Neighbor-Cell Assisted Error Correction for MLC NAND Flash Memories

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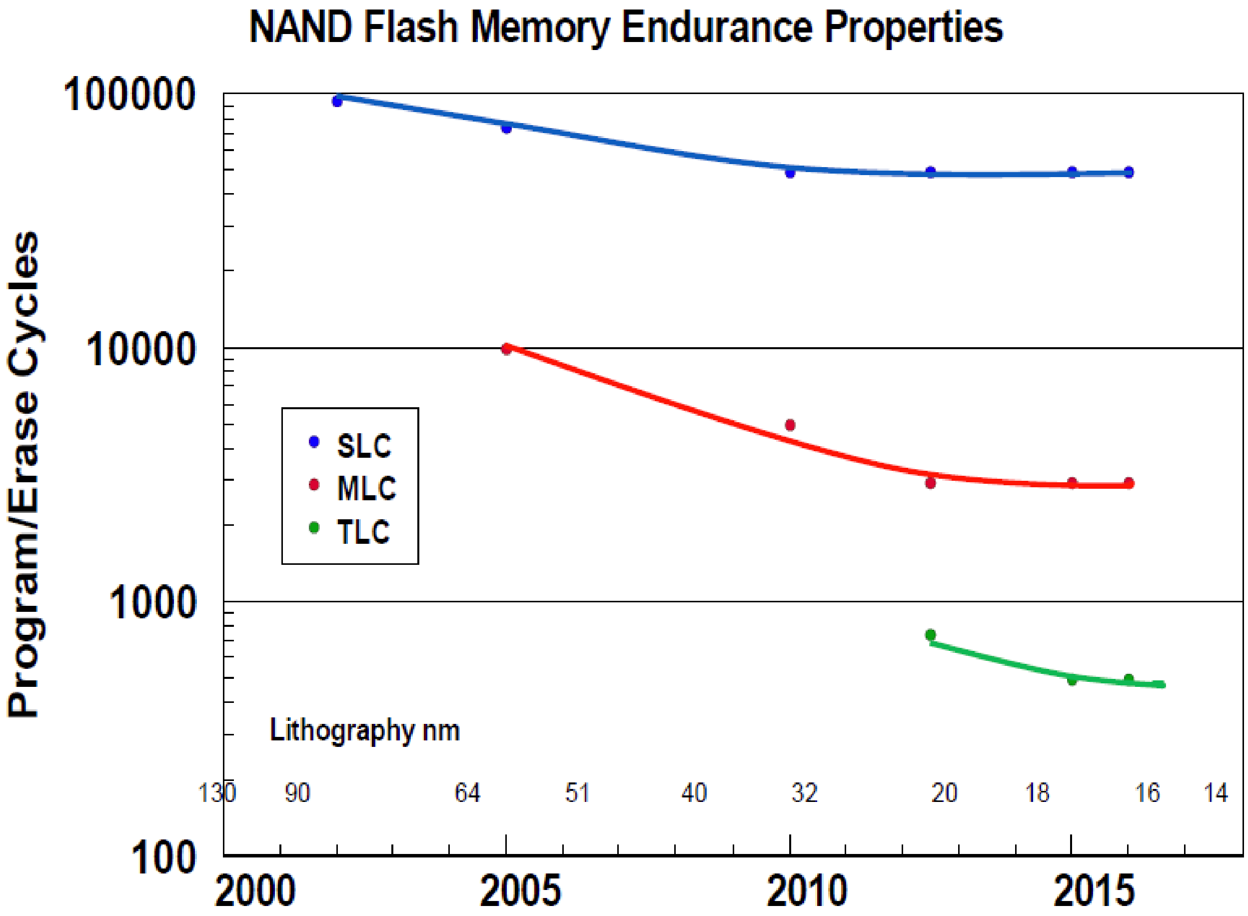
Executive Summary

- Problem: Cell-to-cell Program interference causes threshold voltage of flash cells to be distorted even they are originally programmed correctly
- Our Goal: Develop techniques to overcome cell-to-cell program interference
  - Analyze the threshold voltage distributions of flash cells *conditionally upon the values of immediately neighboring cells*
  - Devise new error correction mechanisms that can *take advantage of the values of neighboring cells* to reduce error rates over conventional ECC
- Observations: Wide overall distribution can be decoupled into multiple narrower conditional distributions which can be separate easily
- Solution: Neighbor-cell Assisted Correction (NAC)
  - Re-read a flash memory page that initially failed ECC with a set of read reference voltages corresponding to the conditional threshold voltage distribution
  - Use the re-read values to correct the cells that have neighbors with that value
  - Prioritize reading assuming neighbor cell values that cause largest or smallest cell-to-cell interference to allow ECC correct errors with less re-reads
- Results: NAC improves flash memory lifetime by 39%
  - Within nominal lifetime: no performance degradation
  - In extended lifetime: less than 5% performance degradation

Outline

- Background of Program Interference in NAND Flash Memory
- Statistical Analysis of Cell-to-cell Program Interference
- Neighbor-cell Assisted Correction (NAC)
- Evaluation
- Conclusions

Flash challenges: Reliability and Endurance



E. Grochowski et al., “Future technology challenges for NAND flash and HDD products”, Flash Memory Summit 2012

- **P/E cycles (provided)**

A few thousand

- **P/E cycles (required)**

Writing
the full capacity
of the drive
10 times per day
for 5 years
(STEC)

> 50k P/E cycles

NAND Flash Error Model

Write

Noisy NAND

Read

Dominant errors in NAND flash memory

Solutions?

Write

- **Erase block**
- **Program page**

- **Neighbor page program**

- **Retention**

Read

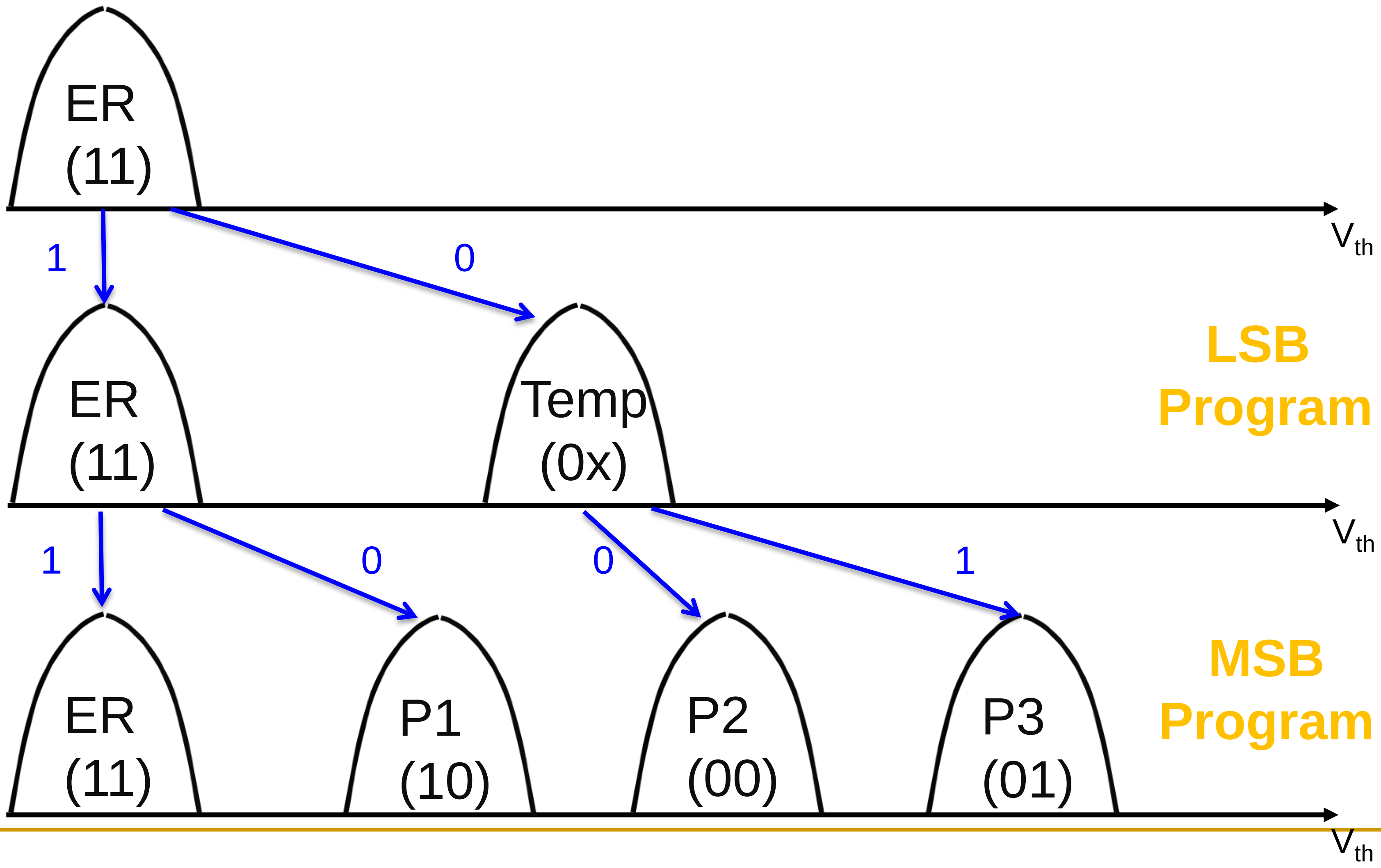
Cai et al., “Threshold voltage distribution in MLC NAND Flash Memory: Characterization, Analysis, and Modeling”, DATE 2013

Cai et al., “Program Interference in MLC NAND Flash Memory: Characterization, Modeling, and Mitigation”, ICCD 2013

Cai et al., “Flash Correct-and-Refresh: Retention-aware error management for increased flash memory lifetime”, ICCD 2012

How Aggressor Cells are Programmed

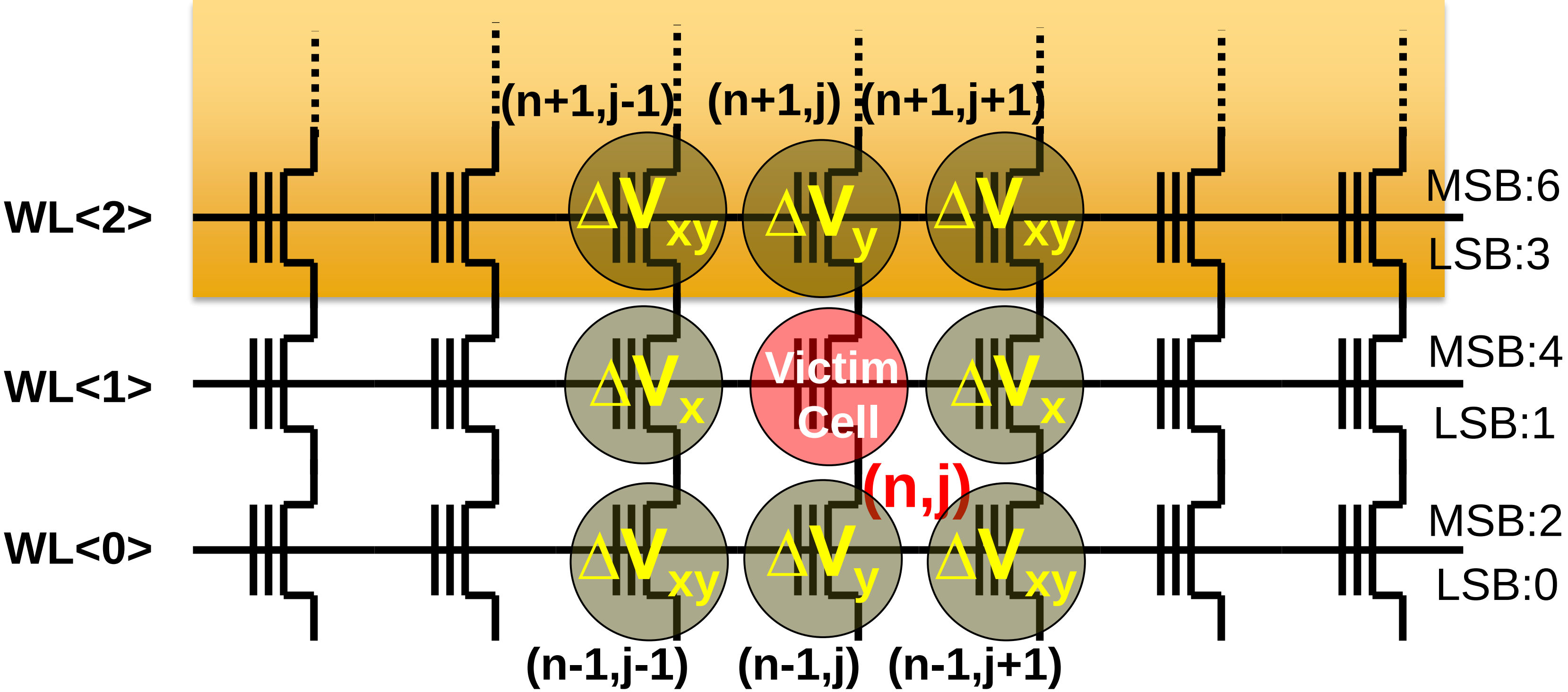
- Programming 2-bit MLC NAND flash memory in two steps



LSB Program

MSB Program

How Program Interference Happens



- Model of victim cell threshold voltage changes when neighbor cells are programmed

$$\Delta V_{victim}(n,j) = \sum_{y=j-K}^{j+K} \sum_{x=n+1}^{n+M} \alpha(x,y)\Delta V_{neighbor}(x,y) + \alpha_0 V_{victim}^{before}(n,j)$$

Cai et al., "Program Interference in MLC NAND Flash Memory: Characterization, Modeling, and Mitigation", ICCD 2013

Our Goals and Related Work

- Our goals
  - Analyze the threshold voltage distributions of flash cells *conditionally upon the values of immediately neighboring cells*
  - Devise new error correction mechanisms that can *take advantage of the values of neighboring cells* to reduce error rates over conventional ECC

- Limitations of previous work
  - Program interference mitigation [Cai+ICCD 2013]
    - Predict optimum read reference voltage for overall distribution (Unaware of the value dependence of neighbor aggressor cells)
  - Signal processing [Dong + TCAS-I 2010]
    - Assumes threshold voltage changes of neighbor aggressor cells are known (difficult to record)
    - Assume the average of threshold voltage of cells in erased state are known (not known for state-of-art flash memory)
    - Assume the threshold voltage of cells in the same state are close enough (greatly different)
    - Read the victim cells and neighbor aggressor cells with 2^n times, where n is in the range of 4 and 6 (large latency)

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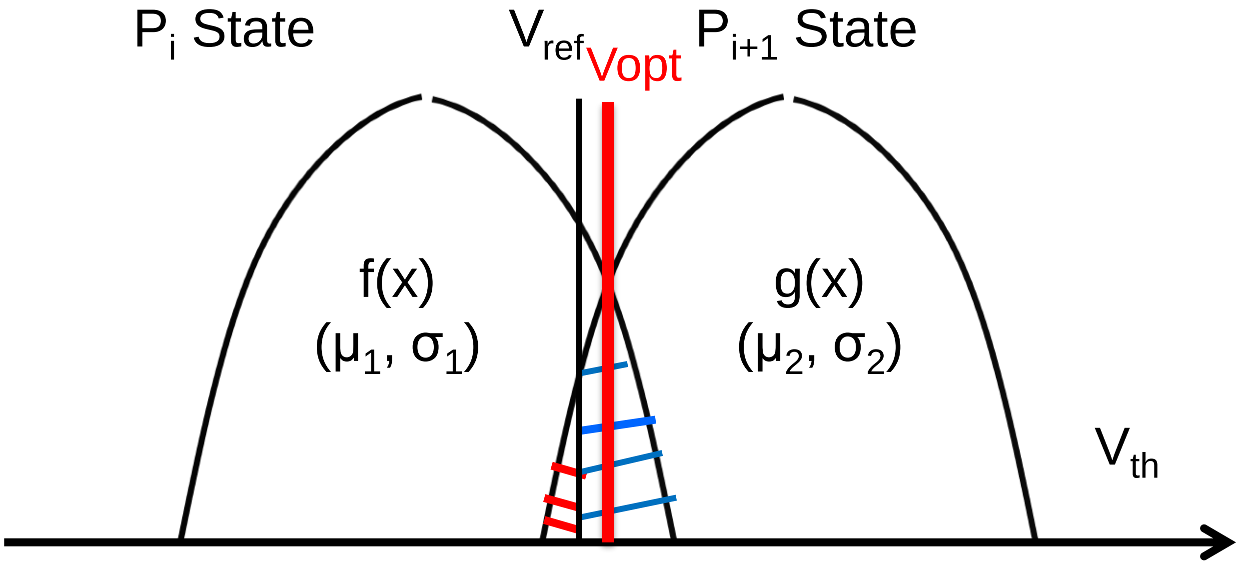
Flash Voltage Distribution Analysis

- Formal statistically analyze
  - How to optimize read reference voltage?
  - What determines minimum raw bit error rate?
  - Overall distribution vs conditional distribution
  - Can we achieve smaller BER than minimum raw BER of overall distribution?
- Empirical silicon measurement and validation

Optimizing Read Reference Voltage

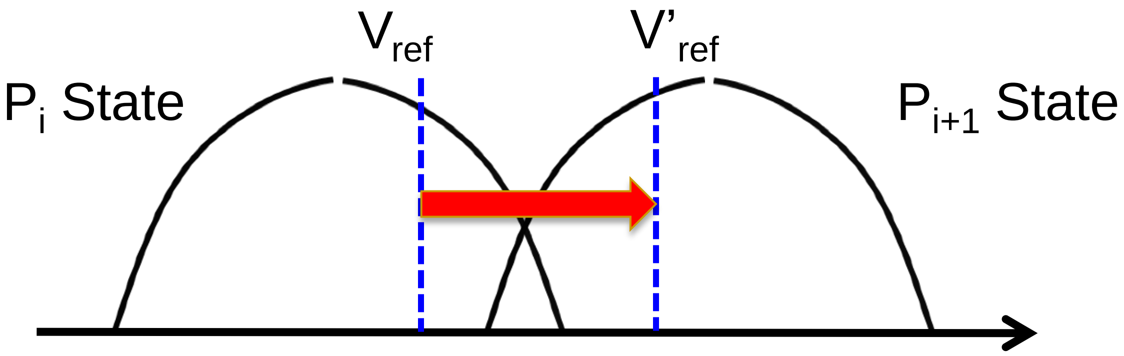


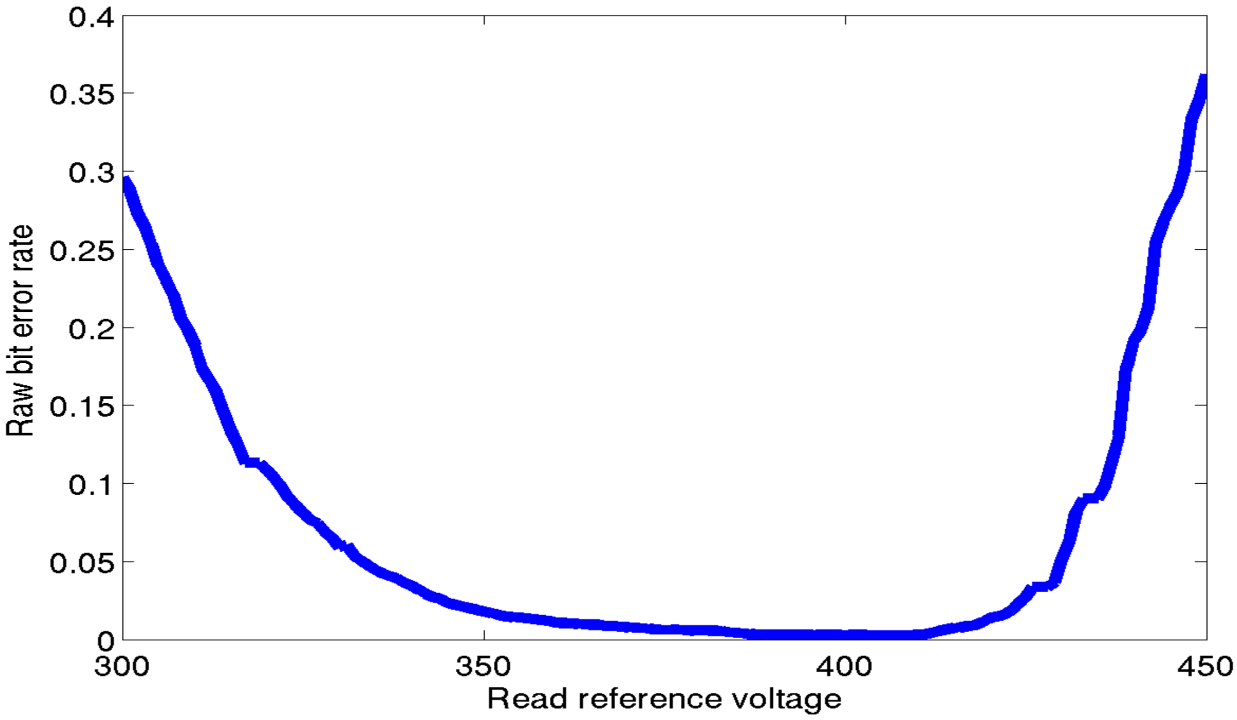
- Raw bit error rate (BER)

$$ErrRate^{total} = P_0 \times \int_{v}^{+\infty} f(x)dx + P_1 \times \int_{-\infty}^{v} g(x)dx$$

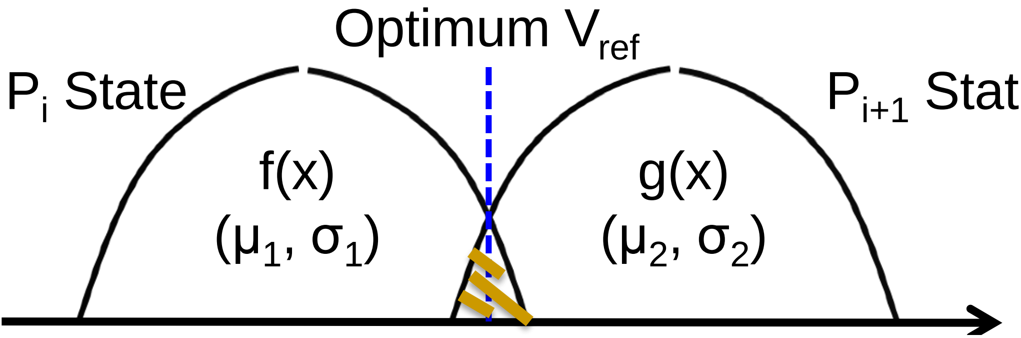
- Optimum read reference voltage that achieves the minimum raw BER is at the cross-point of neighbor distributions when random data are programmed

BER with Read Reference Voltage





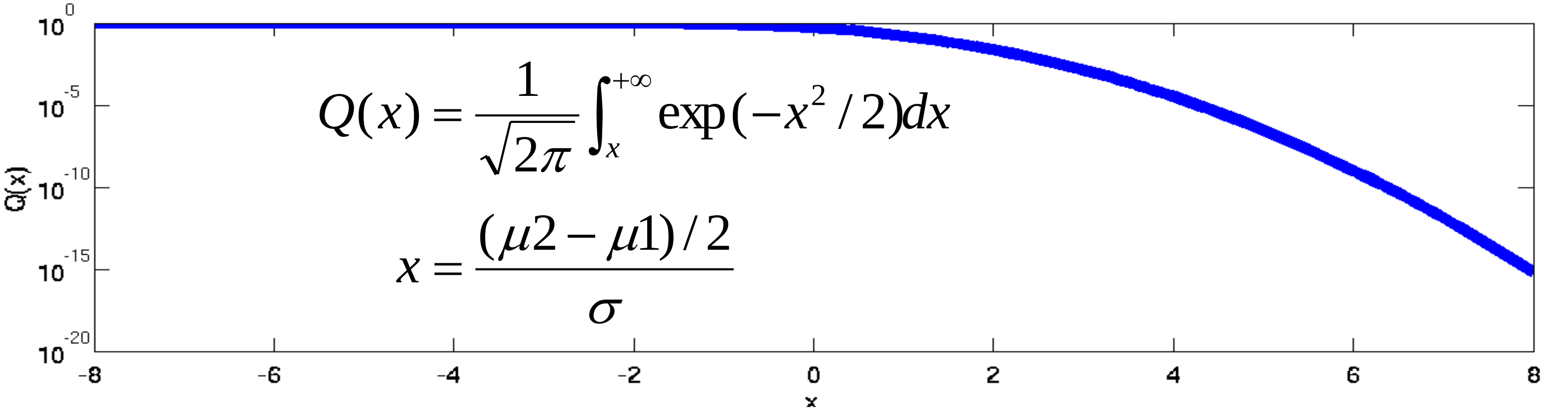
Modeling the Minimum BER



When

1. f(x) and g(x) are Gaussian
2. $\sigma_1 = \sigma_2 = \sigma$

$$RBER\min = \frac{1}{\sqrt{2\pi}}\int_{\boxed{(\mu2-\mu1)/2\sigma}}^{+\infty}\exp(-x^2/2)dx$$

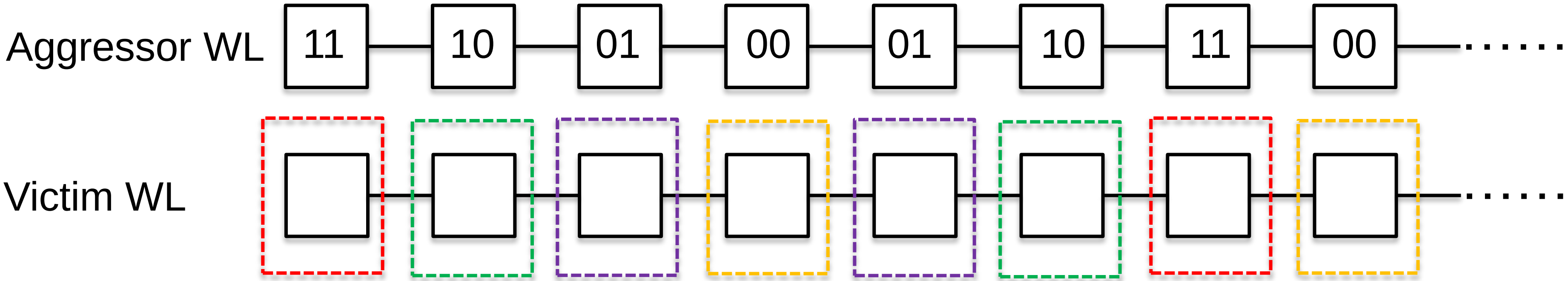


$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_{x}^{+\infty}\exp(-x^2/2)dx$$

$$x = \frac{(\mu2-\mu1)/2}{\sigma}$$

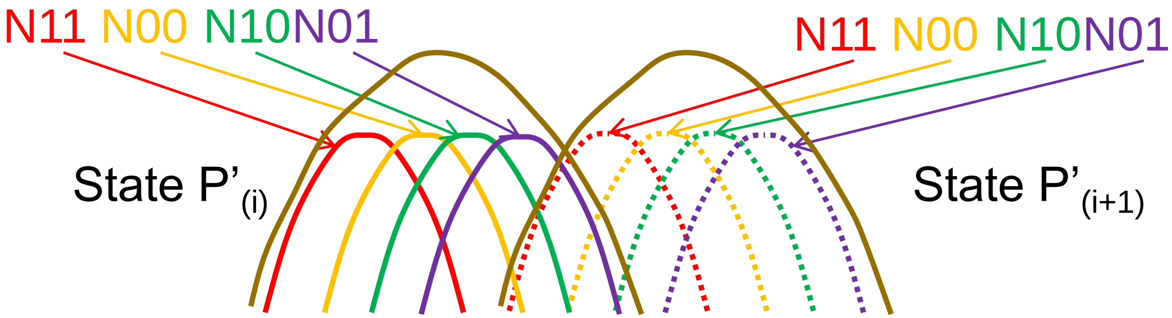
- Minimum raw BER can be further minimized by
    - Increasing distance between neighbor distributions (μ_2-μ_1)
    - Decreasing the standard deviation (σ)

Secrets of Threshold Voltage Distributions

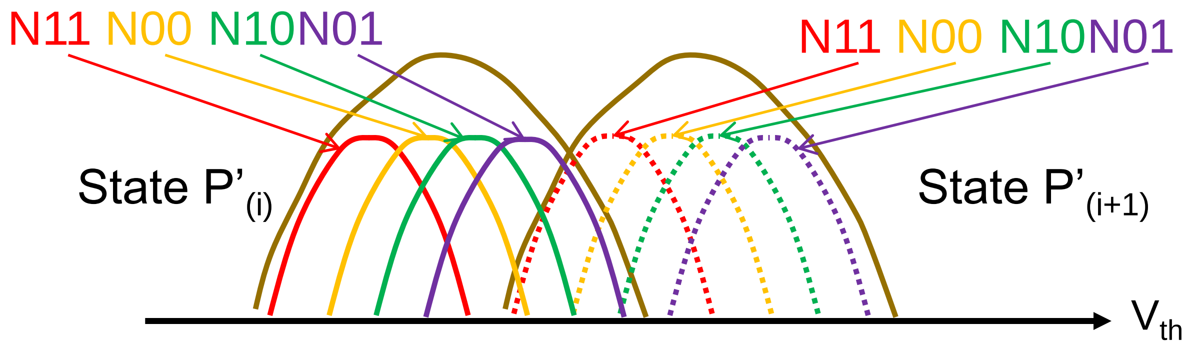


Victim WL before MSB page of aggressor WL are programmed

Victim WL after MSB page of aggressor WL are programmed



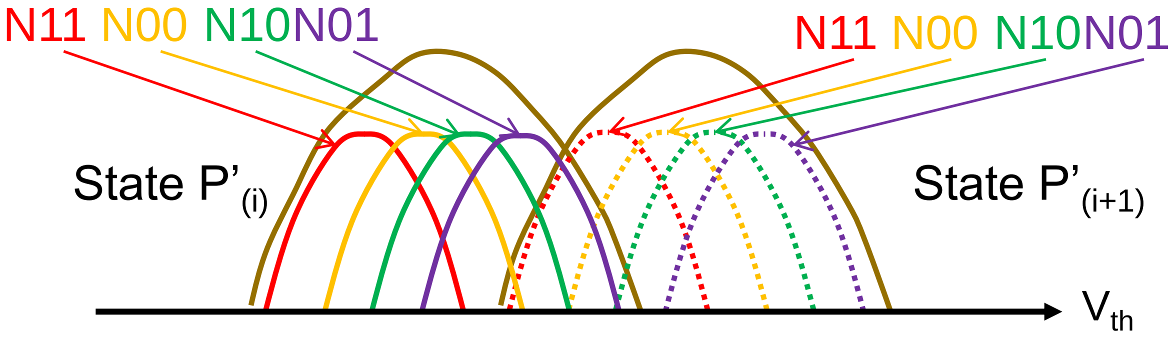
Overall vs Conditional Distributions (1)



- Overall distribution: p(x)
- Conditional distribution: p(x, z=m)
  - m could be 11, 00, 10 and 01 for 2-bit MLC all-bit-line flash
- Overall distribution is the sum of all conditional distribution

$$p(x) = \sum_{m=1}^{2^n} p(x, z = m)$$

Overall vs Conditional Distributions (2)

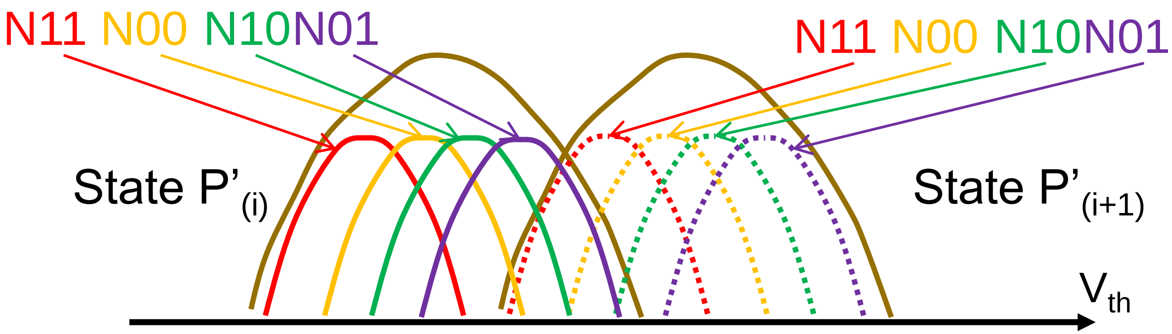


- Distance of two neighbor overall distribution is the average of the distances of neighbor conditional distributions

$$E(X^{P(i+1)}) - E(X^{P(i)}) = \frac{1}{N}\sum E(x_m^{P(i+1)}) - \frac{1}{N}\sum E(x_m^{P(i)}) = \frac{1}{N}\sum (E(x_m^{P(i+1)}) - E(x_m^{P(i)}))$$

- Distance of conditional distribution of different type is close
  - Average interference is same when aggressor cells are programmed with the same value
- Distance of two neighbor overall distribution is close to the distances of any neighbor conditional distributions

Overall vs Conditional Distributions (3)



- Variance of overall distribution is larger than the average of the variance of all conditional distributions

$$Var(X)=\frac{1}{N}\sum Var(x_m)+\frac{1}{N^2}\sum\sum(E(x_m)-E(x_n))^2$$

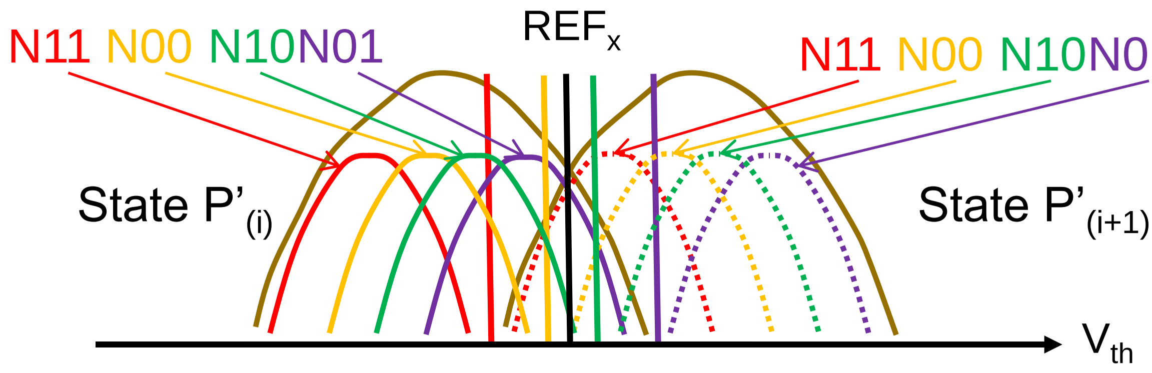
Variance of overall distribution

Variance of conditional distribution

Distance of conditional distribution pair

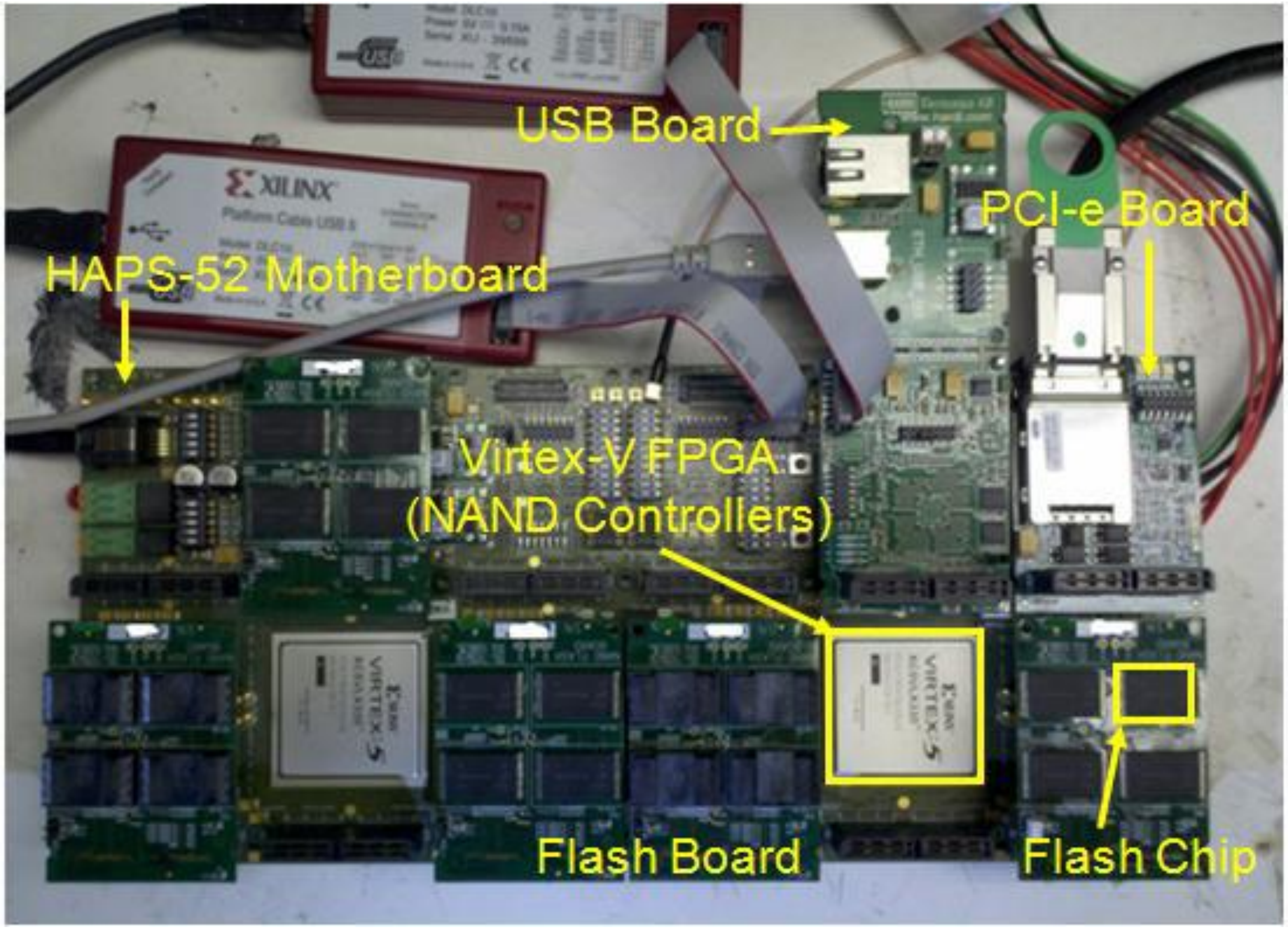
  - Different conditional distributions do not overlap
- Variances of conditional distribution of different type are close
- Variance of overall distribution is larger than that of any conditional distributions

Overall vs Conditional Reading



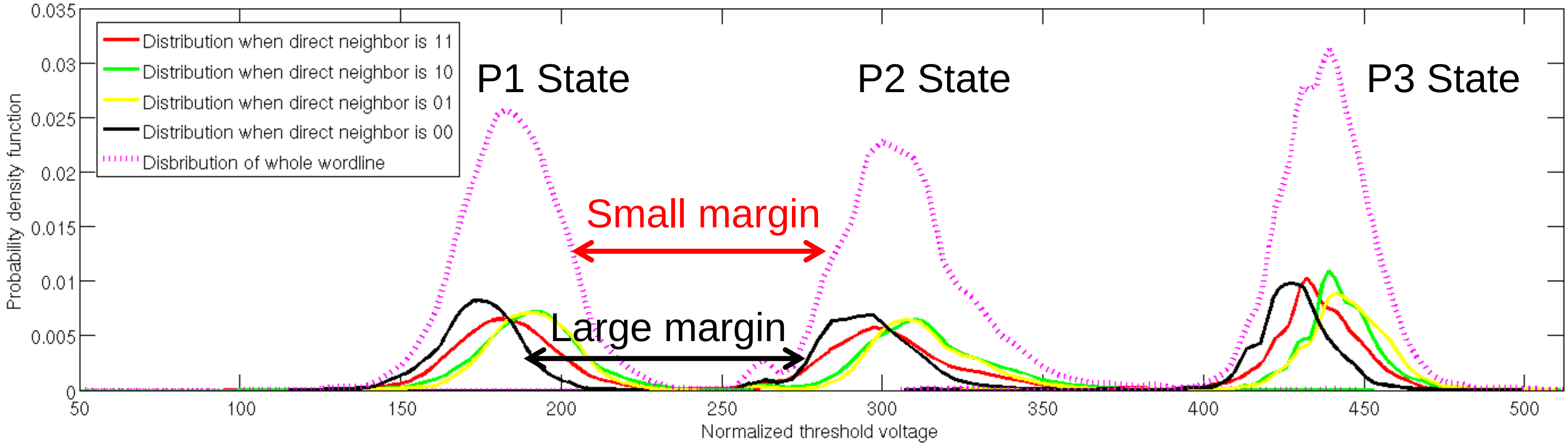
- Distance of two neighbor overall distribution is close to the distances of any neighbor conditional distributions
- Variance of overall distribution is larger than that of any conditional distributions
- Minimum raw BER when read with overall distribution will be larger than that when read with conditional distribution

Hardware Platform for Measurement



Cai et al., "FPGA-based solid-state drive prototyping platform", FCCM 2011
Cai et al., "Error patterns in MLC NAND flash memory: Measurement, characterization, and analysis", DATE 2012

Measurement Results



Small margin

Large margin

	Overall	x_{11} (ER)	x_{10} (P1)	x_{00} (P2)	X_{01} (P3)
Distance	65.4	65.4	64.7	66.4	65.8
Variance	385.9	286.2	256.7	242.8	252.1
SNR	3.4	3.8	3.9	4.2	4.1
BER	$3\text{x}10^{-4}$	$7\text{x}10^{-5}$	$5\text{x}10^{-5}$	$2\text{x}10^{-5}$	$3\text{x}10^{-5}$

Raw BER of conditional reading is much smaller than overall reading

Summary

- There exists an optimum read reference that can achieve the minimum raw BER
- The minimum raw BER decreases as signal-to-noise ratio increases
- The distance (signal) of the overall distribution between neighboring states is close to that of each of the conditional distributions
- The variance (noise) of each conditional distribution is smaller than that of the overall distribution
- The variances of different conditional distributions are close
- The signal-to-noise ratio of the conditional distribution is larger than that of the overall distribution
- The minimum raw BER obtained after reading with the conditional distribution is much smaller than that obtained after reading with the overall distribution.

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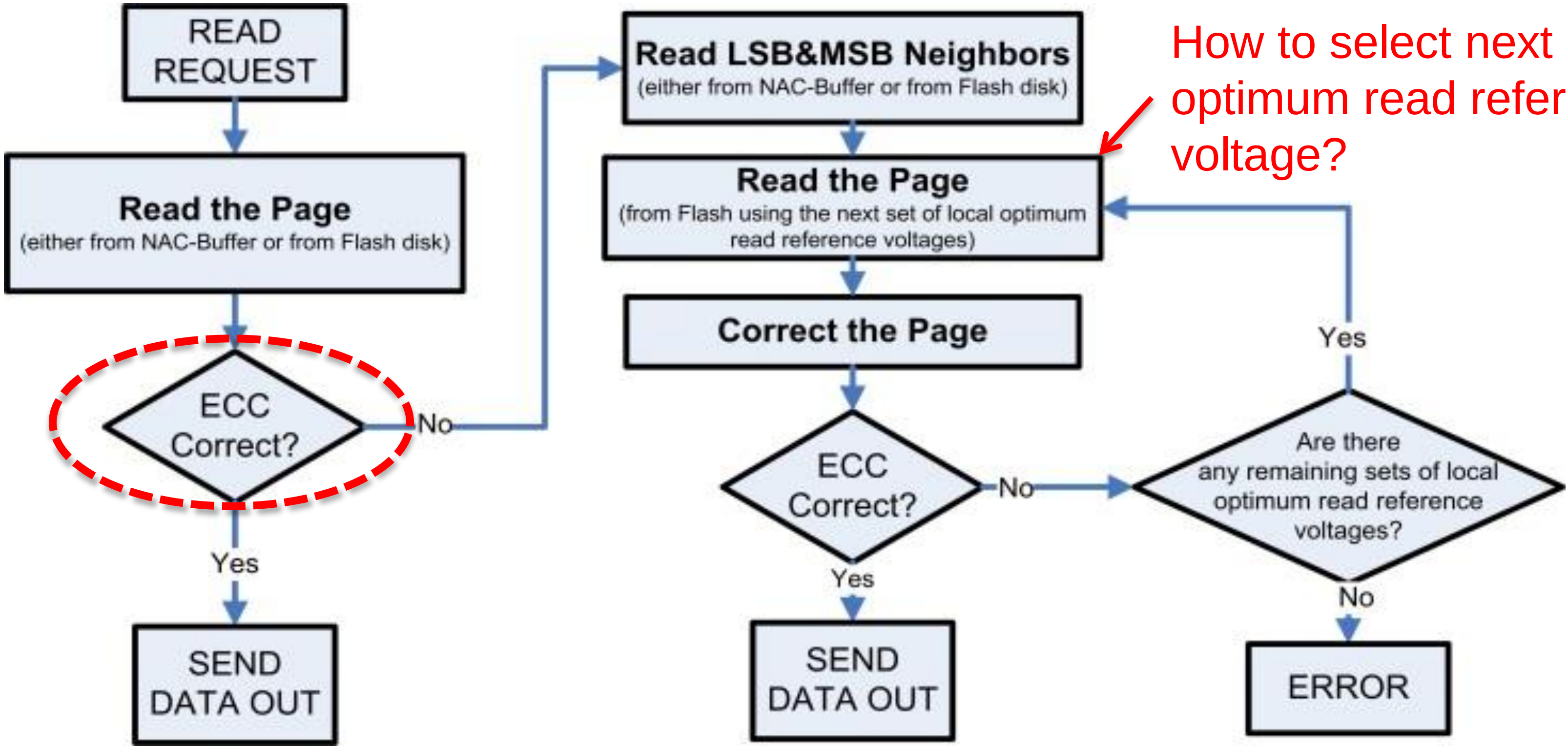
Neighbor Assisted Reading (NAR)

- Neighbor assisted reading
  - Read neighbor pages and classifie the cells in a wordline into N types based on the values stored in the corresponding direct-neighbor aggressor cells (N=4 for 2-bit MLC flash)
  - Read the cells of each type, a different set of local optimum read reference voltages (that minimizes the bit error rate) is used (i.e., REF_{x11}, $REF_{x00,}$ REF_{x10}, REF_{x01})
  - Combined all reads as one complete read and send to ECC

- Performance degradation
  - $\log_2(N)$ neighbor reads plus N reads on the selected wordline
  - Down to 16.7% performance for 2-bit MLC flash memory

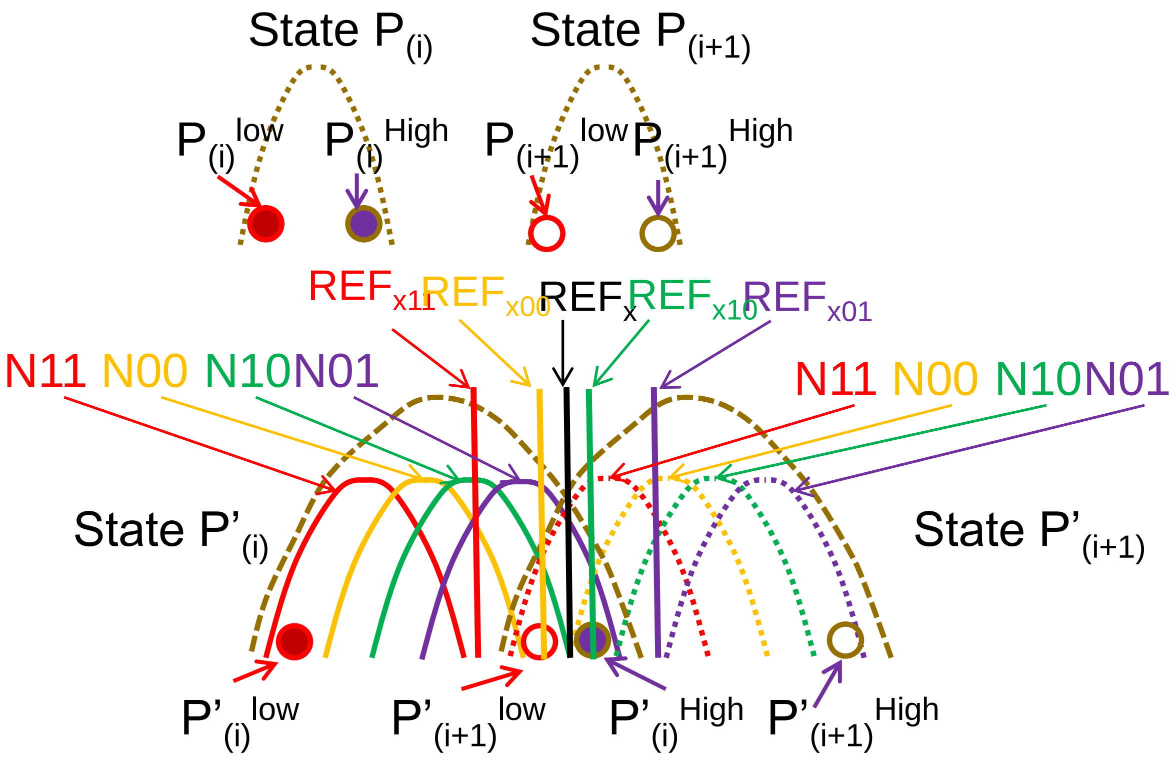
Neighbor Assisted Correction (NAC)



How to select next local optimum read reference voltage?

- NAC is build upon NAR, but only triggered when optimum reading based on overall distribution fails
  - Performance degraded to $\frac{1}{(1+P_{fail}(N+\log_2(N)))}$ $(P_{fail} < 0.01)$

Prioritized NAC

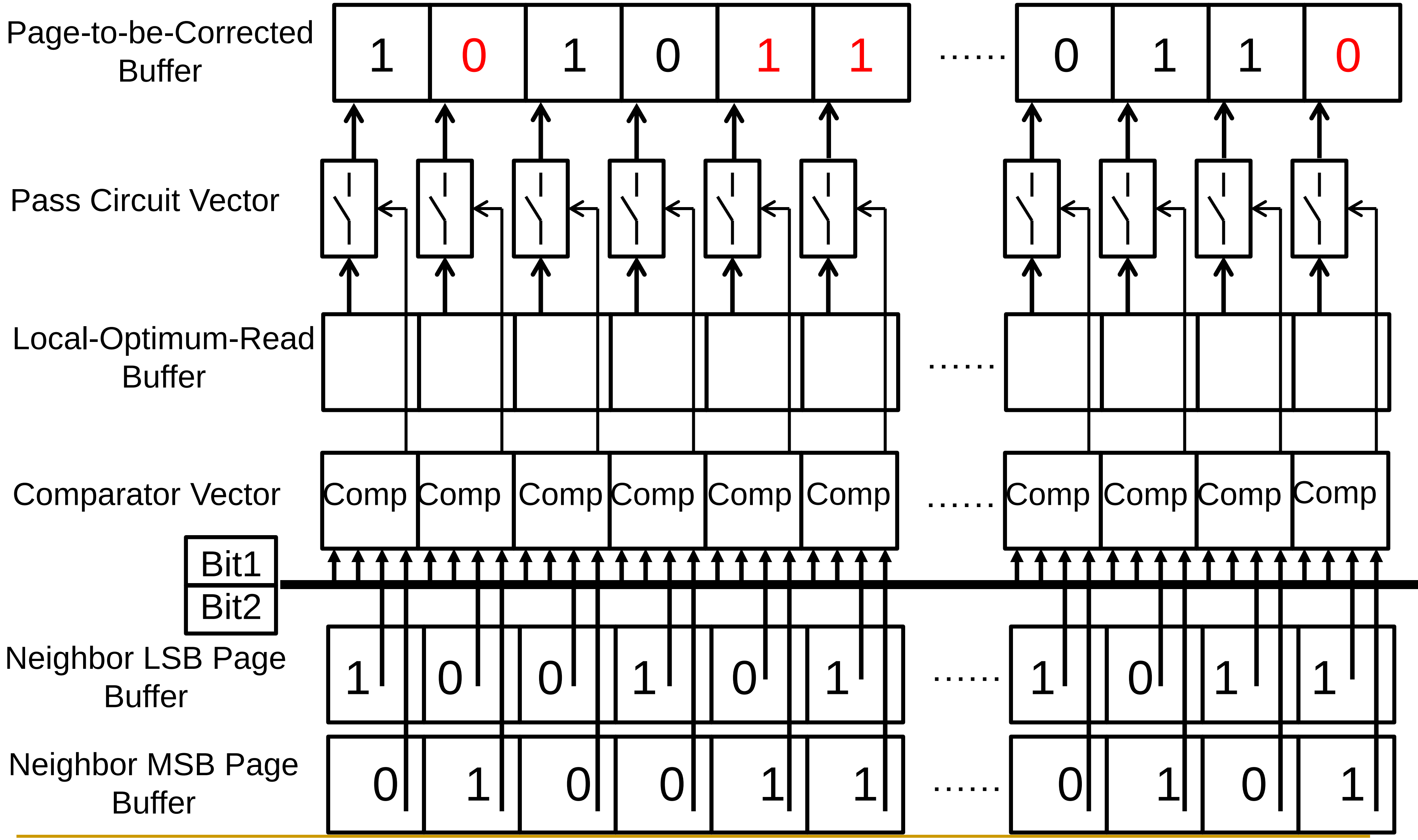


- Dominant errors are caused by the overlap of lower state interfered by high neighbor interference and the higher state interfered by low neighbor interference

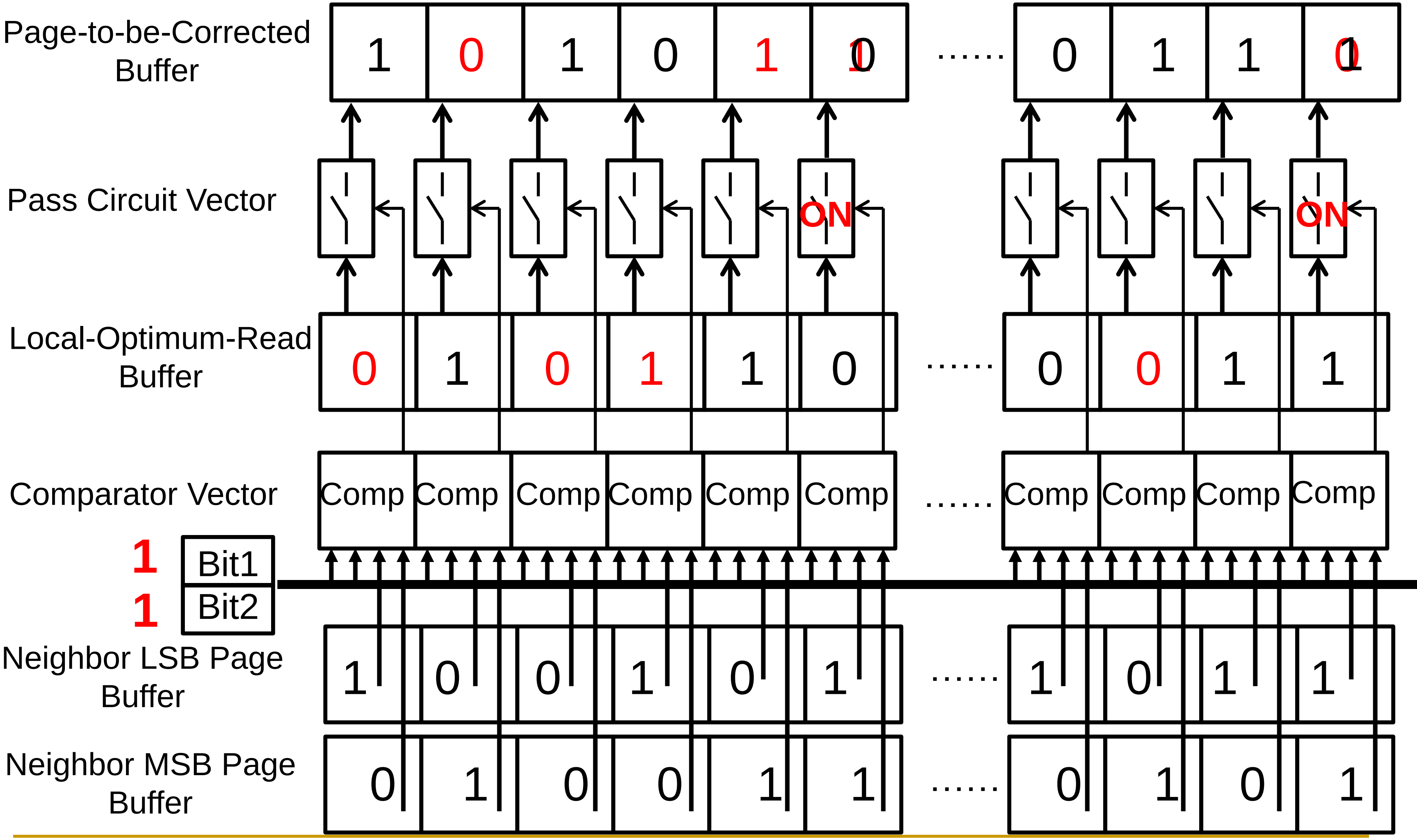
Procedure of NAC

- Online learning
  - Periodically (e.g., every 100 P/E cycles) measure and learn the overall and conditional threshold voltage distribution statistics (e.g. mean, standard deviation and corresponding optimum read reference voltage)
- NAC procedure
  - Step 1: Once ECC fails reading with overall distribution, load the failed data and corresponding neighbor LSB/MSB data into NAC
  - Step 2: Read the failed page with the local optimum read reference voltage for cells with neighbor programmed as 11
  - Step 3: Fix the value for cells with neighbor 11 in step 1
  - Step 4: Send fixed data for ECC correction. If succeed, exit. Otherwise, go to step 2 and try to read with the local optimum read reference voltage 10, 01 and 00 respectively

Microarchitecture of NAC (Initialization)



NAC (Fixing cells with neighbor 11)



Page-to-be-Corrected Buffer: 1 0 1 0 1 1 0 …… 0 1 1 0 1

Pass Circuit Vector: ON …… ON

Local-Optimum-Read Buffer: 0 1 0 1 1 0 …… 0 0 1 1

Comparator Vector: Comp Comp Comp Comp Comp Comp …… Comp Comp Comp Comp

1 Bit1

1 Bit2

Neighbor LSB Page Buffer: 1 0 0 1 0 1 …… 1 0 1 1

Neighbor MSB Page Buffer: 0 1 0 0 1 1 …… 0 1 0 1

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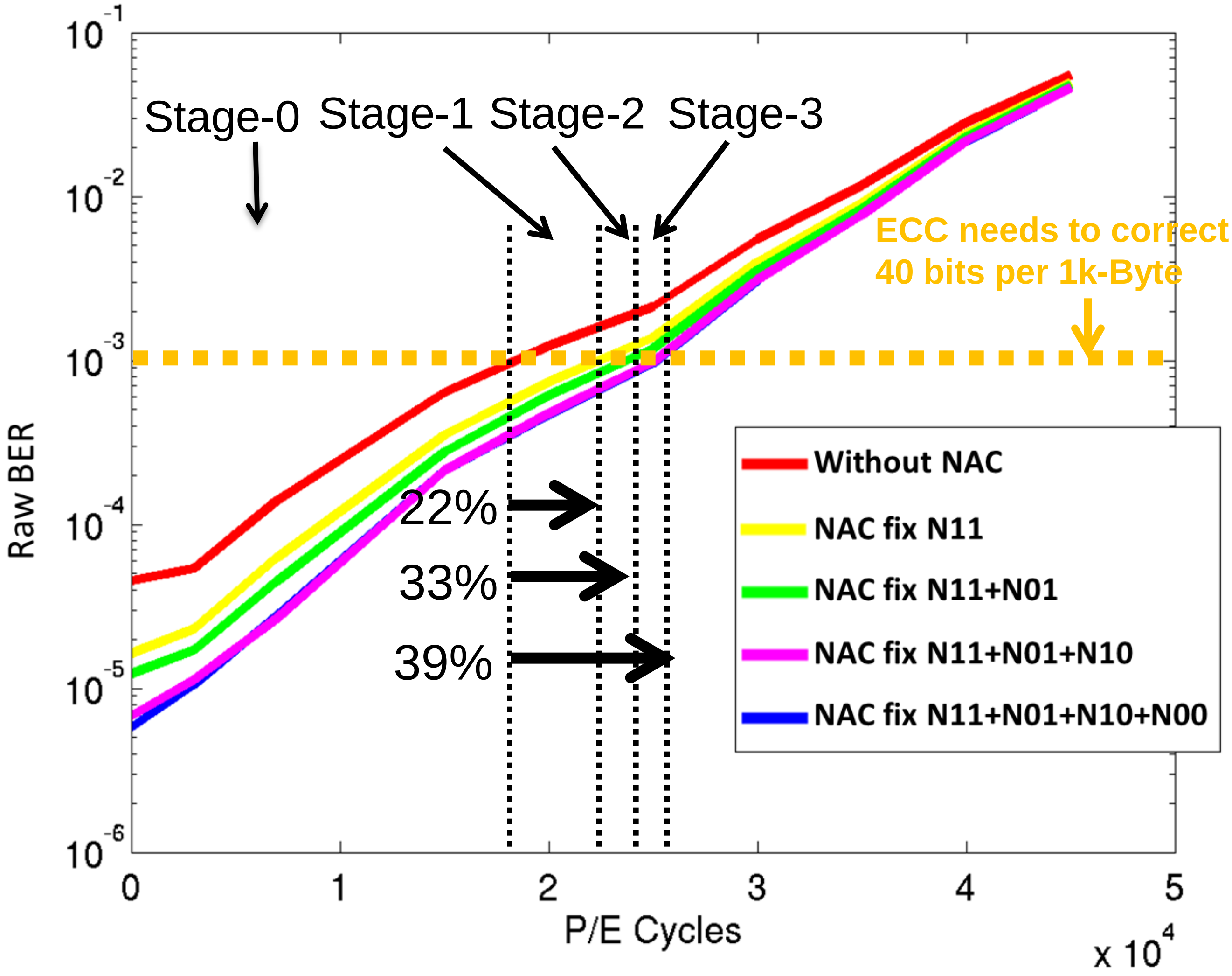
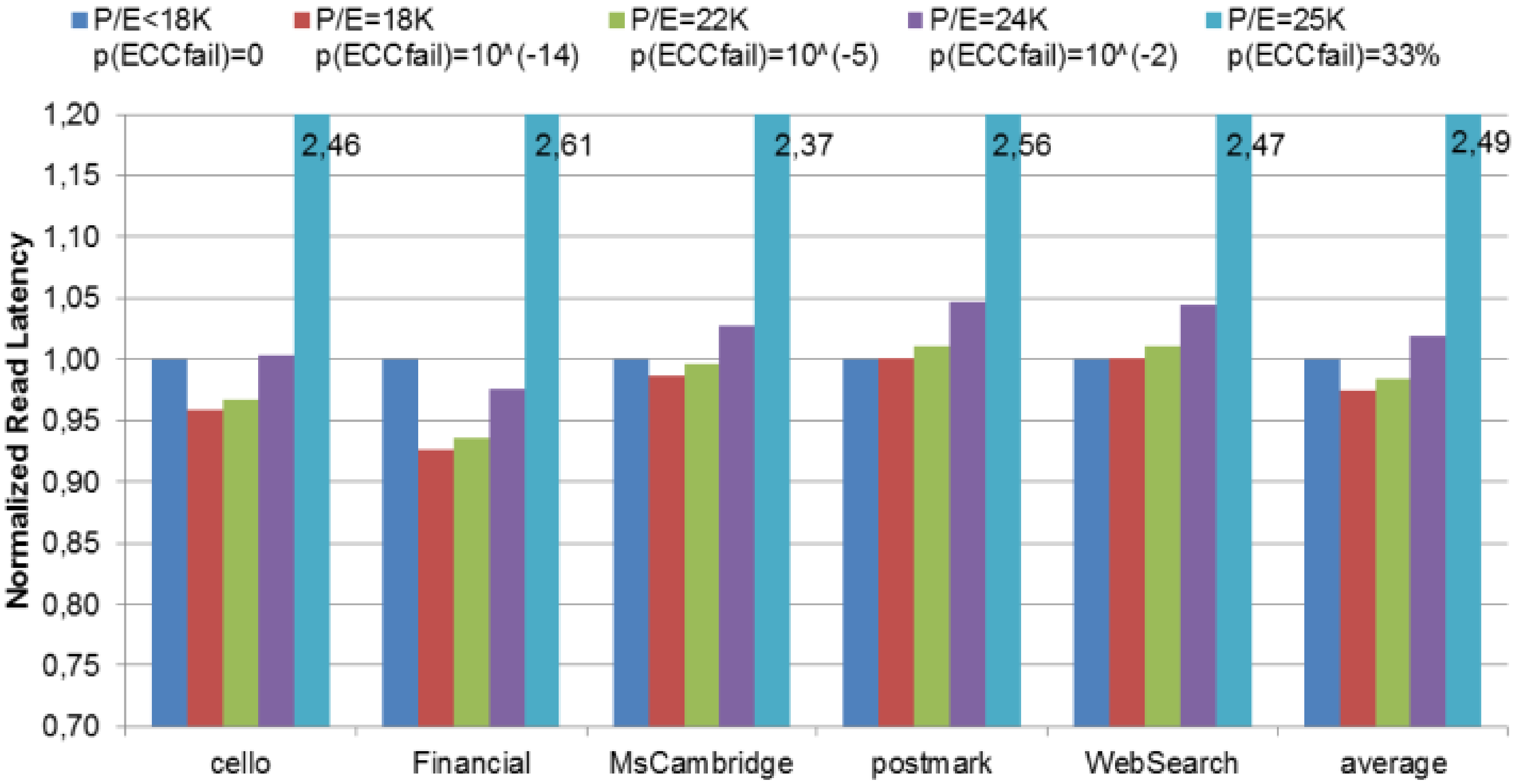
Lifetime Extension with NAC



Performance Analysis of NAC



Conclusion

- Provide a detailed statistical and experimental analysis of threshold voltage distributions of flash memory cells conditional upon the immediate-neighbor cell values
- Observation: conditional distributions can be used to determine read reference voltages that can minimize raw bit error rate (RBER) when the cells are read
- Neighbor-cell assisted error correction (NAC) techniques extend flash lifetime with negligible overhead
  - First read with global optimum read reference voltage
  - Correct the failed data with conditional reading
  - Conditional reading can be executed in prioritized order
  - Lifetime extend by 39% with negligible overhead

Thank You.

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