Advanced I/O Stack for Zone-based Mobile Flash Storage

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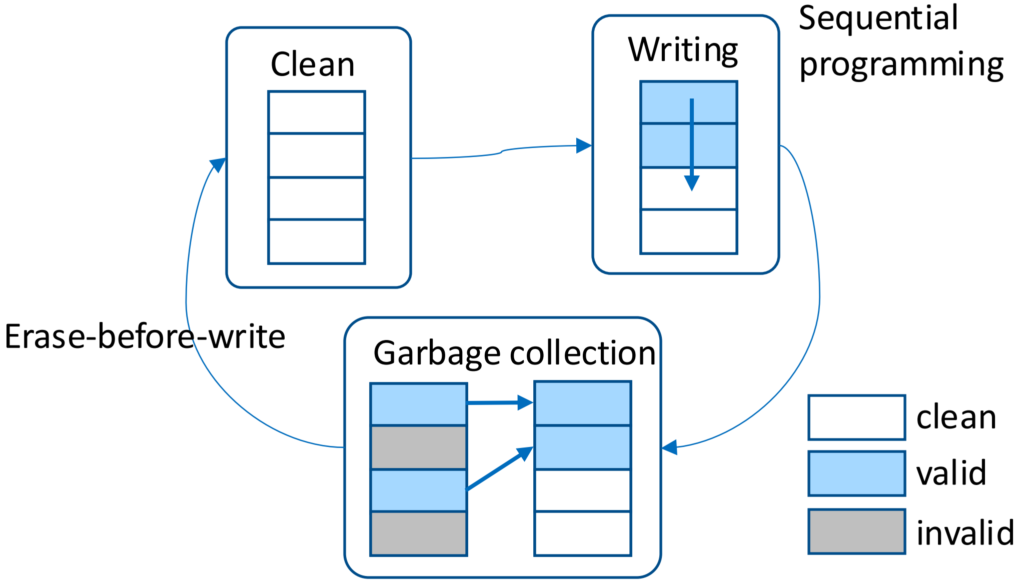
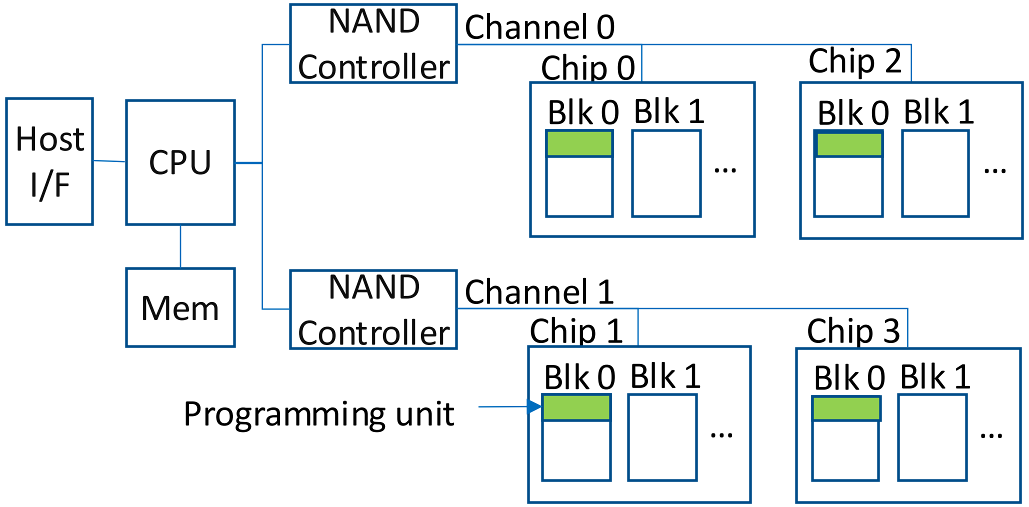
Background

Conventional SSD (Block Interface)

- Flash memory has sequential programming and “erase-before-write” characteristics.
- Logical-to-physical (L2P) mapping and garbage collection provides block interface for flash memory.
- Data striping over multiple chips for parallel operation.



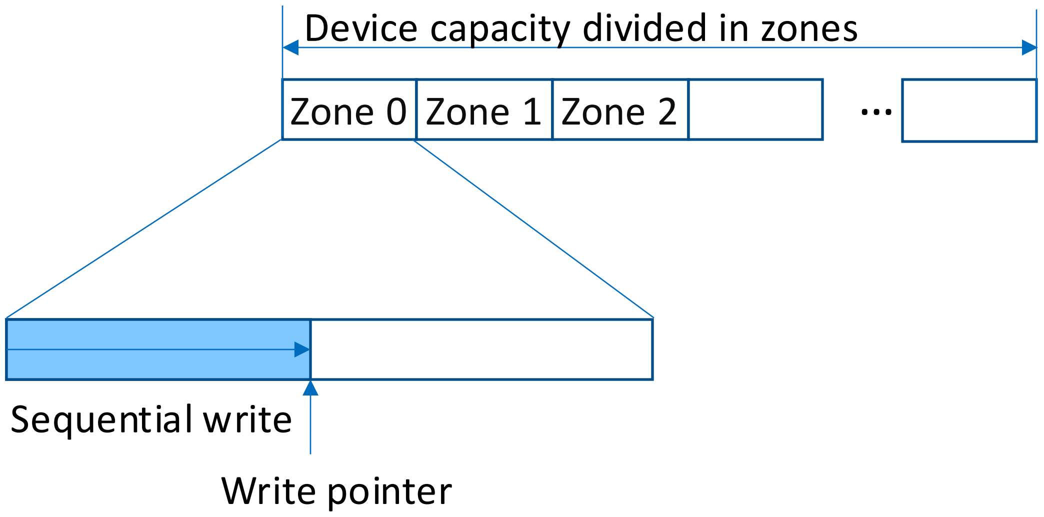


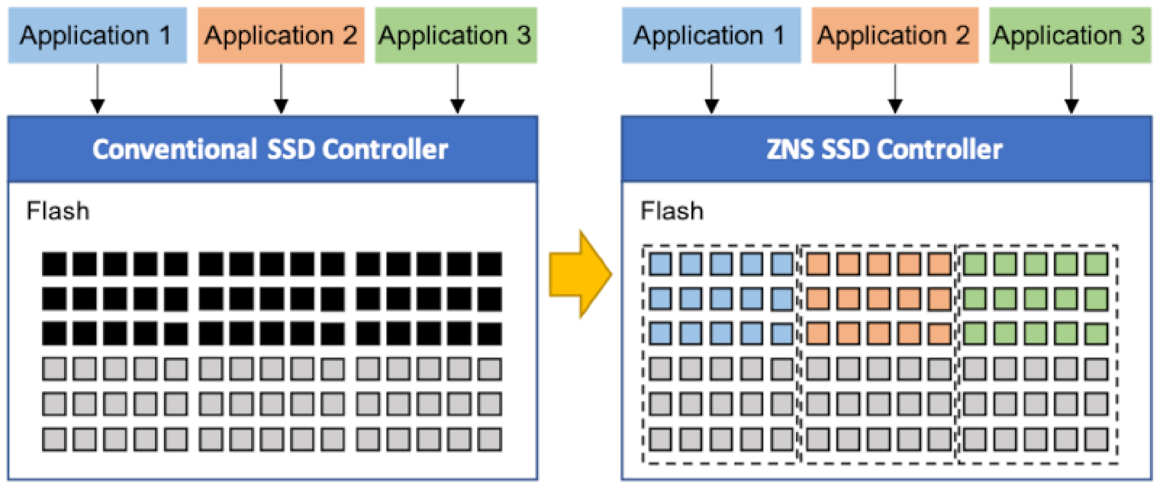
- **Superblock**: the set of flash blocks where data is striped
- **Superpage**: the set of programming units on the same offset of the superblock

- Issues
  - Memory cost for L2P mapping table (← page mapping)
  - Write amplification (← data with different lifetimes are mixed)

Zoned Namespace SSD

- Sequential write constraint → coarse-grain (zone) mapping → reduced L2P map
- Host controls data placement → removes device garbage collection
  - Host is responsible for data separation to reduce write amplification.





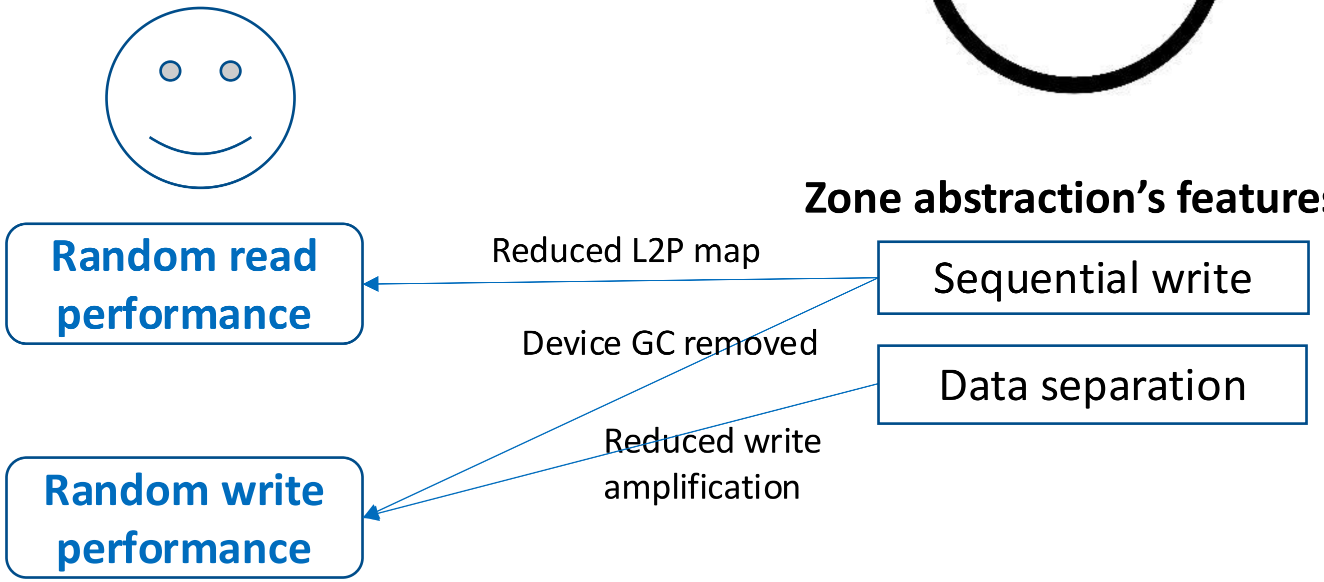
Regular SSD: Device controls data placement

ZNS SSD: Applications control data placement in zones

Does mobile storage benefit from zone abstraction?

Responsiveness is critical in mobile devices.

Zone abstraction's features



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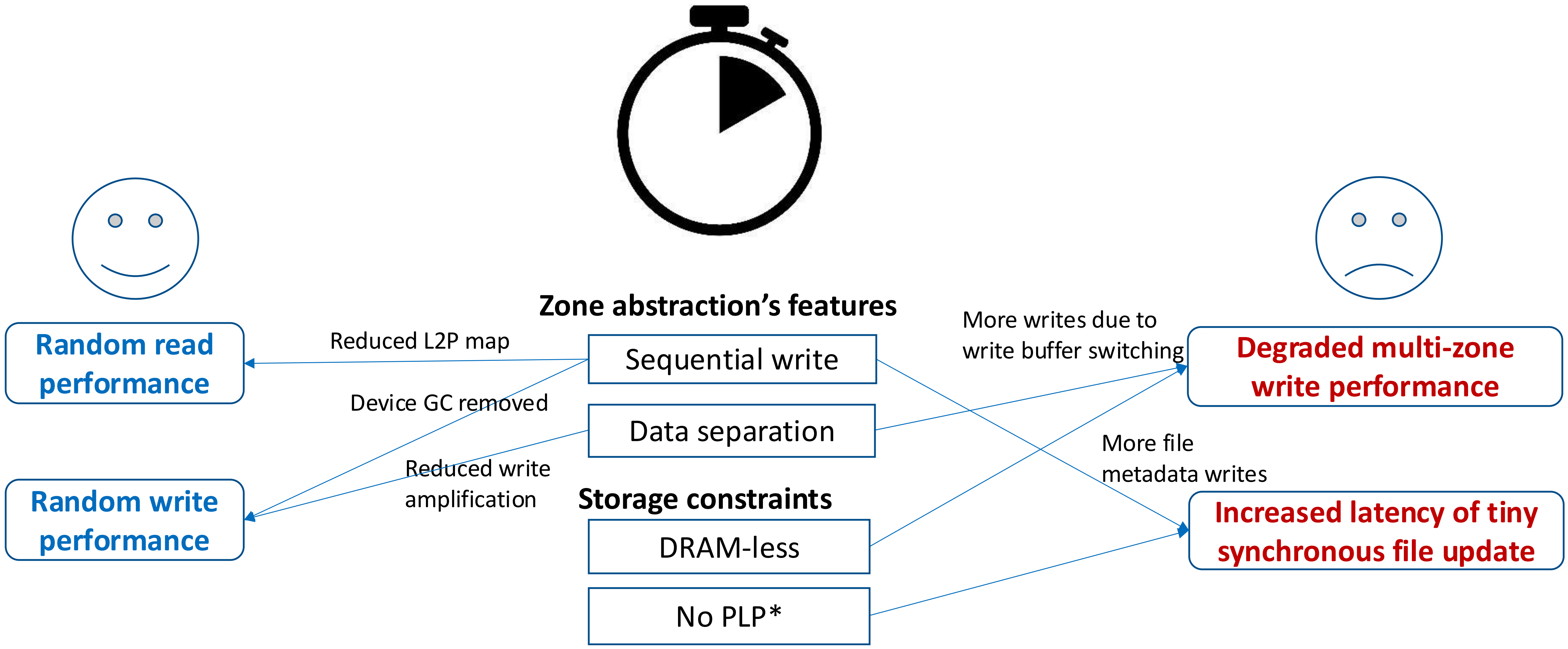
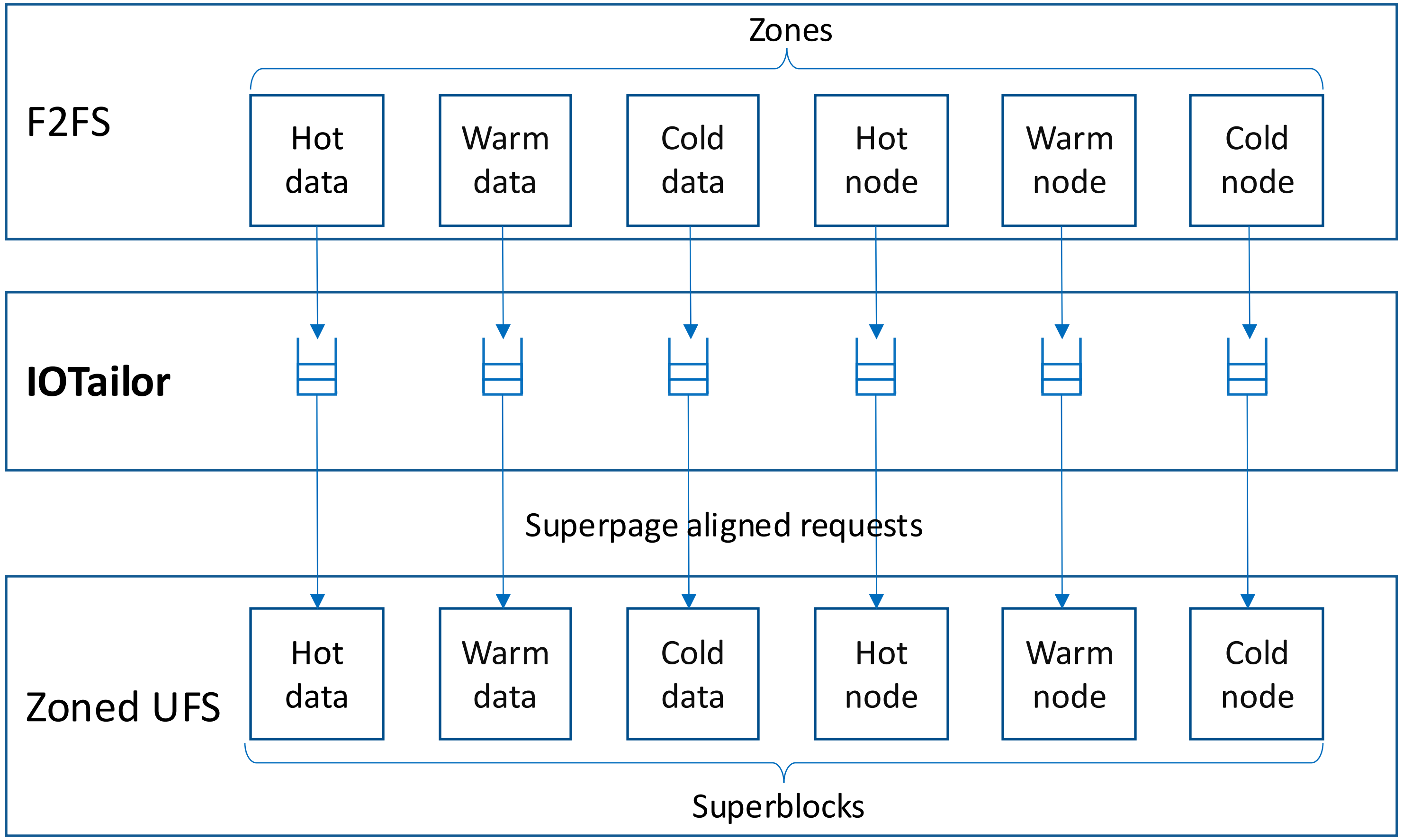


*PLP: Power loss protection

ZMS (Zoned Mobile I/O Stack)

- Utilizing F2FS*, data is separated according to six temperature types.
- Techniques to address the challenges: **IOTailor, budget-based in-place update**
- Optimization techniques: copy offloading, multi-granularity mapping (not covered in this talk)



- **Budget-based in-place update**
- Copy offloading to reduce GC cost
- Multi-granularity mapping

*F2FS: A new file system for flash storage, Lee et al. USENIX FAST '15

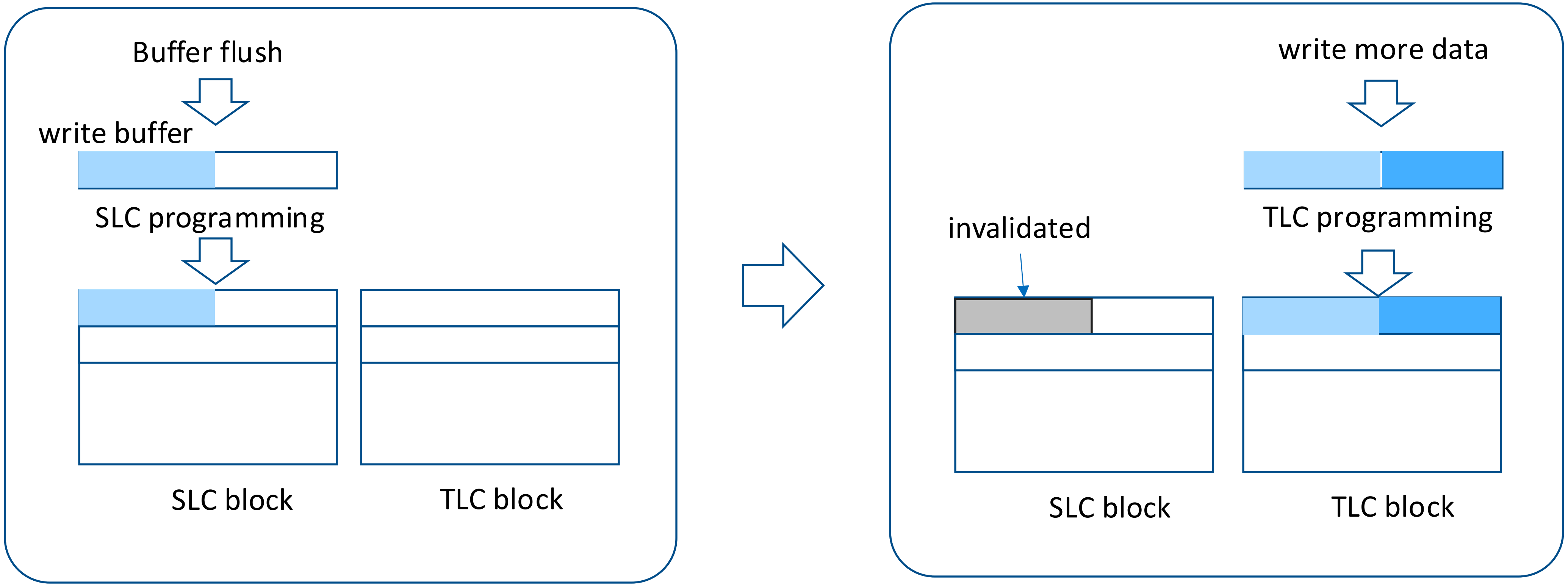
Talk Outline

- Challenge #1: Multi-zone write performance
- Challenge #2: Latency of Tiny Synchronous File Update
- Evaluation
- Conclusion

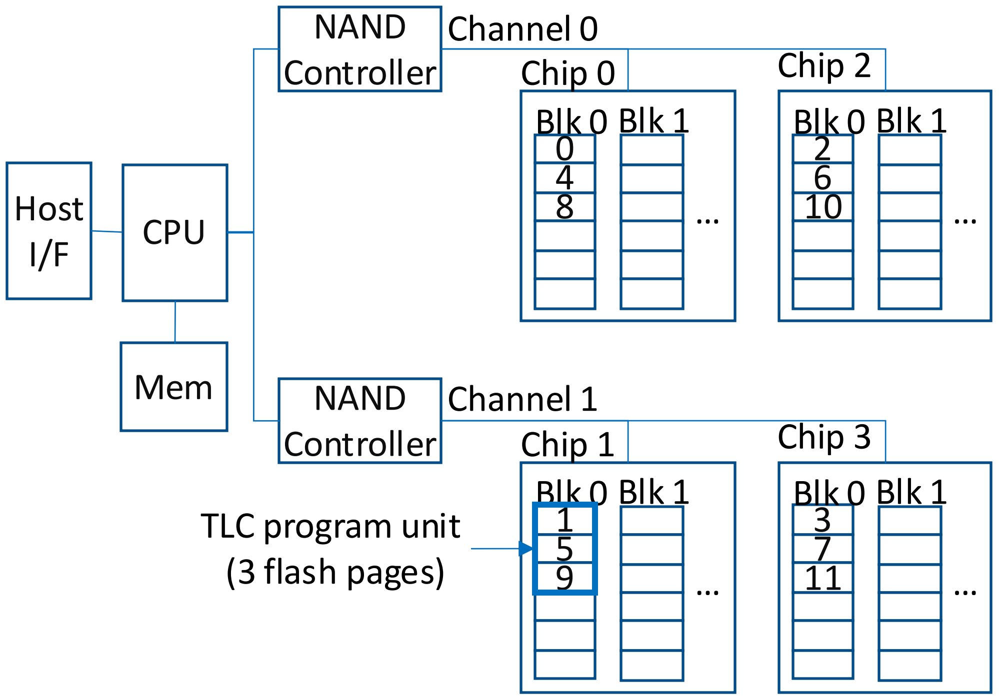
Challenge #1:
Multi-zone Write Performance

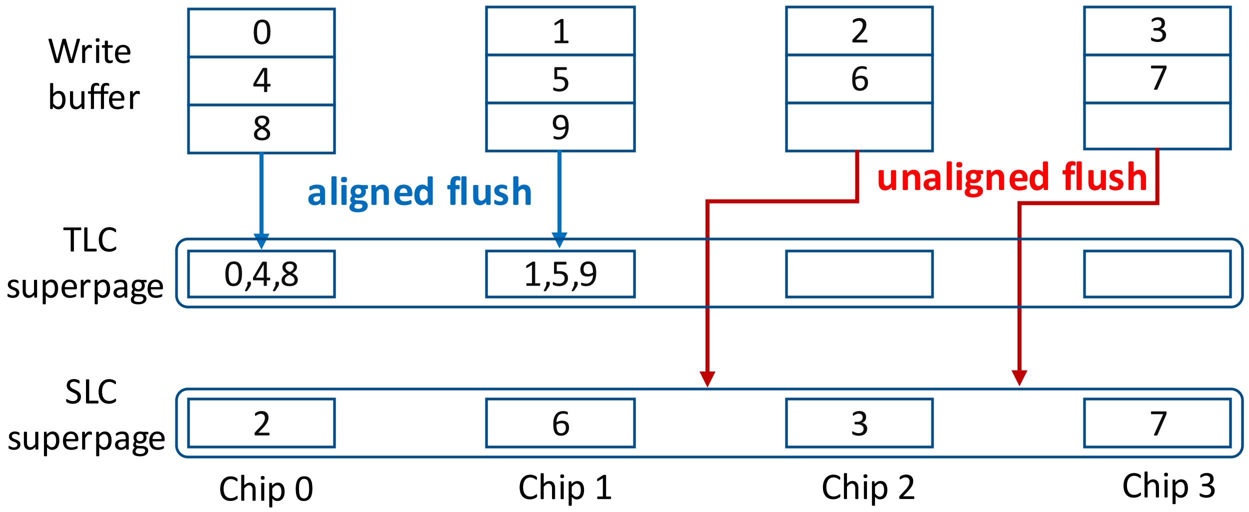
SLC Buffering to Handle Unaligned Buffer Flushes

- Unaligned buffer flush: flush data that is smaller than TLC programming unit.
- Backup data to SLC, later migrate data to TLC
- Side-effect: double writes



Example of Unaligned Buffer Flush Handling

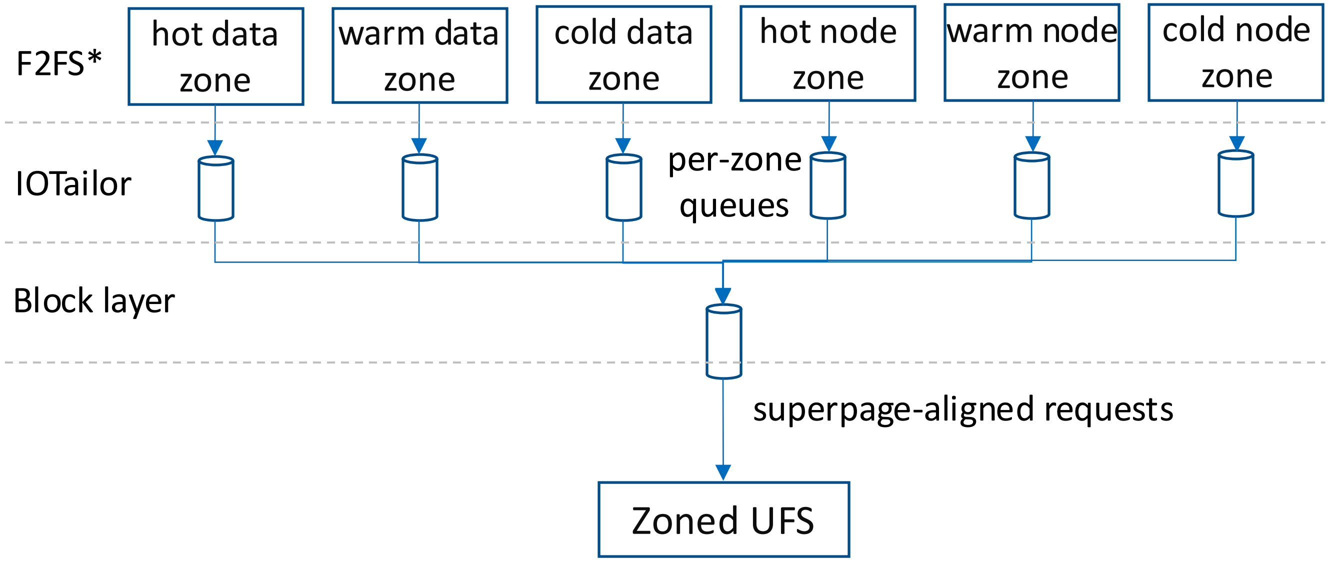


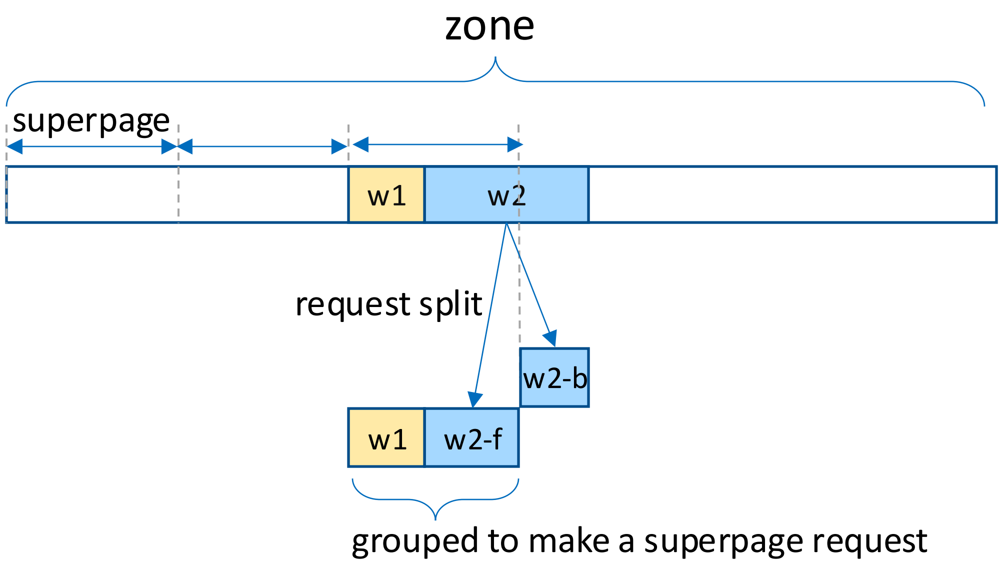


Stripe unit: 32KiB (16 KiB page x 2 planes)
Superpage = 12 stripe units (384 KiB)

IOTailor

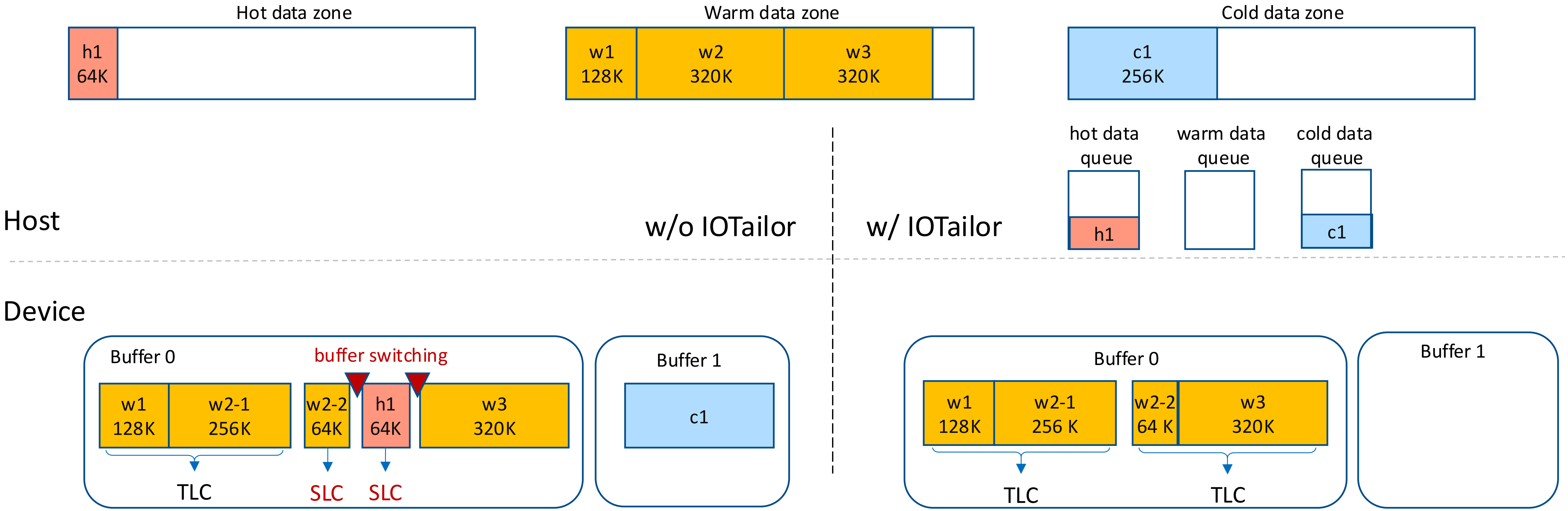
- Superpage-aligned request is good for parallelism and avoids unaligned buffer flushes.
- For each zone, IOTailor transforms requests to superpage-aligned requests
- Request split & request grouping in the per-zone queues





Example of Writing to Multiple Zones

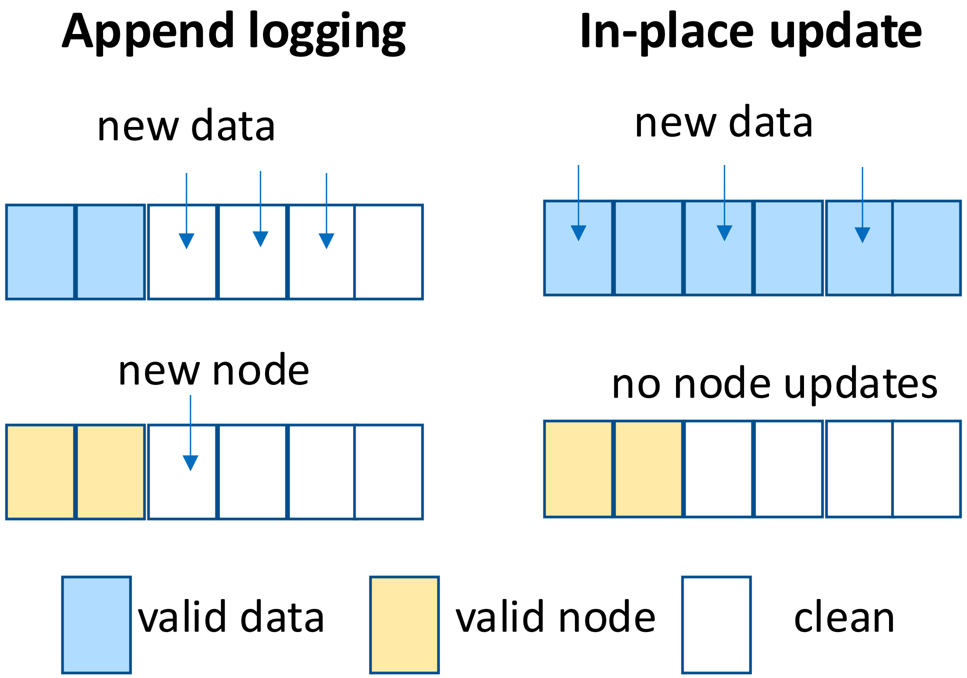
Command order: w1 – c1 – w2 – h1 – w3



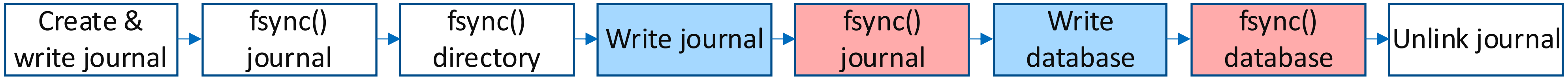
Challenge #2:
Latency of Tiny Synchronous File Update

F2FS write optimization does not work for zoned device

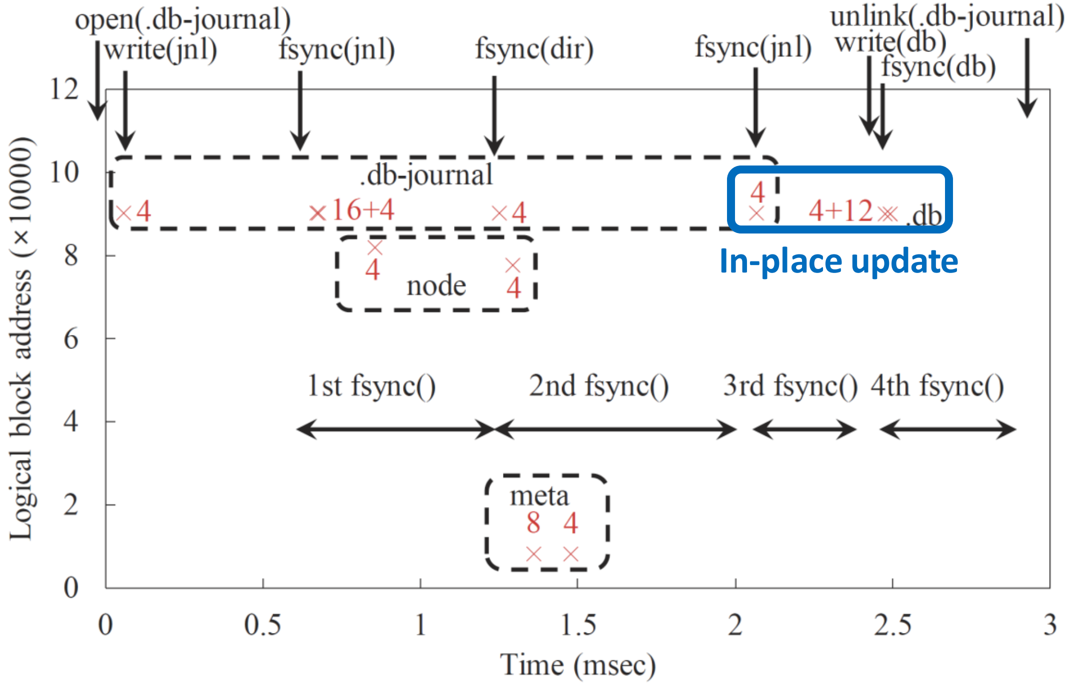
- Tiny synchronous file update is latency critical.
- For conventional block device, F2FS uses in-place update policy for tiny (< 32KiB) synchronous file update.
- In-place update policy cannot be used on zoned devices.



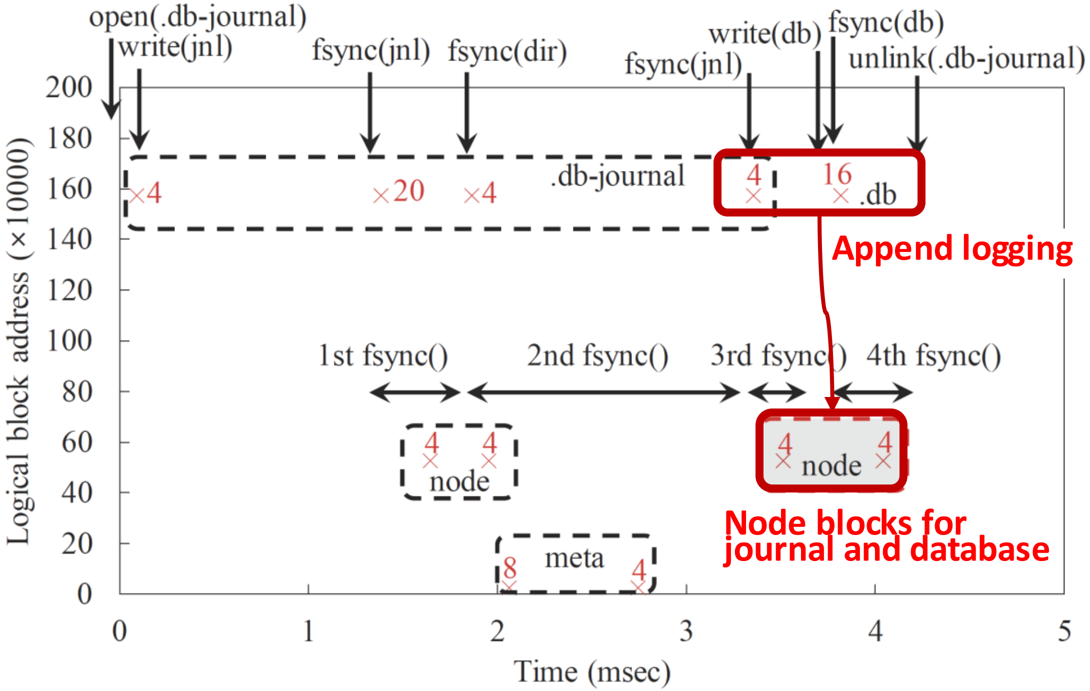
I/O Pattern of SQLite insert() Transaction



<Block device>

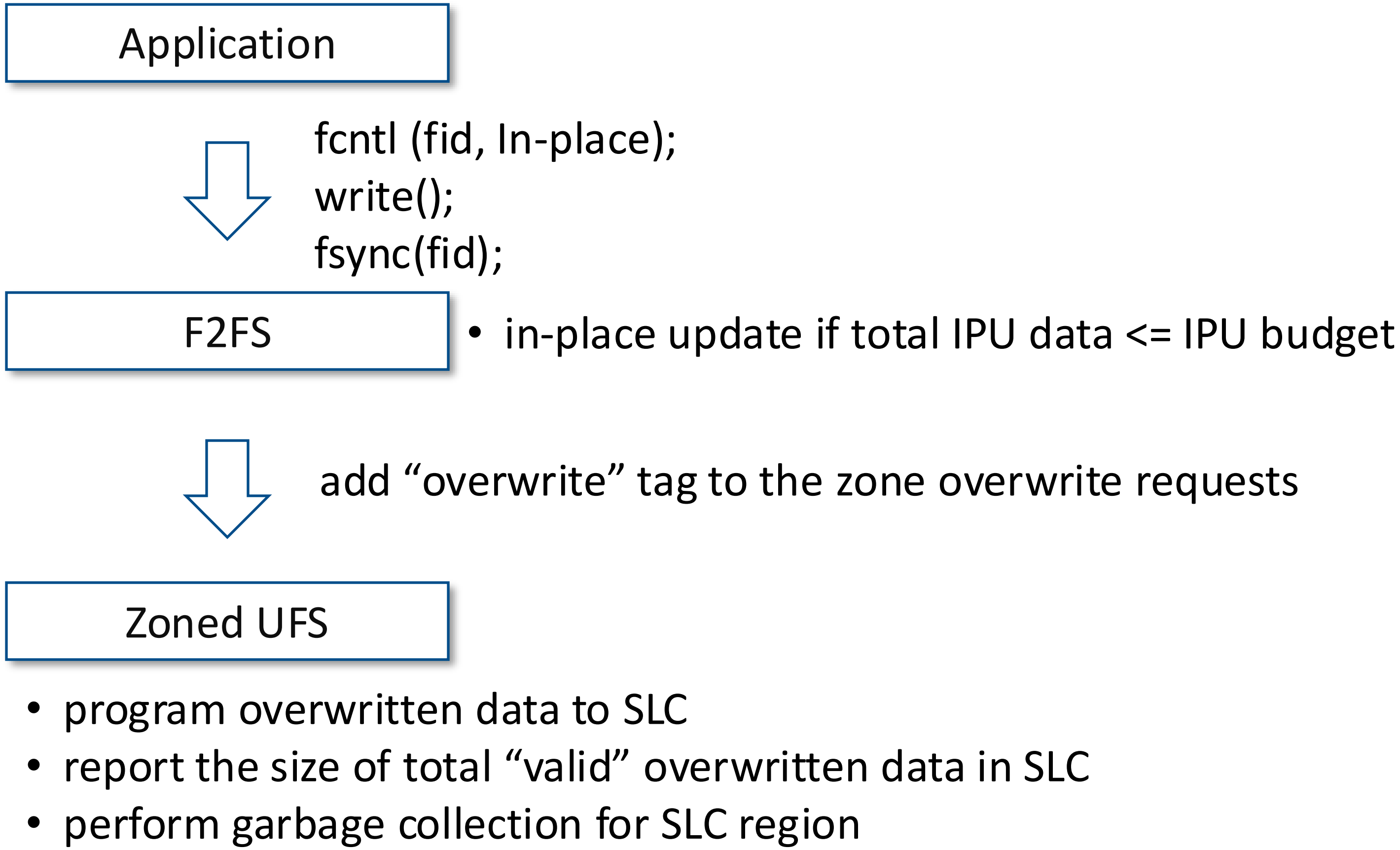


<Zoned device>



Budget-based In-Place Update

- Allow in-place update for files as per the application request
- Device writes the In-place updated data into SLC blocks.
- Cap total valid data size in SLC blocks for efficient garbage collection.

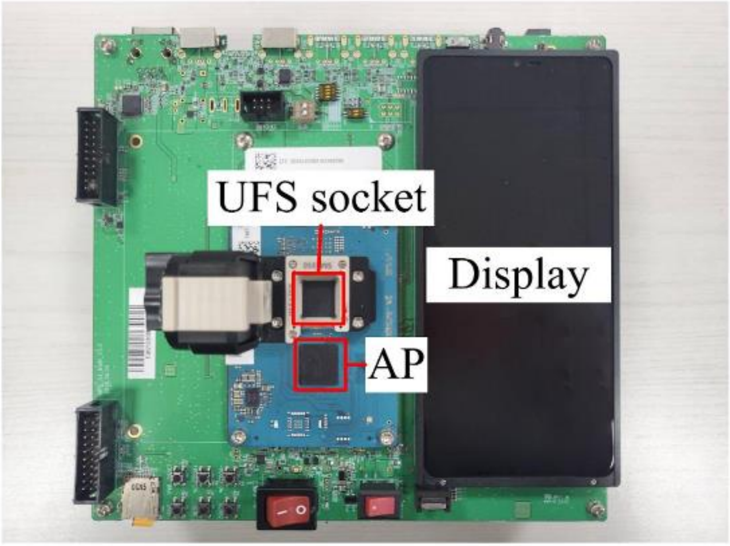


Evaluation

- How much are the benefits of zone abstraction for mobile storage?
- are the challenges addressed well?

Evaluation Setup

- Host platform: SM8350 (8 cores), 12GiB DRAM, Android 11, Linux 5.4
- Zoned UFS: 128GiB, UFS 2.1
  - zone size: 138MiB
  - a conventional logical unit for F2FS meta area
- Baseline: the same device with a firmware that supports legacy block interface

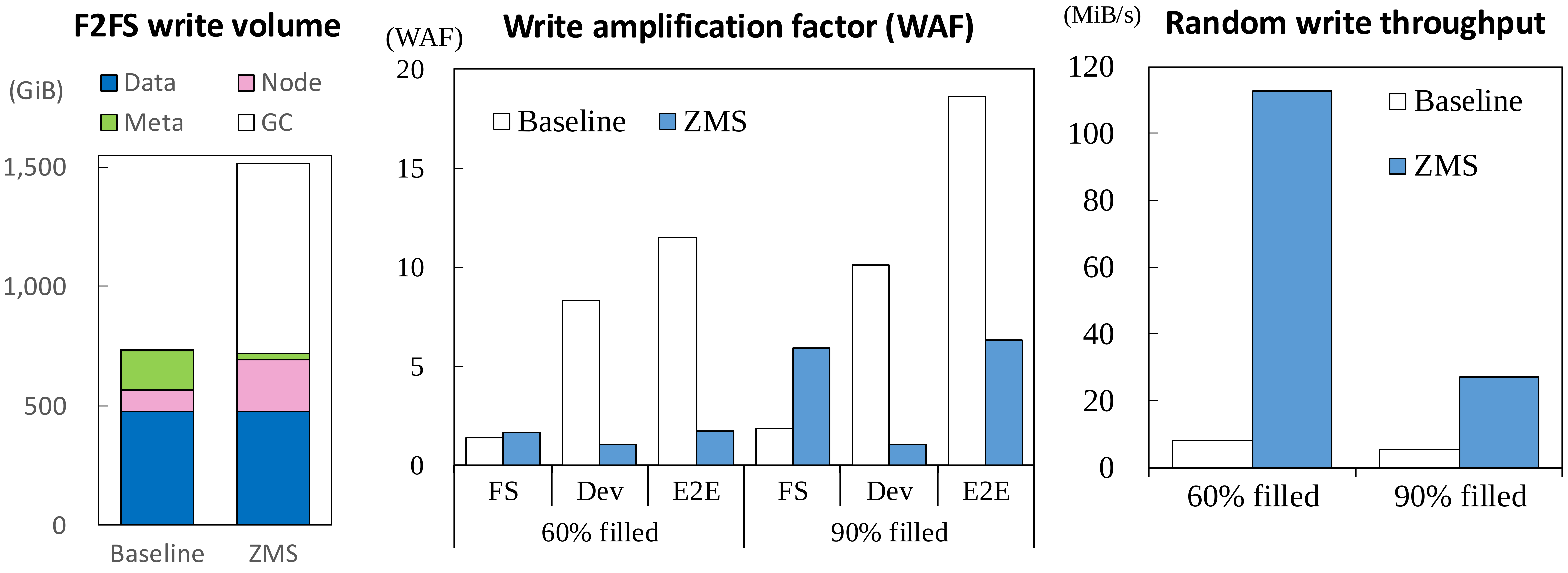


Workload	Configuration
Sequential read/write	Fio[1], 512 KiB IO size
Buffered random read/write	Fio, 4 KiB IO over 1 GiB file
Synchronous random write	Fio, 4 KiB write followed by fsync()
Wide range random read	Fio, 4 KiB read over 8 GiB file
Concurrent writing to multiple zones	Three concurrent Fio writing jobs, each writing to its own files
SQLite benchmark (Mobibench[2])	1M insert() transactions, 3.9 MiB WAL[3] file, 385 MiB database file
Application launch	Category (number of apps): basic (8), image (3), video (5), education (4), game (17)

[1]FIO: https://fio.readthedocs.io/en/latest/fio_doc.html
[2]Mobibench: https://github.com/ESOS-Lab/Mobibench
[3]WAL: Write ahead logging

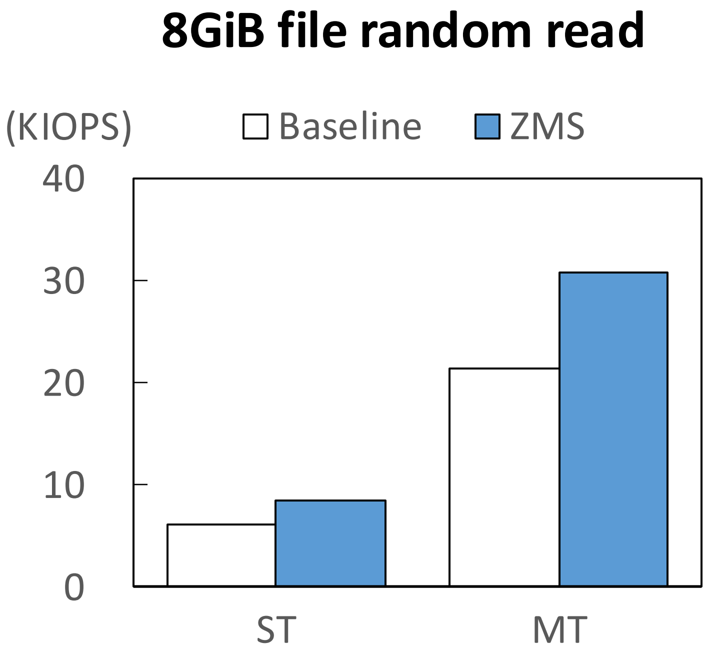
Random Write Performance & Write Amplification

- **2.85x ~ 6.4x** lower write amplification
- **5x ~ 13.6x** higher random write throughput

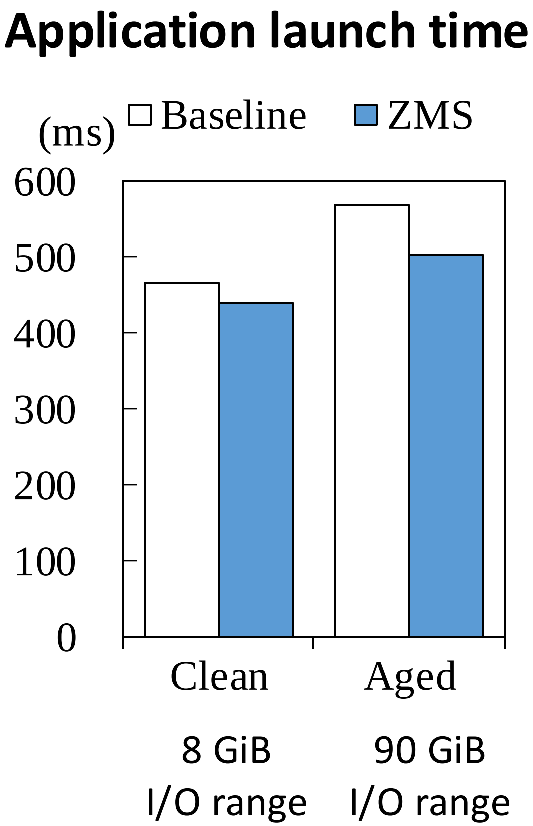


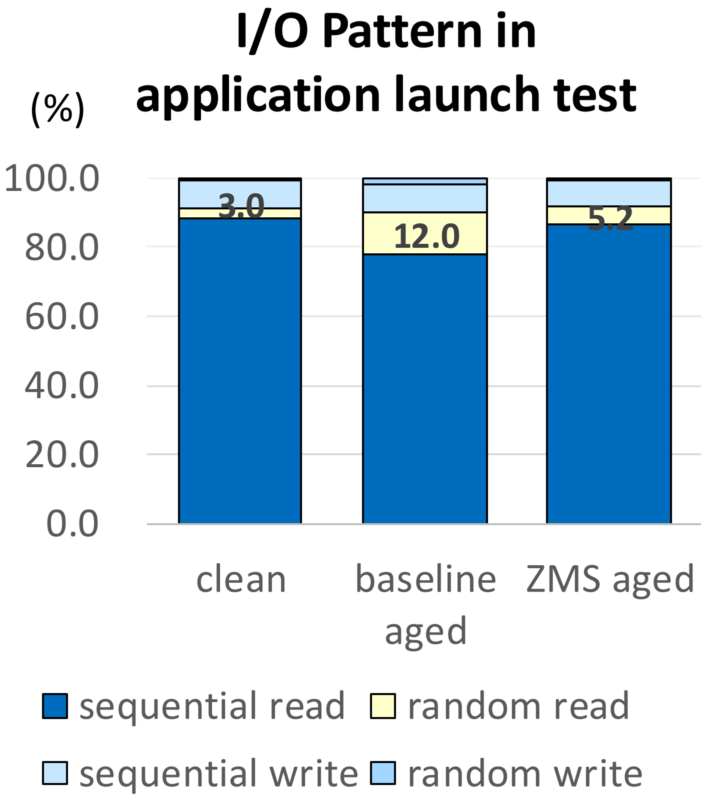
Random Read Performance

- **37~44%** better random read performance
- Application launch time: **5.8 ~ 11.6%** reduction



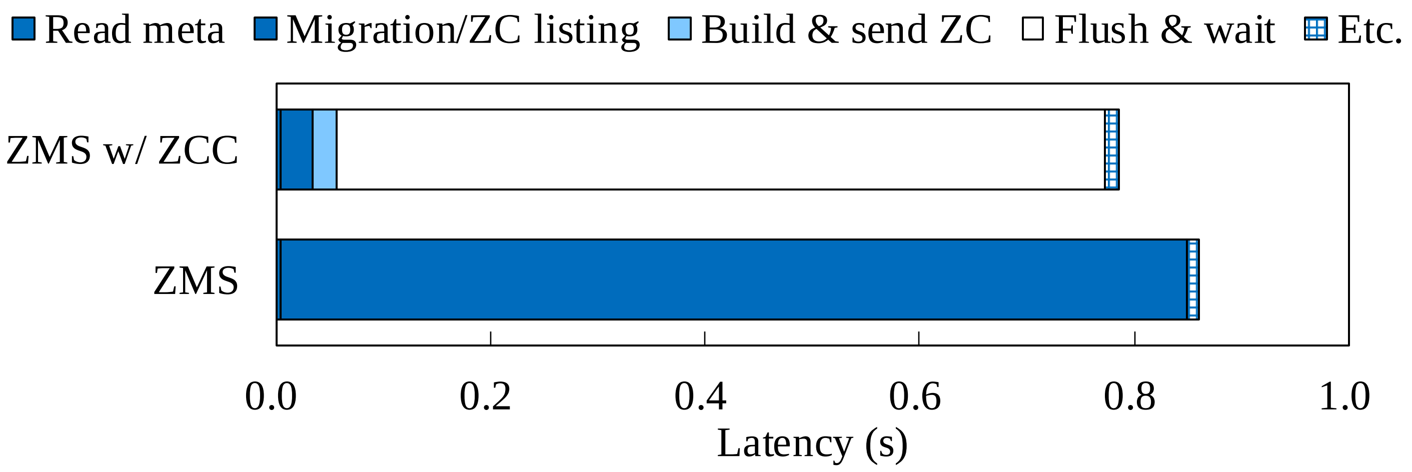
Baseline: map cache miss ratio: 27.1%
ZMS: no map cache miss



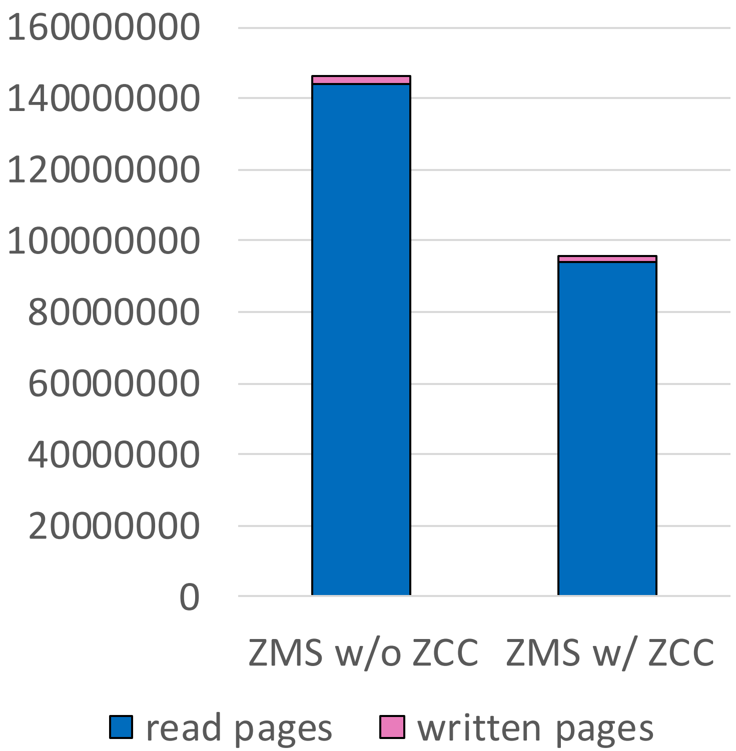


Copy Offloading Impact

- **8.7%** reduction of F2FS garbage collection latency
- **34%** reduction of I/O in application launch test (improved page cache efficiency)
- **7.3%** reduction of power in random write test (reduced CPU load)

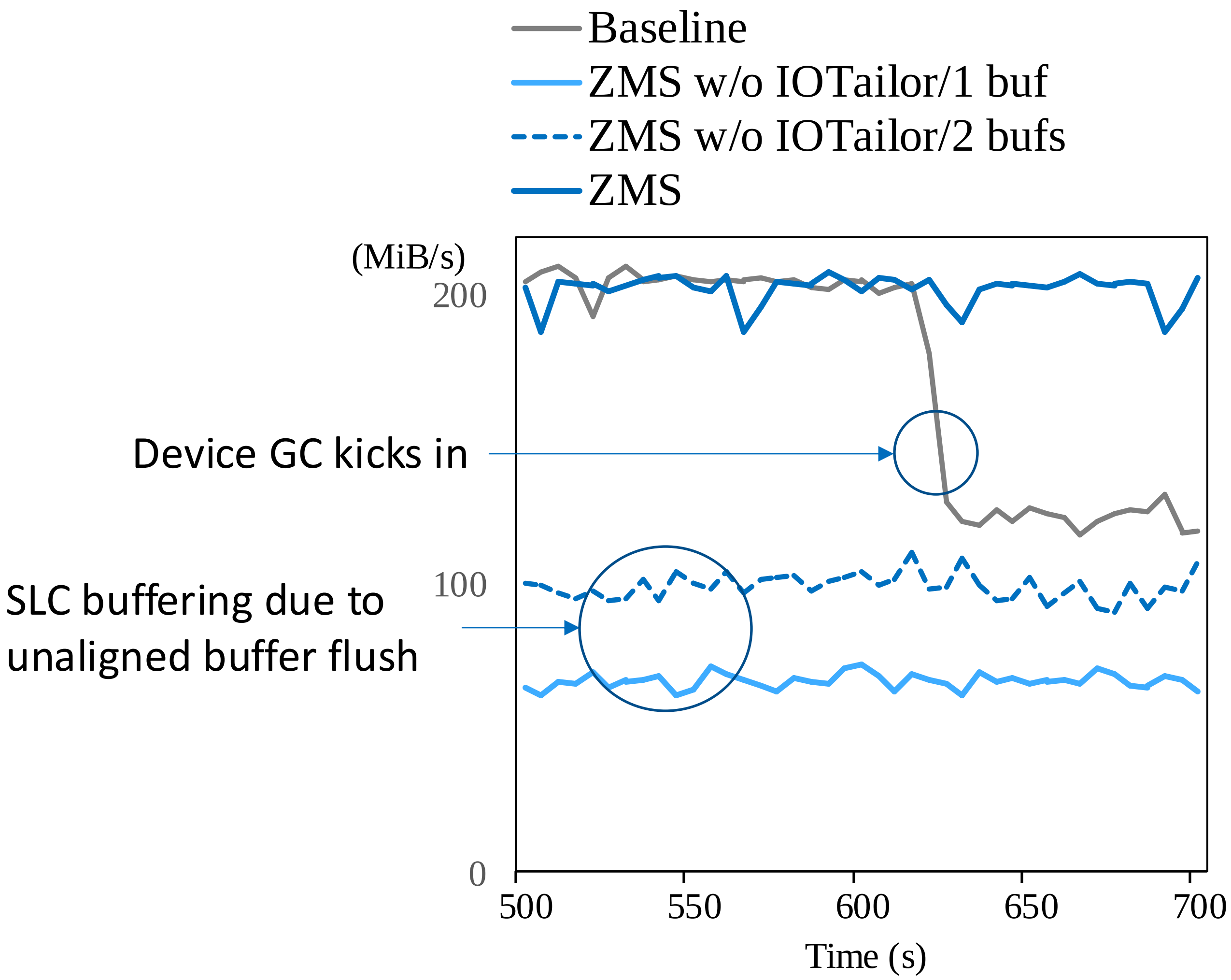


Fio random write test (76 GB file)	Baseline	ZMS w/o ZCC	ZMS w/ ZCC
Throughput (MiB/sec)	22.2	60.4	63.4
Test runtime (sec)	3461	1272	1210
Average CPU load	55.1	100.8	65.3
Average power during runtime (Wh)	2.76	1.24	1.15



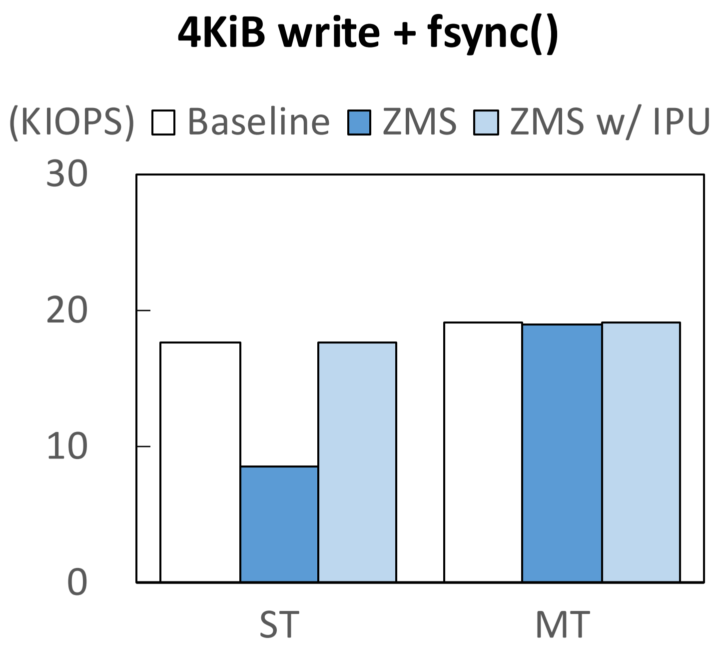
Performance of Writing to Multiple Zones

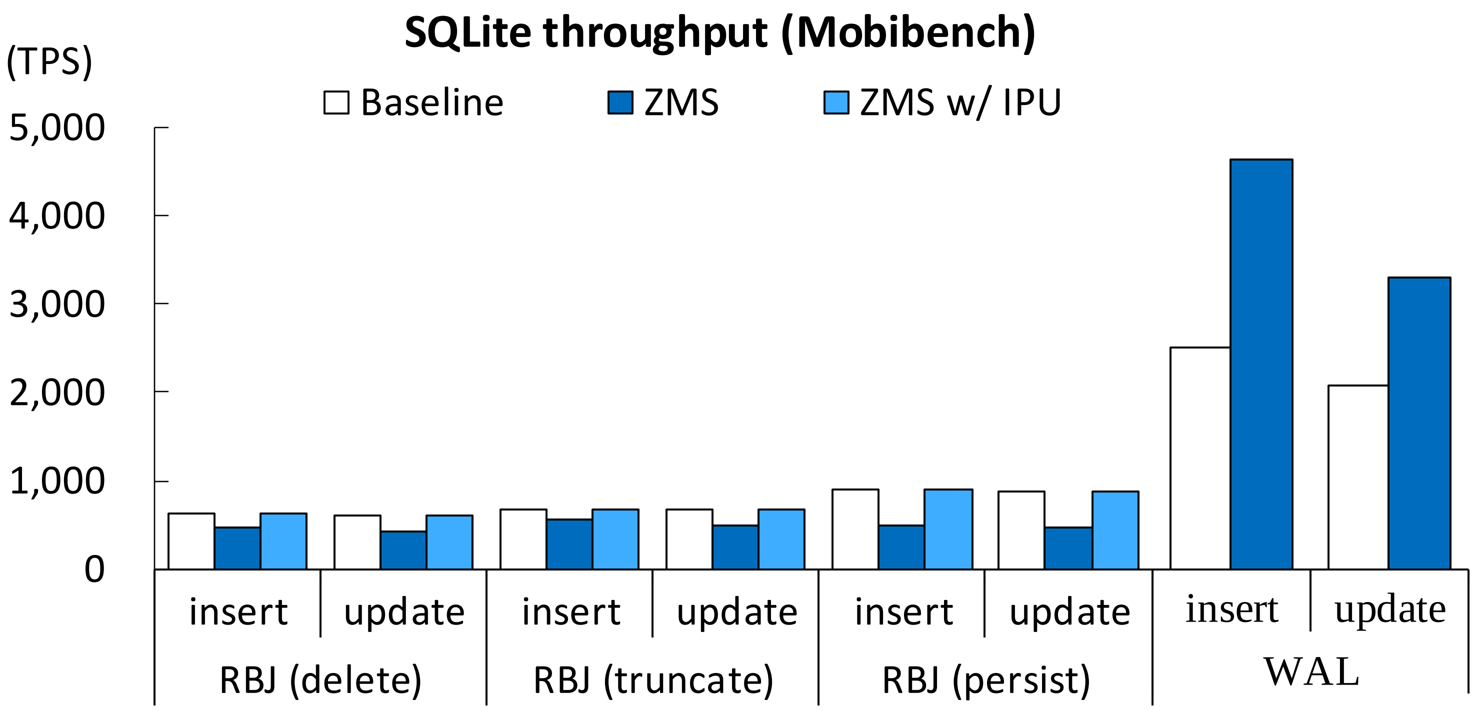
- IOTailor improves multi-zone write performance by reducing SLC buffering.



Synchronous Update Performance

- Using the budget-based in-place update, ZMS shows no performance degradation in tiny synchronous update and SQLite rollback journal mode.
- **60~100%** performance gain in write-ahead log (WAL) mode (append logging).





Baseline: In-place update
ZMS: append logging
ZMS w/ IPU: append logging with budget-based in-place update

Conclusion

- Zone abstraction is promising for enhancing responsiveness of mobile devices.
- Two challenges in zoned mobile storage
  - Degraded multi-zone write performance
  - Increased latency of tiny synchronous file update
- ZMS techniques address the challenges
  - IOTailor improves performance of writing to multiple zones by avoiding unaligned buffer flushes due to buffer switching.
  - Budget-based in-place update improves synchronous update performance.
- ZMS improves random read/write performance and write amplification significantly.

Thank You!