RIO: Order-Preserving and CPU-Efficient Remote Storage Access

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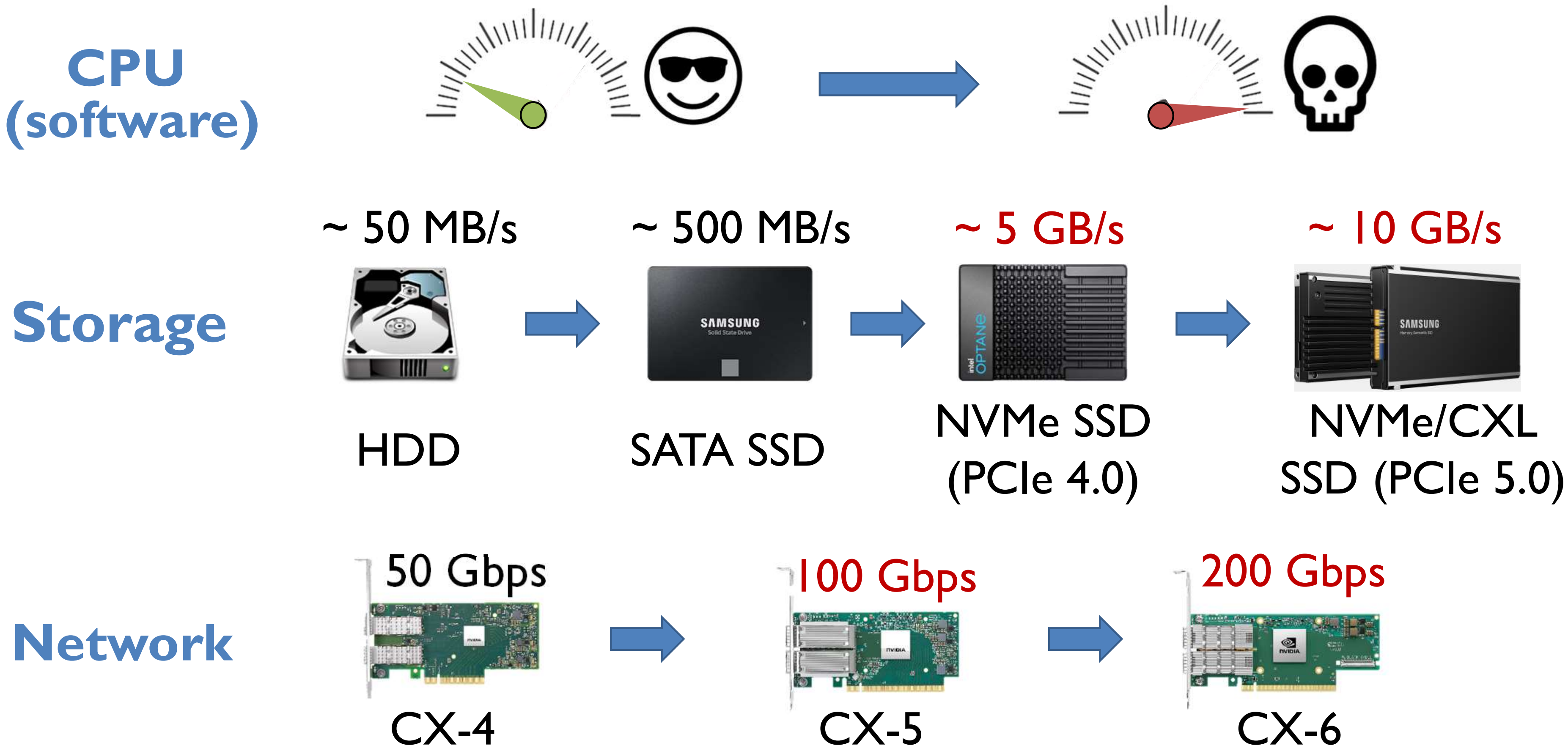
Agenda

- Background and Motivation
- RIO Design and Implementation
- Evaluation
- Conclusion

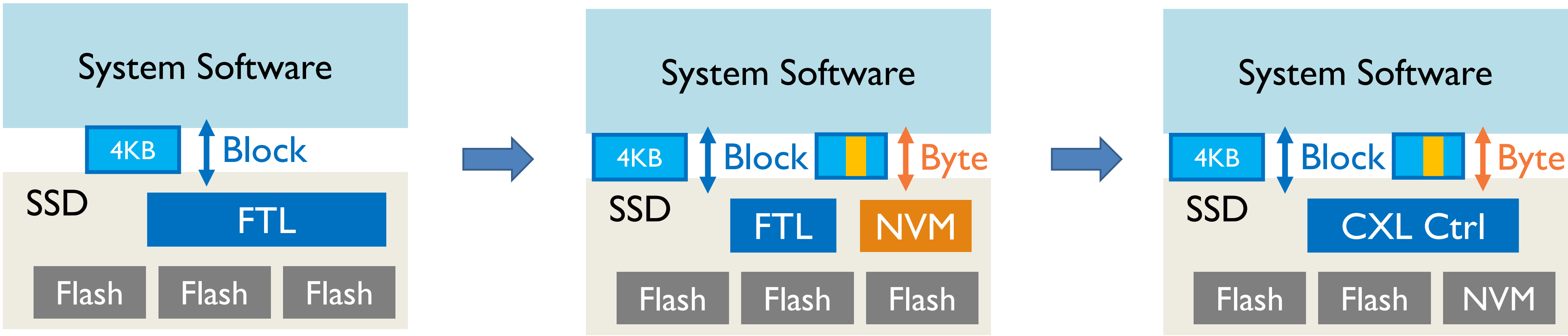
Hardware and software trend

Hardware performance boosts, software overhead increases



Hardware and software trend

- Commodity RDMA NICs already offer a byte/memory interface
- Research SSDs offer a byte/memory interface to aid the design of system software



Standard SSD
NVMe block storage

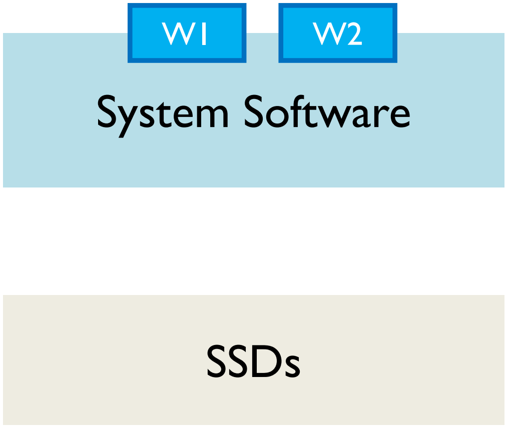
Byte-addressable SSD
PCIe BAR-based[1-3]
CMB, PMR

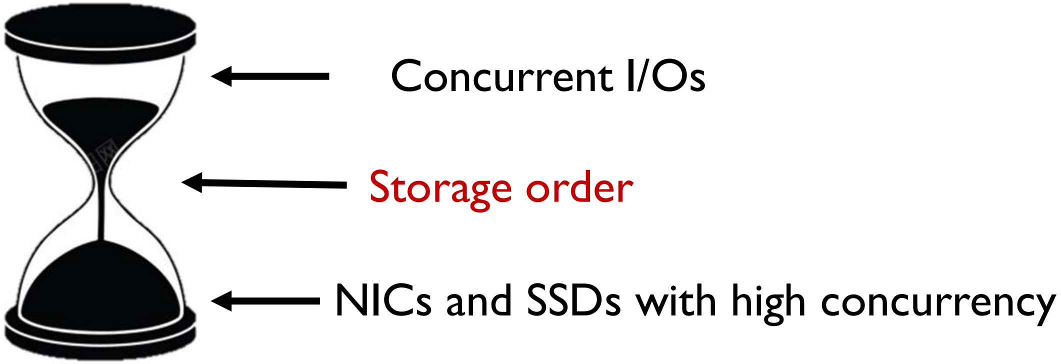
Byte-addressable SSD
CXL-based[4-5]

[1] 2B-SSD: The Case for Dual, Byte- and Block-Addressable Solid-State Drives, ISCA'18
[2] FlatFlash: Exploiting the Byte-Accessibility of SSDs within a Unified Memory-Storage Hierarchy, ASPLOS'19
[3] Crash Consistent Non-Volatile Memory Express, SOSP'21
[4] Hello bytes, bye blocks: PCIe storage meets compute express link for memory expansion, Hotstorage'22
[5] Samsung's Memory-Semantic SSD, https://samsungmsl.com/ms-ssd/

System software design: storage order

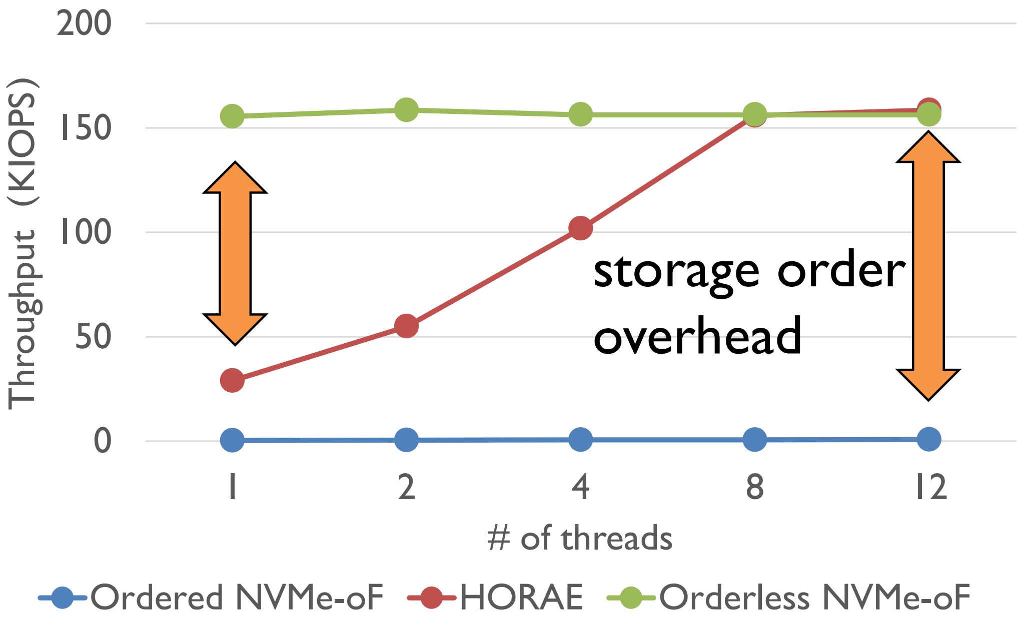
- The system software design this paper focuses on: storage order
- What is storage order: the persistence order of a set of data blocks
- Why does storage order matter: storage reliability (crash consistency)
- How is storage order enforced: almost a synchronous fashion



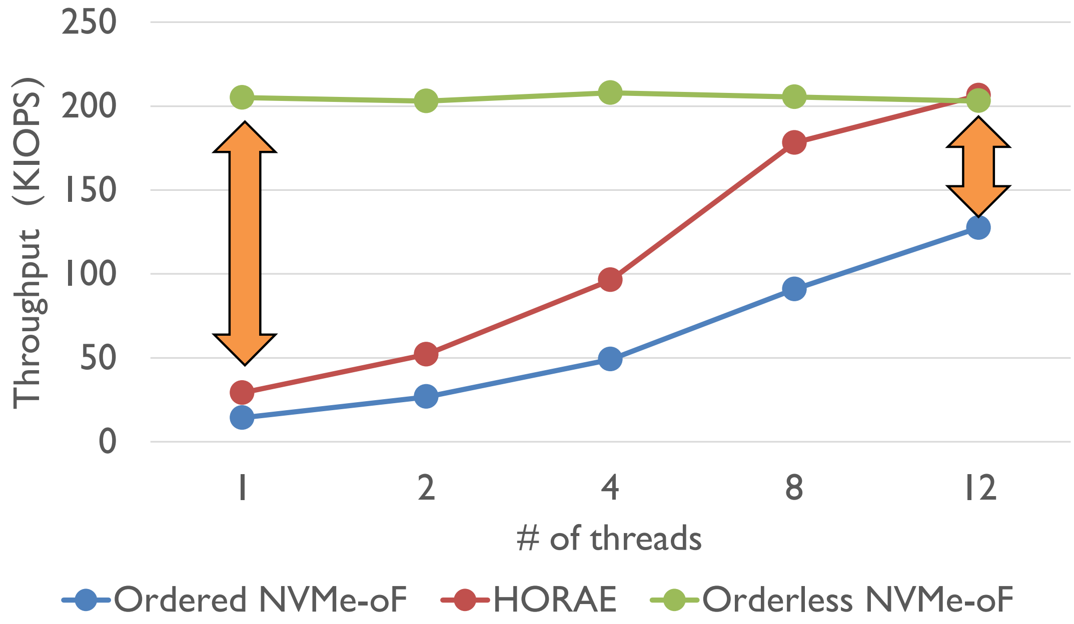


The overhead of keeping storage order

- Measured tool: FIO. Workloads: append writes + fsync
- Network: Mellanox CX-6, RDMA. Storage: Samsung PM981 flash SSD, Intel 905P Optane SSD
- Compared systems: Linux NVMe over Fabrics, HORAE [OSDI'20][1]



Flash SSD (w/o PLP)



Optane SSD (w/ PLP)

[1]Write Dependency Disentanglement with HORAE, OSDI'20

Overhead analysis

- Linux's approach to storage order

Block layer | NIC driver | Network transfer | SSD driver | PCIe transfer | FLUSH

Next ordered req.

Low concurrency

- HORAE's approach to storage order

Store ordering metadata | Block layer | NIC driver | Network transfer | SSD driver | PCIe transfer

Block layer | NIC driver | Network transfer | SSD driver | PCIe transfer

Block layer | NIC driver | Network transfer | SSD driver | PCIe transfer | FLUSH

Low concurrency

> 4µs in NVMe over RDMA

Try to minimize or avoid synchronous processing!

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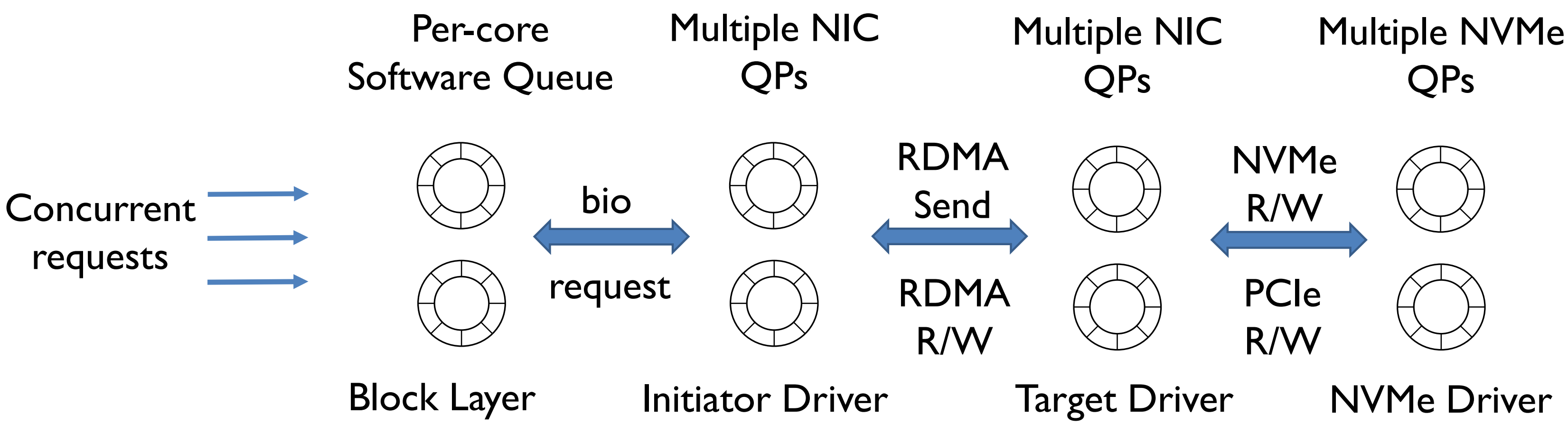
RIO's design insight

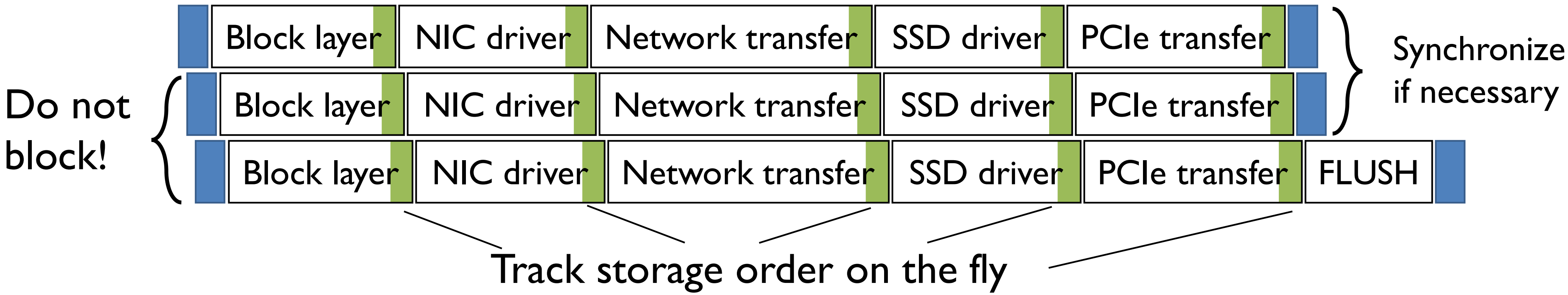
- Key observation: the layered design of modern I/O stack is similar to the pipeline.
  - Each layer performs a single functionality, and can process multiple requests concurrently (by the multi-queue interface).
  - Ordered write requests on non-overlapping LBAs can be parallelized.



The storage order should not stall the concurrent requests

RIO's design overview

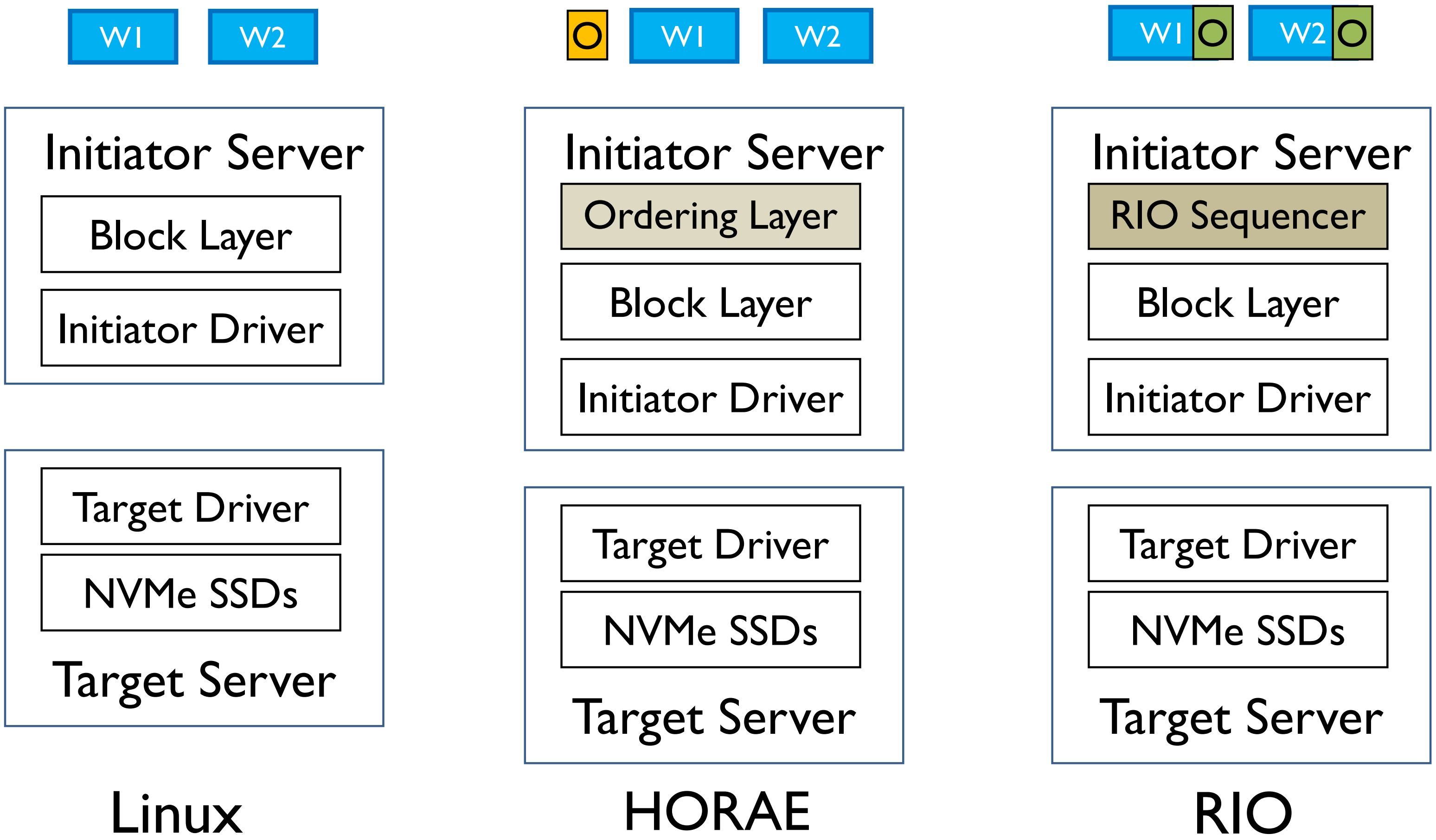
- Key idea: I/O pipeline for ordered write requests
  - Asynchronous processing: do not block, enables higher concurrency
  - Track storage order: enforce necessary synchronization, handle crashes
- RIO's approach: speculative, optimistic, higher concurrency, recovery needed



- Linux's approach: sequential, pessimistic, lower concurrency, no recovery

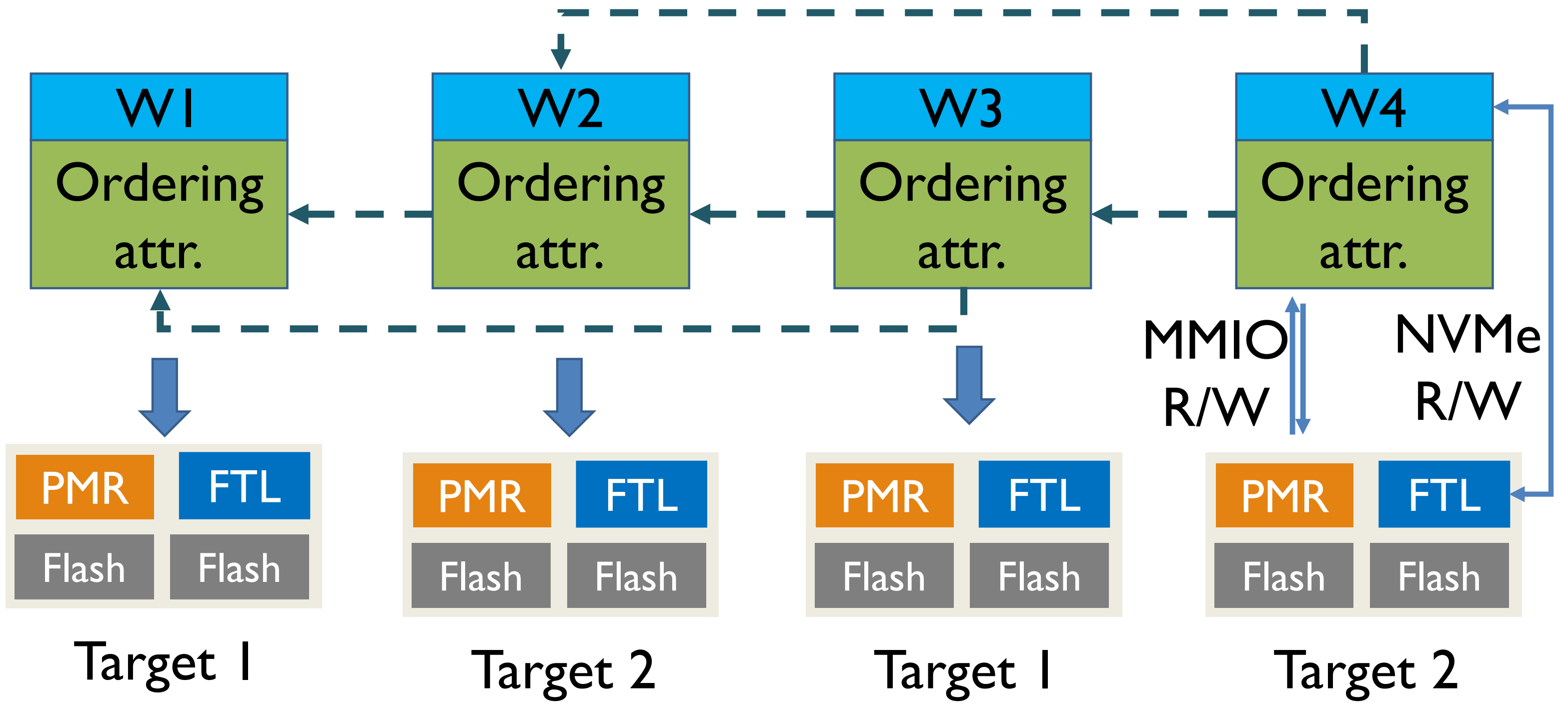
RIO's I/O path

- W1 must be durable before W2



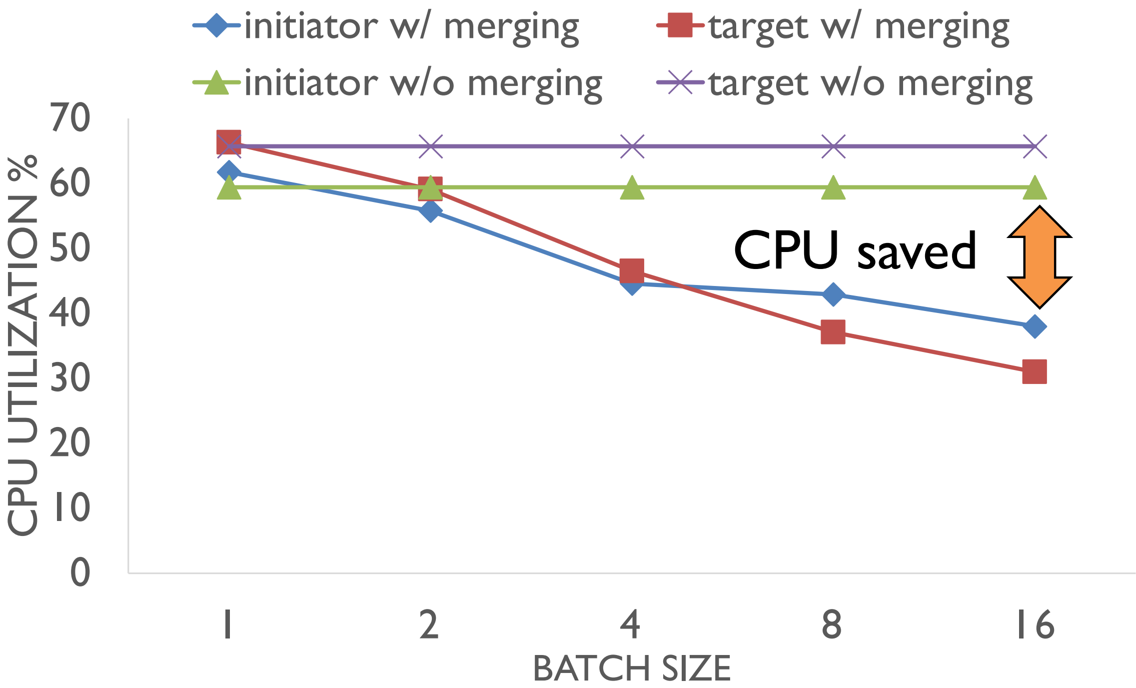
Tracking storage order in RIO

- Embed ordering attr. (describe the storage order) in each request
- Store ordering attr. to SSDs via MMIOs powered by the NVMe PMR feature

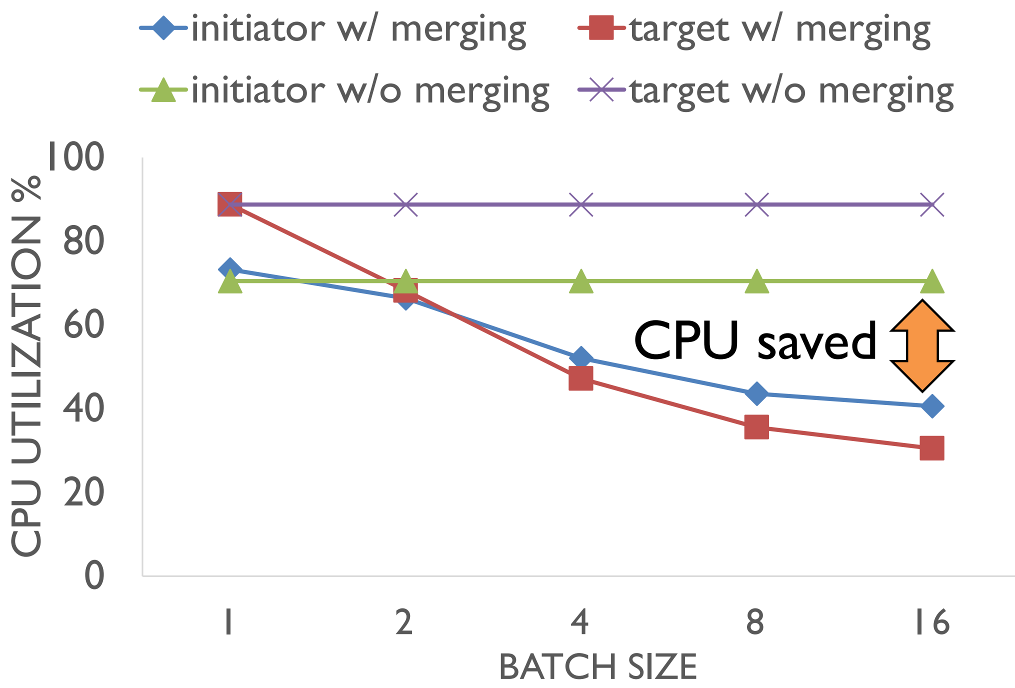


The motivation of RIO's I/O scheduling

- Ordered write requests in RIO can be scheduled and merged
- Request merging reduces the overall CPU overhead of remote storage access, although merging itself requires some CPU cycles



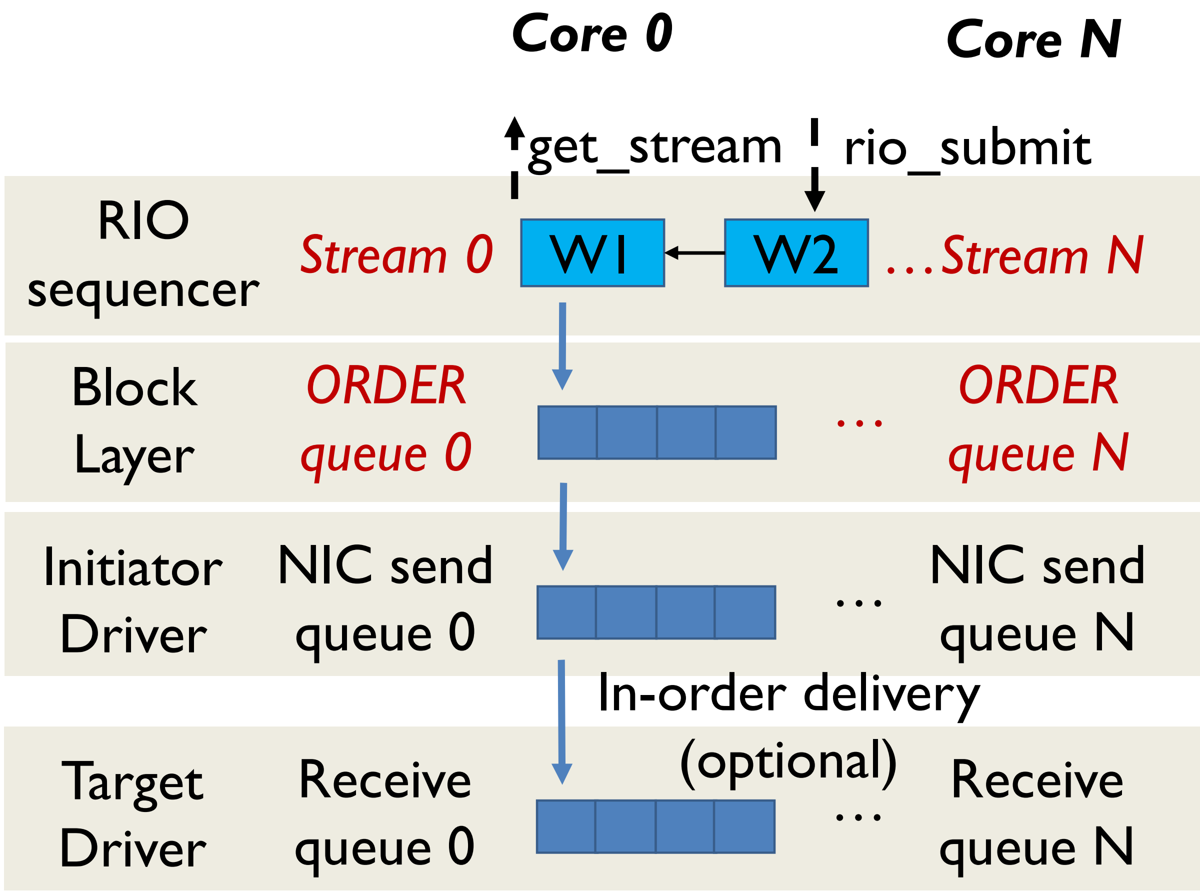
Flash SSD



Optane SSD

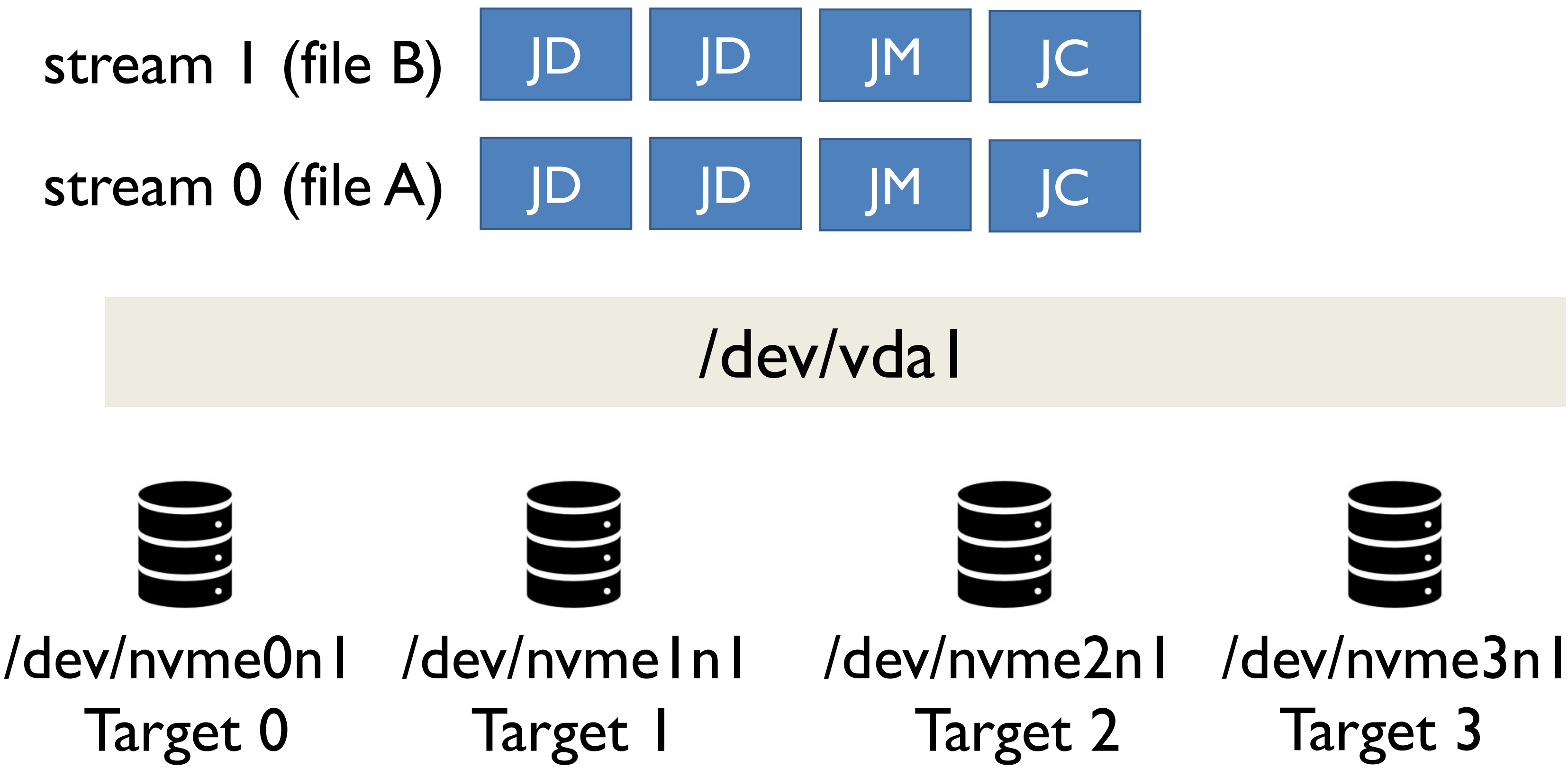
RIO’s I/O scheduling

- Separate ordered requests from the orderless via the ORDER queue
- Merge consecutive ordered requests in the ORDER queue without sacrificing the storage order
- Introduce the stream notion (a sequence of ordered write requests) for better scalability
- Align each stream to each NIC QP to exploit the in-order delivery of the network



Reorganizing journaling with RIO

- Concurrent JD, JM and JC, no barrier needed
- Per-file journal, each journal uses a dedicated stream



RIO’s Crash Recovery

- More details in the paper
  - Basic cases: out-of-place updates
  - Other cases: in-place updates
  - Data consistency and version consistency support
- Recovery overhead: 180 ms in the worst case (4 SSDs, 3 servers, 200Gbps RDMA)

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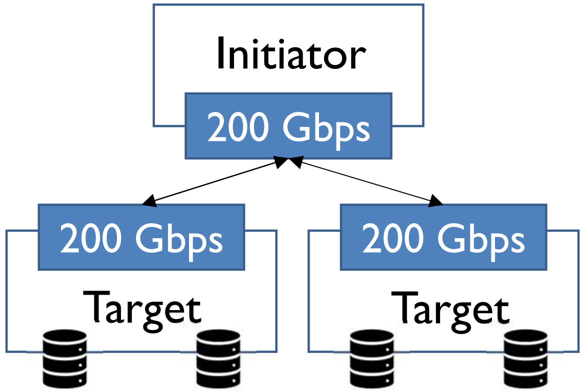
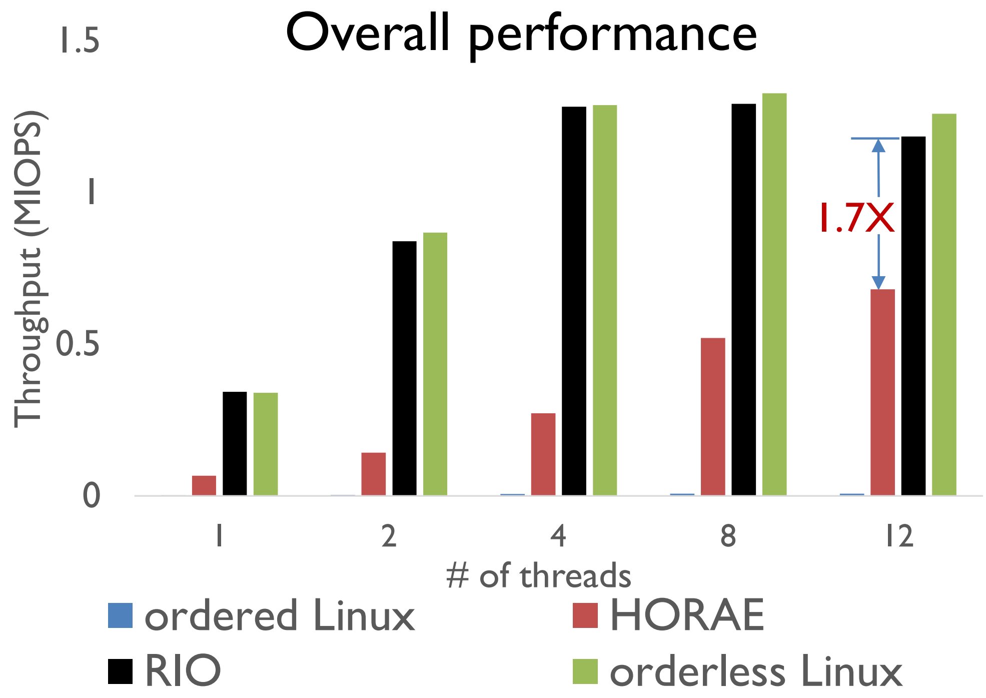
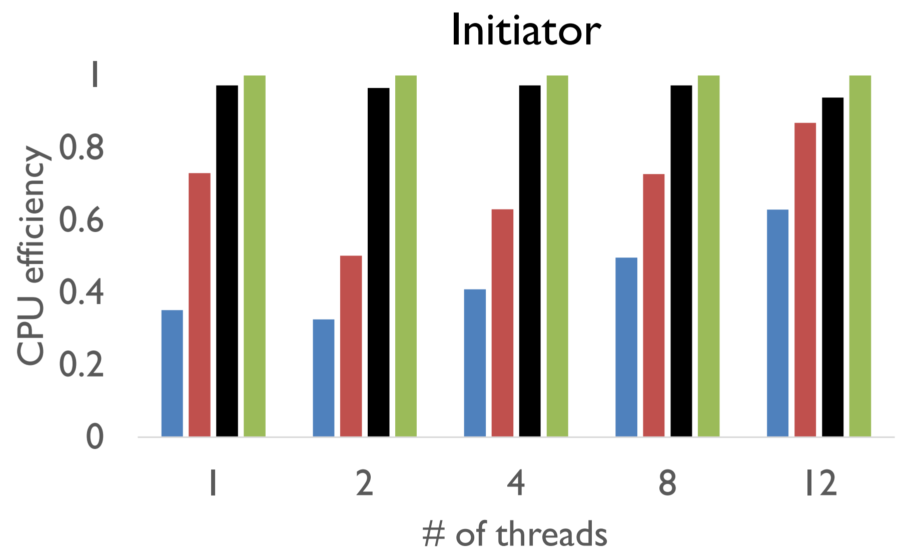
Evaluation setup

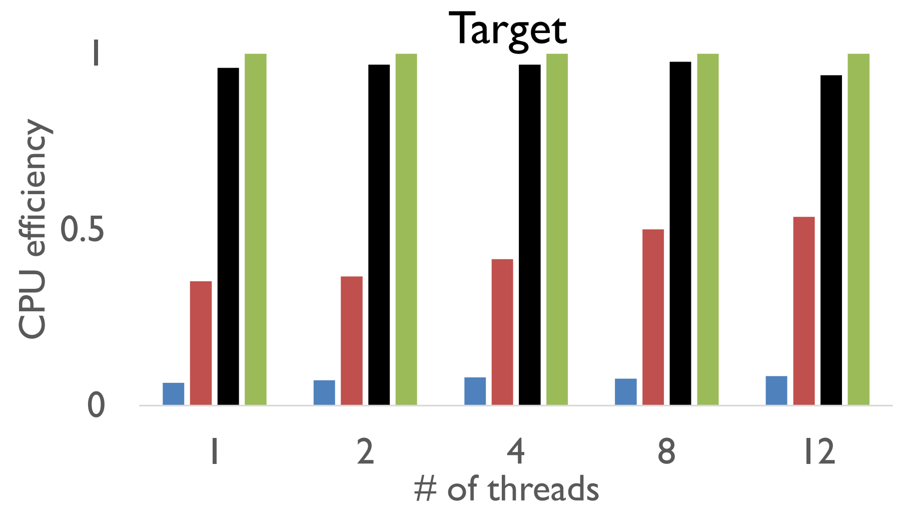
- 3 Servers: 1 Initiator server and 2 target servers
- CPUs: each server 2 Intel Xeon Gold 5220, 18 cores, 2.2 GHZ
- SSDs: Intel 905P(Optane), Intel P4800X(Optane), 2 * Samsung PM981(Flash)
- Network: NVIDIA ConnectX-6, 200 Gbps, RDMA
- OS: Ubuntu 18.04 LTS
- Compared Systems: Linux NVMe over RDMA from NVIDIA, an NVMe-oF version of HORAE[OSDI'20], RIO based on the same codebase of Linux NVMe over RDMA



Microbenchmark: ordered writes





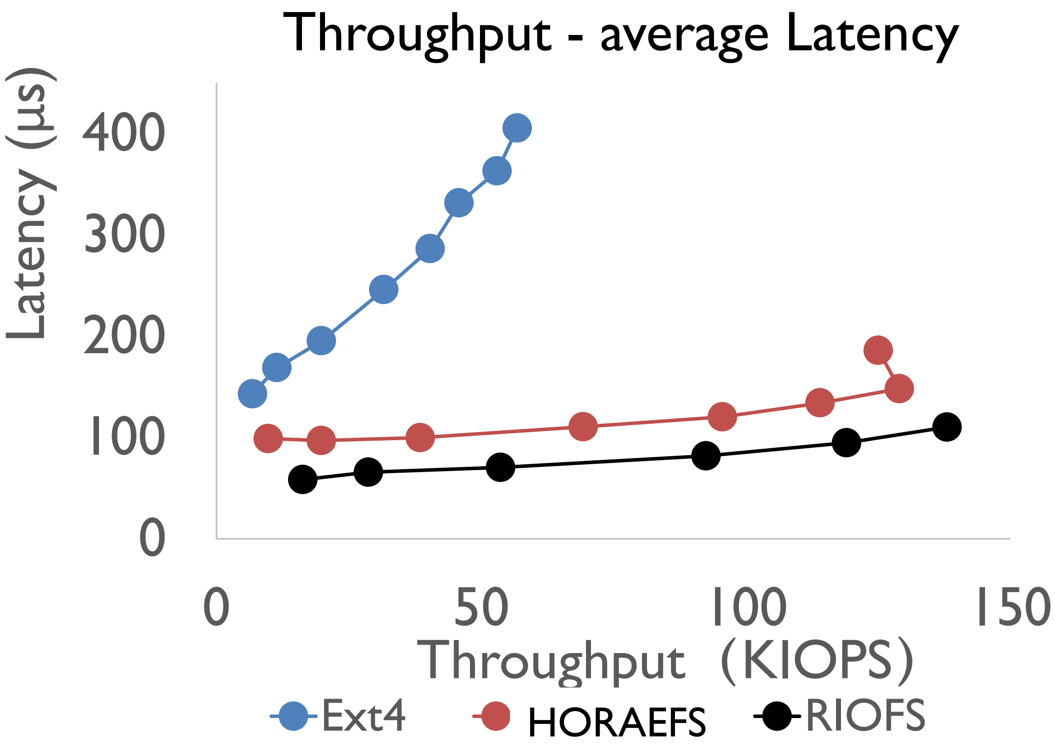


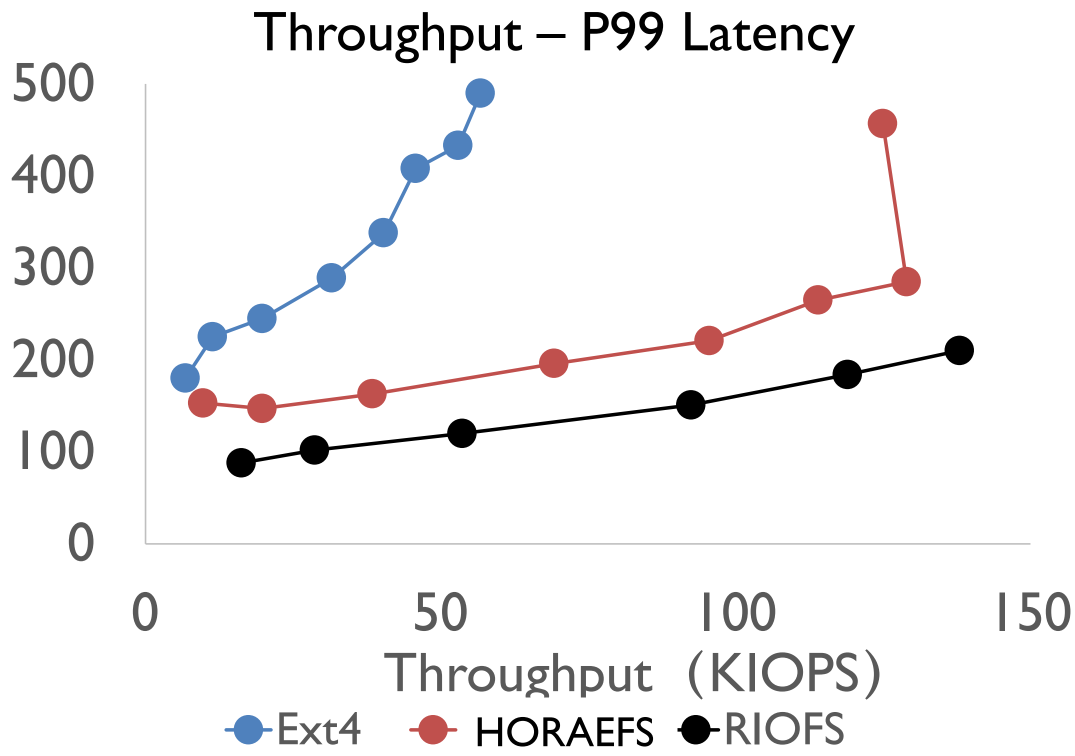
- Workloads: multiple threads concurrently append 4 KB data blocks with storage ordering guarantee
- CPU efficiency: throughput / CPU utilization, normalized to the orderless Linux.

RIO ≈ orderless Linux

Evaluation: file systems

- Workloads: FIO 4KB append writes with fsync
- HORAEFS: the original HORAE + per-file journal; RIOFS: RIO + Ext4 + per-file journal

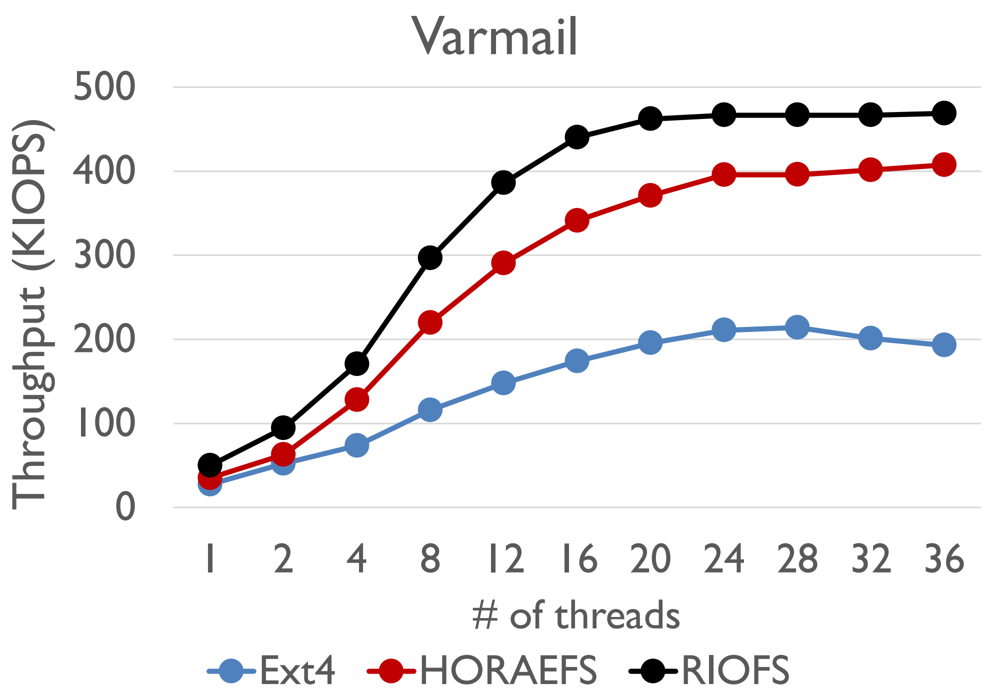


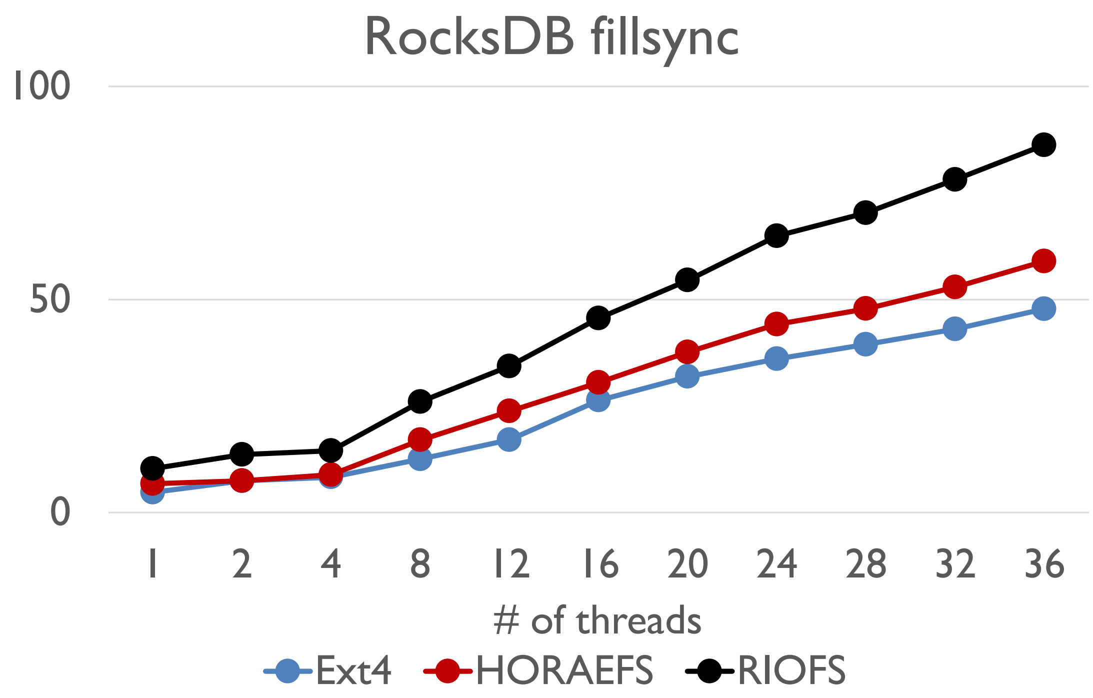


RIO achieves higher throughput, lower and more stable latency.

Evaluation: Varmail & RocksDB

- Varmail: Filebench default settings, create, unlink and fsync intensive
- RockDB: compaction intensive, 16B keys, 1024B values





RIO achieves higher throughput with less CPU cores

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Conclusion

- RIO: Order-Preserving and CPU-Efficient Remote Storage Access
  - Problem: Storage order overhead. Root cause: synchronization.
  - Solution: RIO's I/O pipeline = asynchronous processing + tracking storage order + recovery.
  - Result: higher CPU and I/O efficiency compared to existing systems.
- Takeaways:
  - Asynchronous processing (even in a synchronous interface) is the key to unleash the performance of fast storage and network hardware.
  - The byte interface is well suited for storing the temporary yet persistent metadata or control information of the storage systems.

Q&A

Thank You!

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