Latest Developments with NVMe/TCP

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NVMe-oF - Short Recap

- Early 2014: Initial NVMe/RDMA pre-standard prototypes
- Later 2014: NVMe-oF 1.0 standardization
- 2015: NVMe.org formed Fabrics Linux Driver Task Force
  - Converged on the starting point prototype
  - Developed from there on a main git repository
  - Heavy lifting of NVMe stack reorg contributed even before NVMe-oF support
- 2016 (Oct): NVMe over Fabrics support (host and target) merged into the Linux kernel (v4.8)
NVMe-oF - Since than...

- Hardening: various stability fixes
- Instrumentation: tracing support
- Additional transports: FC
- Tool chain enhancements:
  - `queue_size`, `nr_io_queues`, `hostnqn`, `hostid`, `reconnect_delay`, `ctrl_loss_tmo`, `kato`, `host_traddr`, `duplicate_connect` etc...
- Compliance: UUID support
- Enhancements: TCG Opal support, I/O Polling support, ANA support, etc..
NVMe-oF 1.1

- **Scope:**
  - NVMe/TCP
  - Dynamic Resource Enumeration
  - SQ flow control disabled mode
  - Traffic Based Keep Alive

- The Fabrics Linux Driver Task Force is developing the TPs to both drive the spec and provide early adoption for the proposed enhancements.
Why NVMe/TCP?

- Ubiquitous - runs on everything everywhere…
- Well understood - TCP is probably the most common transport.
- High performance - TCP delivers excellent performance scalability.
- Well suited for large scale deployments and longer distances
- Actively developed - maintenance and enhancements are developed by major players.
NVMe/TCP ratification

- Standard was ratified on Nov 15th, 2108
- Multi-vendor joint effort to ensure interoperability
- Designed for simplicity and efficiency
- First NVMe/TCP plugfest POC in UNH-IOL on Nov 12nd, 2018
Association Model

- Controller association maps 1x1 NVMe queue to a TCP connection
  - No controller-wide sequencing
  - No controller-wide reassembly constraints

- Connection binding is performed in NVMe-oF connect time (binding queue to controller)
Protocol Data Unit

- NVMe-oF Capsules and Data are encapsulated in PDUs
- PDU structure varies per PDU type
  - 8-byte Common Header
  - Variable length PDU specific header
- PDUs optionally contain Header and/or Data digest protection
- PDUs contain optional PAD used for alignment enhancements
PDU Types

- ICReq/ICResp: Connection Initialization PDUs
- H2CTermReq/C2HTermReq: Connection Termination PDUs (only for error flow)
- CapsuleCmd/CapsuleResp: NVMe-oF Command and Response Capsule PDUs
- H2CData/C2HData: Unidirectional Data PDUs
- R2T: Ready to Transfer PDU (solicit H2CData)
I/O flow

- Host to Controller data can come in-capsule (if the controller supports it) or in a solicited H2CData PDU (R2T PDU)
NVMe/TCP - Linux Support

- 2017: Fabrics Linux Driver Task Force took on developing the NVMe/TCP driver
  - Few different vendors provide NVMe/TCP solution (Lightbits, SolarFlare, Chelsio, etc)
  - Converged on a single code-base moving forward

- As the spec evolved, code adjustments followed providing feedback to the standardization

- Code is in solid shape, exist in kernel 5.0 a.k.a 4.21 (Currently RC 5).
Driver Design Guidelines

- Single reactor thread per-cpu (private bound workqueue)
  - Keep context switches to an absolute minimum
  - NVMe queues are spread among reactor threads
- **NEVER** block on I/O (unlike other TCP implementations)
- Aggressively avoid data copy (only copy RX data)
- Reuse common interfaces!
  - bio_vec, iov_iter, socket/datagram operations
- RX is either handled in soft-IRQ or in the same reactor context
- Keep atomic operations to an absolute minimum and keep uncontended (in the data path)
- Fairness and budgeting mechanisms multiplexing between NVMe queues
NVMe Host Stack

- TCP transport driver naturally plugs into the existing stack
- Almost no special additions for TCP (to this point)
- Control plane very similar to RDMA
  - Still have plenty of room for code reuse
NVMe Target Stack

- TCP transport driver naturally plugs into the existing stack
- Very few changes to the existing core/fabrics stack
NVMe Stack - LOC count

- The Linux NVMe subsystem is in pretty good shape (most of the code is common)
- Still has plenty of room for improvement in error handling code reuse
Online Data Digest Hash Updates

- We use existing `skb_copy_datagram_iter` interface for incoming data placement
  - Both skb and bio_vec walks are abstracted away

- **Problem**: Calculate data digest while data is still hot in the cache
- **Solution**: Provide new interface that will perform online digest updates
  - `skb_copy_and_hash_datagram_iter` which receives a pre-initialized ahash_request and updates it on the fly
  - Provides the same level of abstraction and allows consumer to not open code iterator walks when online digest operations are needed
slab, *sendpage*, and kernel hardening

- NVMe/TCP PDU headers are pre-allocated from the memory allocator
- Like any other buffer, PDU headers are never copied when sent to the network
- When the queue depth is high and network is congested, PDU headers might get coalesced together
- Kernel Hardening will panic the kernel when *usercopy* attempts to read slab originated buffer if they cross slab objects
  - Heuristic attempt to catch an exploit
slab, sendpage, and kernel hardening

- Userspace programs is allowed to use packet filters and read
  - bpf, tap (nit), etc…
  - dhclient was the culprit in this case
- Basically every userspace program can panic the kernel if a slab page will be passed to sendpage
- **Solution**: Page fragments API
  - NVMe/TCP PDUs will keep a per-queue `page_frag_cache` that will use normal page allocation not originating from the memory allocator
  - Also very cacheline friendly for network stack page refcounts (avoid cpu cores sharing atomic areas)
Features

- Zero Copy Transmission
- Header/Data Digest
- CPU/NUMA affinity assignments for I/O threads
- TLS Support - Future
  - Will probably be trampolined to userspace for TLS handshake
- Polling Mode I/O - Future
  - Need to continue polling with an inherent context switch
- Automatic aRFS support - Future
  - Need to figure out atomicity of NIC steering table updates
- Out-of-Order Data transfers - Future
  - Probably fabrics 1.2 material
In-Transit Encryption - TLS

- A NVMe/TCP enabled subsystem port can optionally support TLS
  - TLS indication appears in the TSAS field of the discovery log entry
  - One mandatory cipher-suite, three other recommended

- TLS handshake in Linux is supported in userspace
- Two possible implementations:
  - Trampoline to userspace that implements TLS handshake
  - Port TLS handshake to the kernel

- Support is expected post initial submission
Canonical Latency

- Latency is higher than RDMA but still pretty good
- @ the tail percentiles the difference is not even noticeable

* 100% 4KB Random Read @ QD=1 (using RAM device)
Scaling with threads

- Test represents multithreaded application using synchronous I/O
- IOPs scale linearly and Latency is almost not affected

* 12 cpu cores @ 2GHz (Intel® Xeon® Processor E5-2620)
Host side CPU utilization

- CPU utilization decreases with higher block size
  - NIC offloads come into play (LRO, TSO)
- READs are naturally more intensive than WRITE
  - Involves data copy
- Target cpu utilization is roughly ½ than the host

* 12 cpu cores @ 2GHz (Intel® Xeon® Processor E5-2620)
* Mellanox ConnectX-4/LX
* QD=32/64
Backup
Dynamic Resource Enumeration

- A Discovery Subsystem provide information on available fabric subsystems to hosts
  - Theory of operation is to simply connect, retrieve discovery log page and teardown

- Dynamic Resource Enumeration enables discovery subsystems to notify interested hosts about new fabric subsystems
  - Define persistent discovery controllers (support Keep Alive)
  - Define discovery log change AEN
Dynamic Resource Enumeration
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Dynamic Resource Enumeration
Thank you!