KVAccel: A Novel Write Accelerator for LSM-Tree-Based KV Stores with Host-SSD Collaboration

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- Motivation
- Design
- Evaluation
- Conclusion

Background

LSM-tree based Key-Value Stores (LSM-KVS)

- Log-Structured Merge-Tree(LSM-tree)
  - Designed for write-intensive workloads
  - Optimized for large-scale data
  - Out-of-place updates
  - Sequential batch operations

RocksDB [1]

levelDB [2]

ZippyDB [3]

[1]: Facebook, "RocksDB" https://rocksdb.org, 2012
[2]: Google, "LevelDB" https://github.com/google/leveldb, 2017
[3]: Meta, "ZippyDB" https://engineering.fb.com/2021/08/06/core-infra/zippydb/, 2021

LSM-tree based Key-Value Stores (LSM-KVS)

- LSM KVS(e.g. RocksDB) stores data in an append-only manner in the active MemTable
- Data in MemTable is moved to and managed on disk through background jobs(Flush, Compaction)

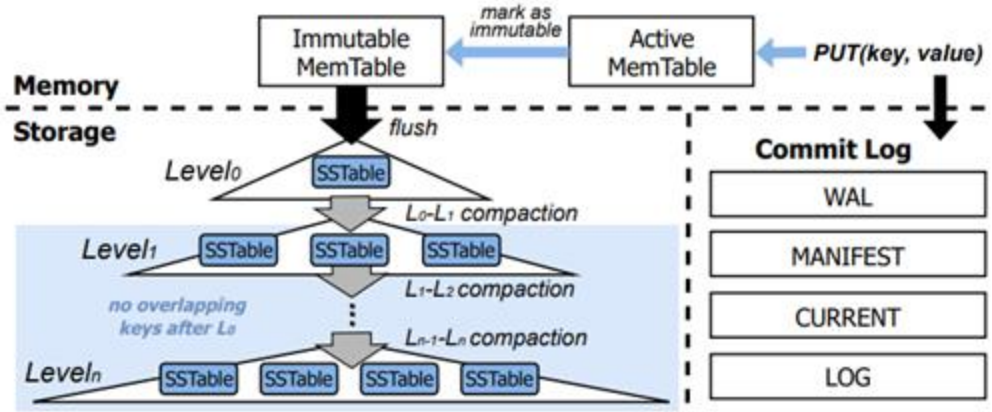


Fig. 1: An architecture of LSM-tree.

Write Stall Problem

- Write Stall: write operation blocked, due to bottlenecks in Flush, Compaction
- In RocksDB, Write stall occurs under these 3 scenarios[4][5]
  - Incoming Writes > Flush
  - Flush > Level 0 to Level 1 Compaction
  - Pending deep level compaction size becomes heavier

[4]: SILK: Preventing Latency Spikes in Log-Structured Merge Key-Value Stores, Oana Balmau et al., USENIX ATC'19
[5]: ADOC: Automatically Harmonizing Dataflow Between Components in Log-Structured Key-Value Stores for Improved Performance, Jinghuan Yu et al. (USENIX FAST'23)

Existing Work: ADOC[5]

- In three types of overflow scenarios, ADOC alleviates write stalls by adjusting two tuning knobs
- Two tuning knobs: # of Compaction threads, MemTable size

	# of Compaction Threads	MemTable Size
Incoming Writes > Flush	↓	↑
Flush > Level 0 to Level 1 Compaction	↑	
Pending deep level compaction size becomes heavier	↑	↓

[5]: ADOC: Automatically Harmonizing Dataflow Between Components in Log-Structured Key-Value Stores for Improved Performance, Jinghuan Yu et al. (USENIX FAST'23)

Existing Work: ADOC[5]

- In three types of overflow scenarios, ADOC alleviates write stalls by adjusting two tuning knobs
- Two tuning knobs: # of Compaction threads, MemTable size

1. Not an immediate remedy → Write stalls still occur

2. Tuning knobs does not stop write slowdowns from occurring.

Pending deep level compaction size becomes heavier		

[5]: ADOC: Automatically Harmonizing Dataflow Between Components in Log-Structured Key-Value Stores for Improved Performance, Jinghuan Yu et al. (USENIX FAST'23)

Motivation

Observation 1.
Slowdowns[6]: The Inefficient Write Stall Solution

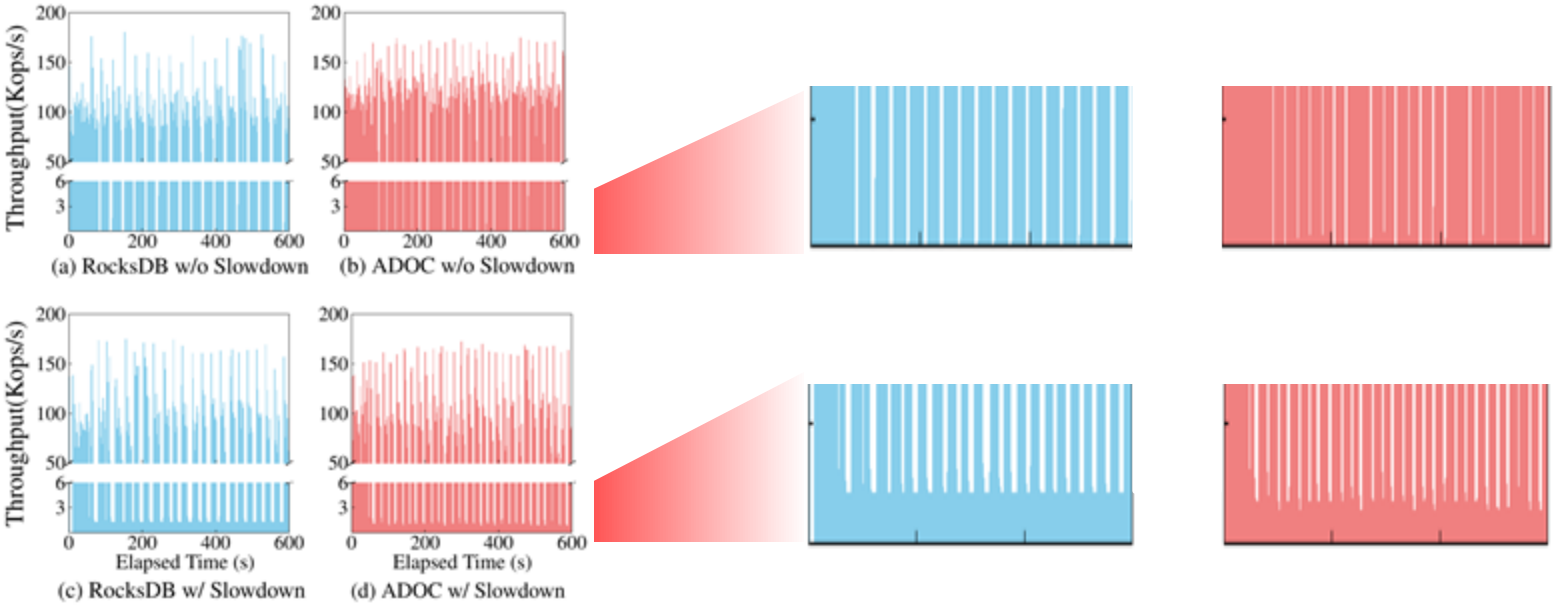
- RocksDB uses the *slowdown*[6] method to prevent user writes from becoming completely blocked
- The state of the art solution ADOC[5] also uses *slowdowns*

➡ Both RocksDB and ADOC[5] ultimately fall back to using *slowdown* to avoid a write stall

[5]: ADOC: Automatically Harmonizing Dataflow Between Components in Log-Structured Key-Value Stores for Improved Performance, Jinghuan Yu et al. (USENIX FAST'23)
[6]: https://github.com/facebook/rocksdb/wiki/Write-Stalls

Observation 1.
Slowdowns[6]: The Inefficient Write Stall Solution

- *Slowdowns*, while preventing a complete write stall from occurring, harms overall performance



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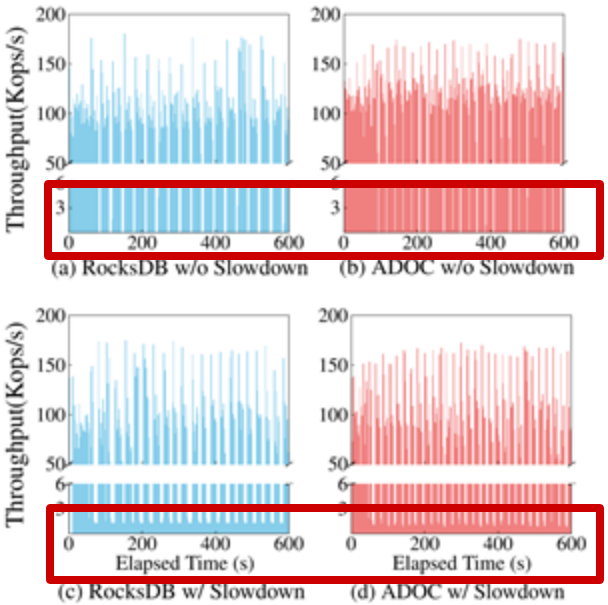
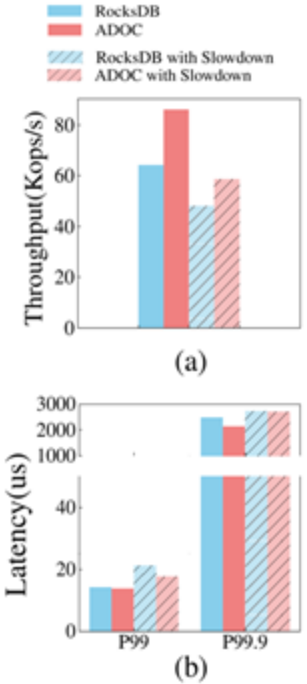


I/O service is uninterrupted thanks to slowdowns preventing write stalls...

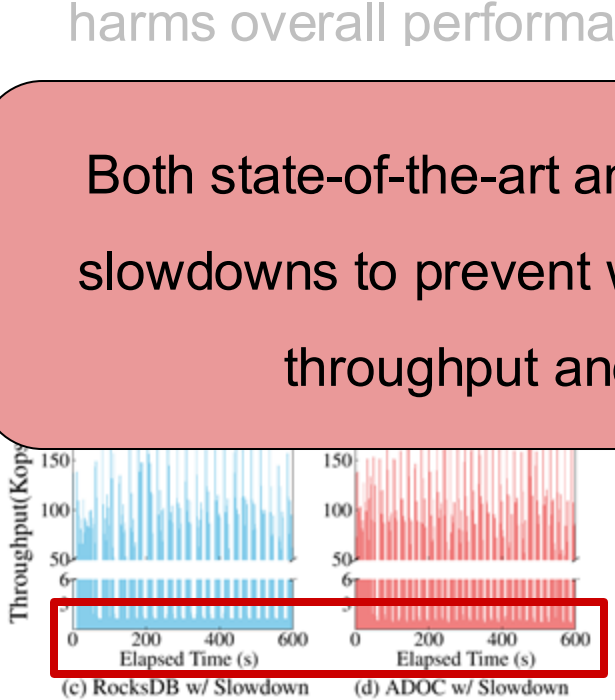


…At the cost of overall throughput and latency

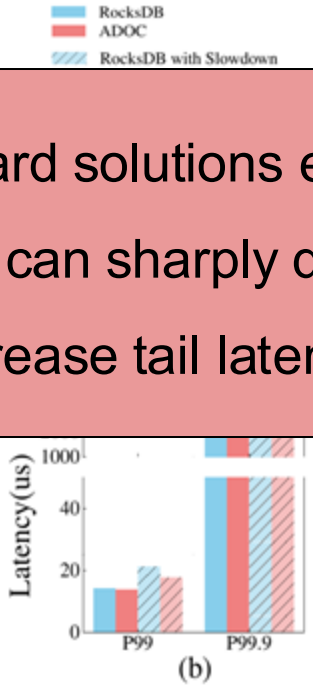
Observation 1.
Slowdowns[6]: The Inefficient Write Stall Solution

- *Slowdowns*, while preventing a complete write stall from occurring, harms overall performance.

Both state-of-the-art and industry-standard solutions employ write slowdowns to prevent write stalls, which can sharply degrade over throughput and significantly increase tail latency.



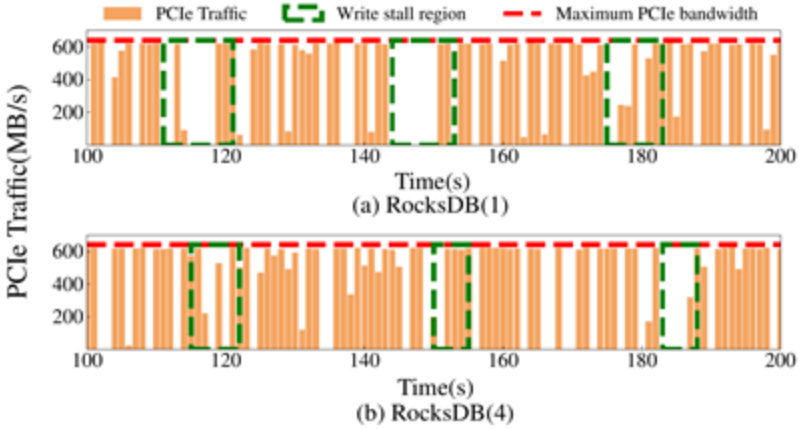
stalls...

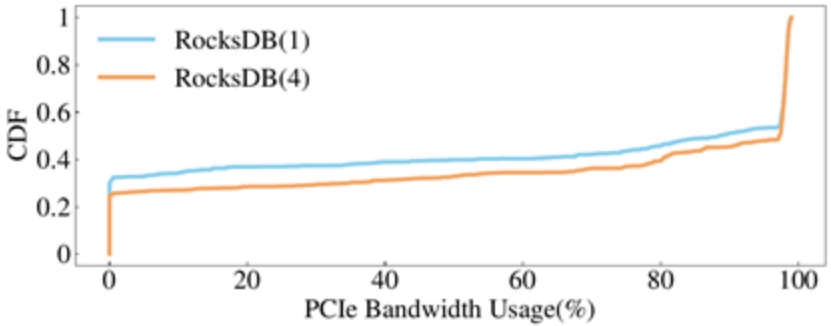


Observation 2.

Under-utilization of PCIe Bandwidth

- PCIe Traffic drop sharply during a write stall, implying inefficient device resource usage

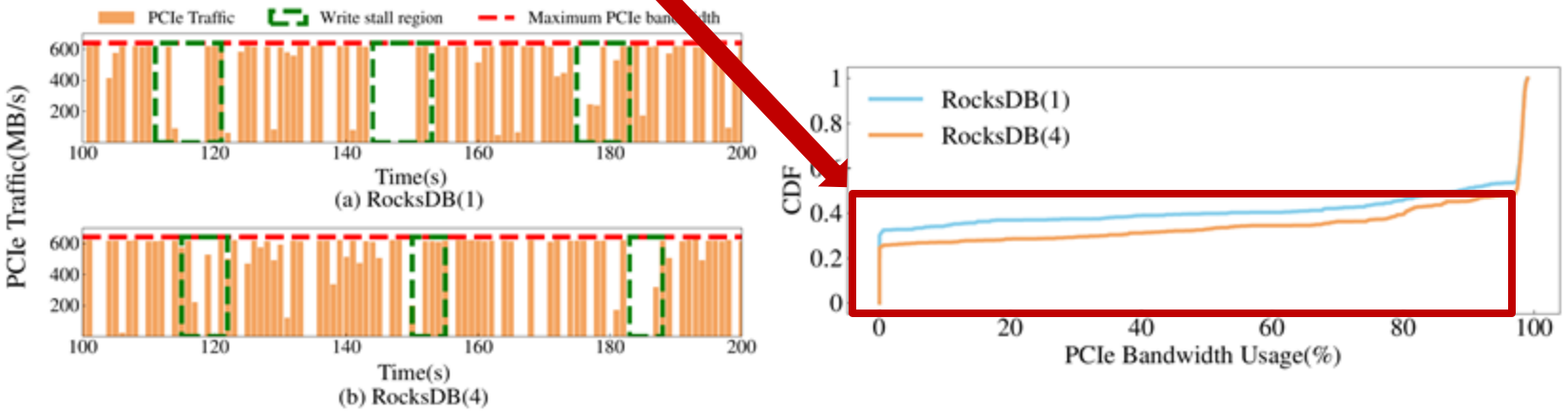




Observation 2.

Under-utilization of PCIe Bandwidth

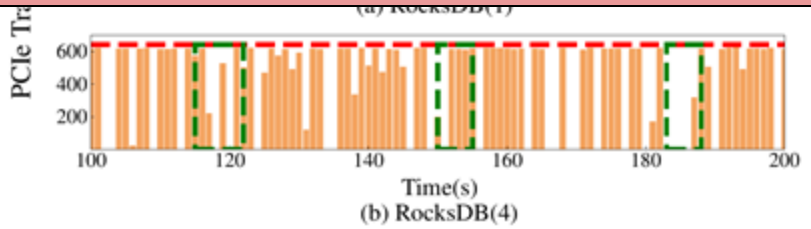
- PCIe Traffic drop sharply during a write stall, implying inefficient device resource usage
  - RocksDB is shown to leave up to **90%** of available PCIe bandwidth around **50%** of the time during a write stall



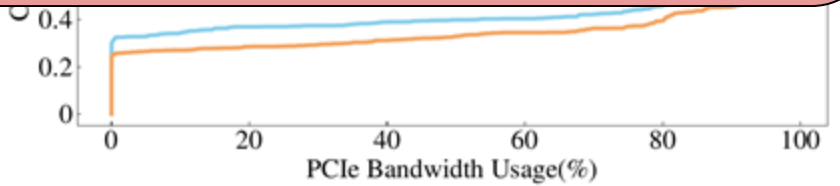
Observation 2.
Under-utilization of PCIe Bandwidth

- PCIe Traffic drop sharply during a write stall, implying inefficient device resource usage.

PCIe bandwidth is under-utilized during write stalls in industry standard LSM-KVS due to the compaction operation blocking device I/O.



(b) RocksDB(4)



The status quo

- **Observation 1.** ultimately leads to the following options for write stalls

Slowdowns	VS	Allowing Write Stalls
• Maintains I/O service at all times • Overall throughput and latency penalty due to said slowdowns		• Overall throughput and latency conserved • Complete interrupts in I/O service as write stalls are allowed to occur

- **Observation 2.** reveals an unexploited resource to help mitigate write stalls and increase performance without sacrificing system resources: underutilized PCIe and device bandwidth during write stalls

The status quo

- **Observation 1.** ultimately leads to the following options for write stalls.

Slowdowns VS Allowing Write Stalls

Can write stalls be mitigated without sacrificing system resources by leveraging underutilized PCIe and device bandwidth during write stalls?

- **Observation 2.** reveals an unexploited resource to help mitigate write stalls and increase performance without sacrificing system resources: underutilized PCIe and device bandwidth during write stalls.

Proposed Solution: *KVAccel*

Proposed Solution: ***KVAccel***

- ***KVAccel***'s design is based on two key factors: Disaggregation and Aggregation

Disaggregation

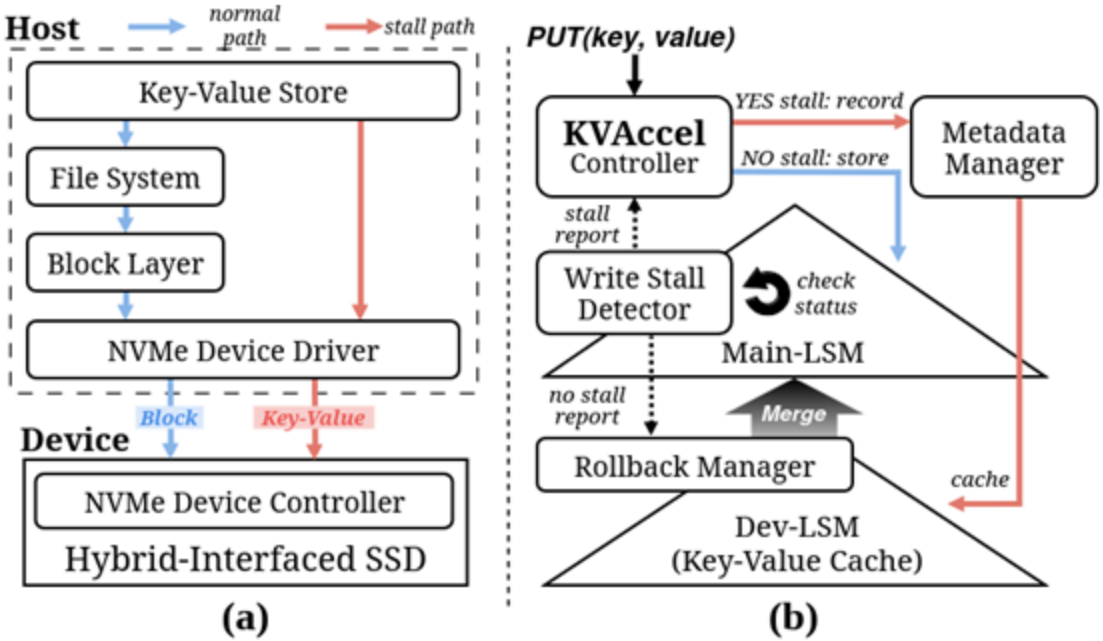
- Division of SSD into hybrid interface (block and key-value) and its required I/O paths
- Maintenance of each interface's separate LSM-Tree

Aggregation

- Manage data from each interface as if it was one database instance
- Unify separate I/O commands and database state with rollback

Overview of ***KVAccel***

- Co-Design of Hardware & Software provides 2 I/O paths
- Different I/O paths taken based on the presence of a write stall



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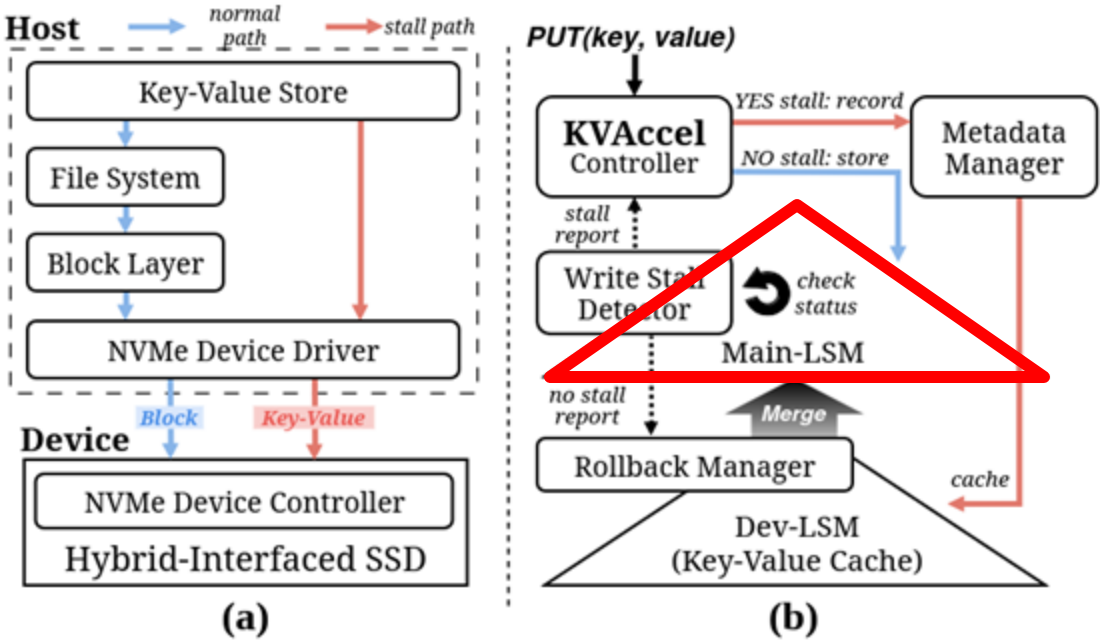

Overview of ***KVAccel***

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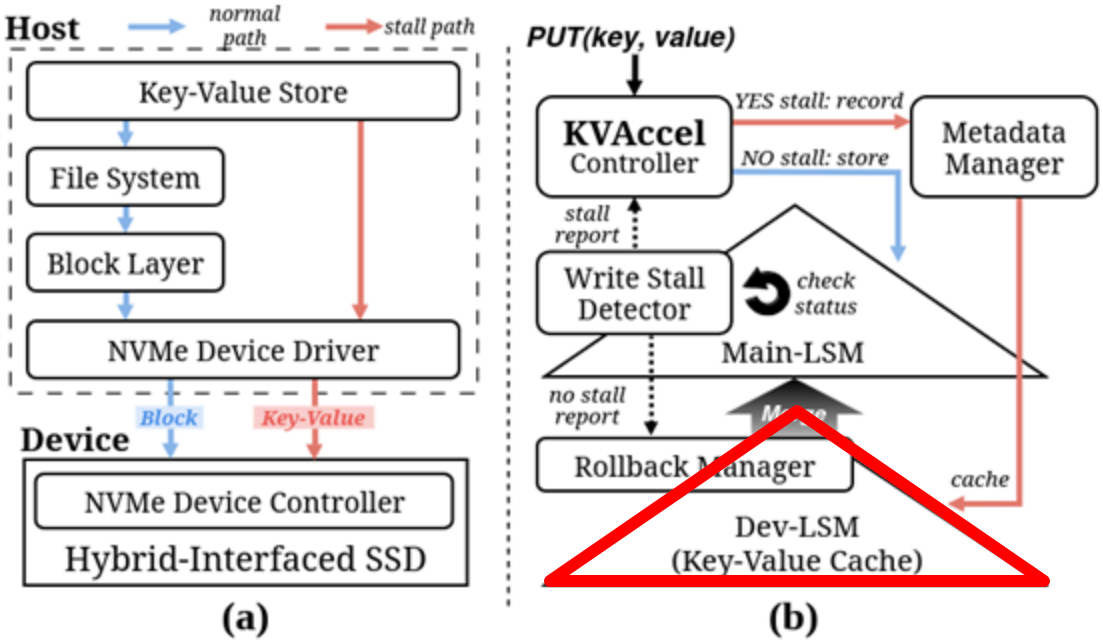
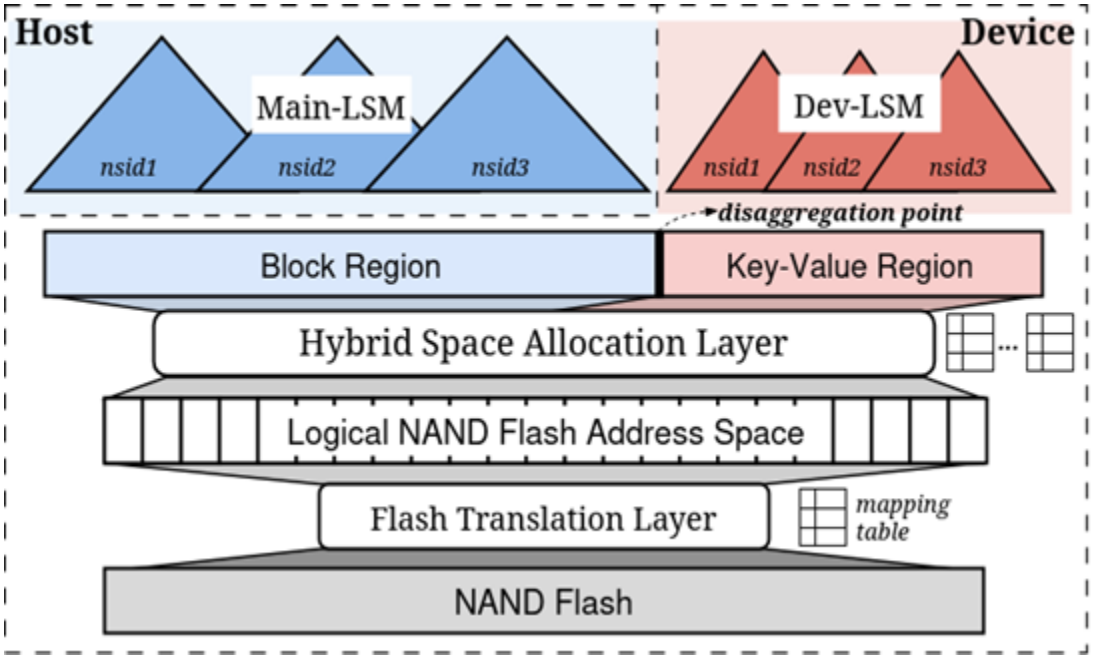
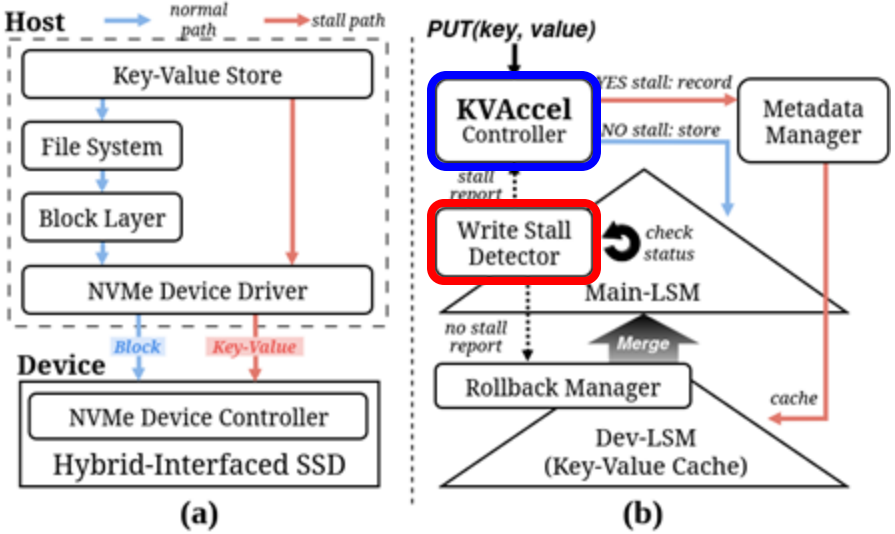


Hybrid Dual-Interface SSD

- Hybrid interface SSD achieved by logical NAND flash address disaggregation via a specified address boundary
  - SSD issues different commands for each interface

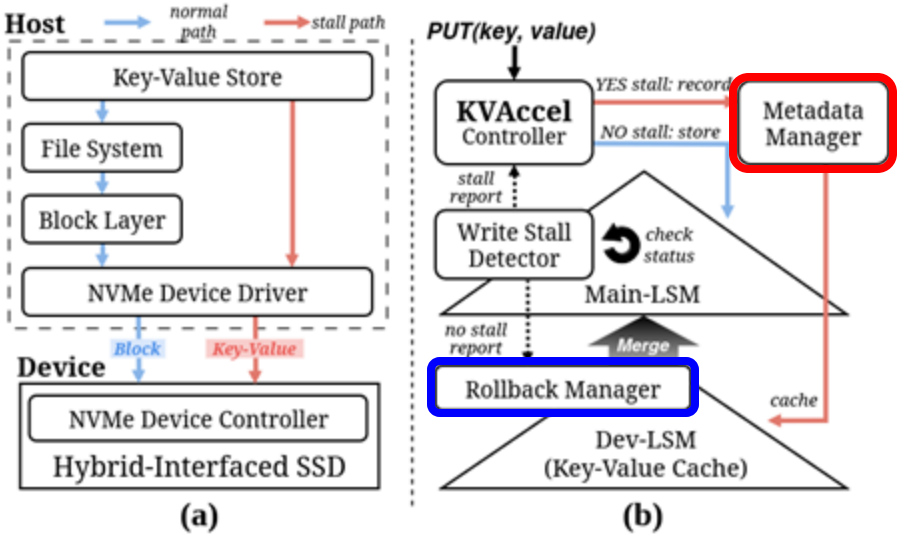


Software Modules(1)



- Detector
  - Detects write stalls checking 3 components
    - # of Level 0 SSTs
    - Memtable size
    - Pending compaction size
- Controller
  - Directs I/O commands to the correct interface based on the Detector's output.

Software Modules(2)



- Metadata Manager
  - Keeps track of KV pairs located in Dev-LSM via a hash table for membership testing
- Rollback Manager
  - Initiates and performs the rollback operation based on the rollback scheduling policy and the Detector's output

Rollback Operation: Scheduling

- Rollback refers to return the KV pairs in Dev-LSM back to Main-LSM into one LSM-KVS instance
- Rollback operation can be scheduled *eagerly* or *lazily* based on workload characteristics

Eager Rollback

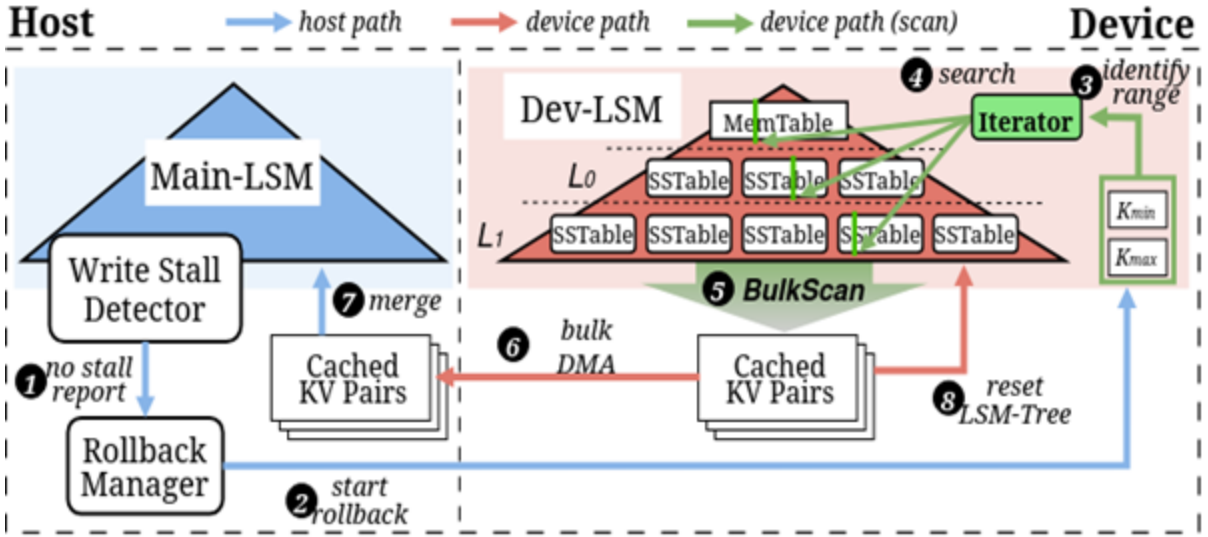
- Perform rollback as soon as there are enough resources available (by using L_0 file count threshold)
- Ideal for a read orientated workload to avoid slow Dev-LSM read operations

Lazy Rollback

- Delay rollback until the current write workload is completely finished
- Ideal for a write intensive workload to lower interference of rollback with write operations

Rollback Operation

- To accelerate rollback, KV pairs are read in bulk using a range scan operation
- Iterator reads Dev-LSM in its entirety and serializes the KV pairs
- KV pairs are then sent to the host by performing DMA multiple times



Evaluation

Evaluation Setup

- Testbed:

KV-SSD on Cosmos+ OpenSSD Platform[7]

TABLE I: Specifications of the OpenSSD platform.

SoC	Xilinx Zynq-7000 with ARM Cortex-A9 Core
NAND Module	1TB, 4 Channel & 8 Way
Interconnect	PCIe Gen2 ×8 End-Points

TABLE II: Specifications of the host system.

CPU	Intel(R) Xeon(R) Gold 6226R CPU @ 2.90GHz (32 cores), CPU usage limited to 8 cores.
Memory	384GB DDR4
OS	Ubuntu 22.04.4, Linux Kernel 6.6.31

[7]: Cosmos+ OpenSSD Platform: http://www.openssd-project.org/platforms/cosmospl/

LSM-KVS and Benchmark Configurations

TABLE III: LSM-KVS configurations. For all figures, the numbers next to each LSM-KVS refer to compaction thread count. For KVACCEL, the settings refer to the Main-LSM.

LSM-KVS	Compaction Threads (n)	MT Size
KVACCEL(n)	1	128 MB
	2	
	4	
RocksDB(n)	1	
	2	
	4	
ADOC(n)	1	
	2	
	4	

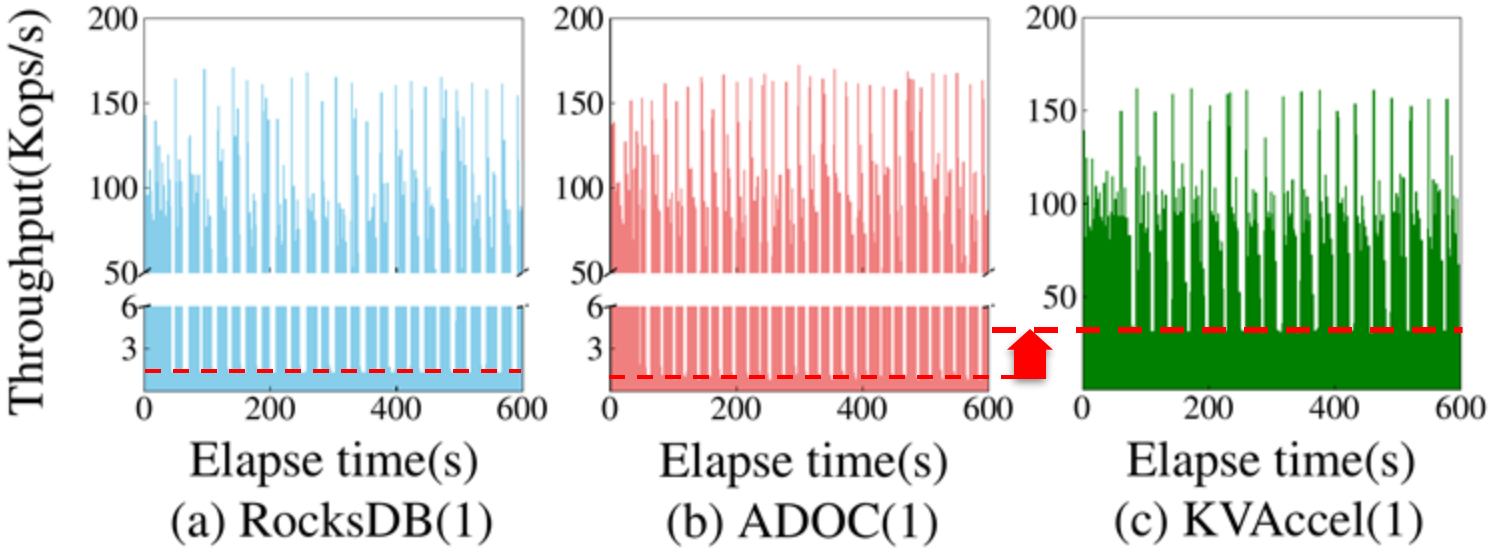
TABLE IV: *db_bench*[8] workload configurations. Each benchmark was run with a 4 B key and 4 KB value size. Workload A,B,C were run for 600 seconds, and Workload D performed 60K read operations.

Name	Type	Characteristics	Notes (write/read ratio)
A	fillrandom	1 write thread	No write limit
B	readwhilewriting	1 write thread + 1 read thread	9:1
C			8:2
D	seekrandom	1 range query thread (Seek + 1024 Next)	Run after initial 20GB fillrandom

[8]: Facebook, "DB Bench" https://github.com/facebook/rocksdb/wiki/

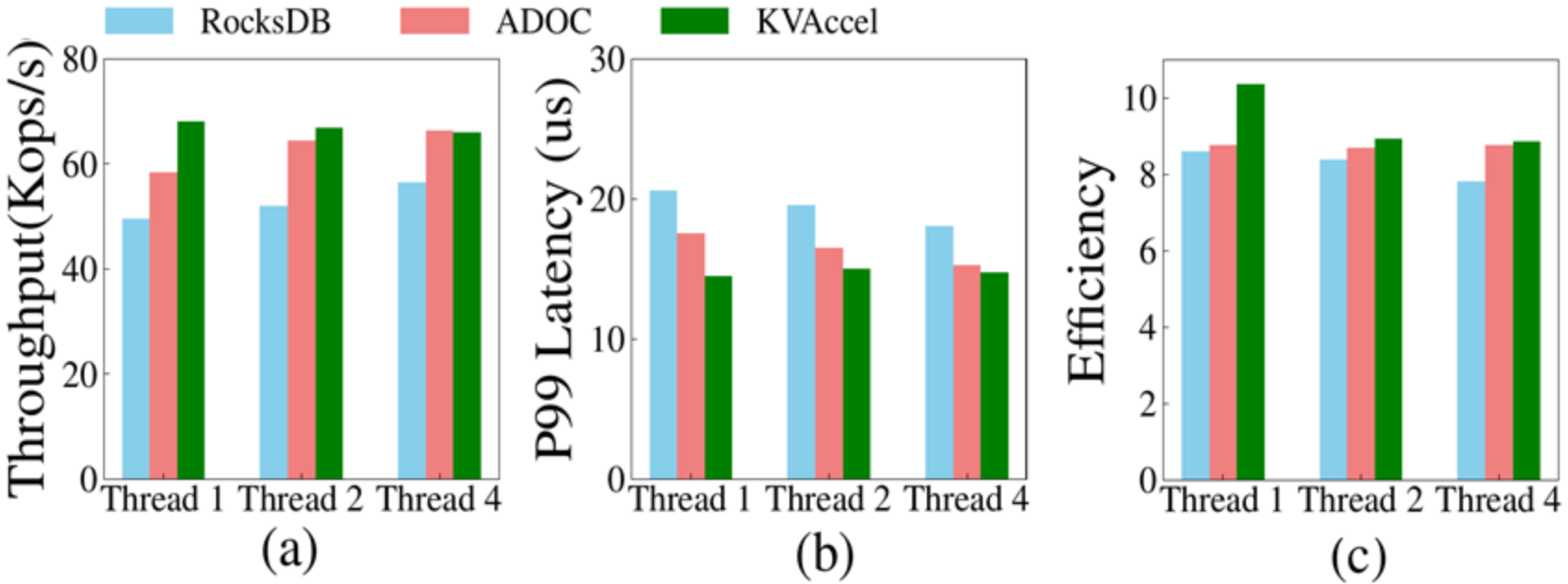
Write Stall Avoidance

- Throughput minimum values greatly increased, as ***KVAccel*** is designed to allow as much throughput as the SSD and system allows without slowdowns



Performance Evaluation

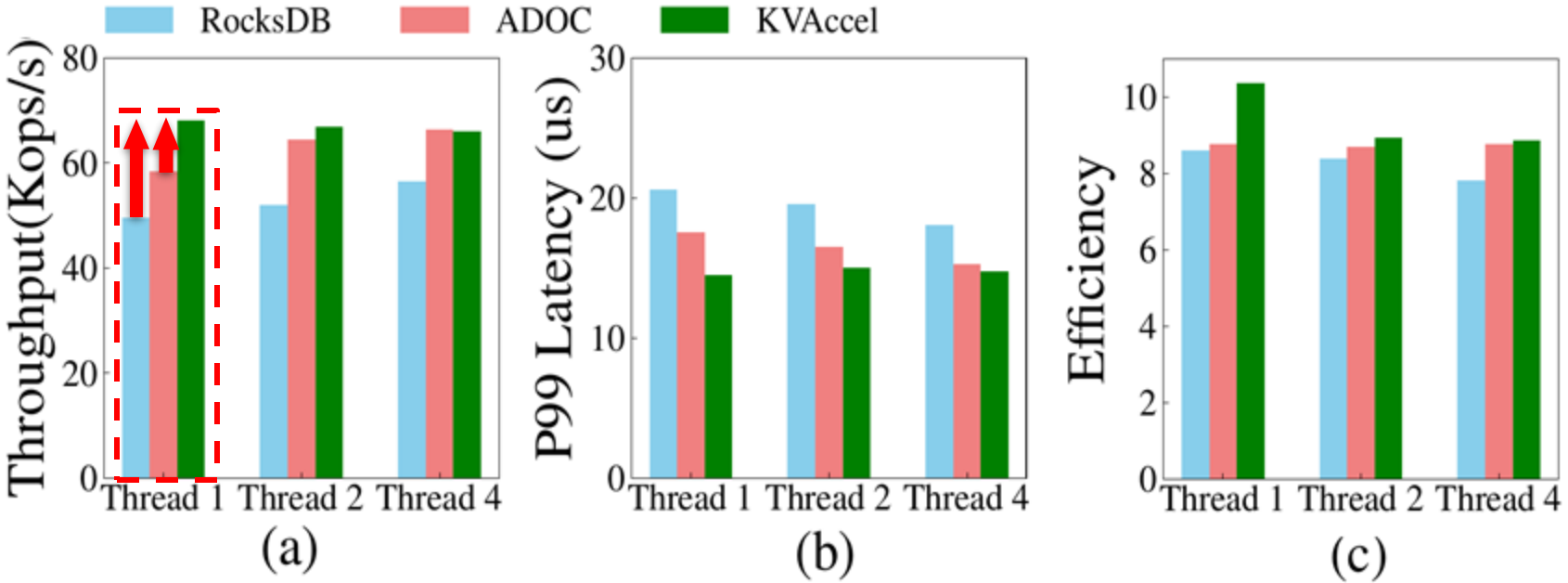
- (a) Throughput, (b) P99 Latency, (c) Efficiency



Performance Evaluation

(a) Throughput

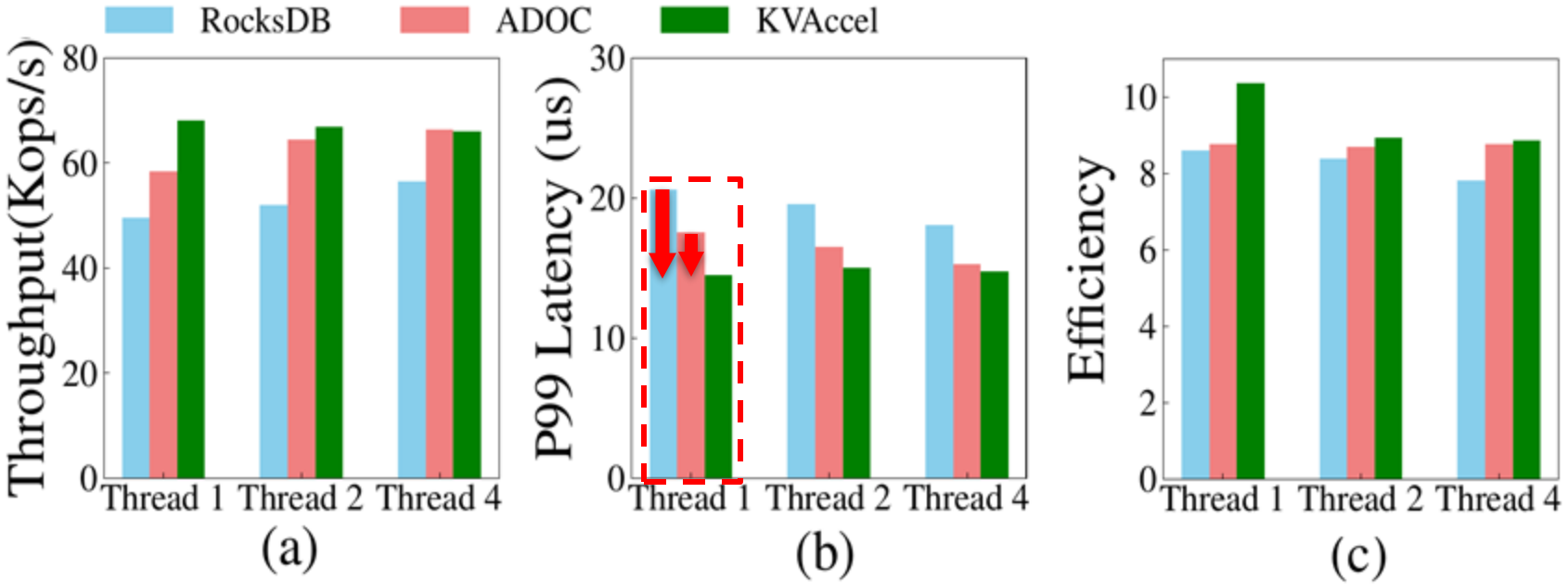
- ***KVAccel*** shows at most a **37%** and **17%** improvement over than RocksDB and ADOC, respectively



Performance Evaluation

(b) Throughput

- Maximum of **30%** and **20%** decrease in latency was also observed between ***KVAccel*** and RocksDB, ADOC, respectively

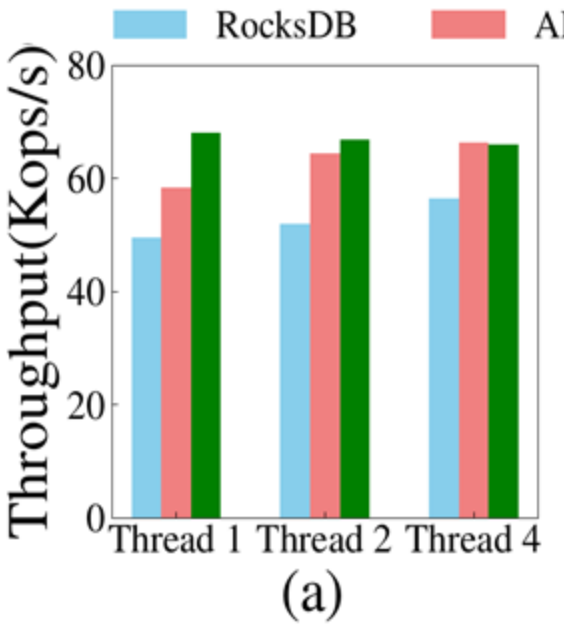


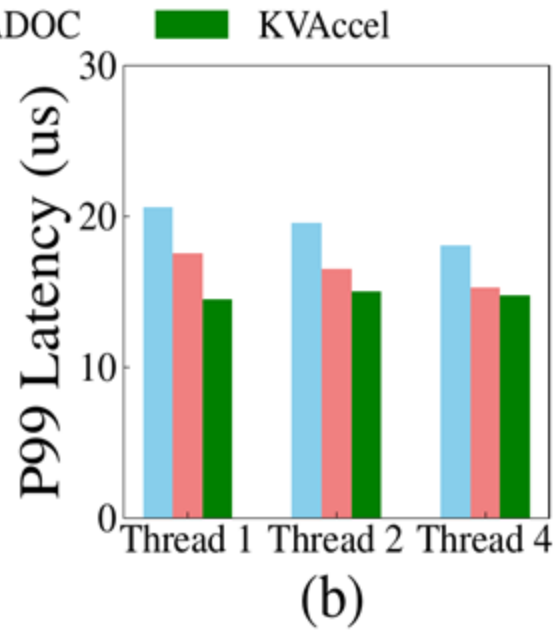
Performance Evaluation

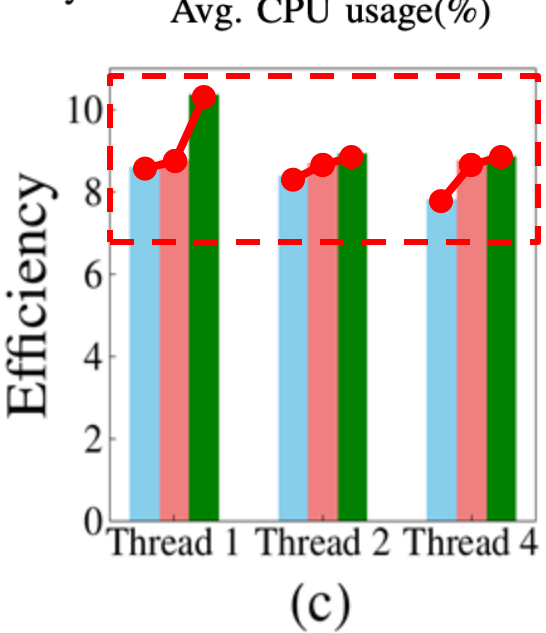
(c) Efficiency

- ***KVAccel*** maintains the better efficiencies in host machine's resources between all LSM-KVS compared

$$\text{Efficiency} = \frac{\text{Avg. Throughput(MB/s)}}{\text{Avg. CPU usage(\%)}}$$



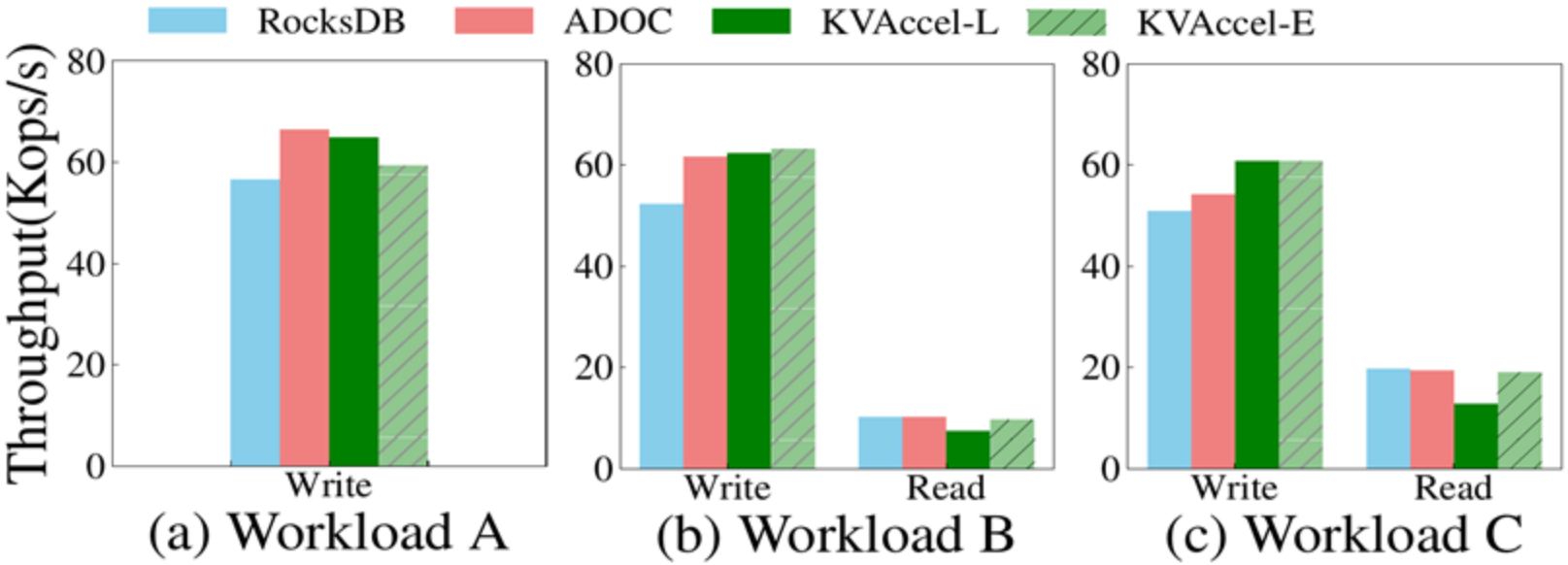




Rollback Policies Evaluation

Eager vs Lazy Rollback analysis

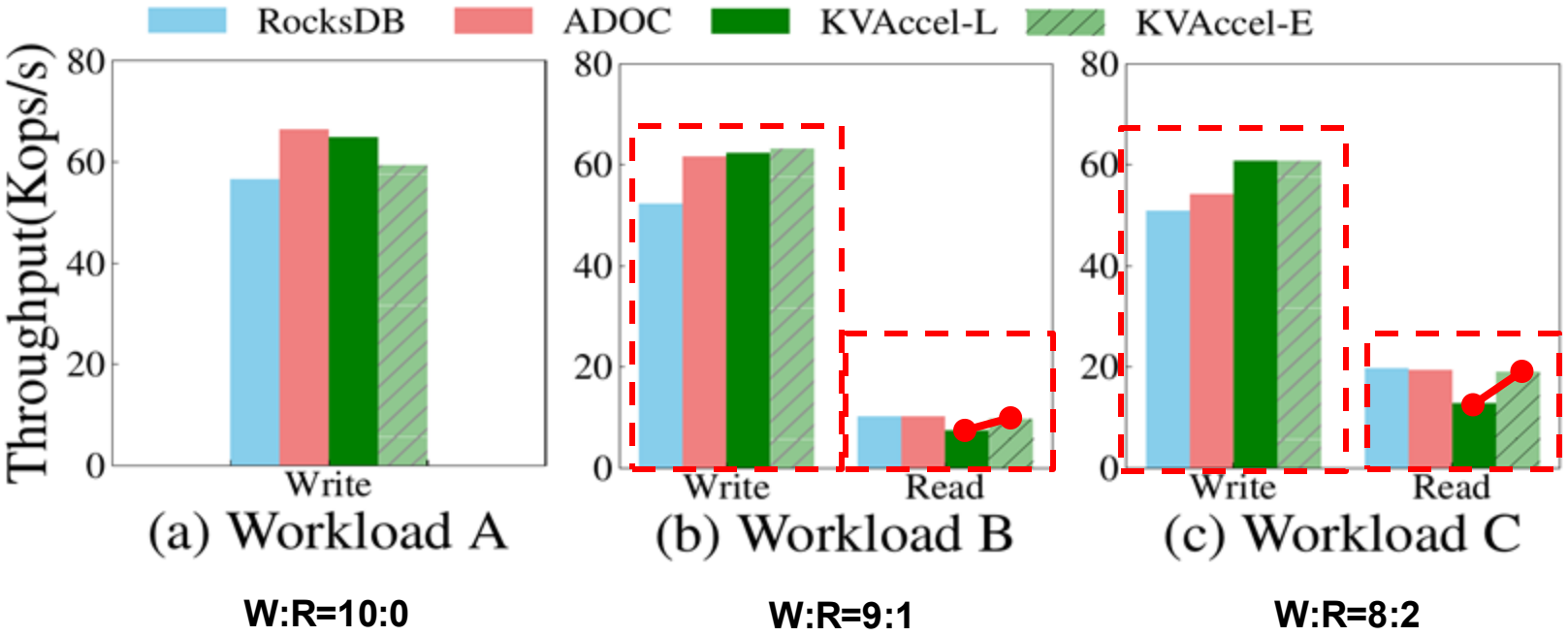
- From (b) and (c), we observe that it still outperforms RocksDB and ADOC under read-oriented workloads



Rollback Policies Evaluation

Eager vs Lazy Rollback analysis

- As the read ratio increases, Eager Rollback becomes increasingly advantageous



Conclusion

Conclusion

- Prior work addresses write stalls to a limited extent
  - Hardware and software are treated in isolation

- ***KVAccel*** achieved a 17% improvement in throughput and a 20% reduction in latency compared to ADOC.

- ***KVAccel*** demonstrates the effectiveness of hardware-software co-design
  - Alleviates write stalls by utilizing:
    - Under-used PCIe bandwidth
    - Computational capabilities within SSDs

Thank you!

<Camera-ready paper>
Can be found on Google Scholar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