ScaleLFS: A Log-Structured File System with Scalable Garbage Collection for Commodity SSDs

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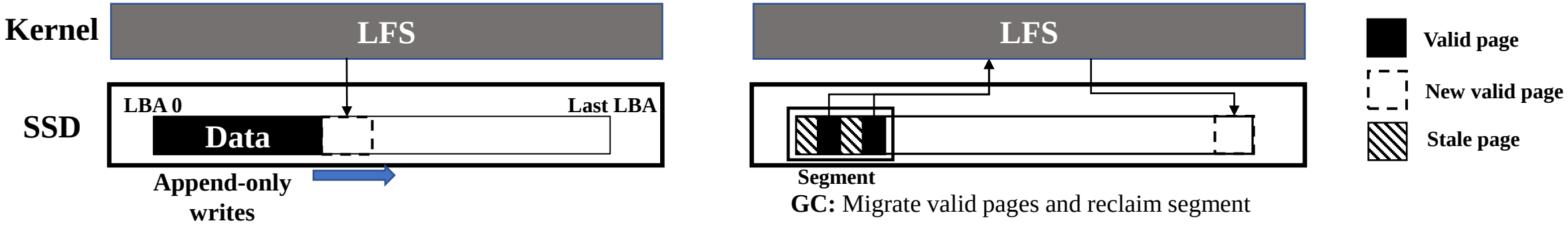
Log-structured File System (LFS)

❖Append-only manner

- Data are placed to consecutive logical block address (LBA)
- Leverage high **sequential write performance** of block device
- **Stale pages induced by out-of-place update**
- F2FS, JFFS, NILFS, Etc.

❖Garbage collection (GC)

- **Reclaim spaces** occupied by stale pages in segment unit
- Migrate dispersed valid pages (non-stale pages) to consecutive space



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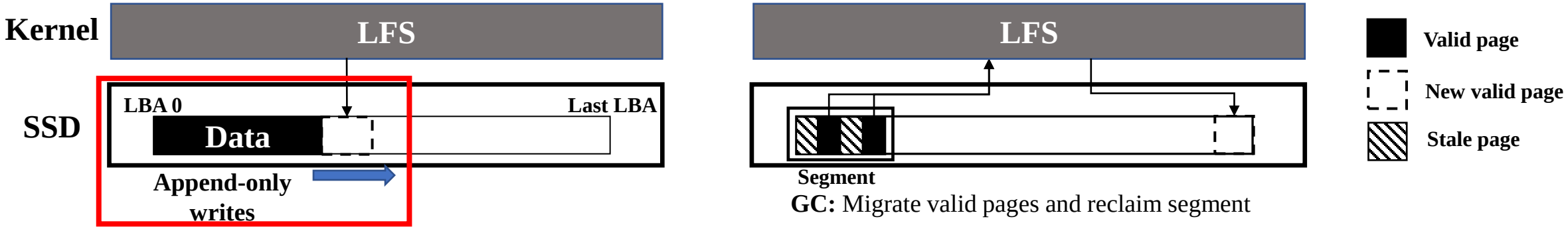

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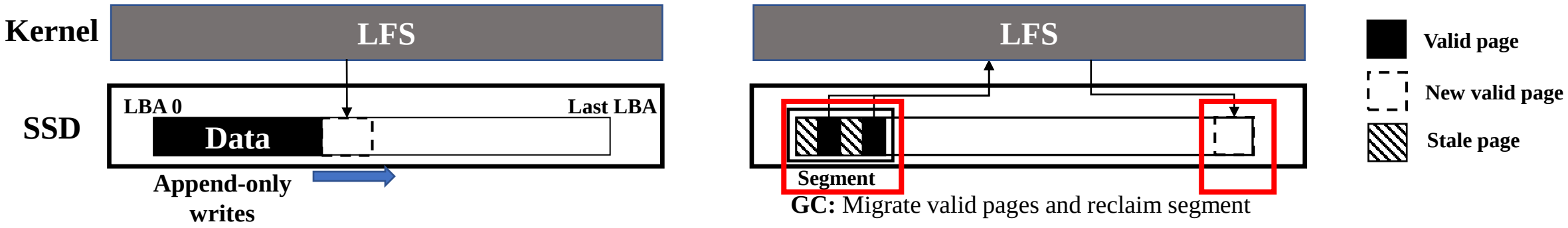

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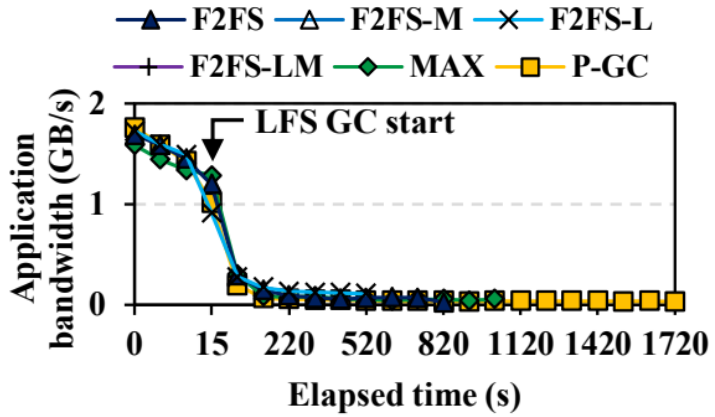
Sustained Performance of LFS

❖Overhead of GC

- Bottleneck induced by **single threaded GC**
- Application bandwidth decreases by up to **68 times**



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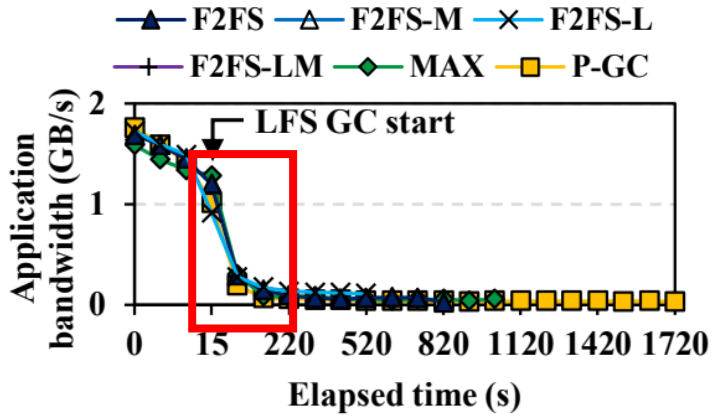

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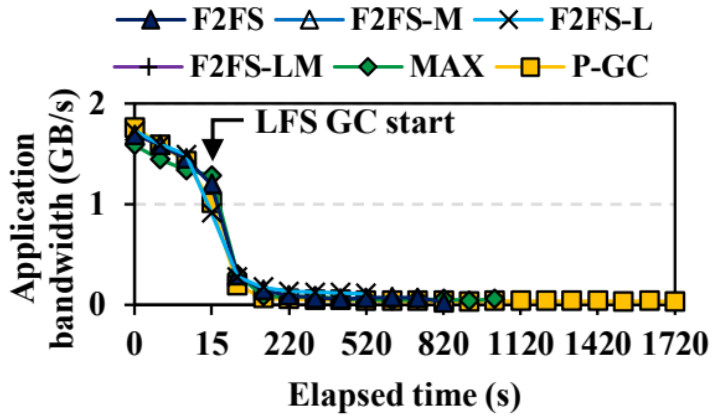

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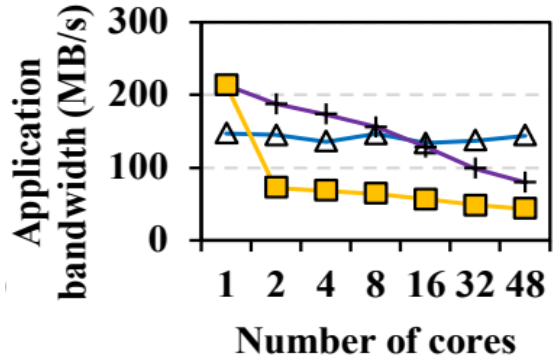

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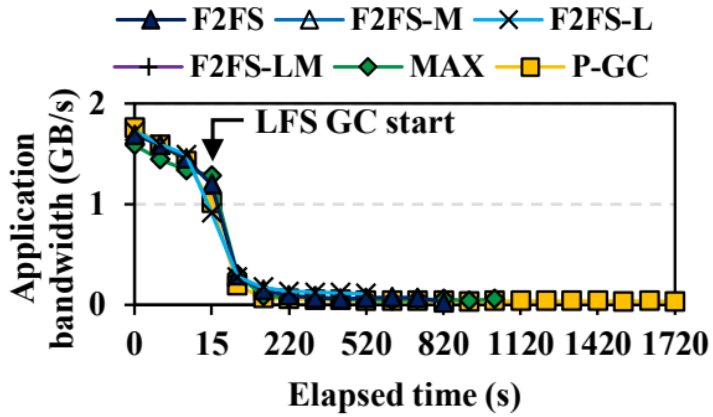

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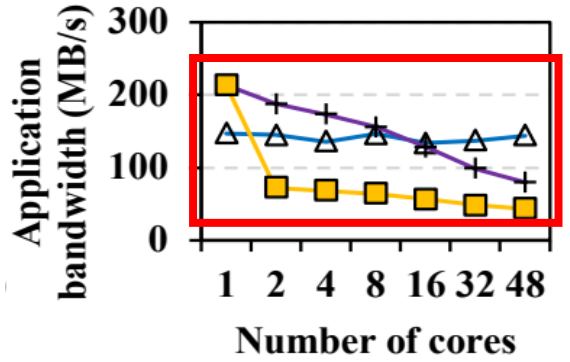

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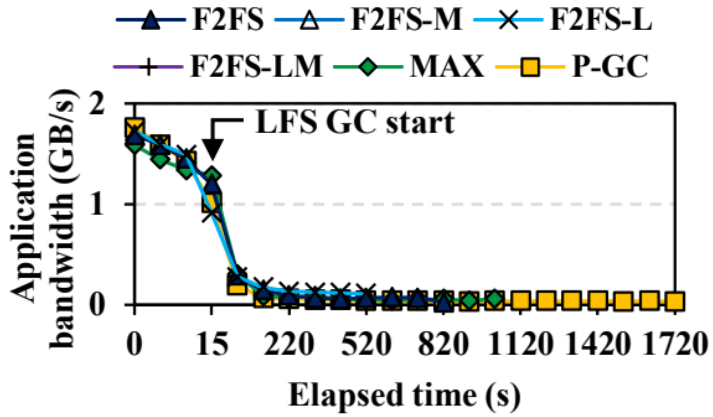

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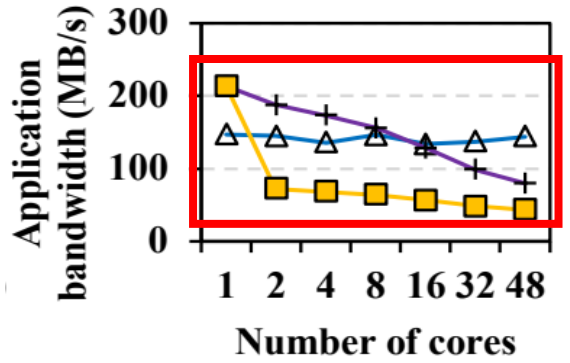

Concurrent and scalable techniques are required

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❖**Coarse-grained data protection**
- File level data consistency management between GC and I/O threads

→ **Page-level data consistency management**

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❖Dedicated garbage collector (DGC)

- GC thread with dedication strategies
  - **Dedicated** page buffer
  - **Dedicated** destination segment (write stream)

❖Scalable victim manager (SVM)

- Victim selection
  - Atomic victim bitmap
  - **Concurrent victim selection**
- Segment metadata management
  - Atomic valid page bitmap
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  - **Loose-synchronization update**

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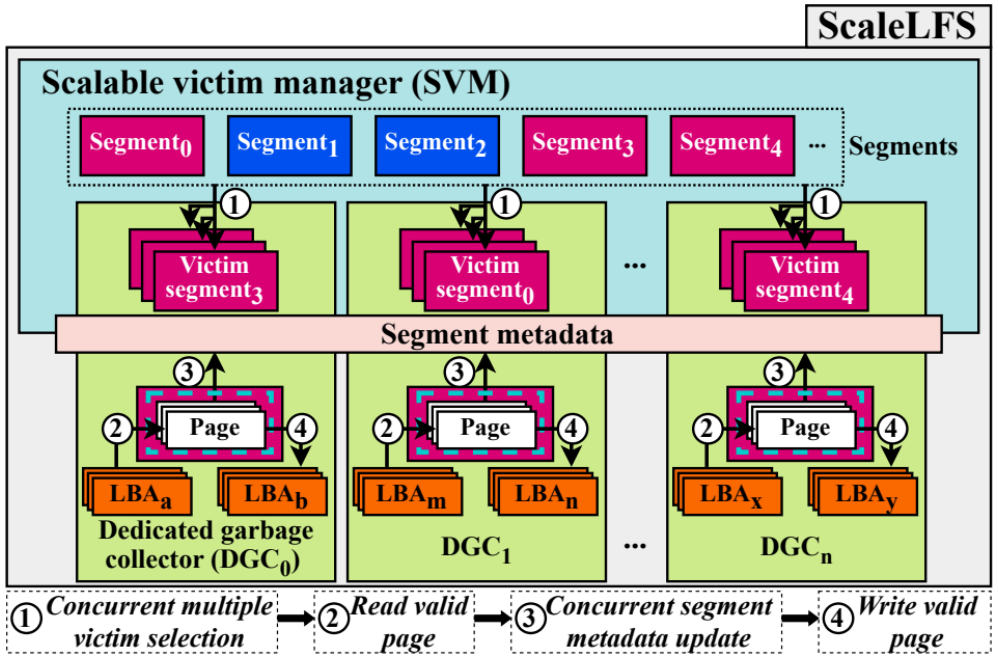

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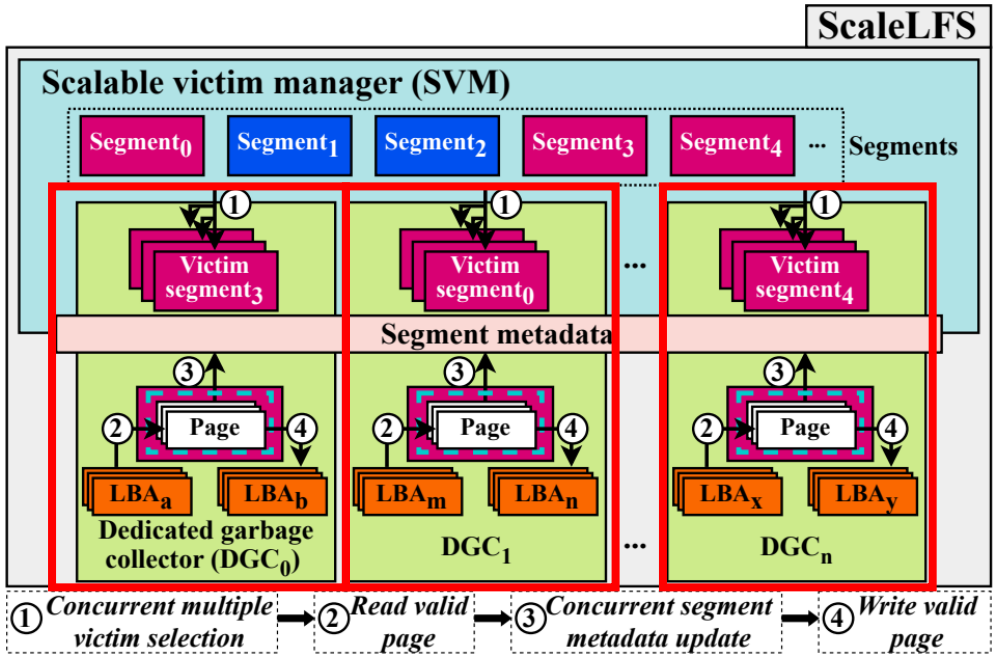

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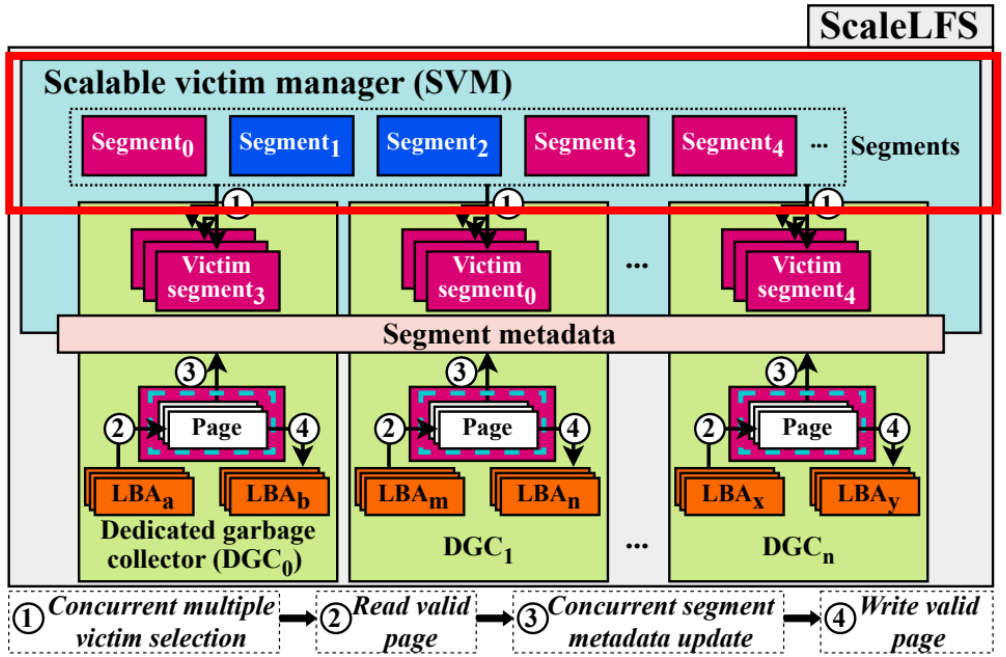

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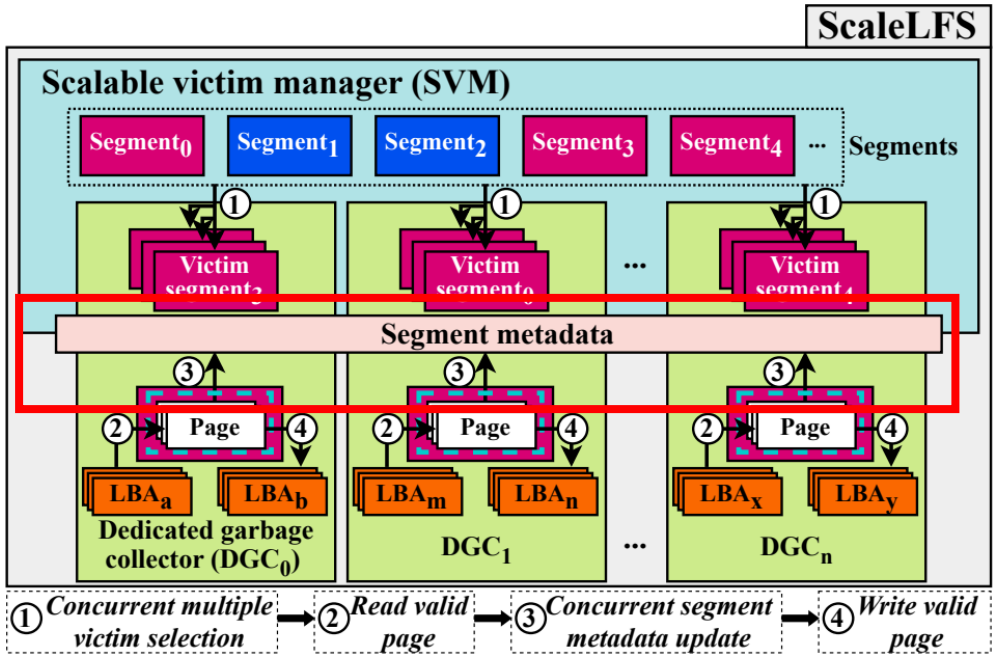

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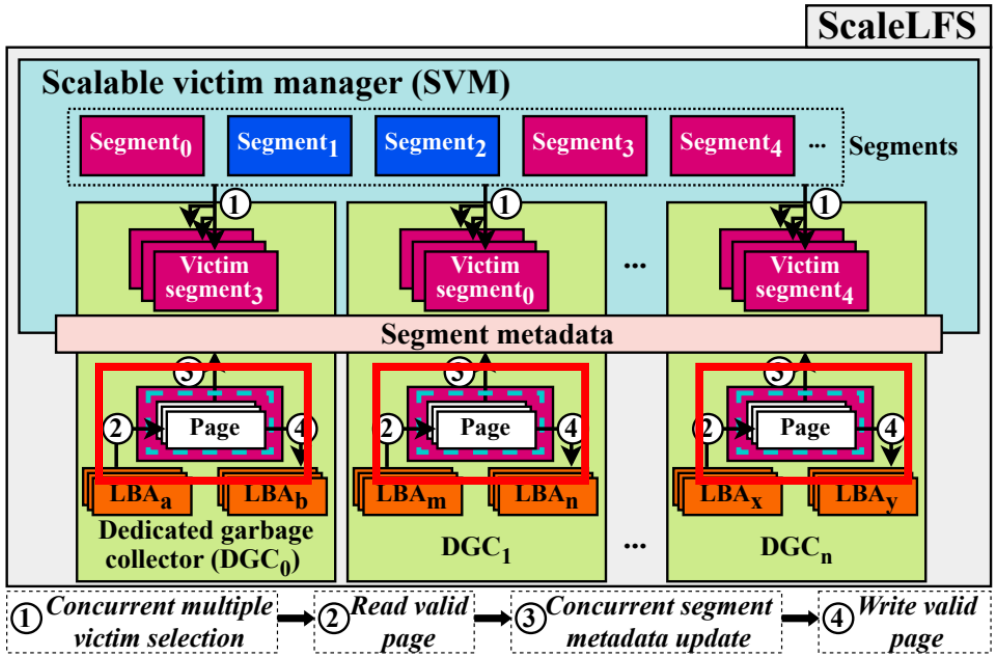

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❖Dedicated page buffer (DPB)

- Per-GC-thread GC data buffer
- **Avoid expensive page cache overhead**

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- **Lock-free**
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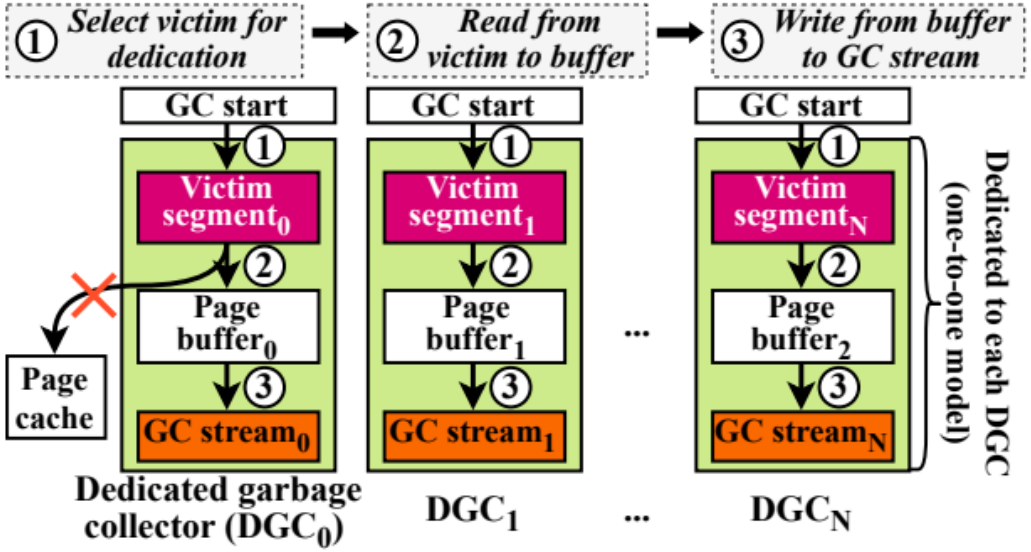

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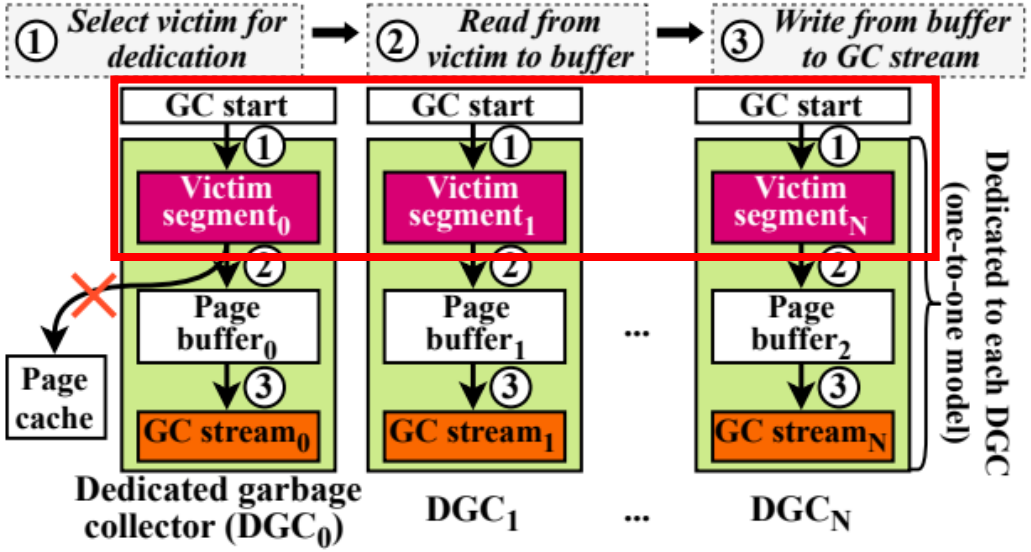

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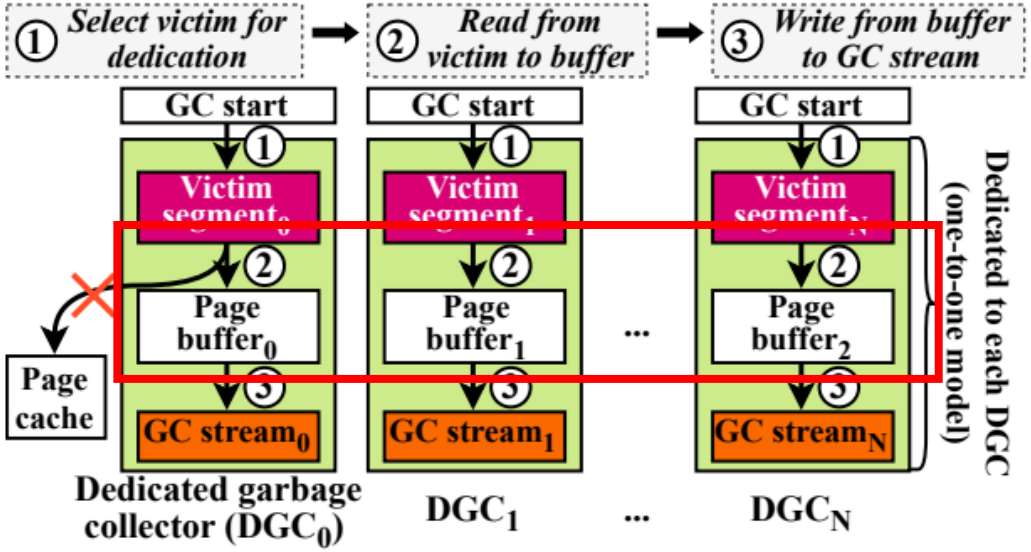

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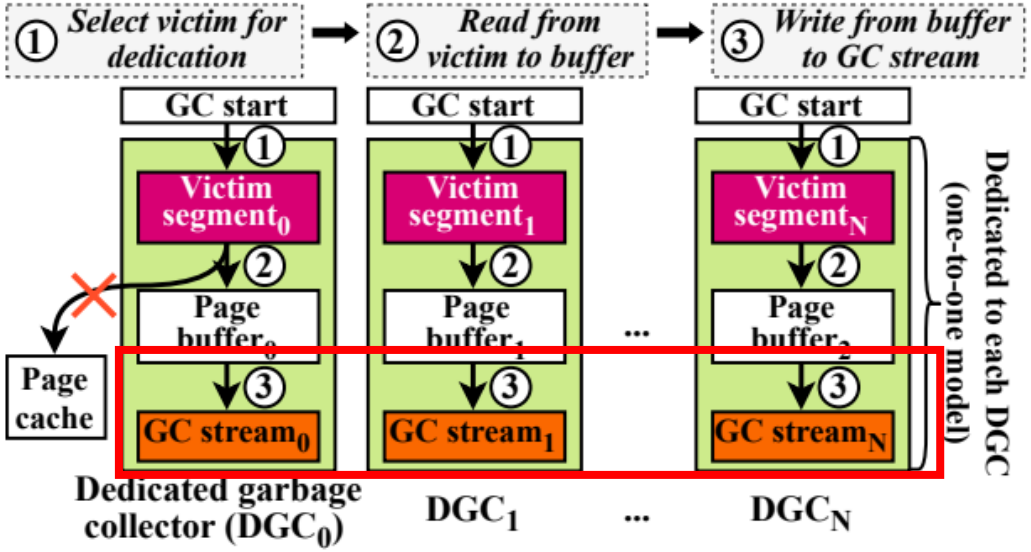

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- Two atomic bitmaps
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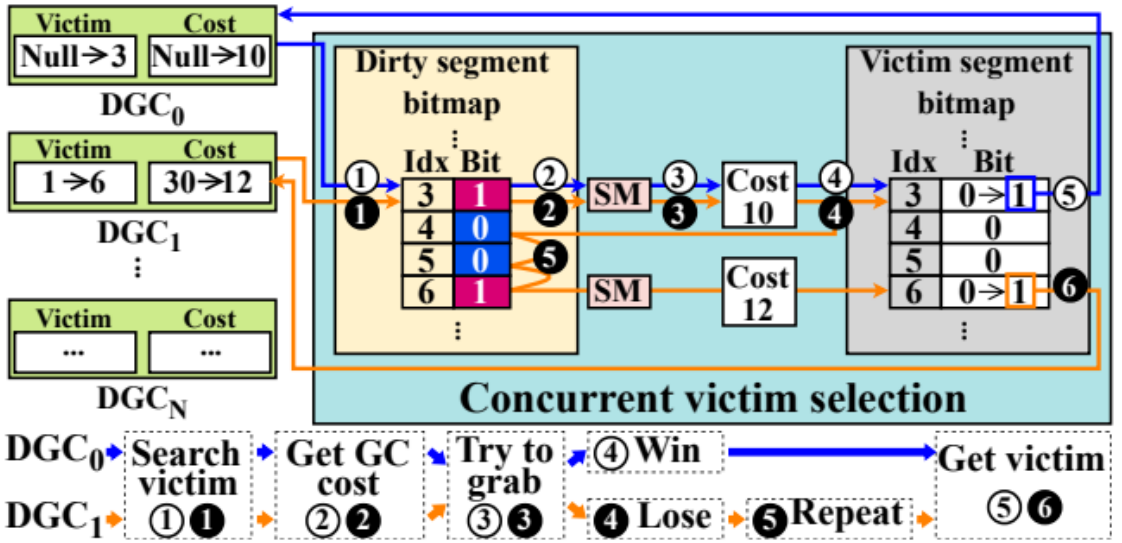

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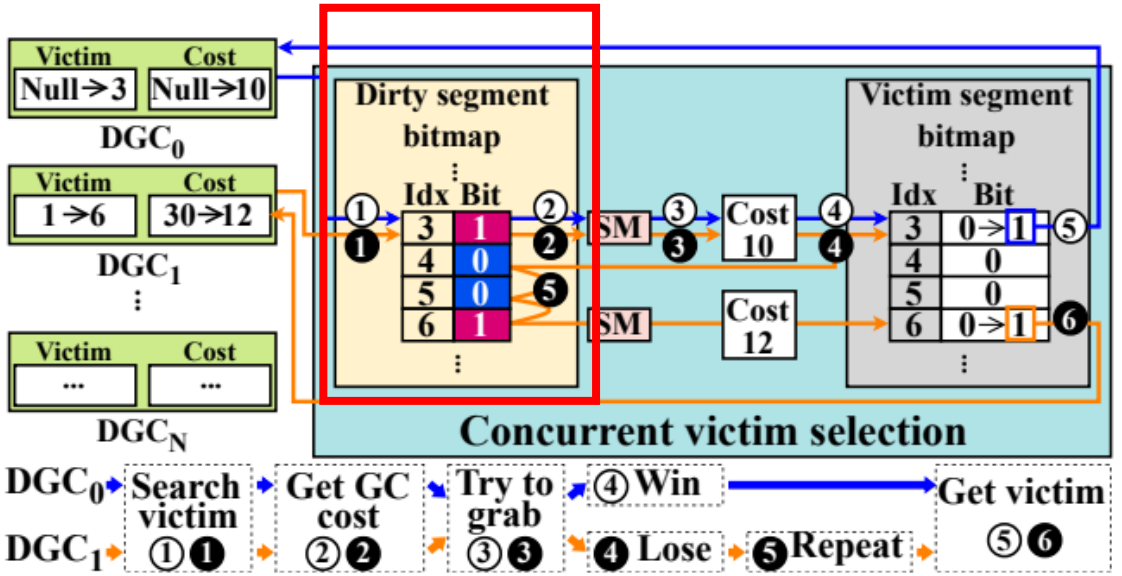

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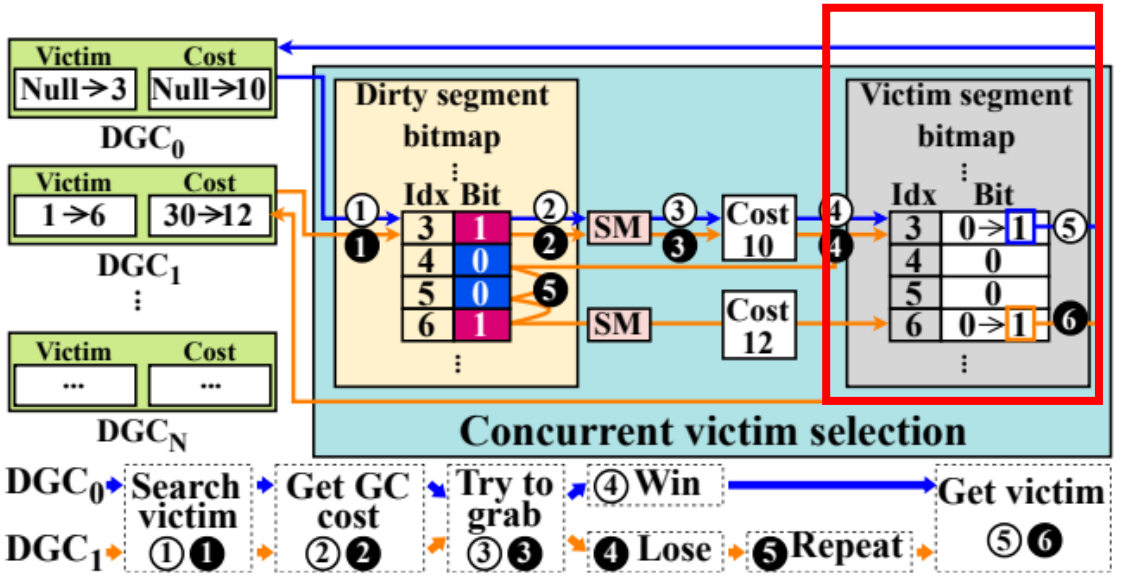

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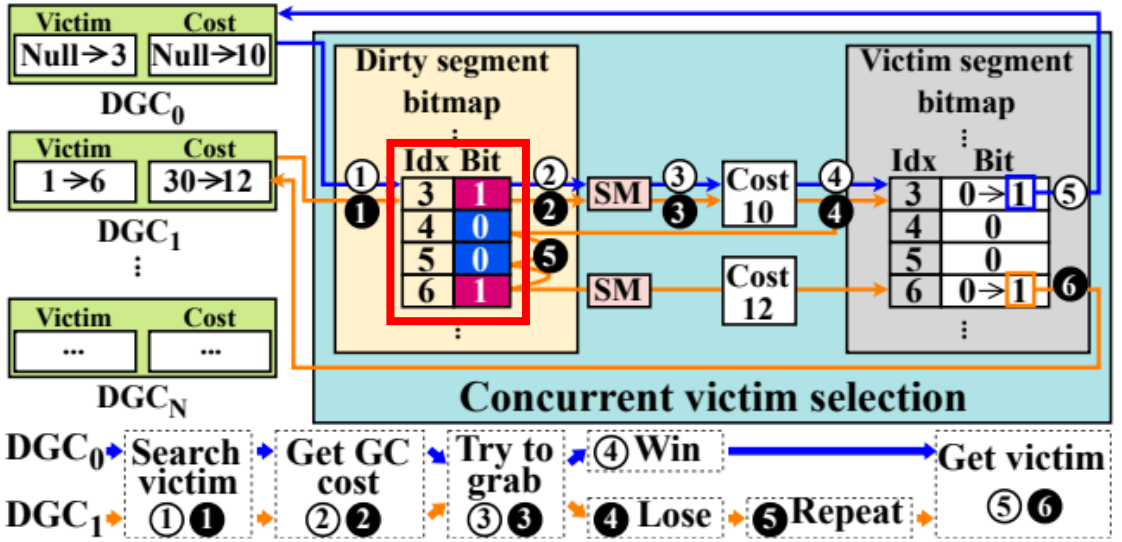

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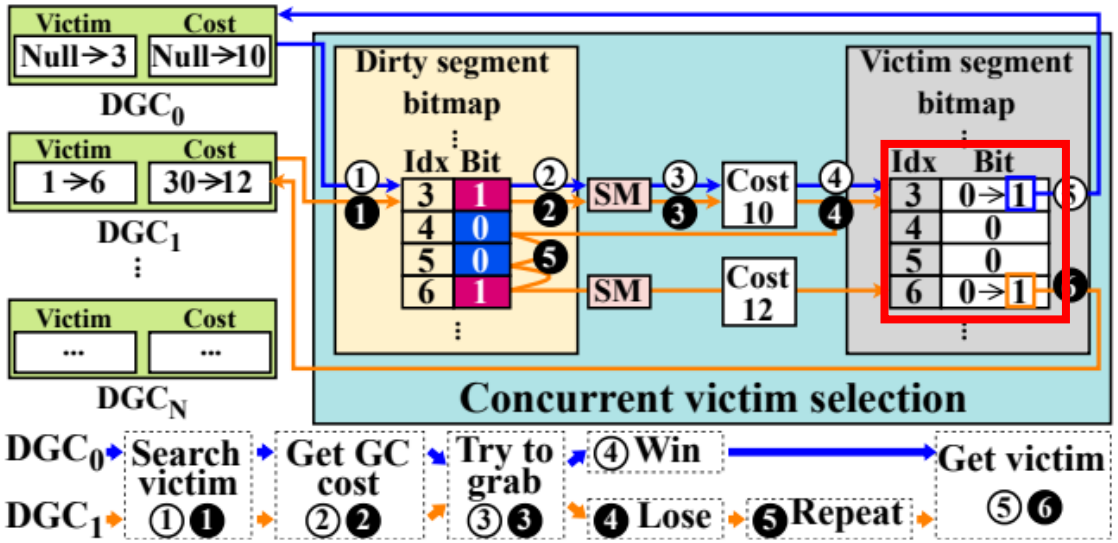

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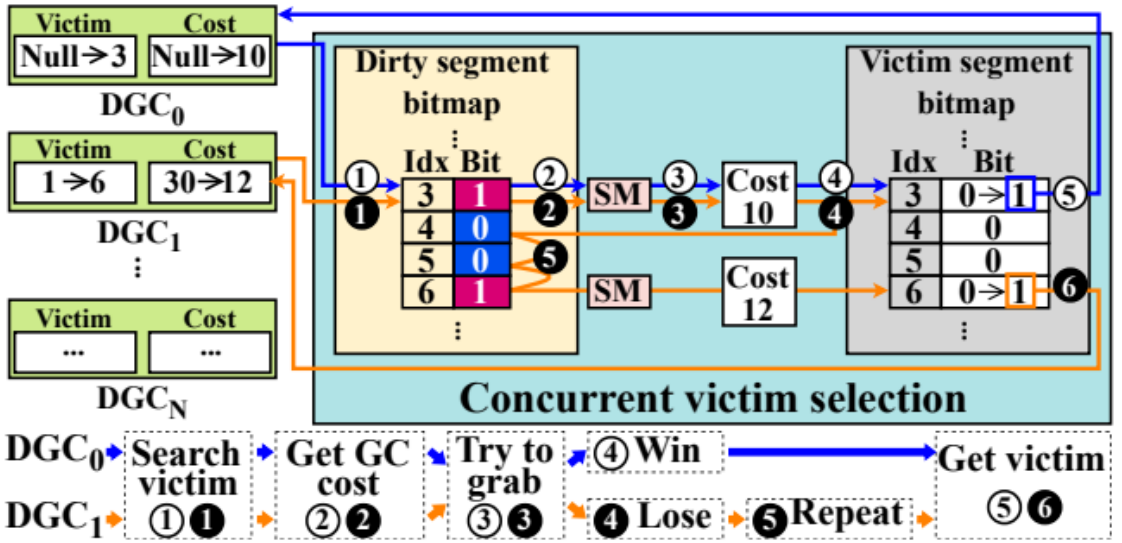
❖Data race between DGCs

- Multiple DGCs try to select the same victim segment
- Utilize atomic ***test_and_set_bit()***
  - Try update same offset of victim segment bitmap
  - **Only one DGC can update bit to 1 (win)**
  - DGC that lost try to select another segment



Scalable Victim Manager (2)

❖**Loose-synchronization Update (LSU)**

- Manage per-segment metadata
  - Atomic valid page bitmap (VPB)
  - Atomic valid page count (VPC)
- **Lock-free update and access** to valid bitmap and valid count

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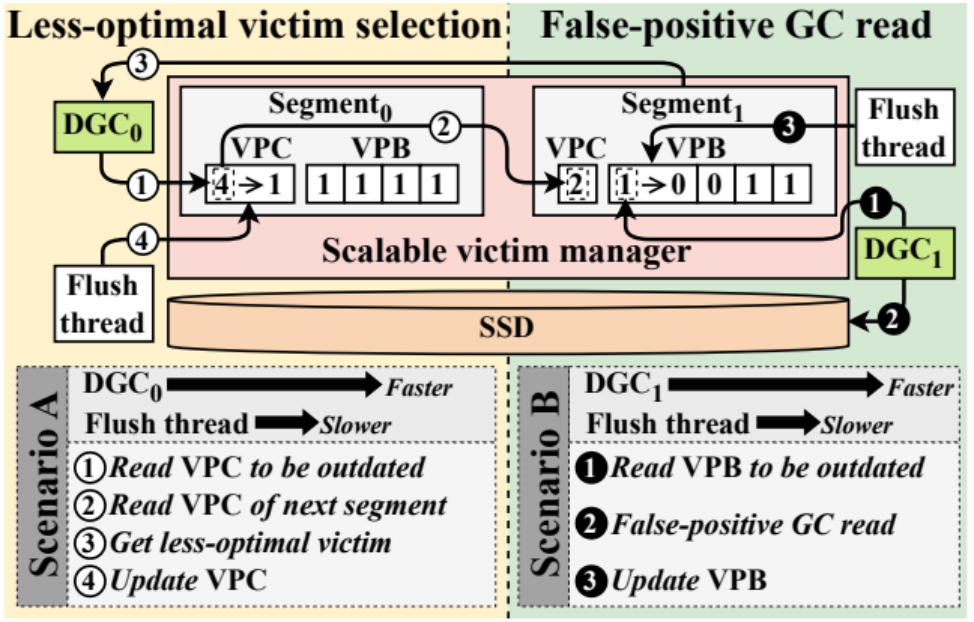
❖Two side effects due to separately updated VPB and VPC

- Less-optimal victim selection
  - Selecting best victim segment is not guaranteed
- False-positive GC read
  - Unnecessary GC read can be submitted

Scalable Victim Manager (3)

❖Less-optimal victim selection

- Scenario
  - VPC decreases during victim selection
  - Update is not aware to DGC (**outdated VPC**)
  - Less-optimal victim selection caused by outdated VPC
- **Negligible write amplification** observed



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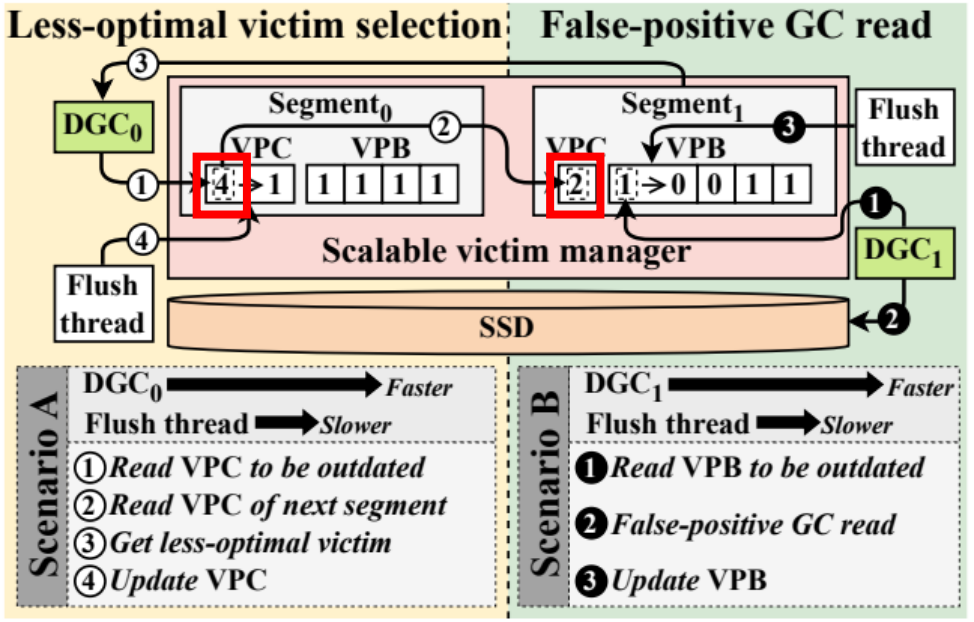

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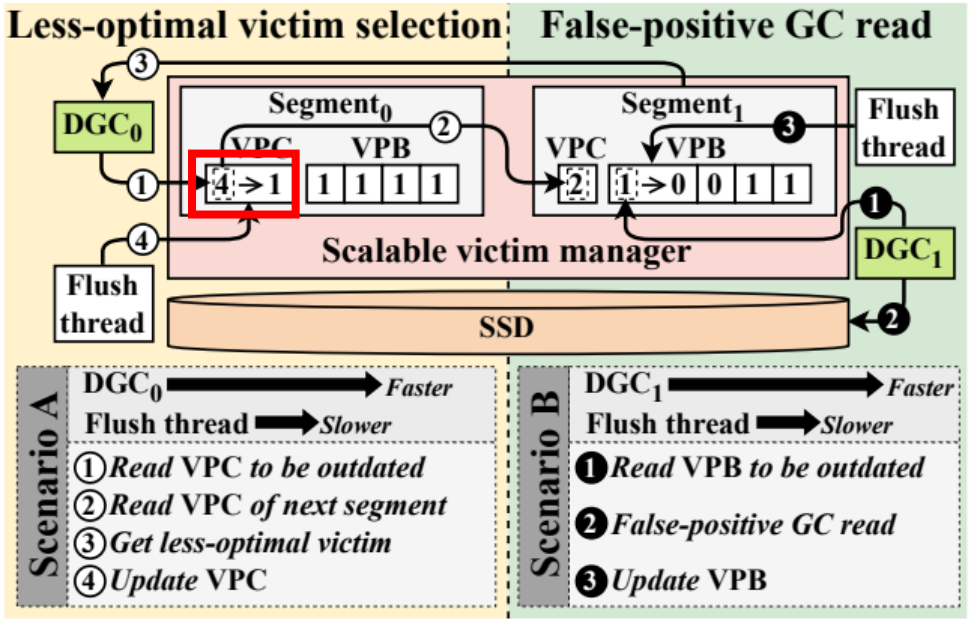

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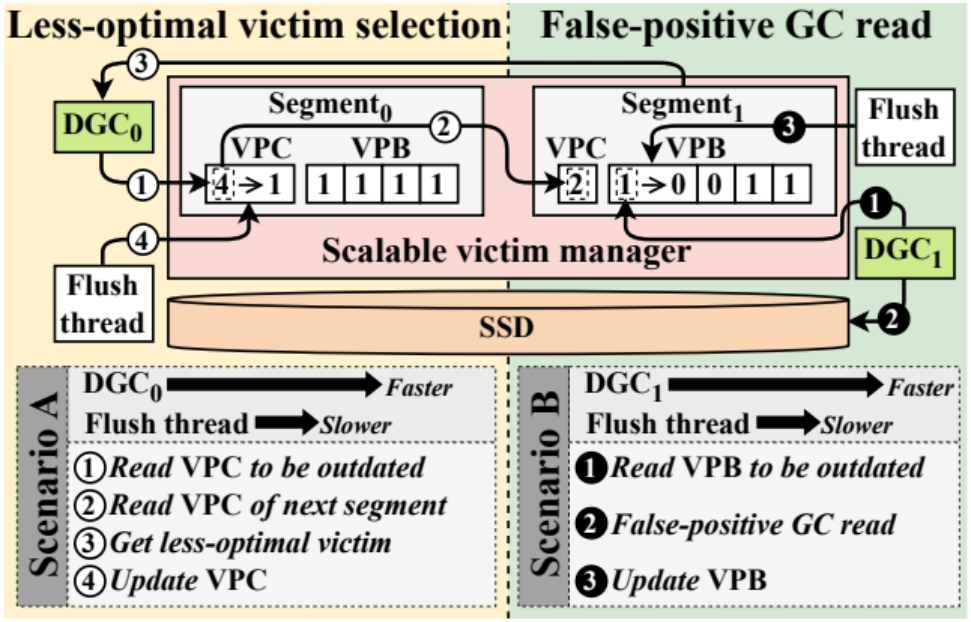

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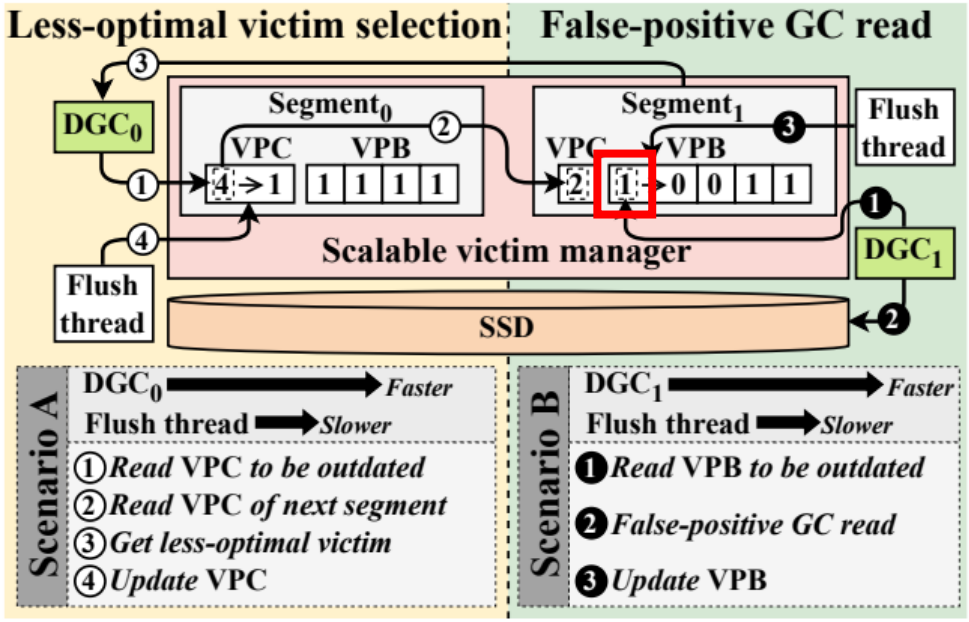

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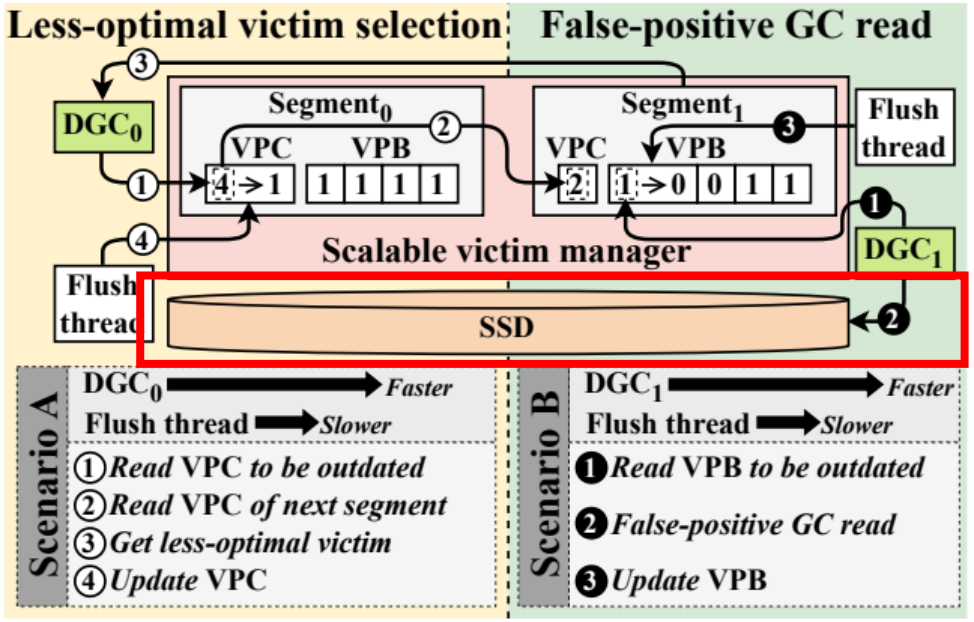

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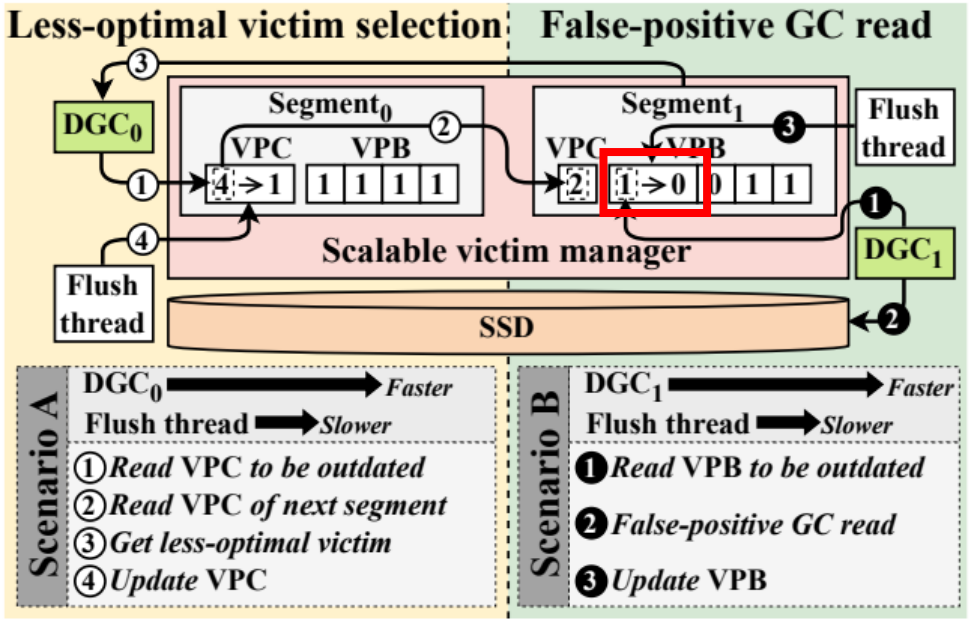
- **Negligible write amplification** observed

❖False-positive GC read

- Scenario
  - VPB is cleared during GC read
  - Update is not aware to DGC (**outdated VPB**)
  - GC read to stale page is submitted
- **Data consistency can be violated**



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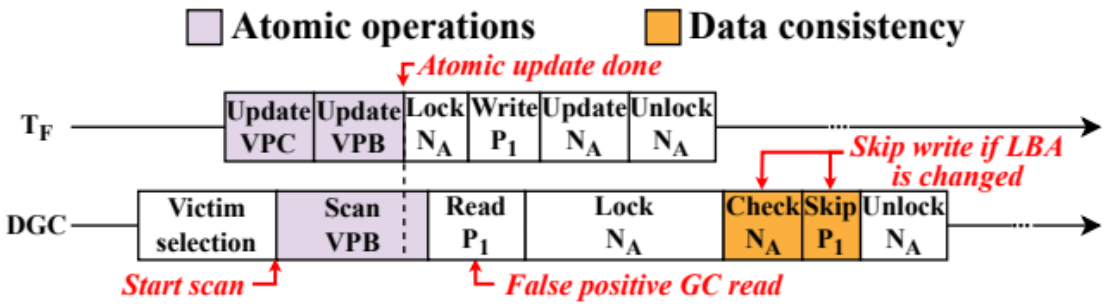

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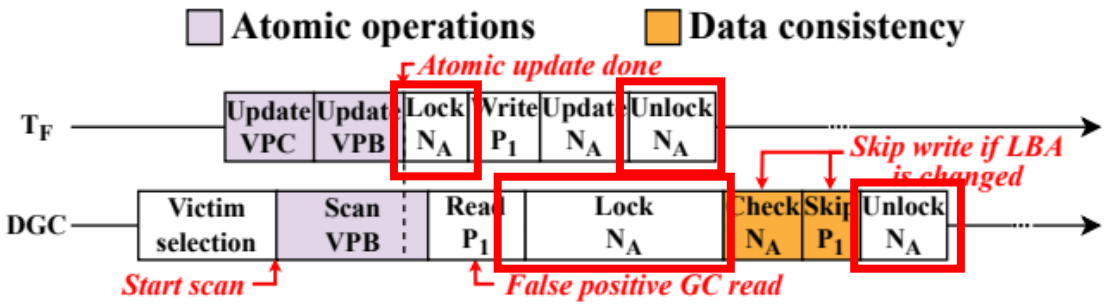

Scalable victim protector (SVP)

❖Per-file concurrent hash table

- **Concurrently insert/remove** page before/after access
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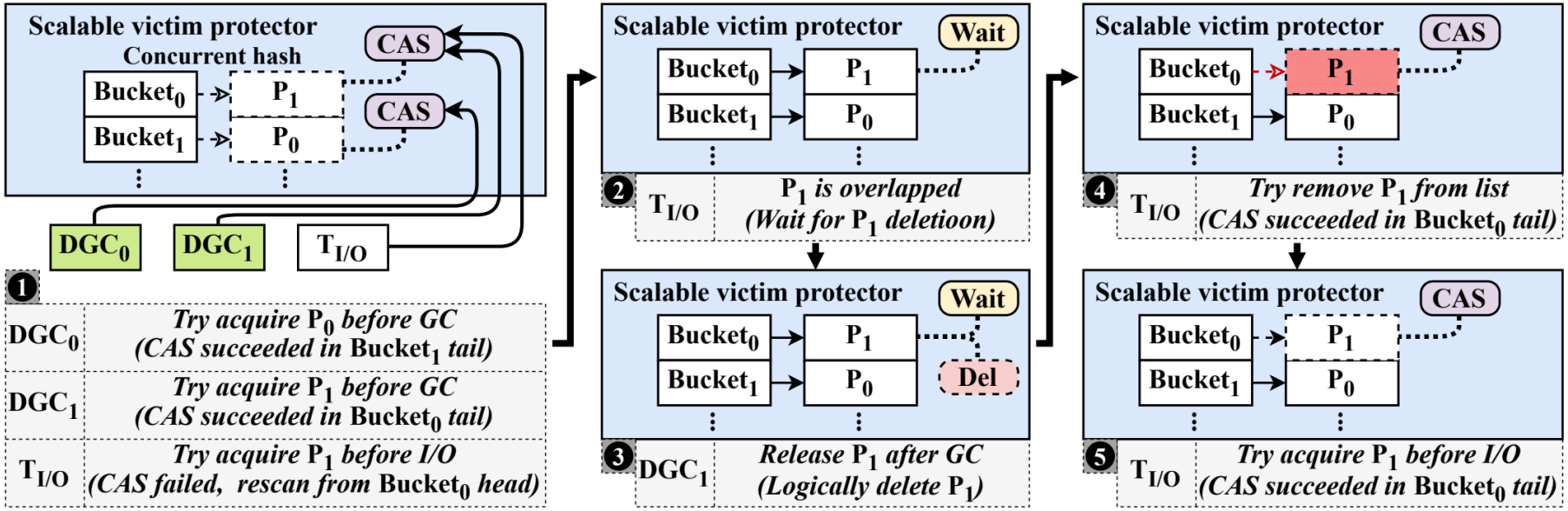

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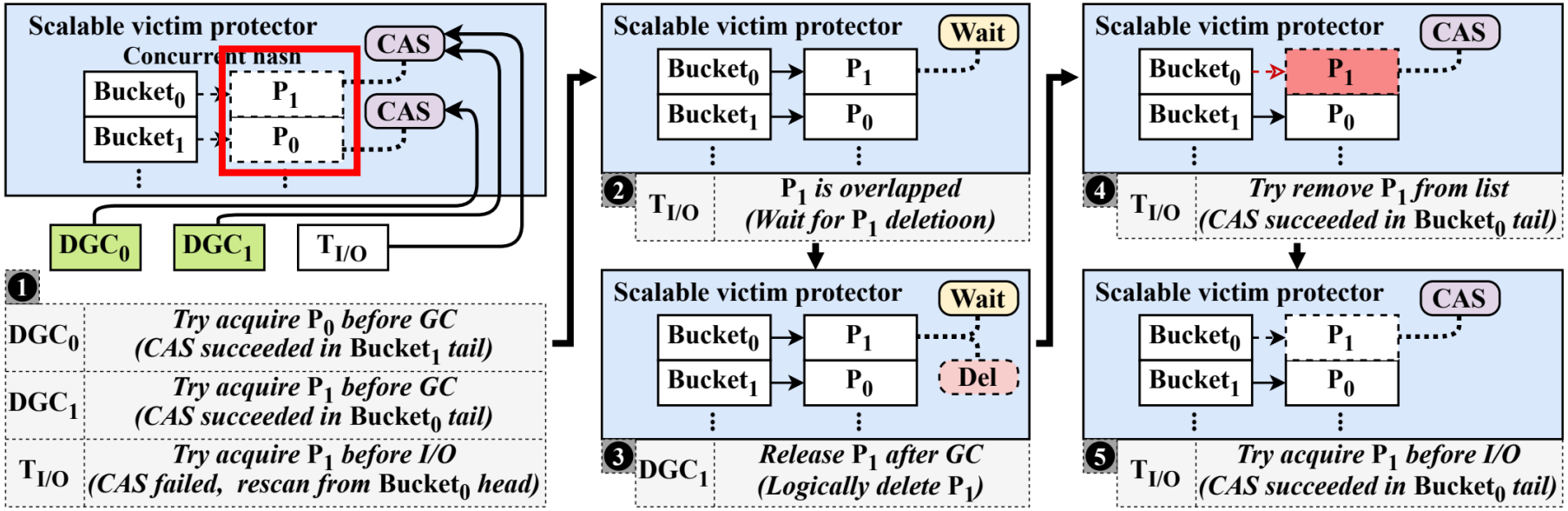

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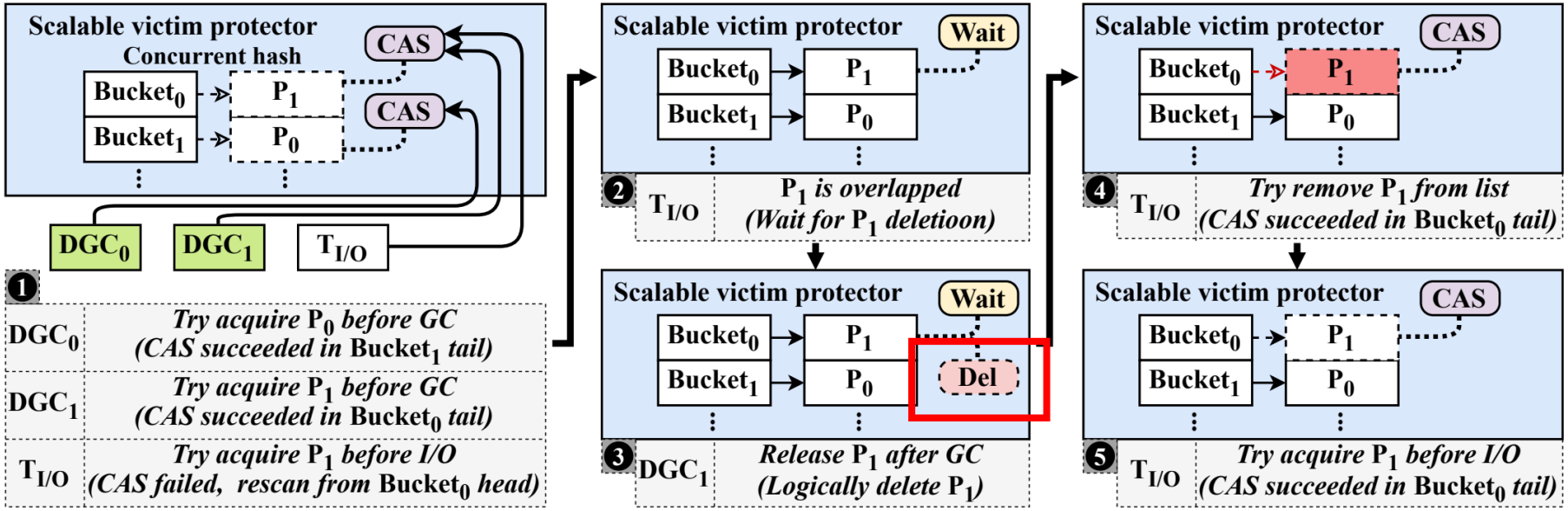

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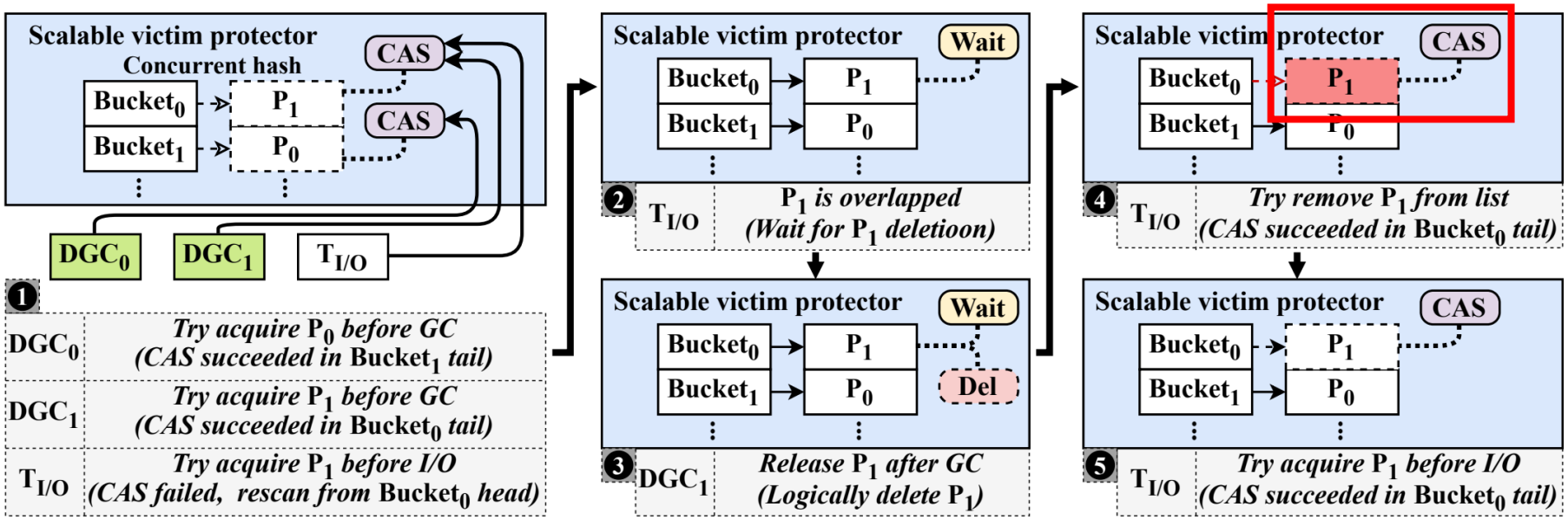

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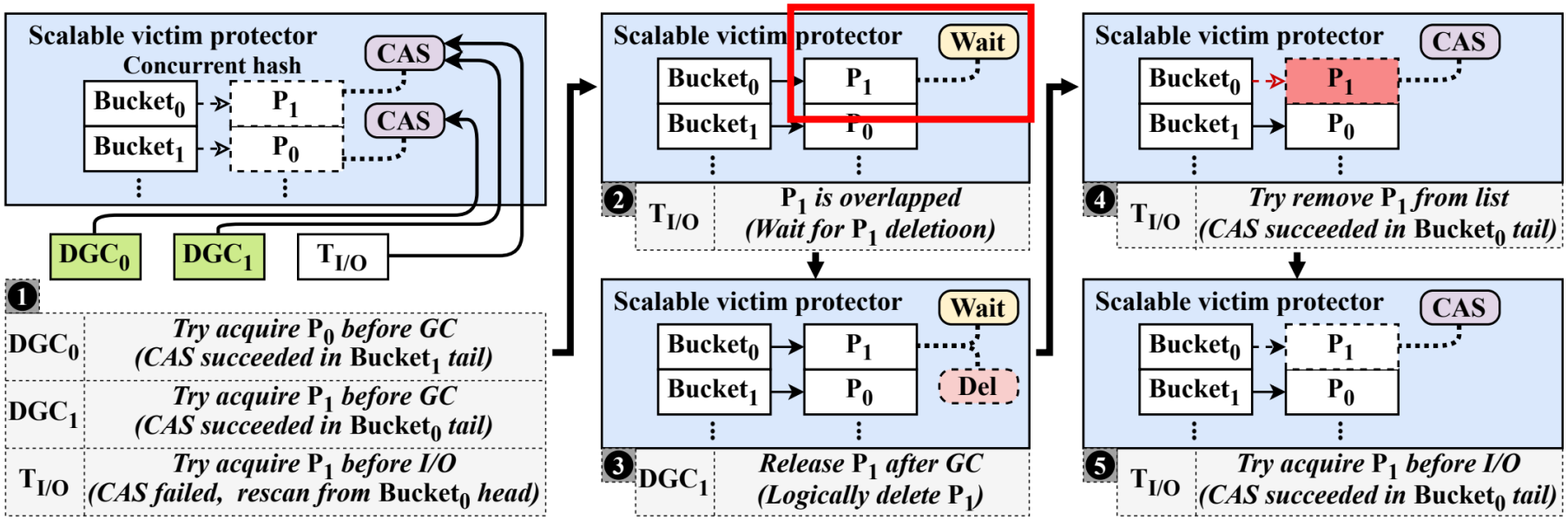

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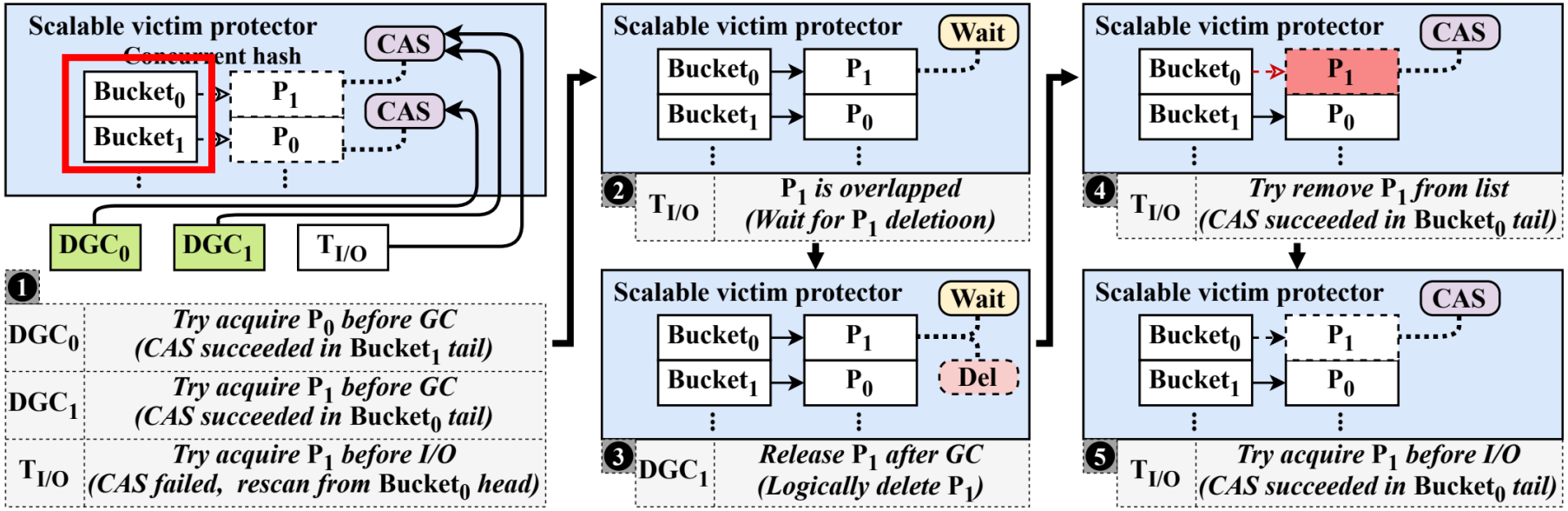

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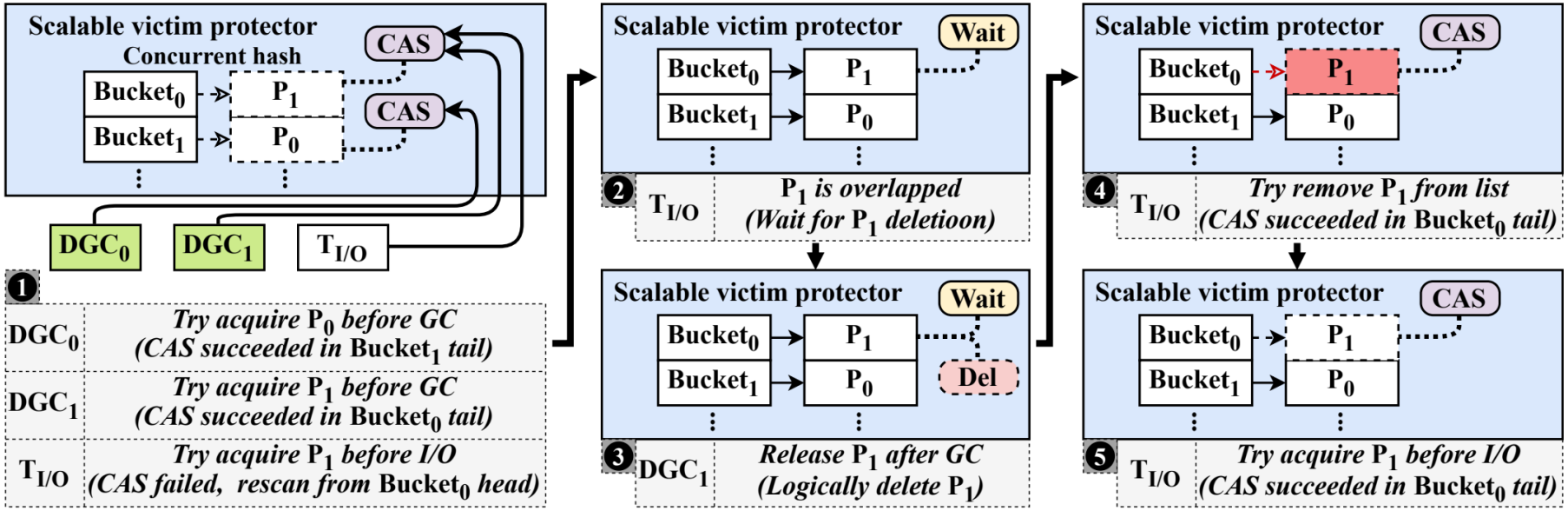

Experimental Setup

- **Test bed**
  - Intel Xeon E5-2650 CPU with 48 logical cores
  - 160 GB DRAM
    - Limited to 8 GB for evaluation in 30 GB partition
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- Micro-benchmark (FIO)
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❖Comparison

- F2FS
  - LFS in Linux kernel
- F2FS-L
  - F2FS in pure LFS mode (no SSR, in-place update)
- MAX
  - State-of-the-art scalable LFS
- P-GC
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- **ScaleLFS**
  - Proposed idea implemented based on F2FS (LFS mode)

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❖Evaluation on small partition

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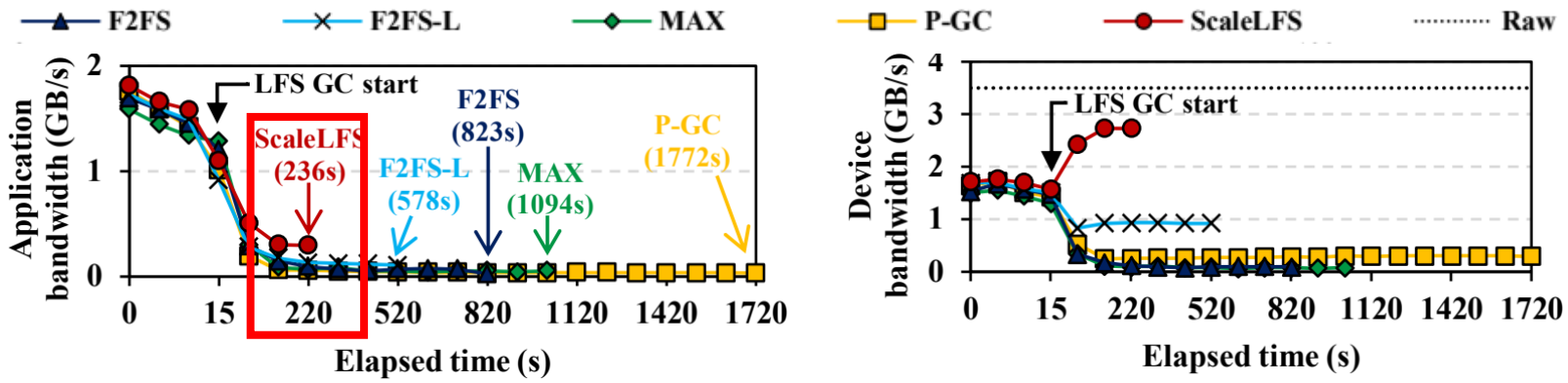

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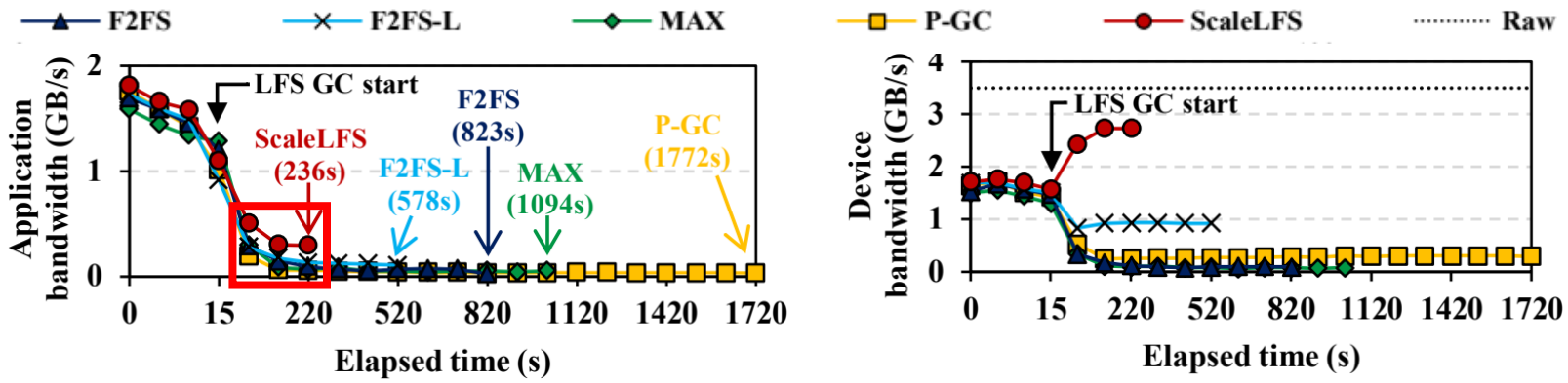

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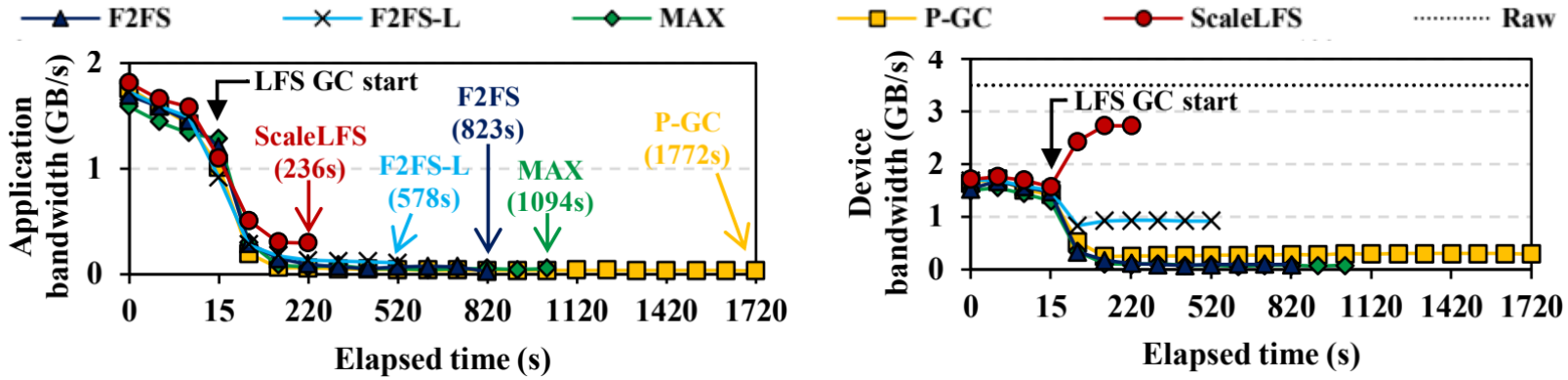

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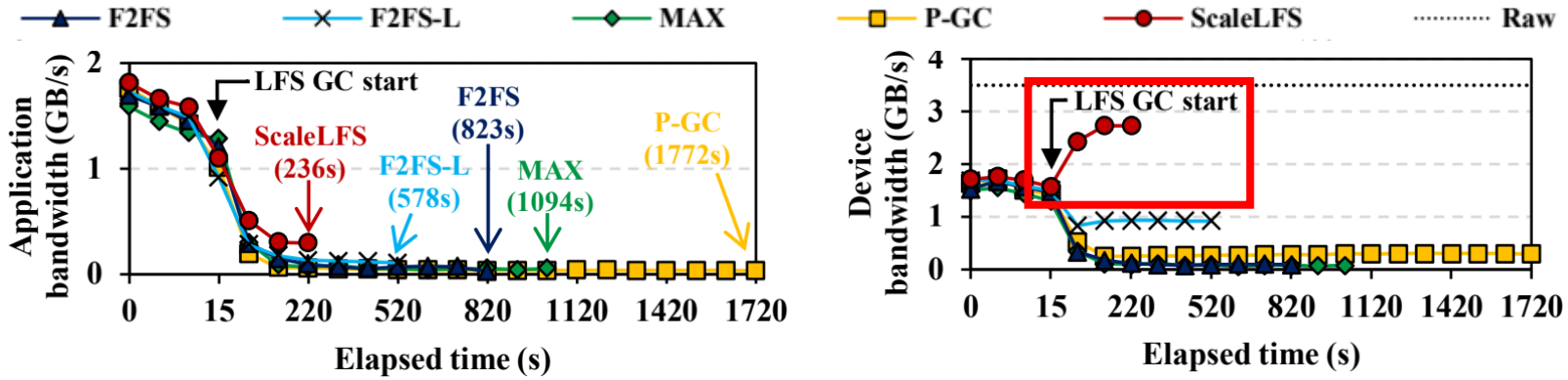

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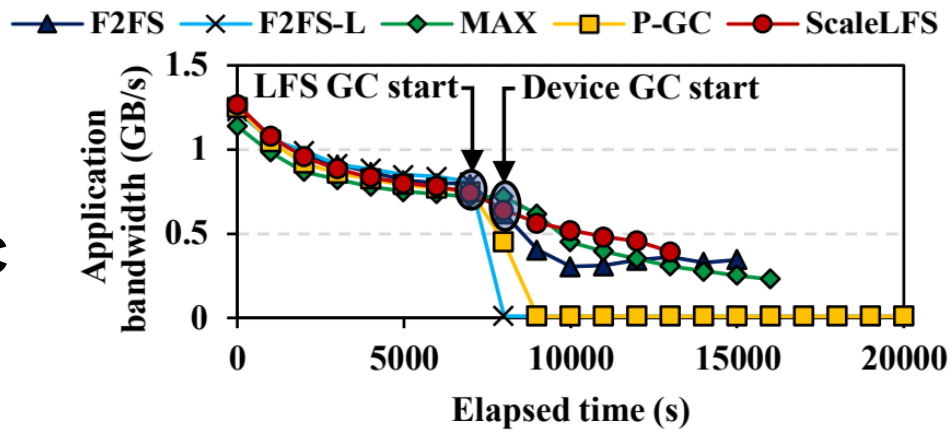
  - Improve **37 minutes** compared to F2FS



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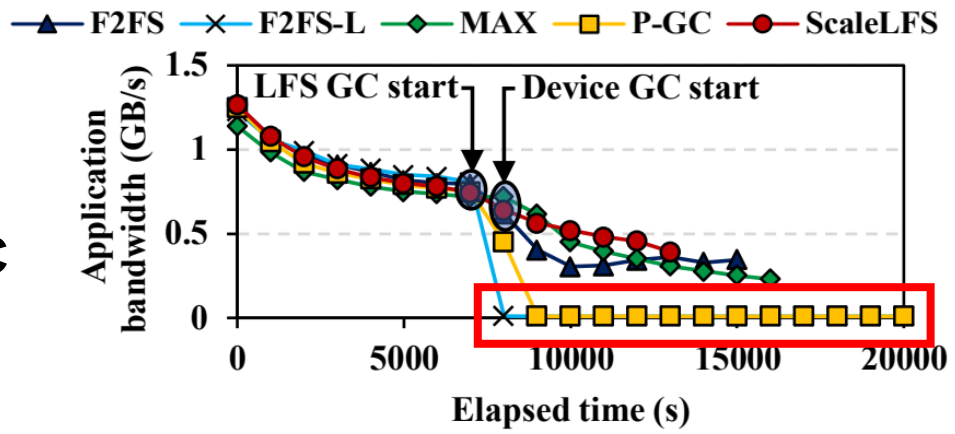

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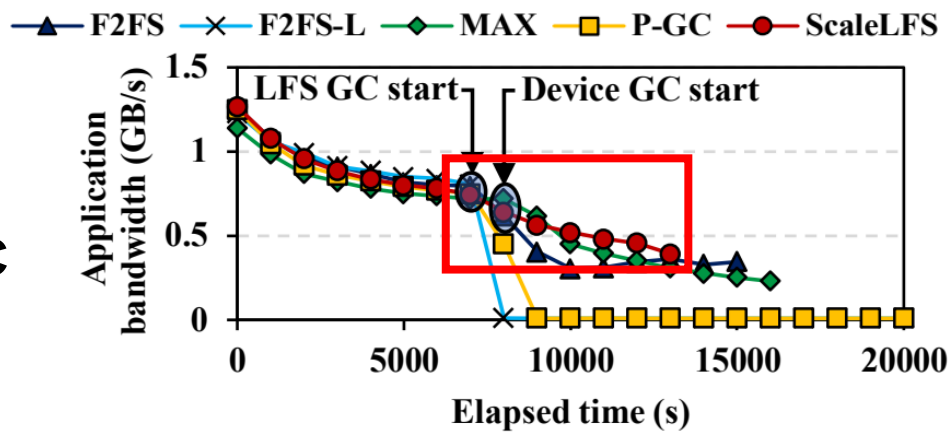

Macro-benchmark

❖**Evaluation on three write-intensive workloads**

- Improve throughput **up to 83.1%**
- Less improvement than FIO
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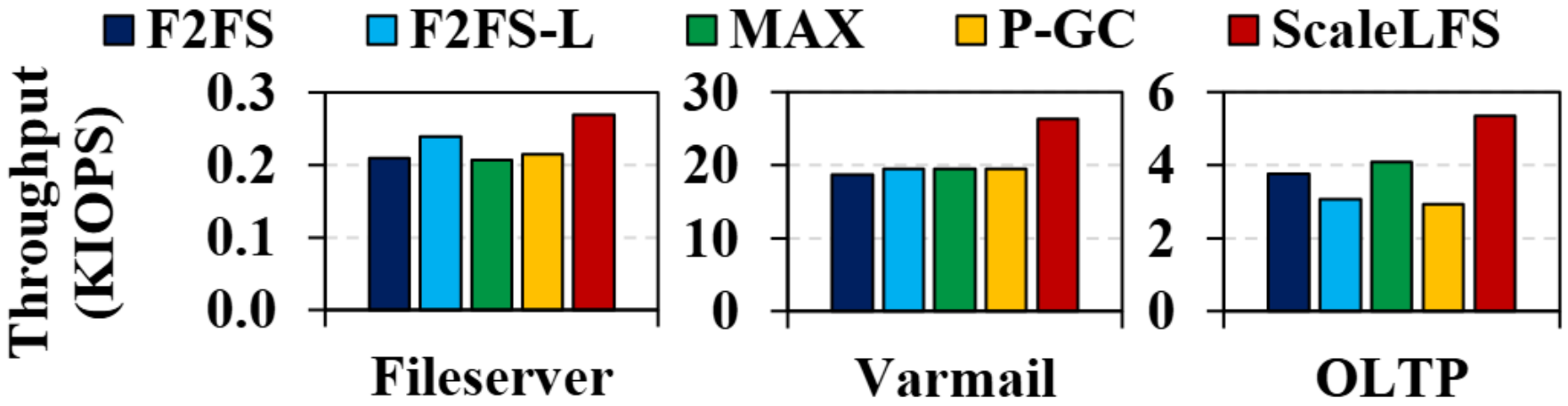

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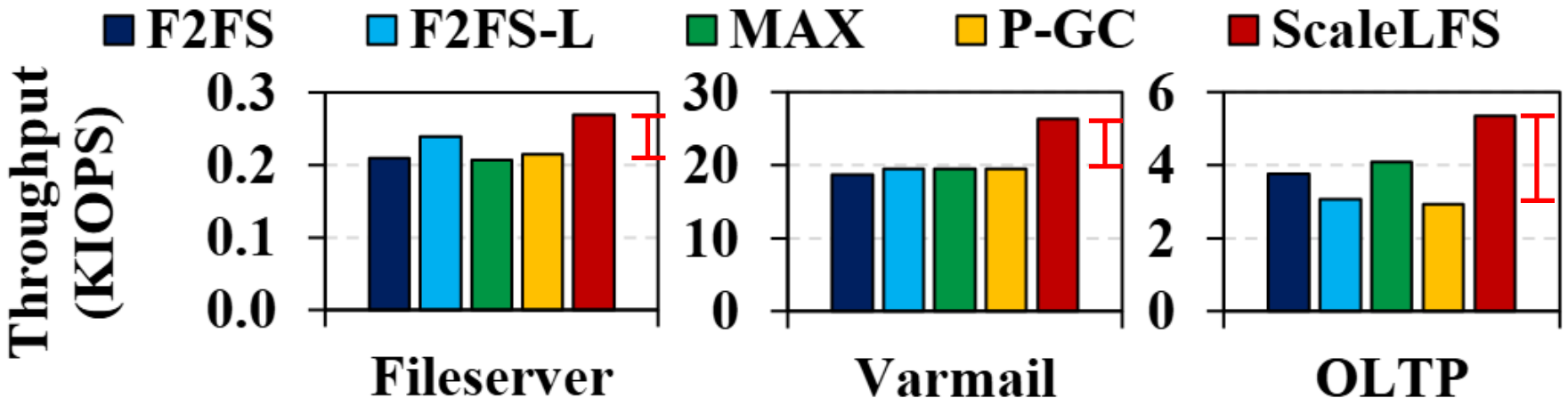

Real Application

❖MySQL with YCSB benchmark

- Initially 6.5 million records are inserted
  - 70 % of total capacity occupied
- Workload A (Write intensive)
  - Update 50%, read 50%
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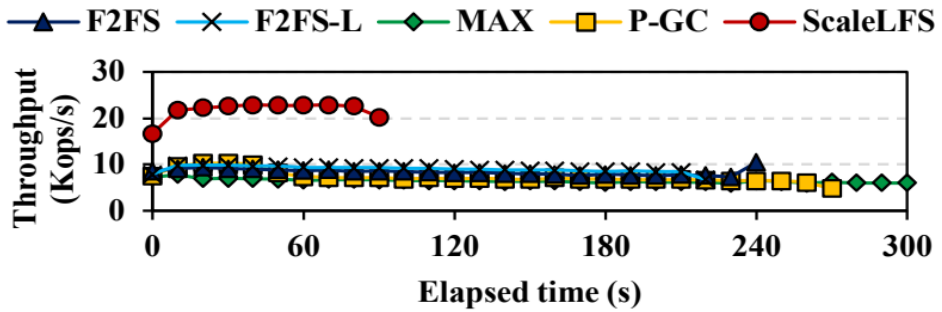
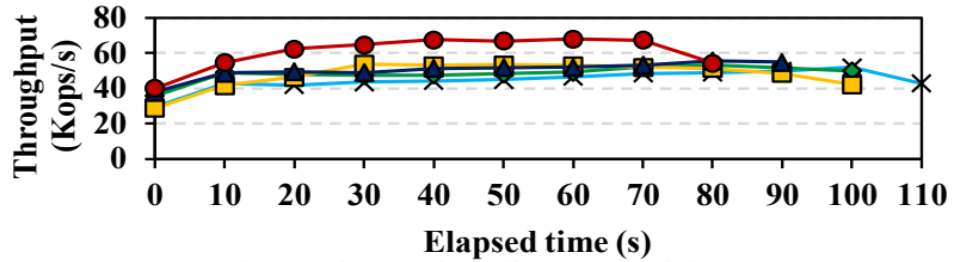
  - Update 5%, read 95%



Throughput timeline (Workload A).



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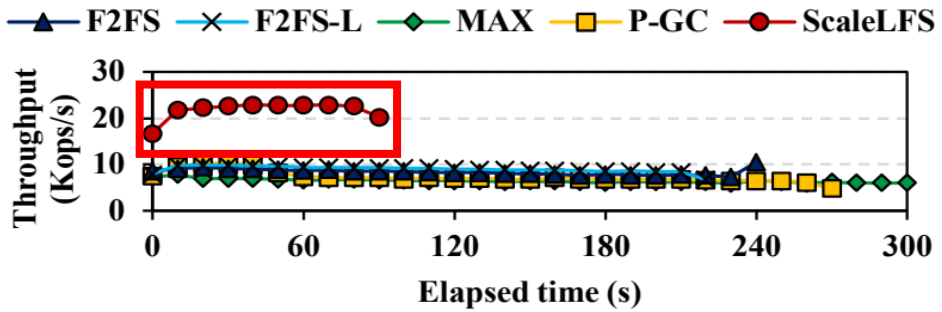

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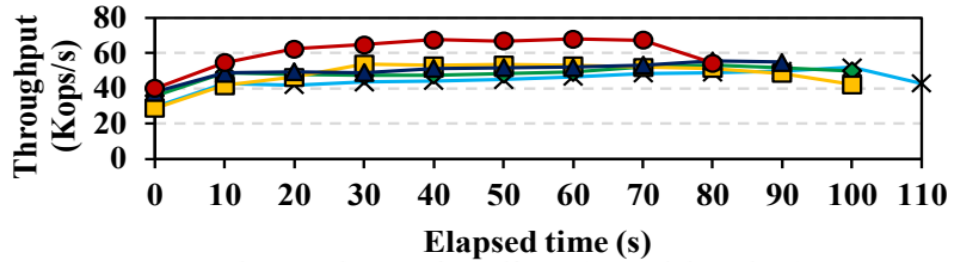

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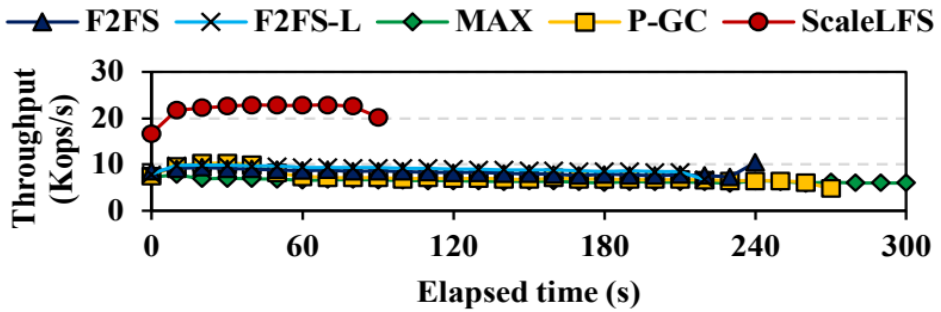

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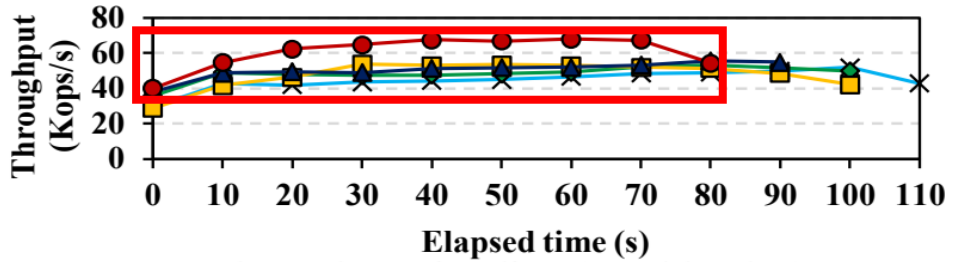

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Conclusion

- **ScaleLFS accelerate LFS-level GC with multi-thread friendly designs**
  - Utilize multiple GC threads with **dedicated strategy** on GC segments and page buffers
  - Increase concurrency of GC with **concurrent data structures**, **lock-free victim management** policies and **loose-synchronization** for GC metadata
  - Enable a **page-level GC procedure** with scalable while resolving the conflict with victim pages
  - ScaleLFS increases LFS performance by up to **7.0x** compared to existing LFSs

Thank you