Lifetime Management of Flash-Based SSDs Using Recovery-Aware Dynamic Throttling

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Flash-based SSDs in Enterprise

- Flash-based SSDs (Solid-State Drives) are becoming an attractive storage solution for enterprise systems.

<PCIe-based Flash Array>

<MLC-based SSD>

- The limited lifetime caused by poor write endurance is a main barrier for wider adoption of SSDs in the enterprise market.

SSD Lifetime

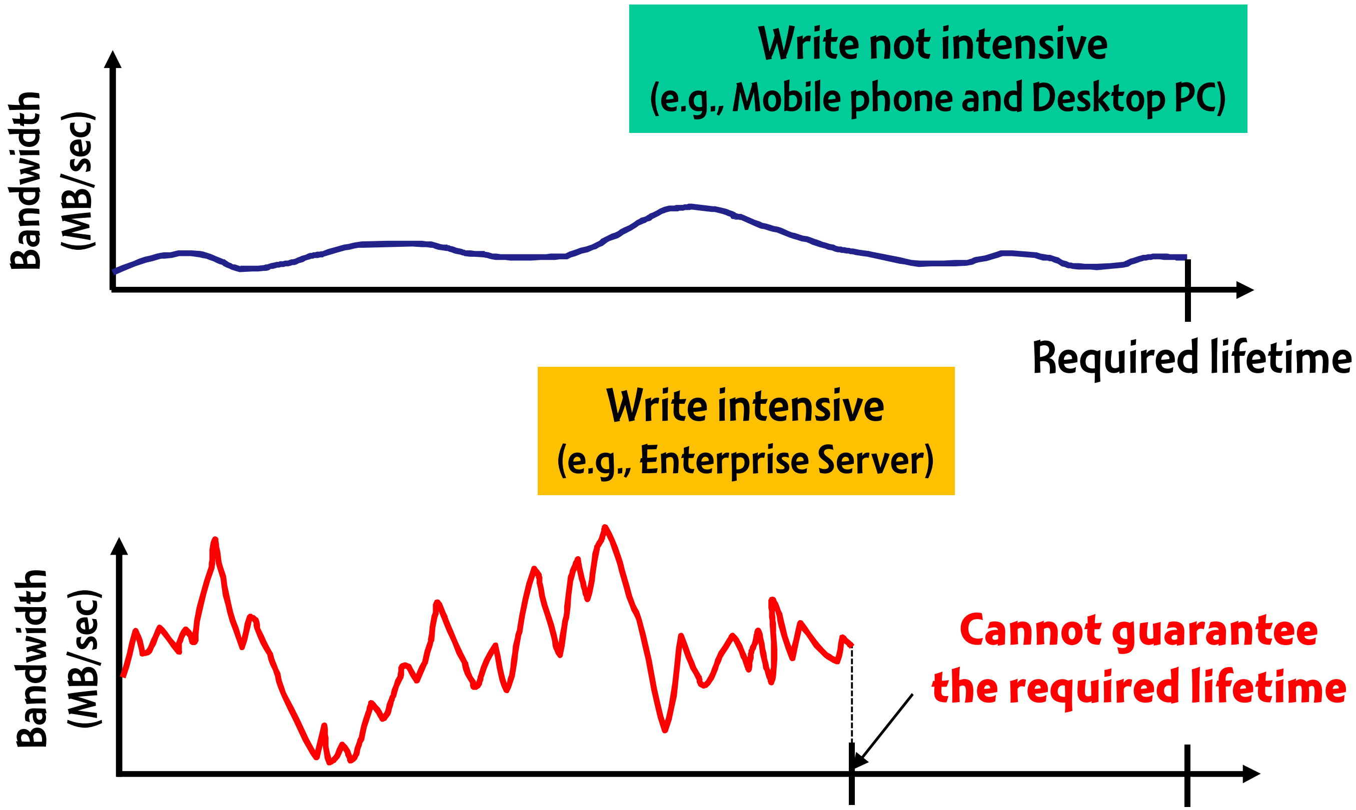
- The SSD lifetime is determined by two main factors:

$$\text{SSD lifetime (days)} = \frac{\text{The total number of bytes that can be written to the SSD}}{\text{The number of bytes written per day}}$$

- (1) SSD capacity
- (2) Number of program/erase (P/E) cycles
- (3) Incoming write traffic
- (4) Write Amplification Factor (WAF)
  - Efficiency of FTL algorithms

Intensive Write Traffic

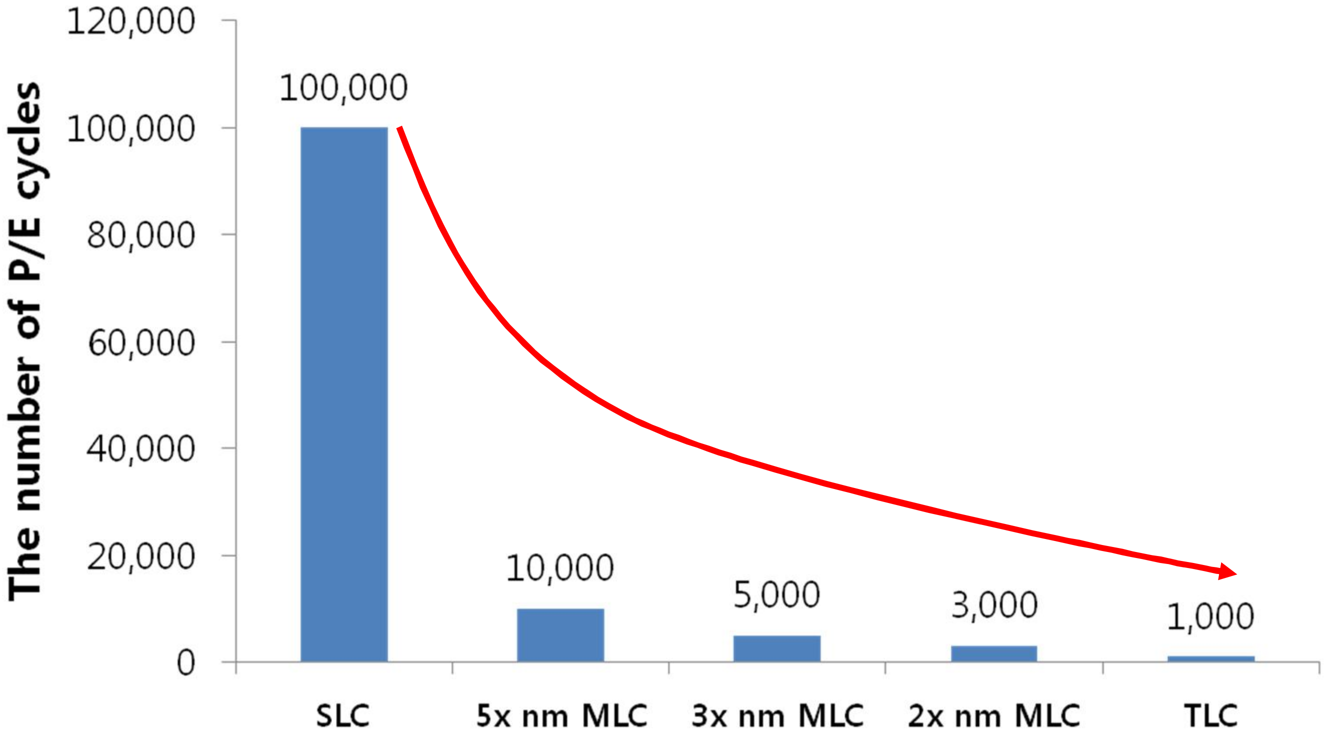
- Enterprise systems exhibit high write traffic



$$\text{Lifetime} = \frac{\text{Capacity} \cdot \text{\# of P/E cycles}}{\boxed{\text{Write traffic (day)}} \cdot \text{WAF}}$$

Decreasing P/E Cycles

- The number of P/E cycles is continuously decreasing as the semiconductor process is scaled-down



(Source: JMicron, Western Digital, Morgan Stanley Research)

$$\text{Lifetime} = \frac{\text{Capacity} \cdot \boxed{\text{\# of P/E cycles}}}{\text{Write traffic (day)} \cdot \text{WAF}}$$

Existing Lifetime-Enhancement Schemes

- Reduce WAF
  - Optimize garbage collection algorithms
  - Optimize wear-leveling algorithms
  - Use more fine-grained mapping schemes

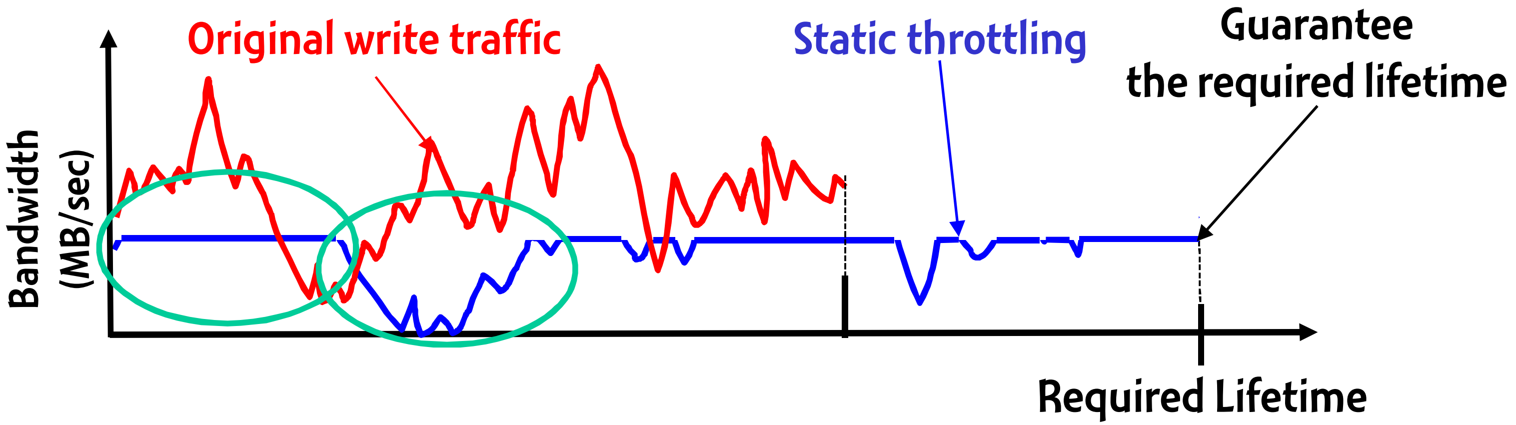
- Reduce incoming write traffic
  - Use lossless data compression
  - Use data deduplication

All those approaches improve the overall SSD lifetime, but cannot guarantee the required SSD lifetime !

$$\text{Lifetime} = \frac{\text{Capacity} \cdot \text{\# of P/E cycles}}{\boxed{\text{Write traffic (day)}} \; \boxed{\text{WAF}}}$$

Static Throttling (Existing Approach)

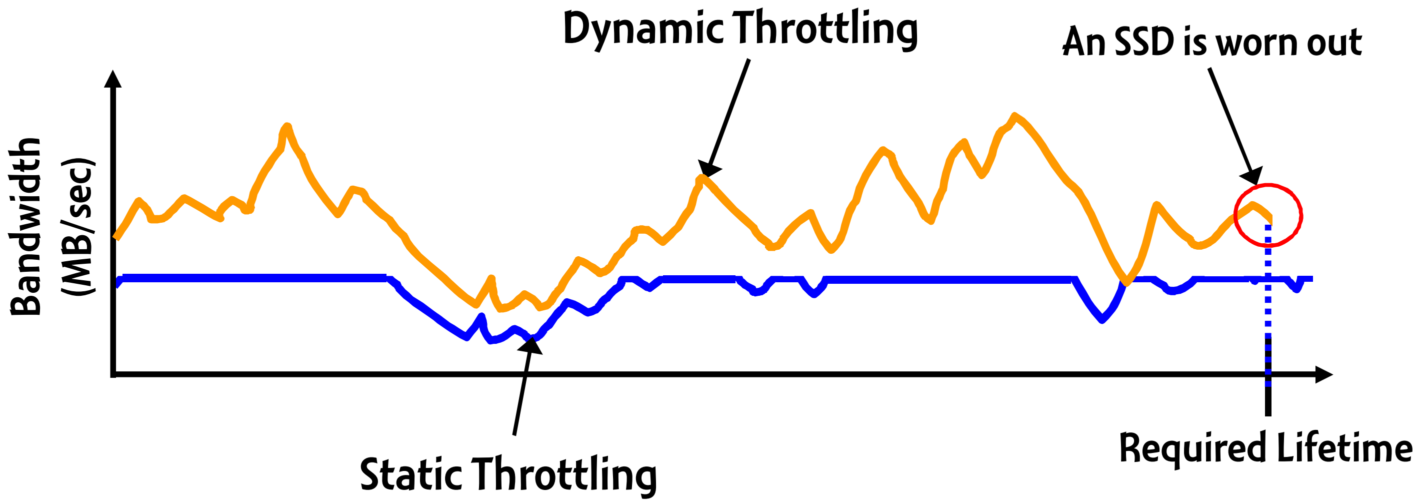
- Limit the maximum throughput of SSDs



- Disadvantages
  - Likely to throttle performance uselessly
    - High performance penalty and high response time variations
  - Underutilize the available endurance

Our Approach (1):
Dynamic Throttling

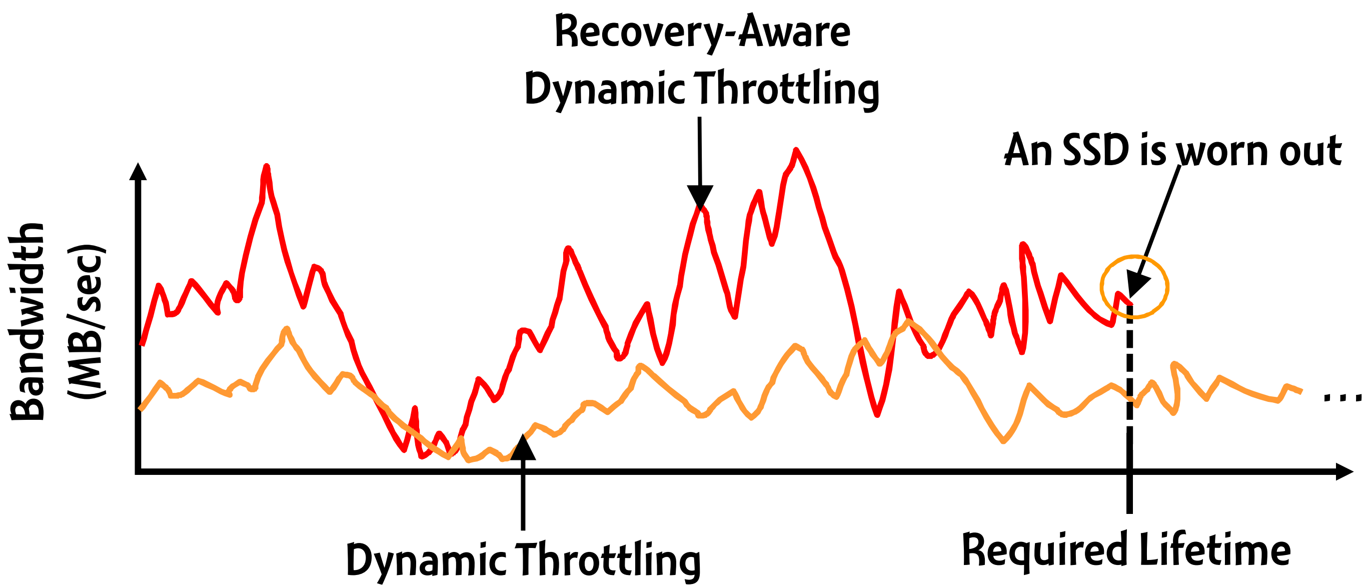
- **Throttle SSD performance dynamically depending on:**
  - **The characteristics of a given workload**
  - **The remaining SSD lifetime**



  - **Less performance penalty and response time variations**
  - **Fully utilize the available endurance**

Our Approach (2): Exploit Self-Recovery Effect

- The effective P/E cycles are much larger than the number on datasheets due to the recovery effect



- Guarantee the SSD lifetime with less throttling overheads

Contribution

- Propose a novel REcovery-Aware DYnamic throttling technique, called READY
  - Throttle the SSD performance to guarantee the required SSD lifetime
  - Exploit the self-recovery property of a flash memory cell to lessen the performance penalty caused by throttling
- Evaluate the proposed READY technique using real-world enterprise traces
  - Guarantee the required SSD lifetime for all evaluated traces
  - Achieve 4.4x higher responses time over a simple static throttling technique

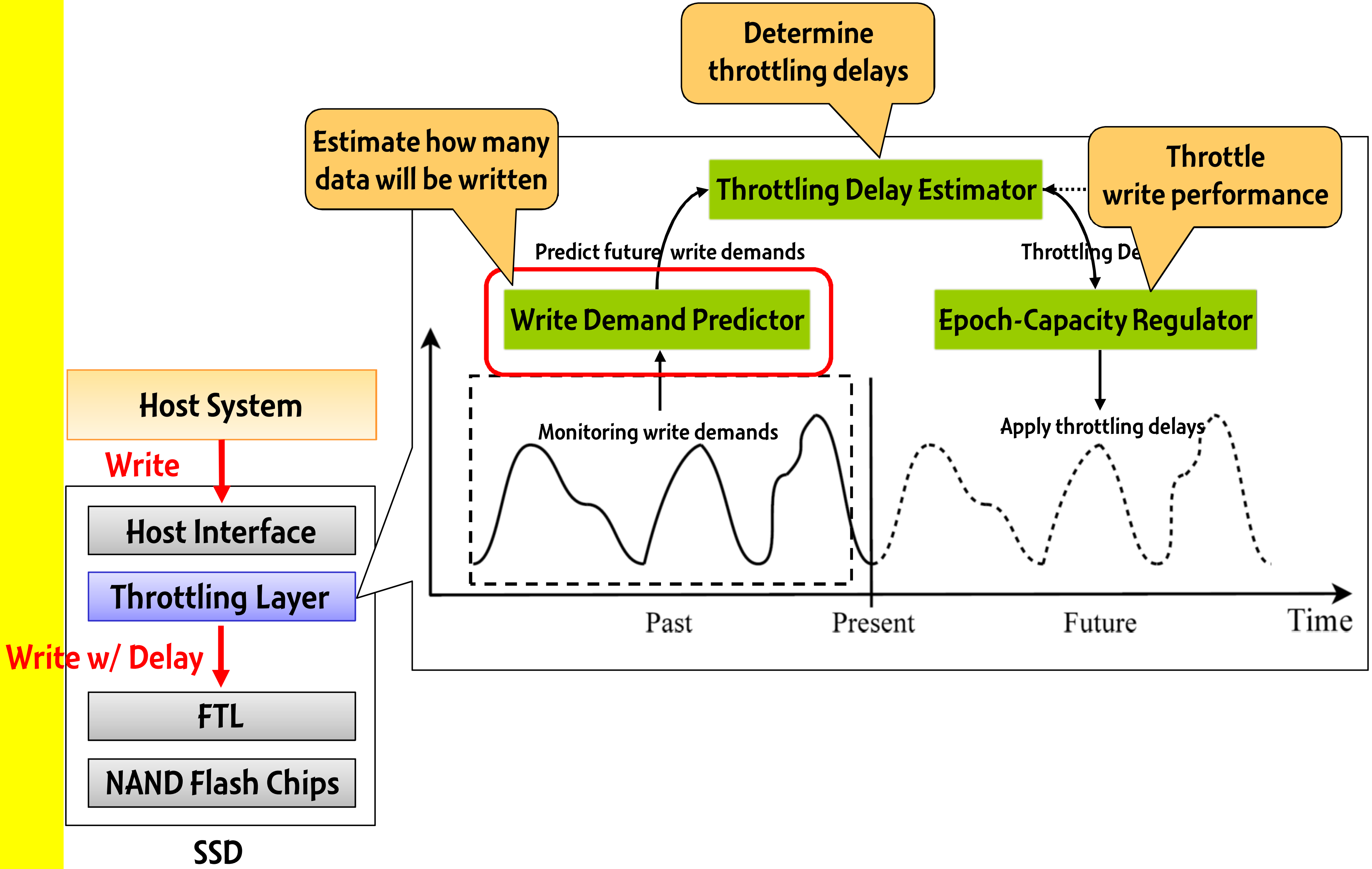
Outline

- Introduction
- Motivation
- Recovery-Aware Dynamic Throttling
- Evaluation Results
- Conclusion

Design Goals of READY

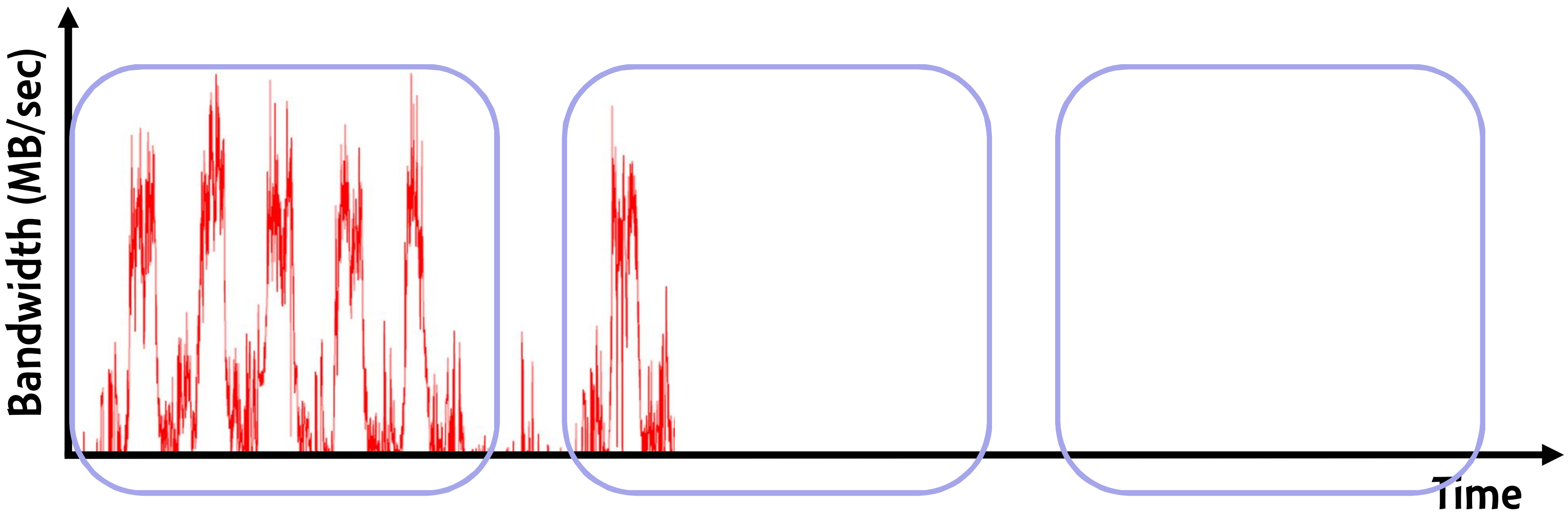
- Design goal 1: guarantee the required SSD lifetime
  - Throttle the write throughput of SSDs by applying throttling delays to write requests
- Design goal 2: minimize average response times
  - Determine a throttling delay as low as possible so that the SSD is completely worn out at the required lifetime
- Design goal 3: minimize response time variations
  - Distribute a throttling delay as evenly as possible over every write request

Overall Architecture of READY



Write Demand Predictor

- The write traffic of enterprise workloads is likely to change significantly over time
- How to predict future write traffic for throttling?
  - Exploit cyclic behaviors of enterprise applications!

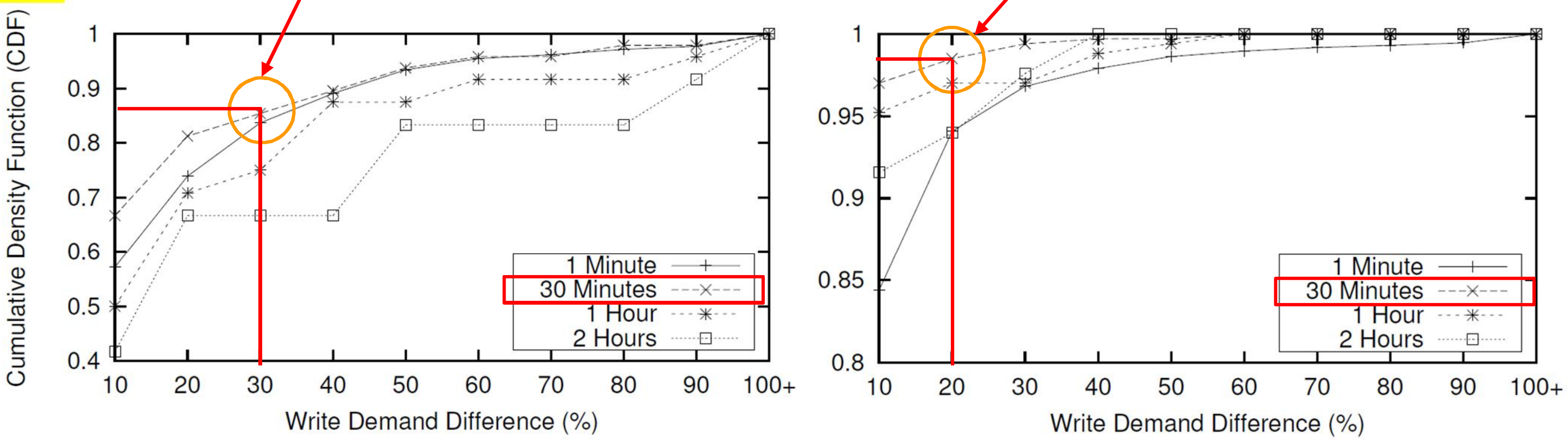


Cyclical Behaviors of Enterprise Workloads

- A strong cyclical behavior is frequently observed in enterprise applications

When a cyclic period is set to 30 min, the write demand difference is less than 30% for 88% periods

When a cyclic period is set to 30 min, the write demand difference is less than 20% for 98% periods

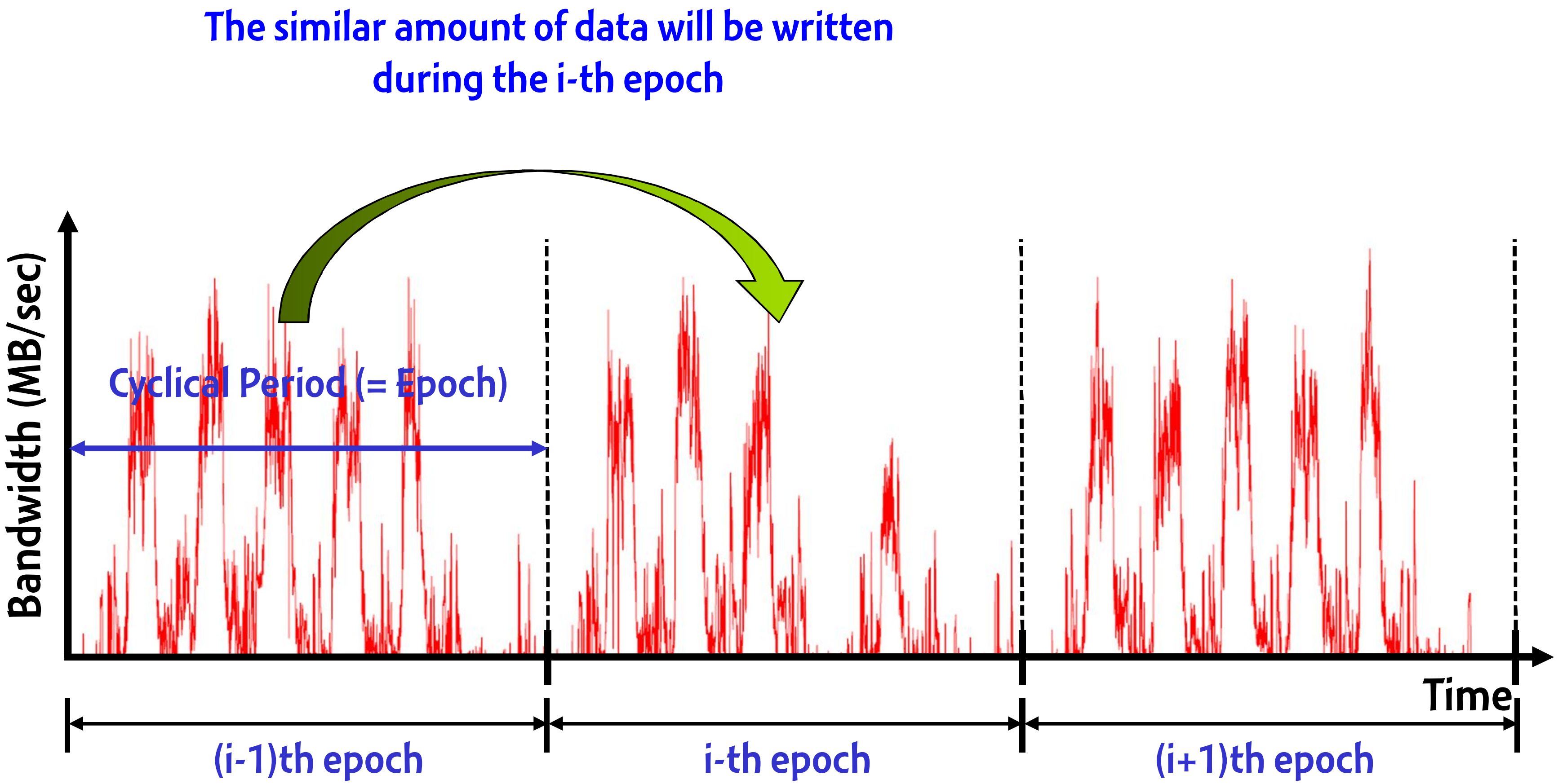


(a) exchange

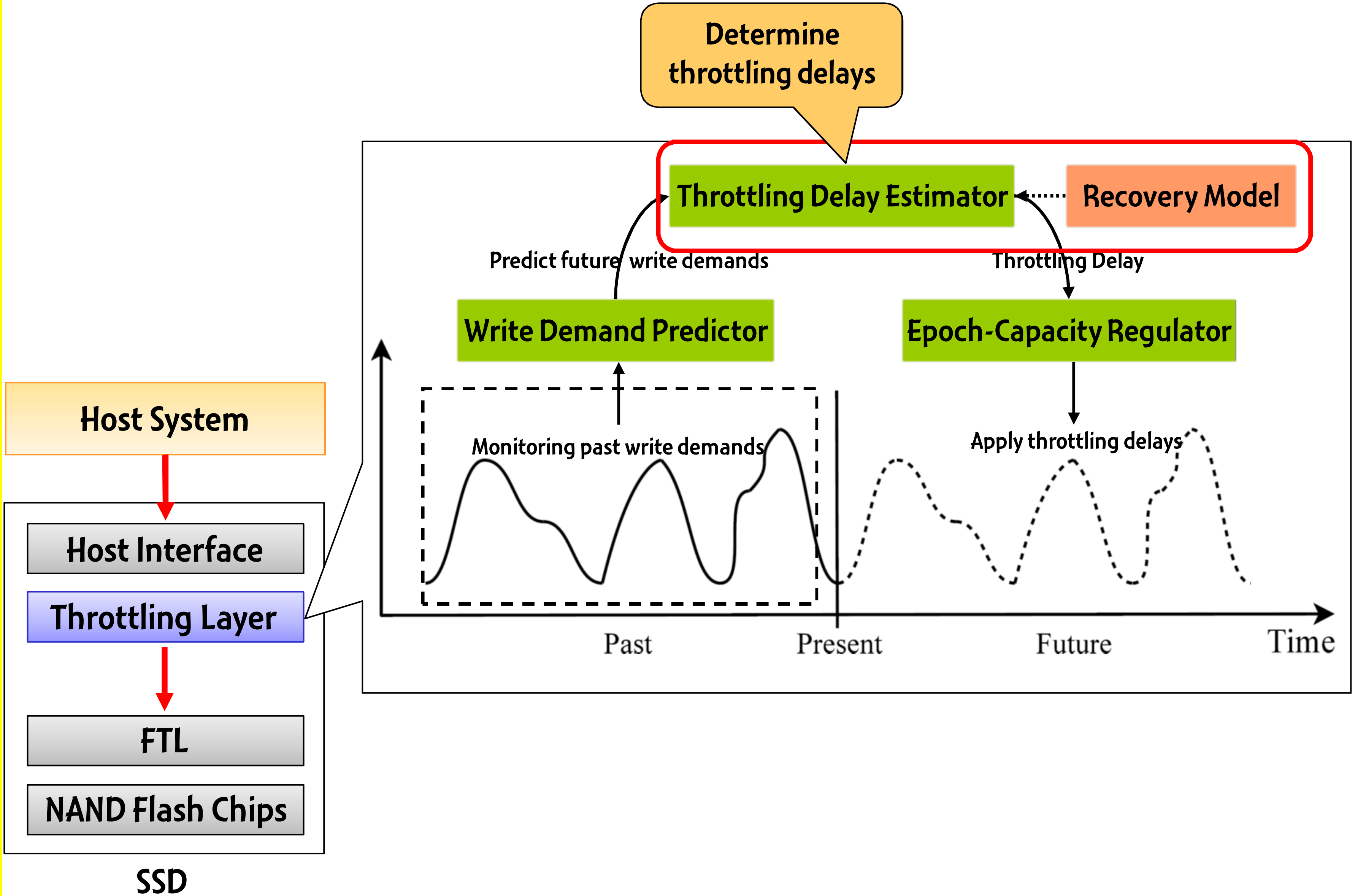
(b) proxy

Future Write Demand Estimation

- (1) Divide time into epochs which exhibit similar write demands
- (2) Estimate the similar amount of data written during the latest epoch will be written during the next epoch



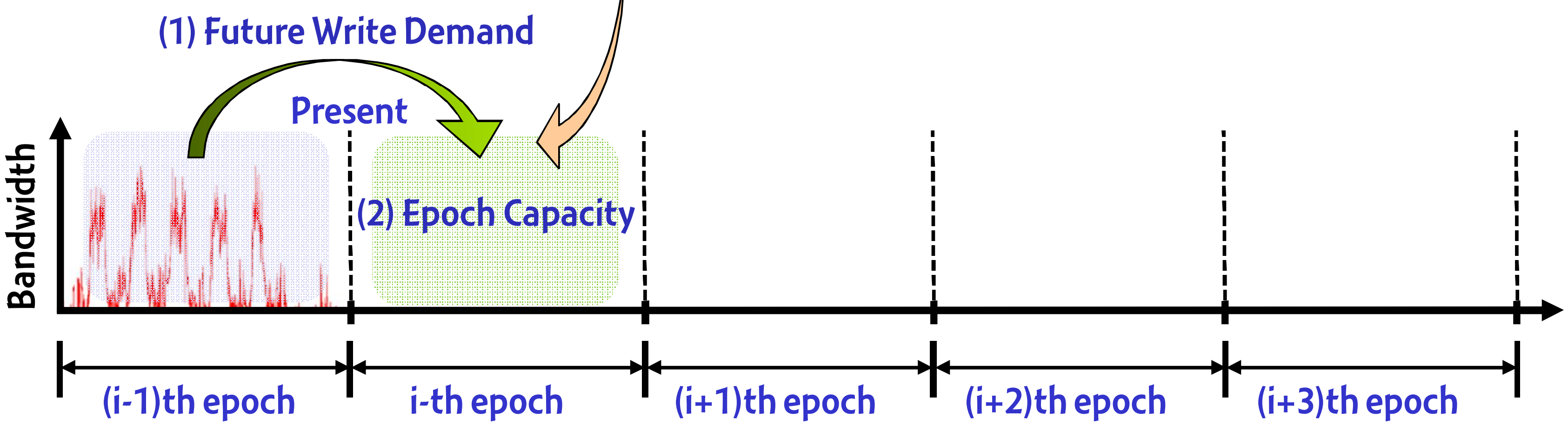
Overall Architecture of READY



Throttling Delay Estimator

- Determine a throttling delay
  - (1) The future write demand for the next epoch ➡ We already know it
  - (2) The epoch capacity
    - The amount of data allowed to be written during the epoch

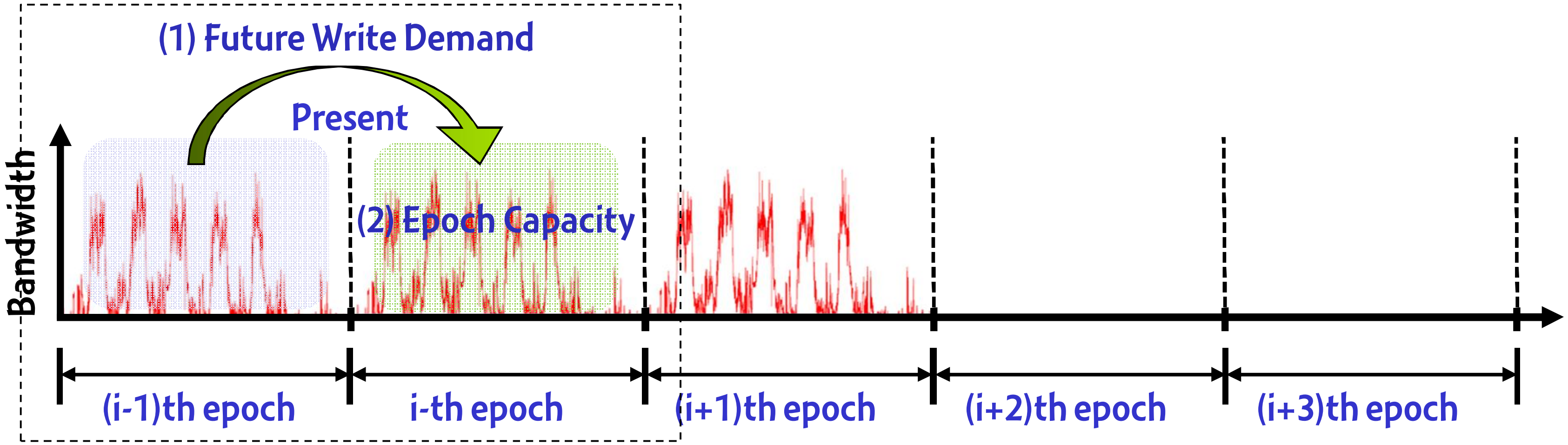
$$\boxed{\text{Epoch capacity}} = \frac{\text{\# of remaining P/E cycles} \times \text{SSD capacity}}{\text{\# of remaining epochs}}$$



Change Throttling Delay

- A throttling delay is initially set to 0 and is changed adaptively at the beginning of each epoch.

- Case 1: future write demand = epoch capacity
  - Don't change a throttling delay
- Case 2: future write demand > epoch capacity
  - Increase a throttling delay
- Case 3: future write demand < epoch capacity
  - Decrease a throttling delay



Exploit Effective P/E Cycles

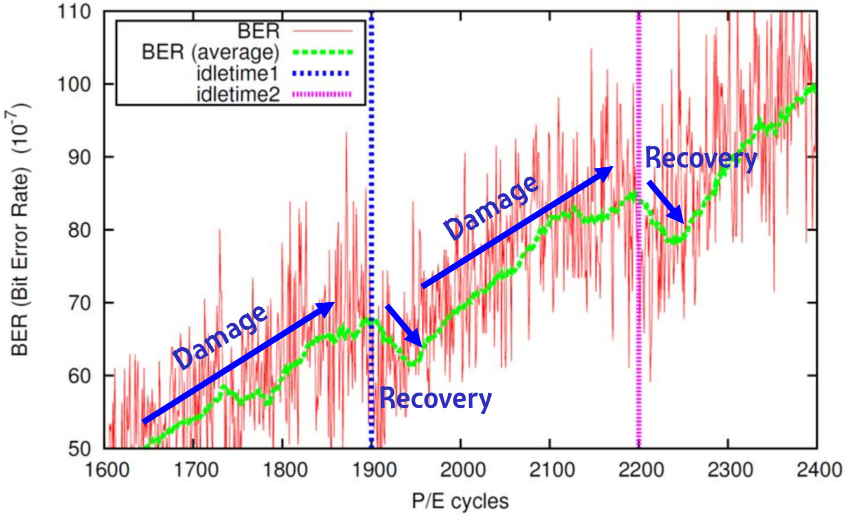
- P/E operations cause damage to NAND flash memory cells
- This damage is partially recovered during the idle time
- ➡ Effective P/E cycles are larger than pre-set P/E cycles

$$\text{Epoch capacity} = \frac{\#\text{ of remaining P/E cycles} \times \text{SSD capacity}}{\#\text{ of remaining epochs}}$$

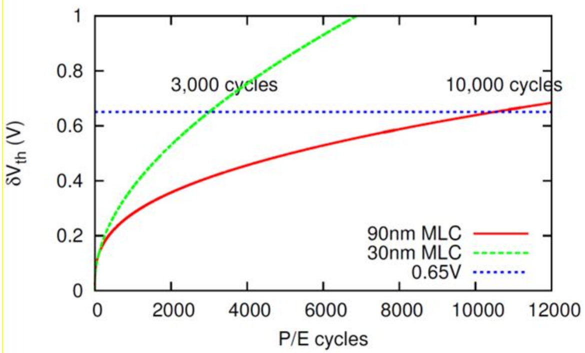
$$< \frac{\#\text{ of effective remaining P/E cycles} \times \text{SSD capacity}}{\#\text{ of remaining epochs}}$$

Effective P/E Cycles Modeling

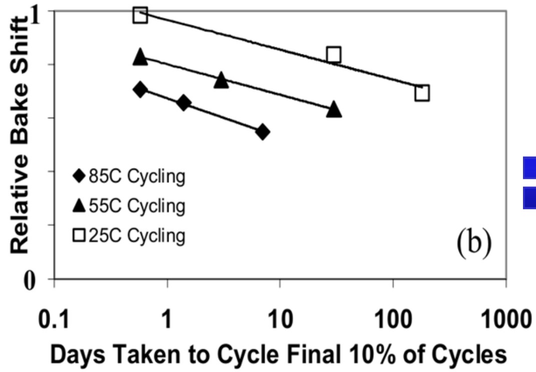
- Self-recovery effect validation from real measurements



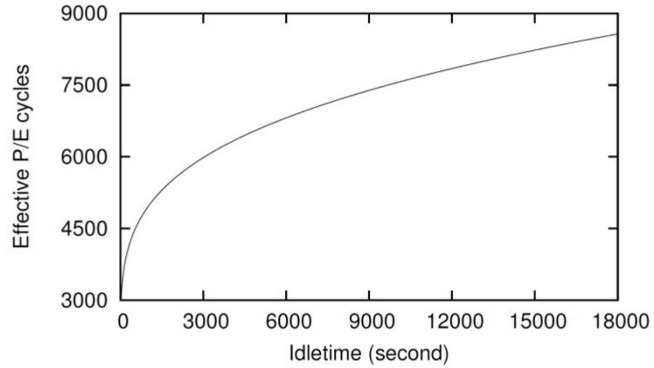
- Effective P/E cycles modeling



<Damage Model>



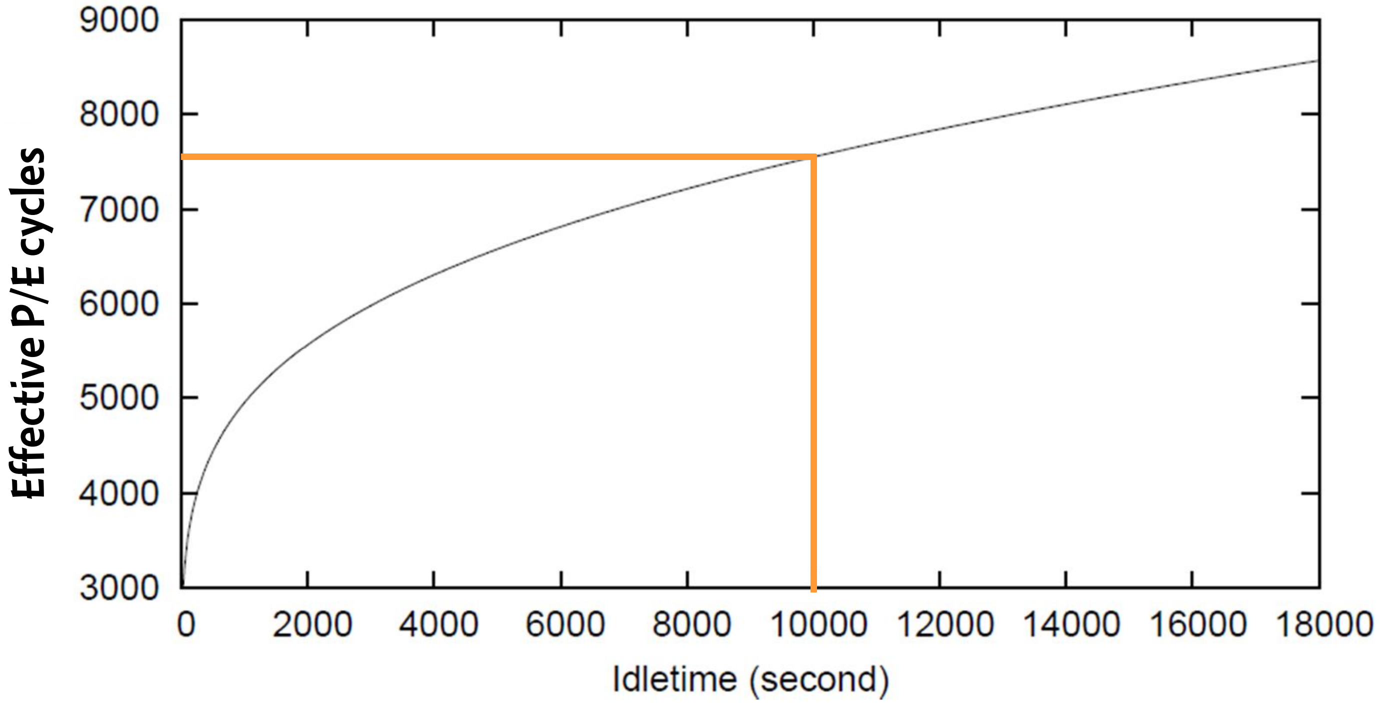
<Self-Recovery Model>



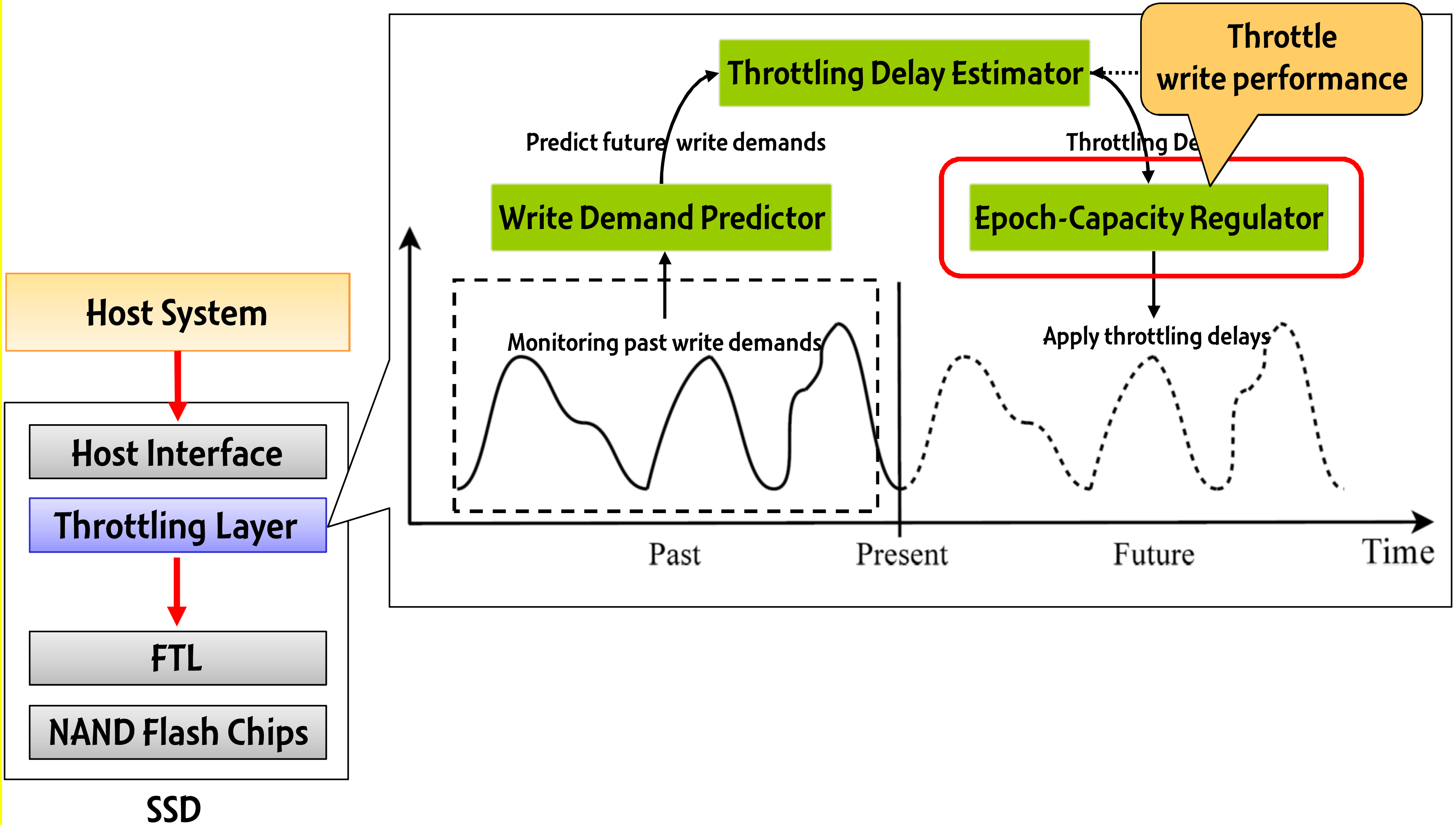
<Effective P/E cycles>

The Effective P/E Cycles

- The maximum P/E cycles without the recovery effect are 3K.
- The effective P/E cycles are gradually increased in proportional to the length of the idle time.



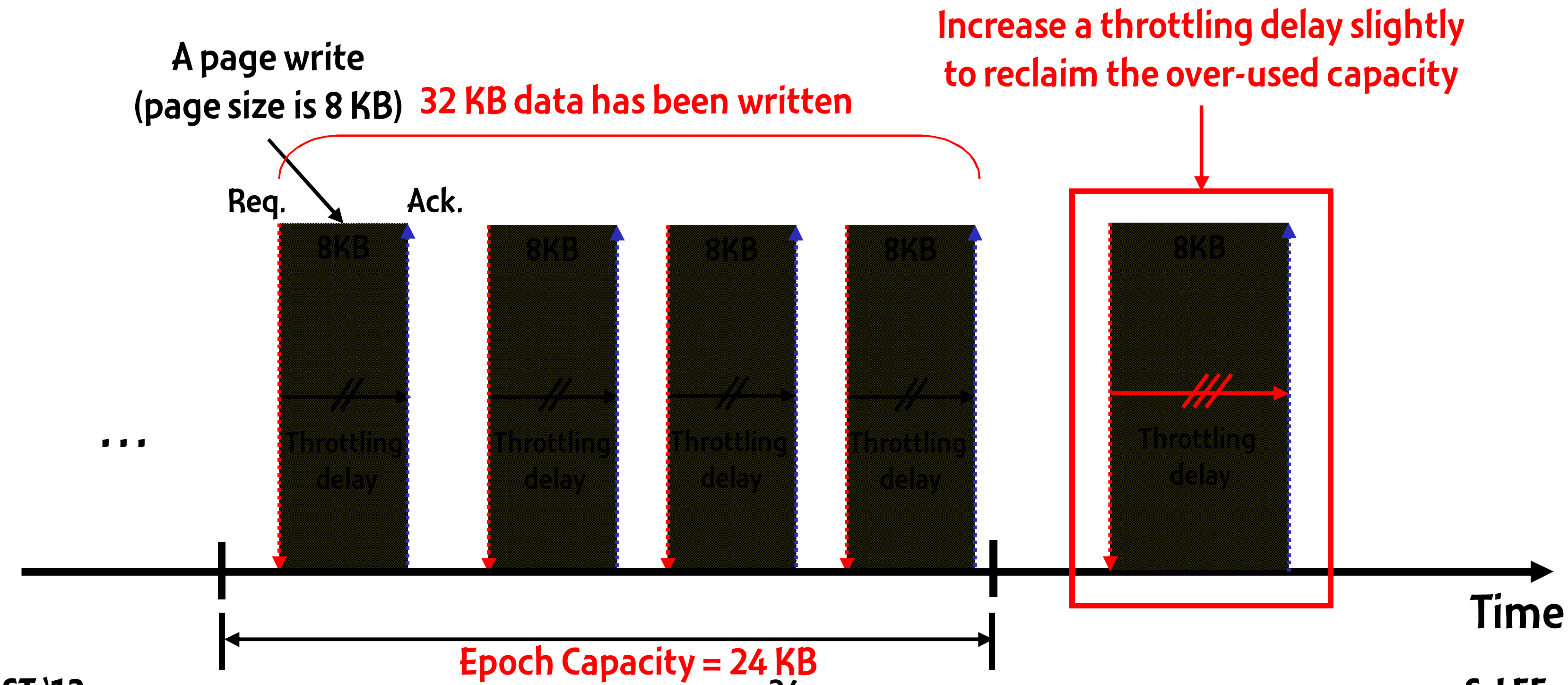
Overall Architecture of READY



Epoch-Capacity Regulator

- Throttle write performance as evenly as possible
  - To minimize response time variations

- (1) Apply the same throttling delay to every page write
- (2) Increase a throttling delay later to reclaim the over-used capacity



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Experimental Setting

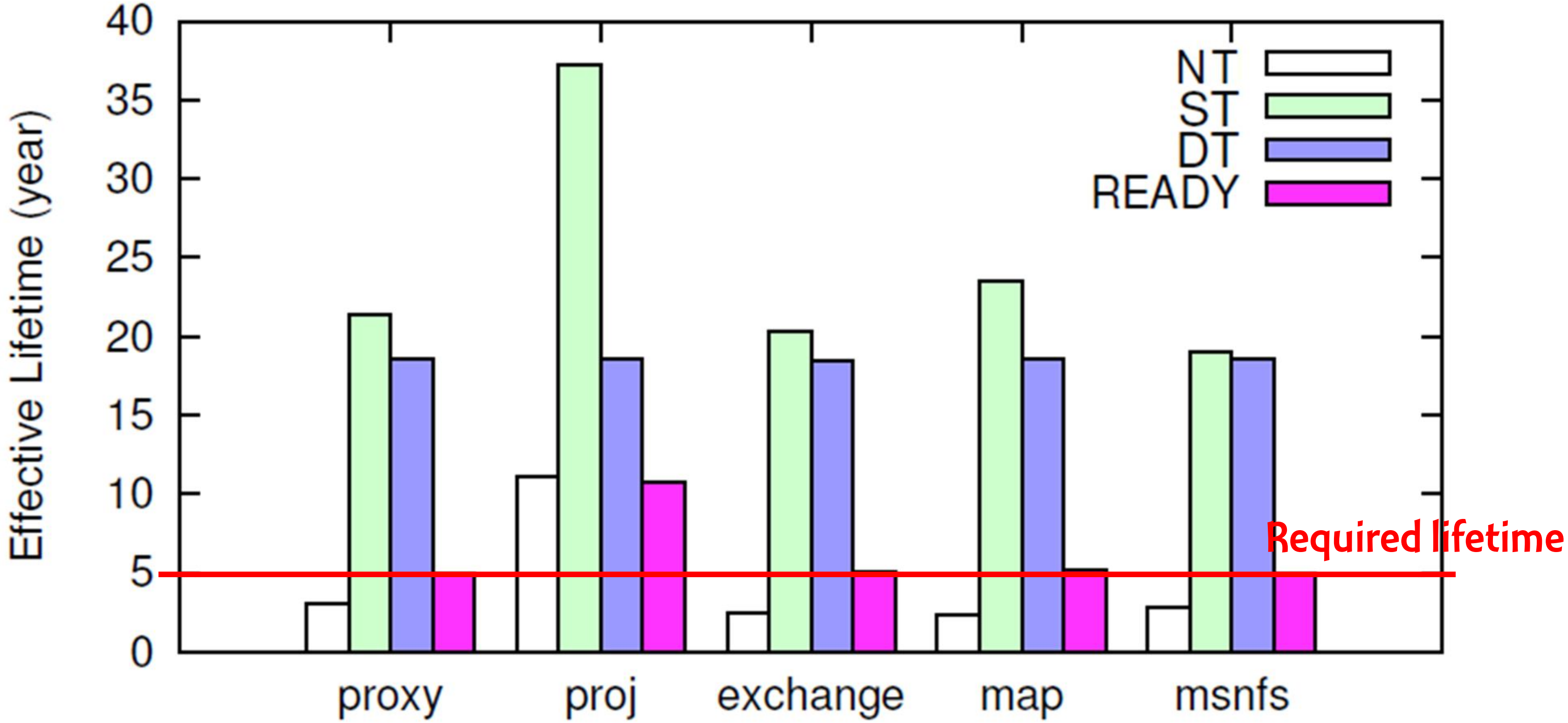
- Used the DiskSim-based SSD simulator for evaluations
  - 20 nm 2-bit MLC NAND flash memory with 3K P/E cycles
  - The target SSD lifetime is set to 5 years
- Evaluated four SSD configurations
  - **NT**: No Throttling
    - No performance throttling; No lifetime guarantee
  - **ST**: Static Throttling
  - **DT**: Dynamic Throttling without Recovery
  - **READY**: Recover-Aware Dynamic Throttling

Benchmarks

- Used the traces from MSR-Cambridge and MS-Production benchmarks

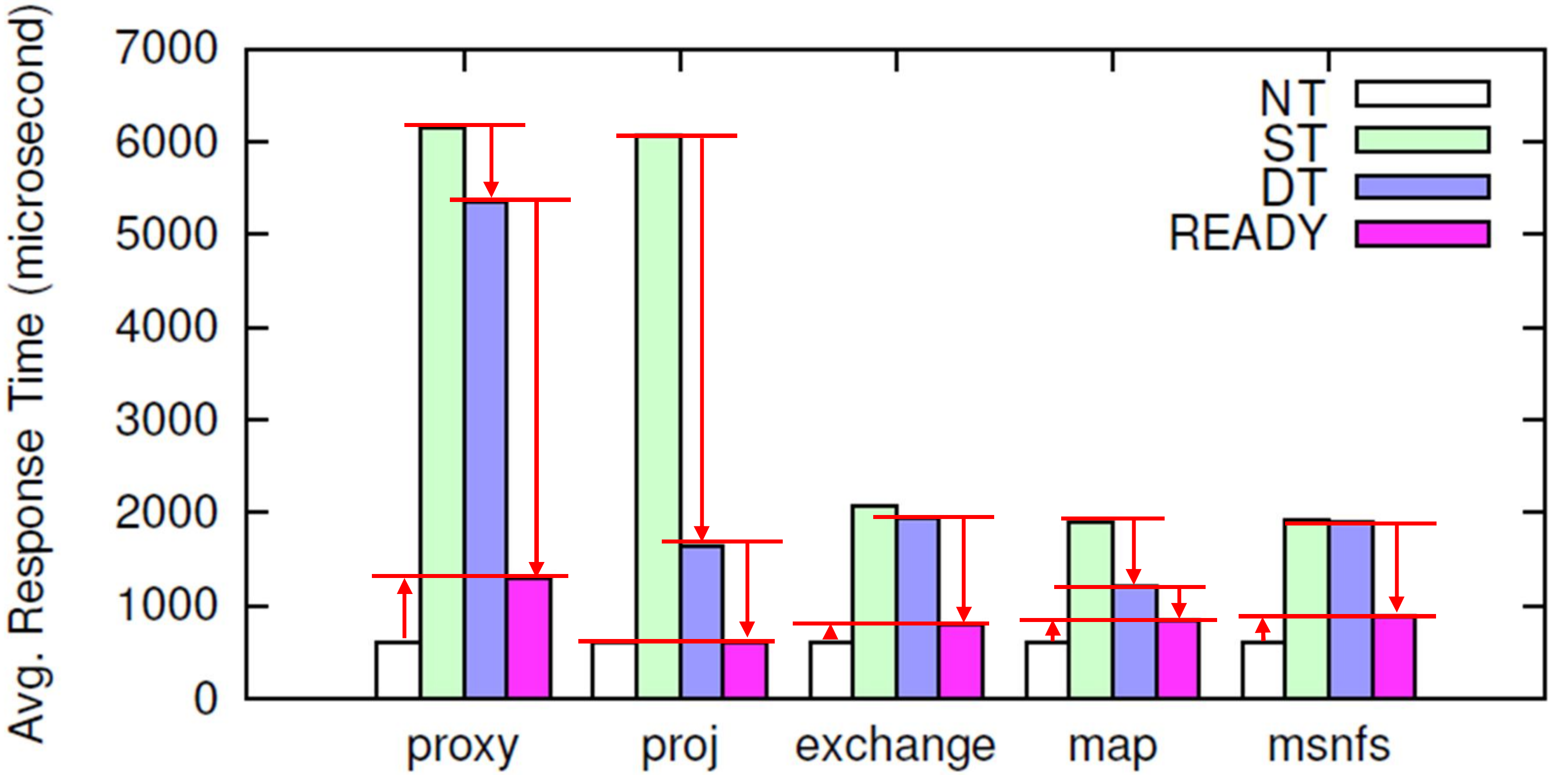
Trace	Duration	Data written per hour (GB)	WAF	SSD capacity (GB)
`proxy`	1 week	4.94	1.93	32
`proj`	1 week	2.08	1.62	32
`exchange`	1 day	20.61	2.24	128
`map`	1 day	23.82	1.68	128
`msnfs`	6 hours	18.19	2.26	128

Lifetime Analysis



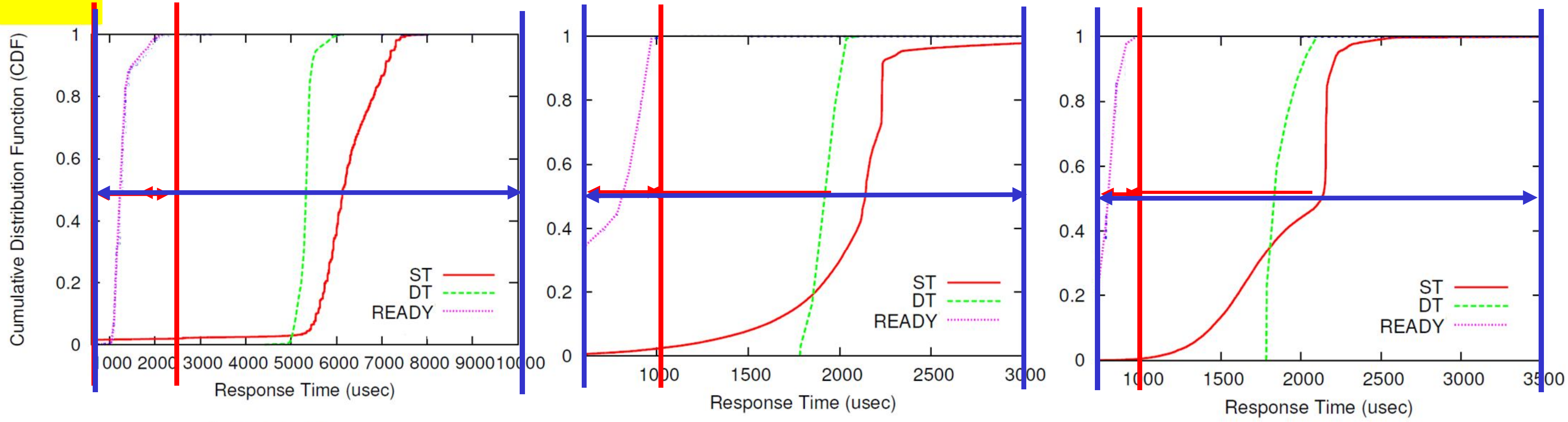
- NT cannot guarantee the required SSD lifetime (except for proj)
- READY achieves the lifetime close to 5 years
- ST and DT exhibit the lifetime much longer than 5 years

Performance Analysis



- NT exhibits the best performance among all the configurations
- READY perform better than ST and DT while guaranteeing the required lifetime

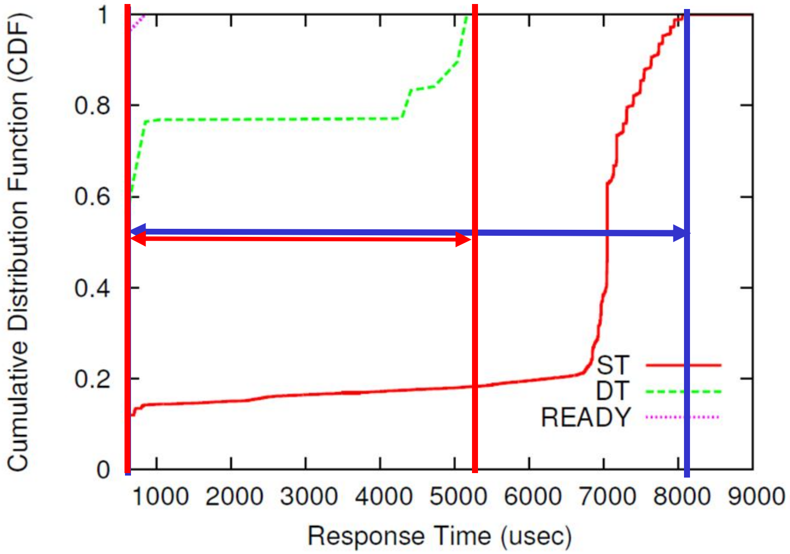
Response Time Variations (1)



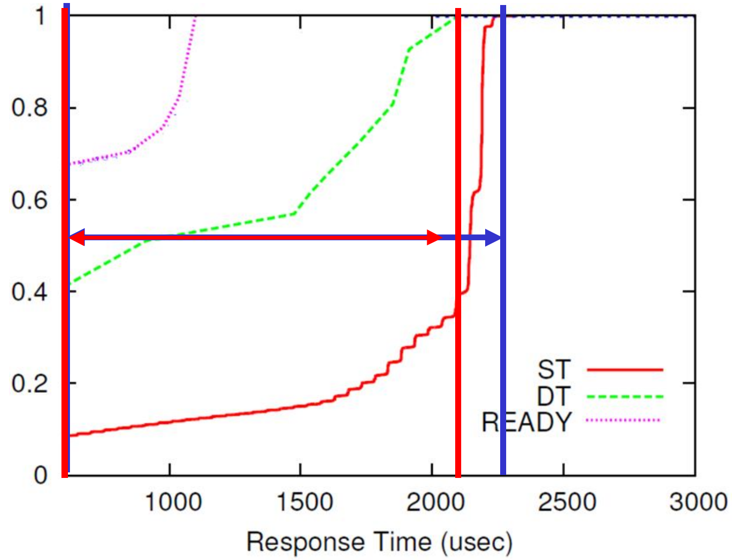
(a) proxy (c) exchange (e) msnfs

- READY shows shorter response times than ST/DT.
- ST exhibits significant response time variations.
  - Stop writing if incoming write traffic is higher than a fixed throughput

Response Time Variations (2)



(b) proj



(d) map

- The write traffic of proj and map changes greatly with time.
  - It is hard to predict future write traffic.
- READY and DT exhibit relatively high fluctuation on response times, but is more stable than ST

Conclusion

- We proposed the recovery-aware dynamic throttling technique, called READY
  - Guarantee the SSD lifetime by throttling SSD performance
  - Reduce throttling overheads by exploiting the self-recovery effect of flash memory cells
  - Achieve about 4.4x higher performance over the existing static throttling with less response time variations

- Future works
  - Implement READY in a real SSD platform
  - Support latency-aware performance throttling

Thank you