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

ISCA 2018

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Executive Summary

- 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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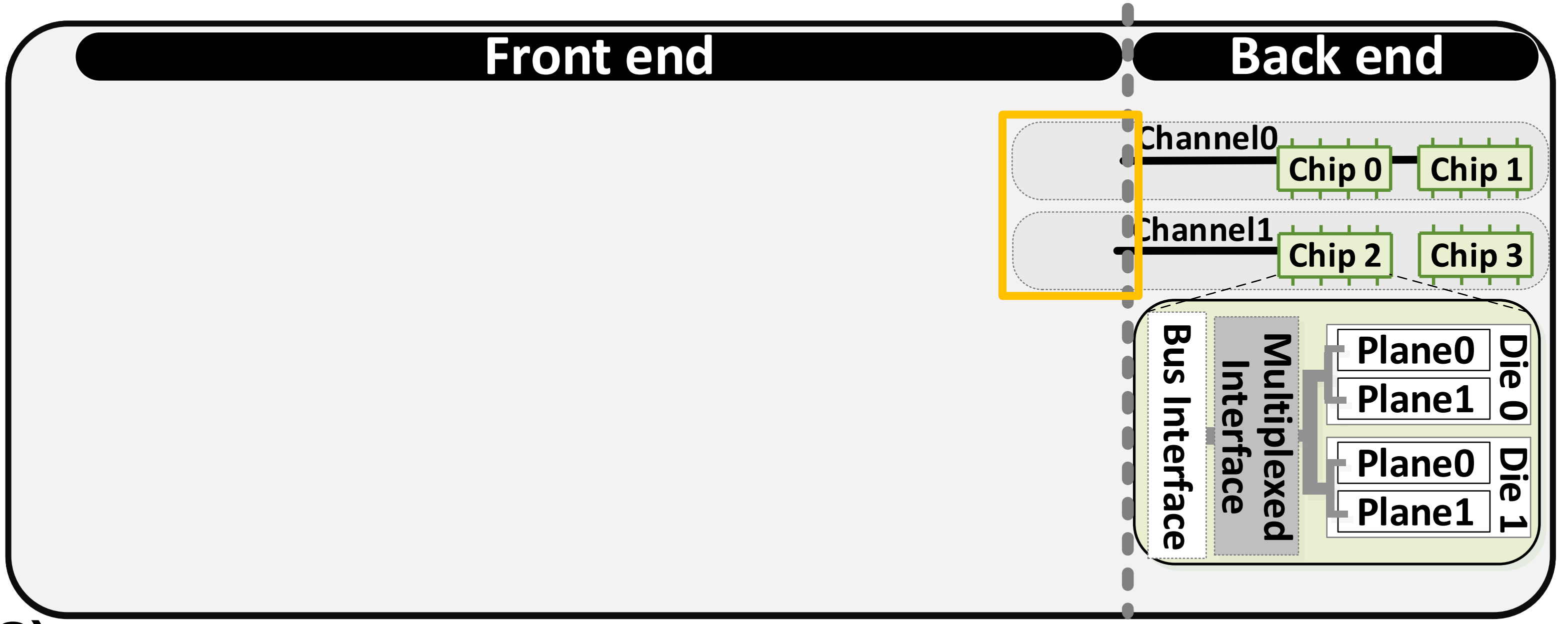
- Background: Modern SSD design
- Sources of unfairness in modern solid state drives
- FLIN: Flash Level Interference-aware scheduler
- Experimental Evaluation

- Strengths and Weaknesses
- Related work
- Open discussion

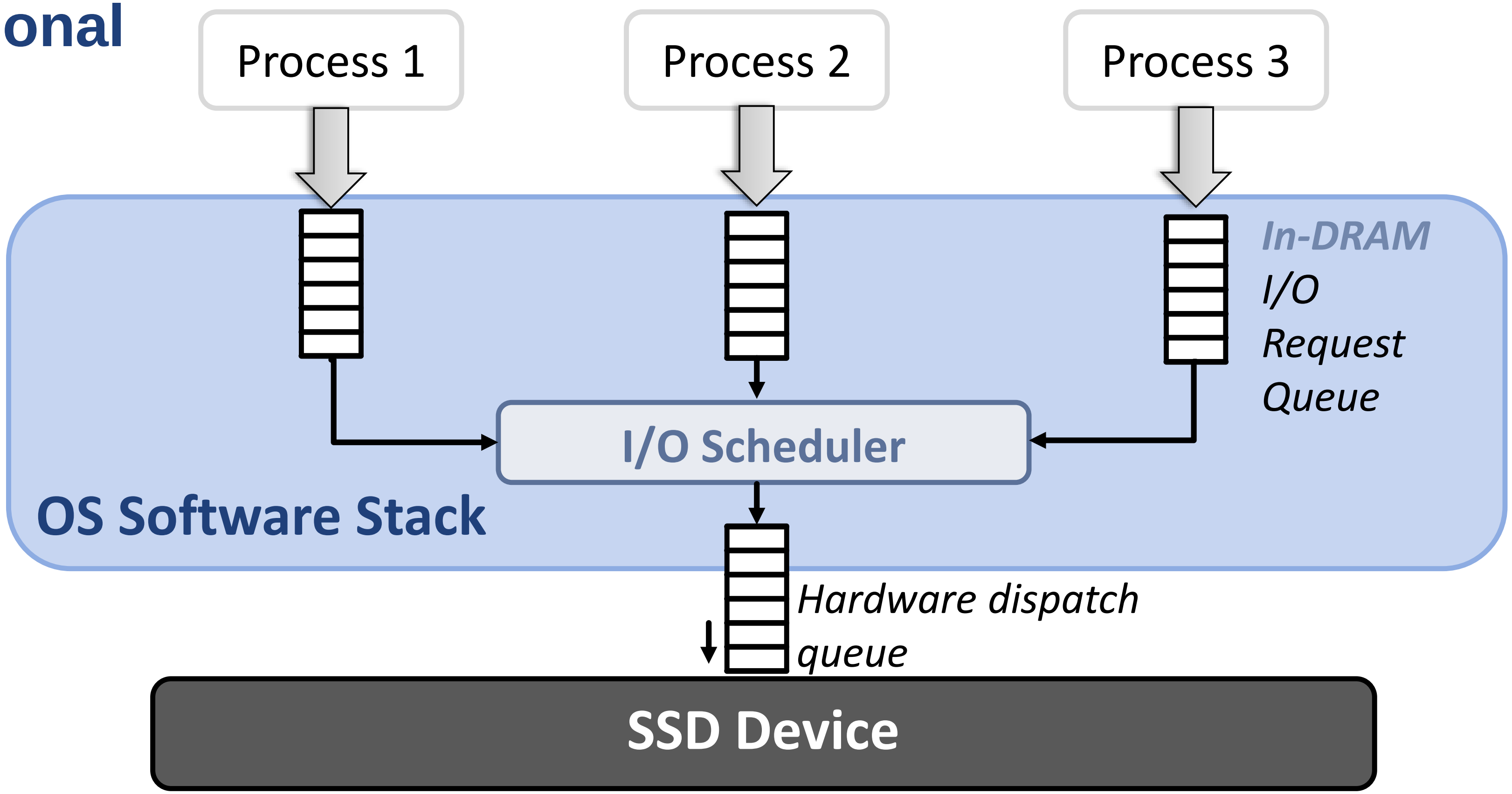
Internal Components of a Modern SSD

- 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



Conventional Host Interface Protocols

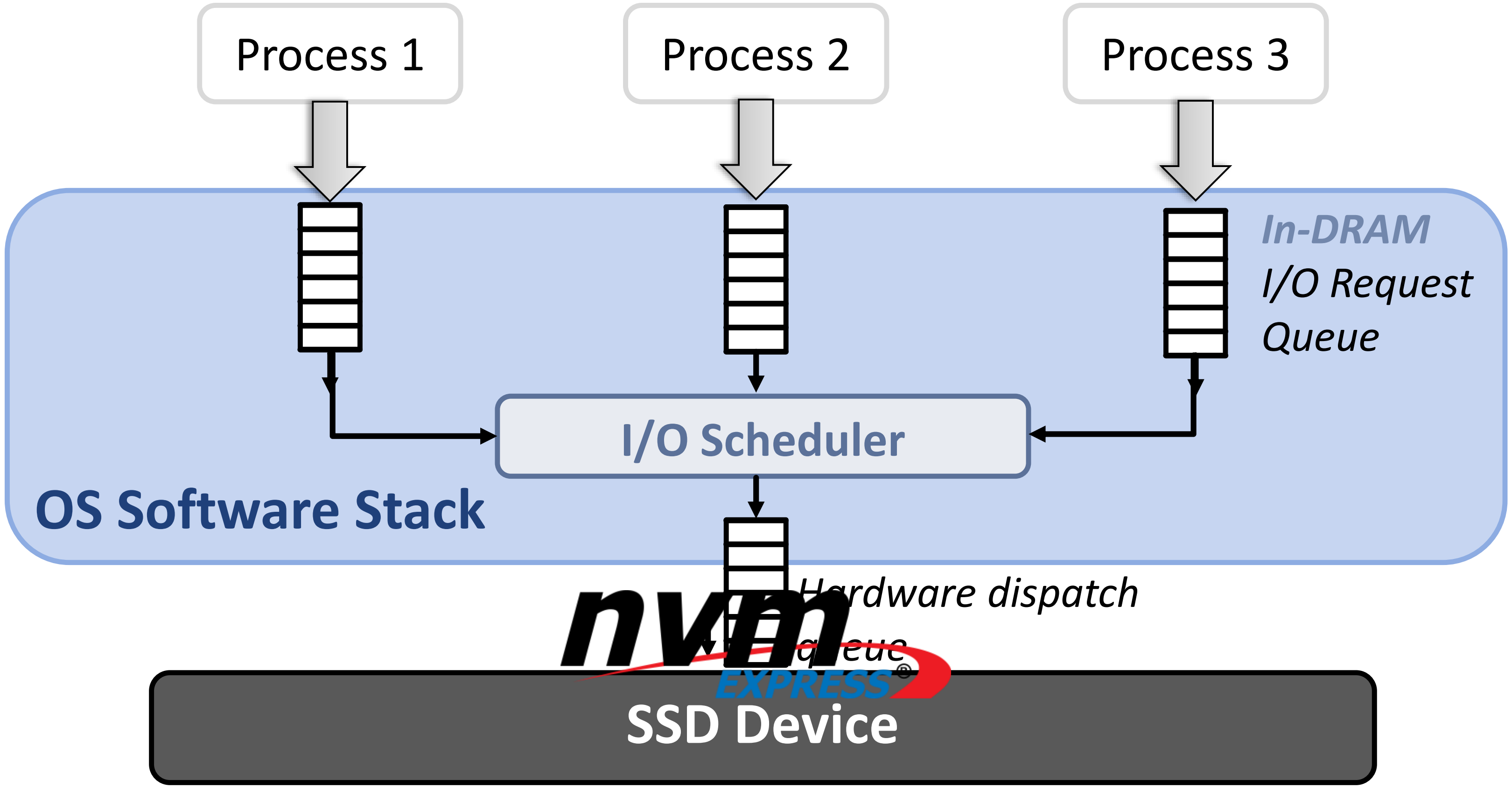
- SSDs adopted **conventional** host interface protocols
  - Designed for magnetic drives
- OS Software Stack handles requests
- Limited to **thousands** of I/O requests



Host Interface Protocols in Modern SSDs

- 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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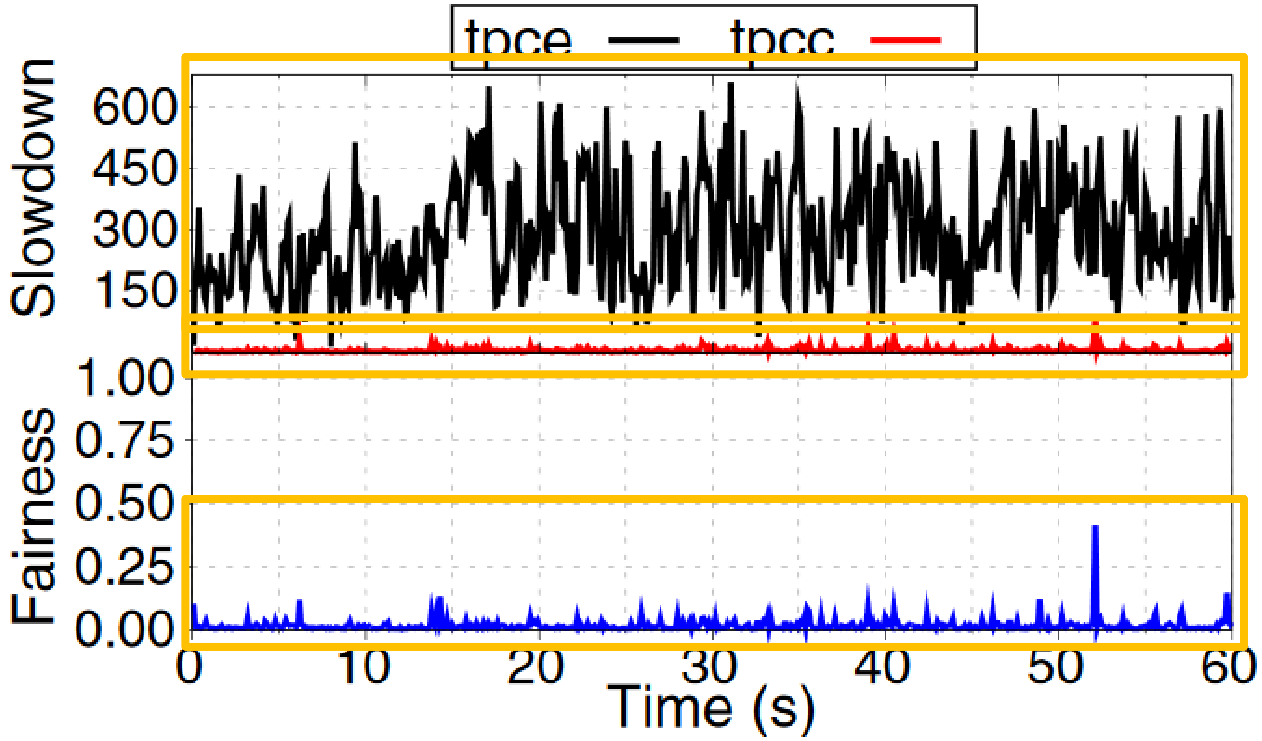
Measuring (Un)fairness

- **Flow**:
  - A series of I/O requests generated by an application
- **Slowdown**:
  - $Slowdown = \frac{Shared\ response\ time}{Non\text{-}shared\ response\ time}$
- **Unfairness**:
  - $Unfairness = \frac{Max\ Slowdown}{Min\ Slowdown}$
- **Fairness**
  - $Fairness = \frac{1}{Unfairness}$

Representative Example



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

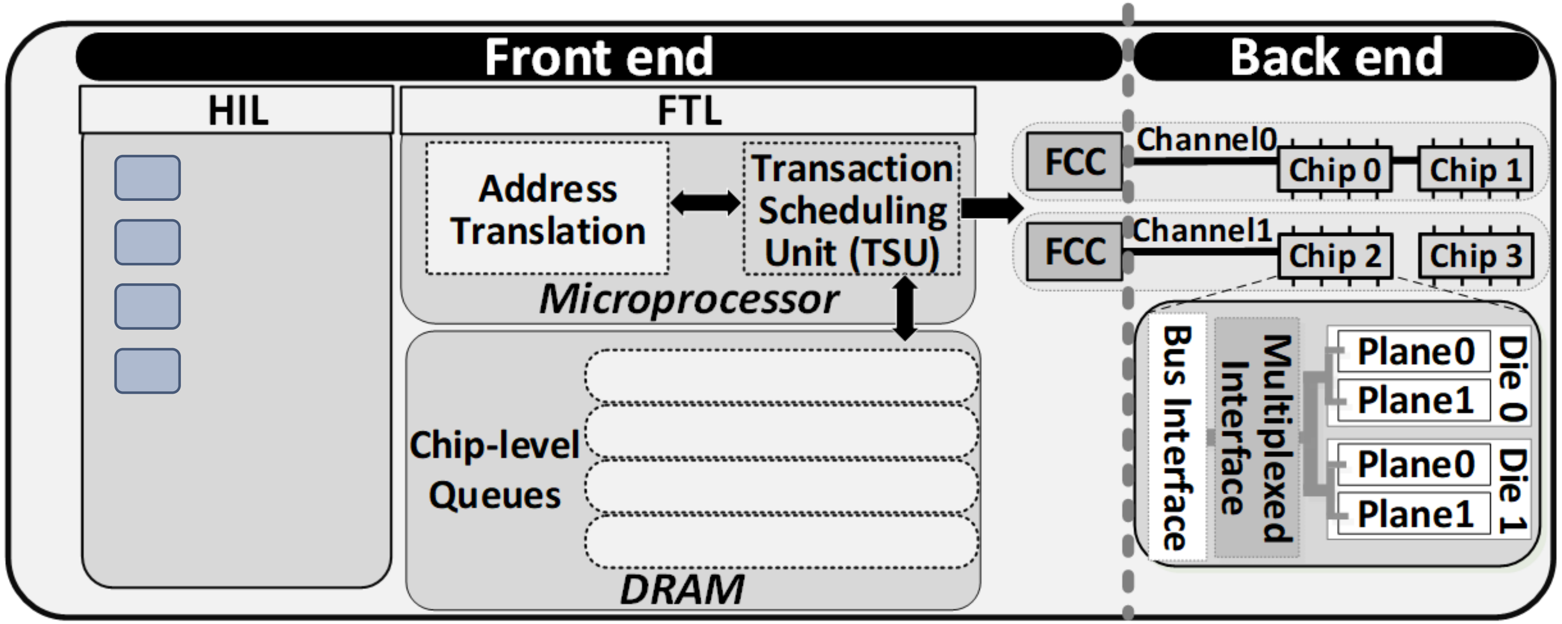
Source 1: Flows With Different I/O Intensities

- 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

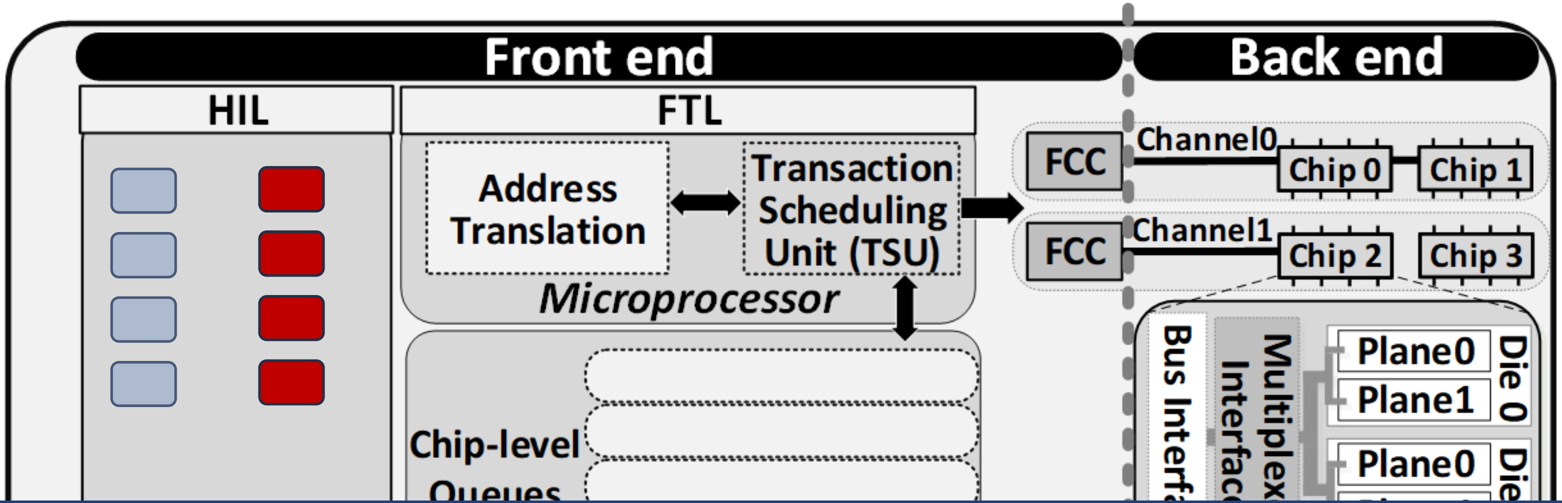
Source 2: Different Request Access Patterns

- Some flows take advantage of **chip level parallelism** in back end
- Leads to low queue time



Source 2: Different Request Access Patterns

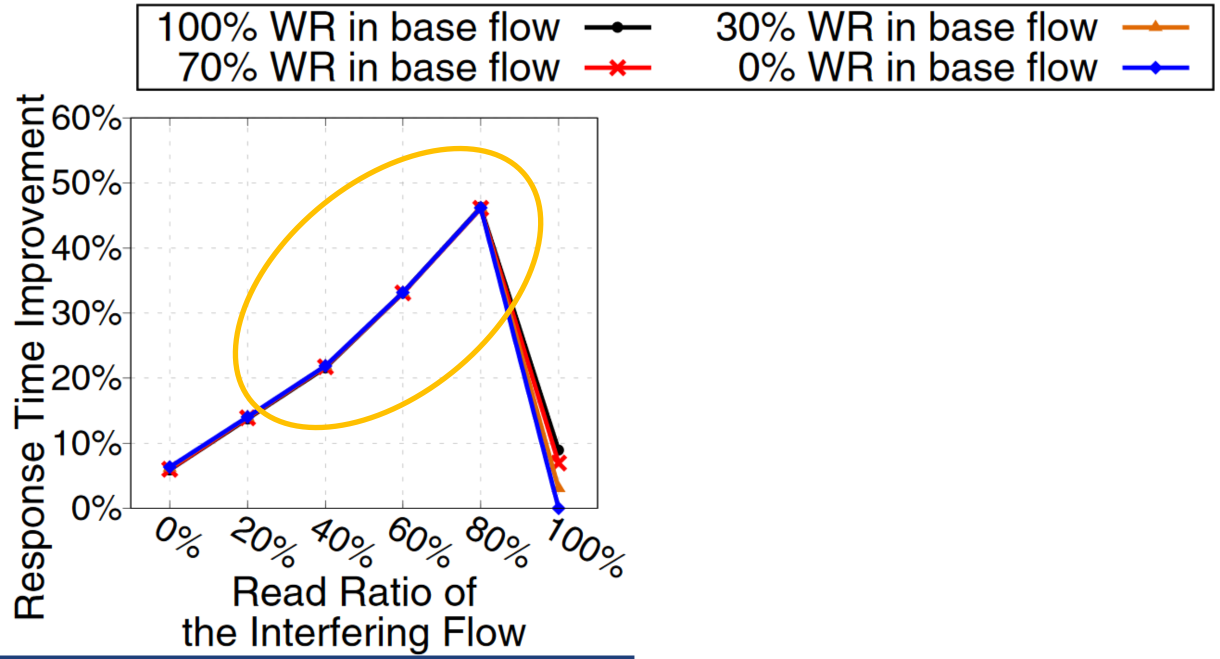
- Other flows have access patterns that **do not exploit patterns**



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 r**
existing schedulers do not effectively provid

Source 4: Different Garbage Collection Demands

- 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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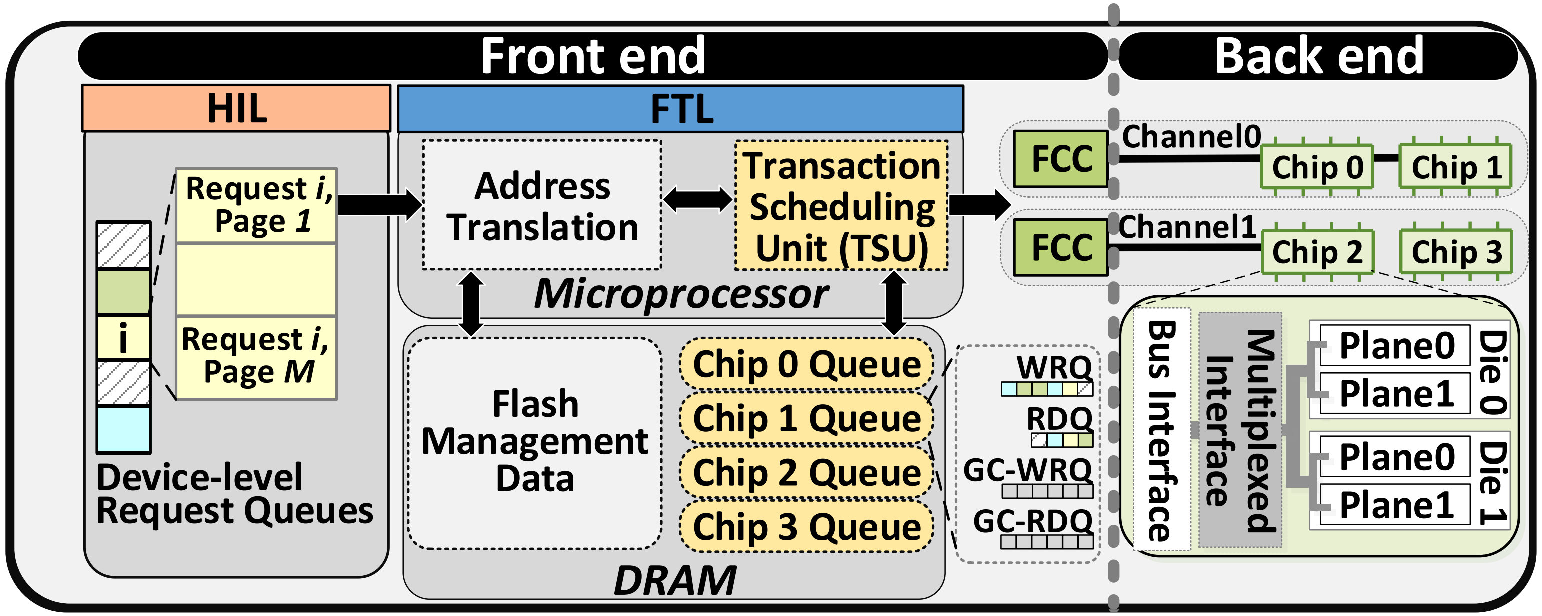
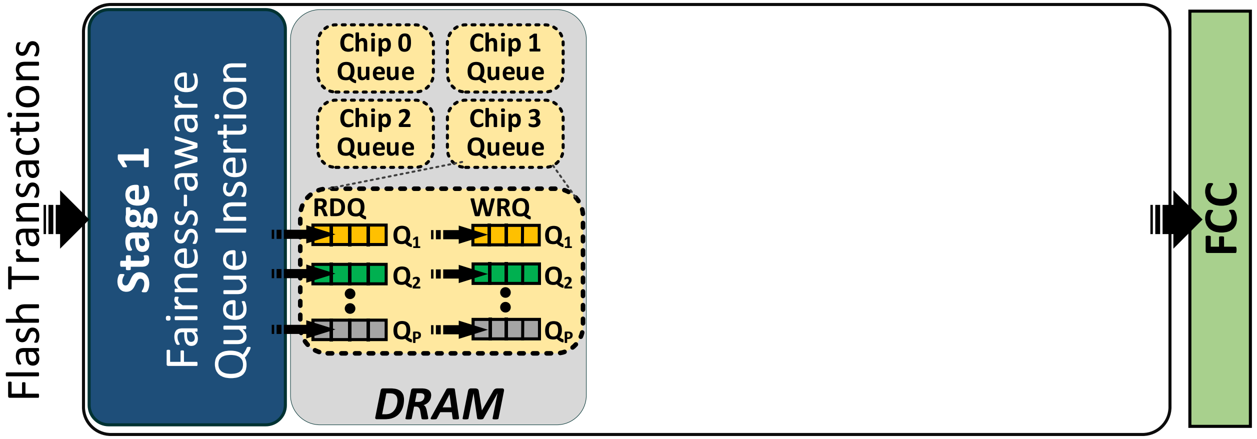
FLIN: Flash Level Interference Aware Scheduler

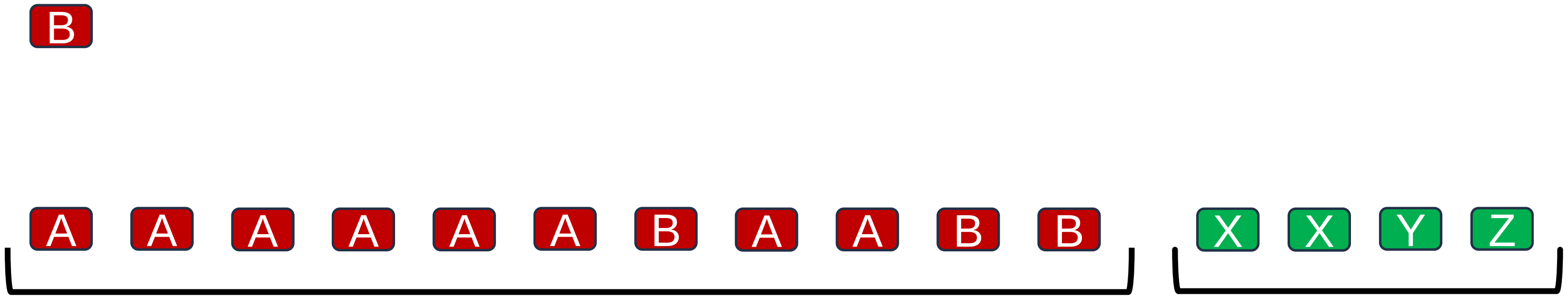
- Improved I/O request scheduler
- Replaces the transaction scheduling unit
- **Improves fairness** while **keeping throughput**
- Implemented in the SSD **firmware**, no hardware modification needed



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

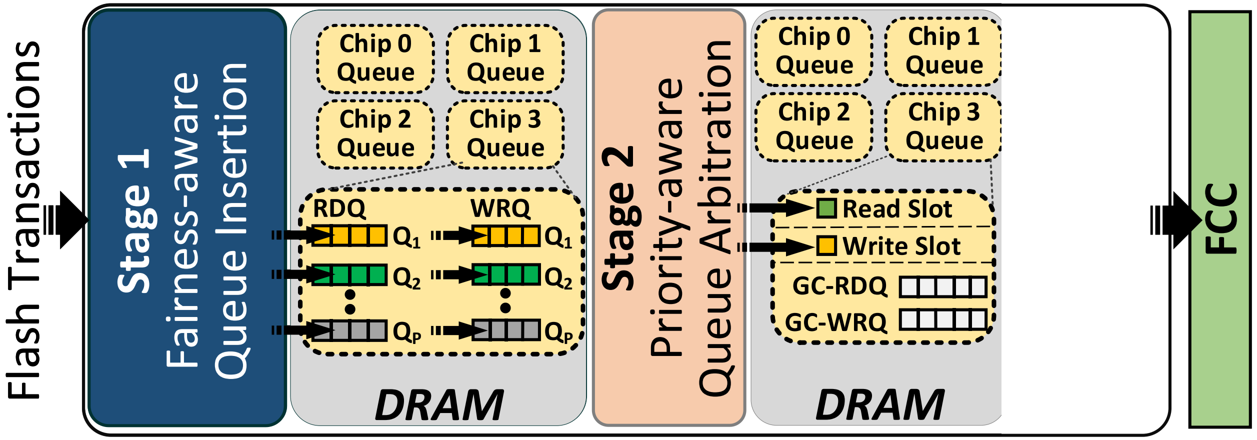


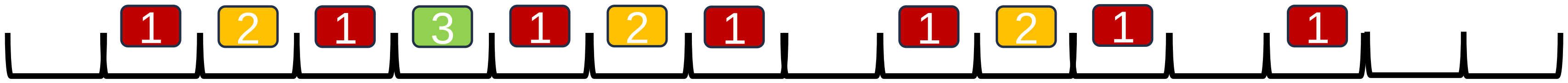


I/O Requests from high intensity flows I/O Requests from low intensity flows

FLIN: Stage 2
Priority-aware Queue Arbitration

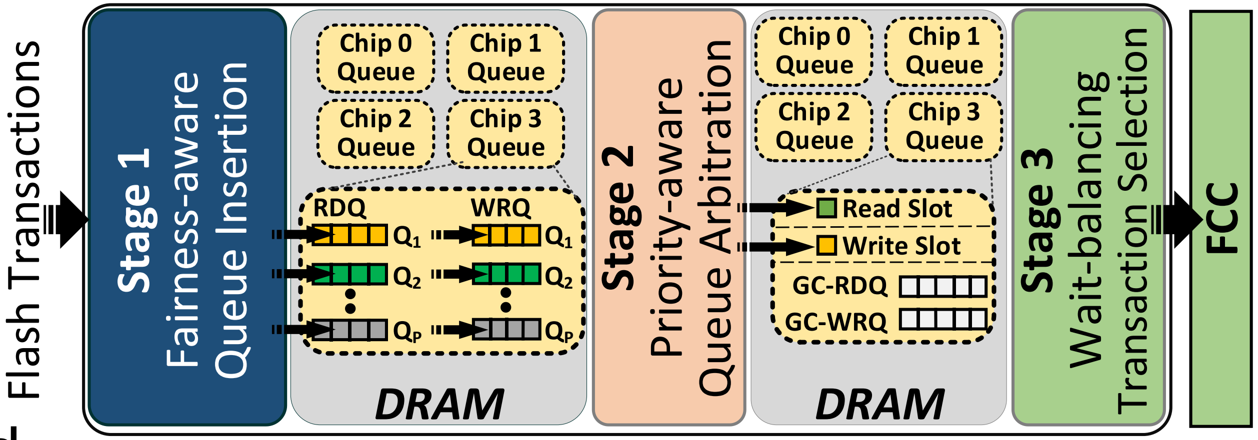
- Host can assign **priority level**
- Select one read and one write transaction and deliver to Stage 3
  - **Weighted round-robin** algorithm
  - Higher priority means more transactions
  - **No starvation**





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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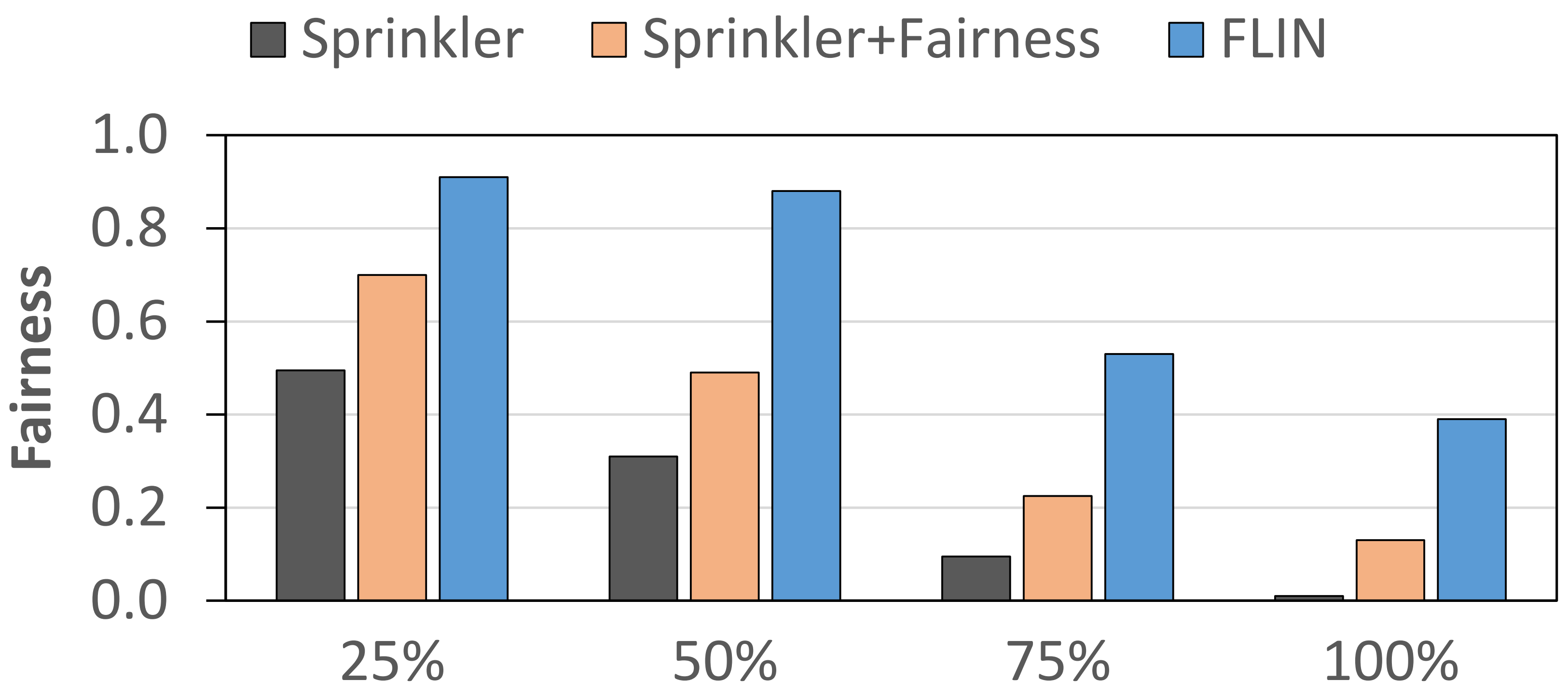
Evaluation Methodology

- **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

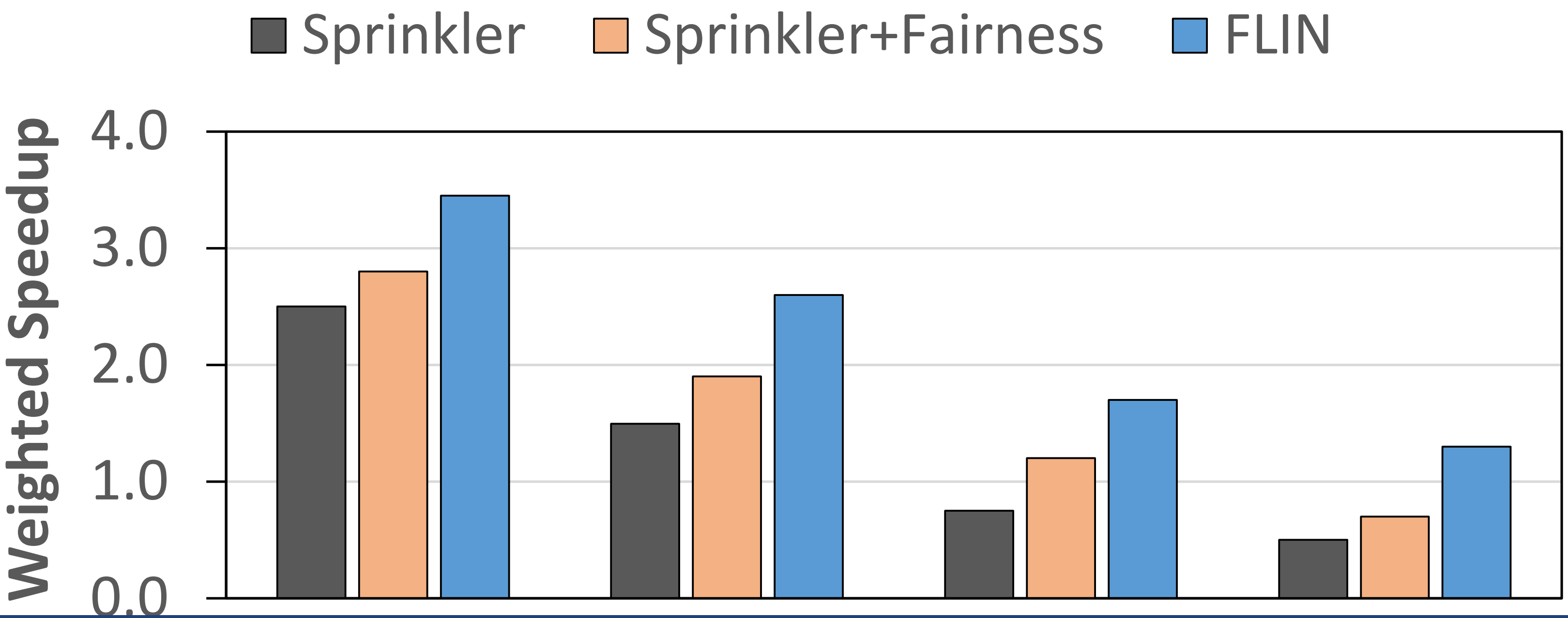
- Sprinkler [Jung et al. HPCA 2014]
  - State-of-the-art high-performance scheduler
- Sprinkler + Fairness [Jung et al. HPCA 2014, Jun et al NVMSA 2015]
  - Sprinkler scheduling algorithm with improved fairness
  - Does not mitigate all sources of interference

Fairness Results



FLIN improves fairness by an **average of 70%,**
by mitigating all four major sources of interference

Speedup Results



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
  - Enables high throughput: millions of IOPS
- OS software stack elimination removes existing fairness mechanisms
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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 focusses 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?