Design Tradeoffs for SSD Reliability

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High-level objectives

Understand the SSD-internal mechanisms behind fail-slow symptoms

- H. Gunawi et al, “Fail-slow at scale: evidence of hardware performance faults in large production systems”, FAST 2018
High-level objectives

Examine SSD-internal reliability enhancement techniques

• Images from Google searches
High-level objectives

Think about system- and device-level approaches for handling errors

• Images from Google searches
How bad is it?

How bad is it?

- H. Sun et al, “Quantifying reliability of solid-state storage from multiple aspects”, SNAPI 2011
How bad is it?

- Data from an industry partner, 2018
SSD’s reliability issue

- How to make SSD reliable?
- Performance overhead?
- Across different chips and wear states?

Error-prone memory

RBER: $10^{-4} \sim 10^{-2}$

Reliable SSD

UBER: $<10^{-15}$
Flash memory errors

Wear-out

\( V_{\text{prog}} \)

CG

FG
Flash memory errors

Wear-out

Retention loss

$V_{\text{prog}}$

CG

FG

CG

FG

0V
Flash memory errors

Wear-out

Retention loss

Disturbance
Flash memory error modeling

\[ RBER \ (cycles, \ time, \ reads) \]

\[ = \ \varepsilon \]

\[ + \ \alpha \cdot cycles^k \]

\[ + \ \beta \cdot cycles^m \cdot time^n \]

\[ + \ \gamma \cdot cycles^p \cdot reads^q \]

• N. Mielke et al, “Reliability of solid-state drives based on NAND flash memory”, Proceedings of the IEEE, 2017
From measurements to model

Measurement (data)

- H. Sun et al, “Quantifying reliability of solid-state storage from multiple aspects”, SNAPI 2011
- Data from an industry partner, 2018

Model

- 3x-nm MLC (2011)
- 2y-nm MLC (2015)
- 3D TLC (2018)
Error model: 3x-nm MLC (2011)

- Wear up to 10K P/E cycles
- 10K P/E cycles + up to 10K reads or up to 1 year
Error model: 2y-nm MLC (2015)

Wear up to 10K P/E cycles

10K P/E cycles + up to 10K reads or up to 1 year
Error model: 3D TLC (2018)

- Wear
- Retention
- Disturbance

Wear up to 10K P/E cycles
10K P/E cycles + up to 10K reads or up to 1 year
SSD reliability enhancements

• Error correction code
• Data re-reads
• Intra-SSD redundancy
• Background relocation
Error correction code

- ECC encoder
- ECC decoder
- Flash memory
Error correction code

Data -> ECC encoder -> Flash memory

ECC decoder
Error correction code

ECC encoder

ECC decoder

Data

Flash memory

Data P
Data re-reads

Flash memory

ECC encoder

Data

ECC decoder
Data re-reads

ECC encoder

ECC decoder

Flash memory

Data P
Summary: ECC and data re-reads

• Error correction code
  – Predictable performance
  – Is fixed at design-time

• Data re-read
  – Is much more powerful than ECC
  – Increases latency for correcting errors
Evaluation: data re-read

For the 3D TLC (2018)
Why is data re-read bad?

For the 3D TLC (2018)
Observations

• Repeated data re-reads make it worse
  – 75-bit: ~30% increased latency at end-of-life
Intra-SSD redundancy
Intra-SSD redundancy
Summary: intra-SSD redundancy

• Error correction code
  – Is fixed at design-time

• Data re-read
  – Increases latency for correcting errors

• Intra-SSD redundancy
  – Protects against random and sporadic errors
  – Increases write amplification
  – Increases read amplification on errors
Evaluation: redundancy
For the 3D TLC (2018) with 75-bit ECC

For the 3D TLC (2018) with 75-bit ECC
Observations

• Repeated data re-reads make it worse

• Overheads of redundancy outweigh its benefits
  – +56% latency at end-of-life
Observations

• Repeated data re-reads make it worse
• Overheads of redundancy outweigh its benefits
• Scrubbing reduces error-induced latency, but increases internal traffic
  – +25% latency at end-of-life
  – Highly dependent on accuracy of error prediction
Observations

• Repeated data re-reads make it worse
• Overheads of redundancy outweigh its benefits
• Scrubbing reduces error-induced latency, but increases internal traffic
• We need to consider data characteristics and compositionally combine reliability enhancements
Holistic reliability management

• Cold data
  – Need protection against retention errors
  – Least write amplification with redundancy
  – Likely to be identified by GC
Holistic reliability management

• Cold data
  – Selective redundancy for GC-ed data

• Read-hot data
  – Need protection against disturbance errors
  – # of data re-reads can be used as proxy
  – Likely to be identified by scrubber
Holistic reliability management

• Cold data
  – Selective redundancy for GC-ed data
• Read-hot data
  – Cost-benefit scrubbing
• Write-hot data
  – No special attention required
Evaluation

ECC + re-read : Rely on ECC and data re-reads
Oracle scrub : Scrub based on oracle knowledge
HRM : Holistic reliability management

For the 3D TLC (2018) with 75-bit ECC @ end-of-life state
The bright side of flash memory

- S. Lee, “Emerging Challenges in NAND Flash Technology”, Flash Summit 2011
The dark side of flash memory