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

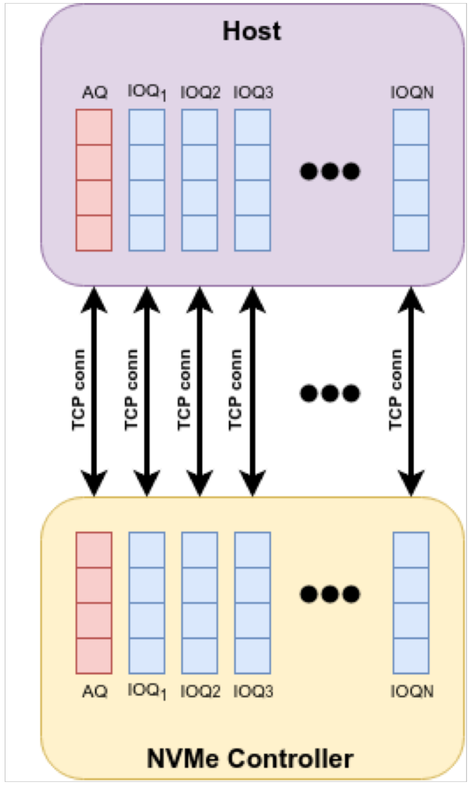
- Standard was ratified on Nov 15th, 2108
- Multi-vendor joint effort to ensure interoperability
- Designed for simplicity and efficiency
- First NVMe/TCP plugfest POC in UNH-IOL on Nov 12nd, 2018

NVM Express / TCP

Association Model

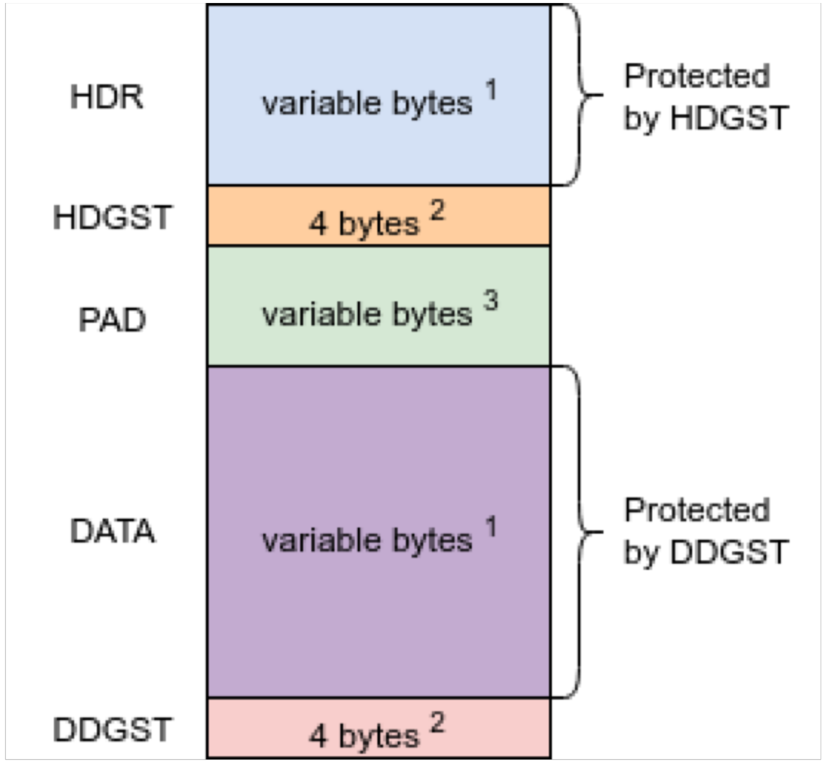
- Controller association maps 1x1 NVMe queue to a TCP connection
  - No controller-wide sequencing
  - No controller-wide reassembly constraints

- 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

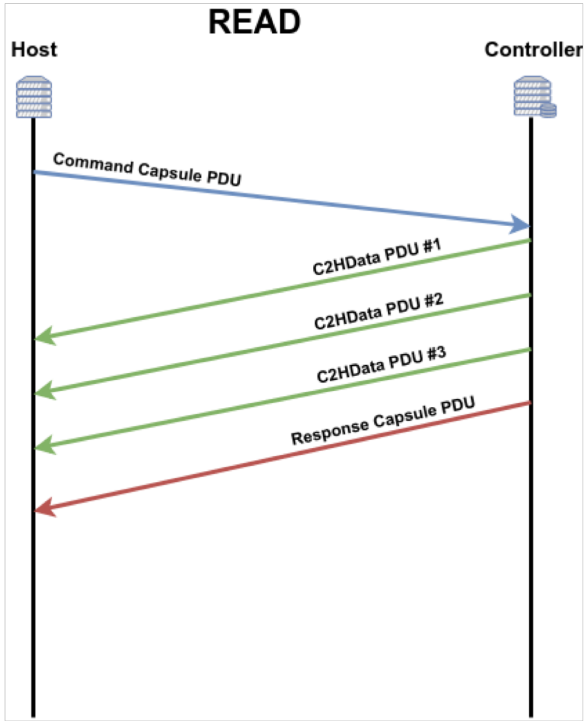


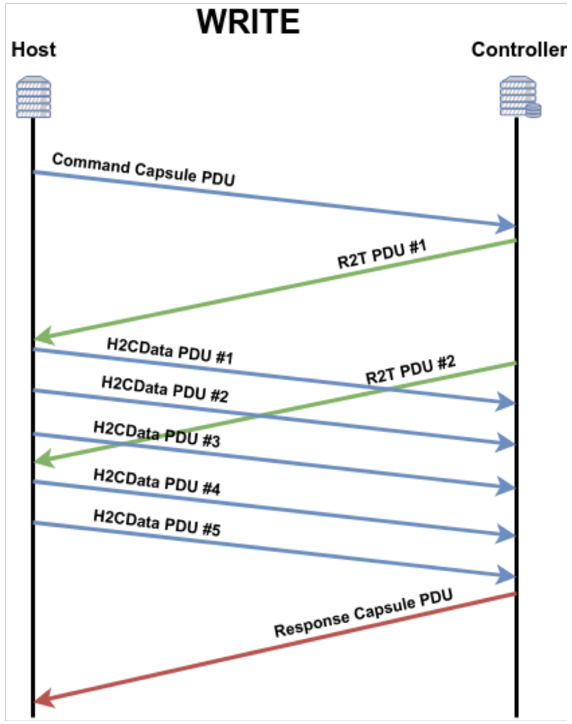
PDU Types

- 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

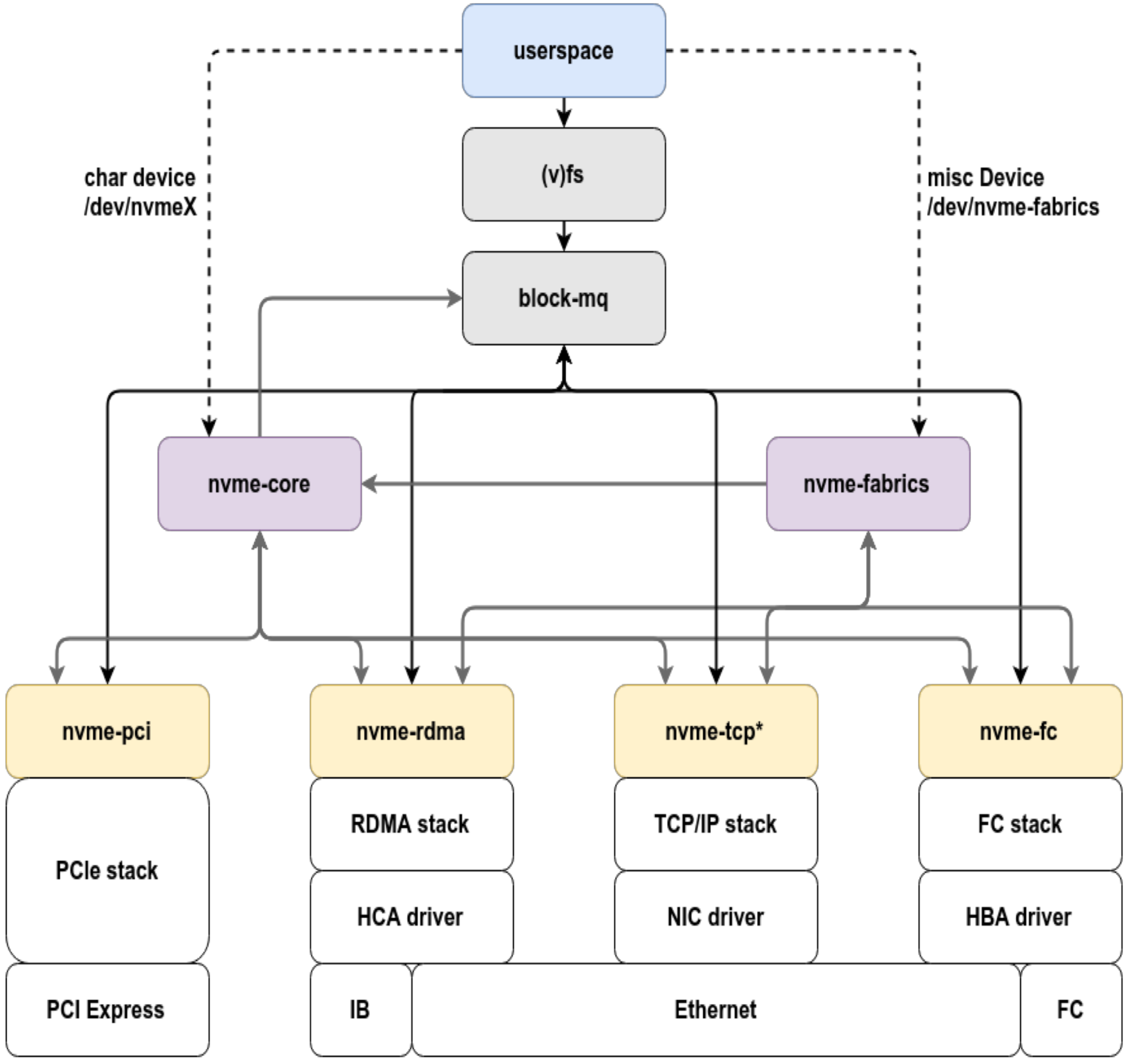
- Code is in solid shape, exist in kernel 5.0 a.k.a 4.21 (Currently RC 5).

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

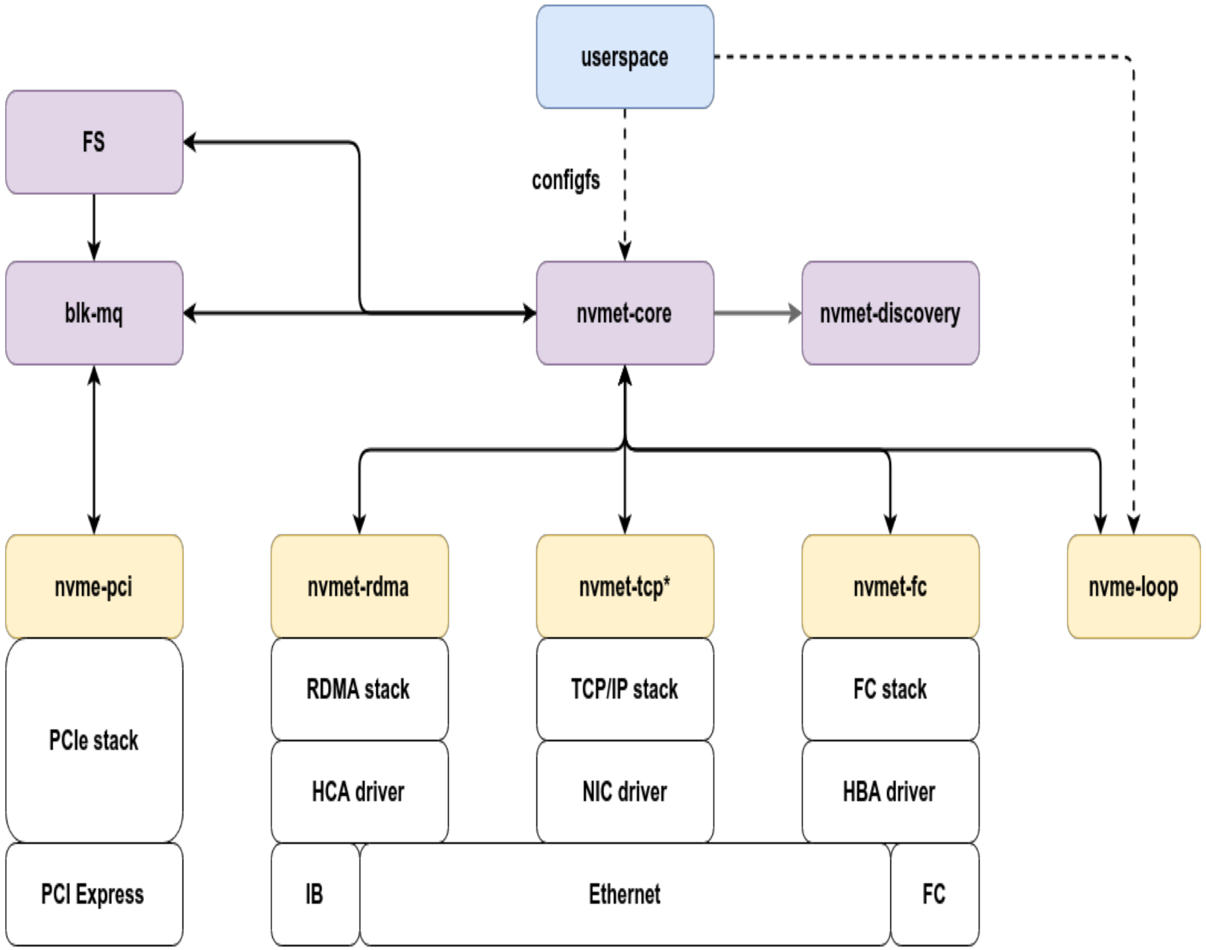
NVMe Host Stack

- 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



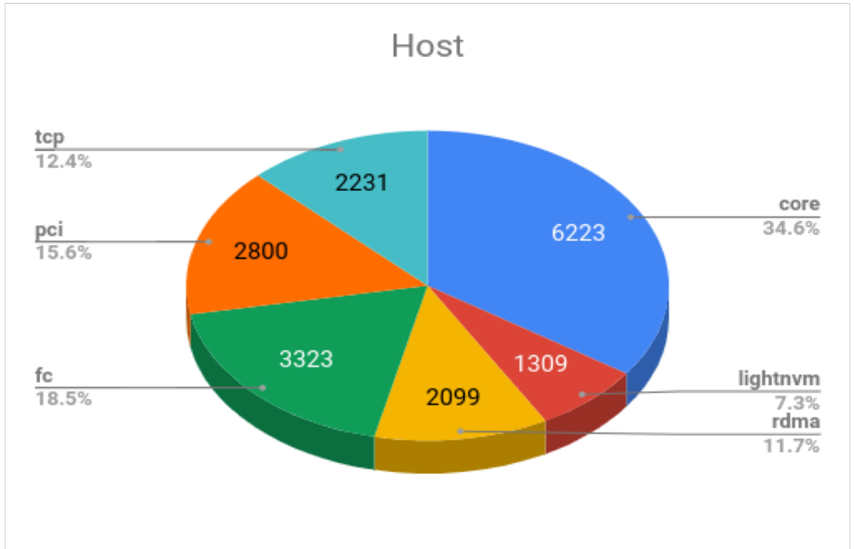
NVMe Target Stack

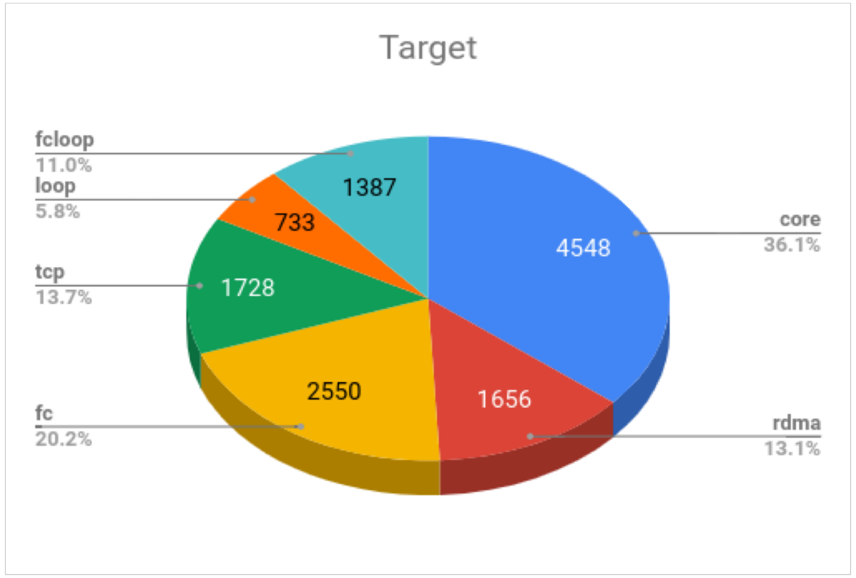
- TCP transport driver naturally plugs into the existing stack
- Very few changes to the existing core/fabrics stack



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*
- <u>Solution</u>: 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

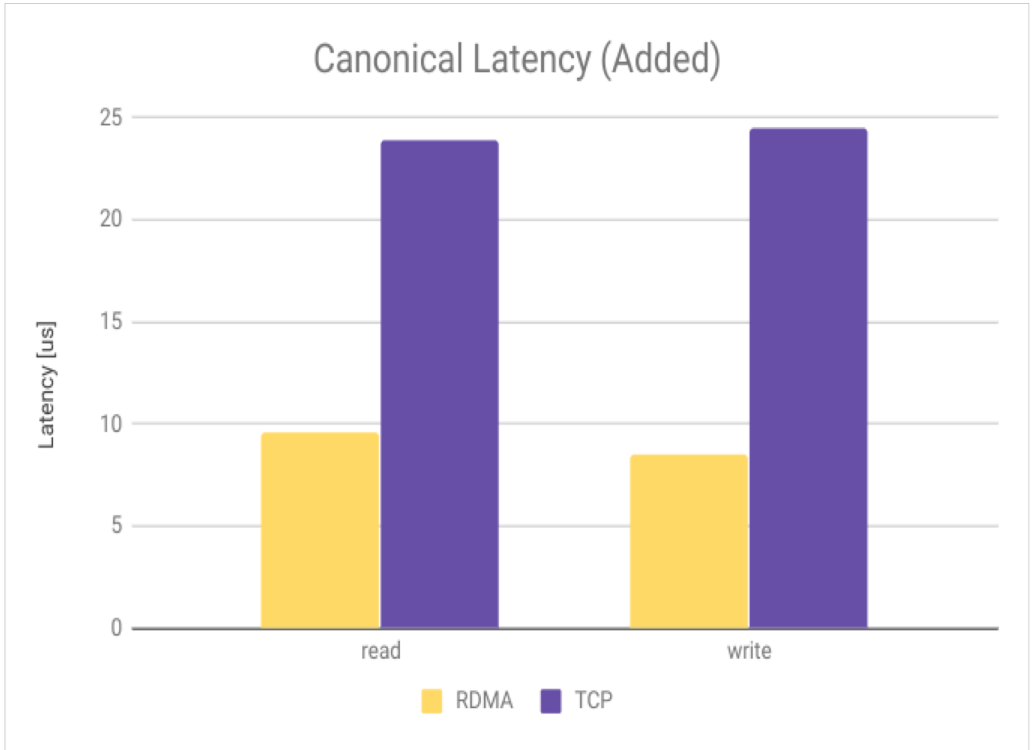
- A NVMe/TCP enabled subsystem port can optionally support TLS
  - TLS indication appears in the TSAS field of the discovery log entry
  - One mandatory cipher-suite, three other recommended

- 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

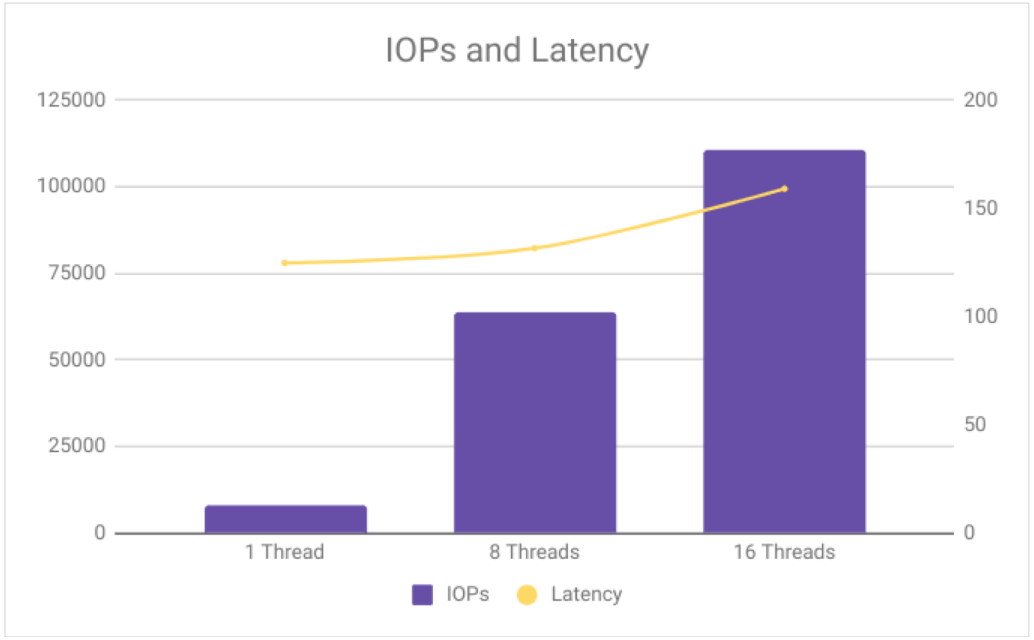
- ❒ Latency is higher than RDMA but still pretty good
- ❒ @ the tail percentiles the difference is not even noticeable



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

Scaling with threads

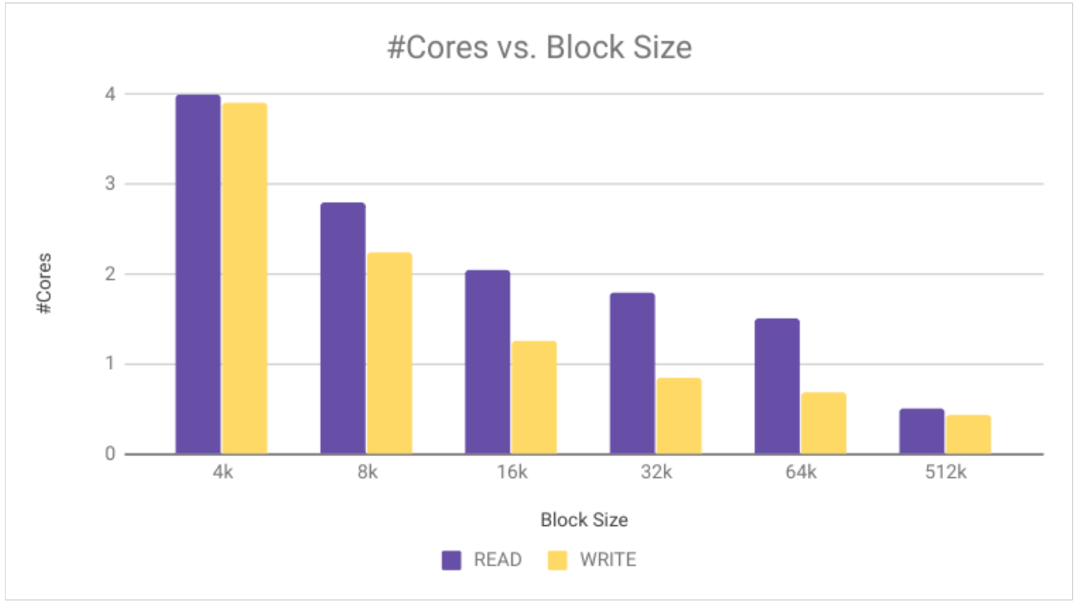
- Test represents multithreaded application using synchronous I/O
- IOPs scale linearly and Latency is almost not affected



* 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

Q&A

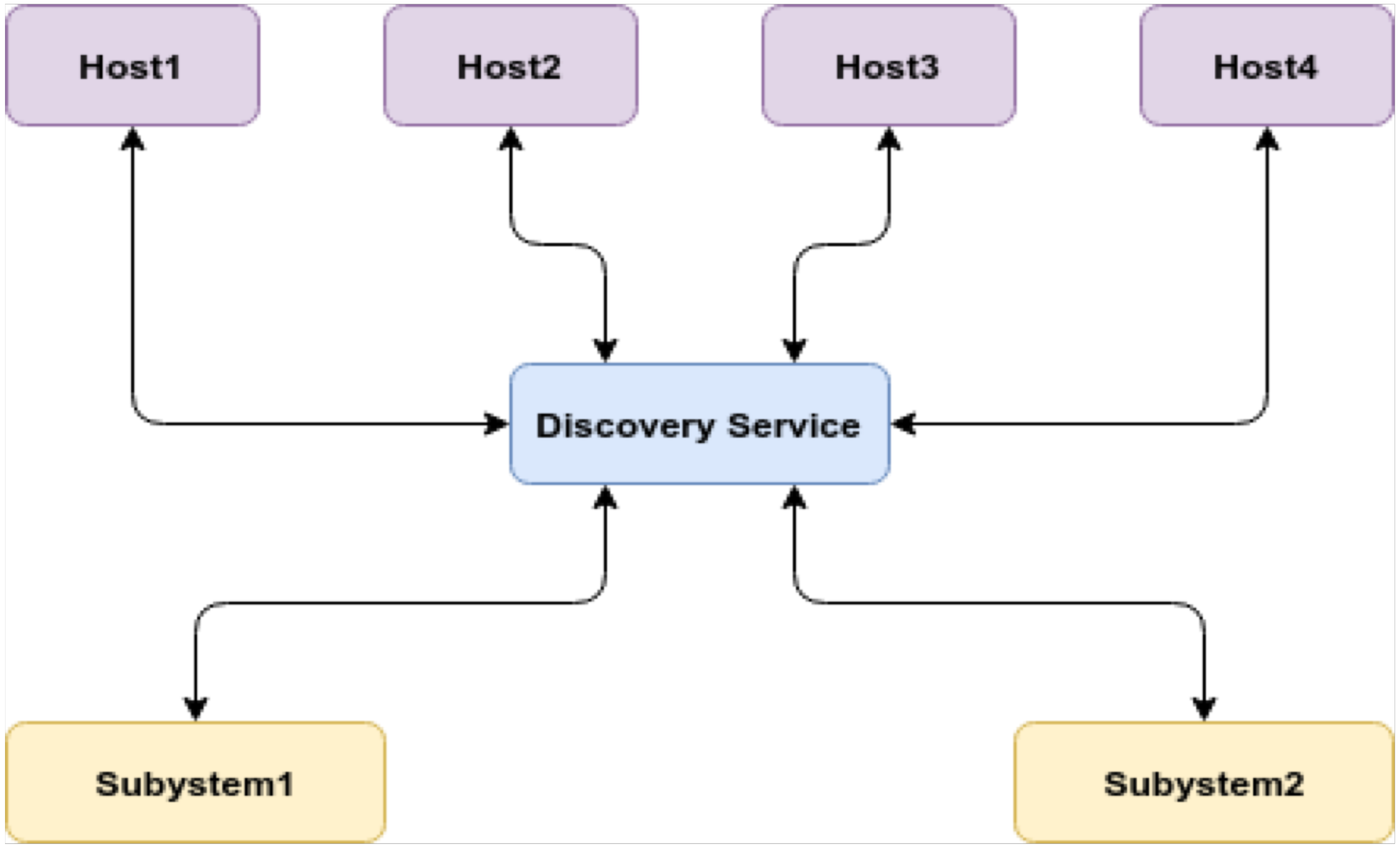
Backup

Dynamic Resource Enumeration

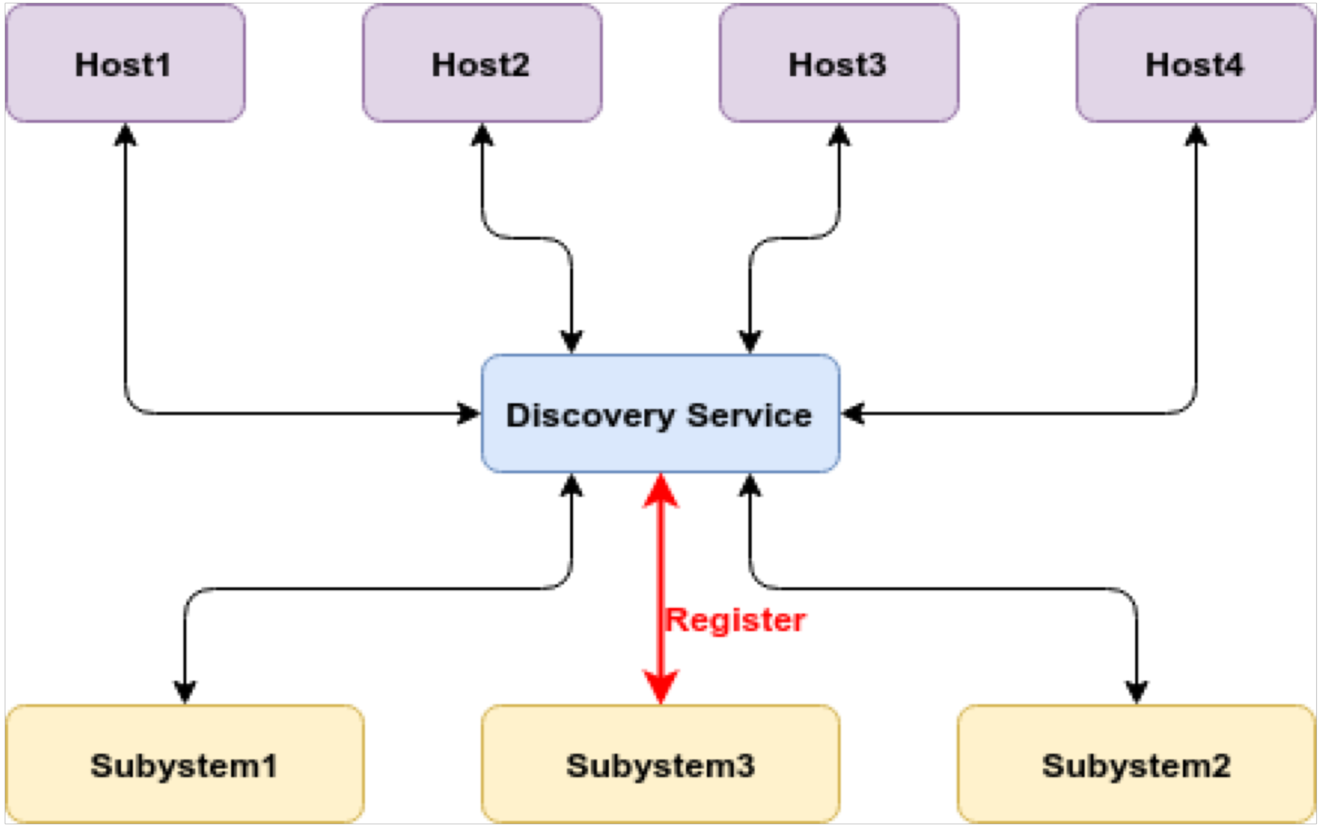
- A Discovery Subsystem provide information on available fabric subsystems to hosts
  - Theory of operation is to simply connect, retrieve discovery log page and teardown

- 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

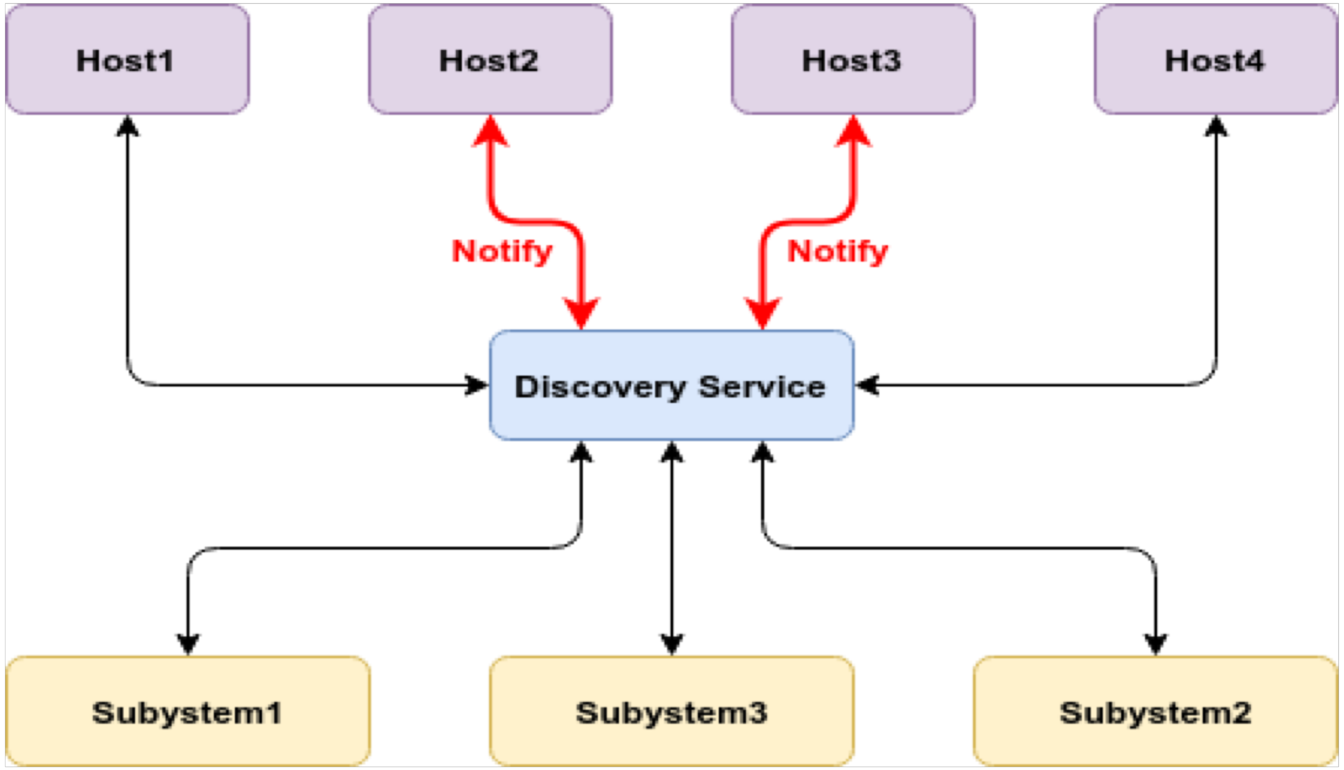
Dynamic Resource Enumeration



Dynamic Resource Enumeration



Dynamic Resource Enumeration



Thank you!