F2FS: A New File System for Flash Storage

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Contents

Introduction

- **Random writes is bad to flash storage device.**
  - Free space fragmentation
    → Sustained random write performance degrades
    → Lifetime reduced

- **Sequential write oriented file systems**
  - log-structured file systems, copy-on-write file systems

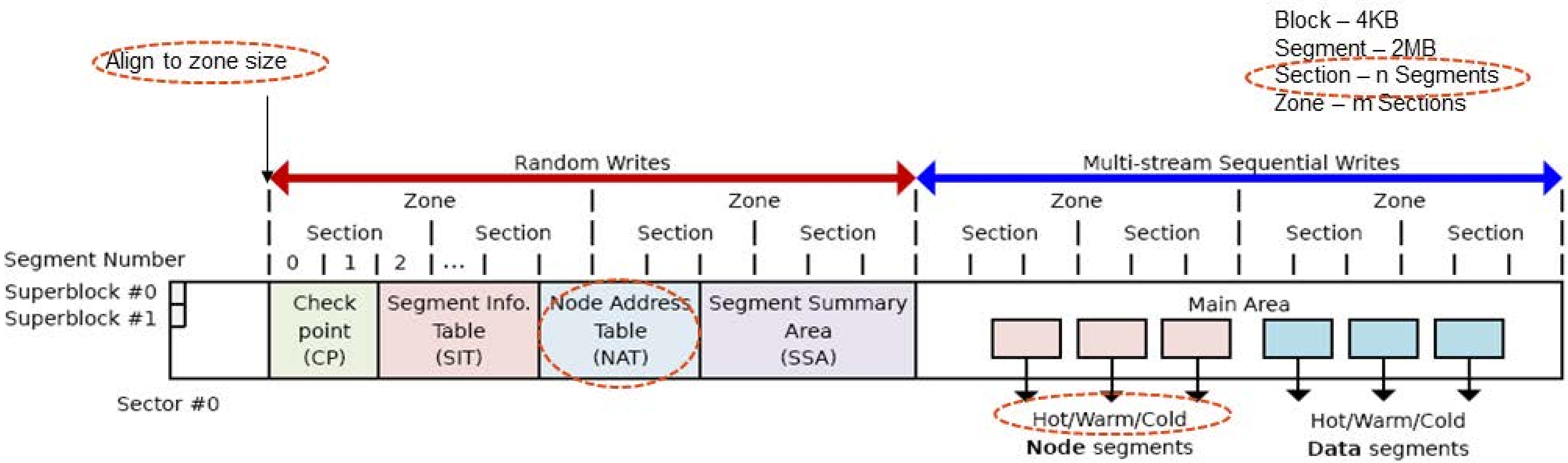
- **Our Contribution**
  - Design and implementation of a new file system to fully leverage and optimize the usage of NAND flash solutions (*with block interface*).
  - Performance comparison with Linux file systems (Ext4, Btrfs, Nilfs2).
    - Mobile system and server system

Key Design Considerations

- Flash-friendly on-disk layout
- Cost-effective index structure
- Multi-head logging
- Adaptive logging
- Fsync acceleration with roll-forward recovery

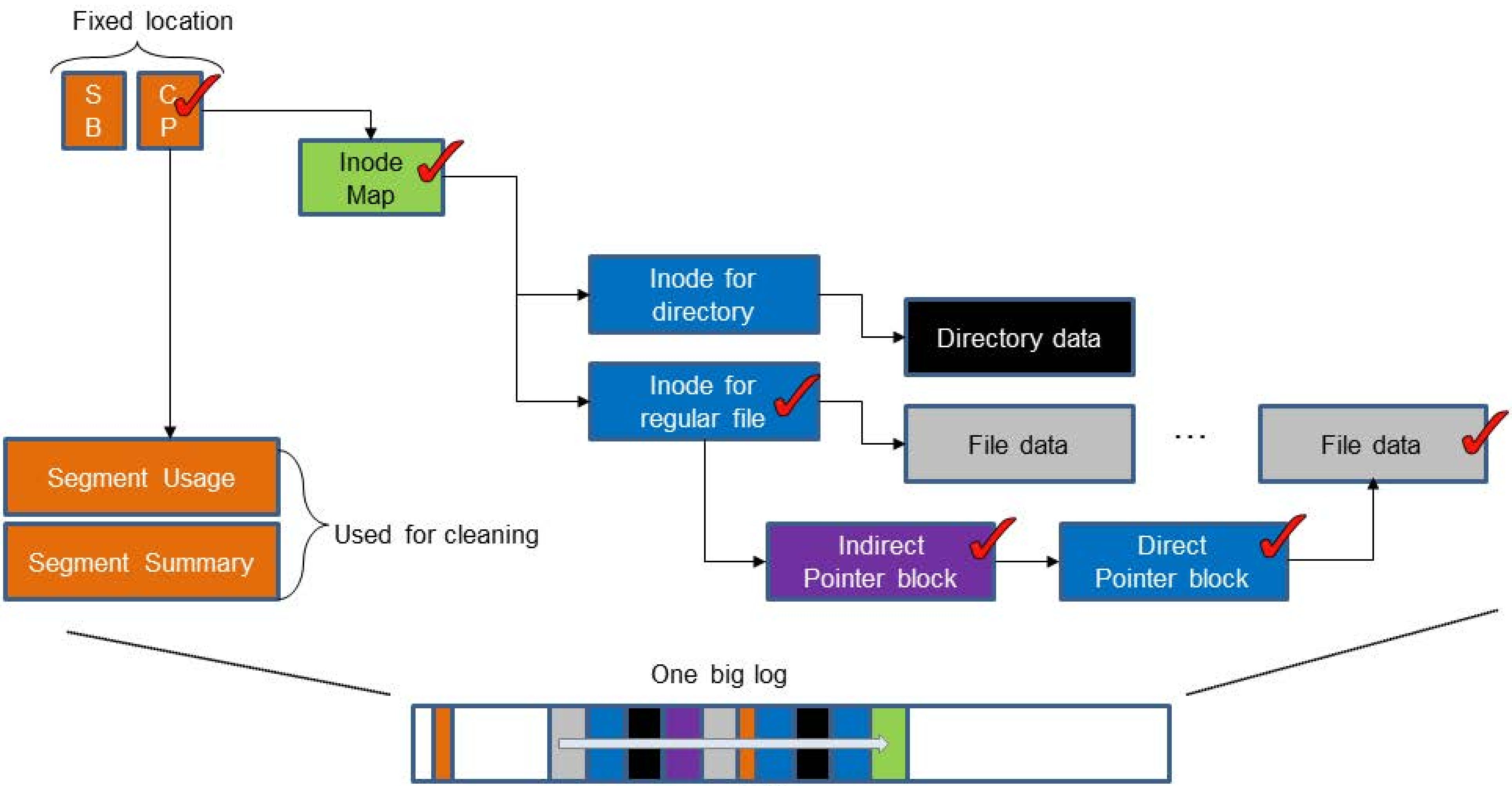
Flash-friendly On-Disk Layout

- **Flash Awareness**
  - All the FS metadata are located together for locality,
  - Start address of main area is aligned to the zone size,
  - File system cleaning is done in a unit of section (FTL's GC unit).
- **Cleaning Cost Reduction**
  - Multi-head logging for hot/cold data separation.



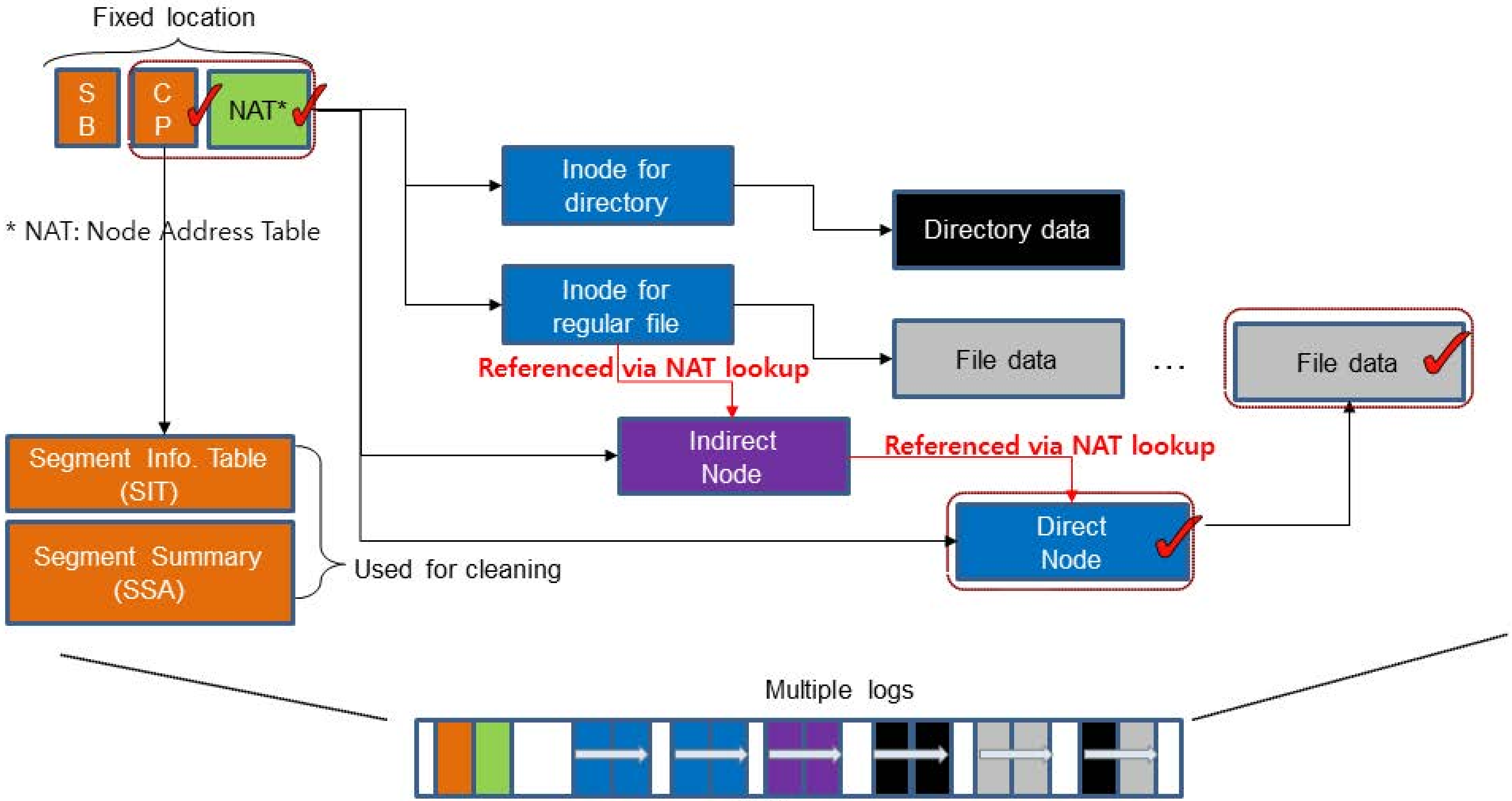
LFS Index Structure

- Update propagation issue: wandering tree
- One big log



F2FS Index Structure

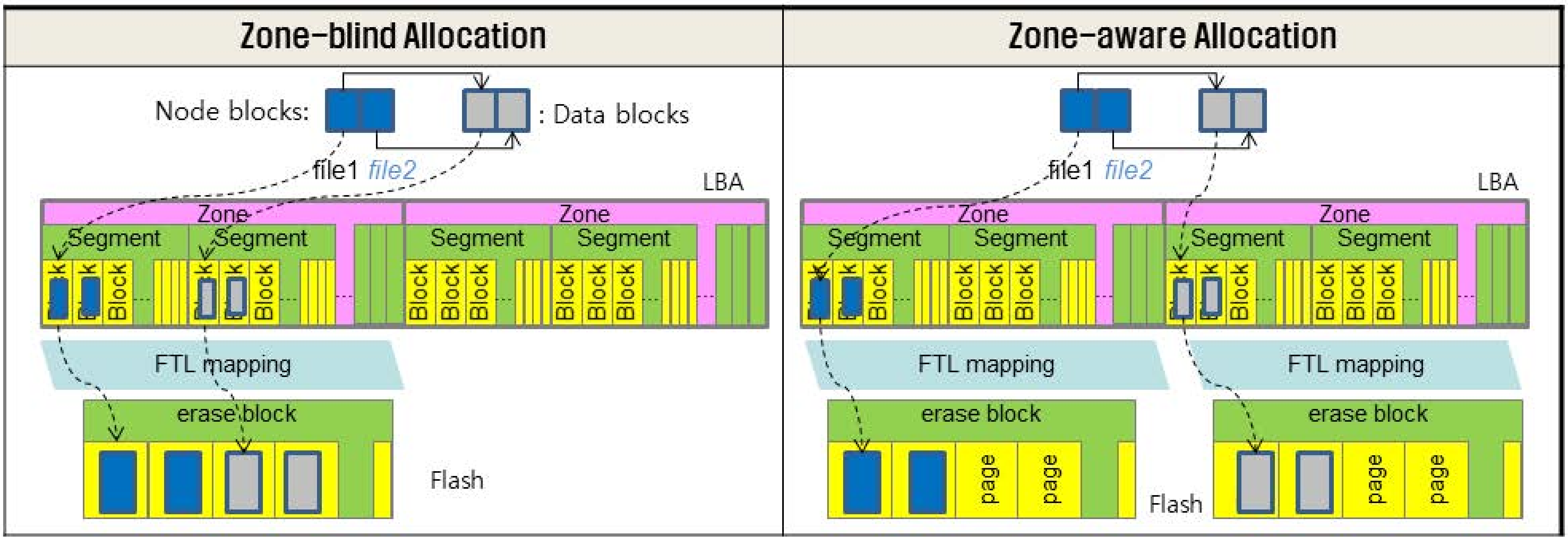
- Restrained update propagation: node address translation method
- Multi-head log



Multi-head Logging

Type	Temp.	Objects
Node	Hot	Direct node blocks for directories
	Warm	Direct node blocks for regular files
	Cold	Indirect node blocks
Data	Hot	Directory entry blocks
	Warm	Data blocks made by users
	Cold	Data blocks moved by cleaning; Cold data blocks specified by users; Multimedia file data

- **Data temperature classification**
  - Node > data
  - Direct node > indirect node
  - Directory > user file
- **Separation of multi-head logs in NAND flash.**
  - Zone-aware log allocation for set-associative mapping FTL mapping.
  - Multi-stream interface



Cleaning

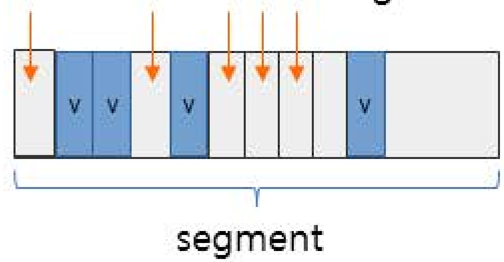
- **Cleaning is done in section unit.**
  - Section to be aligned with FTL's GC unit.

- **Cleaning procedure**
  1. Victim selection: get a victim section through referencing Segment Info. Table (SIT).
     - Greedy algorithm for foreground cleaning job
     - Cost-benefit algorithm for background cleaning job
  2. Valid block check: load parent index structures of there-in data identified from Segment Summary Area (SSA).
  3. Migration: move valid blocks by checking their cross-reference
  4. Mark victim section as "pre-free".
     1. Pre-free sections are freed after the next checkpoint is made.

Adaptive Logging

- **To reduce cleaning cost at highly aged conditions, F2FS changes write policy dynamically.**
  - Append logging (logging to clean segments)
    - Need cleaning operations if there is no free segment.
    - Cleaning causes mostly random read and sequential writes.
  - Threaded logging[1] (logging to dirty segments)
    - Reuse invalid blocks in dirty segments
    - No need cleaning
    - Cause random writes

Threaded logging writes data into invalid blocks in segment.



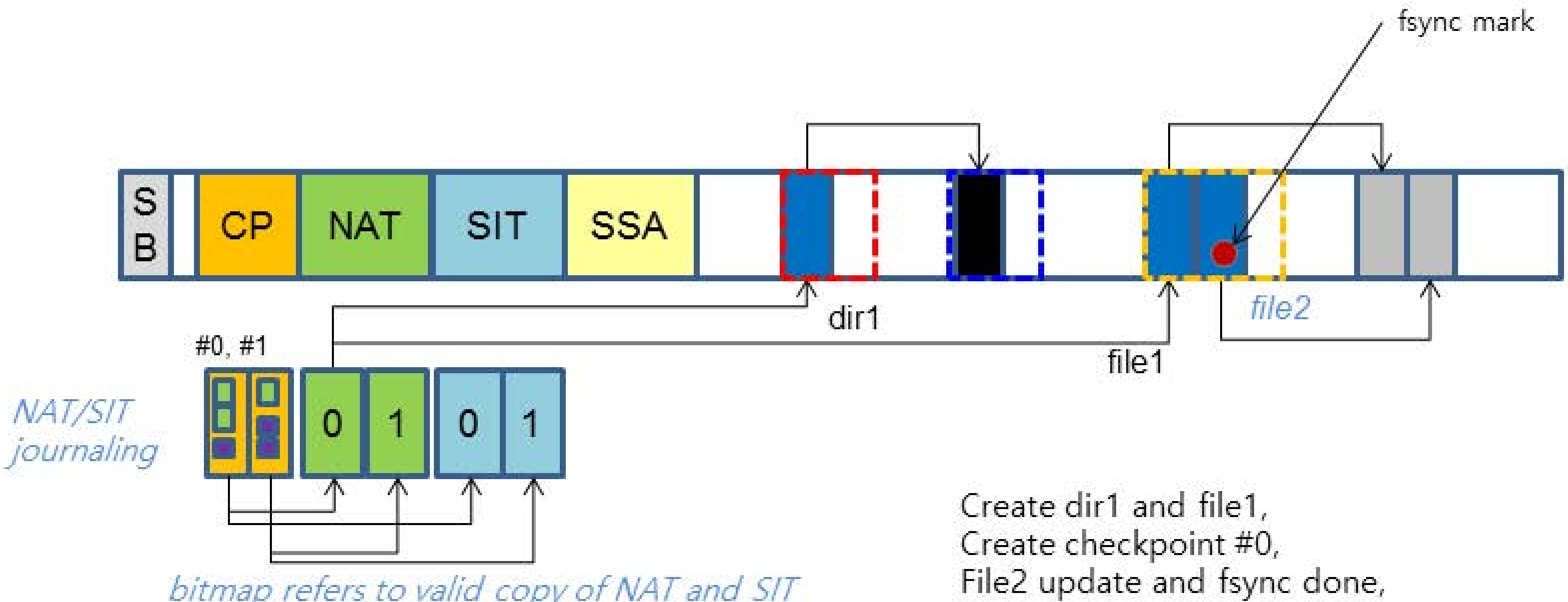
*** Node is always written with append logging policy.**

1. Y. Oh, E. Kim, J. Choi, D. Lee, and S. H. Noh. Optimizations of LFS with slack space recycling and lazy indirect block update. In *Proceedings of the Annual Haifa Experimental Systems Conference*, page 2, 2010.

Sudden Power Off Recovery (1/2)

Checkpoint and rollback

- Maintains shadow copy of checkpoint, NAT, SIT blocks
- Recovers the latest checkpoint
- Keeps NAT/SIT journal in checkpoint to avoid NAT, SIT writes



Create dir1 and file1,
Create checkpoint #0,
File2 update and fsync done,
SPO
Recovery
-> Roll-back to the latest stable checkpoint (#0)
; recover dir1, file1
-> Roll-forward recovery of file2's fsync'ed data

Sudden Power Off Recovery (2/2)

- **Fsync handling**
  - On fsync, checkpoint is not necessary.
  - Direct node blocks are written with fsync mark.

- ***Roll-forward recovery procedure***
  1. Search marked direct node blocks
  2. Per marked node block, identify old and new data blocks by checking the difference between the current and previous node block.
  3. Update SIT; invalidate old data blocks
  4. Replay new data block writes; update NAT, SIT accordingly
  5. Create checkpoint

Evaluation

- **Experimental Setup**
  - Mobile and server systems
  - Performance comparison with ext4, btrfs, nilfs2

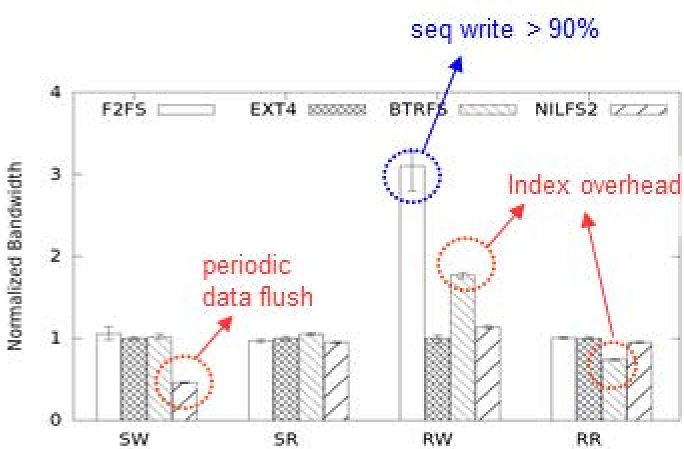
Target	System	Storage Devices
Mobile	CPU: Exynos 5410 Memory: 2GB OS: Linux 3.4.5 Android: JB 4.2.2	eMMC 16GB: 2GB partition: *(114, 72, 12, 12)**
Server	CPU: Intel i7-3770 Memory: 4GB OS: Linux 3.14 Ubuntu 12.10 server	SATA SSD 250GB: *(486, 471, 40, 140)** PCIe (NVMe) SSD 960GB: *(1,295, 922, 41, 254)**

** (Seq-Rd, Seq-Wr, Rand-Rd, Rand-Wr) in MB/s*

Target	Name	Workload	Files	File size	Threads	R/W	`fsync`
Mobile	iozone	Sequential and random read/write	1	1G	1	50/50	N
	SQLite	Random writes with frequent `fsync`	2	3.3MB	1	0/100	Y
	Facebook-app	Random writes with frequent `fsync` generated by the given system call traces	579	852KB	1	1/99	Y
	Twitter-app		177	3.3MB	1	1/99	Y
Server	videoserver	Mostly sequential reads and writes	64	1GB	48	20/80	N
	fileserver	Many large files with random writes	80,000	128KB	50	70/30	N
	varmail	Many small files with frequent `fsync`	8,000	16KB	16	50/50	Y
	oltp	Large files with random writes and `fsync`	10	800MB	211	1/99	Y

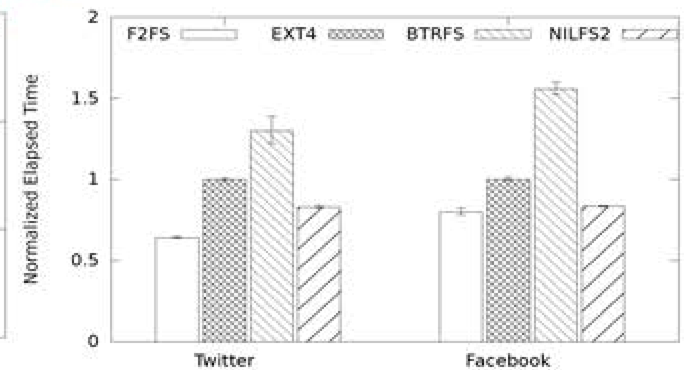
Mobile Benchmark

- **In F2FS, more than 90% of writes are sequential.**
- **F2FS reduces write amount per fsync by using roll-forward recovery.**
  - If checkpoint is done per fsync, write amount in SQLite insert test is 37% more than Ext4, and normalized performance is 0.88.
- **Btrfs and nilfs2 performed poor than ext4.**
  - Btrfs: heavy indexing overheads, Nilfs2: periodic data flush
  - For Iozone-RW, Btrfs, Nilfs2 write 15%, 41% more I/Os than Ext4, respectively.
  - For Iozone-RR, Btrfs has 50% more I/Os than other file systems.



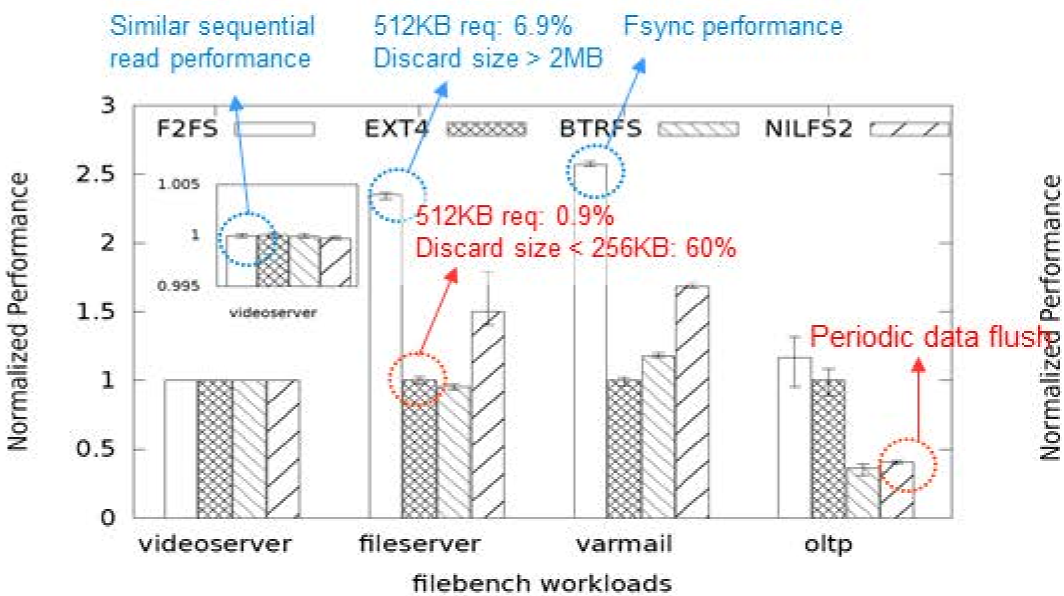
iozone

Sqlite (1000 records, WAL mode)

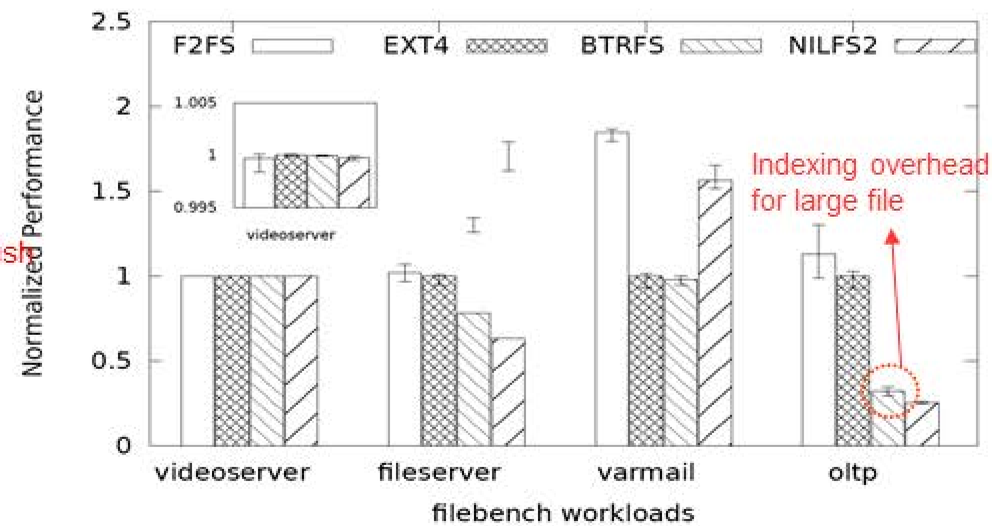


Server Benchmark

- **Performance gain of F2FS over Ext4 is more on SATA SSD than on PCIe SSD.**
  - Varmail: 2.5x on the SATA SSD and 1.8x on the PCIe SSD
  - Oltp: 16% on the SATA SSD and 13% on the PCIe SSD
- **Discard size matters in SATA SSD due to interface overhead.**
  - When using small discard (256KB) for F2FS, fileserver performance is degraded by 18%.



[SATA SSD]



[PCIe SSD]

Multi-head Logging

- **Using more logs gives better hot and cold data separation.**
  - 2 logs: node, data
  - 4 logs: hot node, warm/cold node, hot data, warm/cold data

Test condition:
Run two workloads simultaneously:
1. Varmail (10,000 files in 100 dirs, total writes 6.5 GB)
2. Copy jpg files (500KB, 5,000 files, 2.5GB) ➔ considered as cold

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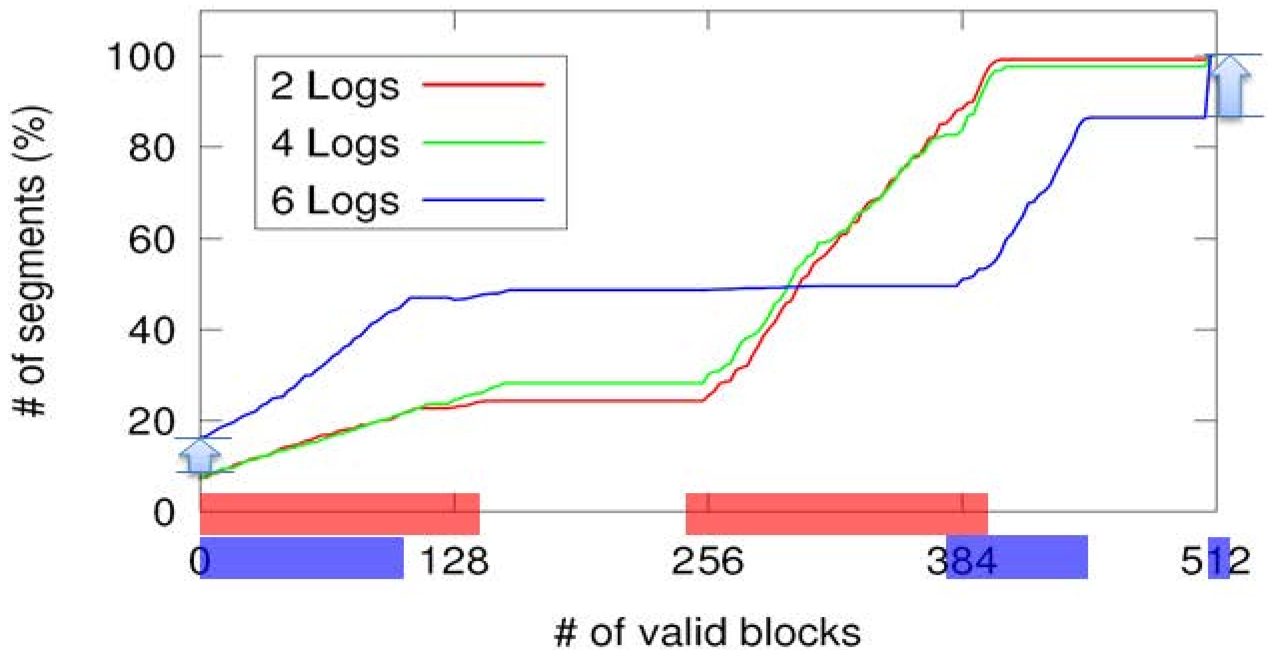
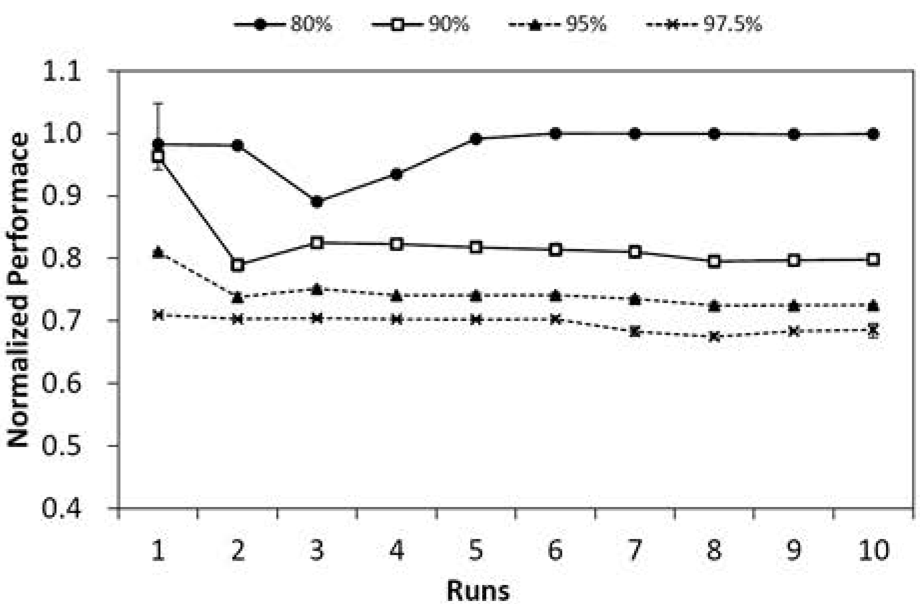


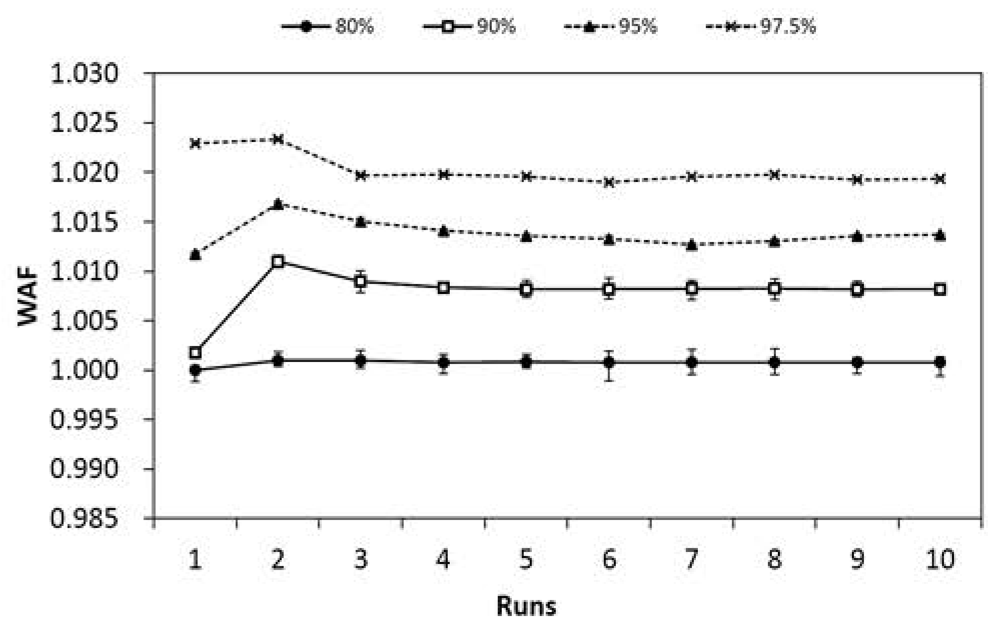
Cleaning Cost Analysis

- **Under high utilization, F2FS uses adaptive logging to restrain FS cleaning cost.**
  - Only node segment cleaning is done.
  - Even in 97.5% util., WAF is less than 1.025.
- **Without adaptive logging, WAF[1] goes up to more than 3.**

Test condition:
120GB of 250GB (SATA SSD)
Util (Cold : Hot) = 80%(60:20), 90%(60:30), 95%(60: 35), 97.5%(60:37.5)
Workload : 20GB 4KB random writes, 10 iterations

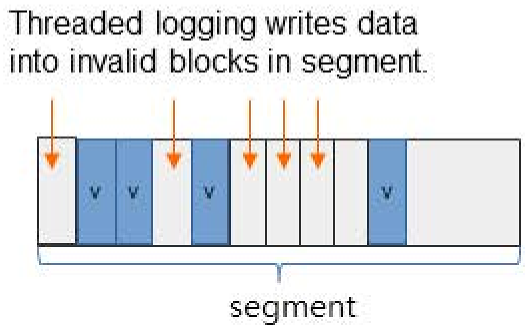
1. WAF: Write Amplification Factor

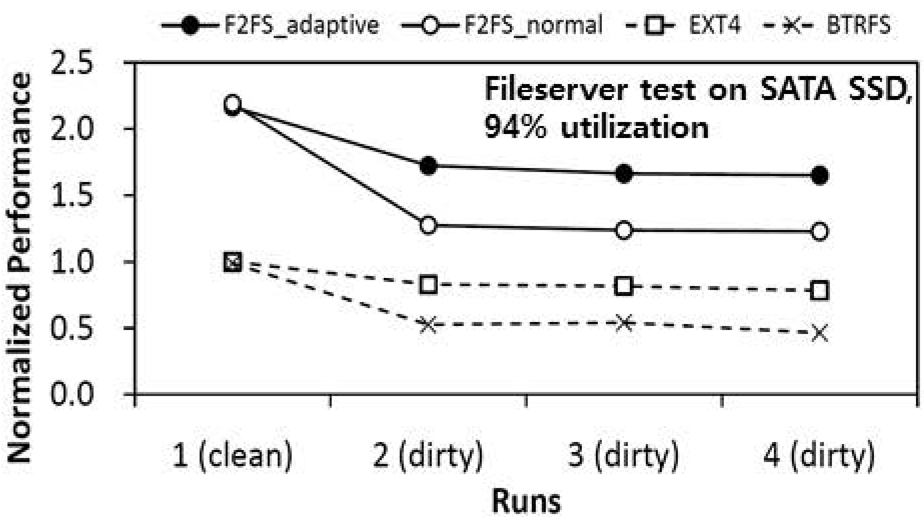


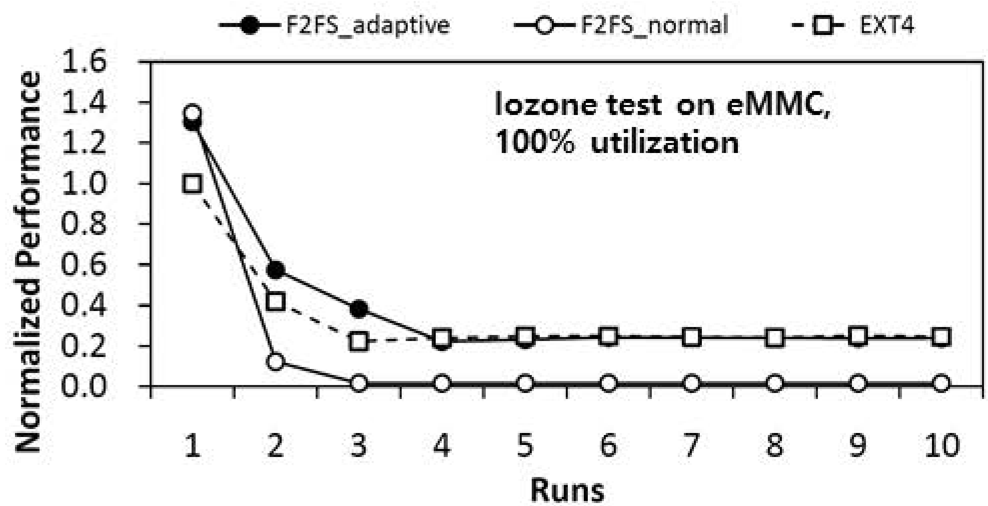


Adaptive Logging Performance

- **Adaptive logging gives graceful performance degradation under highly aged volume conditions.**
  - Fileserver test on SATA SSD (94% util.)
    - Sustained performance improvement: 2x/3x over ext4/btrfs.
  - Iozone test on eMMC (100% util.)
    - Sustained performance is similar to ext4.







Conclusion

- **F2FS features**
  - Flash friendly on-disk layout -> align FS GC unit with FTL GC unit,
  - Cost effective index structure -> restrain write propagation,
  - Multi-head logging -> cleaning cost reduction,
  - Adaptive logging -> graceful performance degradation in aged condition,
  - Roll-forward recovery -> fsync acceleration.

- **F2FS shows performance gain over other Linux file systems.**
  - 3.1x (iozone) and 2x (SQLite) speedup over Ext4,
  - 2.5x (SATA SSD) and 1.8x (PCIe SSD) speedup over Ext4 (varmail)

- **F2FS is publicly available, included in Linux mainline kernel since Linux 3.8.**

Thank You!