STORAGE DEVELOPER CONFERENCE
SDC 23
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Breaking Boundaries: Expanding Ceph's Capabilities with NVMe-oF

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What Is Ceph?

The buzzwords

- "Software defined storage"
- "Unified storage system"
- "Scalable distributed storage"
- "The future of storage"
- "The Linux of storage"

The substance

- Ceph is open source **software**
- Runs on commodity hardware
  - Commodity servers
  - IP networks
  - HDDs, SSDs, NVMe, NV-DIMMs, ...
- A single cluster can serve **object** , **block** , and **file** workloads

Ceph is Free and Open Source

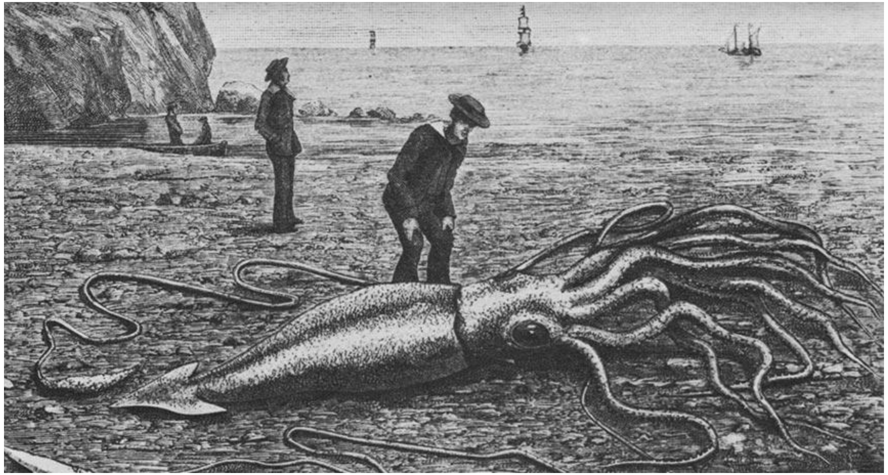
- Freedom to use (free as in beer)
- Freedom to introspect, modify, and share (free as in speech)
- Freedom from vendor lock-in
- Freedom to innovate

Cep is Reliable

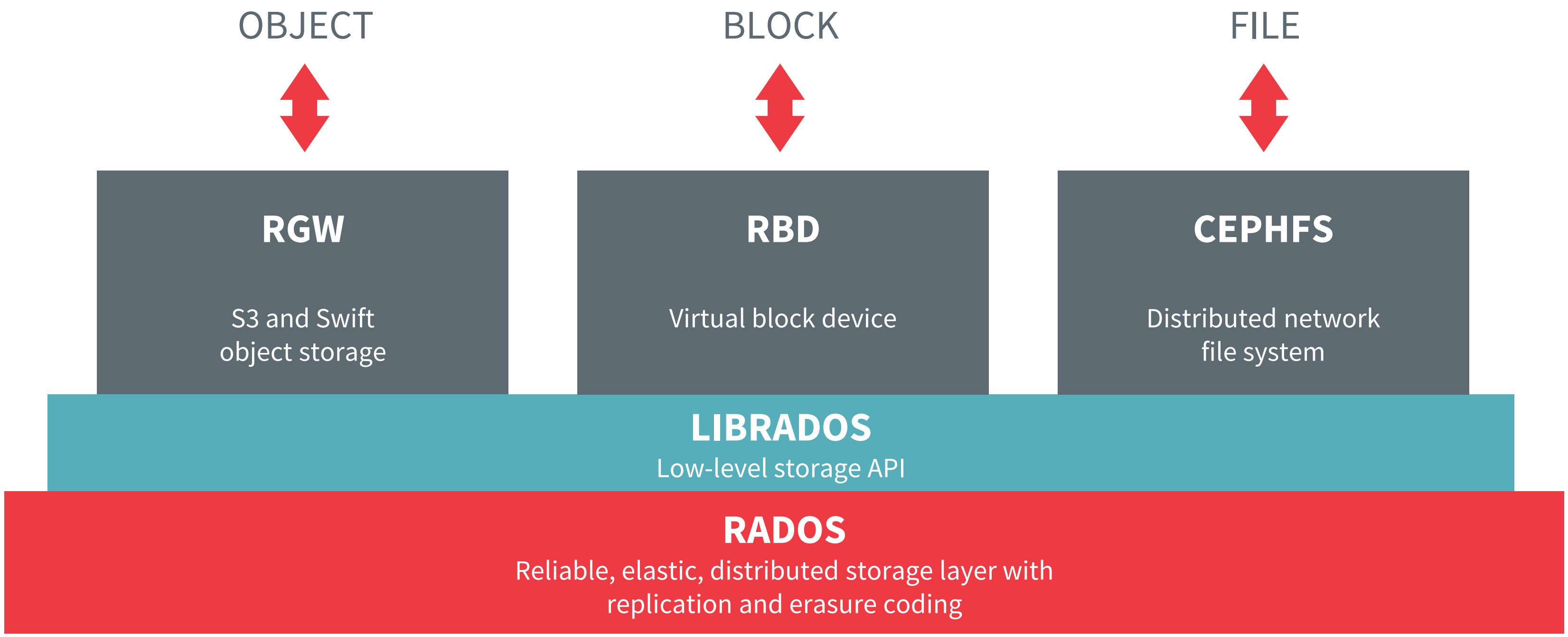
- **Reliable storage** service out of **unreliable components**
  - No single point of failure
  - Data durability via replication or erasure coding
  - No interruption of service from rolling upgrades, online expansion, etc.
- Favor consistency and correctness over performance

Ceph is Scalable

- Ceph is elastic storage infrastructure
  - Storage cluster may grow or shrink
  - Add or remove hardware while system is online and under load
- Scale **up** with bigger, faster hardware
- Scale **out** within a single cluster for capacity and performance
- **Federate** multiple clusters across sites with asynchronous replication and disaster recovery capabilities



Ceph is a Unified Storage System



OBJECT

BLOCK

FILE

RGW

S3 and Swift object storage

RBD

Virtual block device

CEPHFS

Distributed network file system

LIBRADOS

Low-level storage API

RADOS

Reliable, elastic, distributed storage layer with replication and erasure coding

RADOS

RADOS

- **R**eliable **A**utonomic **D**istributed **O**bject **S**torage
  - Common storage layer underpinning object, block, and file services
- Provides low-level data object storage service
  - Reliable and highly available
  - Scalable (on day 1 and day 1000)
  - Manages all replication and/or erasure coding, data placement, rebalancing, repair, etc.
- Strong consistency
  - CP, not AP
- Simplifies design and implementation of higher layers (file, block, object)

LIBRADOS API

- **Efficient key/value storage inside an object (OMAP)**
- Atomic single-object transactions
  - update data, attr, keys together
  - atomic compare-and-swap
- Object-granularity snapshot infrastructure
- Partial overwrite of existing data
- Single-object compound atomic operations
- RADOS classes (stored procedures)
- **Watch/Notify on an object**

RADOS Components

ceph-mon

Monitor

- Central authority for authentication, data placement, policy
- Coordination point for all other cluster components
- Protect critical cluster state with Paxos
- 3, 5, 7 per cluster

ceph-mgr

Manager

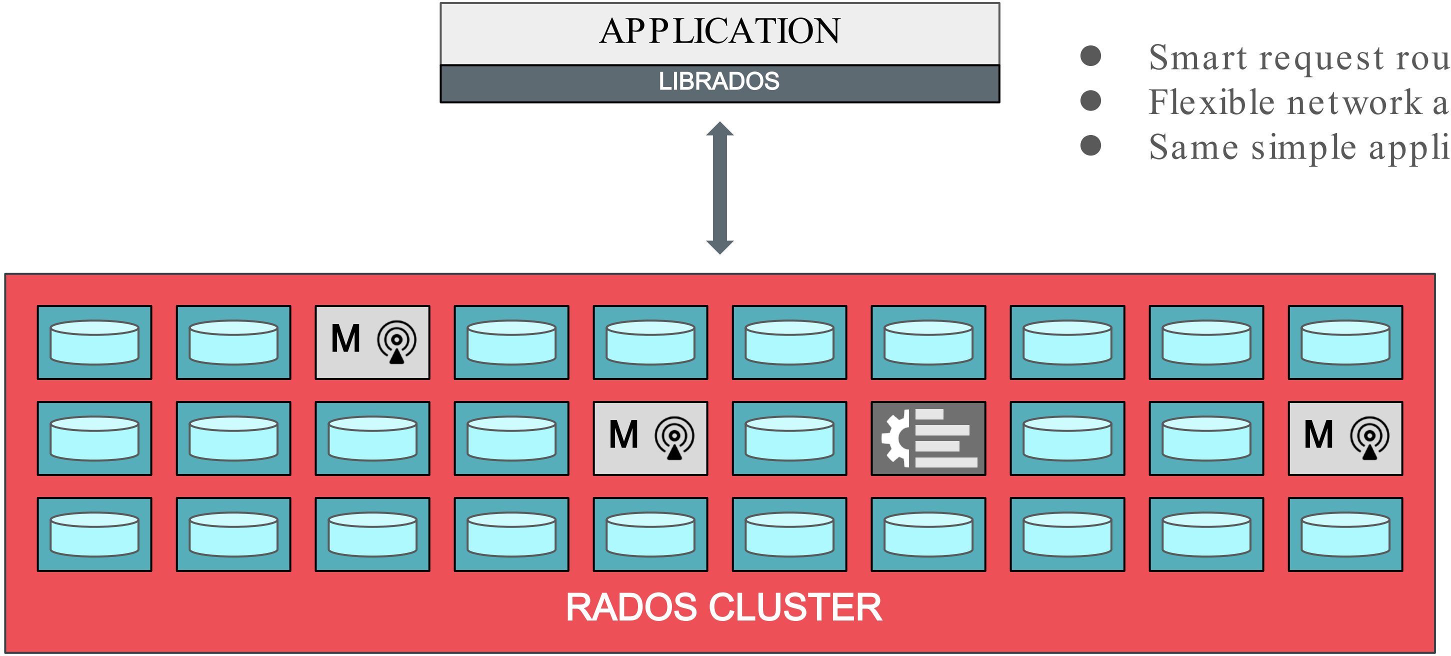
- Aggregates real-time metrics (throughput, disk usage, etc.)
- Host for pluggable management functions
- 1 active, 1+ standby per cluster

ceph-osd

OSD (Object Storage Daemon)

- Stores data on an HDD or SSD
- Services client IO requests
- Cooperatively peers, replicates, rebalances data
- 10s-1000s per cluster

Client/ Cluster Architecture

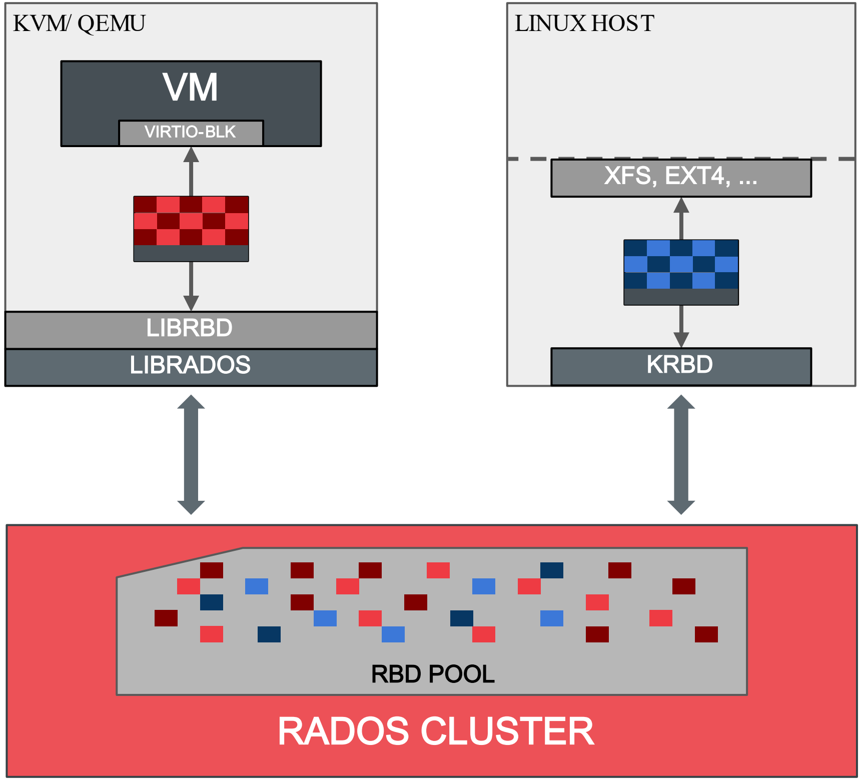


- Smart request routing
- Flexible network addressing
- Same simple application API

RBD: BLOCK STORAGE

RBD: RADOS Block Device

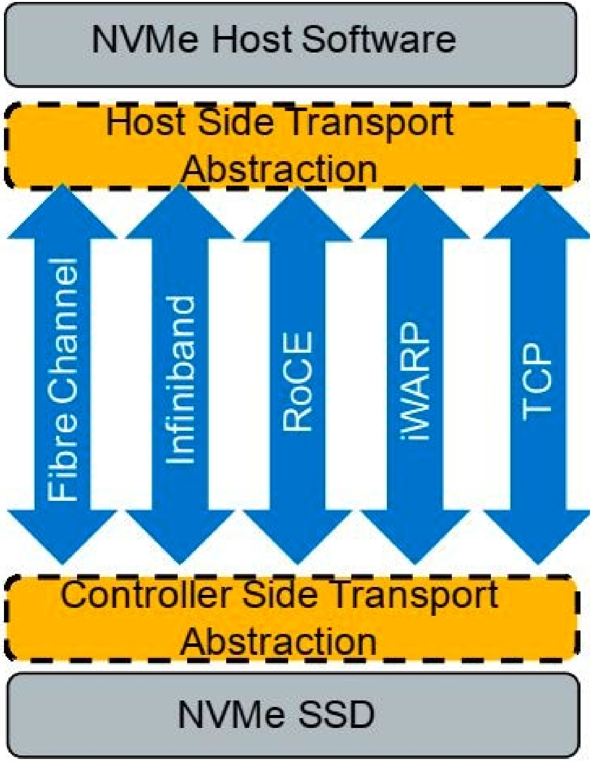
- Virtual block device
  - Store disk images in RADOS
  - Stripe data across many objects in a pool
- Storage decoupled from host, hypervisor
  - Analogous to AWS EBS
- Client implemented in KVM and Linux
- Integrated with
  - Libvirt
  - OpenStack (Cinder, Nova, Glace)
  - Kubernetes
  - Proxmox, CloudStack, Nebula, …
- Ceph iSCSI gateway
  - LIO stack + userspace tools to manage gateway configuration



NVMe Over Fabric

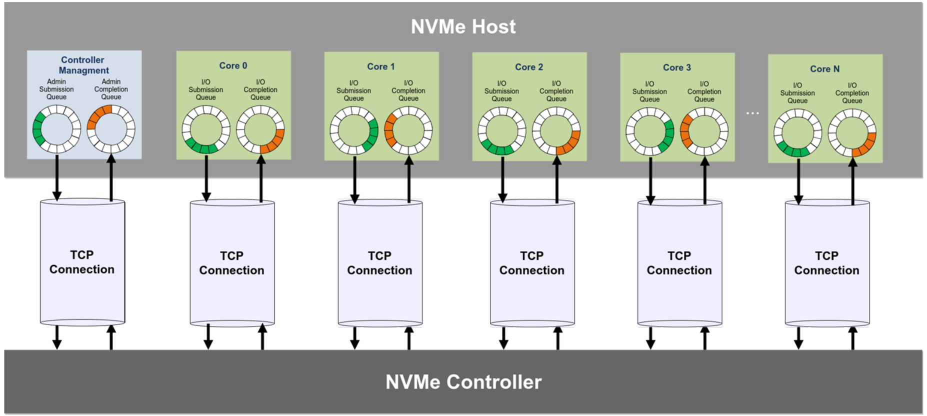
NVMe Over Fabric

- Non Volatile Memory Express (NVMe)
  - Fast PCIe attached storage
  - Local storage
- Expand NVMe efficiency and performance over network fabrics
- Eliminate unnecessary protocol translations
- Enable low-latency and high IOPS remote NVMe storage
- TCP:
  - Well-known and common transport
  - No networking infrastructure requirements and constraints
  - Ratified Nov, 2018


NVMe Host Software
Host Side Transport Abstraction
Fibre Channel
Infiniband
RoCE
iWARP
TCP
Controller Side Transport Abstraction
NVMe SSD

Association Model

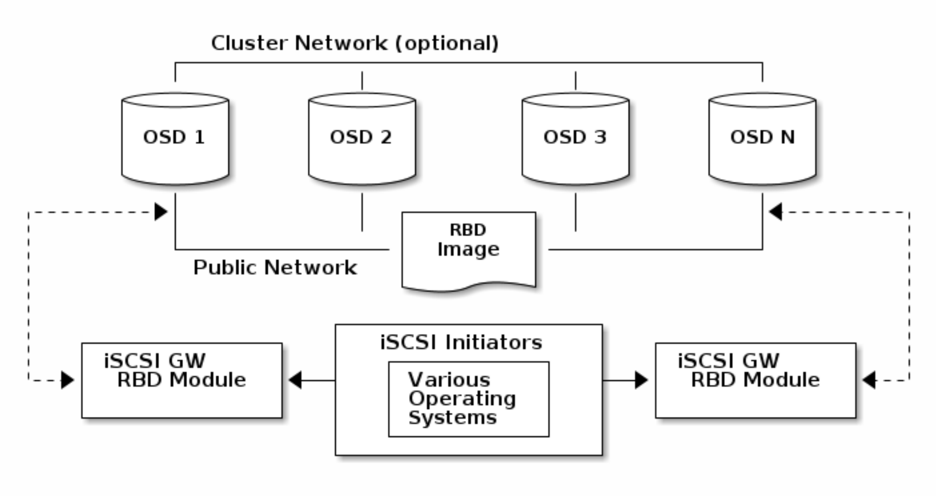
- Controller association maps 1x1 NVMe queue to a TCP connection
- No controller-wide sequencing
- No controller-wide reassembly constraints
- No shared state across NVMe queues and TCP



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

Why not Ceph iSCSI?

- Legacy
- Performance
  - Higher throughput and IOPS
    - 30-70%
  - Reduced latency
    - 30-40%
- Reduced CPU usage
    - 30-40%
- Scalability



Why NVMe-over-Fabrics?

RADOS Block Device (RBD)

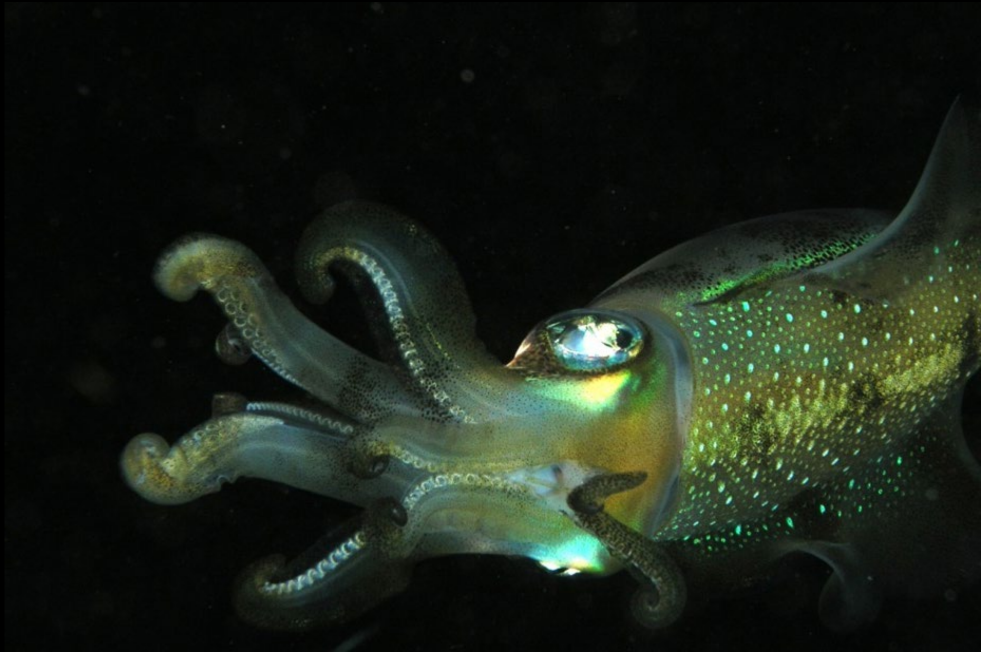
- RADOS protocol
- Distributed n-to-m protocol
- Reliable object access to sharded and replicated/erasure coded storage

Why do we need another protocol to access block storage in Ceph?

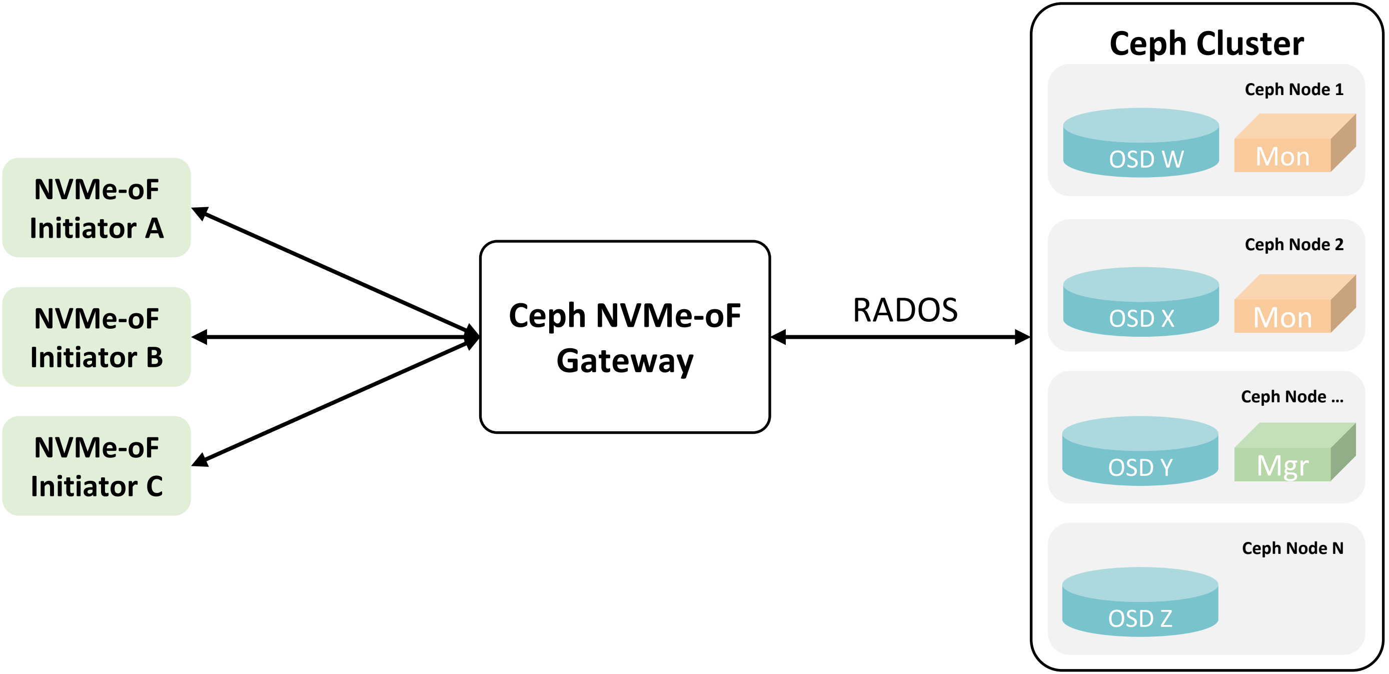
NVMe-over-Fabrics (NVMe-oF)

- Open, widely adopted ***industry standard***
- Enable use-cases where NVMe-oF is already part of ***ecosystem***
- Take advantage of NVMe-oF ***offloading*** in DPUs

Ceph NVMe-of Gateway



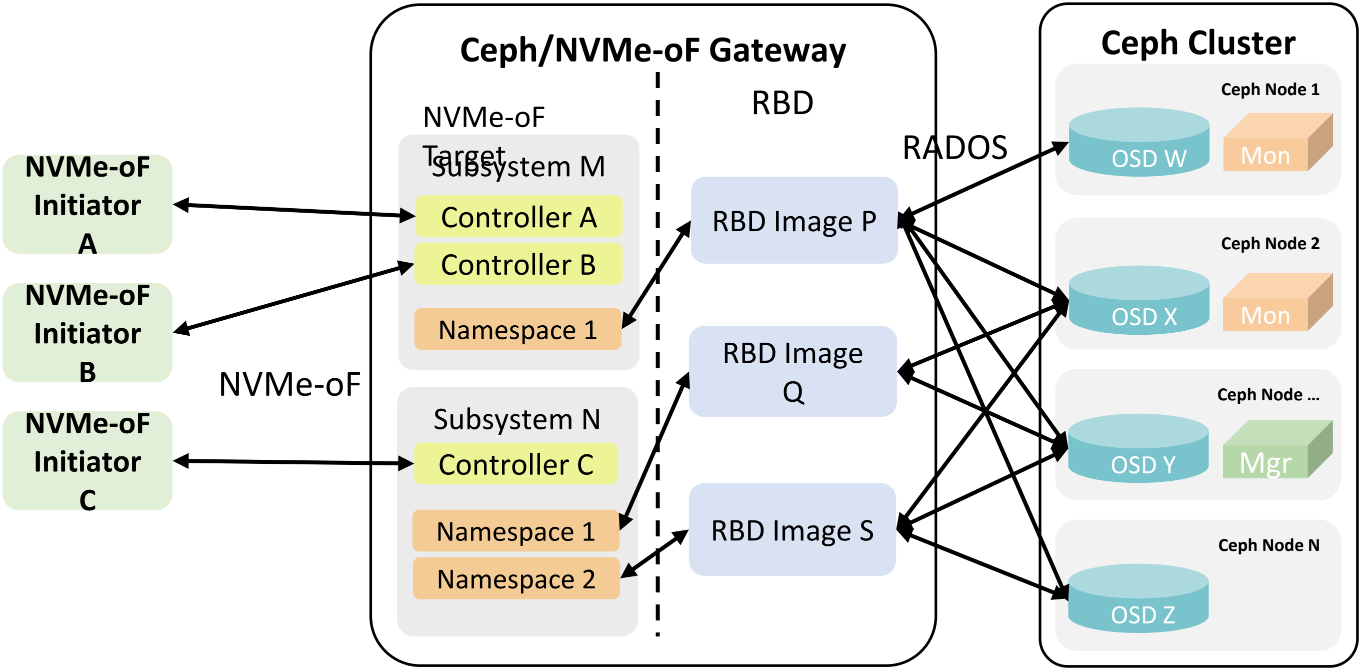
Overview



Fabrics:

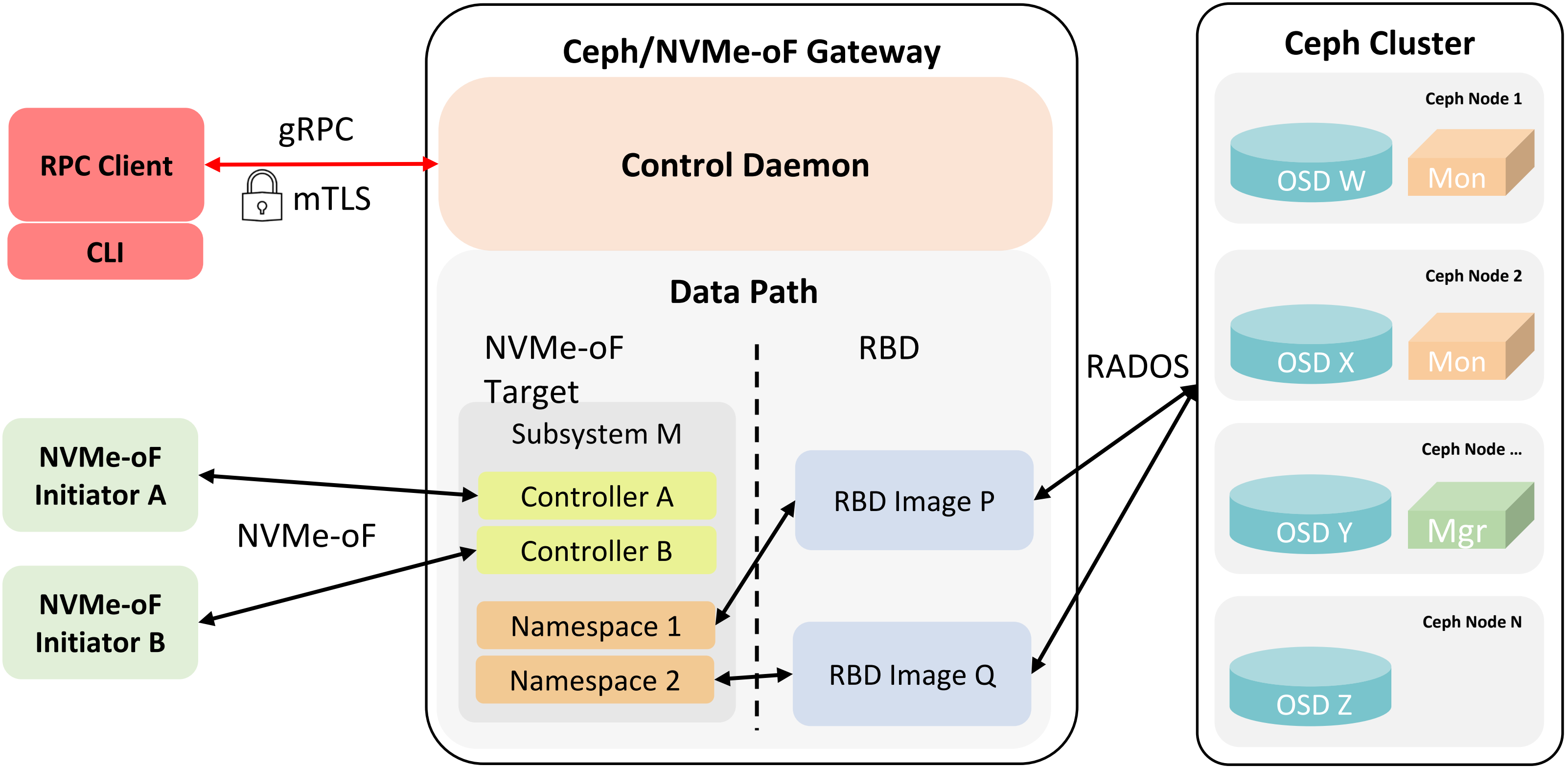
- **TCP**
- RDMA
- FC

NVMe-oF and Ceph

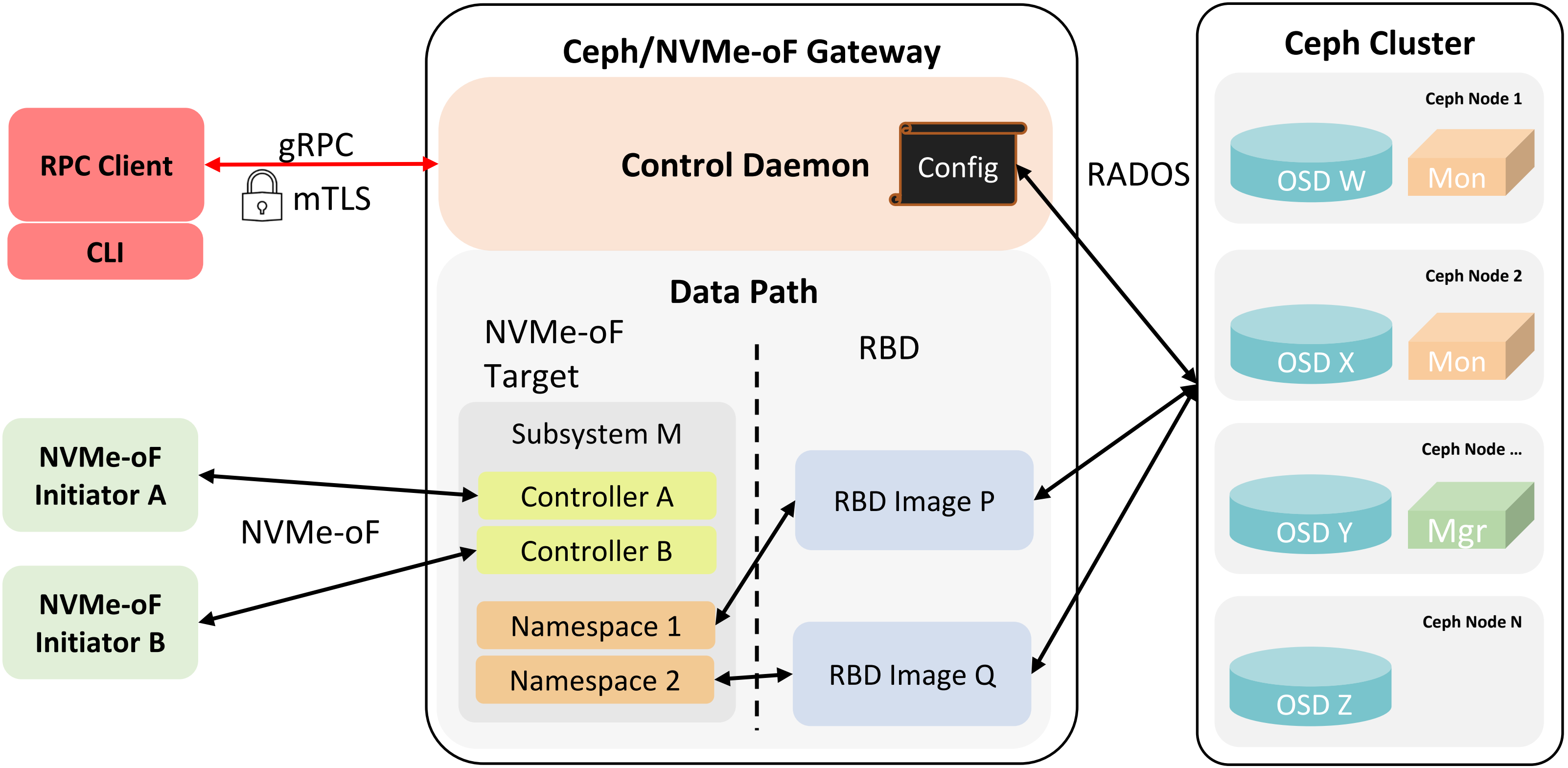


- Namespace mapped to an RBD image
- Subsystems logical grouping of Namespaces
- Each initiator get a Controller

Gateway Control Plane

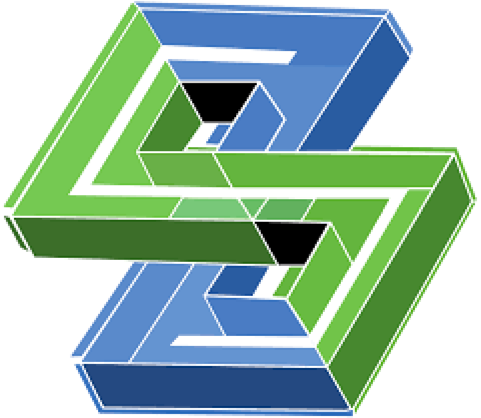


Gateway Configuration

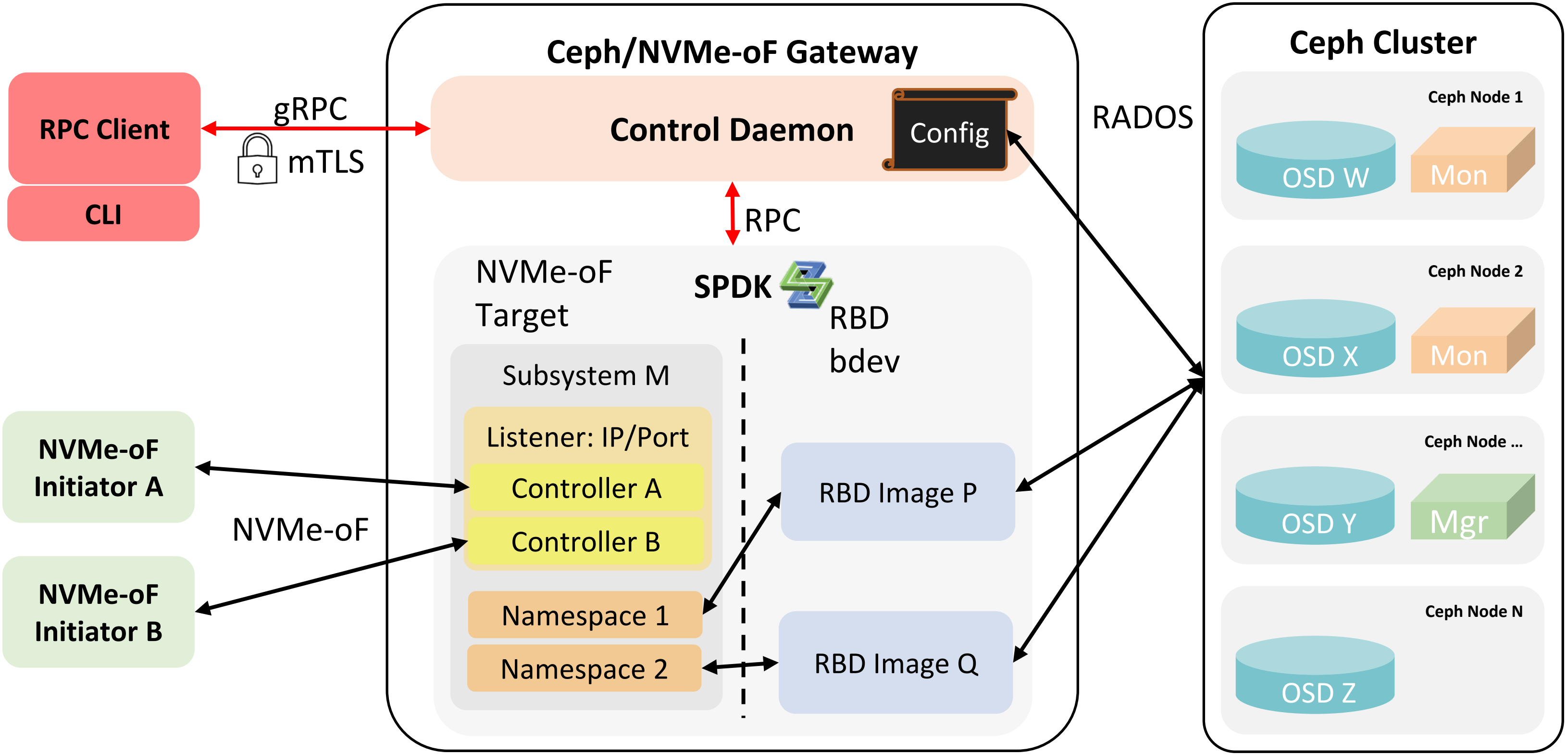


SPDK

- Storage Performance Development Kit (SPDK)
- https://spdk.io/
- Provides a tools and libraries for writing high performance, scalable, user-mode storage applications
- Userspace NVMe Over Fabric target
- Support for Ceph RBD with bdev_rbd
- Open source (BSD)

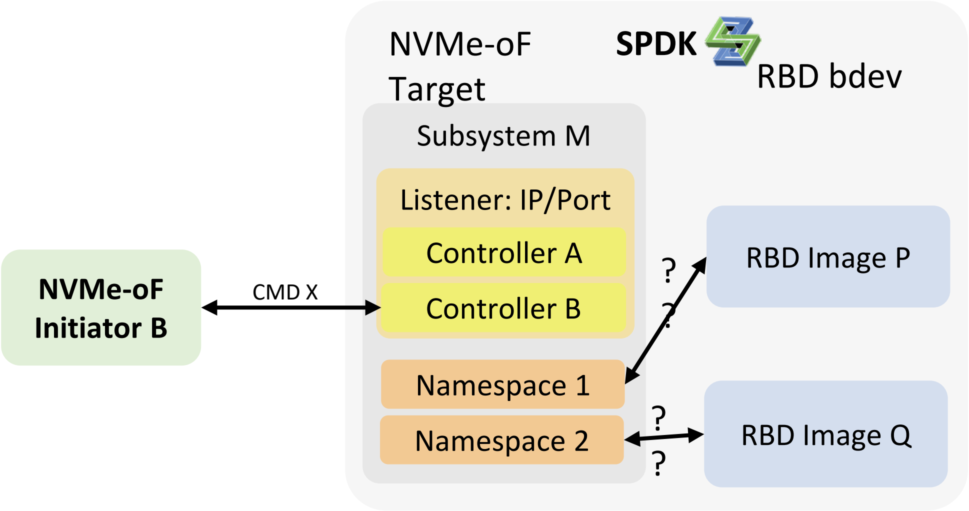


Data Path: SPDK

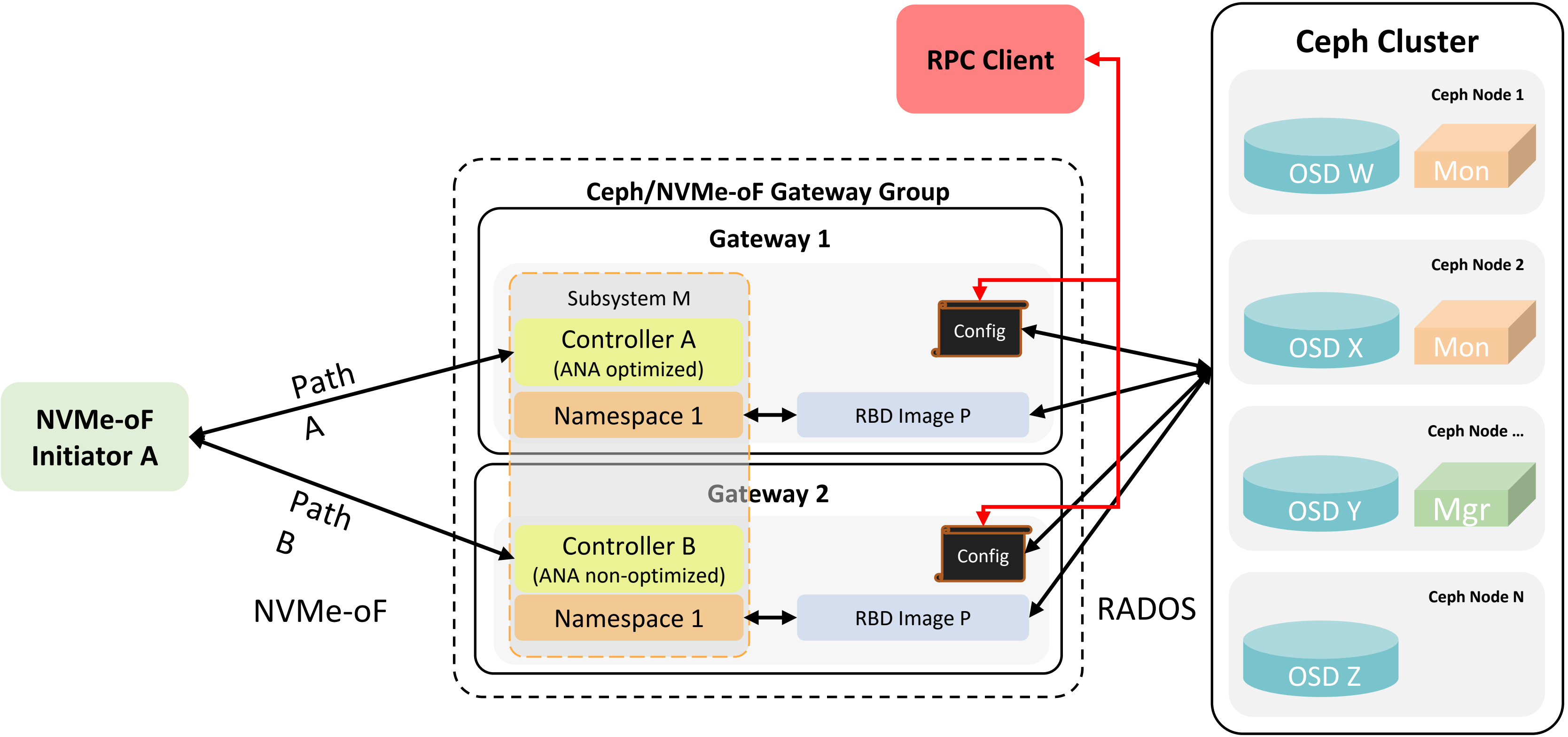


NVMe to RBD Commands Mapping

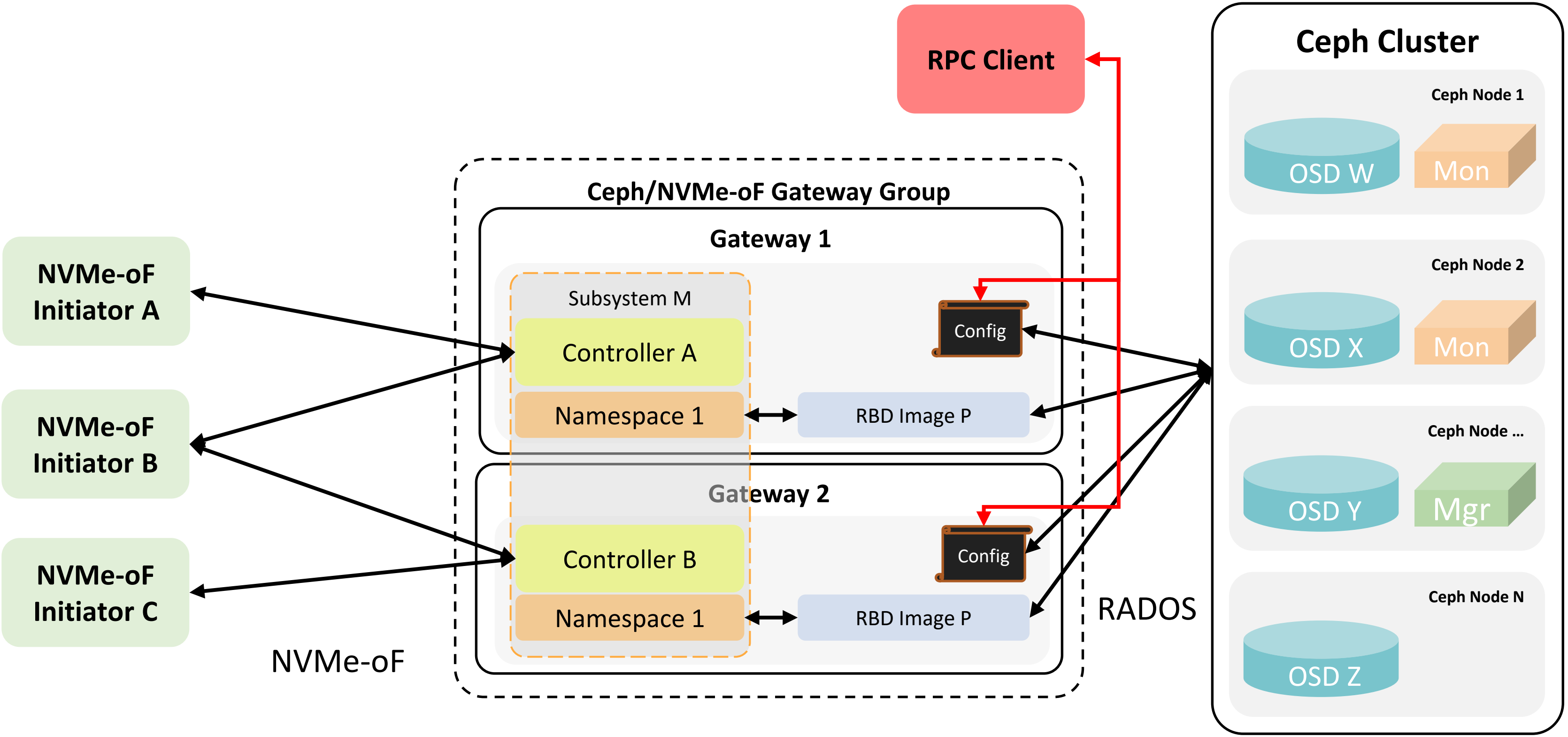
- RBD backend in SPDK maps NVMe operations to RBD API
- Natively supported
  - Read
  - Write
  - Unmap
  - Flush
  - Write zeroes
  - Compare and write
- Emulated
  - Compare
  - Copy
  - Abort**



Gateway Groups & Multi-pathing

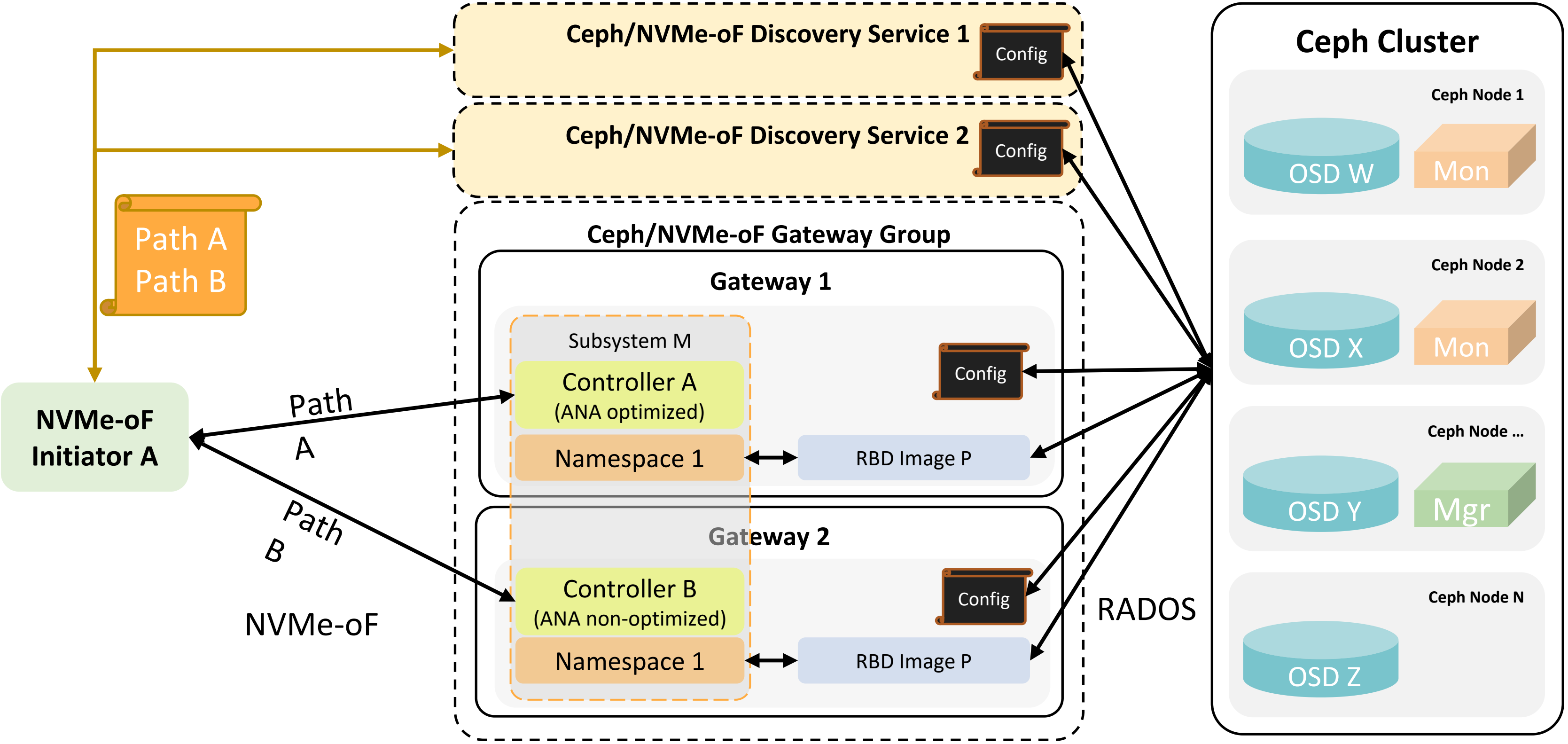


Gateway Groups: Load Balancing / Scaling



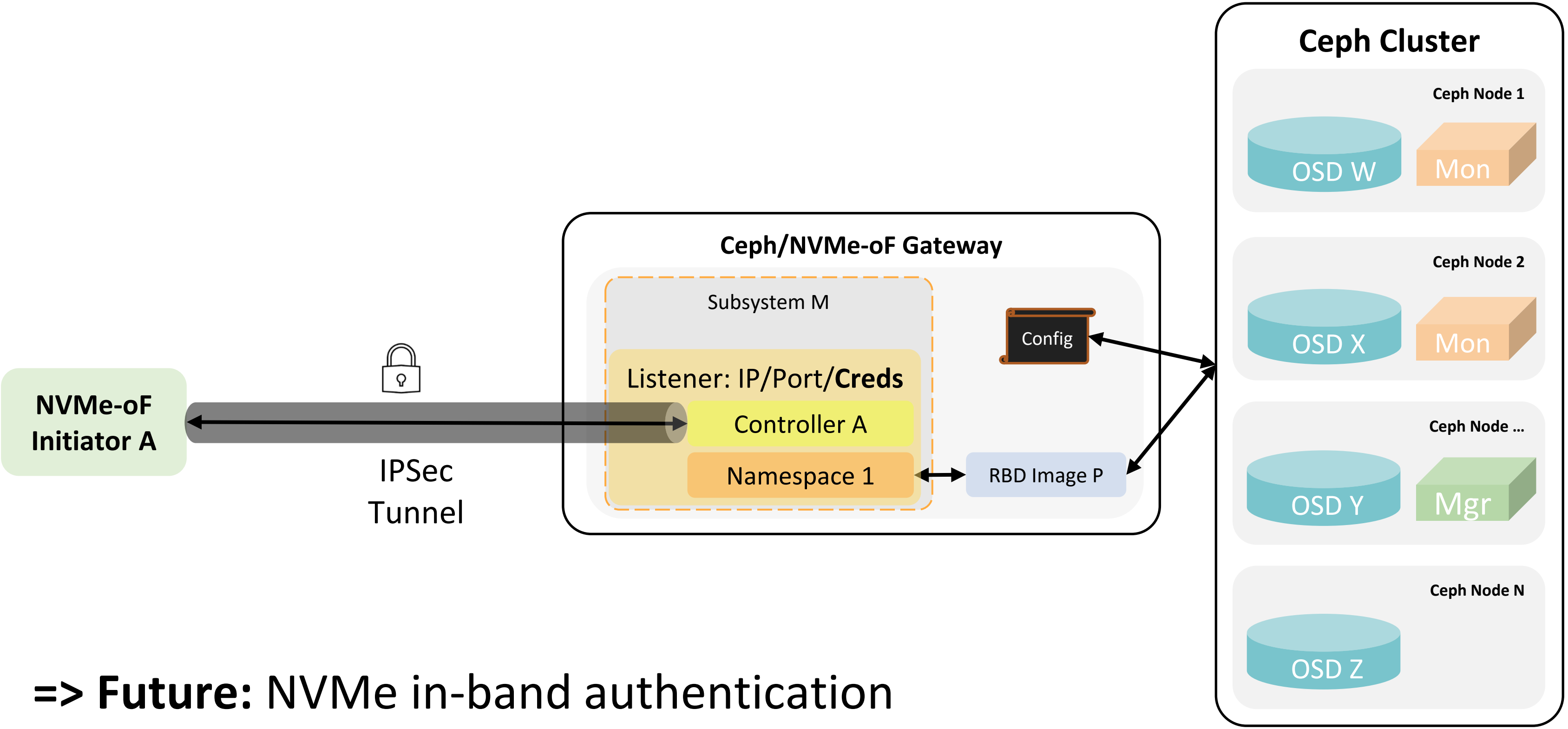
Planned/Future Features

Discovery



Ceph/NVMe-oF Discovery Service 1
Config
Ceph/NVMe-oF Discovery Service 2
Config
Path A
Path B
NVMe-oF Initiator A
Path A
Path B
NVMe-oF
Ceph/NVMe-oF Gateway Group
Gateway 1
Subsystem M
Controller A
(ANA optimized)
Namespace 1
Config
RBD Image P
Gateway 2
Controller B
(ANA non-optimized)
Namespace 1
Config
RBD Image P
RADOS
Ceph Cluster
Ceph Node 1
OSD W
Mon
Ceph Node 2
OSD X
Mon
Ceph Node ...
OSD Y
Mgr
Ceph Node N
OSD Z

Authentication / Encryption: IPSec

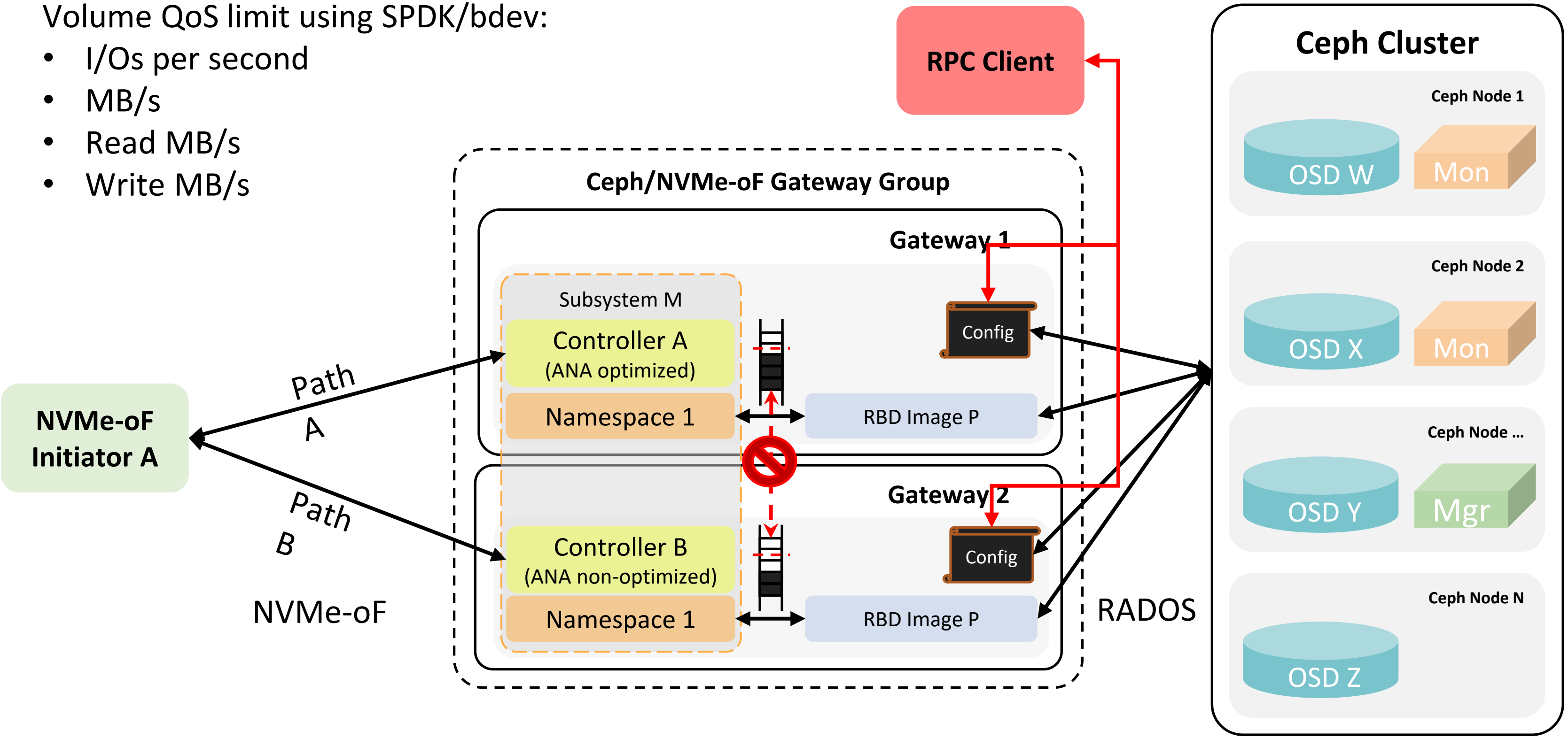


=> **Future:** NVMe in-band authentication

Quality of Service (QoS)

Volume QoS limit using SPDK/bdev:

- I/Os per second
- MB/s
- Read MB/s
- Write MB/s

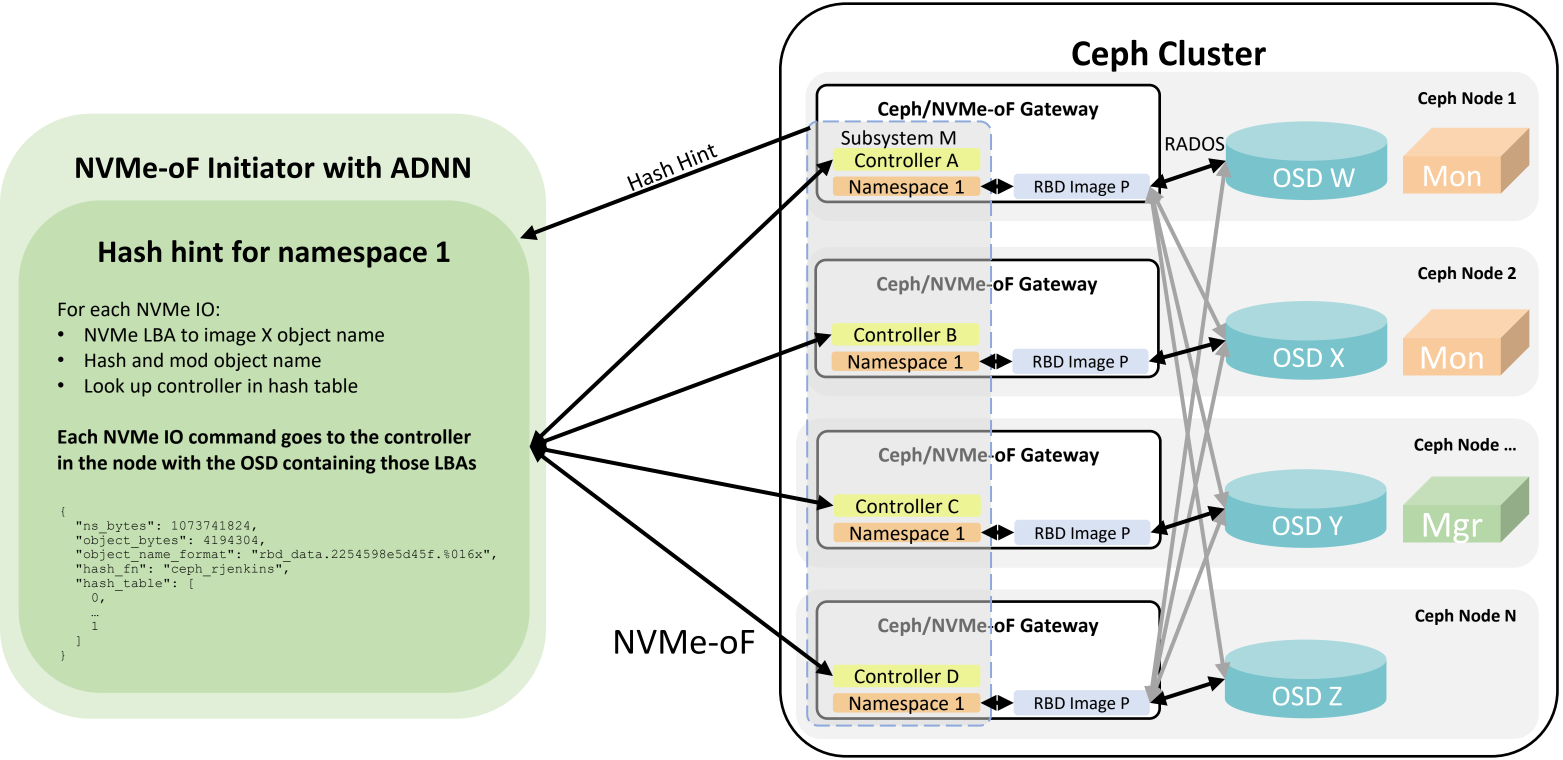


*Global QoS across gateways in a group is not planned

VMWare vSphere/ VAAI Support

- Use shared volumes to create single storage pool
- VMware vSphere Storage APIs – Array Integration (VAAI): Set of storage primitives that enable storage offloading
  - Atomic Test & Set (ATS)
    - Support in using NVMe compare & write fused operation
    - Cmp & write limited to RBD object size resp. stripe size (alignment*) => only 4K/ 1 block required
  - XCOPY (extended copy)
    - Copy NVMe command is supported in SPDK but QoS difficult
  - Write same (zero)
    - Write zeroes NVMe command => maps directly to RBD operation
  - Unmap (delete)
    - Supported as dataset management command => discard in RBD

Adaptive Distributed NVMe-oF Namespaces (ADNN)



NVMe-oF Initiator with ADNN

Hash hint for namespace 1

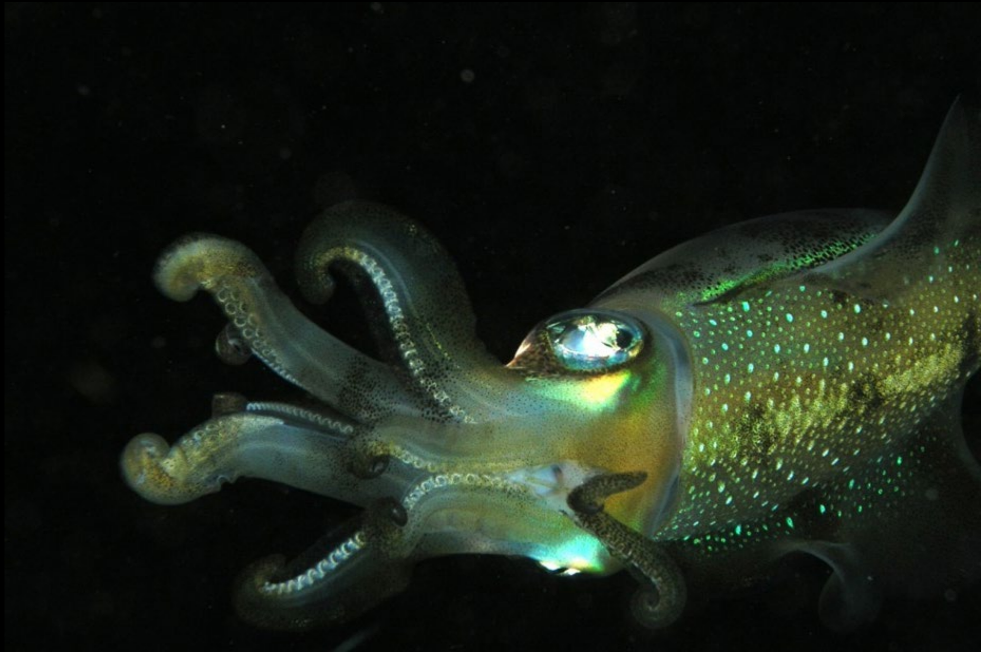
For each NVMe IO:
- NVMe LBA to image X object name
- Hash and mod object name
- Look up controller in hash table

Each NVMe IO command goes to the controller in the node with the OSD containing those LBAs

```
{
  "ns_bytes": 1073741824,
  "object_bytes": 4194304,
  "object_name_format": "rbd_data.2254598e5d45f.%016x",
  "hash_fn": "ceph_rjenkins",
  "hash_table": [
    0,
    …
    1
  ]
}
```

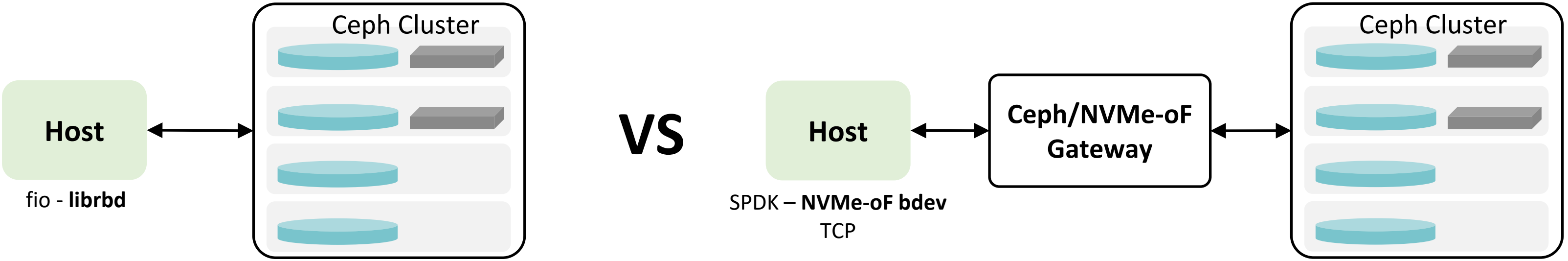
- Move gateway group into OSD nodes
- Hosts route each NVMe IO to the correct node with hash function
- Dedicated gateways (and extra hop) eliminated
- Host overhead much less than librbd (more offload friendly)

Performance



Performance: Setup

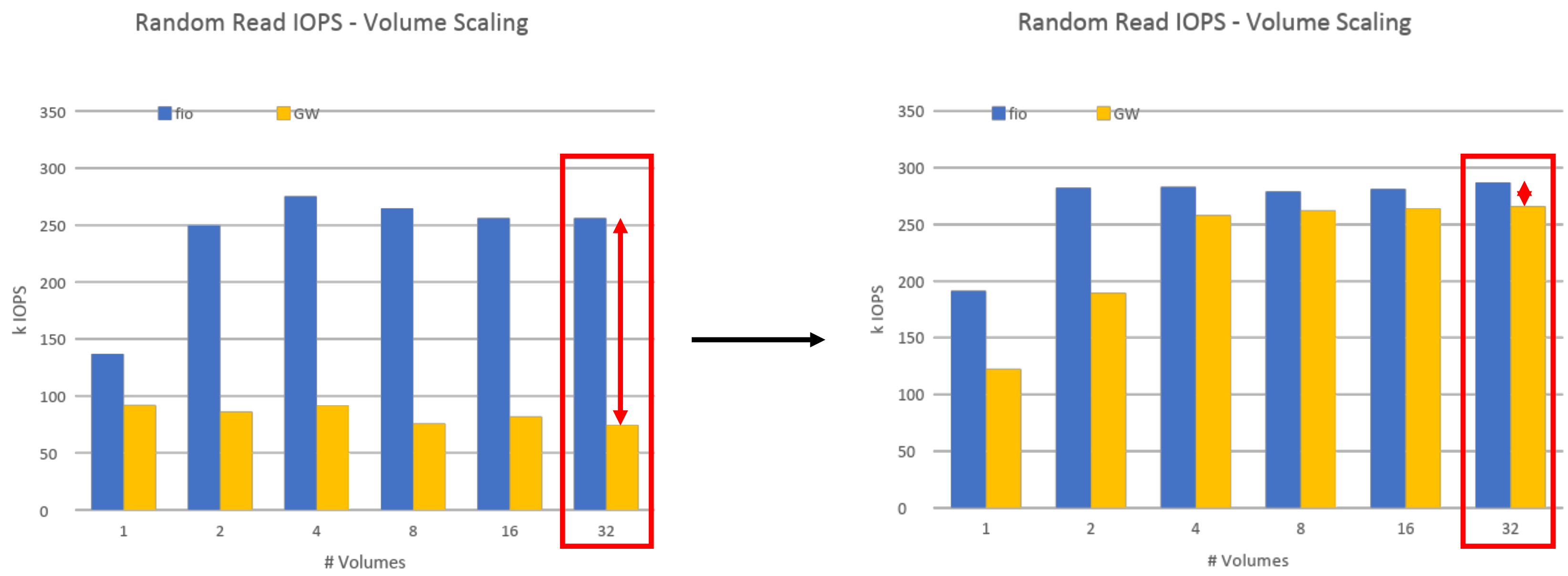
Goal: As close as possible to non-gateway performance



***Nodes:** 2x Intel(R) Xeon(R) Gold 6258R CPU @ 2.70GHz (**28 cores**), **100 Gbit/s** Mellanox ConnectX-5, Samsung PM1725a*
***3-node Ceph cluster:** Pacific & Quincy with rbd_cache=FALSE*

https://ci.spdk.io/download/2022-virtual-forum-prc/D2_4_Yue_A_Performance_Study_for_Ceph_NVMeoF_Gateway.pdf

Performance: Improvements



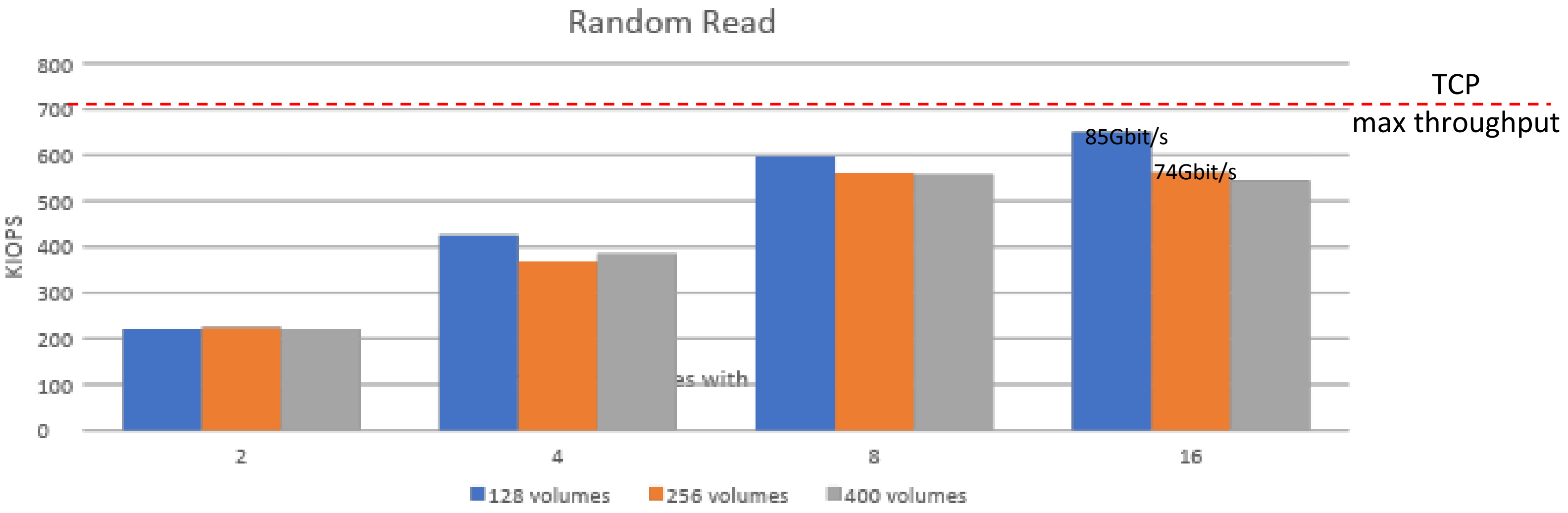
Random Read IOPS - Volume Scaling

Random Read IOPS - Volume Scaling

IO size = 16KiB, **Total QD** = 256
NVMe backed OSDs

Performance: Volume Scaling

- Use multiple Ceph client instances to improve performance in SPDK

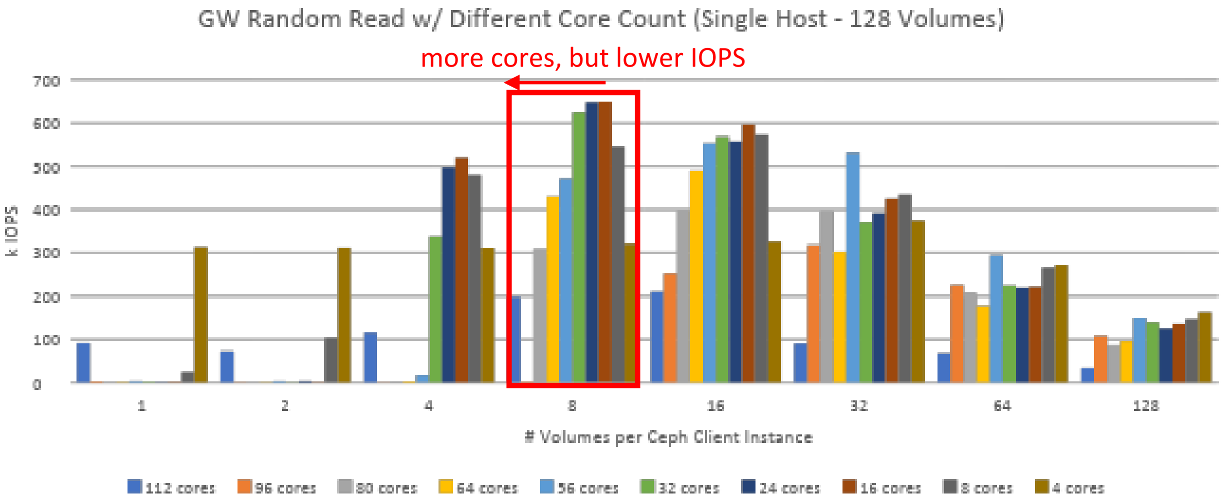


IO size = 16KiB, **Total QD** = 1024, **SPDK core mask** = 16 cores

RAMDisk backed OSDs

Performance: 128 volumes

- Use multiple Ceph client instances to improve performance in SPDK
- Check how core count effects performance



IO size = 16KiB, **Total QD** = 256

RAMDisk backed OSDs

Thank You!

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https://pad.ceph.com/p/rbd_nvmeof

Ceph Slack channel: **#nvmeof**

Weekly meeting: every Tuesday at 7am PT
https://meet.jit.si/ceph-nvmeof

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