FLIN: Enabling Fairness and Enhancing Performance in Modern NVMe Solid State Drives

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Modern solid-state drives (SSDs) use new storage protocols (e.g., NVMe) that eliminate the OS software stack
- I/O requests are now scheduled inside the SSD
- Enables high throughput: millions of IOPS

OS software stack elimination removes existing fairness mechanisms
- We experimentally characterize fairness on four real state-of-the-art SSDs
- Highly unfair slowdowns: large difference across concurrently-running applications

We find and analyse four sources of inter-application interference that lead to slowdowns in state-of-the-art SSDs

FLIN: a new I/O request scheduler for modern SSDs designed to provide both fairness and high performance
- Mitigates all four sources of inter-application interference
- Implemented fully in the SSD controller firmware, uses < 0.06% of DRAM space
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- Background: Modern SSD design
- Sources of unfairness in modern solid state drives
- FLIN: Flash Level Interference-aware scheduler
- Experimental Evaluation

- Strengths and Weaknesses
- Related work
- Open discussion
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Internal Components of a Modern SSD

- **Back end: Storage**
  - Flash chips

- **Front end: Control**
  - Host Interface Logic (**HIL**)  
    - Communicates with host
  - Flash Translation Layer (**FTL**)  
    - Manages resources
    - Processes I/O
  - Flash Channel Controllers (**FCC**)  
    - Direct access to back end
SSDs adopted conventional host interface protocols
- Designed for magnetic drives
- OS Software Stack handles requests
- Limited to thousands of I/O requests
Modern SSDs use **high performance** host interface protocols.

Bypasses OS, **SSDs** handle requests directly.

- Very **high throughput**
- Fairness implemented through software stack is lost.
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Measuring (Un)fairness

- **Flow:**
  - A series of I/O requests generated by an application

- **Slowdown:**
  \[ \text{Slowdown} = \frac{\text{Shared response time}}{\text{Non-shared response time}} \]

- **Unfairness:**
  \[ \text{Unfairness} = \frac{\text{Max Slowdown}}{\text{Min Slowdown}} \]

- **Fairness**
  \[ \text{Fairness} = \frac{1}{\text{Unfairness}} \]
Representative Example

![Graph showing slowdown and fairness over time](image-url)
Causes of Unfairness

- **Interference** among concurrently running flows
- Detailed study of a simulation with MQSim [1]
- Four different sources of interference are uncovered

[1] MQSim is a fast and accurate simulator modeling the performance of modern multi-queue (MQ) SSDs
https://github.com/CMU-SAFARI/MQSim
The I/O intensity of a flow affects the average queue wait time of flash transactions.

The average response time of a low-intensity flow substantially increases due to interference from a high-intensity flow.
Some flows take advantage of **chip level parallelism** in back end

- Leads to low queue time
Other flows have access patterns that **do not exploit patterns**

Flows with **parallelism-friendly access patterns** are **susceptible to interference** from flows whose access patterns do not exploit parallelism
Source 3: Flows With Different R/W Ratios

- Common schedulers prioritize Read operations
- Write transactions have increased wait times

When flows have different read/write ratios, existing schedulers do not effectively provide fairness.
NAND flash memory performs writes out of place
- To be rewritten, memory needs to be erased first
- Erases can only happen on an entire flash block (hundreds of flash pages)
- Pages marked invalid during write

Garbage collection (GC) selects mostly empty blocks, moves remaining data and frees block

High-GC flow: flows with a higher write intensity induce more garbage collection activities

The GC activities of a high-GC flow can unfairly block flash transactions of a low-GC flow
Summary

- Four sources of unfairness
  - Differing intensities
  - Differing request access patterns
  - Differing read/write ratios
  - Differing GC demands

The goal is to design a new I/O scheduler that provides fairness, maximum performance and throughput.
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- Improved I/O request scheduler
- Replaces the transaction scheduling unit
- **Implements fairness while keeping throughput**
- Implemented in the SSD firmware, no hardware modification needed
FLIN: Stage 1
Fairness-aware Queue Insertion

- Separate, per chip read and write queues
- Low intensity flows have priority over high intensity flows
- Requests get reordered to guarantee fairness

I/O Requests from high intensity flows
I/O Requests from low intensity flows

A A A A A A A B A A B B

X X Y Z

I/O Requests from high intensity flows
I/O Requests from low intensity flows
FLIN: Stage 2
Priority-aware Queue Arbitration

- Host can assign **priority level**
- Select one read and one write transaction and deliver to Stage 3
  - **Weighted round-robin** algorithm
  - Higher priority means more transactions
  - No starvation
**FLIN: Stage 3**
Wait-balancing Transaction Selection

- Minimizes interference of differing read/write ratios and GC demands
- Chooses which transaction to dispatch to the FCC
- Instead of prioritizing reads, it prioritizes the one with less estimated proportional wait time \( t_{pw} = \frac{t_{wait}}{t_{process}} \)
- If write is selected, perform GC instead if available free space is smaller than some pre-defined threshold
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Evaluation Methodology

- **Simulation** based on MQSim
  - Protocol: NVMe 1.2 over PCIe 3.0
  - Model SSD: 480 GB size
  - Organization: 8 channels, 2 planes per die, 4096 blocks per plane, 256 pages per block, 8kB page size

- 40 Different model workloads
  - Classified as high or low interference

- 4 Metrics
  - Fairness, maximum slowdown, standard deviation of slowdowns and weighted speedup
Evaluation Baseline

- Sprinkler [Jung et al. HPCA 2014]
  - State-of-the-art high-performance scheduler
- Sprinkler + Fairness [Jung et al. HPCA 2014, Jun et al NVMSA 2015]
  - Sprinkler scheduling algorithm with improved fairness
  - Does not mitigate all sources of interference
FLIN improves fairness by an **average of 70%**, by mitigating all four major sources of interference.
FLIN improves performance by an average of 47%, by making use of idle resources in the SSD and improving the performance of low-interference flows.
Conclusions

- Modern solid-state drives (SSDs) use new storage protocols (e.g., NVMe) that eliminate the OS software stack
  - I/O requests are now scheduled inside the SSD
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- OS software stack elimination removes existing fairness mechanisms
  - We experimentally characterize fairness on four real state-of-the-art SSDs
  - Highly unfair slowdowns: large difference across concurrently-running applications
- We find and analyse four sources of inter-application interference that lead to slowdowns in state-of-the-art SSDs
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Strengths

- Solution is fully firmware based
  - Only software of one device needs modification
  - Manufacturers have an incentive to implement FLIN
- Very high fairness and some performance improvement
- Well written paper
  - Good background
Weaknesses

- Only a simulation
  - No actual implementation measured
- Model workloads might not be representative of real world scenarios
  - Designed for testing HDDs
Related Work

- Content Popularity-Based Selective Replication for Read Redirection in SSDs
  - Elyasi et al., 2018, MASCOTS
  - Improves performance and fairness by copying stored data

- CARS: A Multi-layer Conflict-Aware Request Scheduler for NVMe SSDs
  - Yang et al., 2019, DATE
  - Similar approach, but focuses on performance rather than fairness
Related Work

- NCQ-Aware I/O Scheduling for Conventional Solid State Drives
  - Fan et al., 2019, IPDPS
  - Native Command Queuing scheduling that is aware of latencies on the host rather than on the device

- An Efficient Hybrid I/O Caching Architecture Using Heterogeneous SSDs
  - Salkhordeh et al., 2019, TPDS
  - Improves throughput and energy efficiency by caching requests more efficiently, using three different layers
Open Discussion

- Can you think of any further improvements?
- Do you think fairness is a good metric?
- Do you think the host should take over more responsibility again?
- Do you think FLIN will be implemented by hardware manufacturers?