so fast?
 - Primarily the bulk support of the Lock-Free queue
 - Sharedq MPMC bulk elems out with a single cmpxchg
 - thus, amortize the per elem cost
- Currently uses per CPU SPSC queue
 - requires no lock/atomic operations
 - could be made faster with a simpler per CPU stack



Alf_queue building block for qmempool

- The ALF (Array based Lock-Free) queue
 - (Basic building for qmempool)
 - Killer feature is bulking
 - Lock-Free ring buffer, but uses cmpxchg ("LOCK" prefixed)
 - Supports Multi/Single-Producer/Consumer combos.
 - Cache-line effect also amortize access cost
 - 8 pointers/elems per cache-line (on 64bit)
 - Pipeline optimized bulk enqueue/dequeue
 - (pipelining currently removed in upstream proposal, due to code size)
- Basically "just" an array of pointer used as a queue
 - with bulk optimized lockless access



Qmempool purpose: PoC

- Practical implementation, to find out:
 - if it was possible to be faster than `kmem_cache/slab`
- Provoke MM-people
 - To come up with something just-as-fast
 - Integrate ideas into MM-layer
 - Perhaps extend MM-layer with bulking
- Next: SLUB fastpath improvements
 - and potential booster shots through bulk alloc and free



Latest work: SLUB bulk faster than Qmempool

- Optimizing SLUB allocator ([patchset V2](#))
 - Bulk **alloc + free cost** (CPU i7-4790K @4GHz)
 - SLUB fastpath: 42 cycles(tsc) / slowpath: 105 cycles
 - Qmempool fastpath: 31 cycles / slowpath: 58 cycles
 - Hitting: fastpath of SLUB
 - SLUB bulk x1 → 44 cycles(tsc)
 - SLUB bulk x2 → 28 cycles(tsc)
 - SLUB bulk x4-16 → 19 – 18 cycles
 - Hitting: slowpath ... (net stack use-case)
 - SLUB bulk x32-64 → 50 – 65 cycles (WIP: 25 – 29 cycles)
 - SLUB bulk x128-250 → 86 – 98 cycles (WIP: 62 – 63 cycles)



Extra: pktgen stack bench

- Recent: pktgen inject packet into stack
 - Useful for localhost bench without HW
 - See script: [pktgen_bench_xmit_mode_netif_receive.sh](#)
 - Default usage mode: Very early ingress drop in ip_rcv()
 - 52,502,335pps → 19ns (spinning same SKB)
 - Usage: Measures SKB memory allocator performance
 - Param “-b 0” disable burst, same drop point
 - 7,206,871pps → 139ns (CPU i7-4790K @ 4.00GHz)
 - Difference: 120ns – too much other stuff
 - Pktgen own overhead 30% (approx 42ns)
 - 9.71% __build_skb (13.5ns)
 - 10.82% __netdev_alloc_skb+__{free,alloc}_page_frag (15ns)
 - 6.83% kmem_cache_alloc+free (9.5ns) → close to bench=10.814ns
 - 4.55% ktime_get_with_offset+read_tsc (6.3ns) → strange PTP module



Extra: Smarter clearing of SKBs

- Clearing SKB is expensive
 - `__build_skb()` 40% spend in memset
 - Translates into asm: `rep stos`
 - Startup cost 15 cycles
 - Suspect CPU stall/pipeline stall?
- Find smarter clearing or reduce SKB size?



Extra: cost of clear SKB

- SKB “clear” 200 Bytes, SLAB object 256 Bytes (CPU i7-4790K @ 4.00GHz)
 - Compiler optimizes memset, uses special instruction “rep stos”

Note	Bytes-to-clear	Cycles	Cycles per 256B
Hand-optimized	200	26	
Rep-stos	200	36	
Hand-optimized	256	32	
Rep-stos	256	43	
Below: rep-stos	512	72	36.00
3x 256	768	46	15.30
4x	1024	49	12.25
5x	1280	53	10.60
6x	1536	60	10.00
8x	2048	75	9.38
16x	4096	134	8.38
32x	8192	255	7.97



The End

- MM improvements work-in-progress
 - Cooperating with Christoph Lameter
- Any input on
 - network related challenges I missed?



Extra

- Extra slides



Extra: Comparing Apples and Bananas?

- Comparing Apples and Bananas?
 - Out-of-tree bypass solution focus/report
 - Layer2 “switch” performance numbers
 - Switching basically only involves:
 - Move page pointer from NIC RX ring to TX ring
 - Linux bridge
 - Involves:
 - Full SKB alloc/free
 - Several look ups
 - Almost as much as L3 forwarding



Using TSQ

- TCP Small Queue (TSQ)
 - Use queue build up in TSQ
 - To send a bulk xmit
 - To take advantage of HW TXQ tail ptr update
 - Should we allow/use
 - Qdisc bulk enqueue
 - Detecting qdisc is empty allowing `direct_xmit_bulk`?

