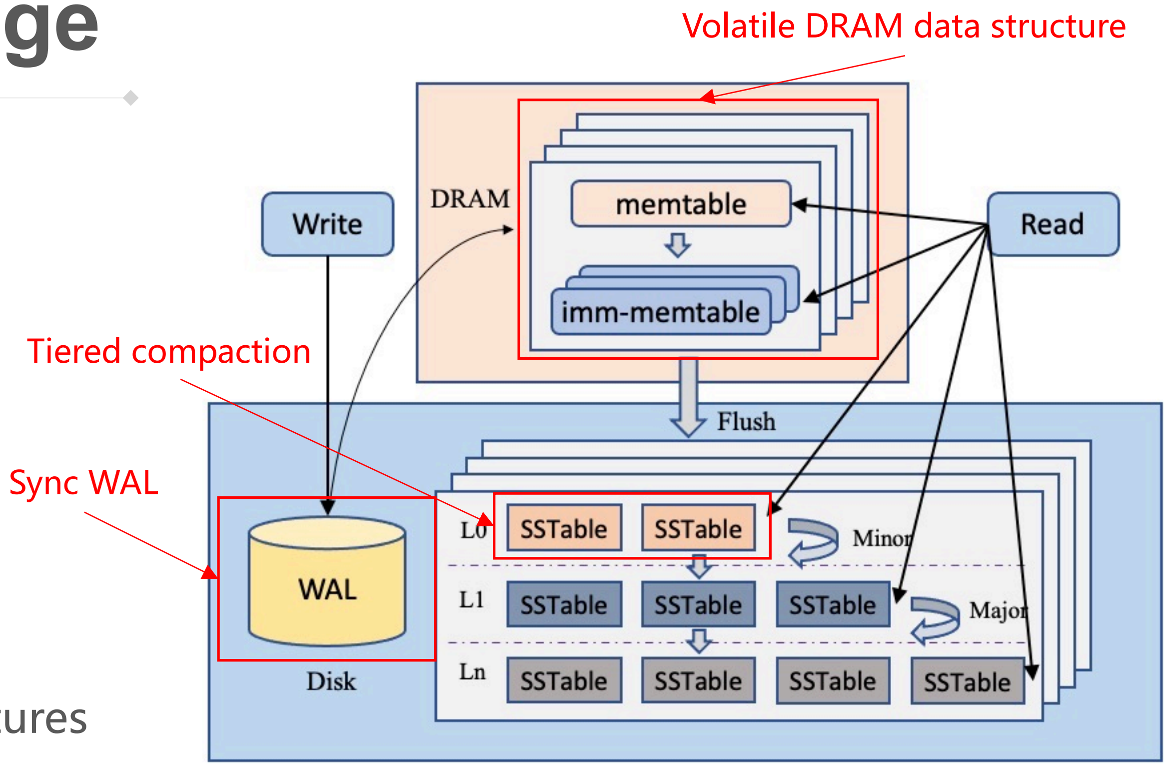
Revisiting the Design of LSM-tree Based OLTP Storage Engine with Persistent Memory

Baoyue Yan[1], Xuntao Cheng[2], Bo Jiang[1,*], Shibin Chen[2], Canfang Shang[2], Jianying Wang[2], Gui Huang[2], Xinjun Yang[2], Wei Cao[2], Feifei Li[2]
[1]Beihang University and [2]AZFT

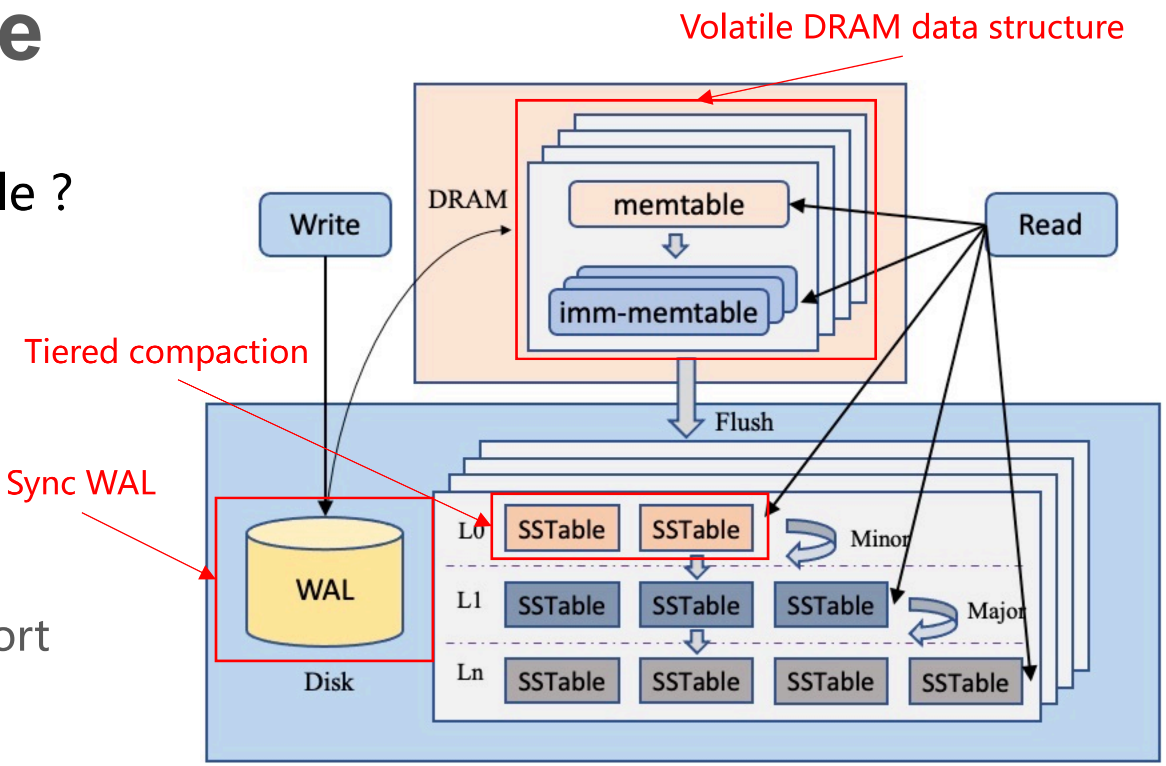
Background and Challenge

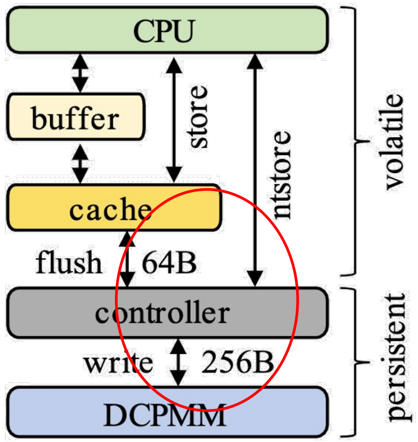
- LSM-tree based OLTP database
  - Fast writes，high compression
  - MyRocks，X-engine in RDS
- Existing problems
  - Write overheads in sync WAL
  - Data piling in level 0
  - Recovery overheads by volatile data structures
- New opportunities by PM
  - Larger capacity (tens of TB)
  - Persistent writes
  - Byte-addressable
  - Lower cost (30% of DRAM)

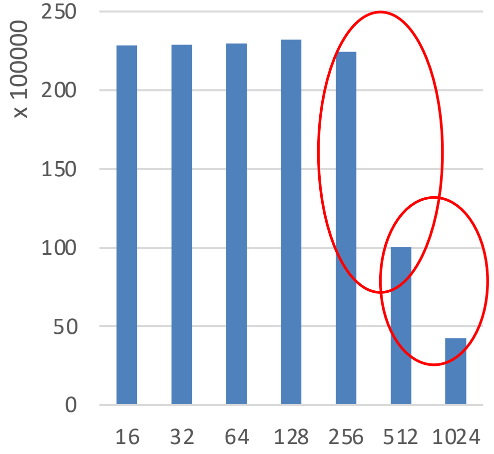


Background and Challenge

- How to design efficient persistent memtable ?
  - High overheads for data persistence
  - Better sequential access for PM
  - Atomicity guarantee
- Can the WAL be removed with PM ?
  - Only support 8-byte atomic write
  - With no hardware transaction memory support
- Can the tiered level 0 be replaced ?
  - Larger capacity of PM enables a larger memory buffer
  - Redesign level 0 data structure with PM
- How to manage the persistent memory allocation ?
  - Efficient memory allocations
  - Memory leaks
  - Memory fragmentations

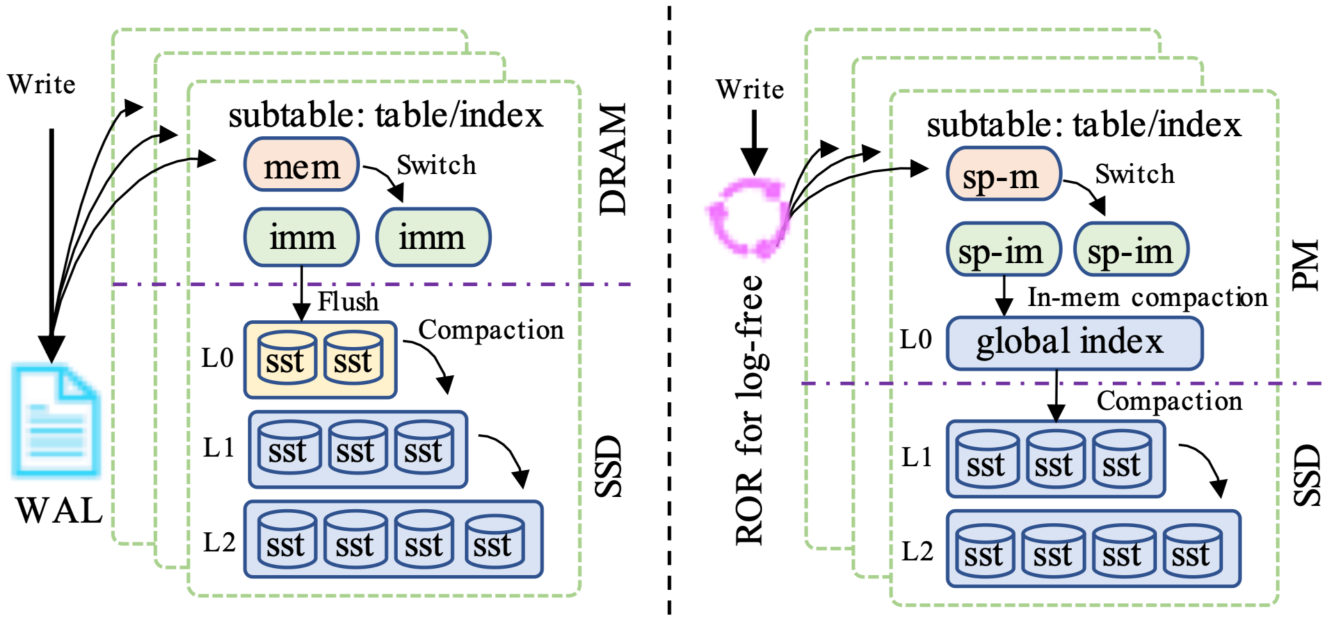






Design Overview

- Semi-persistent memtable
  - Optimized persistent index for memtable
  - High performance and fast recovery
- Reorder Ring
  - Log-as-data to avoid WAL
  - Concurrent lock-free transaction commit in PM
  - Batching to reduce random writes
- Global Index
  - Persistent index working as level 0
  - Globally sorted to reduce read APM
  - No-blocking writes with in-memory compaction
- Halloc
  - PM allocator specifically designed for LSM-tree
  - Pool based object memory pool
  - log-free object allocation
  - hybrid memory management

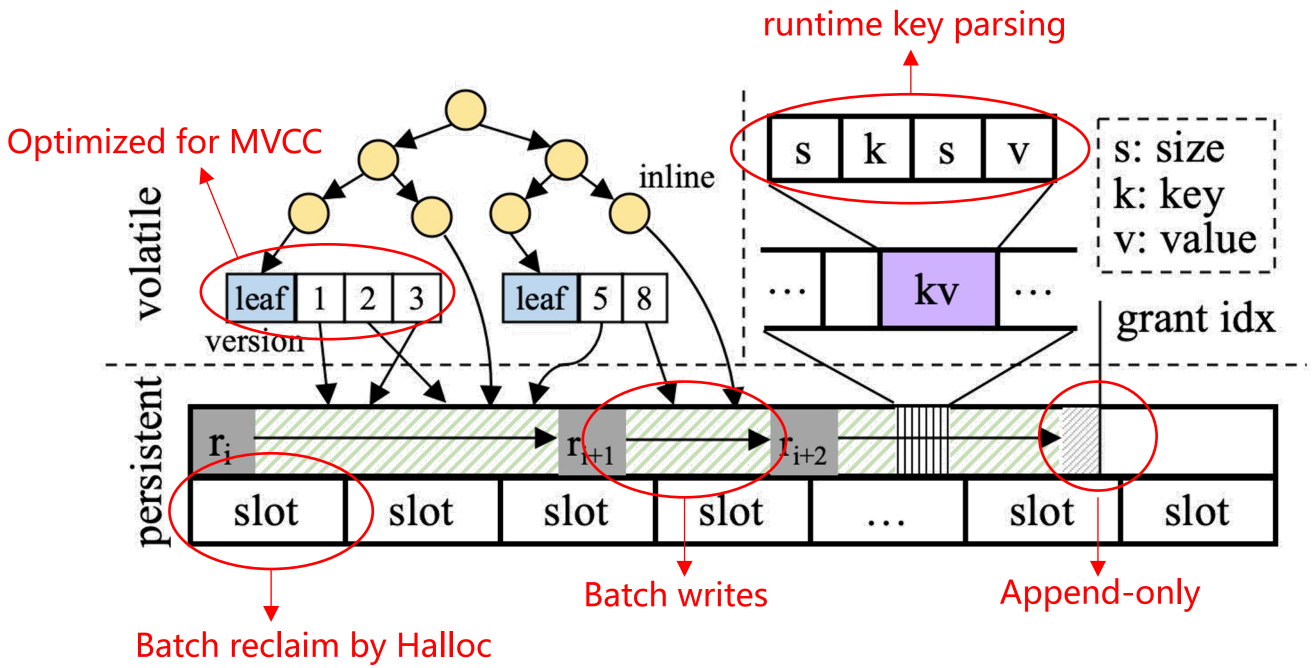


Original solution (left) and our proposal (right)

Design for Semi-persistent Memtable

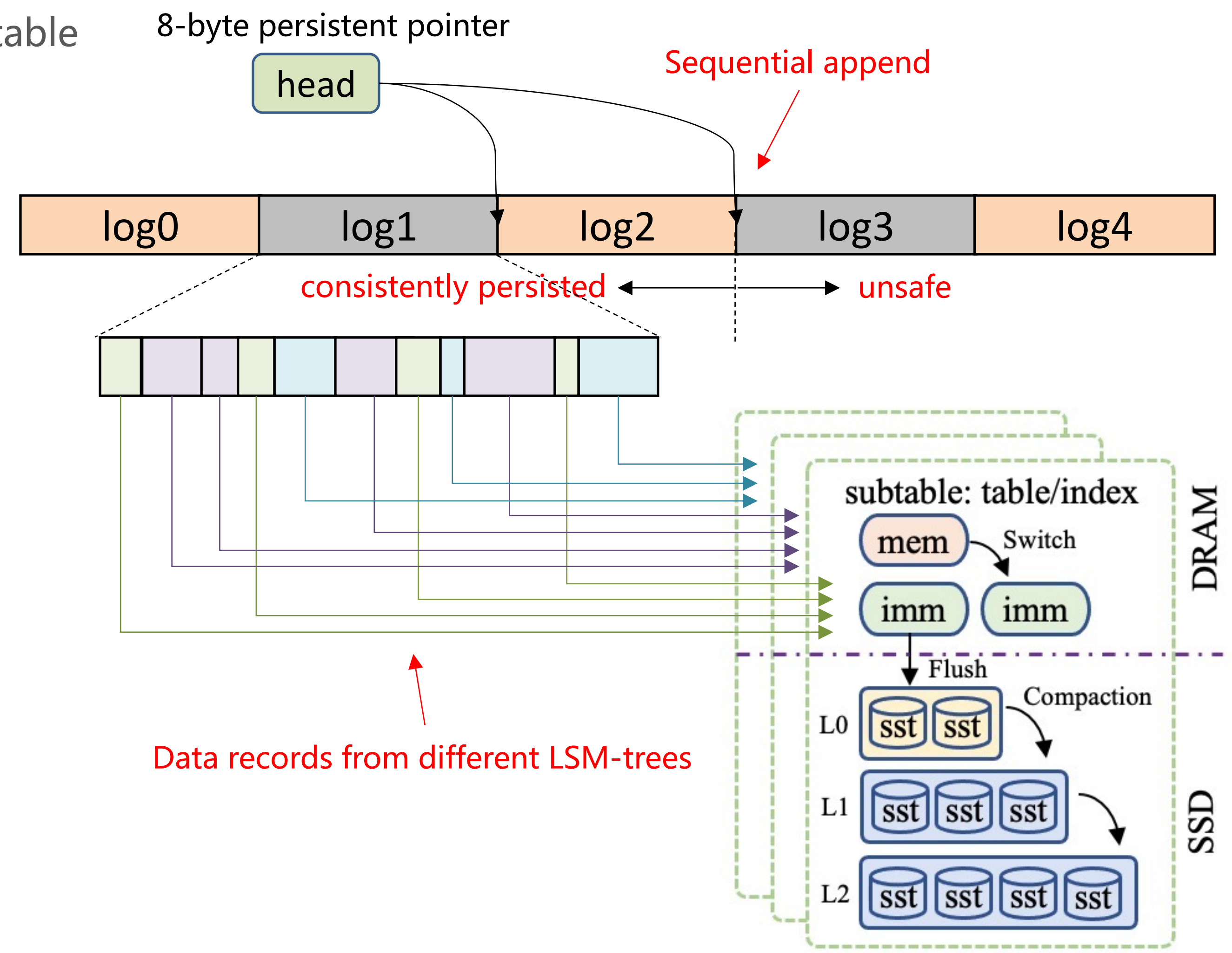
- Three typical range index designs for PM?
  - Fully persistent - F&F, BzTree
  - Semi-persistent - NVTree, FPTree
  - Non-persistent - for DRAM
- Memtable features
  - MVCC
  - Append-only writes
  - Batch memory reclaim
  - Small memory footprint
- Solutions
  - Keep index nodes volatile
  - Stores only pointers to record in PM
  - batch write to reduce write AMP
  - ART + OLC + EBR

	Full	Semi	Non
Performance	low	middle	high
Recovery	fast	middle	no



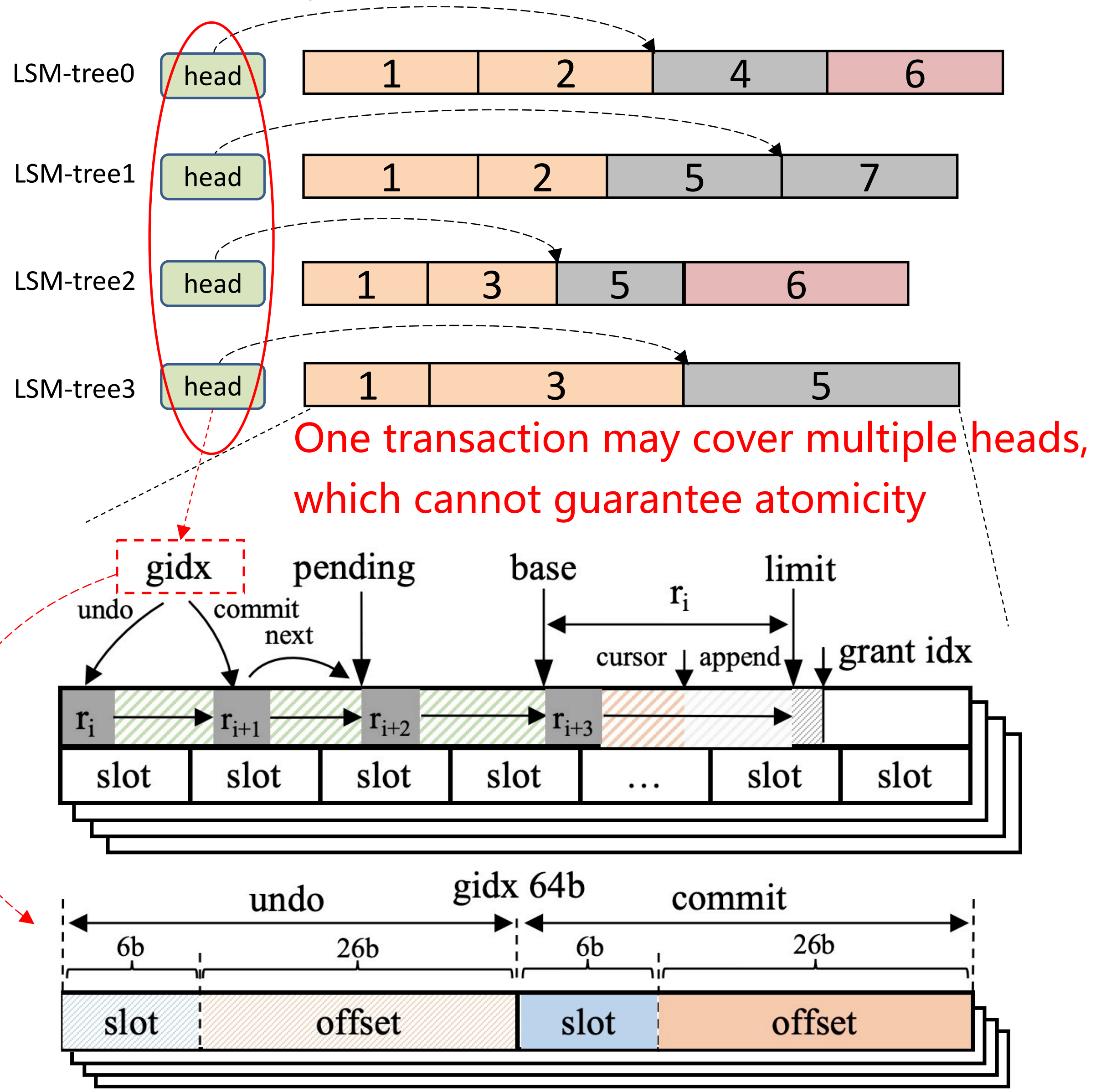
Design for Reorder Ring

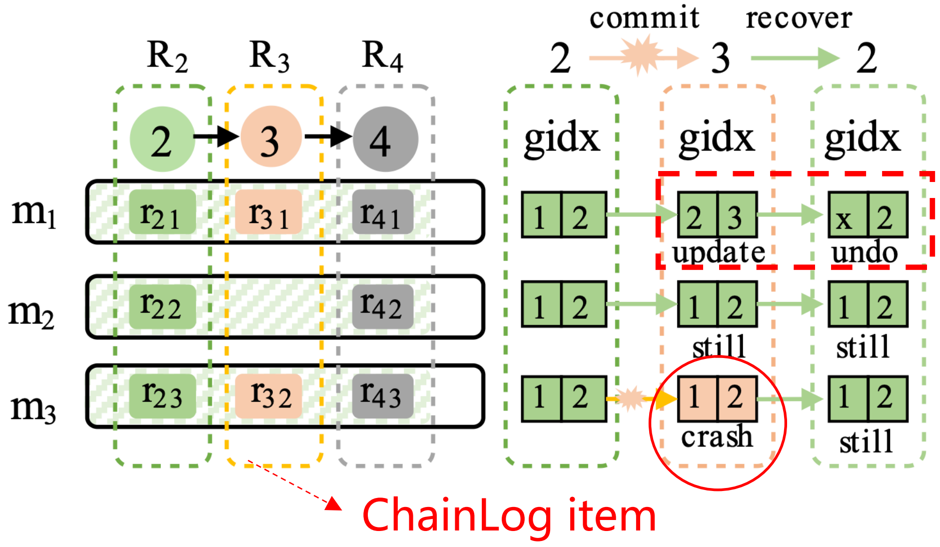
- **Requirements**
  - Atomic writes for multiple KVs to one memtable
  - Atomic persistence for OLTP transactions
  - Performance scales for multi-core platform
- **Design choices**
  - Volatile indexes in memtables
  - Append-only writes in memtables
- **Existing solutions**
  - Log-as-data
  - Build indexes over logs
- **Limitation**
  - Life cycle differences
  - Sequential writes



Design for Reorder Ring

- Distinguish life cycle differences
  - Independent memory regions for LSM-trees
  - May not guarantee atomicity
- Solutions
  - 8-byte gidx pointer
  - Store current pos and previous pos
  - Store LSN and number of heads to update



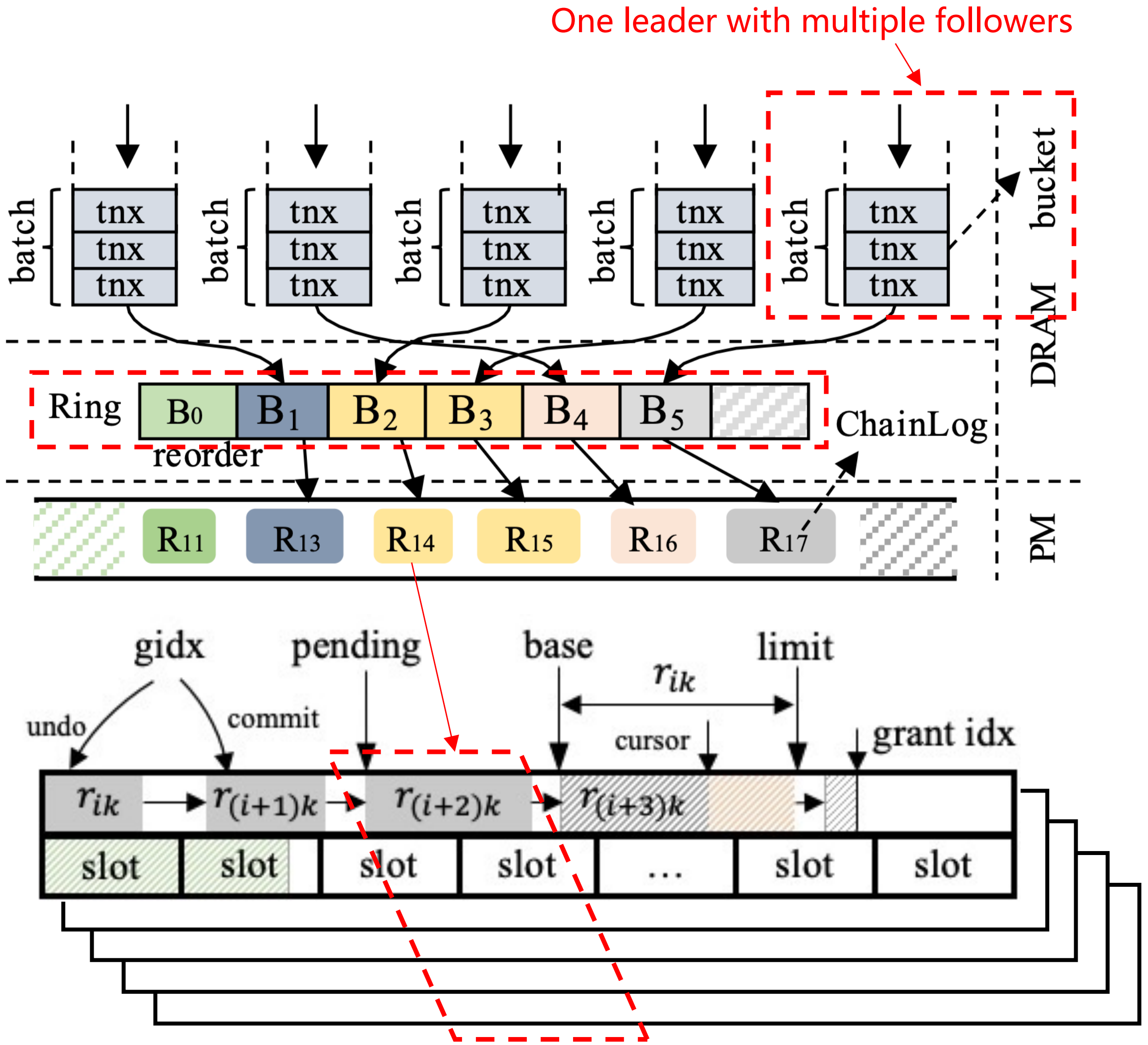


Design for Reorder Ring

- **Enable concurrent persistence**
  - ChainLog requires sequential persistence
  - PM has better performance of sequential writes
- **Solutions**
  - Batching to merge small transaction buffers
  - Concurrent ring to enable parallel persistence
  - Core principle : write ahead
- **Why “Reorder” ?**
  - Get ChainLog descriptors -- serial
  - Parallel buffer initialization -- parallel
  - Grant memory space -- serial
  - Parallel persistence -- parallel
  - No-blocking commit -- serial

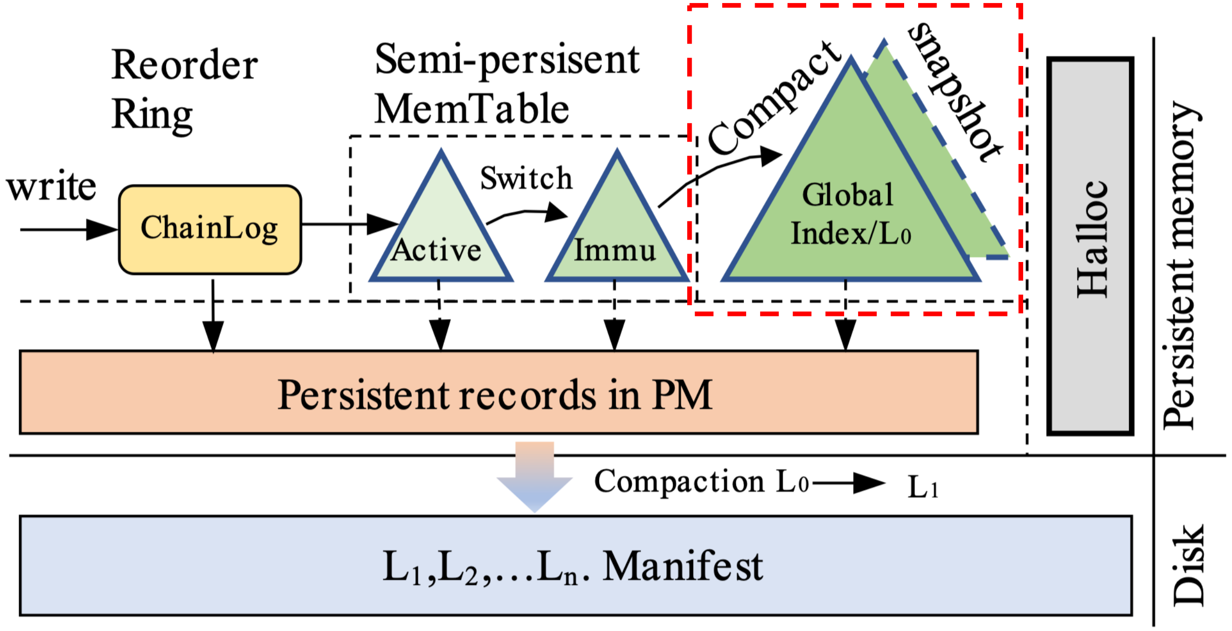
reorder

reorder



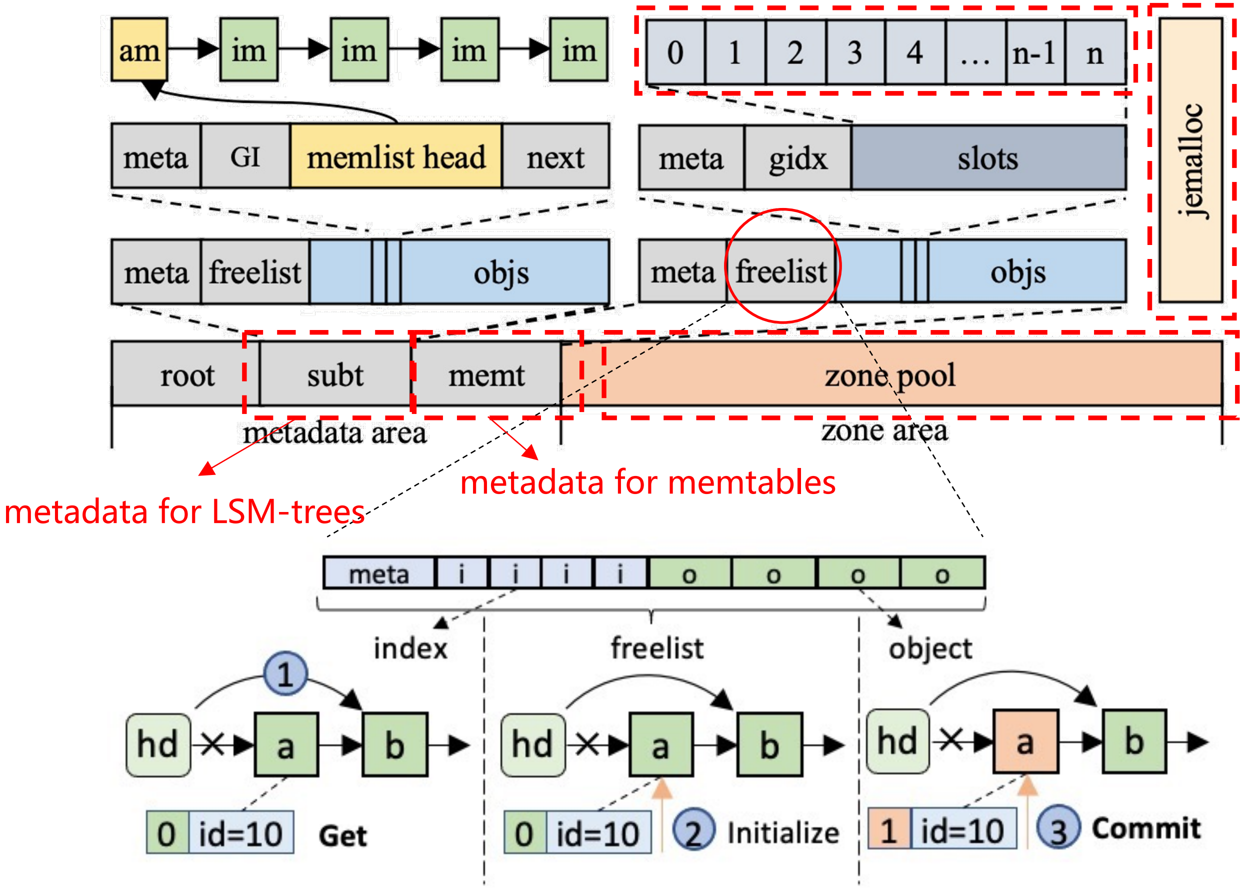
Design for Global Index

- Requirements
  - A globally sorted level 0 in PM
  - No need of transactional writes for multiple records
  - Non-blocking while compacting to disk
- Solutions
  - Introduce Global Index (GI) as new level 0
  - Do not directly store records
  - In-memory compactions to merge memtable into GI
  - Snapshot to enable foreground merge while compaction
- Implementation
  - SoTA persistent range indexes without extra transactional support
  - Volatile range indexes to give a better performance



Design for Halloc

- Specifically designed for LSM-tree
  - Append-only memory allocation
  - Batch memory reclaim
  - Pre-formatted for LSM-tree
- Persistent object pool
  - Log-free persistent freelist
  - Automatic memory leak detection and reclaim
  - Space reservation to reduce fragmentation
- Hybrid memory management
  - Fix-size zone object as minimal unit to allocate
  - Append-only writes for zone object in memtable
  - Delegated to jemalloc for volatile purpose

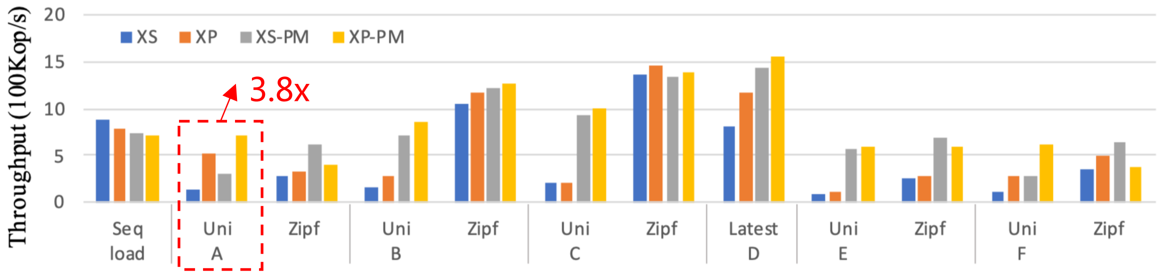


Evaluation

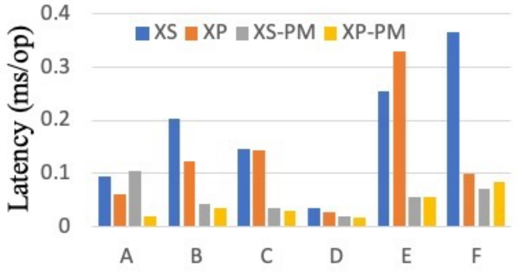
- Hardware configuration
  - Xeon(R) Platinum 8269CY CPUs 104 cores
  - 187GB DRAM
  - 1TB PM
  - 2TB ESSD，2GB R/W bandwidth，200K random 4KB
  - linux kernel 4.19.81
- Overall benchmarks
  - YCSB
  - TPCC
  - Run for 30 minutes

Evaluation for Overall Performance

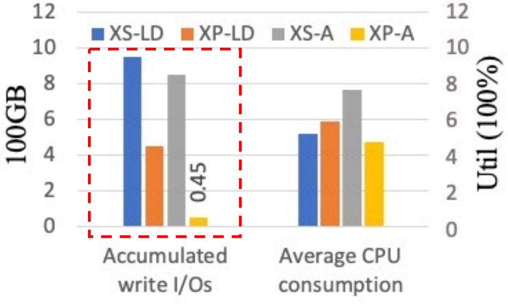
- **YCSB configuration**
  - 8-byte key，500-byte value
  - 800 million KV items，16 tables，500GB dataset
  - 32 client threads
- **TPCC configuration**
  - Storage plugin for MYSQL server
  - 80GB initialized dataset
  - 64 client threads



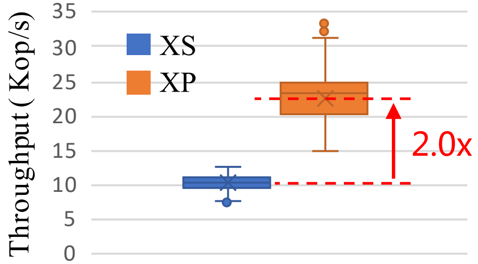
(a) Throughout for ycsb benchamrk

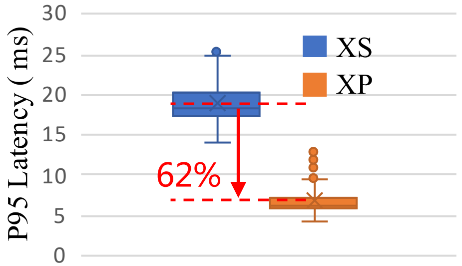


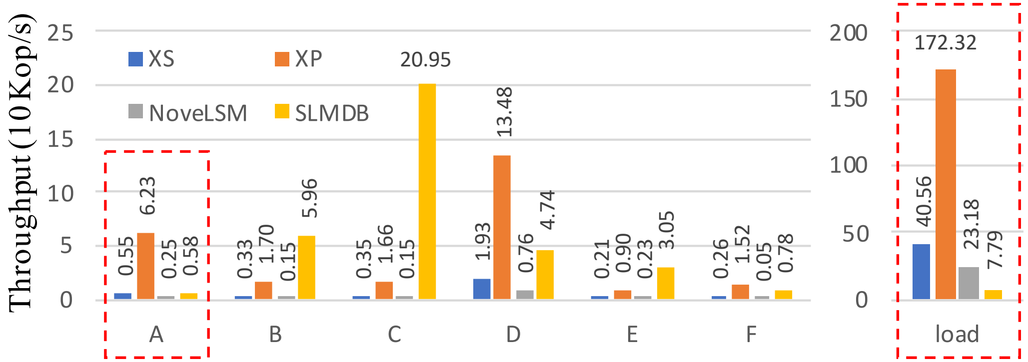
(b) Average latency for uniform workload A



(c) CPU and I/O consumption





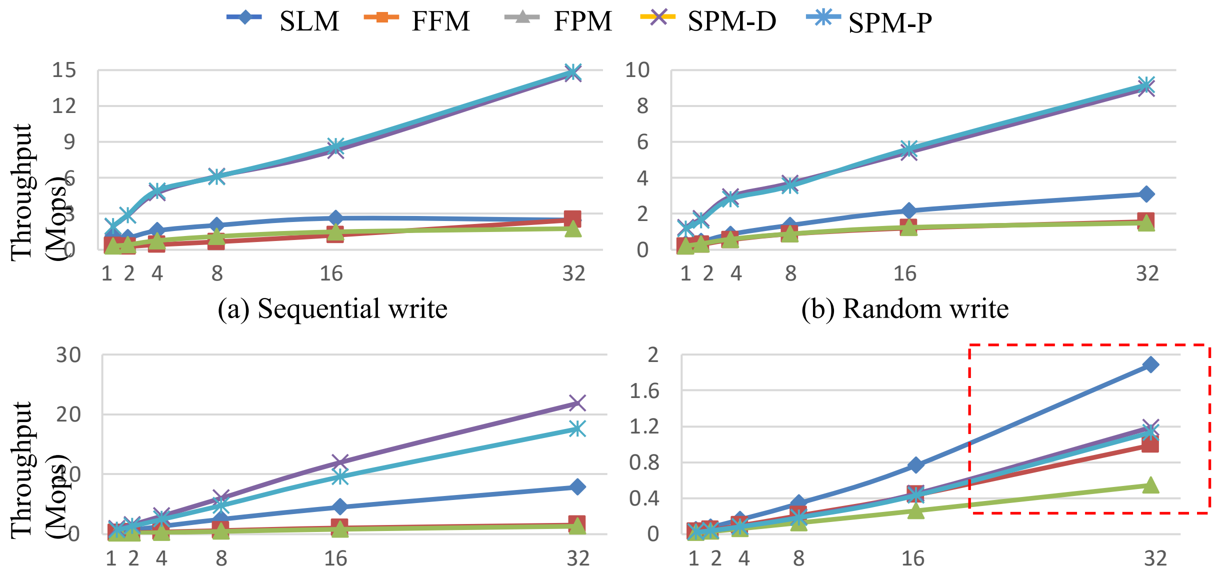


Conclusion

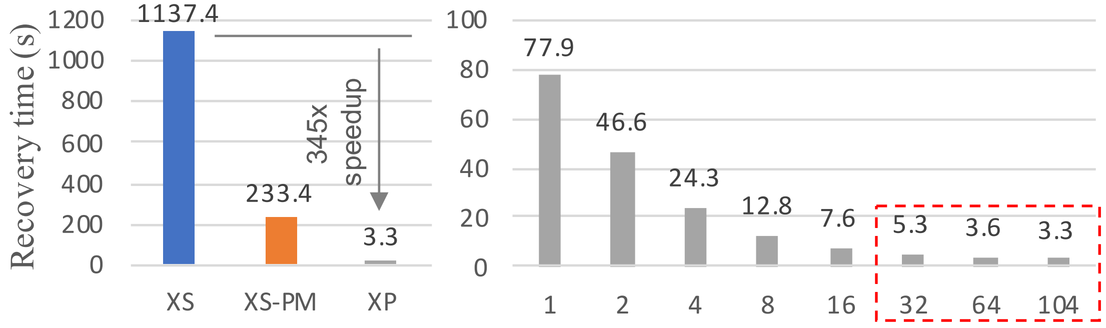
- Semi-persistent memtable significantly outperforms baselines.
- Reorder Ring enables high-performance atomic log-free transactions in PM.
- Global Index largely reduces the read AMP compared with the in-disk one.
- Halloc provides efficient PM allocation specifically for LSM-tree.
- The overall performance improves the baselines by 3.8x in YCSB and 2.0x in TPCC.

Evaluation for Semi-persistent Memtable

- How does the semi-persistent memtable perform compared with SoTA indexes ? Significantly improved
- Memtable configuration
  - 8-byte key , 32-byte value, 50 million items
  - 2GB for single memtable
- Comparisons
  - SLM : Skiplist in DRAM
  - FFM : FAST&FAIR in PM (full)
  - FPM : FPTree in PM (semi)
  - SPM-D : Semi- with indexes in DRAM
  - SPM-P : Semi- with indexes in volatile PM
- Results
  - Random insert by up to 8.3x
  - Sequential insert by up to 6.0x
  - Random point lookup by 16x
  - Random scan slower than Skiplist
  - Fast recovery about 3s for 32GB memtable



(a) Sequential write (b) Random write (c) Random read (d) Random scan



(a) Instances (b) Number of threads

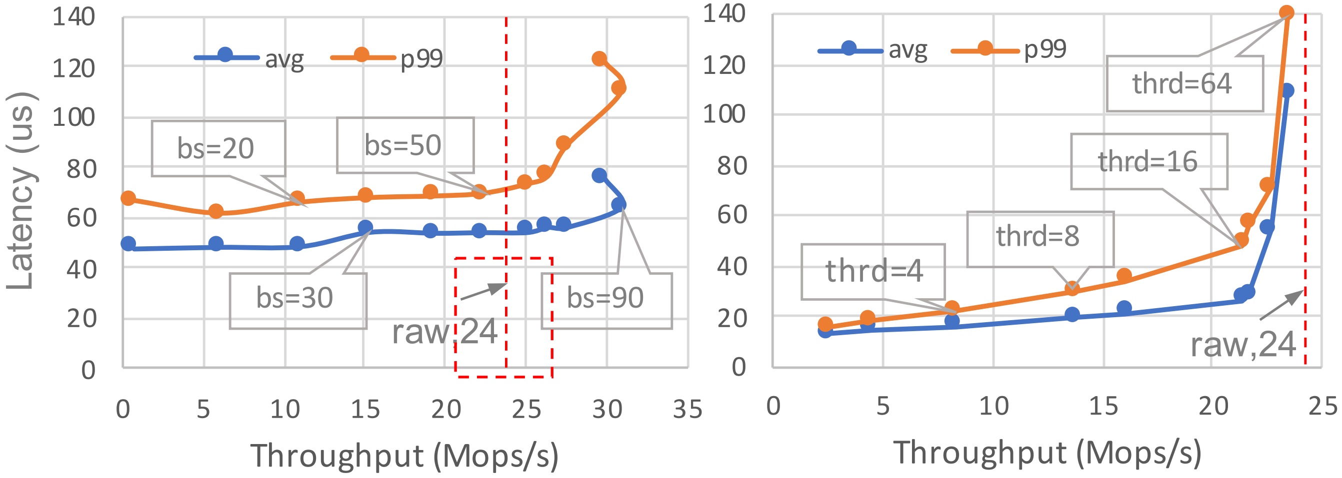
Evaluation for Reorder Ring

- Is the ROR algorithm efficient enough ? Yes

- Configuration
  - 24-byte KV items
  - 1 million items per thread

- Impact of batch size (thrd=32)
  - Higher throughput with longer latency
  - Hardware saturated with batch=90

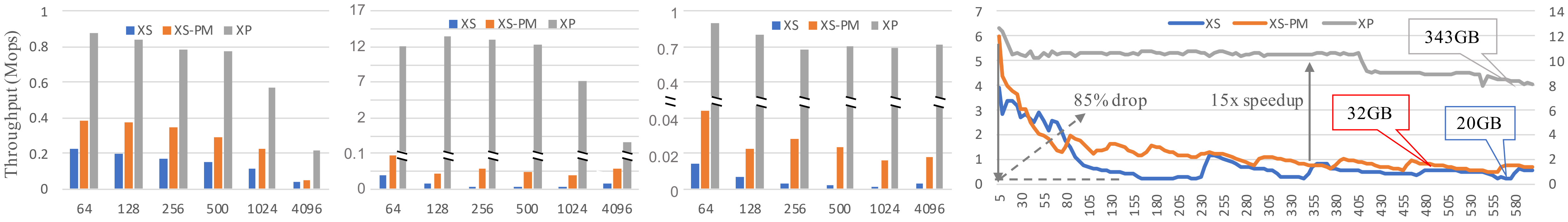
- Impact of thread number (batch=50)
  - More threads, higher throughput, longer latency
  - Hardware saturated with thrd=16
  - P99 latency less than 200us



(a) Impact of batch size (b) Impact of thread number

Evaluation for Global Index

- Does the global Index significantly outperform the in-disk one? Yes



(a) Random write for different sizes (b) Random lookup for different sizes (c) Random scan for different sizes (d) Performance stability

XS : memtable in DRAM and level 0 in disk
XS-PM : memtable in DRAM and level 0 in PM
XP : semi-persistent memtable with new level 0 in PM

- Configuration
  - Disable compactions for L1,L2,...
  - All data written into memtable and level 0
  - Random read/write with 1:1
- Results
  - Significantly reduce the impact of data piling for original level 0
  - Performance drops less than 35% even for 343GB level 0

Evaluation for Halloc

- How does the Halloc perform compared with SoTA general PM allocators ? Significantly improved

- Configuration
  - Average latency for 1 million allocations
  - Persist each object into a persistent list
  - halloc-pool : allocate object from pool
  - halloc-zone : grant memory space for memtable
- Results
  - Less than 1us for all cases with Halloc
  - General PM allocators are expensive for large allocation