BIZA: Design of Self-Governing Block-Interface ZNS AFA for Endurance and Performance

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Why We Need All-Flash Array (AFA)?

DELL EMC VMAX

PureStorage FlashArray

AFA → Superb **performance** & **reliability**!

Datacenters

Supercomputers

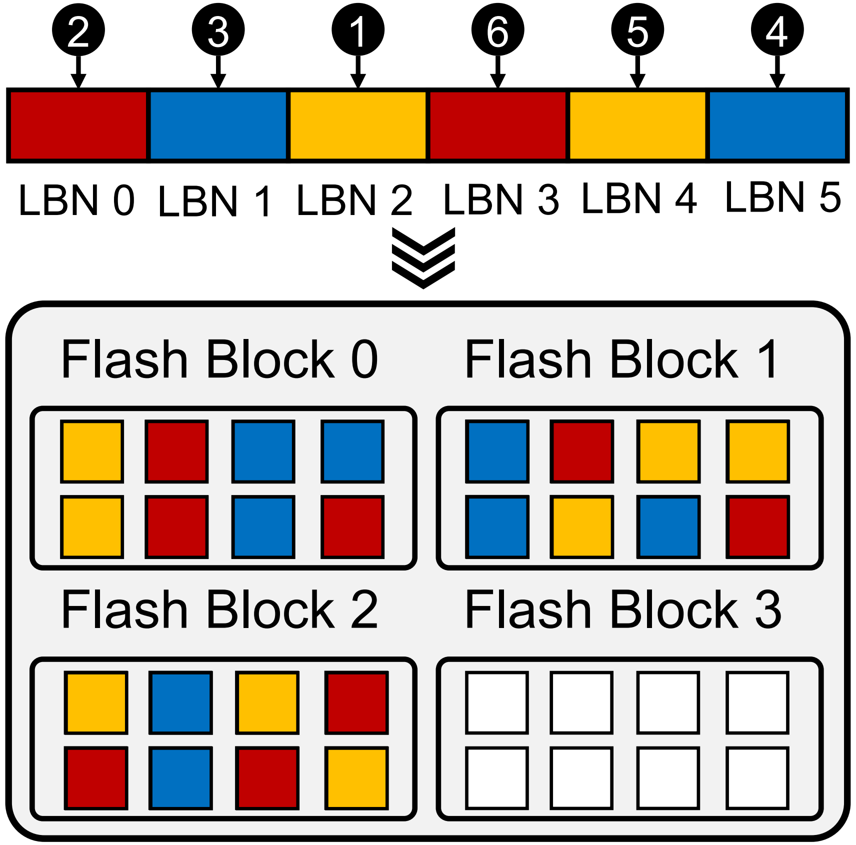
WD OPENFLEX

NetApp AFF

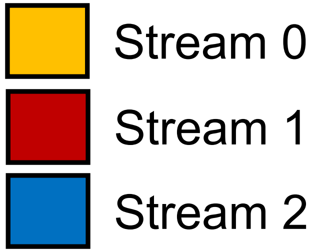
All-flash array are widely adopted in diverse domains.

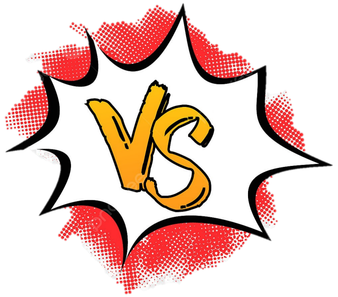
Open Question: I/O Interface Choices

Block Interface

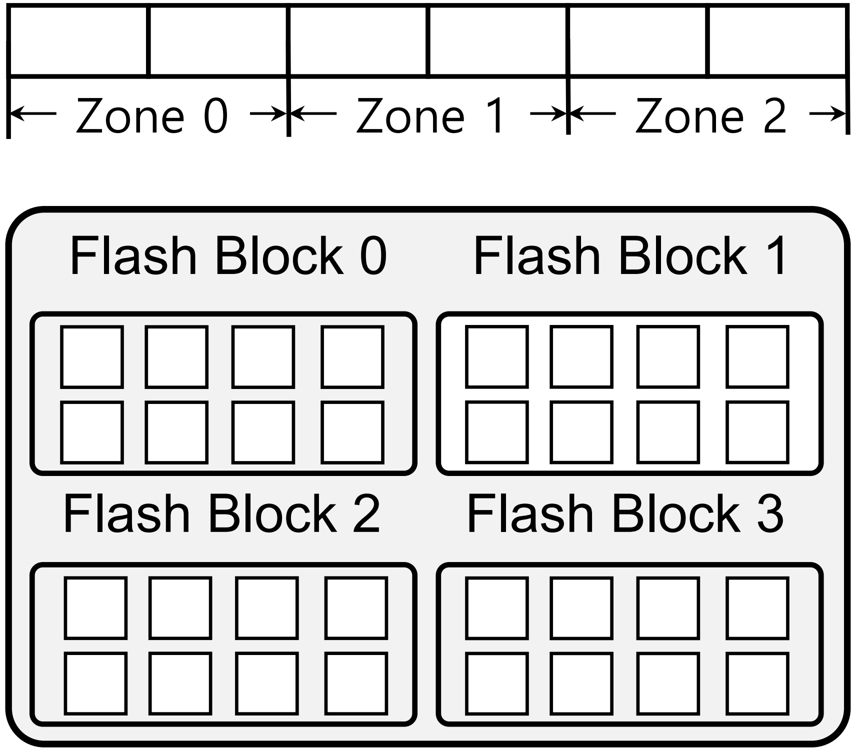


Conventional SSD



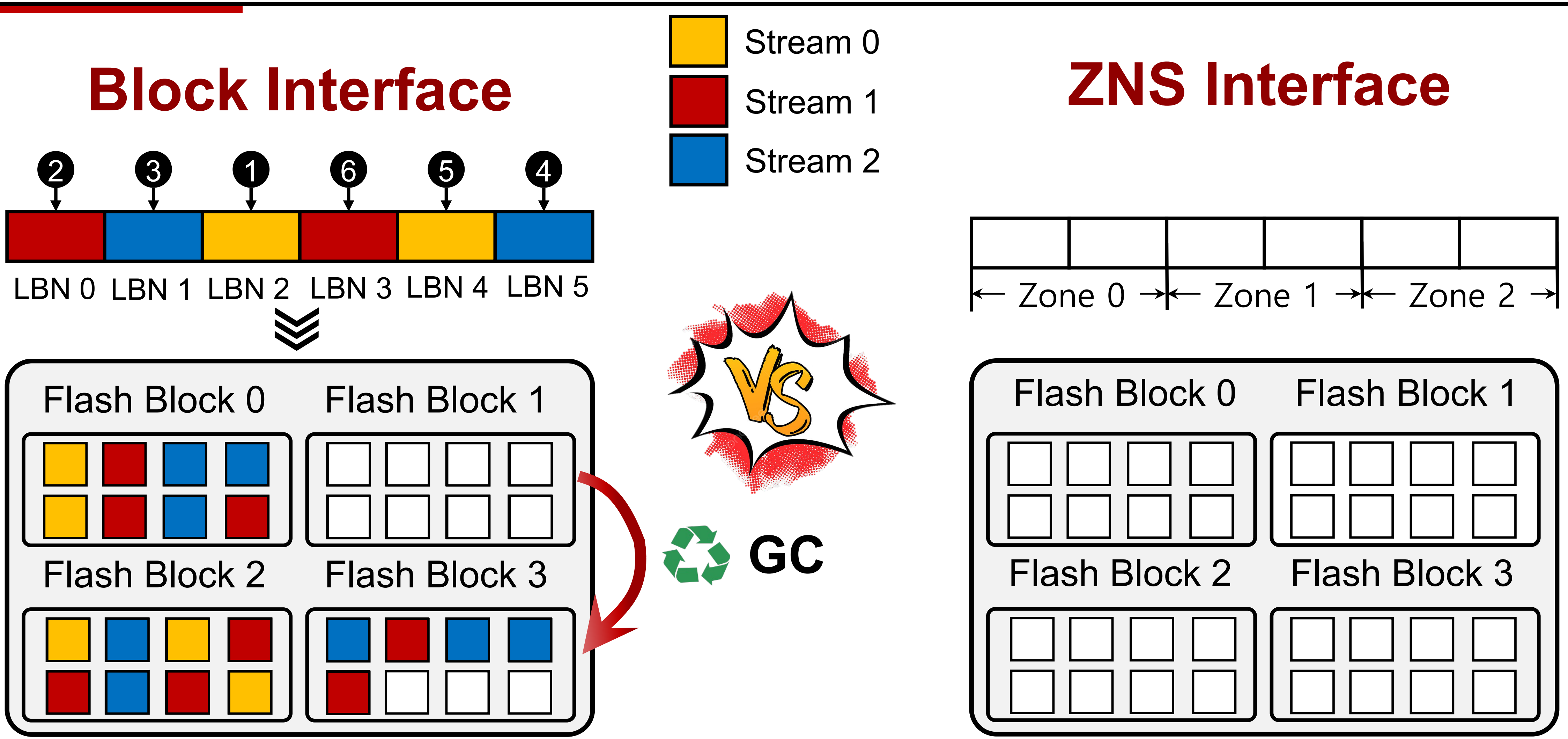


ZNS Interface



Zoned Namespace (ZNS) SSD

Open Question: I/O Interface Choices



Conventional SSD

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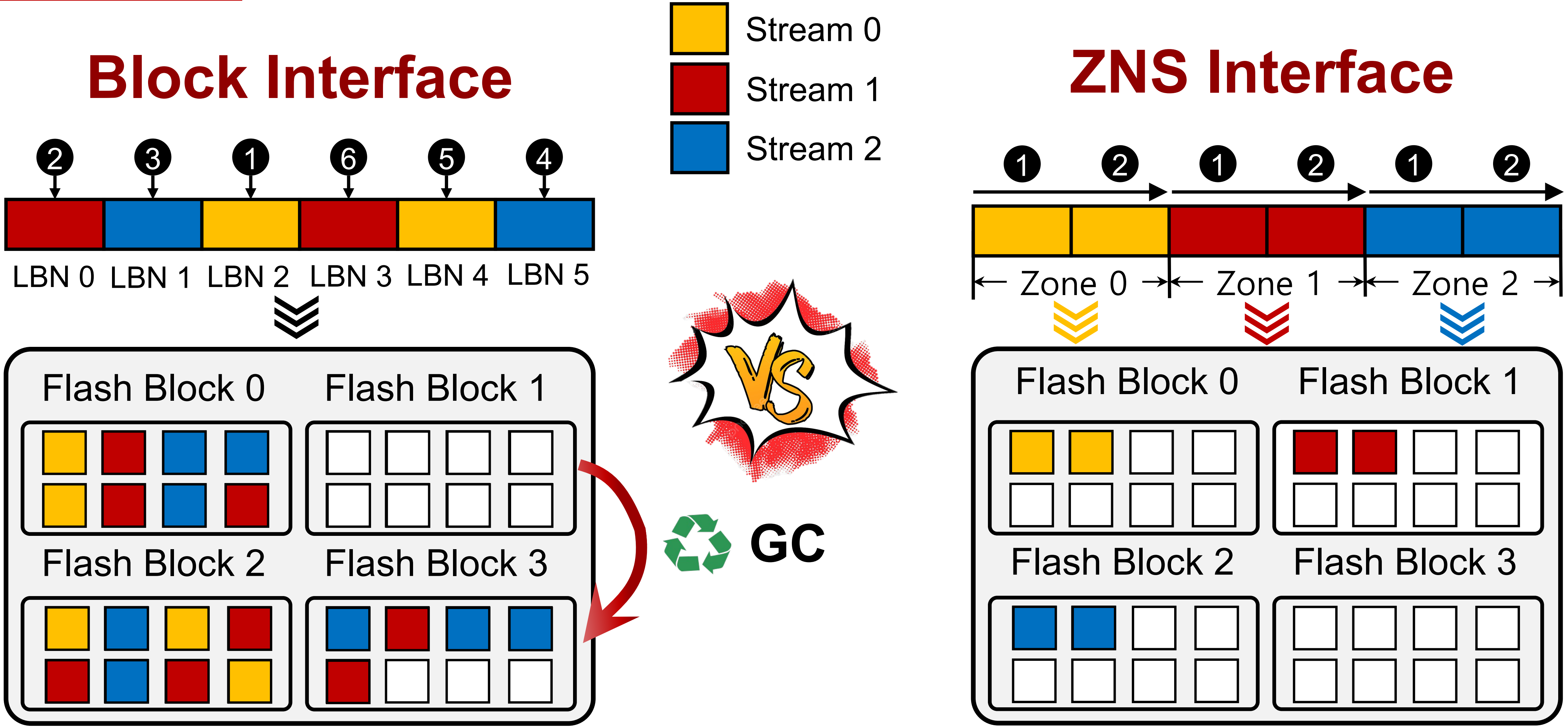
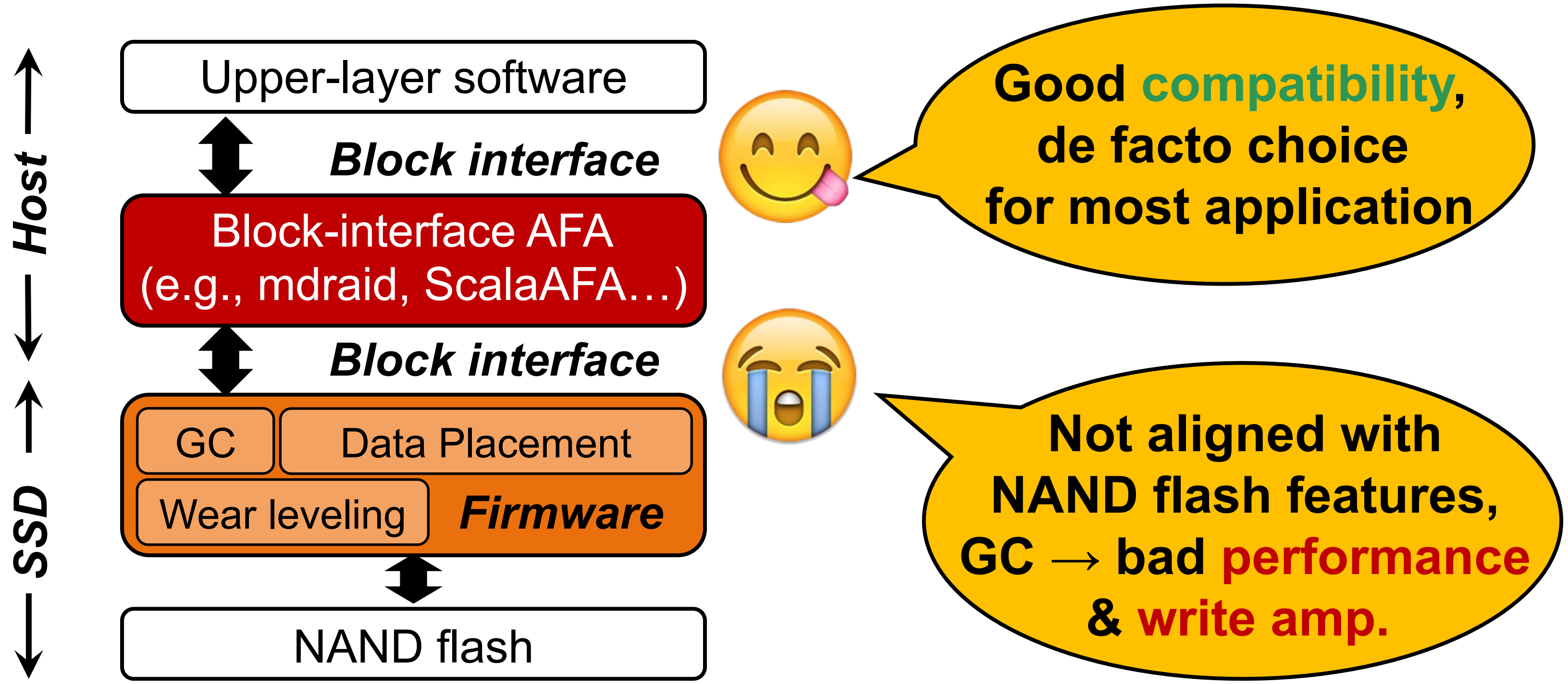


Conventional SSD | **Zoned Namespace (ZNS) SSD**

Existing Designs: Rob Peter to Pay Paul

- **Block-interface AFA:** mdraid (Linux default)[1], ScalaAFA (ATC'24)[2]
  - Random writes → good compatibility, SSD-internal tasks → bad performance & write amplification



[1] Linux. mdraid layer. h!ps://github.com/torvalds/linux/tree/master/drivers/md.
[2] ScalaAFA: Constructing User-Space All-Flash Array Engine with Holistic Designs (ATC'24)

Existing Designs: Rob Peter to Pay Paul

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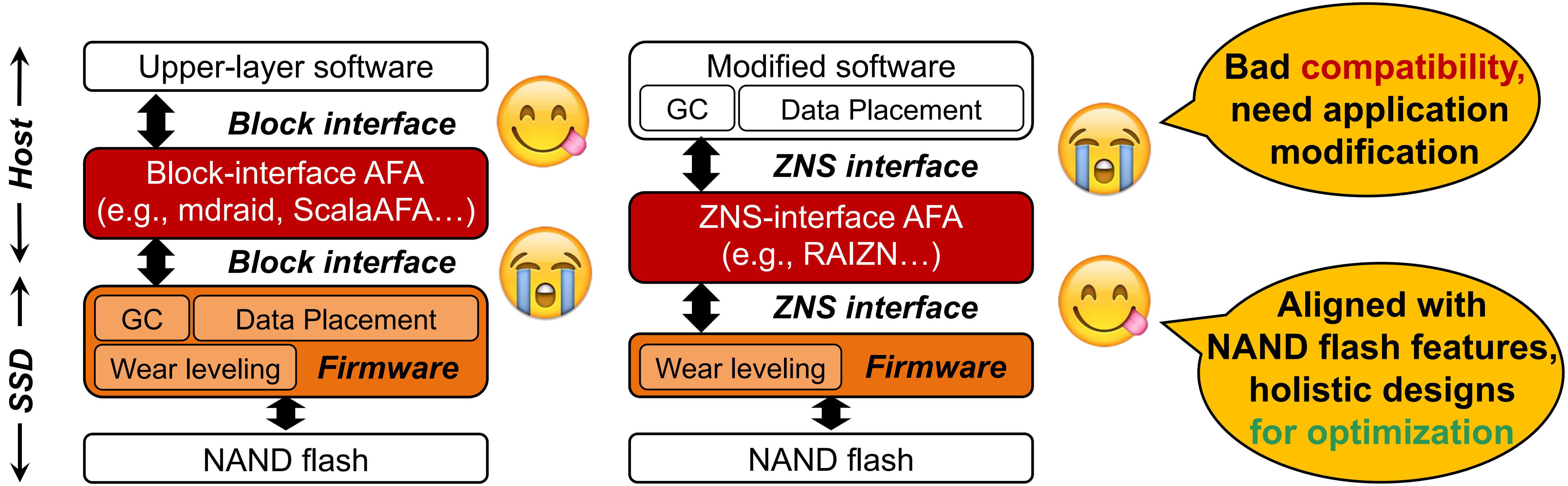
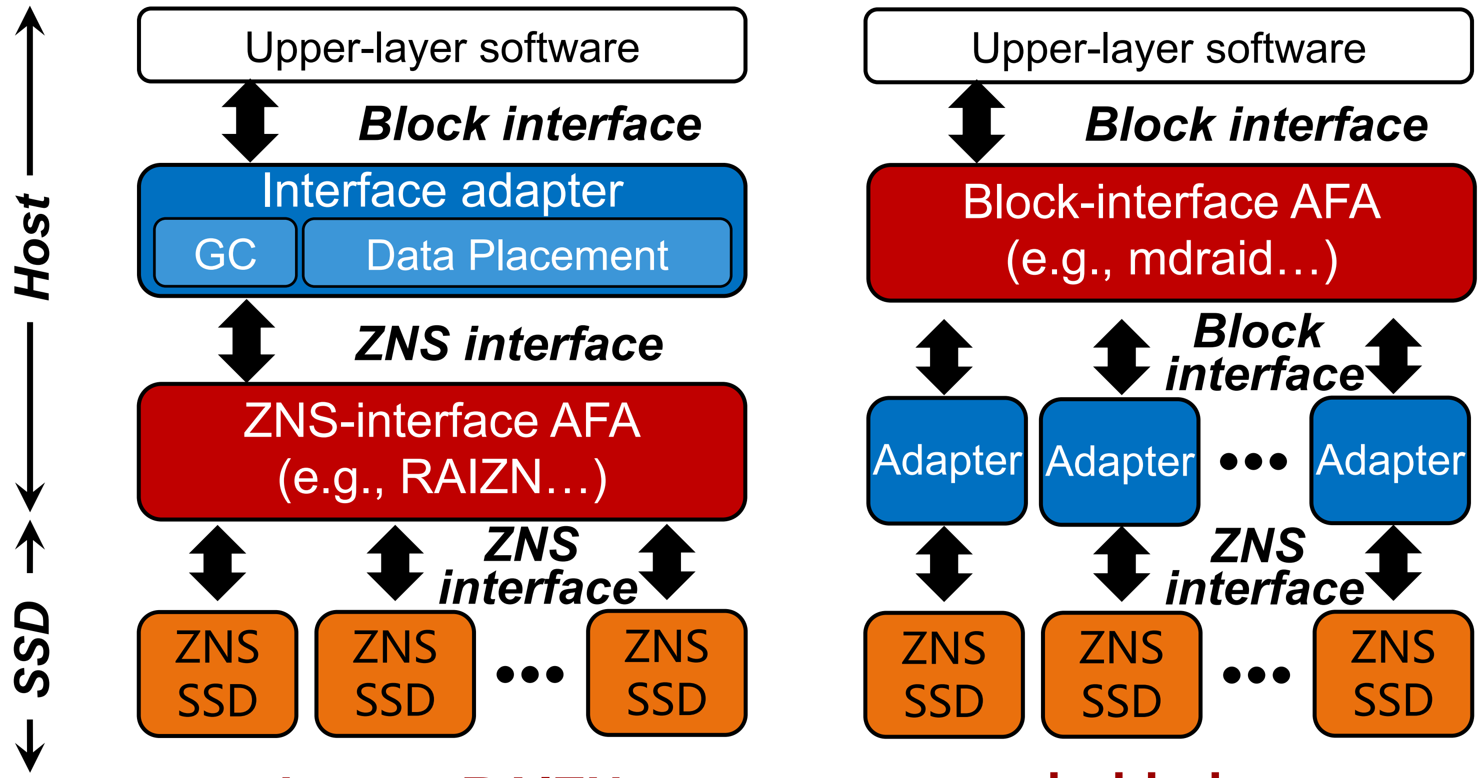
  - Random writes → good compatibility, SSD-internal tasks → bad performance & write amplification
- **ZNS-interface AFA:** RAIZN (ASPLOS'23)[1]
  - host-managed tasks → holistic designs for optimization, Sequential writes → bad compatibility



[1] RAIZN: Redundant Array of Independent Zoned Namespaces (ASPLOS'23)

Interface Adapter: A Simple Solution

- **Interface adapter**: dm-zoned (Linux), dm-zap (Western Digital)
  - Converting ZNS interface to block interface
  - Maintaining mappings from block numbers to zone-related addresses



dmzap+RAIZN **mdraid+dmzap**

Bridged semantic gap, but failed to harvest the benefits of ZNS

Quantitative Analysis

- **Experimental setup:** 3+1 (RAID 5) Western Digital ZN540 4TB SSDs
  - Peak throughput: 3265 MB/s and 2170 MB/s for read and write

WD ZN540 SSD

Challenge 1: Short endurance

- dmzap+RAIZN and mdraid+dmzap generate 33.3% and 54.6% more flash writes
- dm-zap muddles data with dfferent lifetimes in the same zones

Challenge 2: Low throughput

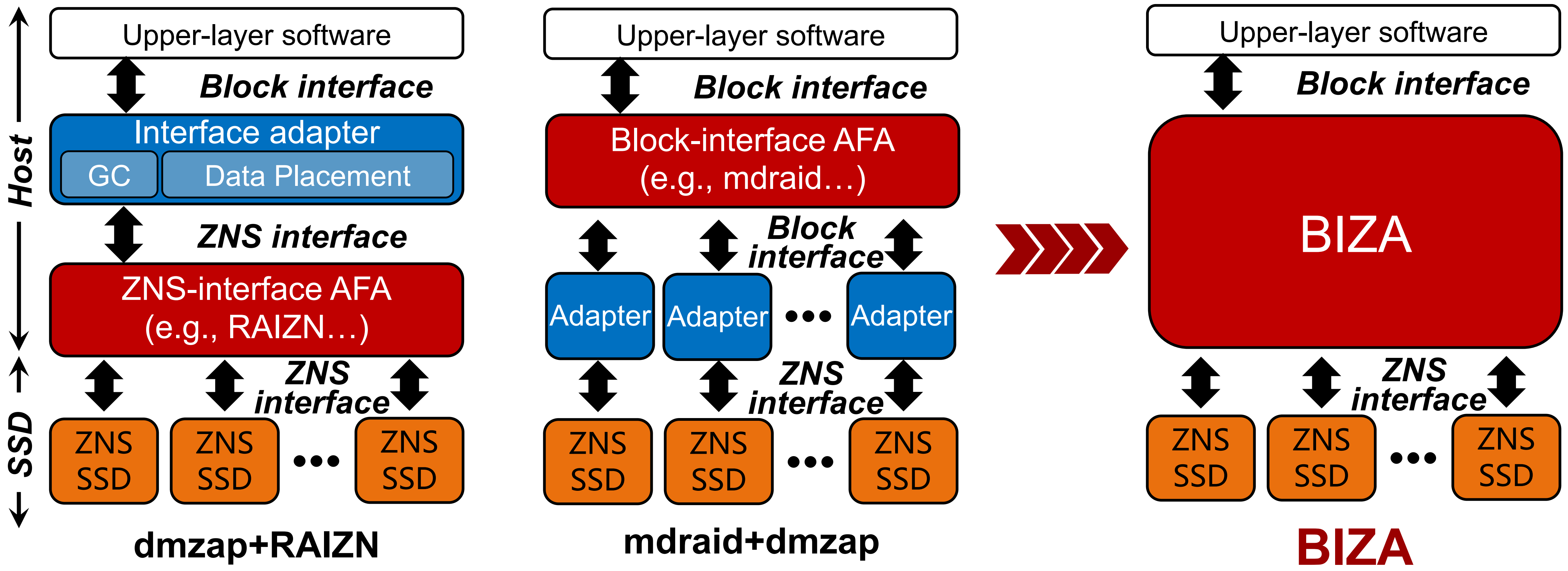
- dmzap+RAIZN and mdraid+dmzap only achieve 47.7% and 18.4% of the ideal throughput
- dm-zap submits writes serially and only allows one in-flight write per zone
- RAIZN relies on a centralized zone to buffer the frequently updated metadata

Challenge 3: High tail latency

- dmzap+RAIZN and mdraid+dmzap increase 99.99^{th} tail latency by 10.3x and 2.2x after GC starts
- dm-zap handle GC and user I/O with the same I/O resources

Please refer to our paper for details.

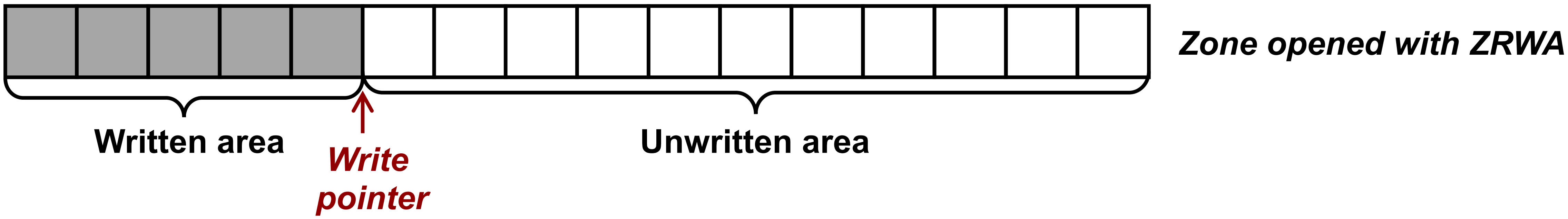
Our Solution: BIZA



Key insight: new features & internal parallelism

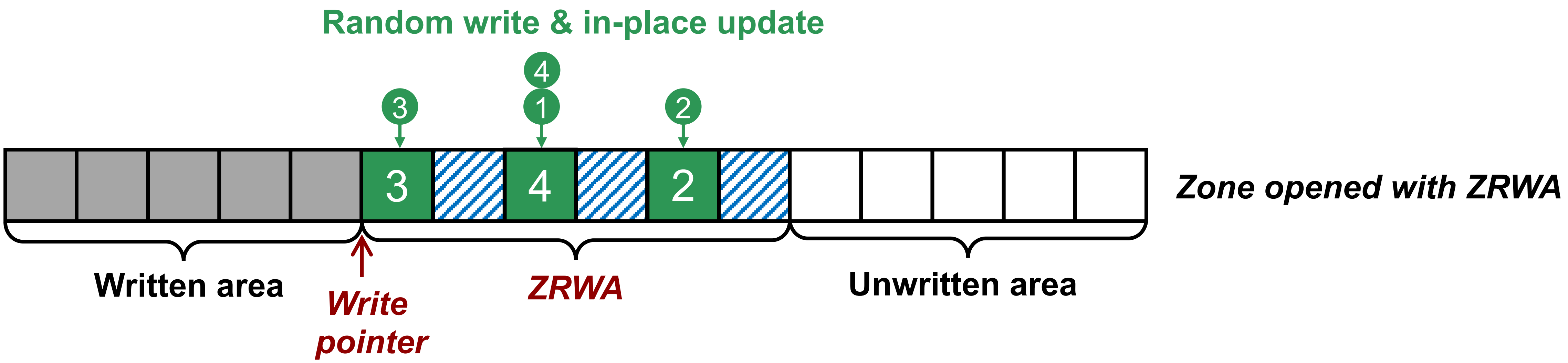
ZNS SSD Exploration: Zone Random Write Area

- NVMe Technical Proposal 4076b: Zone Random Write Area (ZRWA)



ZNS SSD Exploration: Zone Random Write Area

- **NVMe Technical Proposal 4076b: Zone Random Write Area (ZRWA)**
  - Break the strict sequential write constraint
  - An efficient abstraction of the write buffer within SSDs
  - Battery-backed DRAM, NVM, or FTL-mapped high-endurance flash (e.g., SLC)



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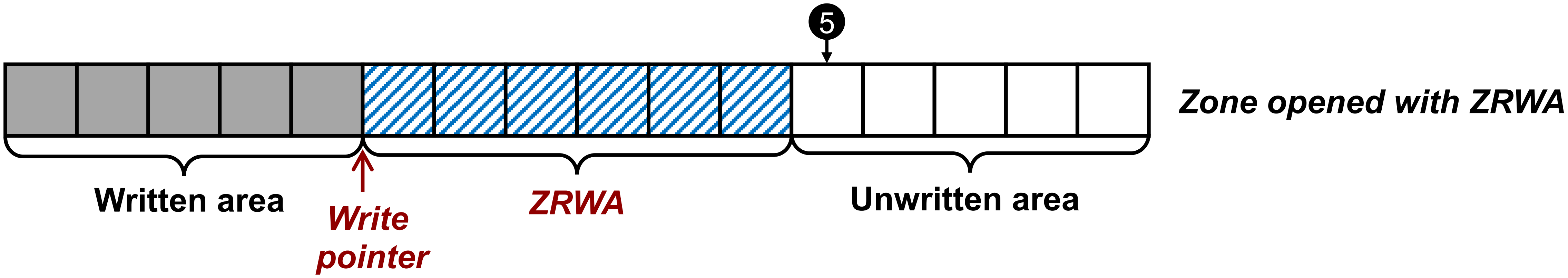

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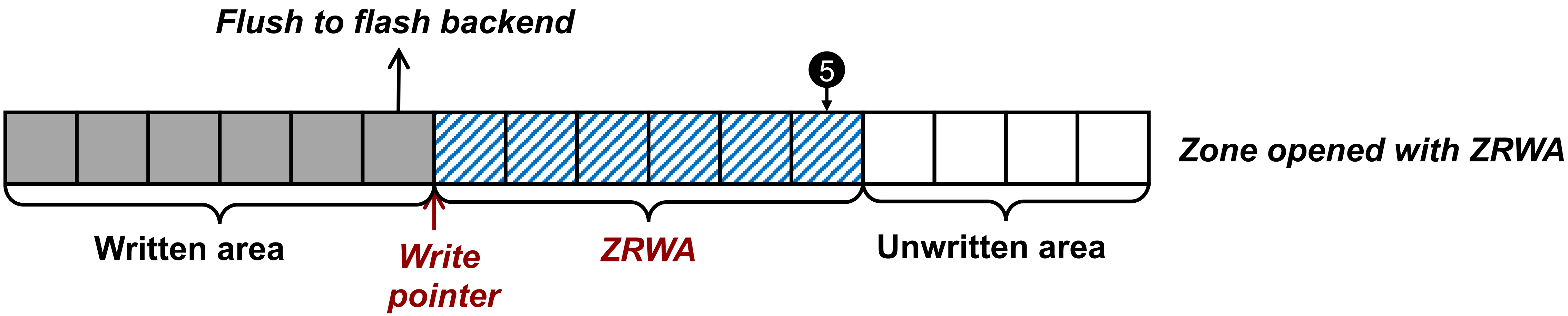

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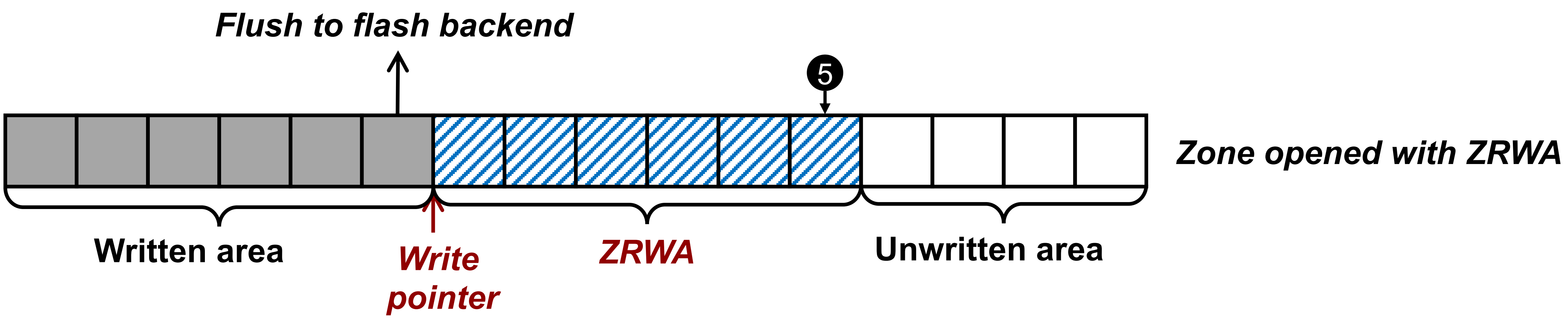

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ZNS SSD Exploration: Zone Random Write Area

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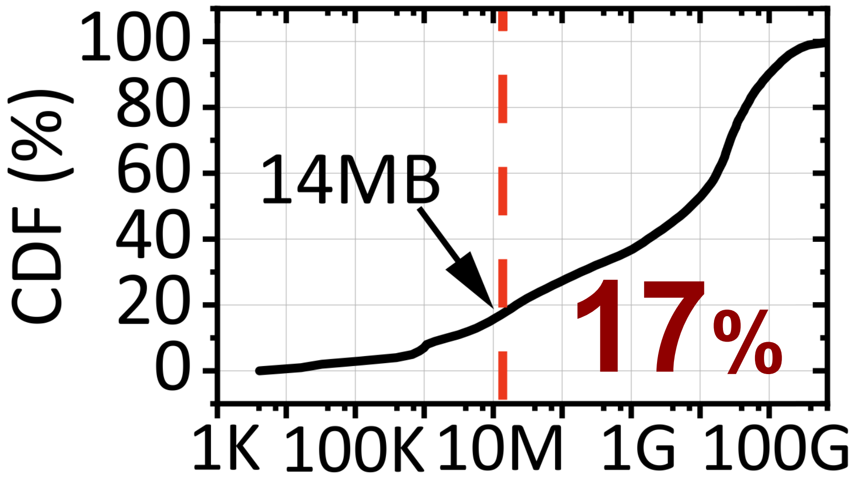
However, the size of ZRWA is very limited per ZNS SSD

ZNS SSD	Zone Capacity	ZRWA size per open zone	Total ZRWA size
WD ZN540	1077 MB	1 MB	14 MB
DapuStor J5500Z	18144 MB	1 MB	16 MB
Inpur NS8600G	96 MB	1440 KB	11.25 MB



Reuse distance of SYSTOR [1]

[1] Understanding storage traffic characteristics on enterprise virtual desktop infrastructure. (SYSTOR'17)

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How to use the limited size of ZRWA efficiently?

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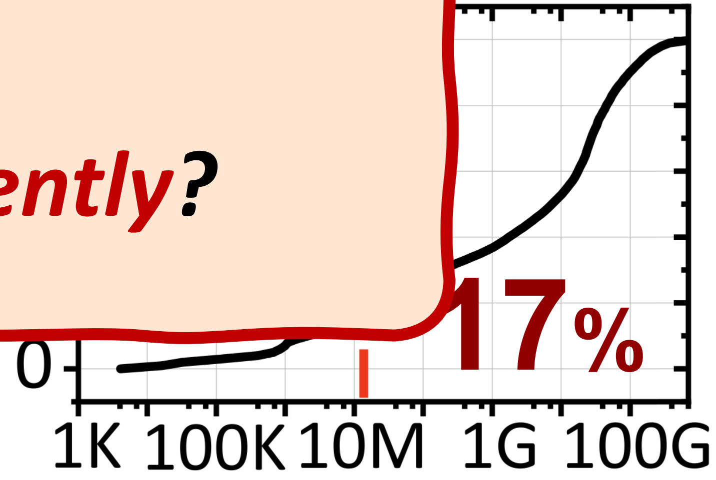

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ZNS SSD Exploration: Intra-Zone Parallelism

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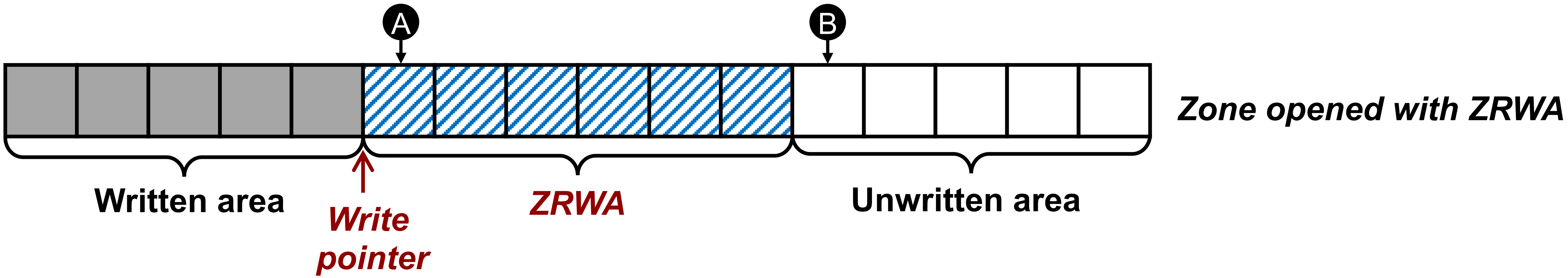

[1] Linux Block IO: Introducing Multi-queue SSD Access on Multi-core Systems (SYSTOR'13)

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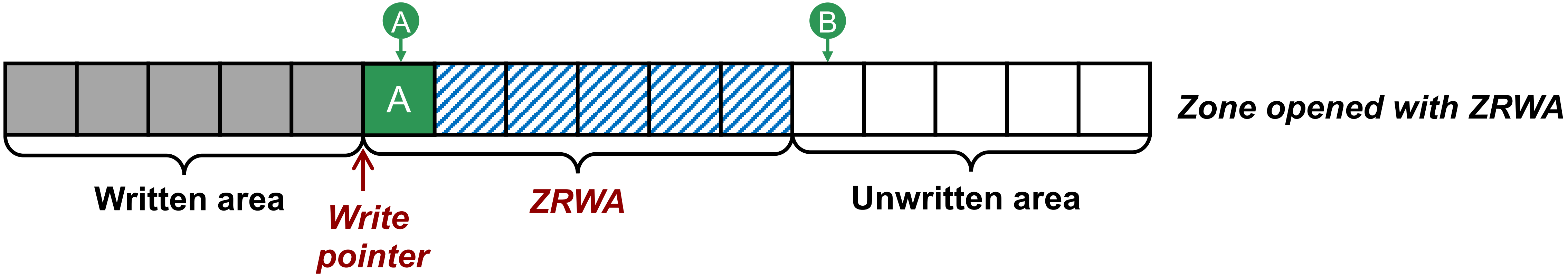

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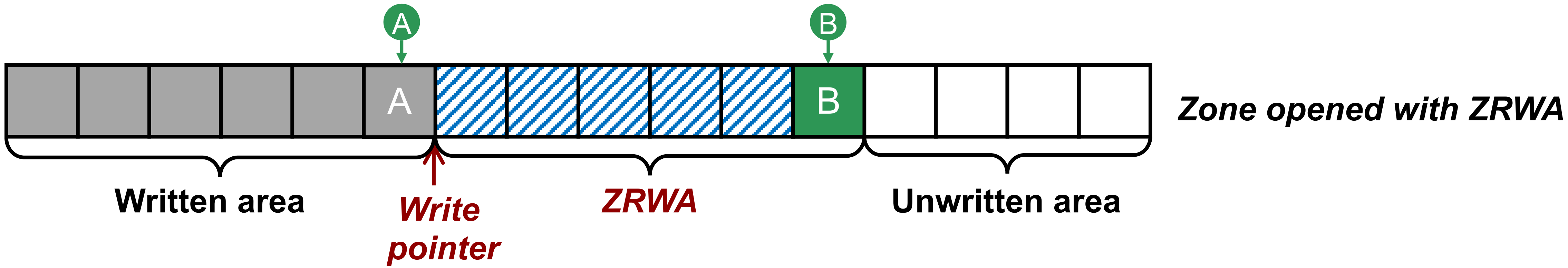

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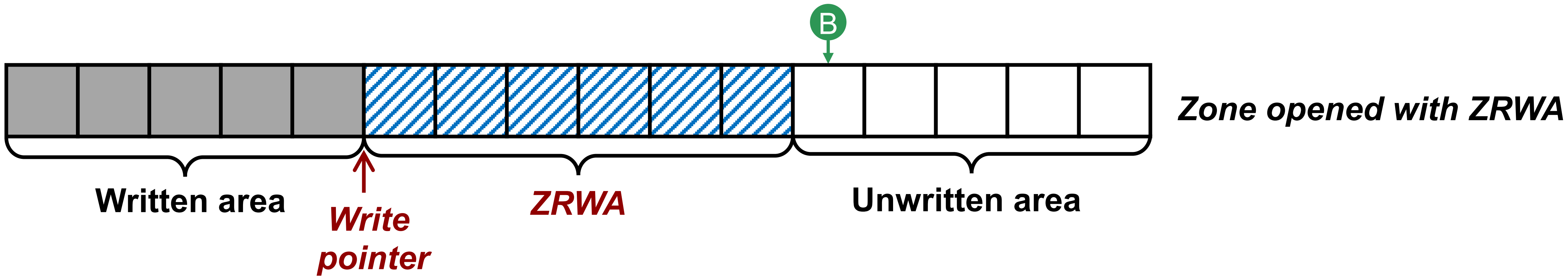

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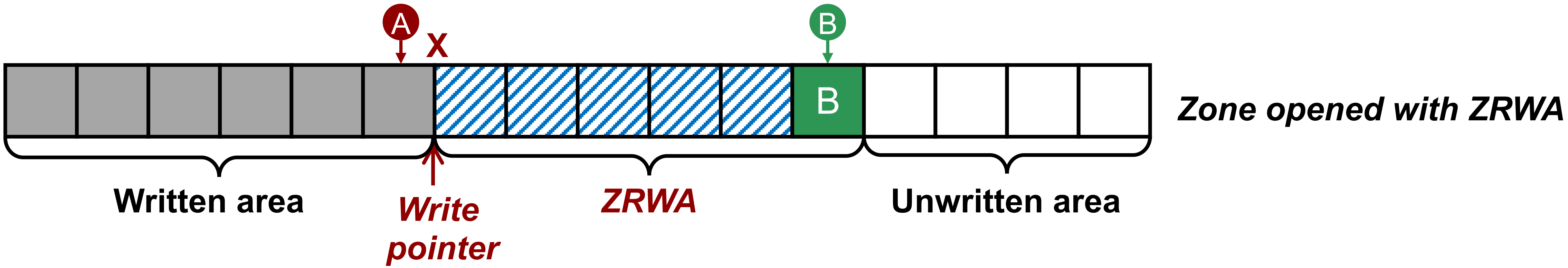

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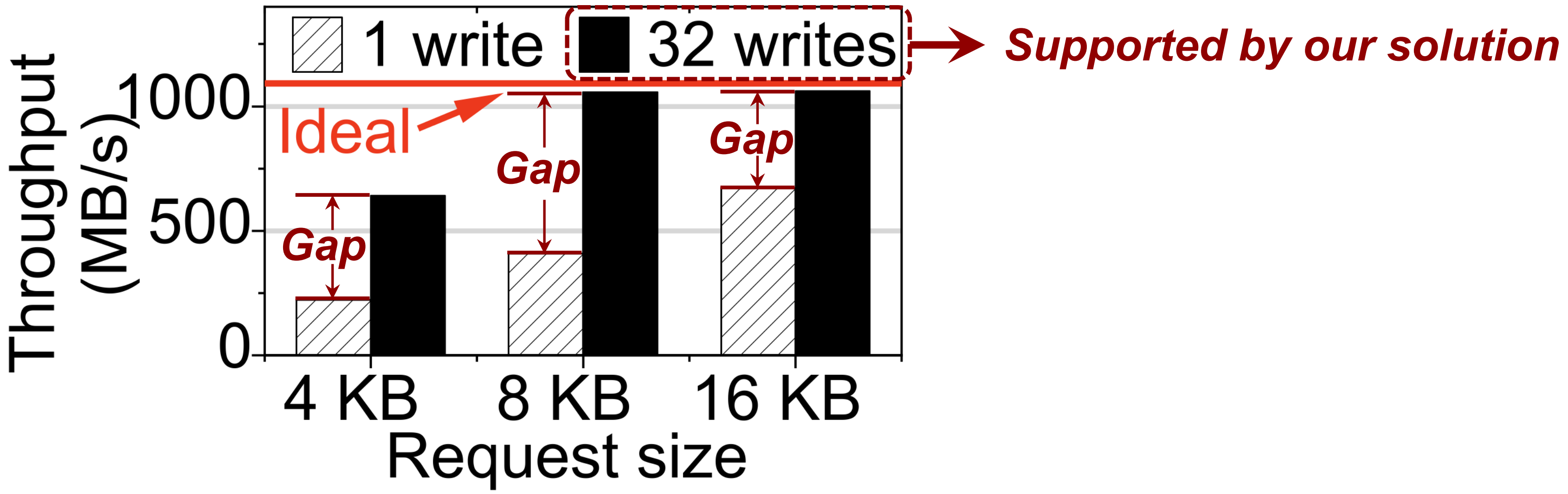
- **Only allow one-inflight write → loses up to 65.3% throughput**



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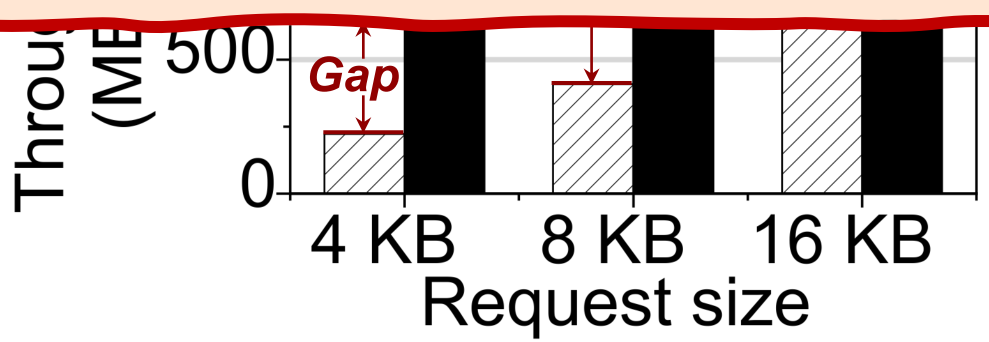
- **Or**

How to enjoy ZRWA while maximizing intra-zone parallelism?



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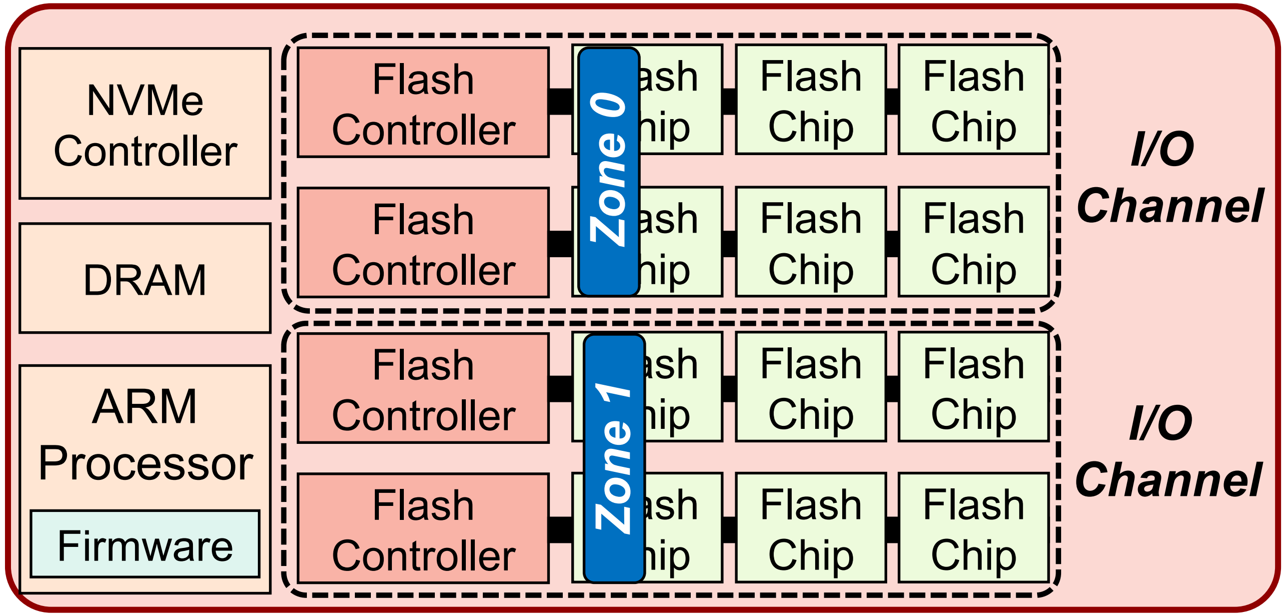

SSD Architecture

Scenario	Bandwidth (MB/s)	Avg. lat. (us)	99.99th lat. (us)
Single zone	1092	59	570
Two zones in **diverse** I/O channels	2170	59	685

Write Tests

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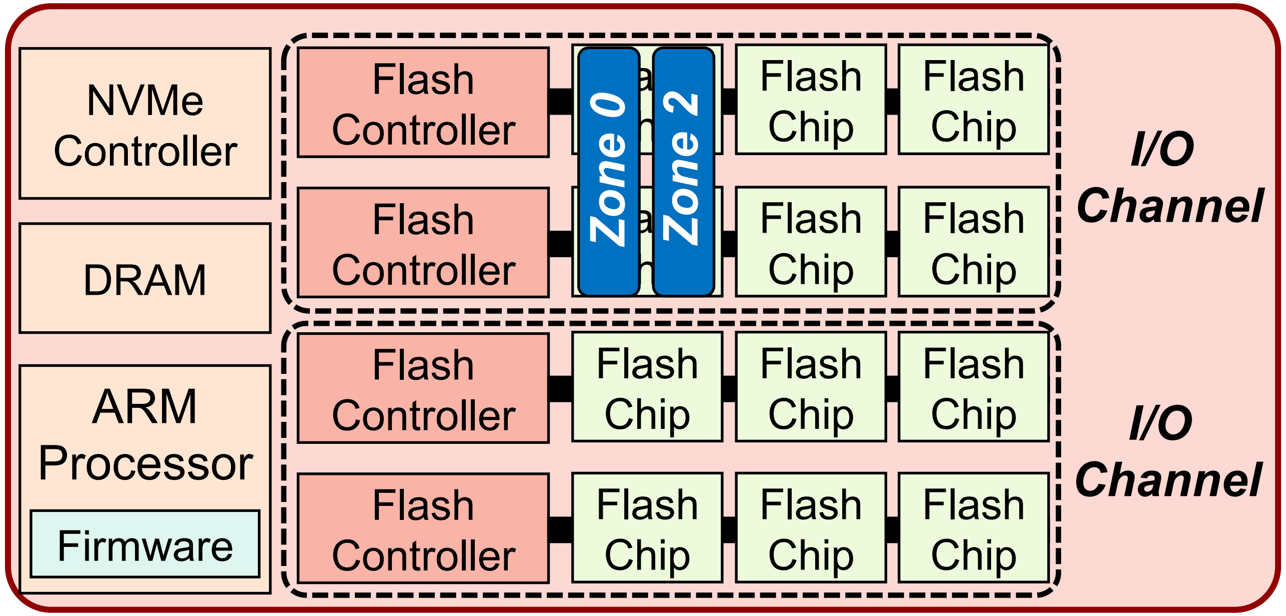
- **Give up the centralized metadata zone**
- **Schedule user I/O and GC with parallel zones**



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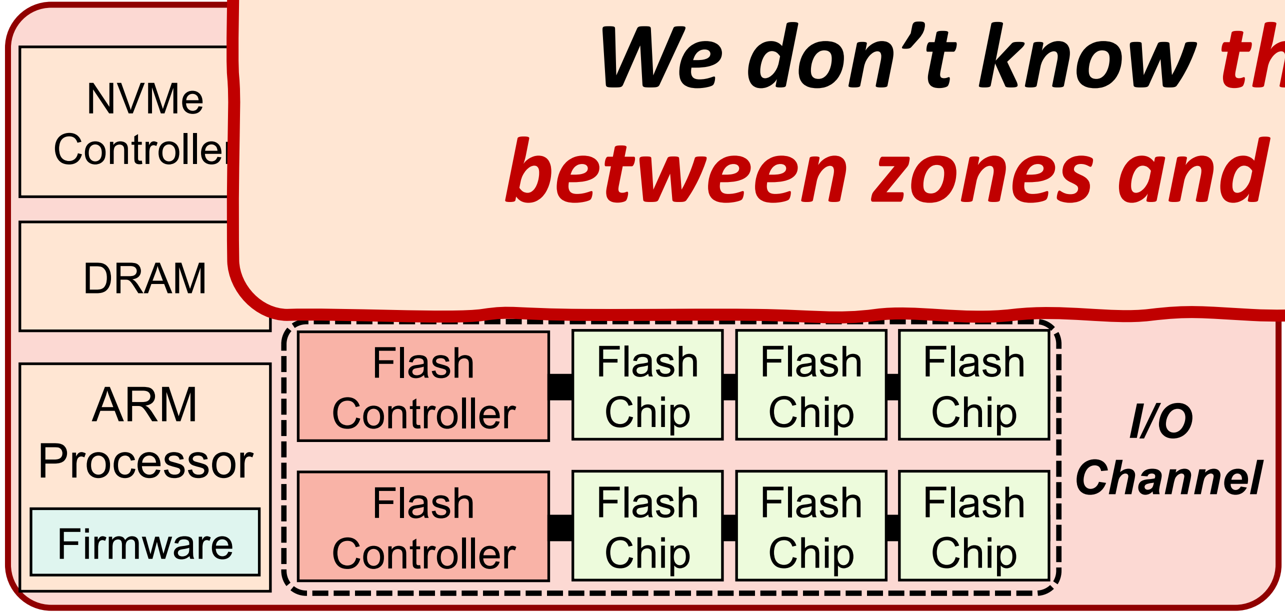
We don't know the mappings between zones and I/O resources!



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BIZA Overview

- **Zone group selector**
  - Isolate hot chunks from cold ones
  - For better utilization of the scarce ZRWA
  - A set of zones mapped with diff. channels
- **GC avoidance mechanism**
  - Schedule I/O and GC with parallel zones
  - Exhaust inter-zone parallelism
- **ZRWA-aware I/O scheduler**
  - Dispatches I/O requests in parallel
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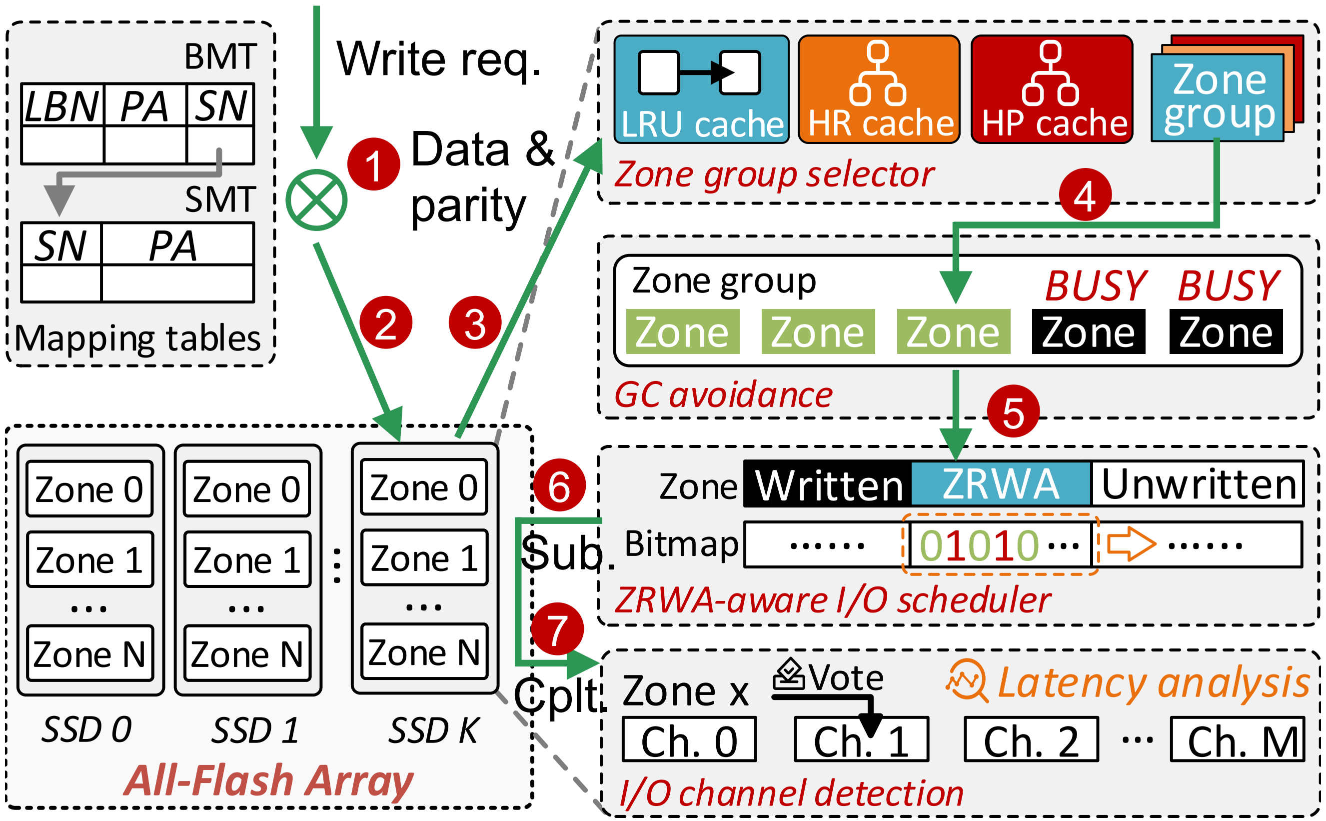
- **I/O channel detection**
  - Collect I/O completion latency
  - Confirm the mappings between channels & zones



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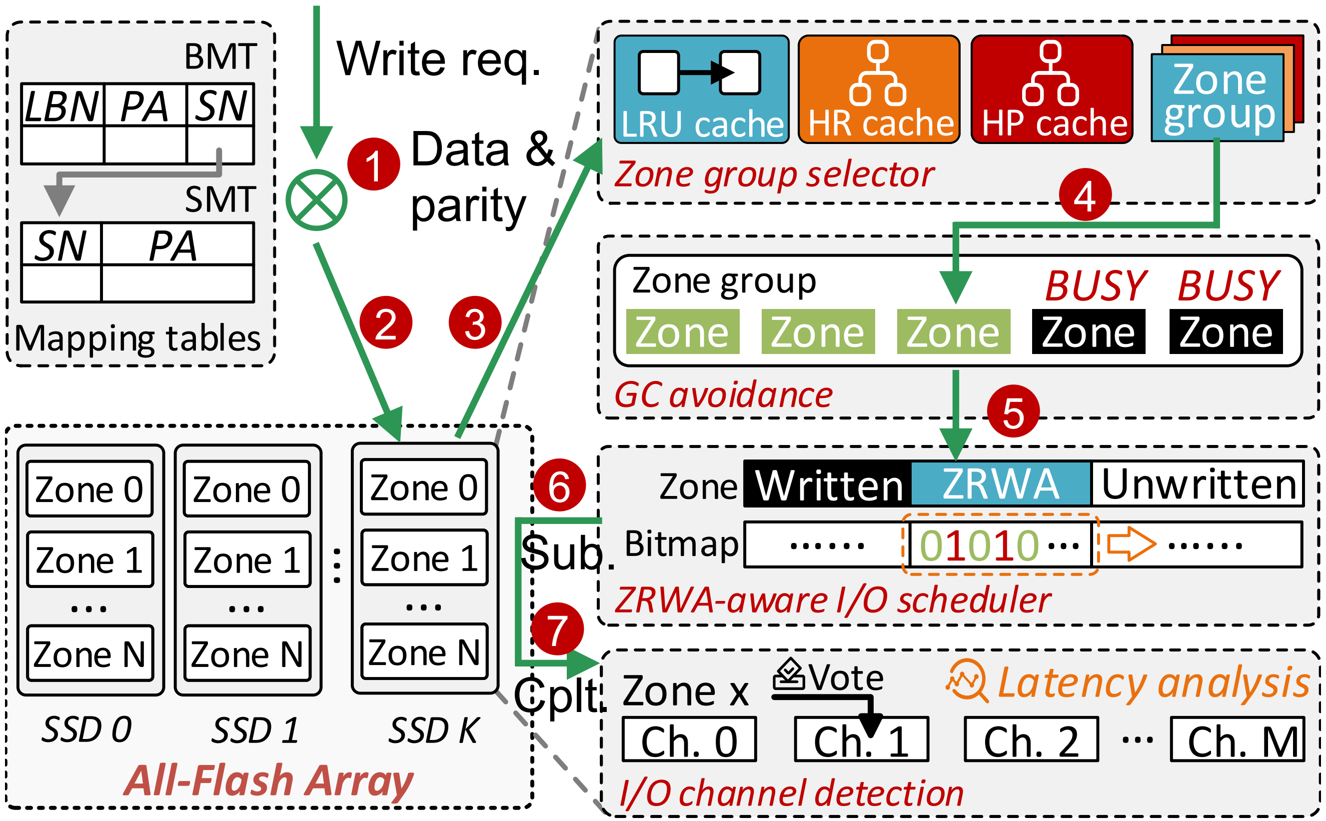
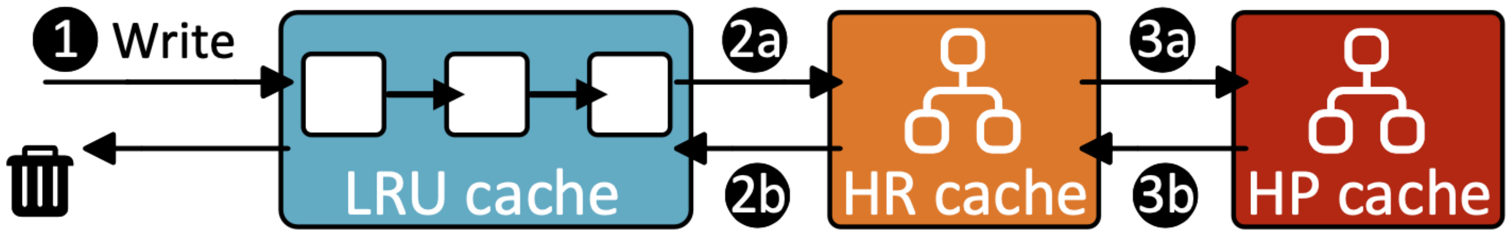


Overview of BIZA

*Please refer to our paper for more details.

Zone Group Selector

- **ZRWA will shift right when multiple new writes arrives**
- **Isolate hot data with cold ones → Keep hot data in ZRWA for a longer time**
- **Ghost-cache-based algorithm** [1]
  - High revenue = the chunk will be updated multiple times
  - High profit = High revenue + Small cost (the chunk has short reuse distance)



HR cache: 2a Reaccess number > threshold T_1

2b Evict minimum reaccess number

HP cache: 3a Reuse distance < threshold T_2

3b Evict maximum reuse distance

[1] S-RAC: SSD friendly caching for data center workloads. (SYSTOR'16)

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- **Select different zone group for chunks in different cache**
  - High profit: can be updated multiple times within the limited ZRWA
  - High revenue: hard to be absorbed in ZRWA but is the main source of GC

[1] S-RAC: SSD friendly caching for data center workloads. (SYSTOR'16)

Experimental Setup

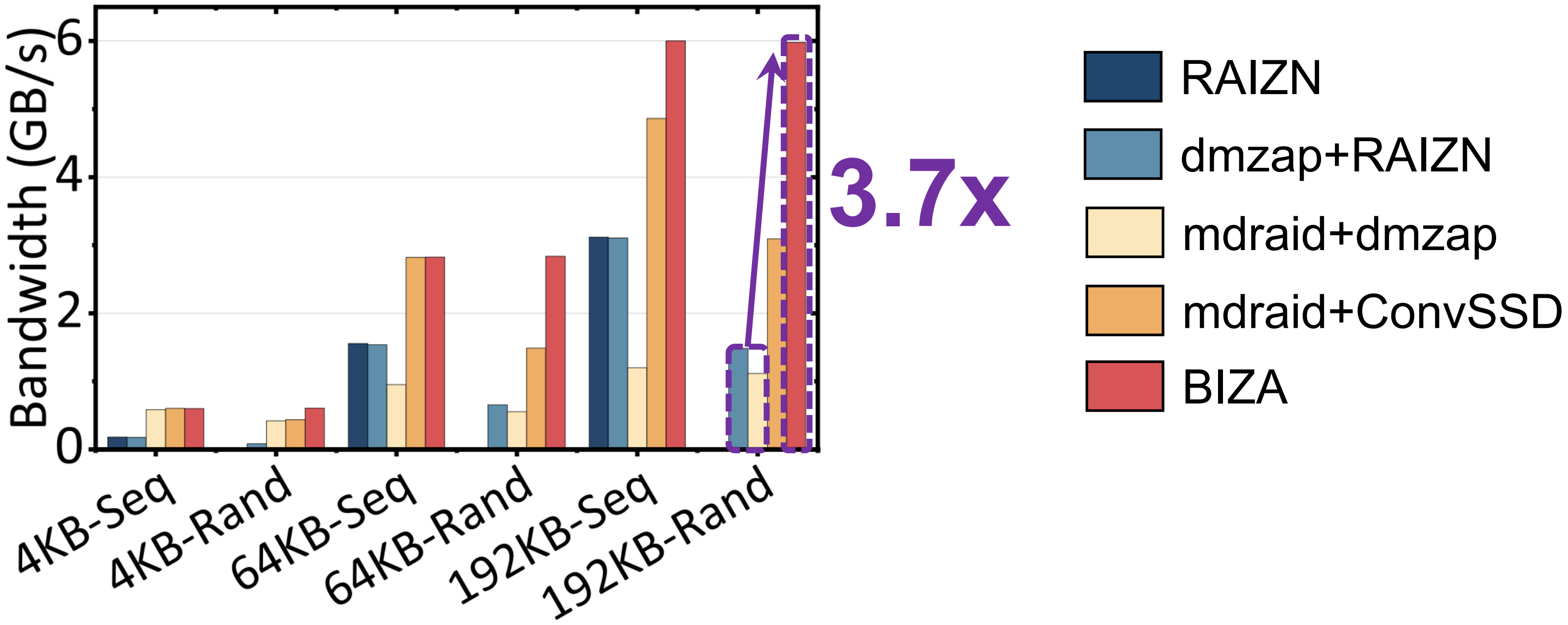
- **Implemented as a device mapper in Linux kernel**
- **Constructing AFA with 4 commodity SSDs as RAID 5**
- **ZNS SSD:** Western Digital ZN540 SSD
  - Read: 3265 MB/s, Write: 2170 MB/s
  - Up to 14 open zones & 14 MB ZRWA
- **Conventional SSD:** Western Digital SN640 SSD
  - Read: 3331 MB/s, Write: 2250 MB/s
  - Developed on a similar hardware basis as ZN540 SSD
- **Comparison**
  - RAIZN: only support sequential write
  - dmzap+RAIZN: stacking dm-zap on RAIZN for random writes
  - mdraid+dmzap: stacking dm-zap on each ZNS SSD
  - mdraid+ConvSSD: constructing AFA with conventional SSDs

WD ZN540 SSD

WD SN640 SSD

Microbenchmark

- **Bandwidth**
  - BIZA achieves 3.7x and 3.5x bandwidth than dmzap+RAIZN and mdraid+dmzap



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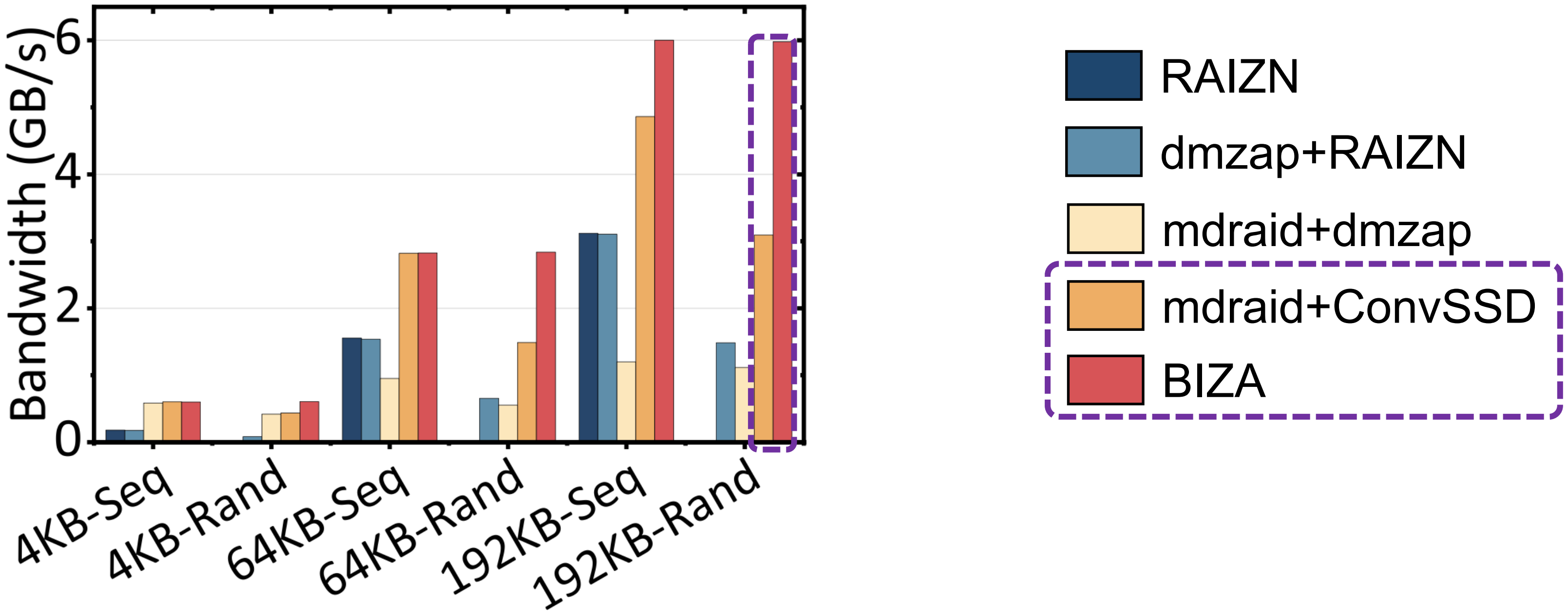

[1] ScalaRAID: Optimizing linux software raid system for next-generation storage. (ATC'24)
[2] stRAID: Stripe-threaded architecture for parity-based RAIDs with ultra-fast SSDs. (ATC'22)

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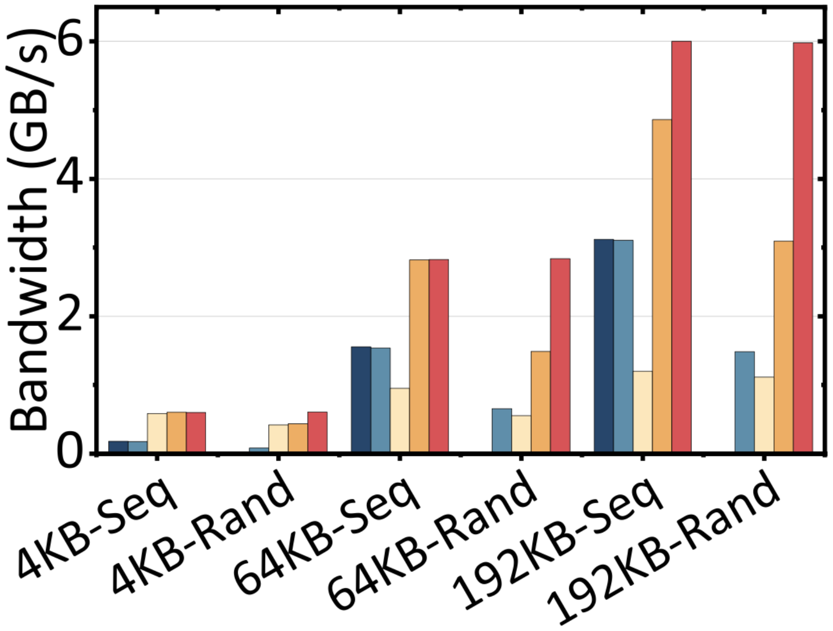
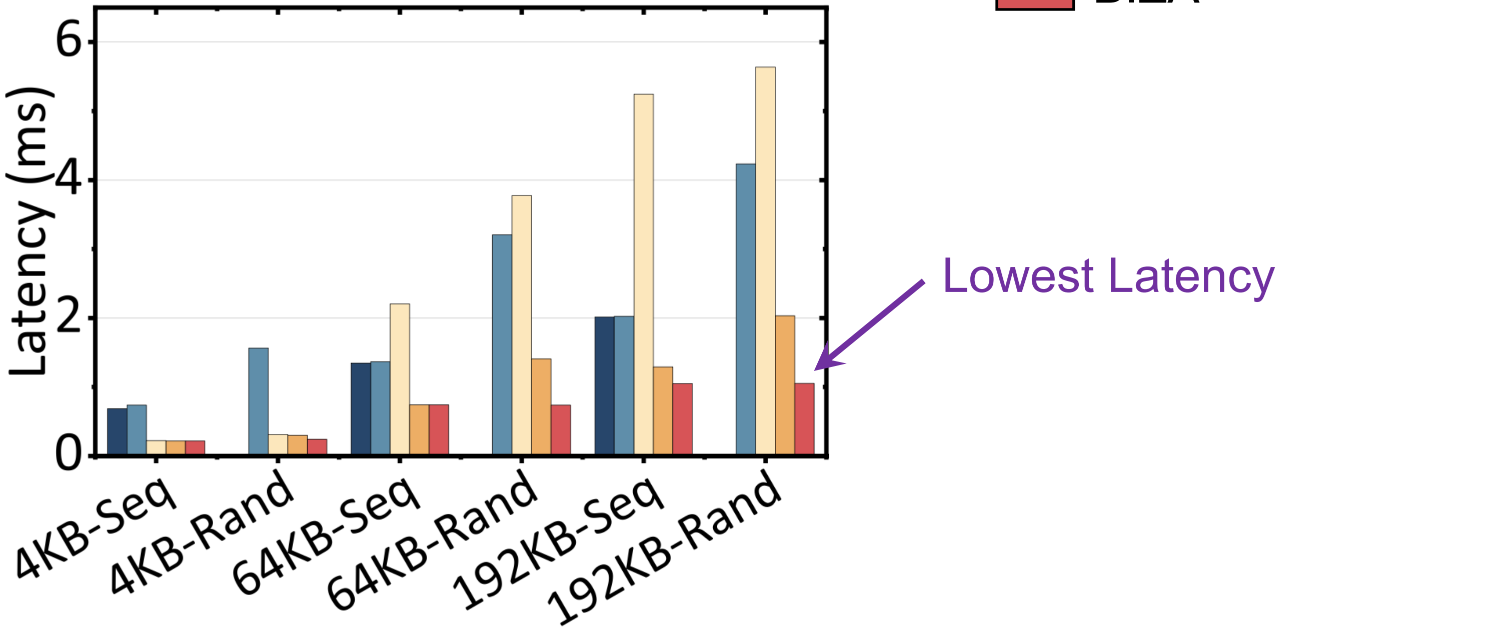
- **Average latency**
  - Outperform RAIZN by 53.8% for sequential writes





Applications

- **Filesystem:** F2FS + filebench
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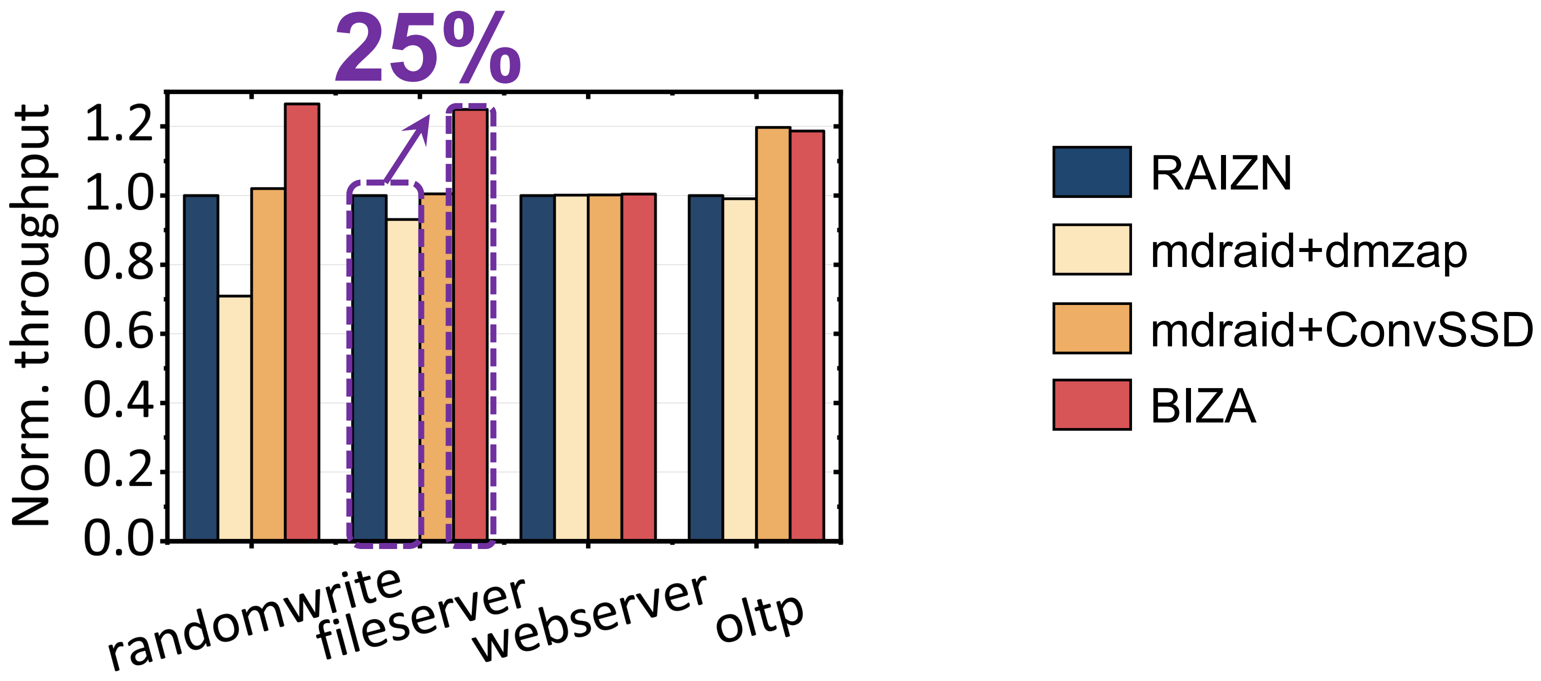

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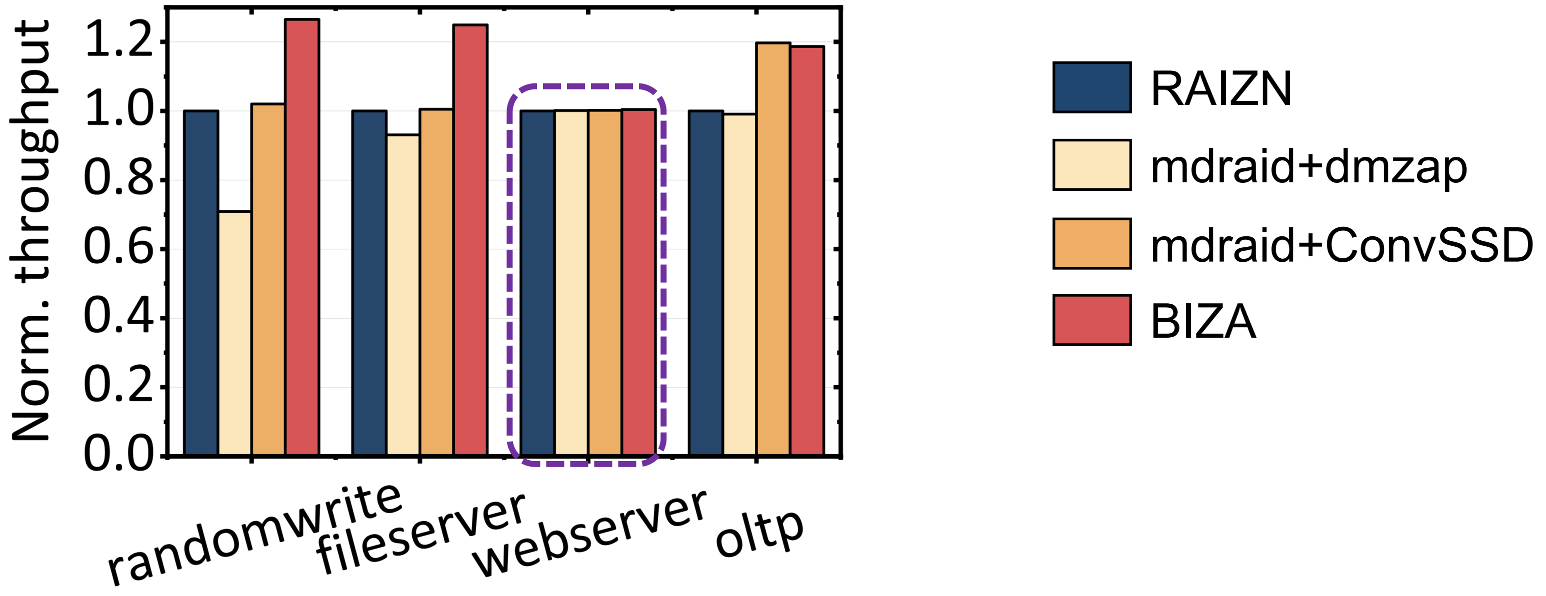

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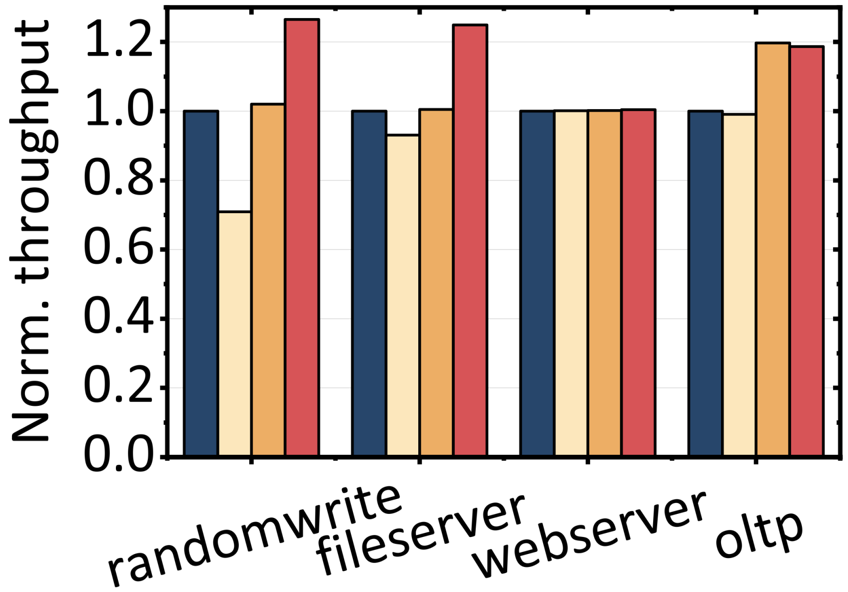
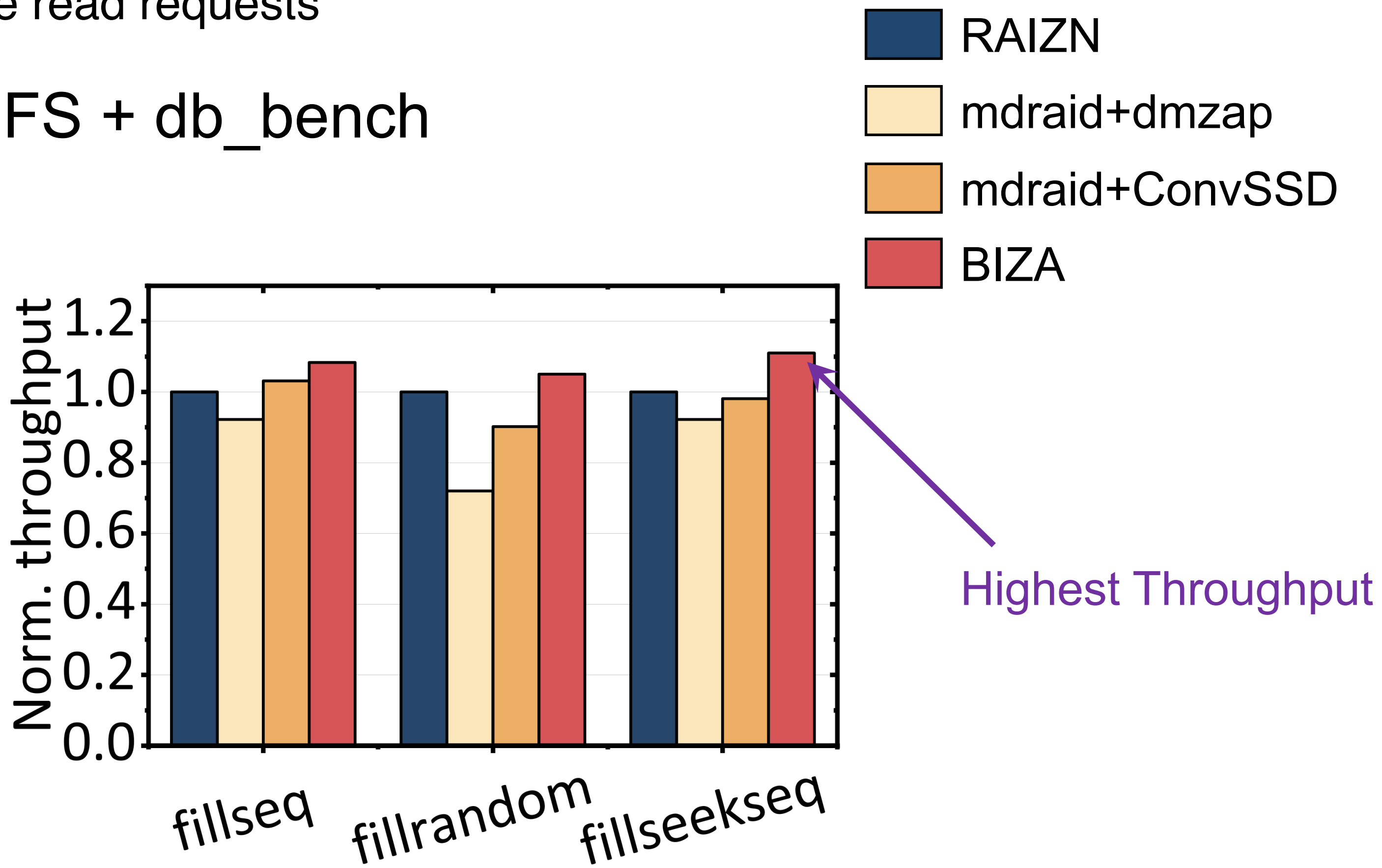
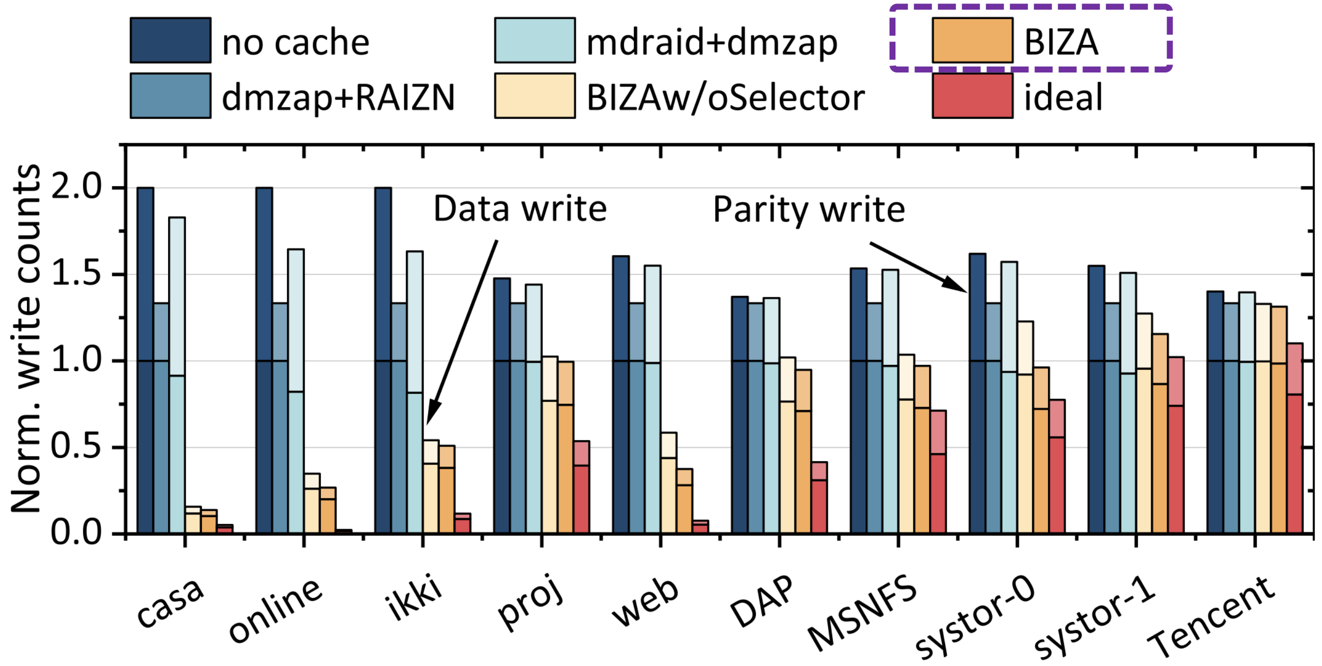
- **Key-value store:** RocksDB + F2FS + db_bench
  - 10.5% higher throughput than RAIZN



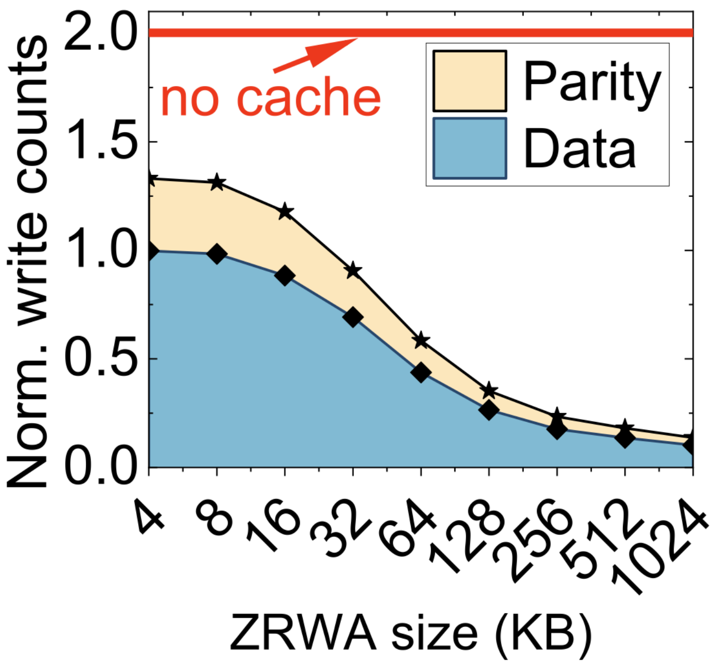


Write Amplification Reduction

- **Reducing 41.0% flash writes (compared with mdraid+dmzap)**
- **Different sizes of ZRWA:** larger ZRWA, less flash writes



Write amplification



Sensitivity study

Conclusion

- **Existing interface choices of AFA are all unsatisfactory**
  - Block-interface alone, ZNS-interface alone, and adapter
  - Endurance, performance, and compatibility
- **BIZA: benefit from the openness of ZNS whilst exposing block interface**
  - Fully exploiting the emerging ZRWA feature
  - Exhausting the intra-zone and inter-zone parallelism
- **Significantly improve I/O performance while mitigates write amplification**
- **Source code is accessible at:**
  - *https://github.com/ChaseLab-PKU/BIZA*

Thanks & QA

BIZA: Design of Self-Governing Block-Interface ZNS AFA for Endurance and Performance

https://github.com/ChaseLab-PKU/BIZA

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