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Optimizing Progressive Reads in Paged Flash

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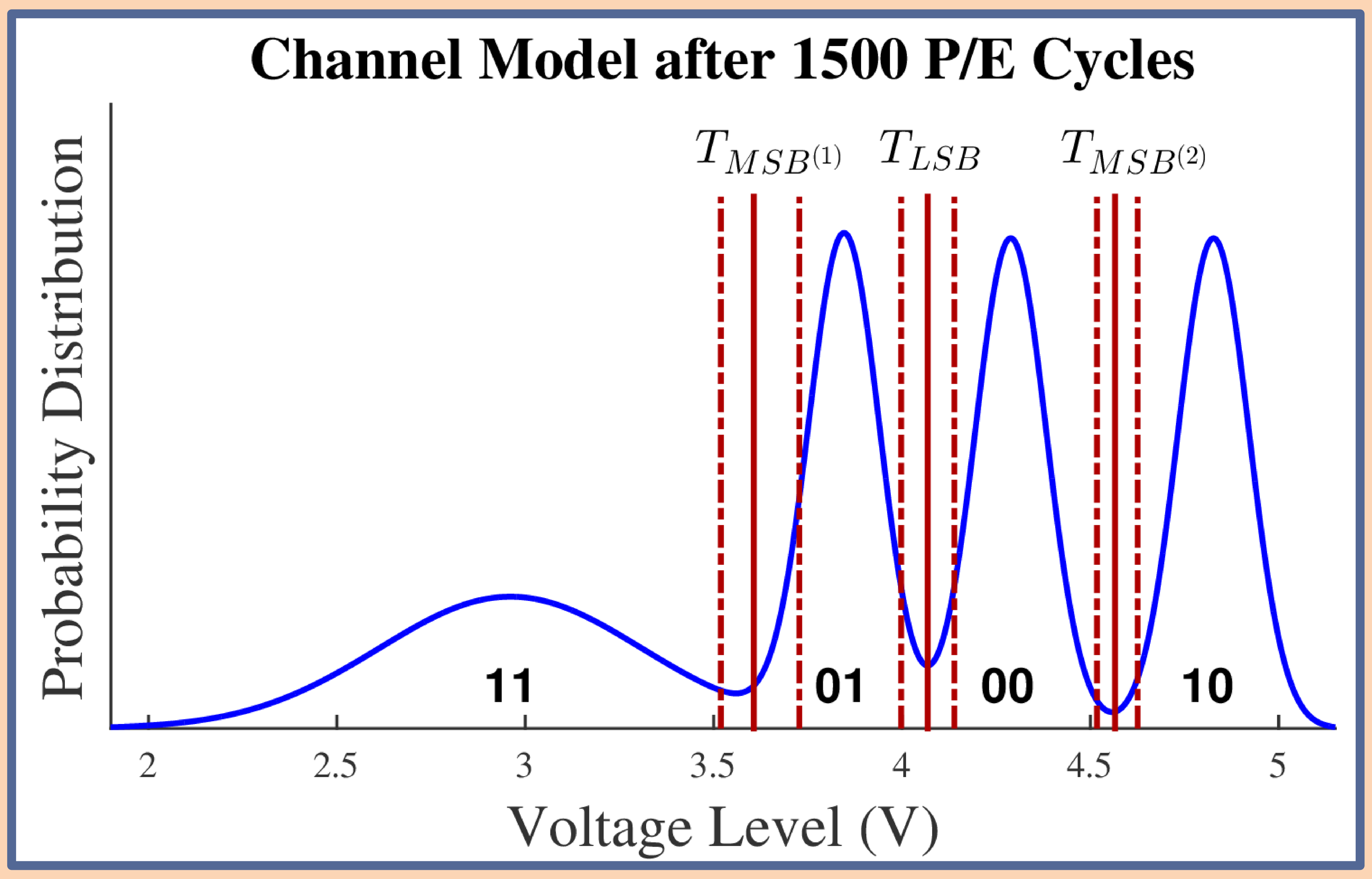
Motivation and Goal

- Flash channels degrade as the number of Program/Erase (P/E) cycles in the system increase.
- **To Improve Performance:** Add enhanced precision to progressive reads when initial decoding fails.
- Current methods jointly optimize a fixed number of thresholds to maximize mutual information. However, industry tends to separate each bit in a cell with a respective page and decode that way.
- This work expands on current enhanced precision techniques to maximize mutual information for each independent page.

Flash Channel Model (MLC)



- **Two-Bit, Two-Variance Channel (Gray Coding)**
- Channel Noise Parameters:
  - **Programming Noise** – Imprecise voltage being allocated into channel
  - **Cell-to-Cell Interference** – Addition effects of adjacent Flash cells
  - **Retention Noise** – Leaking from data written to and stored in a worn-out cell
- Previous work suggests that two extra reads per original read provides sufficient mutual information gains.

Initialization

Initial Read Thresholds $T^{initial}$ (Represented by solid red lines)

$$Y_{LSB}^{initial} = \begin{cases} 1 \text{ when } V \le T_{LSB}^{initial} \\ 0 \text{ when } V > T_{LSB}^{initial} \end{cases}$$

$$Y_{MSB^{(1)}}^{initial} = \begin{cases} 1 \text{ when } V \le T_{MSB^{(1)}}^{initial} \\ 0 \text{ when } V > T_{MSB^{(1)}}^{initial} \end{cases}$$

$$Y_{MSB^{(2)}}^{initial} = \begin{cases} 0 \text{ when } V \le T_{MSB^{(2)}}^{initial} \\ 1 \text{ when } V > T_{MSB^{(2)}}^{initial} \end{cases}$$

- **Thresholds are chosen to maximize mutual informations $I\left(X_{LSB}; Y_{LSB}^{initial}\right)$ and $I\left(X_{MSB}; Y_{MSB^{(1)}}^{initial}, Y_{MSB^{(2)}}^{initial}\right)$.**

$$\hat{X}_{LSB} = Y_{LSB}^{initial}$$

$$\hat{X}_{MSB} = \begin{cases} 1 & \text{when } Y_{MSB^{(1)}}^{initial} = 1 \text{ or } Y_{MSB^{(2)}}^{initial} = 1 \\ 0 & \text{otherwise} \end{cases}$$

LSB Page Optimization

Read Thresholds T_{LSB}^{left} and T_{LSB}^{right} (Represented by dotted red lines)

Maximize $I\left(X_{LSB}; Y_{LSB}^{initial}, Y_{LSB}^{left}, Y_{LSB}^{right}\right)$

$$= I\left(X_{LSB}; Y_{LSB}^{initial}\right) + I\left(X_{LSB}; Y_{LSB}^{left}, Y_{LSB}^{right} \middle| Y_{LSB}^{initial}\right)$$

Equivalently, Maximize

$$I\left(X_{LSB}; Y_{LSB}^{left}, Y_{LSB}^{right} \middle| Y_{LSB}^{initial}\right)$$

$$= P\left(Y_{LSB}^{initial} = 1\right) \cdot I\left(X_{LSB}; Y_{LSB}^{left} \middle| Y_{LSB}^{initial} = 1\right) \quad (1)$$

$$+ P\left(Y_{LSB}^{initial} = 0\right) \cdot I\left(X_{LSB}; Y_{LSB}^{right} \middle| Y_{LSB}^{initial} = 0\right) \quad (2)$$

- Since $Y_{LSB}^{initial}$ is already established, this optimization becomes decoupled:

Select…	To Optimize…
T_{LSB}^{left}	$I\left(X_{LSB}; Y_{LSB}^{left} \middle| Y_{LSB}^{initial} = 1\right)$
T_{LSB}^{right}	$I\left(X_{LSB}; Y_{LSB}^{right} \middle| Y_{LSB}^{initial} = 0\right)$

- Use a Newton's method to optimize.

MSB Page Optimization

Read Thresholds $T_{MSB^{(1)}}^{left}, T_{MSB^{(1)}}^{right}, T_{MSB^{(2)}}^{left}$ and $T_{MSB^{(2)}}^{right}$ (Represented by dotted red lines)

Maximize $I\left(X_{LSB}; Y_{MSB^{(1)}}^{initial}, Y_{MSB^{(1)}}^{left}, Y_{MSB^{(1)}}^{right}, Y_{MSB^{(2)}}^{initial}, Y_{MSB^{(2)}}^{left}, Y_{MSB^{(2)}}^{right}\right)$

$$= I\left(X_{MSB}; Y_{MSB^{(1)}}^{initial}, Y_{MSB^{(2)}}^{initial}\right) + I\left(X_{LSB}; Y_{MSB^{(1)}}^{left}, Y_{MSB^{(1)}}^{right}, Y_{MSB^{(2)}}^{left}, Y_{MSB^{(2)}}^{right} \middle| Y_{MSB^{(1)}}^{initial}, Y_{MSB^{(2)}}^{initial}\right)$$

Equivalently, Maximize

$$I\left(X_{LSB}; Y_{MSB^{(1)}}^{left}, Y_{MSB^{(1)}}^{right}, Y_{MSB^{(2)}}^{left}, Y_{MSB^{(2)}}^{right} \middle| Y_{MSB^{(1)}}^{initial}, Y_{MSB^{(2)}}^{initial}\right):$$

$$= P\left(Y_{MSB^{(1)}}^{initial} = 1\right) \cdot I\left(X_{MSB}; Y_{MSB^{(1)}}^{left} \middle| Y_{MSB^{(1)}}^{initial} = 1\right) \quad (3)$$

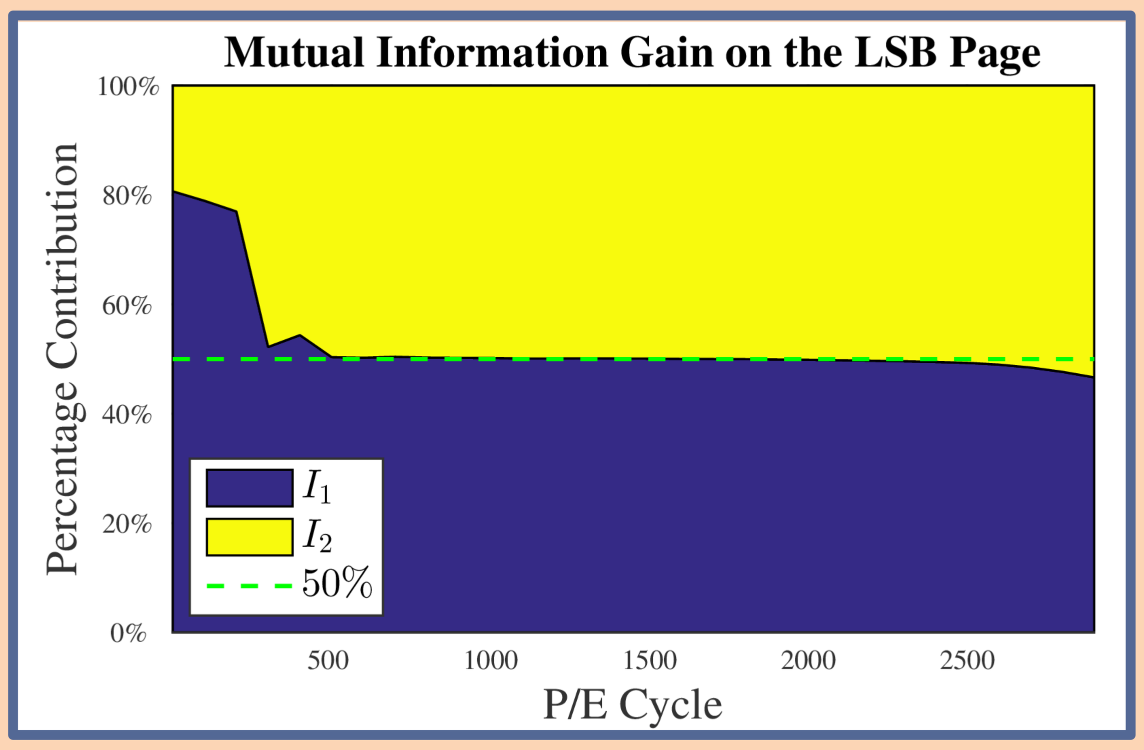
$$+ P\left(Y_{MSB^{(2)}}^{initial} = 1\right) \cdot I\left(X_{MSB}; Y_{MSB^{(2)}}^{right} \middle| Y_{MSB^{(2)}}^{initial} = 1\right) \quad (4)$$

$$+ P\left(\varepsilon_{00}\right) \cdot I\left(X_{MSB}; Y_{MSB^{(1)}}^{right}, Y_{MSB^{(2)}}^{left} \middle| \varepsilon_{00}\right) \quad (5)$$

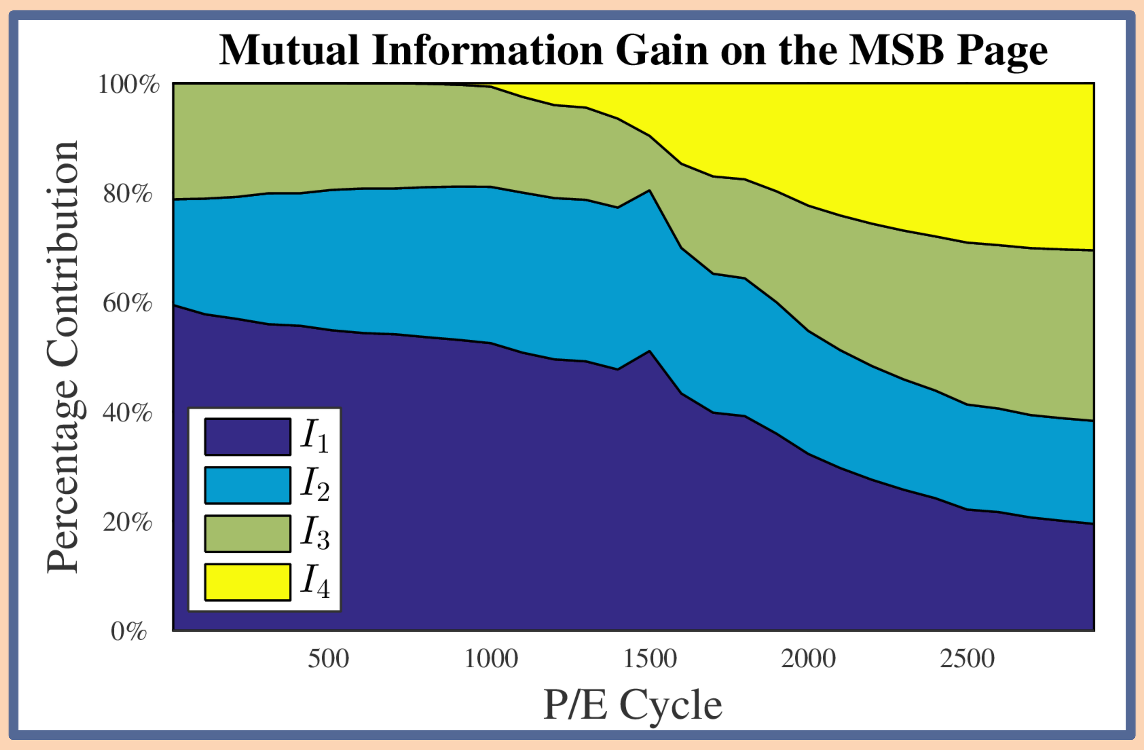
where ε_{00} is the event that $Y_{MSB^{(1)}}^{initial} = Y_{MSB^{(2)}}^{initial} = 0$

- $T_{MSB^{(1)}}^{left}$ and $T_{MSB^{(2)}}^{right}$ are decoupled optimizations.
- $T_{MSB^{(1)}}^{right}$ and $T_{MSB^{(2)}}^{left}$ are jointly optimized. Expanding to TLC and QLC reveals that **these progressive read thresholds require at most 2 thresholds to be jointly optimized.**

Normalized Mutual Information Contribution of Enhanced Precision Thresholds



$I_1 = (2)$ and $I_2 = (1)$



$I_1 = P(\varepsilon_{00}) \cdot I\left(X_{MSB}; Y_{MSB^{(1)}}^{right} \middle| \varepsilon_{00}\right)$

$I_2 = (3), I_3 + I_1 = (5)$, and $I_4 = (4)$

Future Work

- For Hard Decision Reads, compare the effects of Minimize Error Probability vs. Maximizing Mutual Information.
- Consider the effects of Joint Decoding and how it compares in Mutual Information gains to Enhanced Precision.
- Expansion of Enhanced Precision and Joint Decoding analysis to TLC and QLC.
- An analysis of frame error rate using a combination of the following:
  - Enhanced Precision
  - Joint Decoding
  - LDPC Decoders