InDeF: An Advanced Defragmenter Supporting Migration Offloading on ZNS SSD

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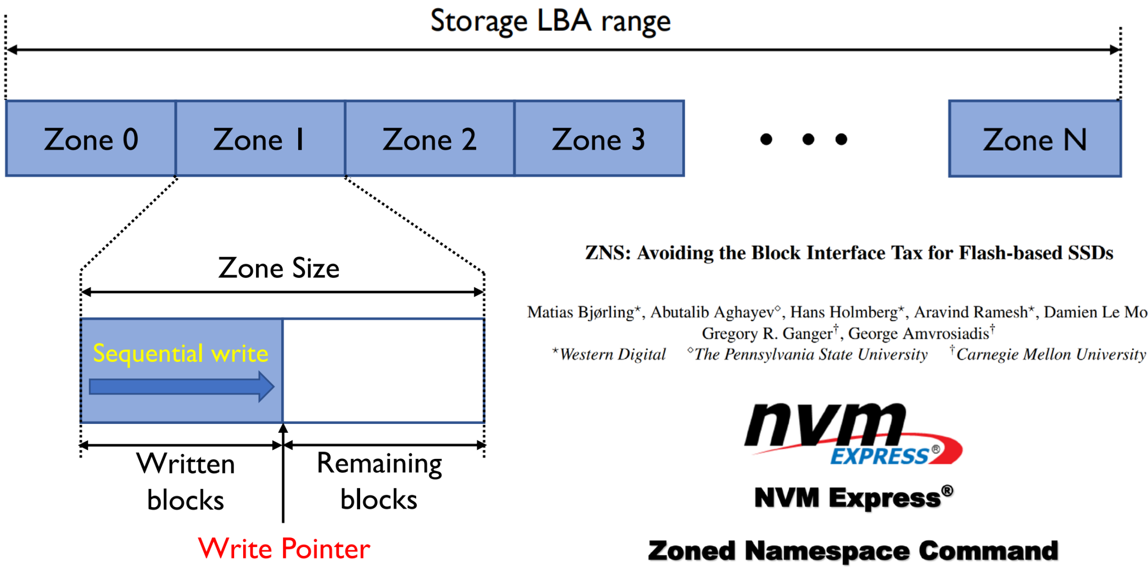
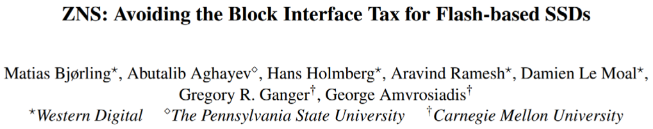
Outline

- **Background and motivation**
- **Our Work: InDeF**
- **Performance Evaluation**
- **Conclusion**

Background : What is ZNS SSD?

- ➢The logical address space is divided into fixed-sized zones
- ➢Each zone must be written sequentially and reset explicitly for reuse

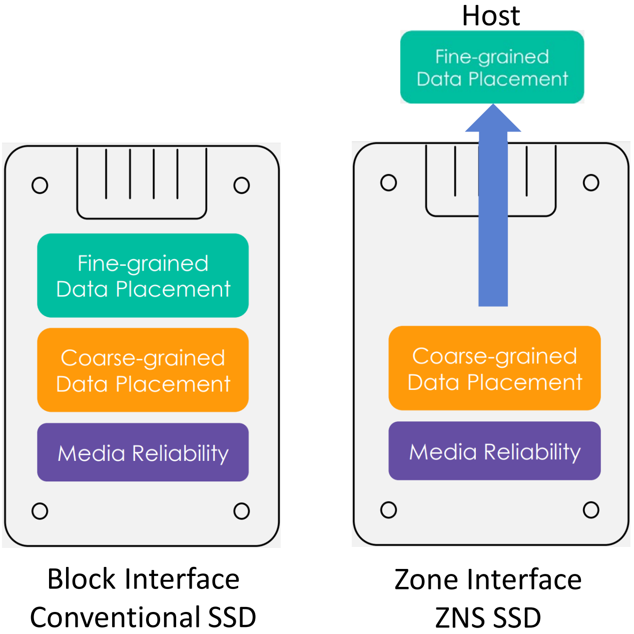



ZNS: Avoiding the Block Interface Tax for Flash-based SSDs

Matias Bjørling*, Abutalib Aghayev◇, Hans Holmberg*, Aravind Ramesh*, Damien Le Moal*,
Gregory R. Ganger†, George Amvrosiadis†
*Western Digital ◇The Pennsylvania State University †Carnegie Mellon University

NVM Express®

Zoned Namespace Command Set Specification


Host
Fine-grained Data Placement
Fine-grained Data Placement
Coarse-grained Data Placement
Media Reliability
Coarse-grained Data Placement
Media Reliability
Block Interface Conventional SSD
Zone Interface ZNS SSD

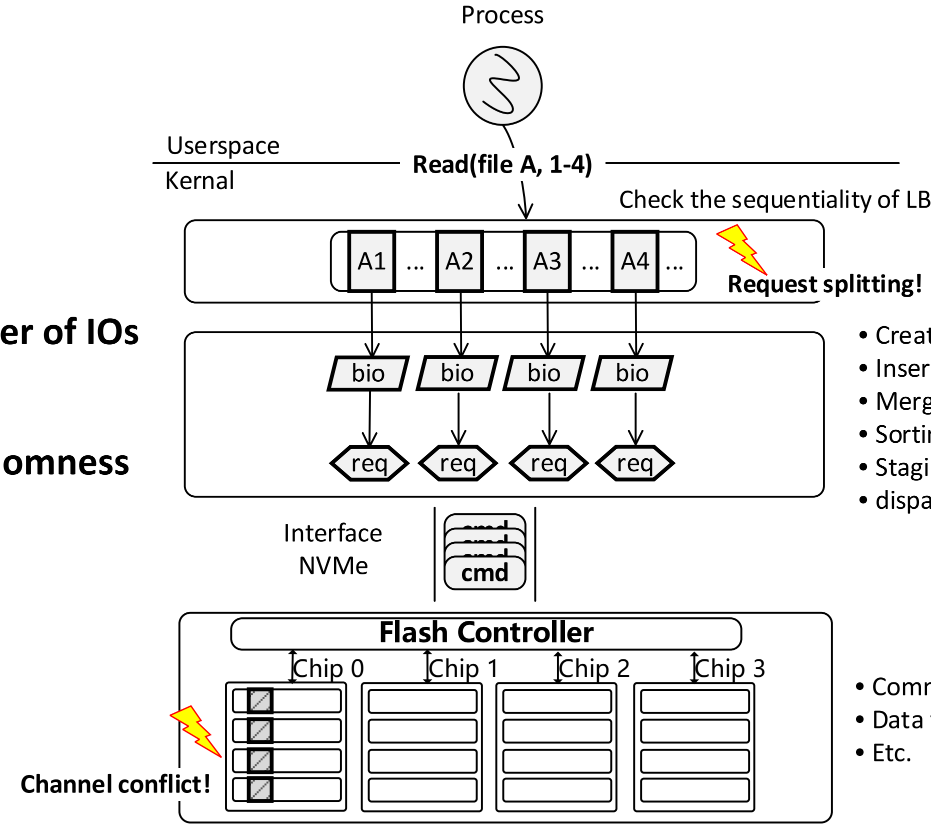
Background : What is fragmentation?

Request splitting

1)Increases the number of IOs

2)Makes I/Os smaller

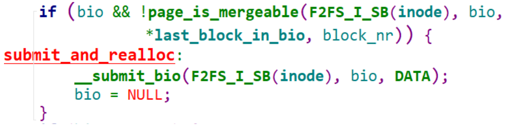
3)Increases their randomness



Check the sequentiality of LBA

Request splitting!

Channel conflict!



```
if (bio && !page_is_mergeable(F2FS_I_SB(inode), bio,
                        *last_block_in_bio, block_nr)) {
submit_and_realloc:
        __submit_bio(F2FS_I_SB(inode), bio, DATA);
        bio = NULL;
}
```

- Creation
- Insertion
- Merging
- Sorting
- Staging
- dispatching

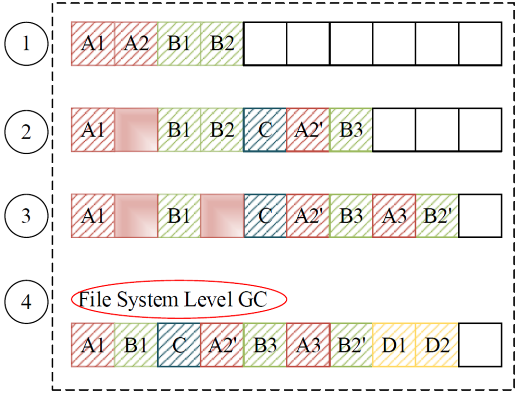
Logical Fragmentation

Physical Fragmentation

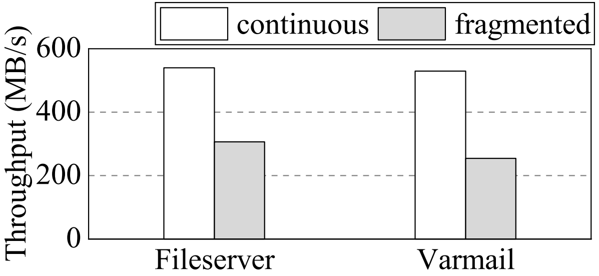
- Command processing
- Data fetching(DMA)
- Etc.

Motivation : Fragmentation accumulation

□ **Free Page** ▨ **Valid Page** 🟥 **Invalid Page**



- **Incoming Data Stream：**
  - **A1A2, B1B2 → C, A2', B3 → A3, B2' → D1D2**



- **Fragmentation on ZNS SSD**

  Sequential read after running Fileserver/Varmail

  Filesystem: F2FS

Motivation : Definition of the fragmentation

- **Definition of the fragmentation of an I/O request**
  - **The degree of logical fragmentation (DoLF) is the number of logical fragments in an I/O range**

  - **The degree of physical fragmentation (DoPF)**

    We measure the degree of physical fragmentation of an I/O request by how evenly the data in the I/O range are distributed among the flash parallel units.

$$DoPF = \frac{\sum_{i=1}^{L} (N_i - \frac{M}{L})^2}{L}$$

Motivation : The impact of fragmentation

➢Evaluation Setup

- ➢32KB 64KB 128KB 256KB O_DIRECT sequential read on F2FS
- ➢Varying DoLF/DoPF

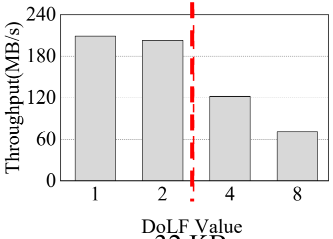
➢Observations

- ➢**A low DoLF value has a small impact on I/O performance**

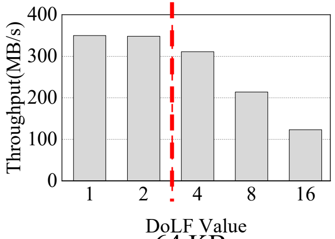
  Low kernel overhead

- ➢**When the DoPF value is small, e.g., less than 40, physical fragmentation has a negligible impact on I/O performance**

  Software overhead of I/O dominates the total I/O latency



32 KB



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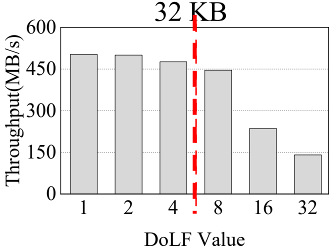

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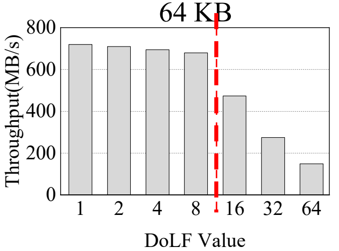

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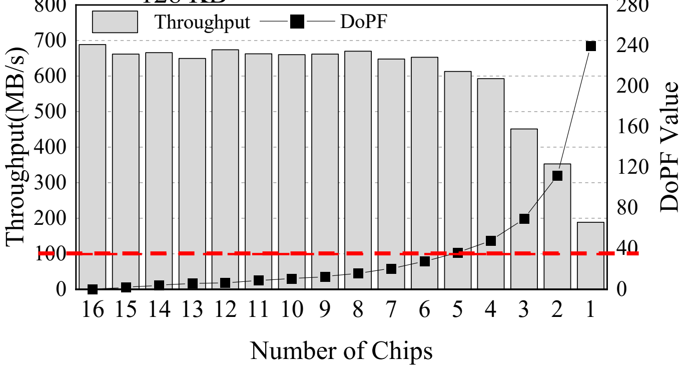


No need to defragment all the fragments!

Motivation : How to Select the Appropriate Data

- **Modern storage systems typically perform data access in non-uniform distribution [1],[2]**
- **Multiple reads to fragmented data accumulate the access latency caused by fragmentation**
- **Our idea:**
  - Defragmenting data with a low degree of fragmentation or cold data that is rarely accessed provides little performance gain
  - **We define the I/O data defragmentation priority (IODP)**

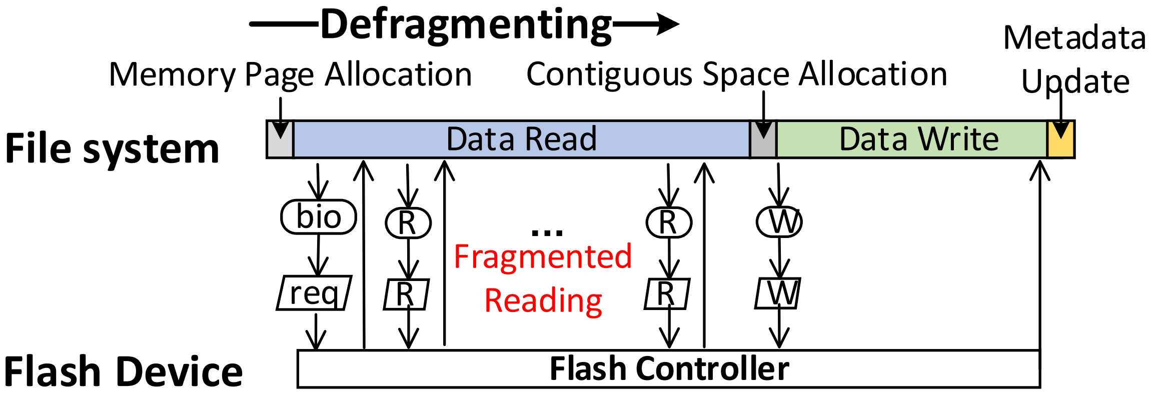
$$IODP = (\alpha \cdot DoLF + \beta \cdot DoPF) \times readcount$$

[1] Q. Wang, J. Li, P. P. Lee, T. Ouyang, C. Shi, and L. Huang, "Separating data via block invalidation time inference for write amplification reduction in log-structured storage," in *Proc. of USENIX FAST*, 2022.

[2] Y. Lv, L. Shi et al., "Access characteristic guided partition for read performance improvement on solid state drives," in 2020 57th ACM/IEEE Design Automation Conference (DAC). IEEE, 2020, pp. 1–6.

Motivation : The Conventional Defragmenter

- Cause a significant increase in the **host memory usage** and invoke page frame reclamation
- Result in a large **chip idle interval** in the SSD
- Migrate **the entire contents of files** even when there are few fragments
- The additional writes **reduce the lifespan** of modern storage devices
- **Degrades the performance** of co-running applications
- Time-consuming

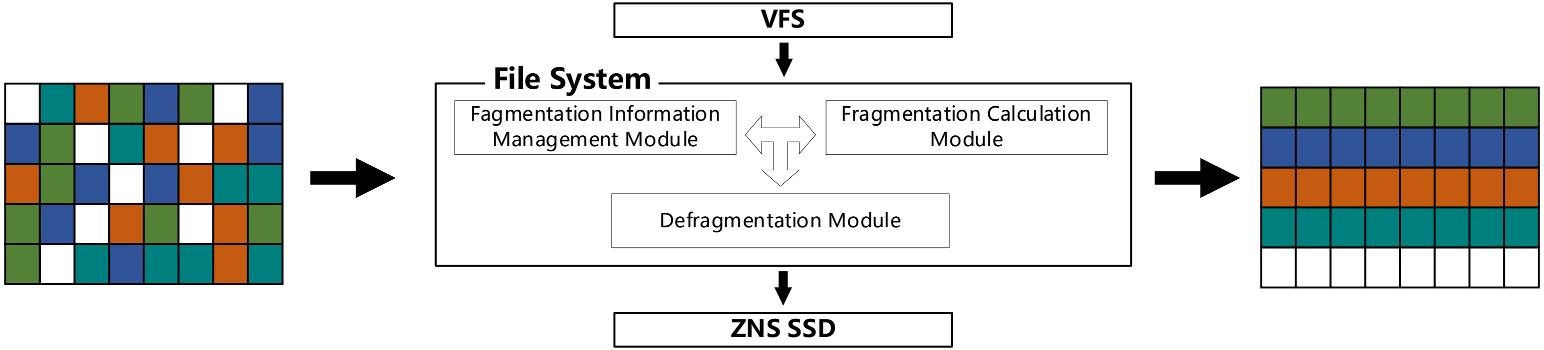


Our Scheme: InDeF for Zoned Namespace SSD

➢Main goals

- ✓ Minimizes the amount of migration data for defragmentation to reduce the write traffic of the underlying device
- ✓ Decreases elapsed time of defragmentation to reduce the impact on co-running application performance

InDeF for Zoned Namespace SSD


VFS
File System
Fagmentation Information Management Module
Fragmentation Calculation Module
Defragmentation Module
ZNS SSD

➢**The Fragmentation Information Management Module**

Collects I/O information from the filesystem

Manages I/O fragmentation information

➢**The Fragmentation Calculation Module**

Calculates the DoLF value and DoLP value based on the collected I/O information

➢**The Defragmentation Module**

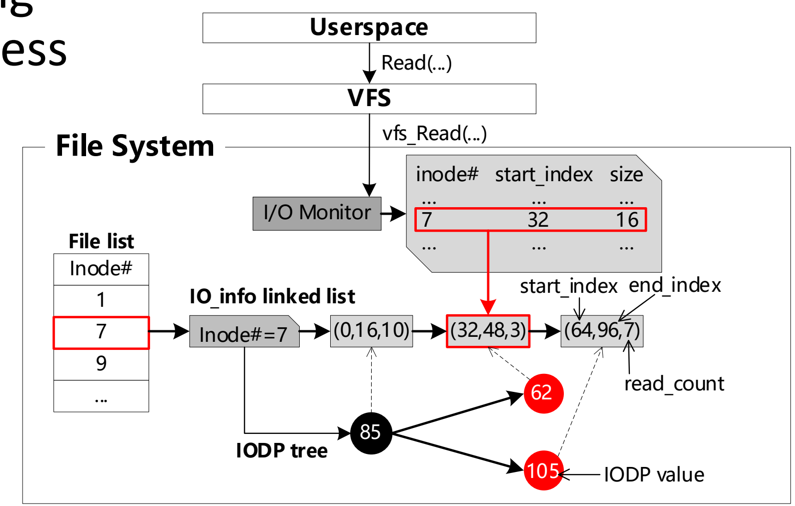
Filters the fragments based on the I/O fragmentation information

Offloads the data migration from the host to the SSD

InDeF for Zoned Namespace SSD

The Fragmentation Information Management Module

- **Monitors** I/O activity at the file system layer
- **Creates** file list and I/O information linked list
- **Merges** I/O requests that have overlapping addresses and preserves the largest address range
- **Inserts** the IODP of each I/O information into a red-black tree (called IODP tree) in order



inode#	start_index	size
...	...	...
7	32	16
...	...	...

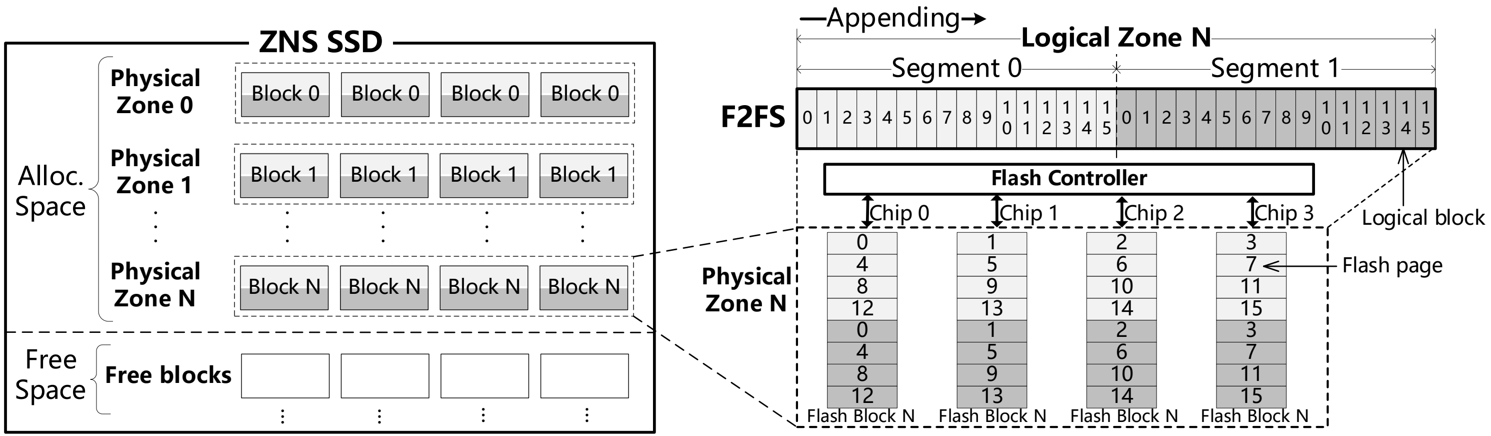
Inode#
1
7
9
...

InDeF for Zoned Namespace SSD

➢The Fragmentation Calculation Module

- ➢Gets the physical location of the logical block inside the device by the segment number and in-segment offset of the logical block

- ➢The i-th logical block of a segment is stored on the j-th flash chip that
j = i % (the number of parallel flash chips)



InDeF for Zoned Namespace SSD

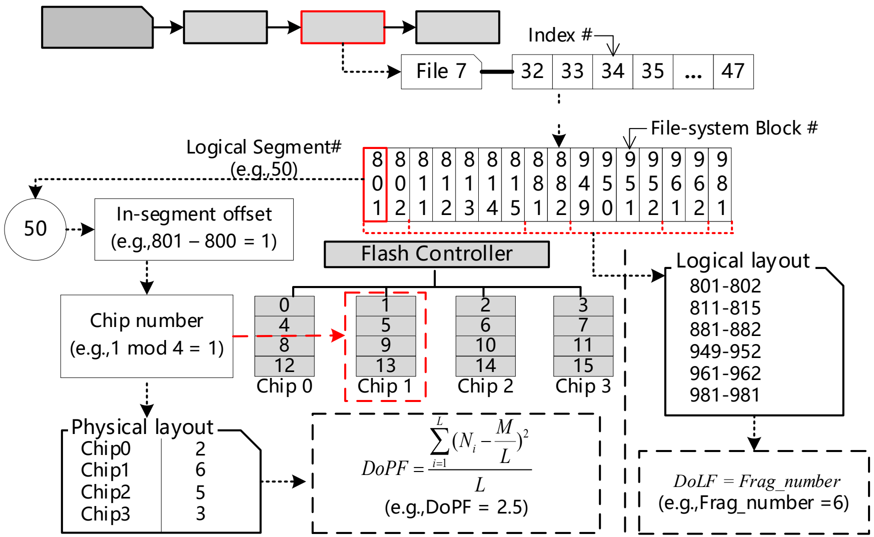
➢The Fragmentation Calculation Module

➢An example of calculating the DoLF and the DoPF

The DoLF can be calculated by the number of logical fragments in the I/O range

The DoPF can be calculated by

$$DoPF = \frac{\sum_{i=1}^{L}(N_i - \frac{M}{L})^2}{L}$$



8	8	8	8	8	8	8	8	8	9	9	9	9	9	9	9
0	0	1	1	1	1	1	8	8	4	5	5	5	6	6	8
1	2	1	2	3	4	5	1	2	9	0	1	2	1	2	1

Chip 0	Chip 1	Chip 2	Chip 3
0	1	2	3
4	5	6	7
8	9	10	11
12	13	14	15

Logical layout
801-802
811-815
881-882
949-952
961-962
981-981

Physical layout

Chip0	2
Chip1	6
Chip2	5
Chip3	3

$$DoPF = \frac{\sum_{i=1}^{L}(N_i - \frac{M}{L})^2}{L}$$

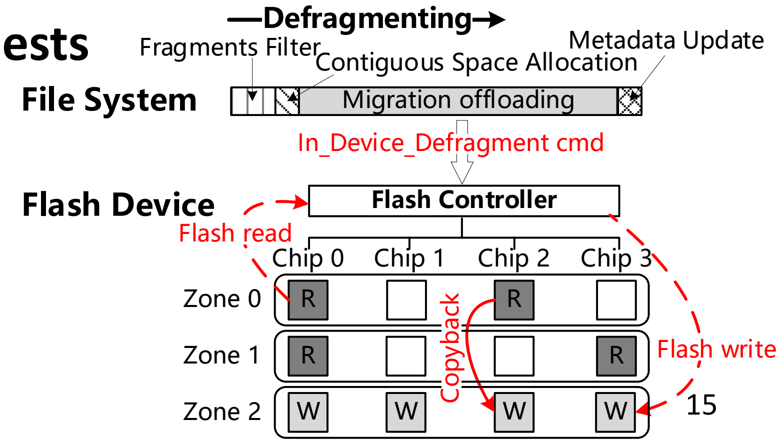
(e.g.,DoPF = 2.5)

$DoLF = Frag\_number$

(e.g.,Frag_number =6)

InDeF for Zoned Namespace SSD

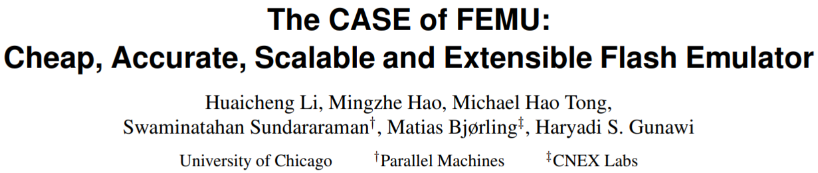
- **The Defragmentation Module**
  - **Truncates I/O information entries with a low IODP value based on the ordered IODP tree**
  - **Groups data based on whether the data page is dirty or not**
  - **Sends the In_Device_Defragment command**
    - Contains a set of source LBAs and a set of destination LBAs
  - **Handles migration offloading and host requests**
    - Flash read and write
    - Copyback



Performance Evaluation

➢Experimental Setup

- ➢InDeF emulator based on FEMU



The CASE of FEMU:
Cheap, Accurate, Scalable and Extensible Flash Emulator

Huaicheng Li, Mingzhe Hao, Michael Hao Tong,
Swaminatahan Sundararaman†, Matias Bjørling‡, Haryadi S. Gunawi

University of Chicago †Parallel Machines ‡CNEX Labs

- ➢A QEMU-based and DRAM-backed NVMe SSD Emulator
- ➢https://github.com/ucare-uchicago/femu

➢Comparison

- ➢defrag.f2fs[3] vs. FragPicker[4] vs. InDeF

➢Workloads

- ➢Synthetic and Macro Benchmarks

➢Objectives

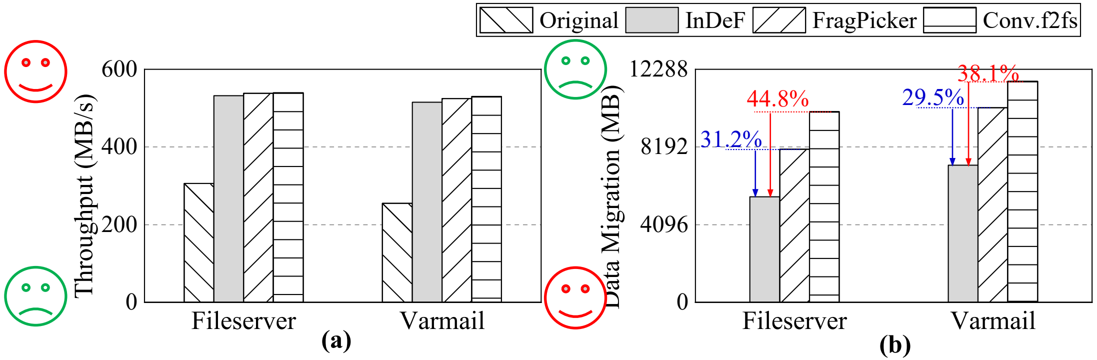
- ➢Does InDeF reduce the amount of writes for defragmentation?
- ➢Does InDeF achieve a similar level of performance gain, compared with conventional tools?
- ➢Does InDeF decrease the elapsed time of defragmentation?

[3] "defrag.f2fs," 2022, https://manpages.debian.org/testing/f2fs-tools/defrag.f2fs.8.en.html.

[4] J. Park and Y. I. Eom, "Fragpicker: A new defragmentation tool for modern storage devices," in Proceedings of the ACM SIGOPS 28th Symposium on Operating Systems Principles, 2021, pp. 280–294.

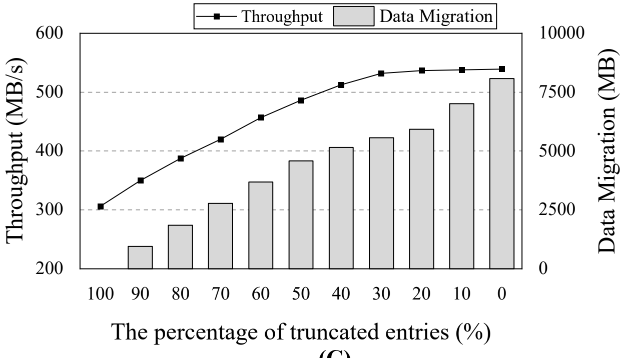
Experiment – Performance and Write Amount

- **Performance**
  - **InDeF improve the throughput by about 72% (fileserver) and 112% (varmail), compared with that before defragmentation**
- **Write amount**
  - **InDeF reduces the amount of writes by around 31.2%-44.8%(Fileserver) and 29.5%-38.1%(Varmail)**



(a)

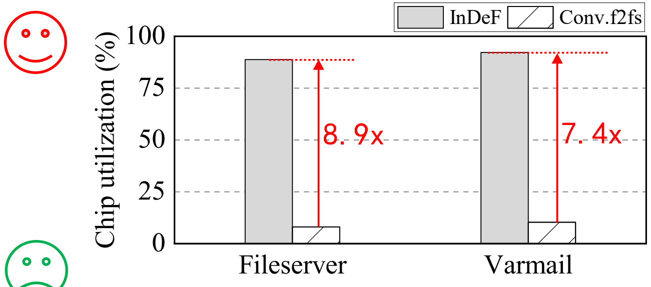
(b)



(C)

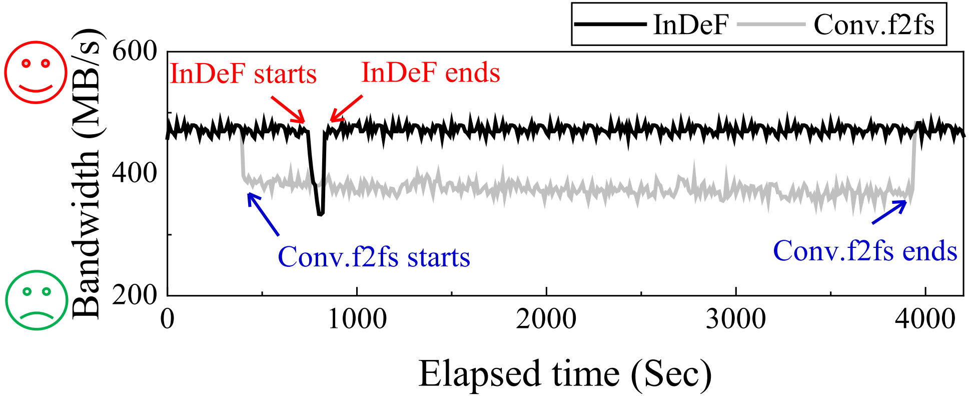
Experiment - Elapsed time of defragmentation

- **Elapsed time of defragmentation**
  - **InDeF increased chip utilization during migration by 8.9x (fileserver) and 7.4x (varmail)**
  - **InDeF decreases the elapsed time of defragmentation time by 94.2% (fileserver) and 91.6% (varmail) due to the higher chip utilization**



Elapsed time (s)	InDeF	Conv.f2fs
Fileserver	21	360
Varmail	35	417

(a)



(b)

More experiments in our paper!

- **Synthetic Benchmarks**
- **Database workloads**
  - **RocksDB YCSB-C**

  …

Conclusion

➢ **Main goals**

- ✓ Minimizes the amount of migration data for defragmentation to reduce the write traffic of the underlying device
- ✓ Decreases elapsed time of defragmentation to reduce the impact on co-running application performance

➢ **InDeF for ZNS SSD**

- ✓ Combines the degree of fragmentation and access hotness to find out the most suitable data set to migrate in each file
- ✓ By the In_Device_Defragment command, InDeF offloads the data migration from the host to the ZNS SSD to improve the efficiency of defragmentation
- ✓ Decreases the elapsed time of defragmentation significantly while minimizing the amount of data migration for defragmentation

Thanks!