We Ain't Afraid of No File Fragmentation: Causes and Prevention of Its Performance Impact on Modern Flash SSDs

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Fragmentation in HDD

- **Discontinue data blocks**

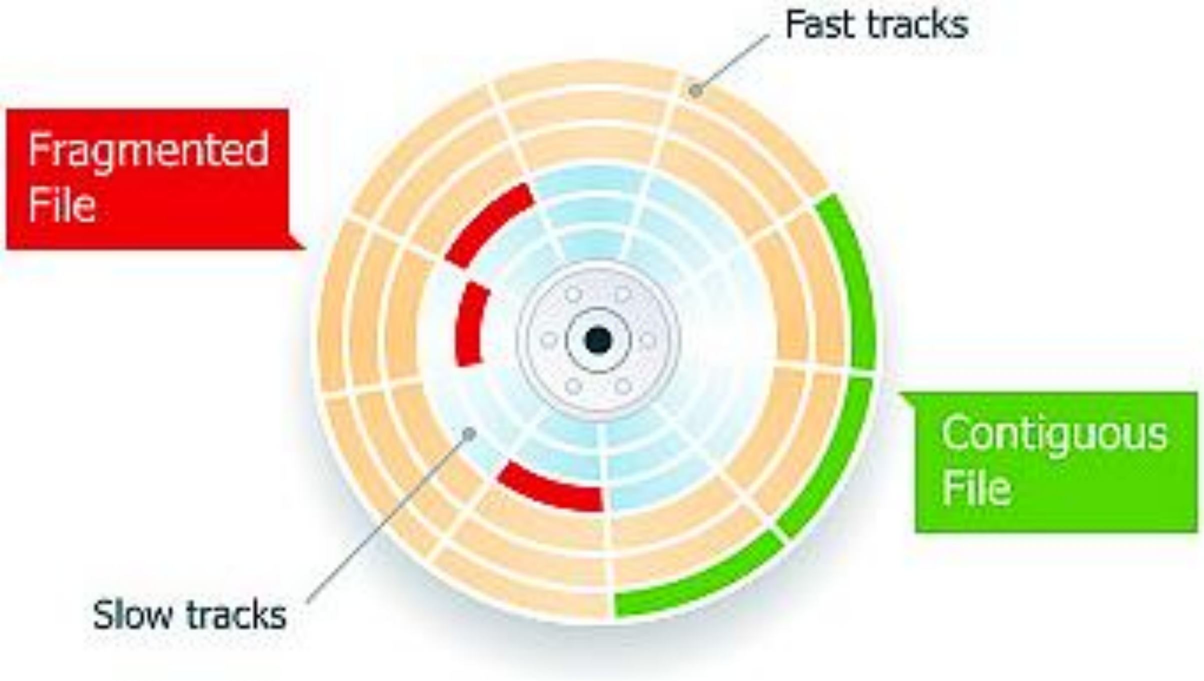
→ Random access to scattered fragment

→ Read performance bad !!!

- **Existing tool**
  - Delay, pre allocation etc …
  - But simultaneously multiple write
    or long time before additional file write

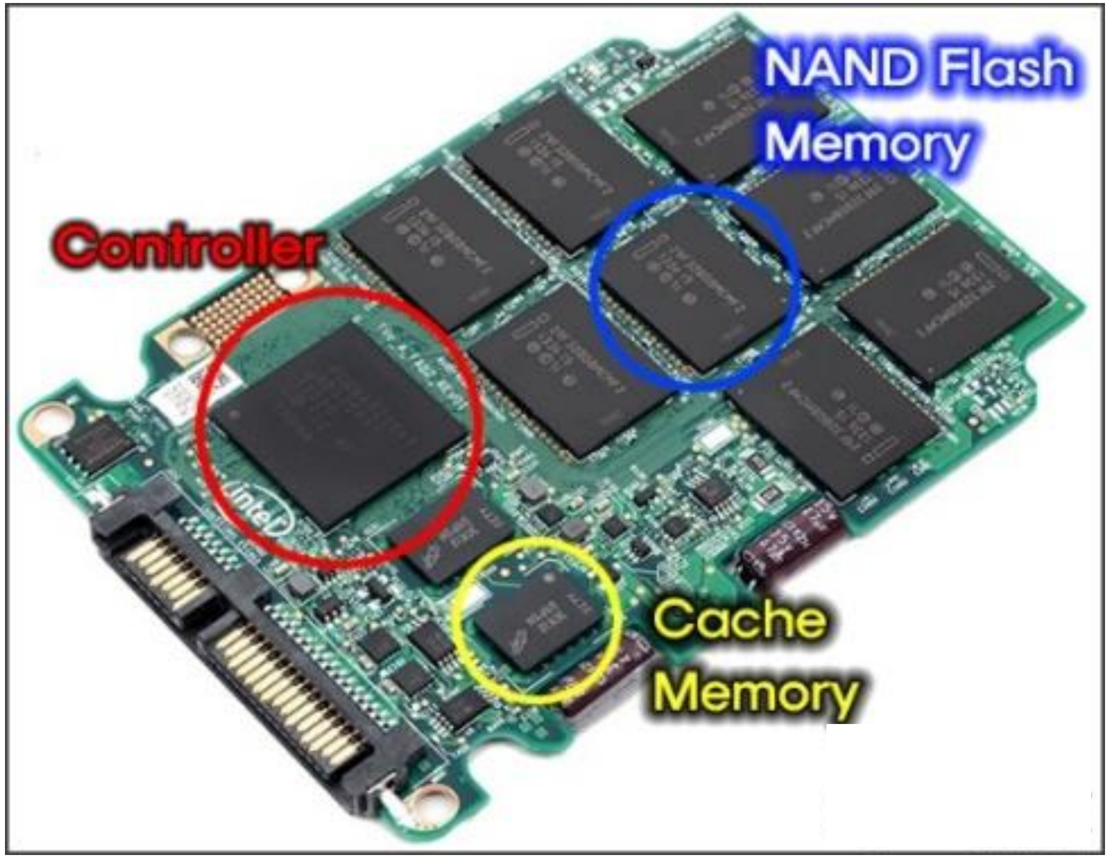
  → Impossible avoid to fragmentation

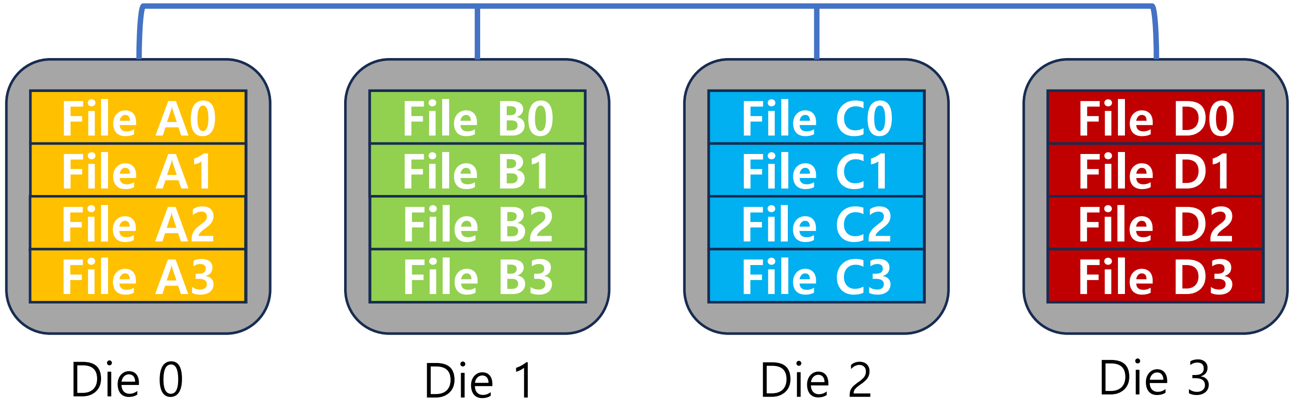
- **Main reason**
  - Kernel I/O path, storage device interface, storage media access



Normal SSD

- **SSD**





Die 0	Die 1	Die 2	Die 3
File A0	File B0	File C0	File D0
File A1	File B1	File C1	File D1
File A2	File B2	File C2	File D2
File A3	File B3	File C3	File D3

Is performance always good?

Fragmentation in SSD

- **SSD**
  - **File Systems Fated for Senescence? Nonsense, Says Science!** *Alex Conway, et al. FAST'17*

  → SSD have 2 to 5 times slower read performance when accessing fragmented files

Fragmentation in SSD

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  - **FragPicker: A New Defragmentation Tool for Modern Storage Devices**
    Park, Jonggyu, and Young Ik Eom. ACM SIGOPS'21

  → Claims that SSD's performance degradation is mainly from request splitting

Fragmentation in SSD

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    → SSD have 2 to 5 times slower read performance when accessing fragmented files
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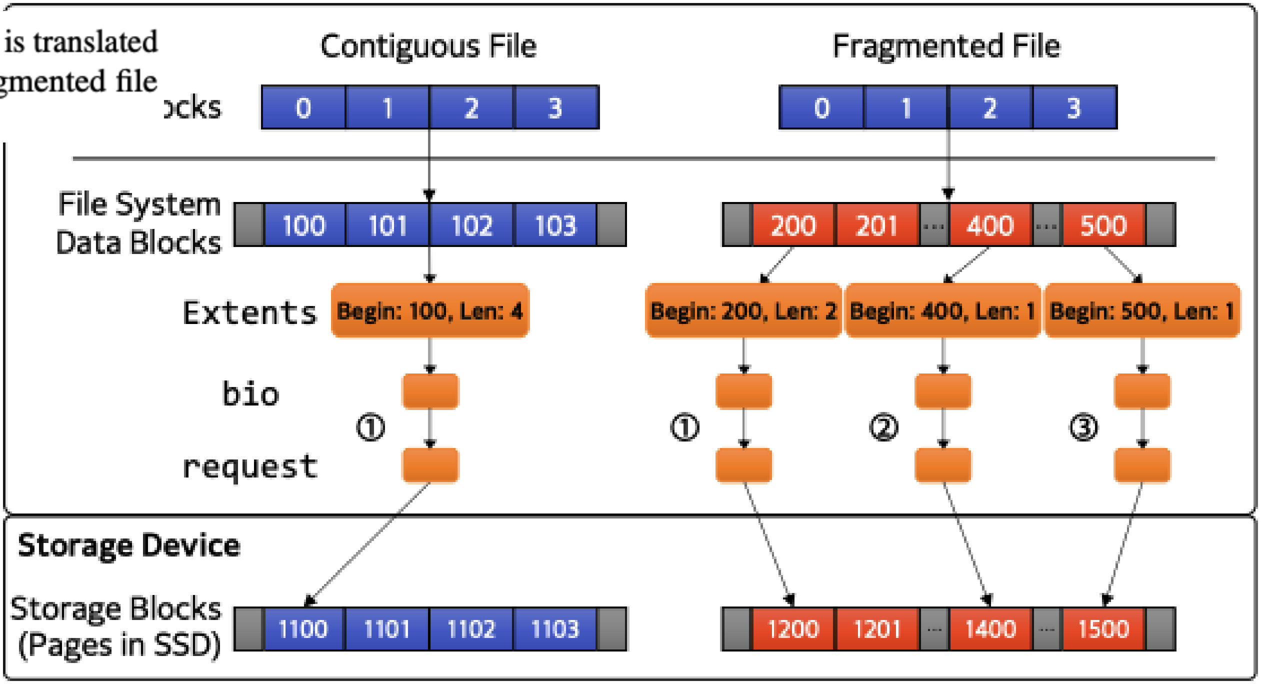
Figure 1: A sequential access to a contiguous file is translated to a single device command while that to a fragmented file ends up with multiple requests.

Kernel I/O path

Storage device interface

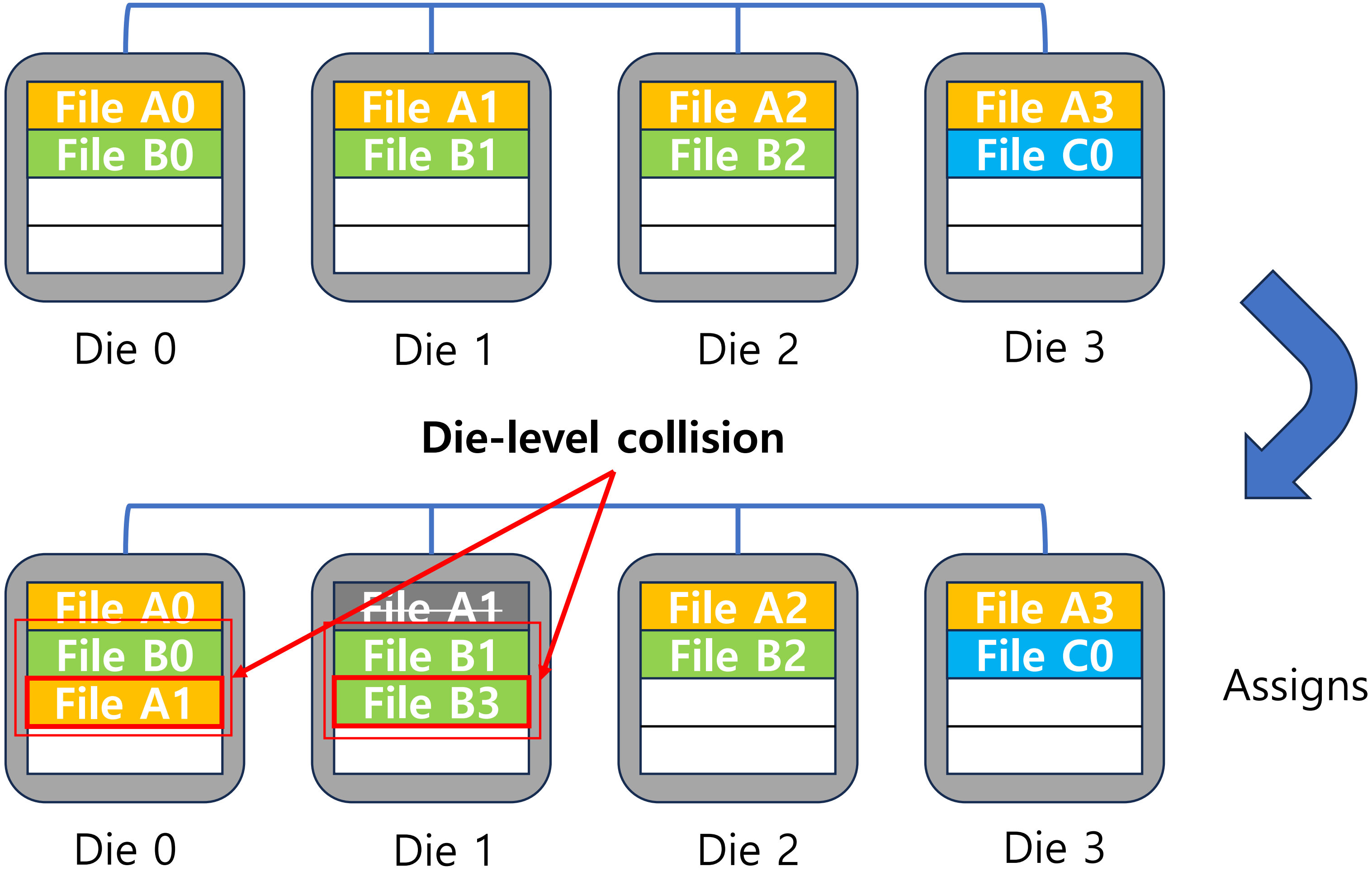
Storage media access



Single I/O operations translated into multiple device commands

Fragmentation in SSD

- **Issue**



- File A Overwrite <A1>
- File B Append <B3>

Assigns in **round-robin manner**

Fragmentation in SSD

- **Reason why?**

→ **Die Level Collisions!**

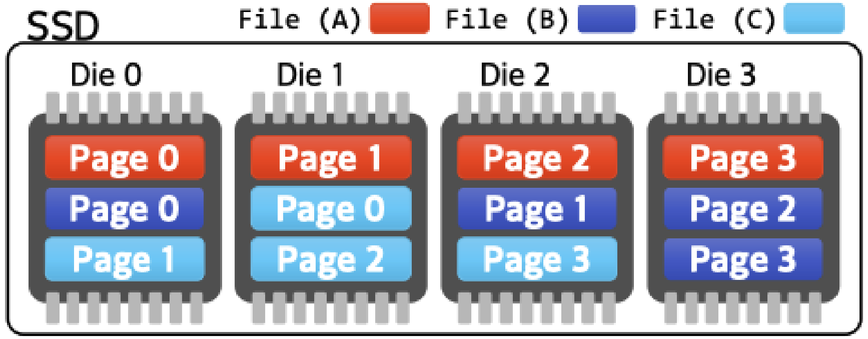
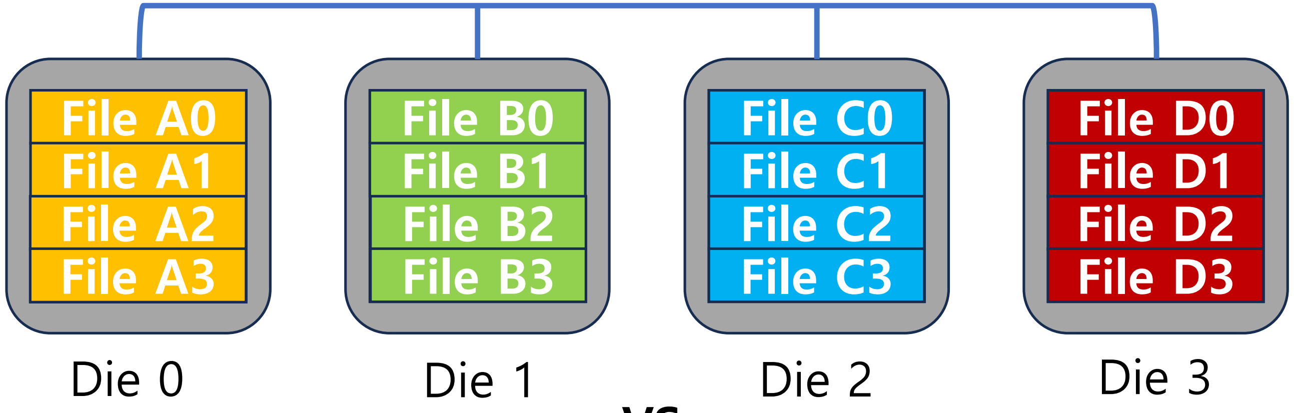


Figure 2: Data placement of three files in a flash SSD where one is contiguous and the other two are fragmented.

→ Die can only process one request at a time



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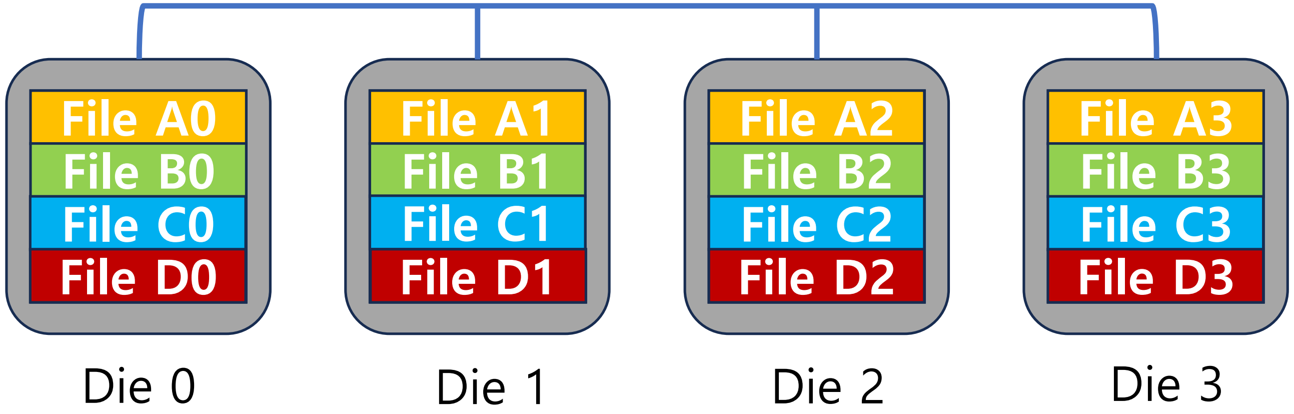
File A2	File B2	File C2	File D2
File A3	File B3	File C3	File D3

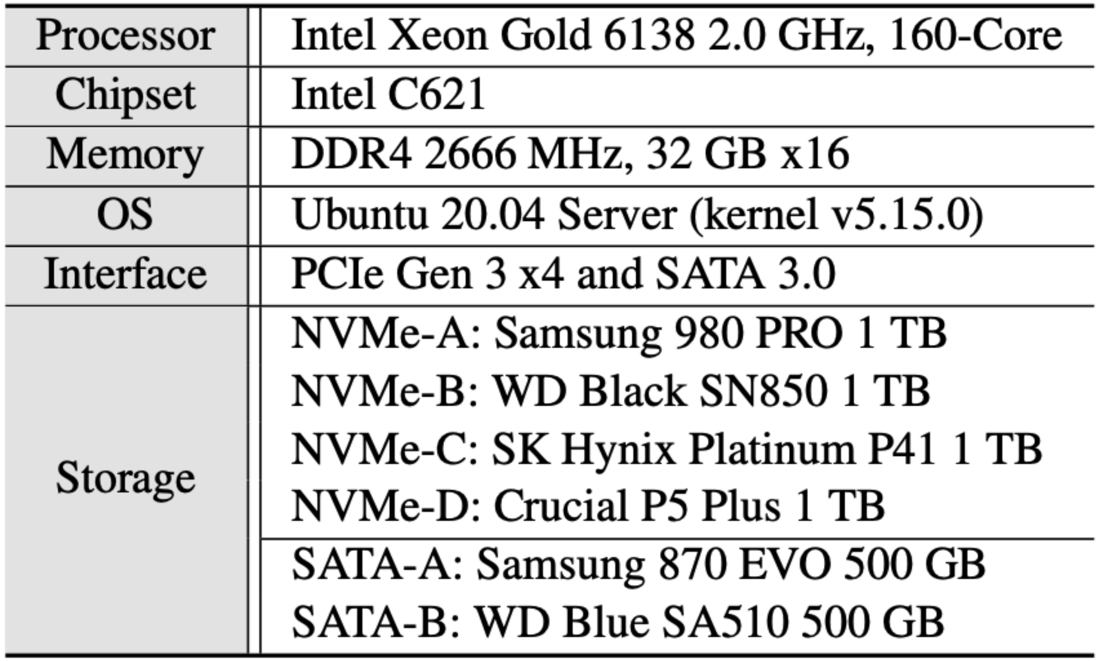
vs.



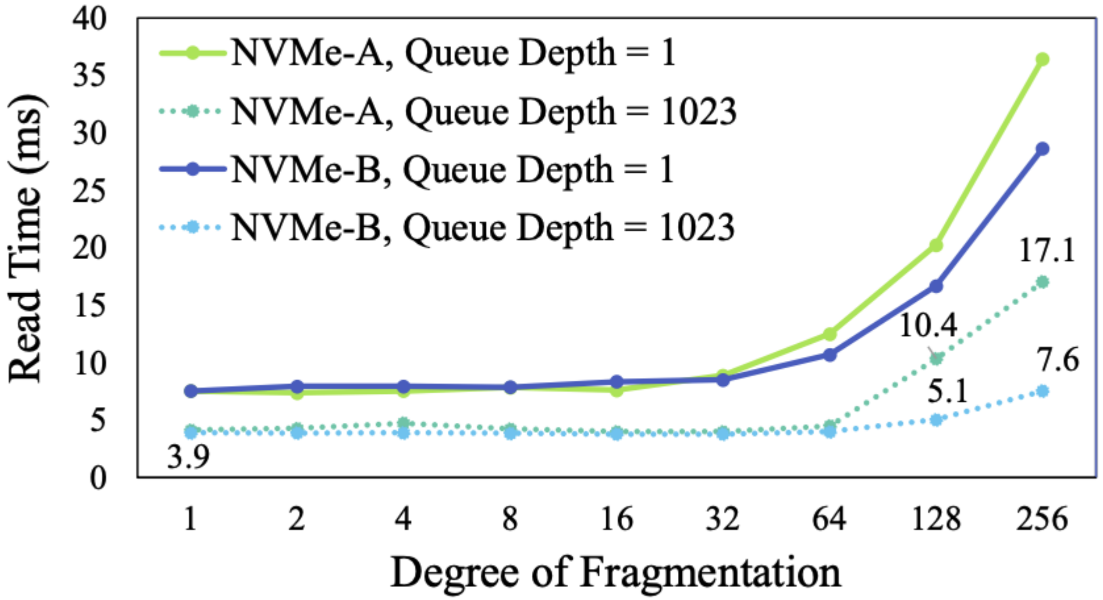
Die 0	Die 1	Die 2	Die 3
File A0	File A1	File A2	File A3
File B0	File B1	File B2	File B3
File C0	File C1	File C2	File C3
File D0	File D1	File D2	File D3

Analysis of File Fragmentation

Table 1: System configurations for experiments.



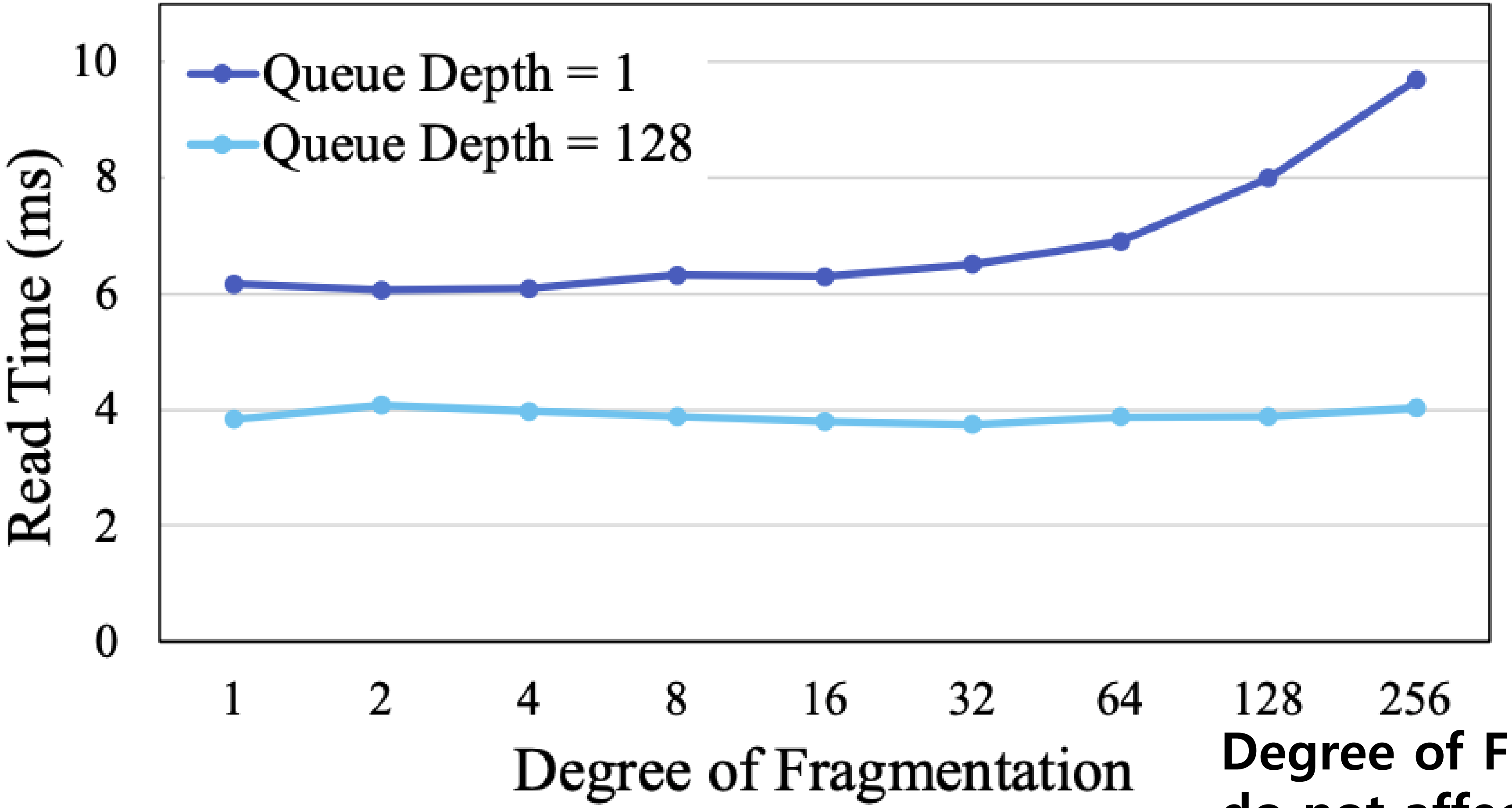
Processor	Intel Xeon Gold 6138 2.0 GHz, 160-Core
Chipset	Intel C621
Memory	DDR4 2666 MHz, 32 GB x16
OS	Ubuntu 20.04 Server (kernel v5.15.0)
Interface	PCIe Gen 3 x4 and SATA 3.0
Storage	NVMe-A: Samsung 980 PRO 1 TB NVMe-B: WD Black SN850 1 TB NVMe-C: SK Hynix Platinum P41 1 TB NVMe-D: Crucial P5 Plus 1 TB
	SATA-A: Samsung 870 EVO 500 GB SATA-B: WD Blue SA510 500 GB



Degree of Fragmentation causes performance degradation.

Analysis of File Fragmentation

- **RAMDisk**



Degree of Fragmentation
do not affect to read time in ramdisk

→ No impact from request splitting

Analysis of File Fragmentation

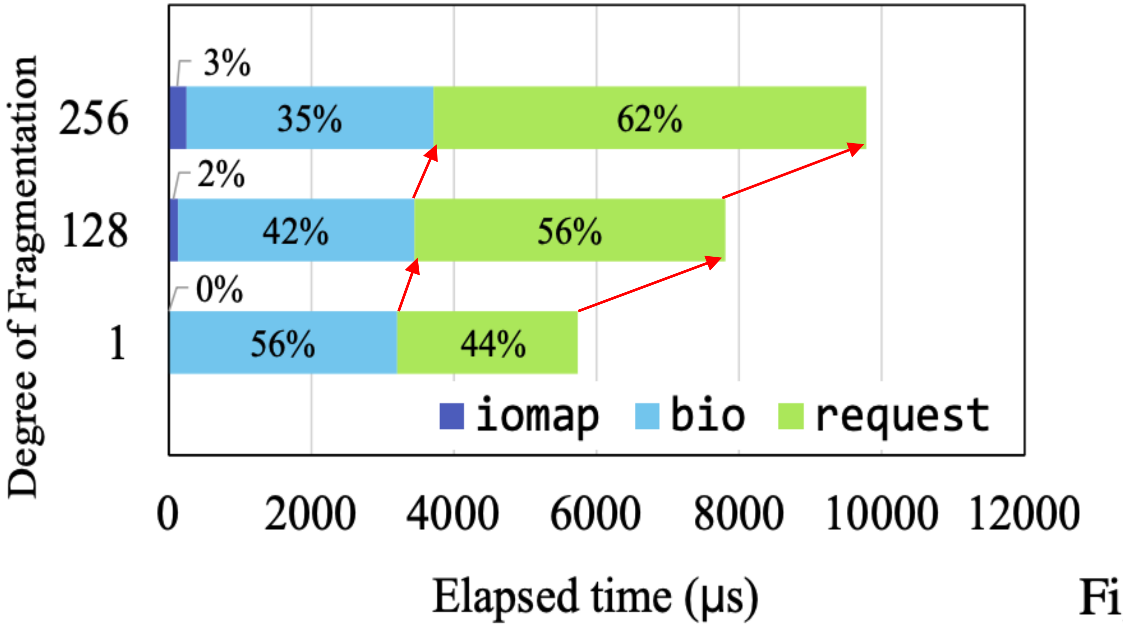


Figure 5: Time composition for creating request data structures in the kernel I/O path depending on File's DoF.

Request time increased proportionally
With the increase in the
Degree of Fragmentation(DoF)

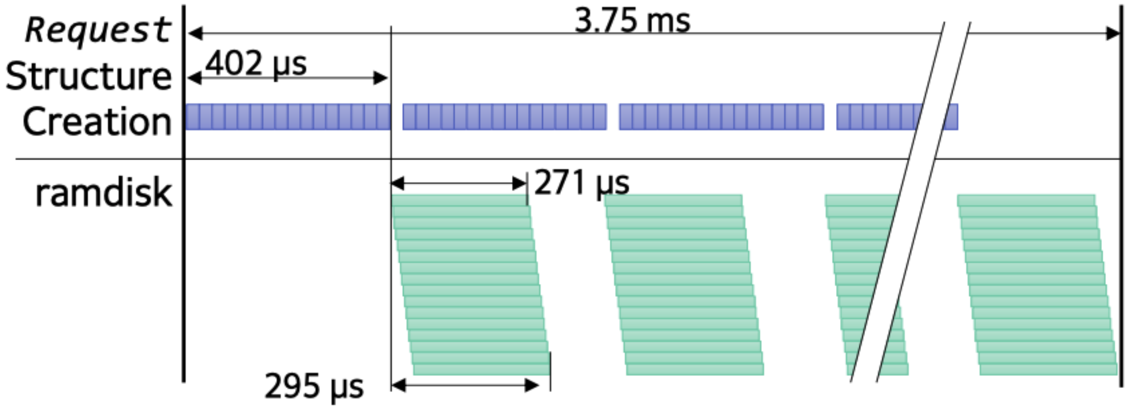
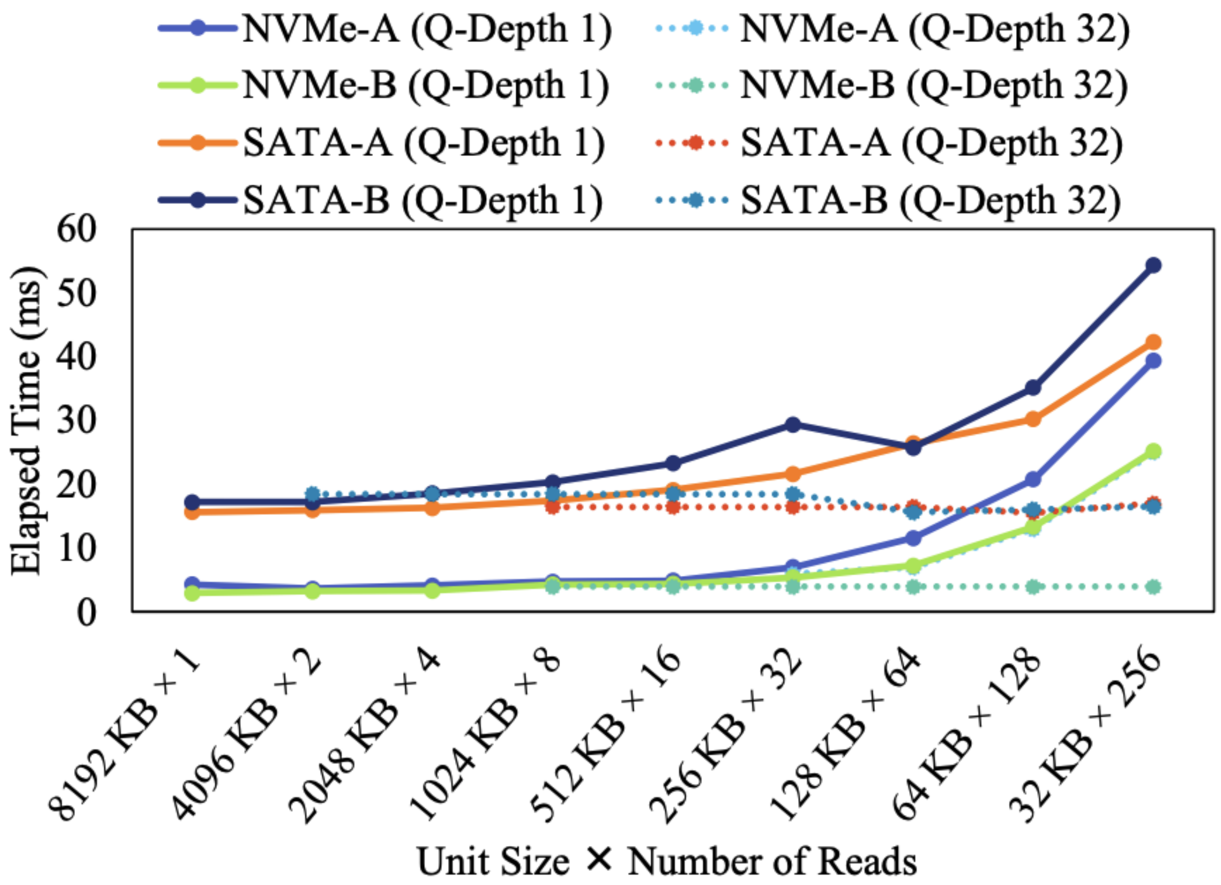


Figure 6: Reduction of read time due to the overlap of storage operations and `request` creation when File's DoF is 128.

"Kernel I/O path can be masked by I/O queueing"

Analysis of File Fragmentation



Result

→Request splitting overhead in the kernel I/O path is negligible

→ Request splitting overhead is mitigated when issuing I/O operations asynchronously through command queueing

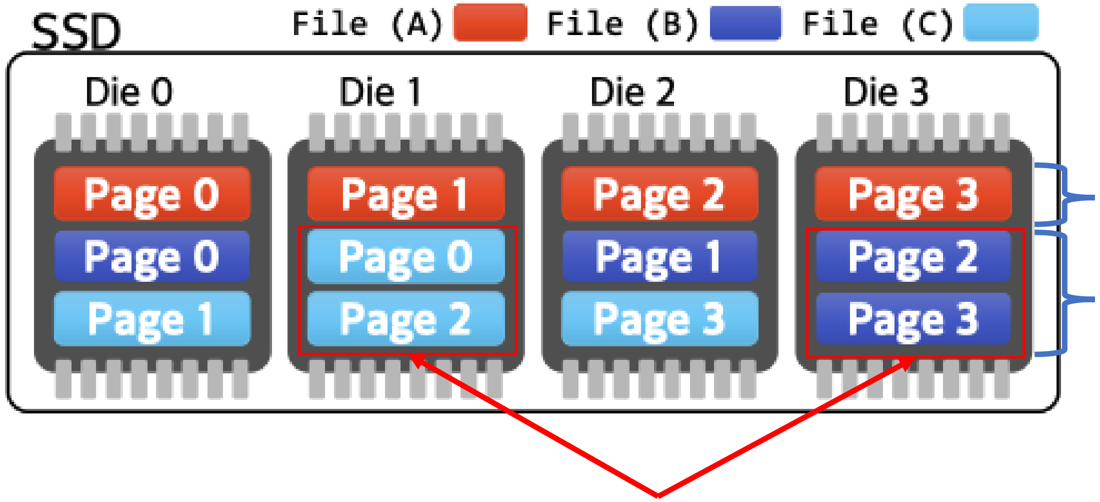
Analysis of File Fragmentation

- **Page misalignment**

time

Write sequence: A A A A B C B B C C C B

Write in round-robin manner



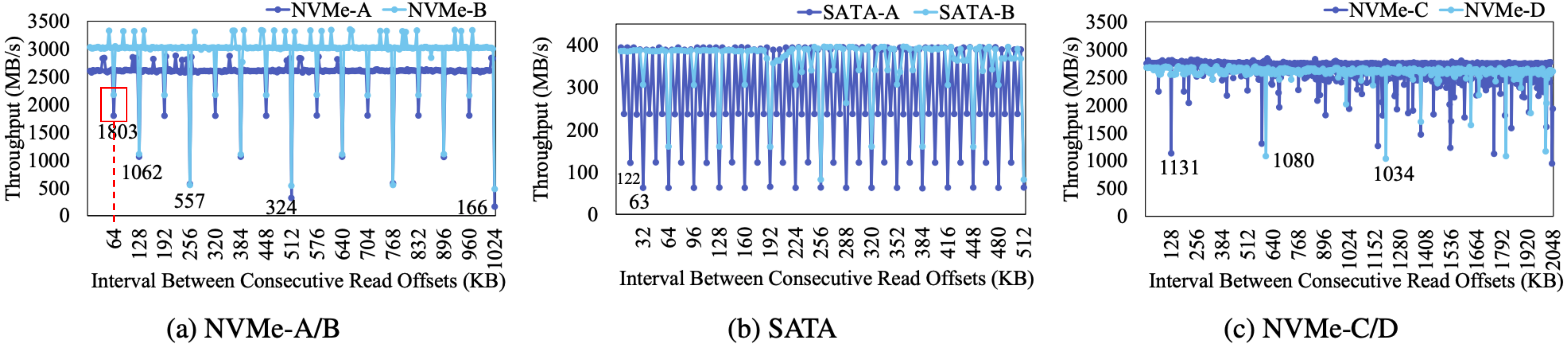
File A: up to 4x more bandwidth than single die

File B and C: 2x slower than File A

Die-level collision

Analysis of File Fragmentation

- **Page misalignment**



(a) NVMe-A/B

(b) SATA

(c) NVMe-C/D

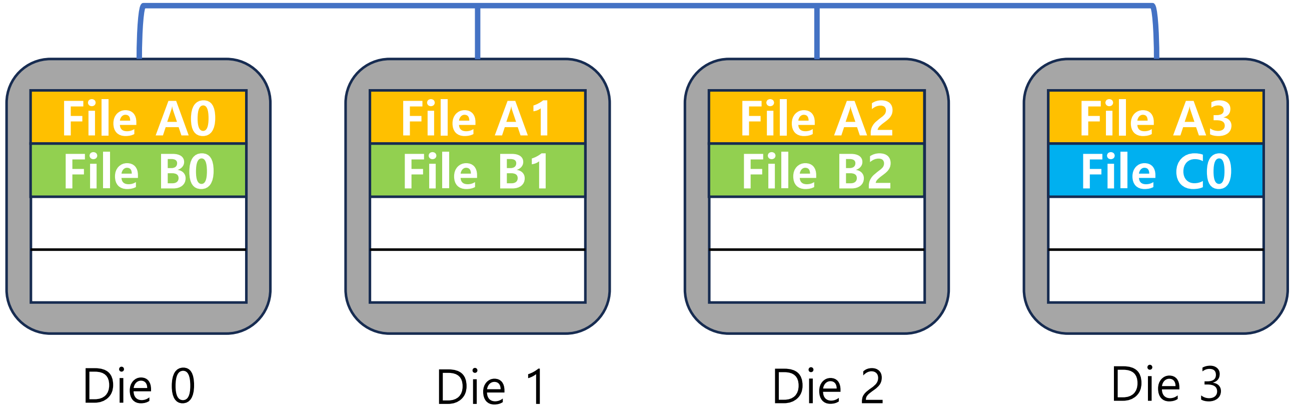
Figure 8: Throughput while varying the interval between starting points of consecutive read operations.

(a) Both NVMe SSD's page size is 16KB -> Allocates 2 pages per die

In SSD, file fragmentation leads to additional die-level collisions

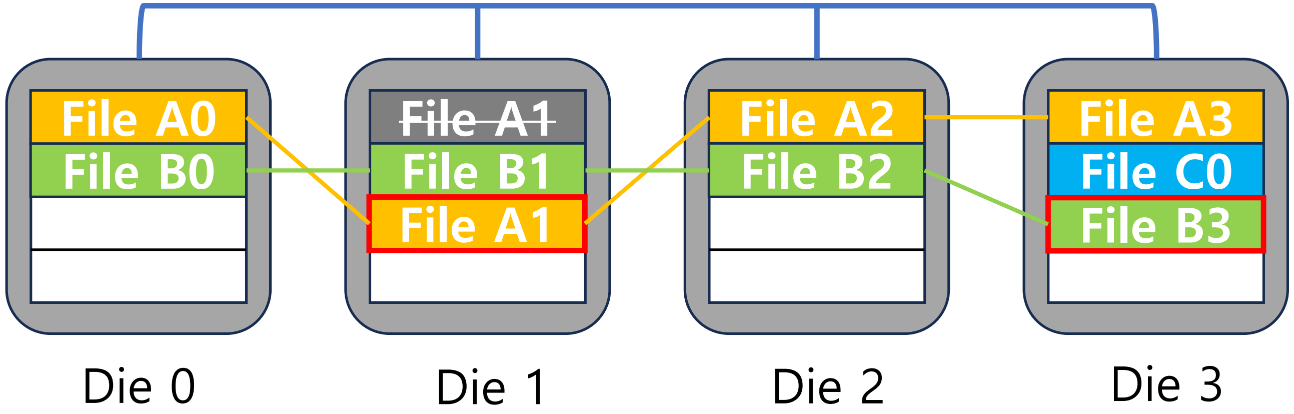
Approach

- **Using the given approach**



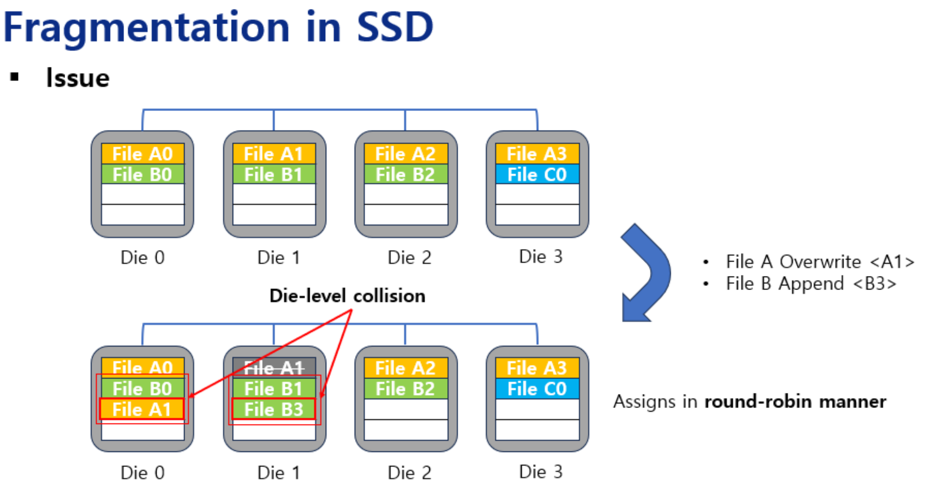
- File A Overwrite <A1>
- File B Append <B3>

Locate in same die



Good parallelism!

Locate in subsequent die



Fragmentation in SSD

- **Issue**

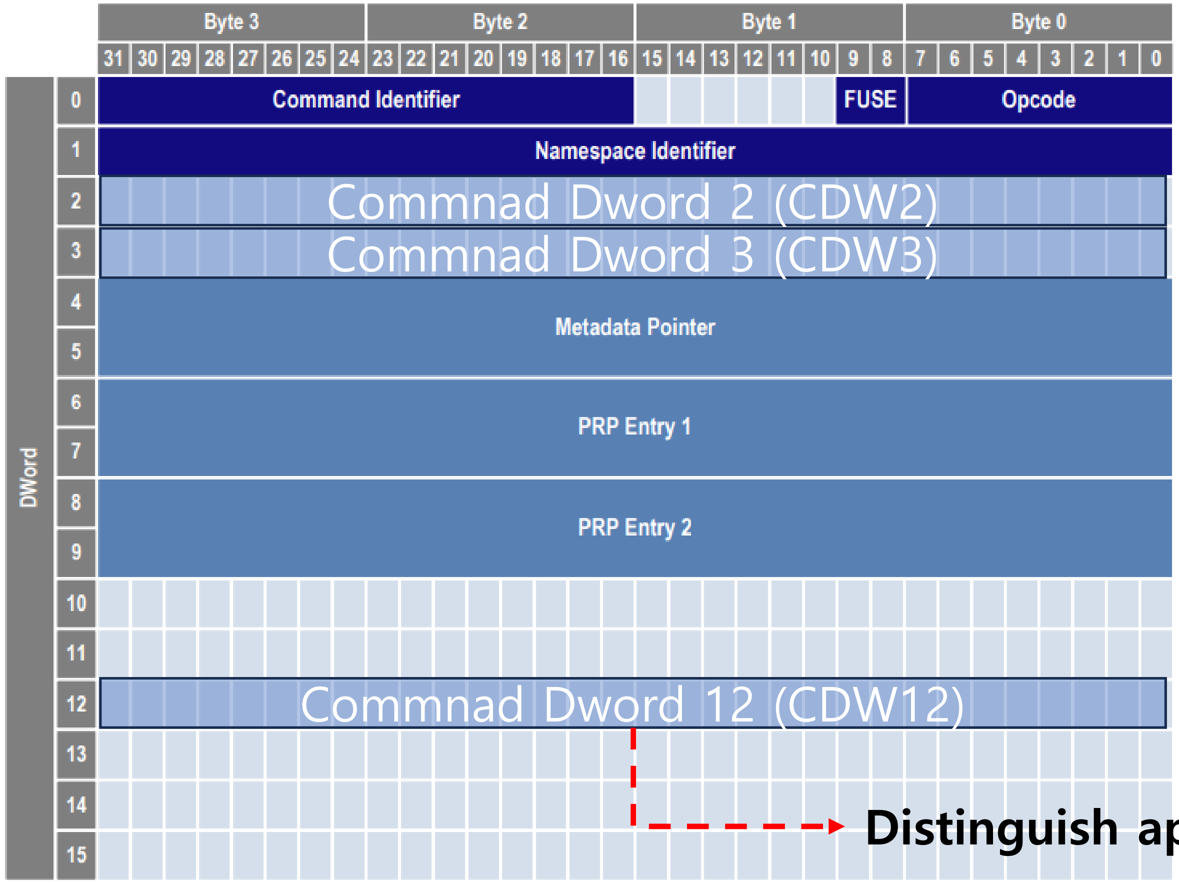
- File A Overwrite <A1>
- File B Append <B3>

Assigns in **round-robin manner**

Approach

- **Uses NVMe protocol's write command**

Submission Queue Entry (64B)



DWord	Byte 3	Byte 2	Byte 1	Byte 0
	31 30 29 28 27 26 25 24	23 22 21 20 19 18 17 16	15 14 13 12 11 10 9 8	7 6 5 4 3 2 1 0
0	Command Identifier		FUSE	Opcode
1	Namespace Identifier			
2	Commnad Dword 2 (CDW2)			
3	Commnad Dword 3 (CDW3)			
4	Metadata Pointer			
5				
6	PRP Entry 1			
7				
8	PRP Entry 2			
9				
10				
11				
12	Commnad Dword 12 (CDW12)			
13				
14				
15				

Convey the LBA of the preceding file block

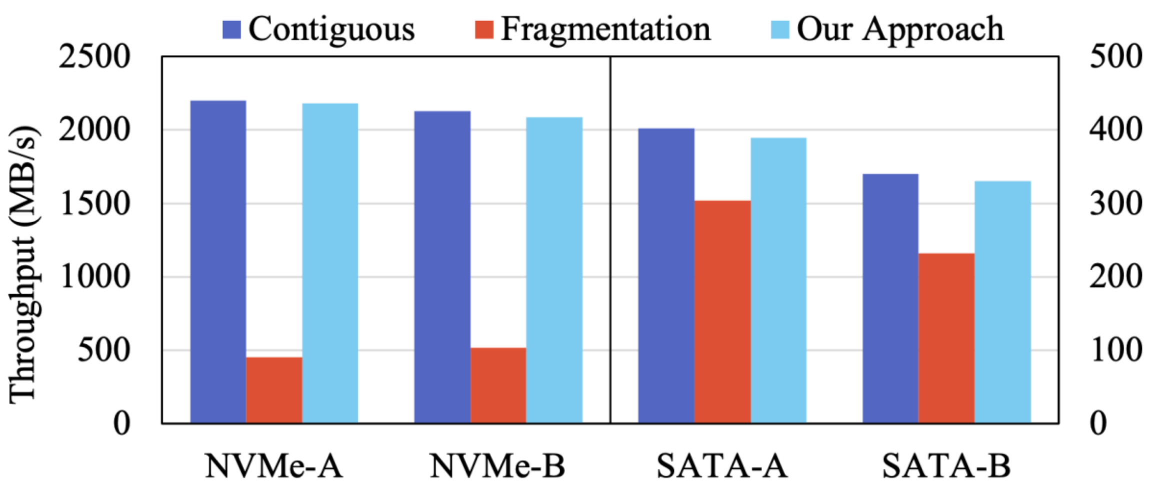
Distinguish append writes and overwrites from conventional writes

Ref: https://files.futurememorystorage.com/proceedings/2012/20120821_TD12_Onufryk.pdf, https://nvmexpress.org/wp-content/uploads/NVM-Express-Base-Specification-Revision-2.1-2024.08.05-Ratified.pdf

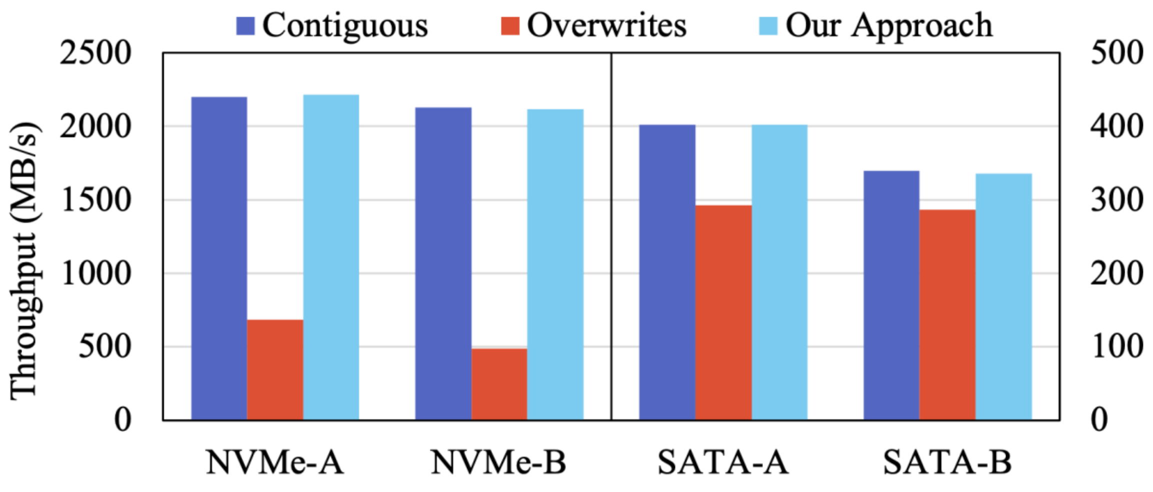
Evaluation

- Modified write patterns
- Showing read throughput

- Form a file by append 256 segments
- Each segement size
  → SSD's die allocation granularity
- Total file size = 8MB



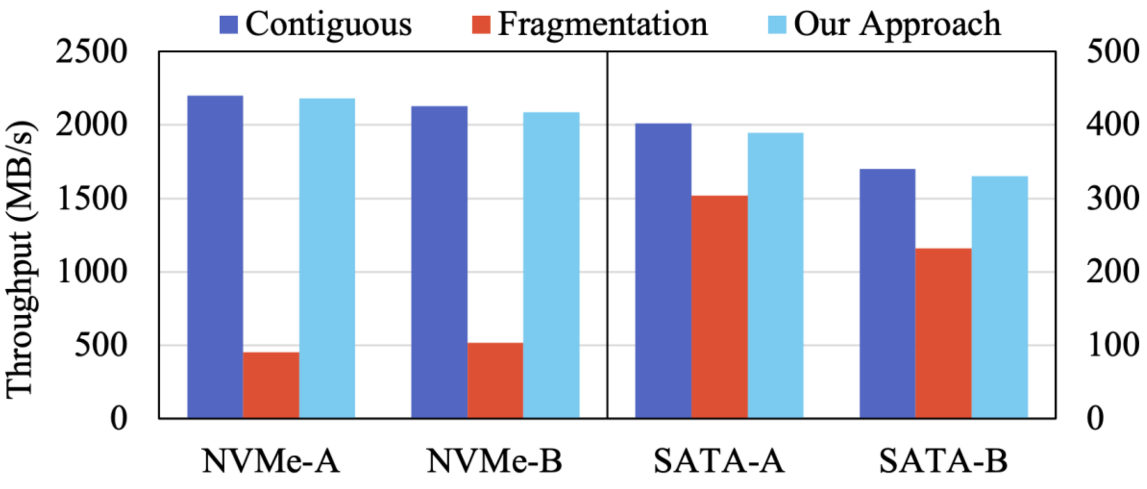
(a) Append Write



(b) Overwrite

Evaluation

- **Why does SATA SSDs performance degradation is less severe than NVMe?**
  - SATA3 Maximum throughput = **600MB/s**
  - Smaller die allocation granularities in SATA SSD
  - Adjusted final append's size to fit 8MB
  - So only the initial segment of the file became fragmenated in SATA SSD



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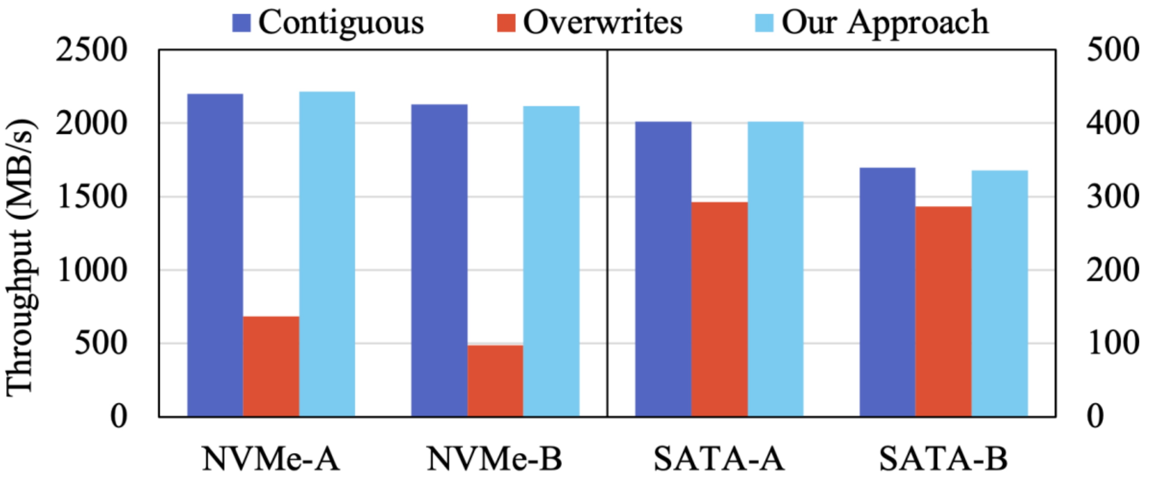
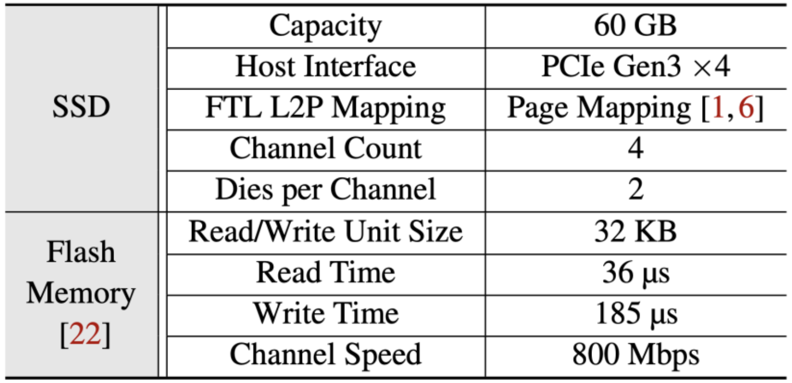


(b) Overwrite

Evaluation

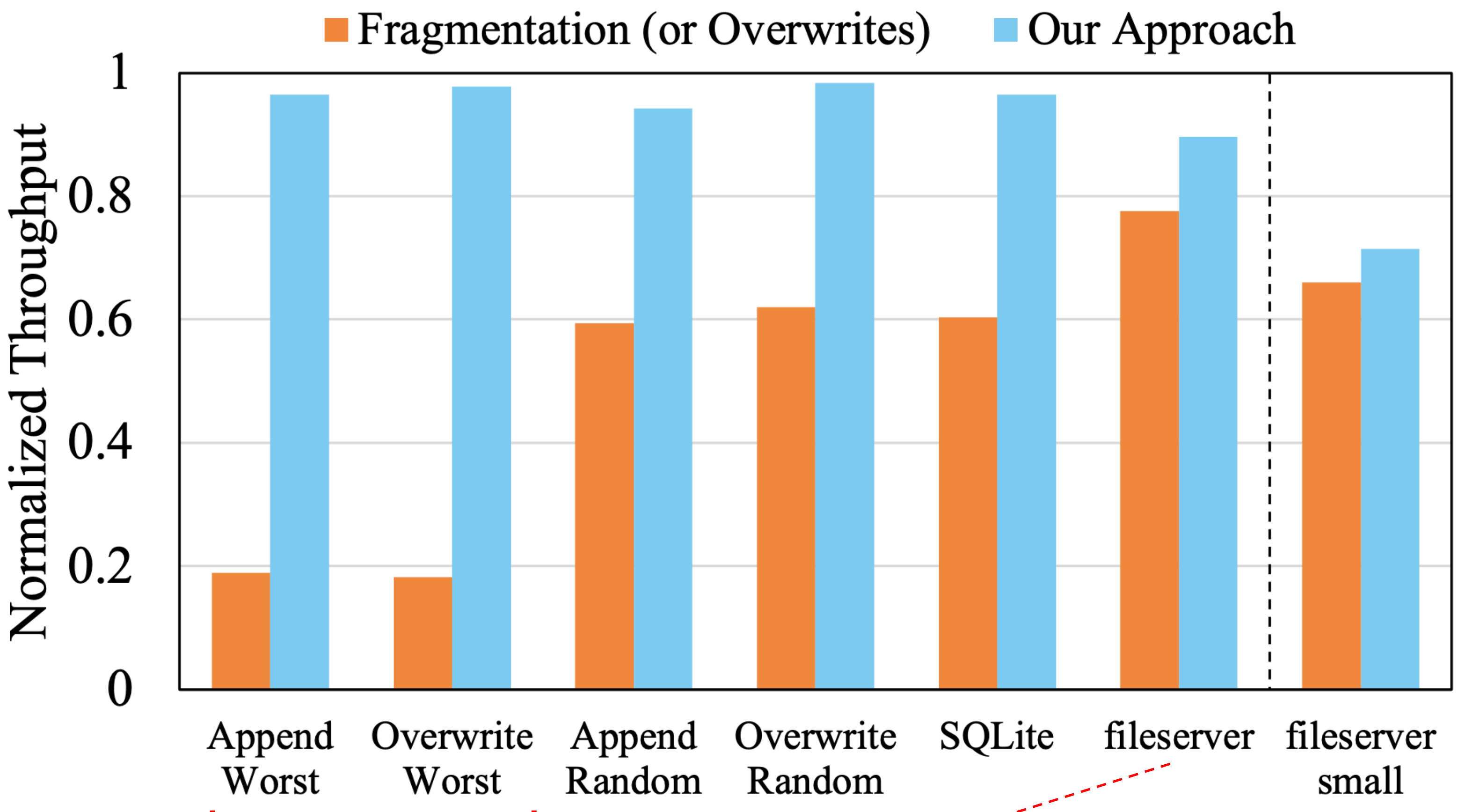
- **NVMeVirt**

Table 2: Parameters used for NVMe emulation.



SSD	Capacity	60 GB
	Host Interface	PCIe Gen3 ×4
	FTL L2P Mapping	Page Mapping [1,6]
	Channel Count	4
	Dies per Channel	2
Flash Memory [22]	Read/Write Unit Size	32 KB
	Read Time	36 µs
	Write Time	185 µs
	Channel Speed	800 Mbps

Mirrors the settings of NVMe-B



10 threads, 32KB size append writes

Worst case: located in single die

Reduced to 16KB

Conclusion

- File fragmentation can indeed declines in read performance in SSD
  - Because of die-level collisions rather than request splitting
  - Misalignments also happens when files are overwritten
- Proposed NVMe command extension for better die-level parallelism
  - Provide hints to SSD -> prevent additional die-level collisions caused by both file fragmentation and overwrites
  - Effectively suppresses the read performance degradation

Thank You !

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