Does soft-decision ECC improve endurance?

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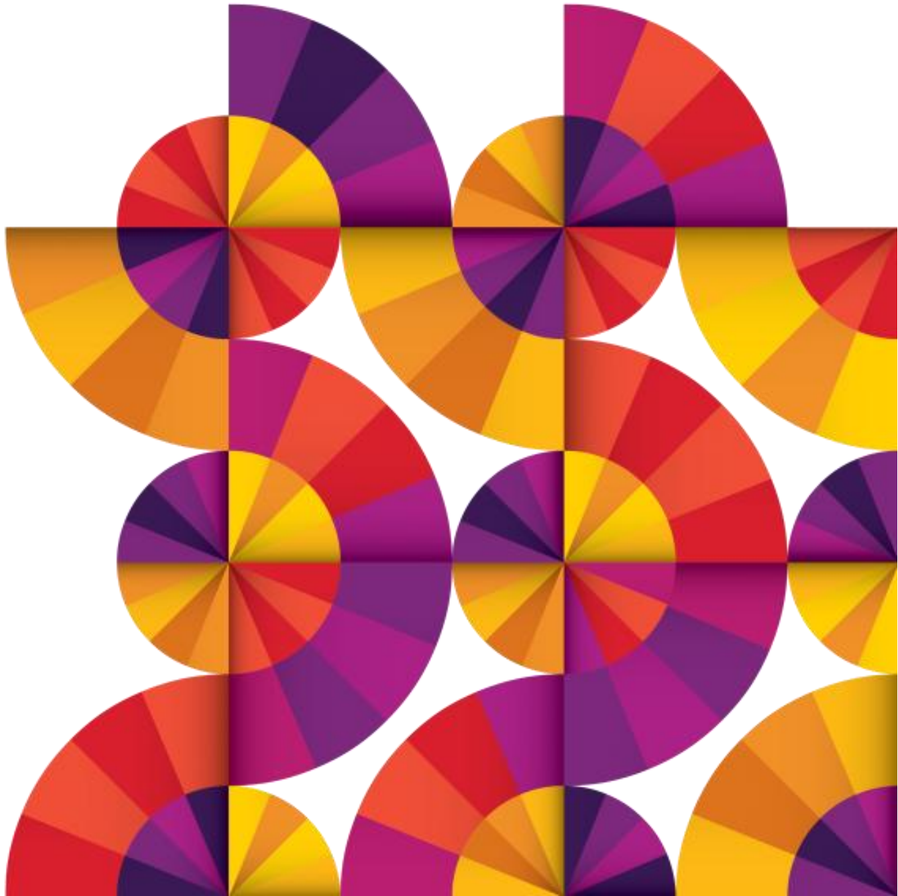


Outline

- Motivation
  - Why do we need more endurance?
- Capacity
  - What is channel capacity?
  - How can it be used to compare different error-correction techniques?
- MLC Flash Channel
  - How do we evaluate capacity for MLC Flash devices?
- Experimental Results + Analysis
  - How much endurance gain can soft-decision ECC offer for real MLC devices?
  - Why does the MLC programming algorithm affect capacity?
- Conclusion

Why do we need more endurance?

All-flash storage solutions are gaining momentum in the enterprise sector

HOW?

High performance and rapidly decreasing $/GB

WHAT IS DRIVING DOWN COST?

In part, the move from SLC → eMLC → cMLC

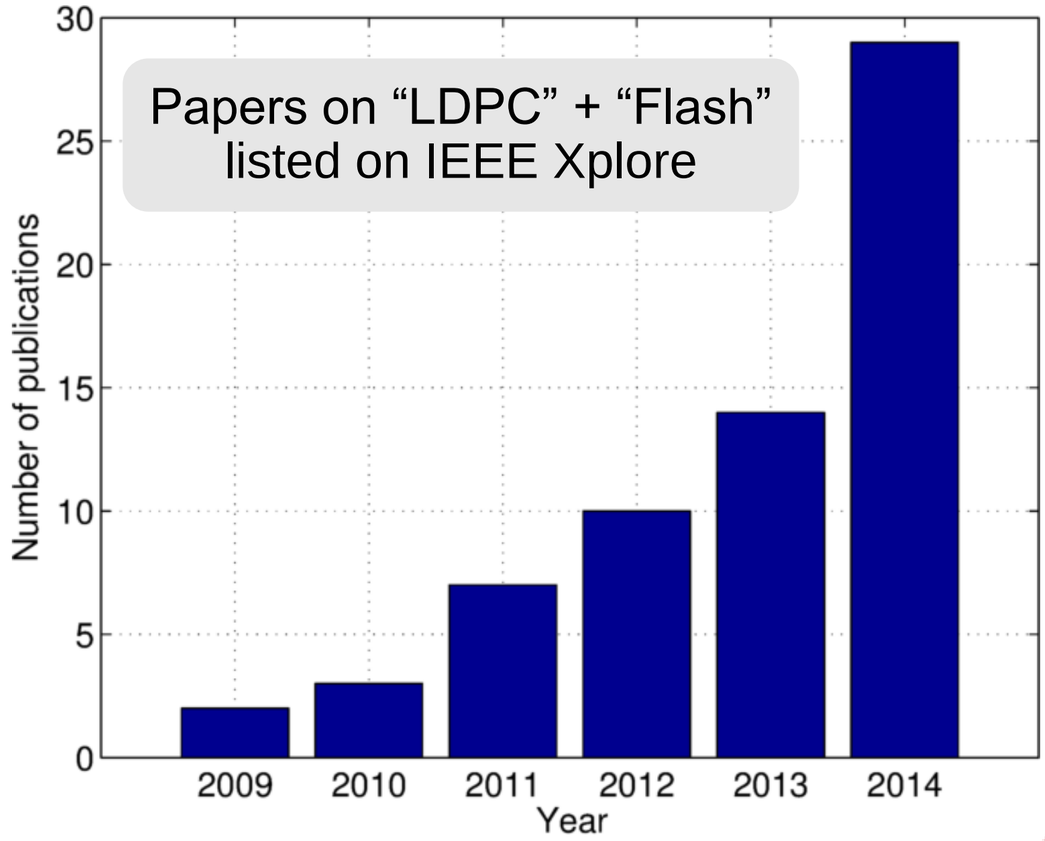
ISN'T cMLC VERY UNRELIABLE?

2D cMLC has ~3k P/E cycling endurance

BUT ENTERPRISE NEEDS >20k?

Advanced ECC is required to boost endurance

LDPC codes can make use of "soft" information from Flash to enhance reliability

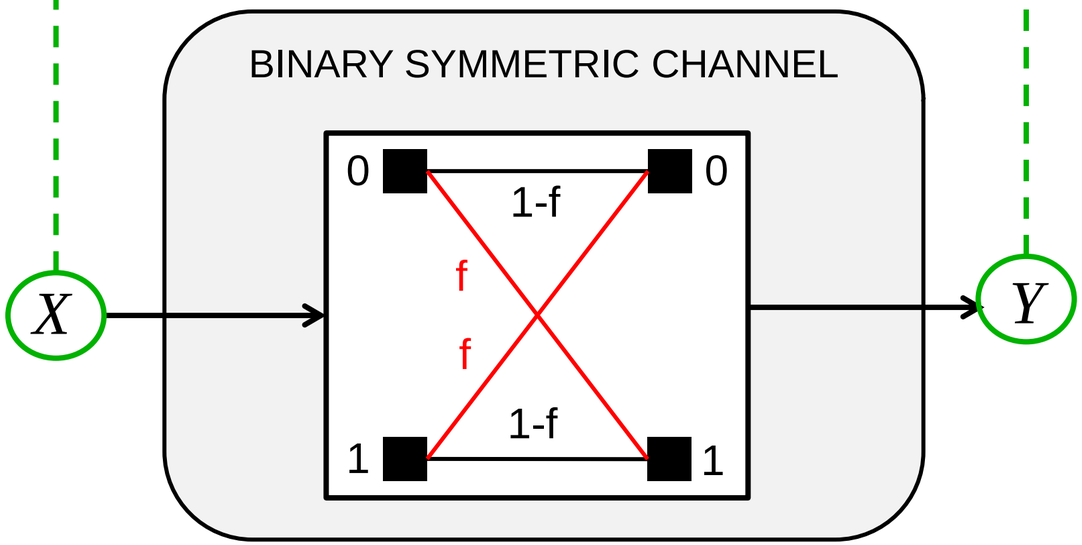


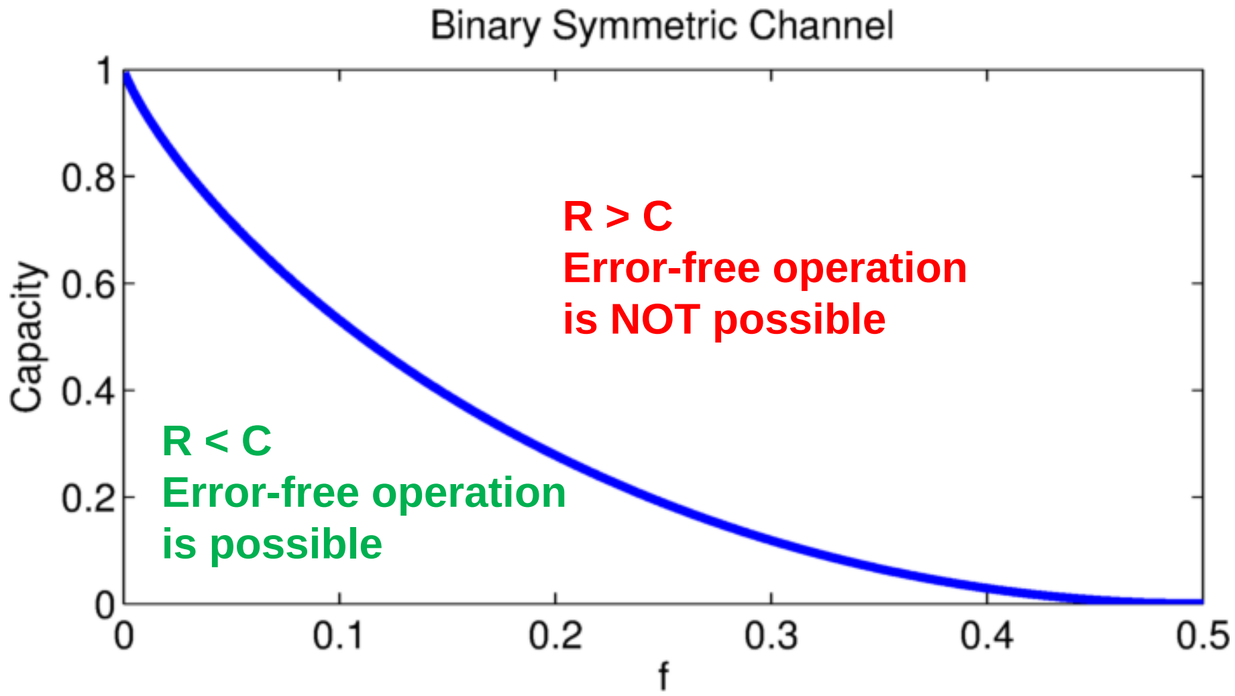
Source: http://ieeexplore.ieee.org/

Channel Capacity (Shannon 1948)

Channel Capacity:
Amount of information (in bits) that channel output (**Y**) contains about channel input (**X**)
(*Maximized over all input distributions*)

$$C = \max_{P(X)} I(X;Y)$$

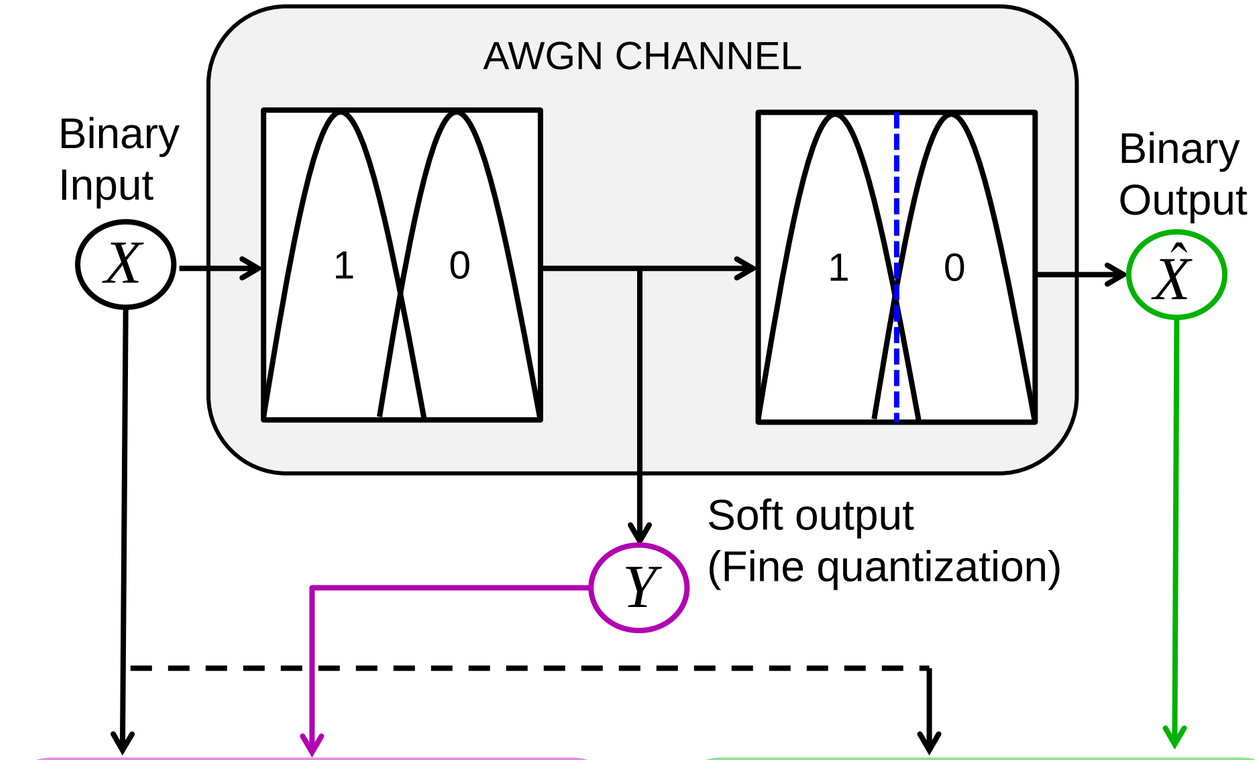




Channel capacity can be used in two ways:

a) For a given level of channel noise, what ECC rate is required in order to operate reliably?
b) For a given ECC rate, how much channel noise can be tolerated?

AWGN Channel: Hard vs. Soft Information

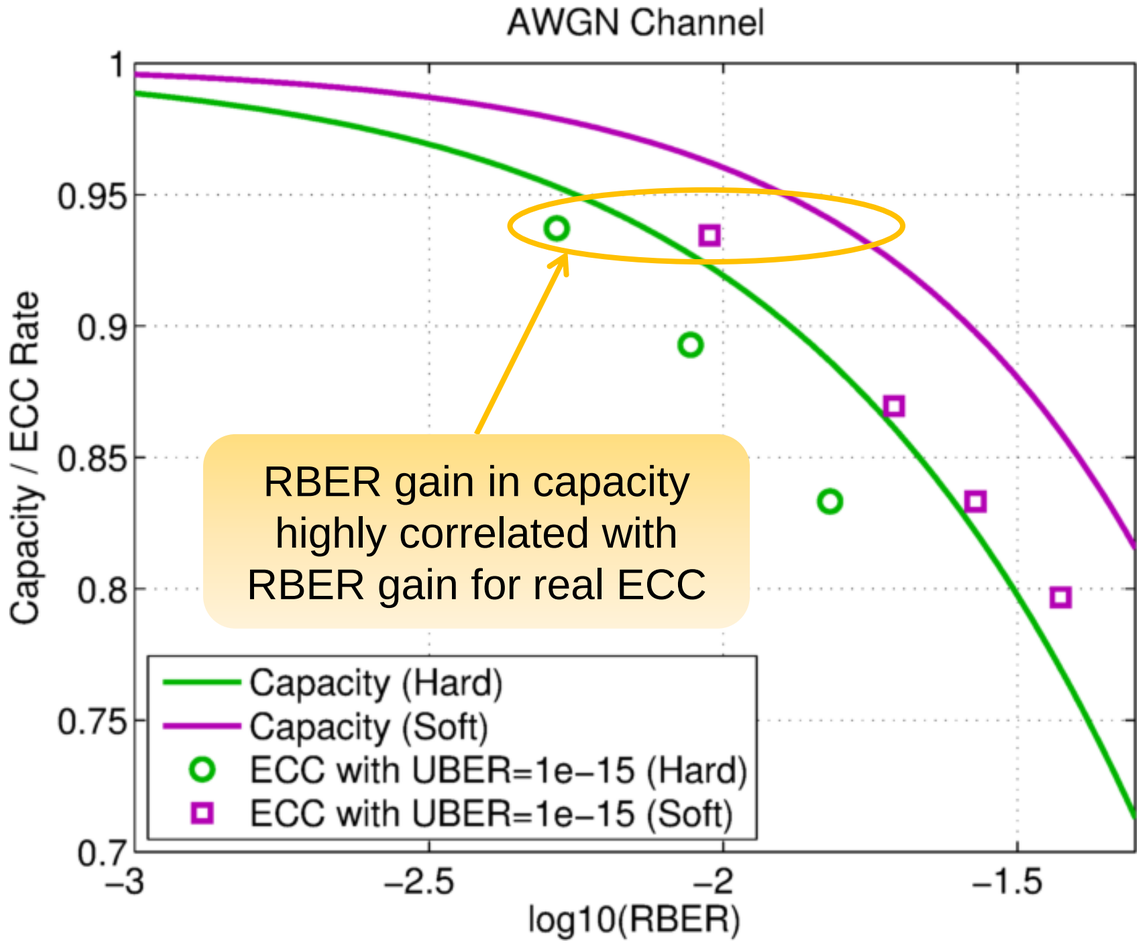


SOFT CAPACITY

$$C_{SOFT} = \max_{P(X)} I(Y;X)$$

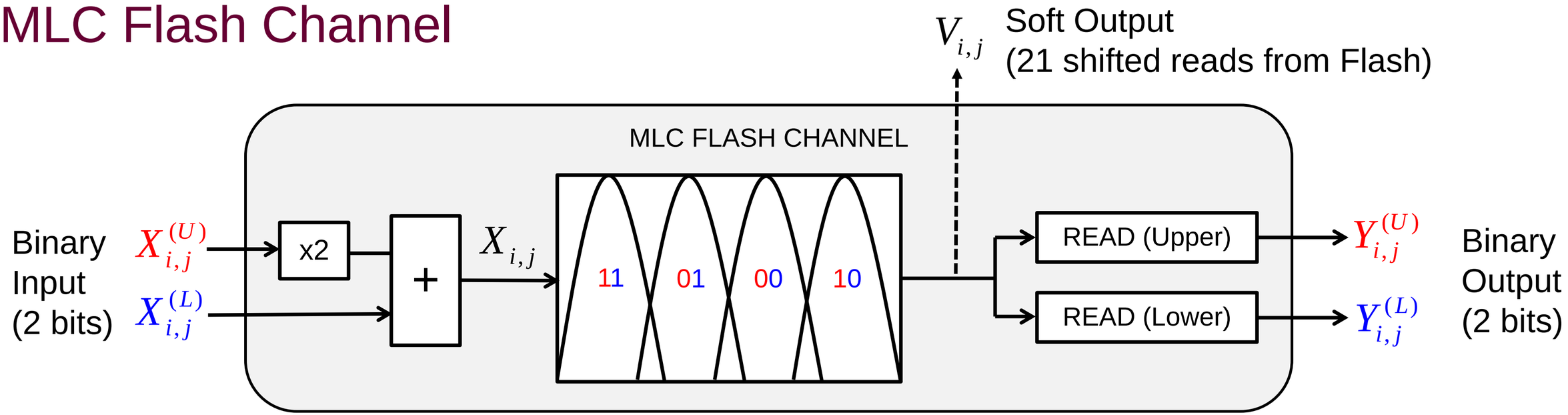
HARD CAPACITY

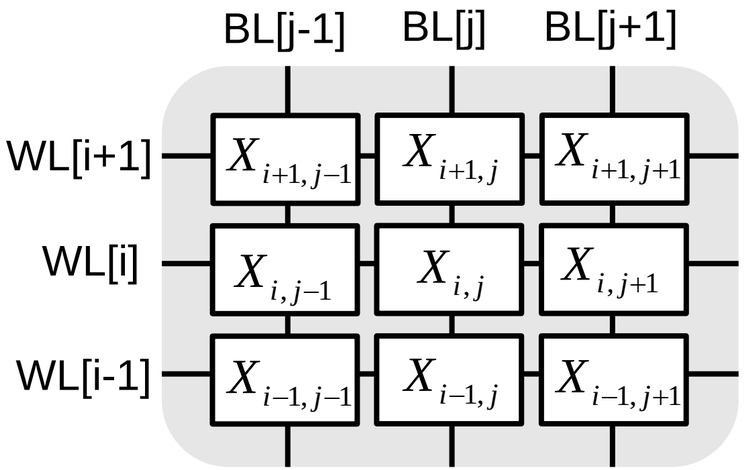
$$C_{HARD} = \max_{P(X)} I(\hat{X};X)$$

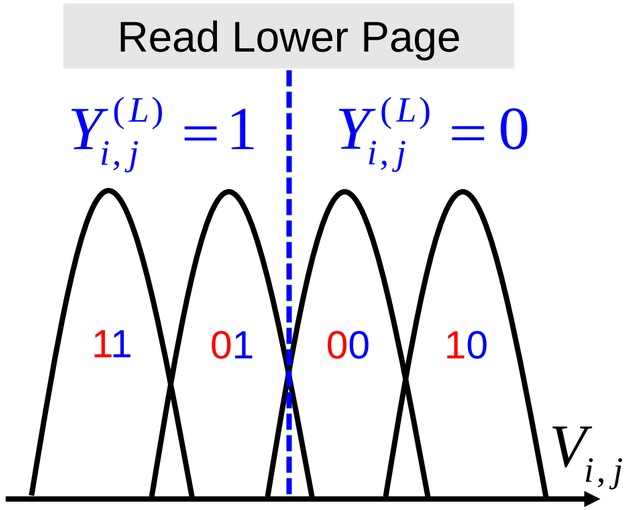


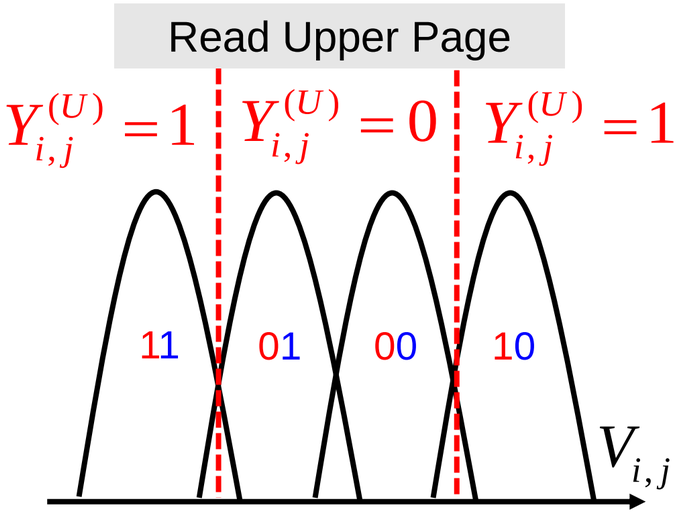
ECC data sourced from: Tzimpragos et al. – '*A Survey on FEC Codes for 100G and Beyond Optical Networks*', IEEE Comm. Surveys & Tutorials, 2014

MLC Flash Channel

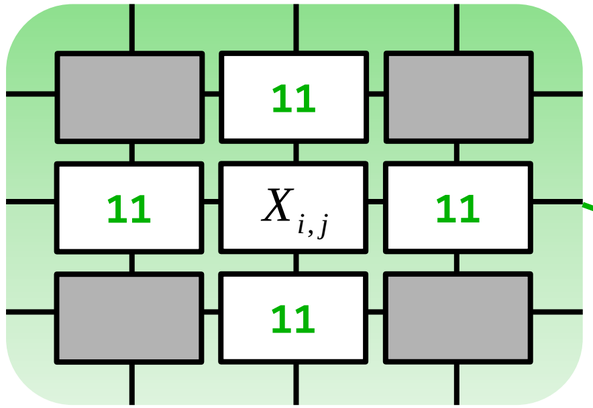




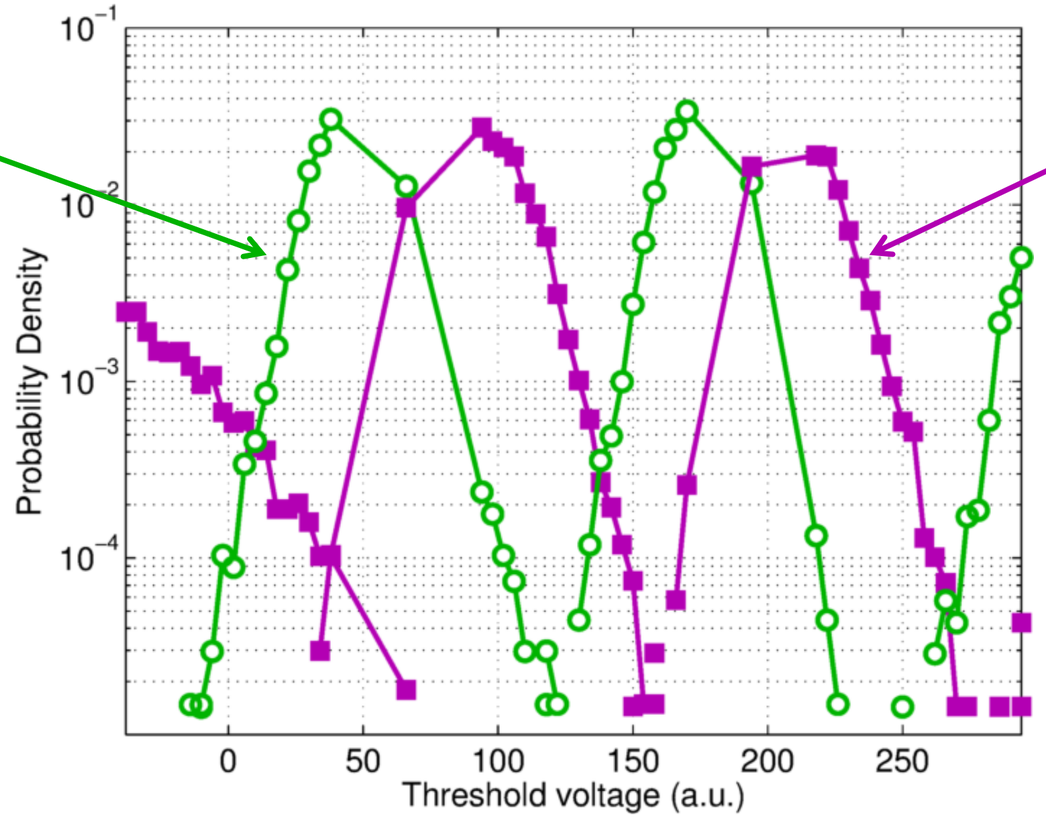


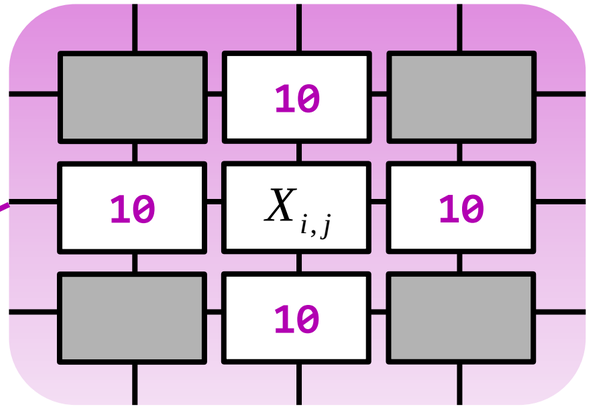


MLC Flash Channel is NOT Memoryless



Threshold voltage distribution conditional on state of aggressor cells





The threshold voltage of a cell depends on the data written to the surrounding cells

MLC flash channel is a **FSMC**:
Finite
State
Markov
Channel

$$\Pr\left(V_{i,0}, V_{i,1} \ldots, V_{i,n-1} \mid \underline{X}\right) = \prod_{j=0}^{n-1} \Pr\left(V_{i,j} \mid X_{i,j-1}, X_{i,j}, X_{i,j+1}, X_{i-1,j}, X_{i+1,j}\right)$$

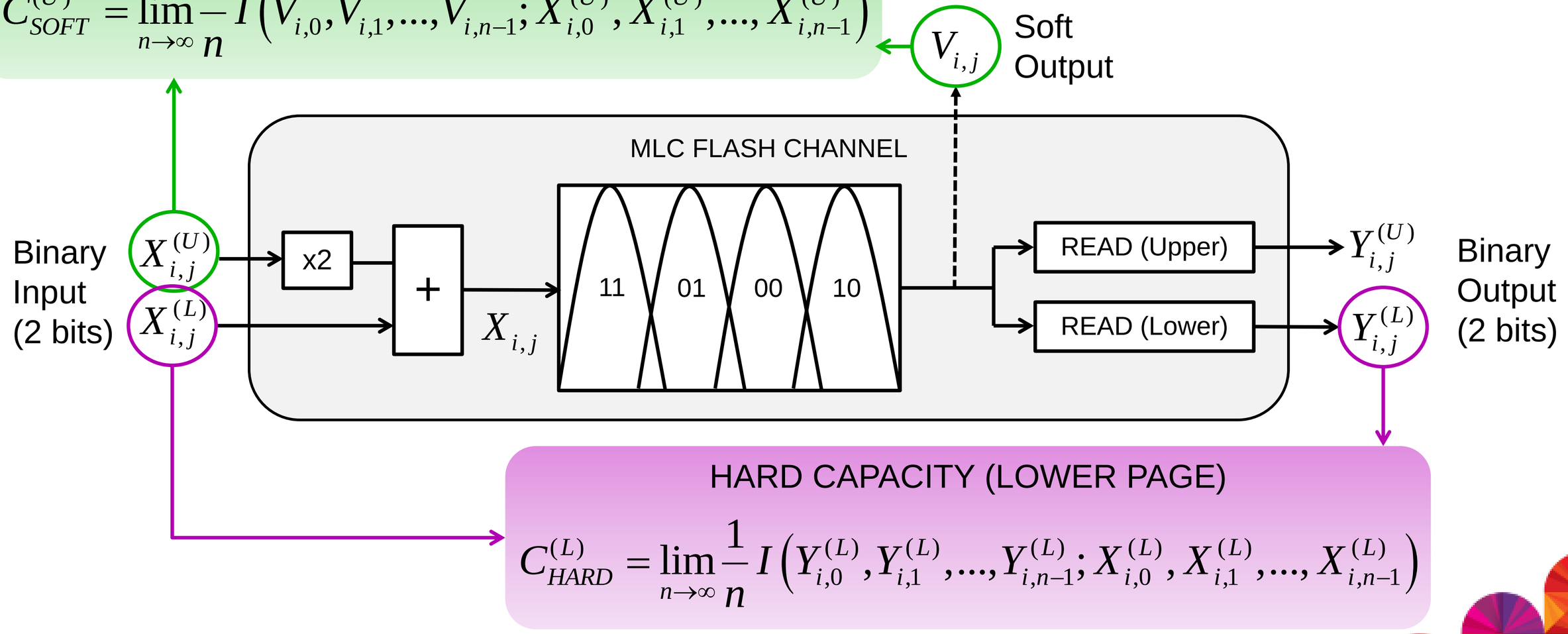
Conditional threshold voltage distributions are extracted from real MLC Flash devices

Calculation of Symmetric Capacity

Capacity* is calculated recursively using a very long sample from the channel ($n=10^7$) assuming i.u.d input distribution [**ICC2015**]

SOFT CAPACITY (UPPER PAGE)

$$C_{SOFT}^{(U)} = \lim_{n\to\infty} \frac{1}{n} I\left(V_{i,0}, V_{i,1}, \ldots, V_{i,n-1}; X_{i,0}^{(U)}, X_{i,1}^{(U)}, \ldots, X_{i,n-1}^{(U)}\right)$$

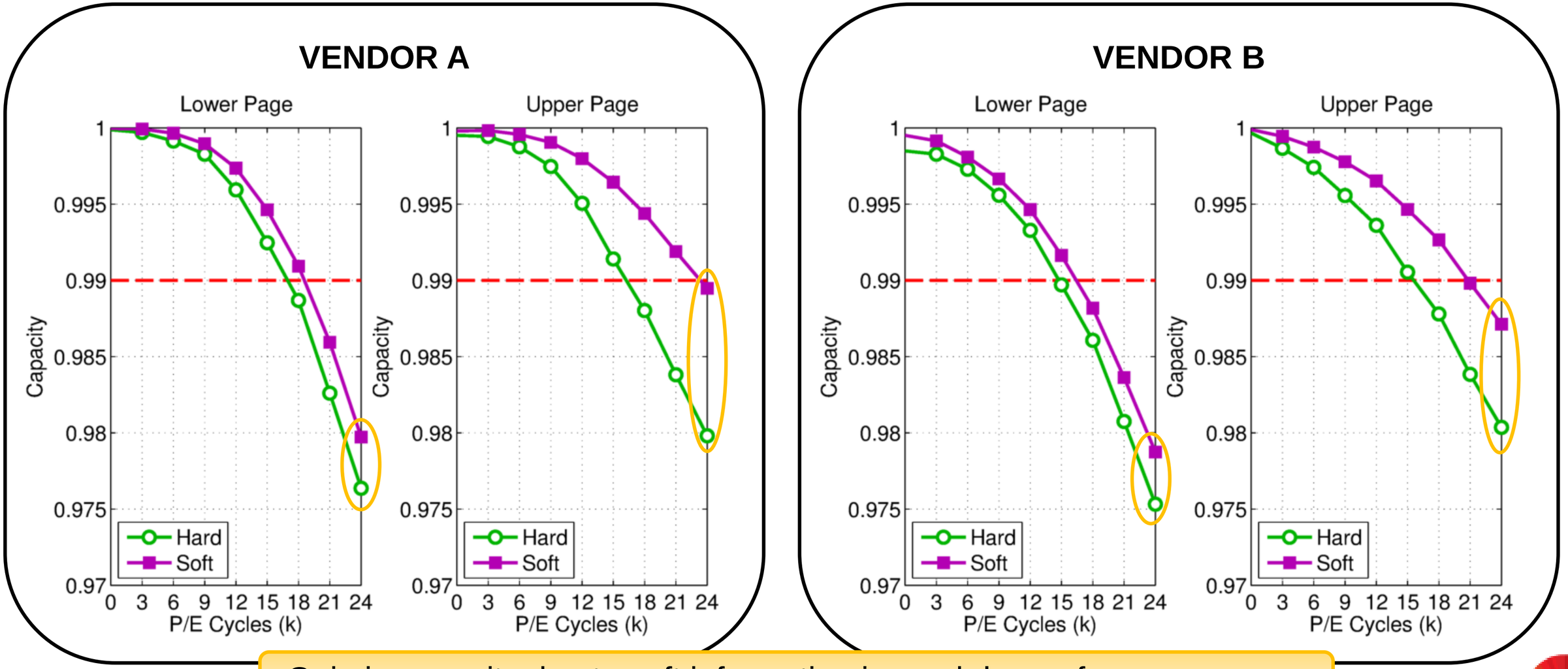


HARD CAPACITY (LOWER PAGE)

$$C_{HARD}^{(L)} = \lim_{n\to\infty} \frac{1}{n} I\left(Y_{i,0}^{(L)}, Y_{i,1}^{(L)}, \ldots, Y_{i,n-1}^{(L)}; X_{i,0}^{(L)}, X_{i,1}^{(L)}, \ldots, X_{i,n-1}^{(L)}\right)$$

Experimental Results

Vendor A/B – 1y-nm MLC devices with approx. same cell area



Gain in capacity due to soft information is much larger for upper pages

How much endurance can we gain using soft information?

Endurance (Balanced ECC)

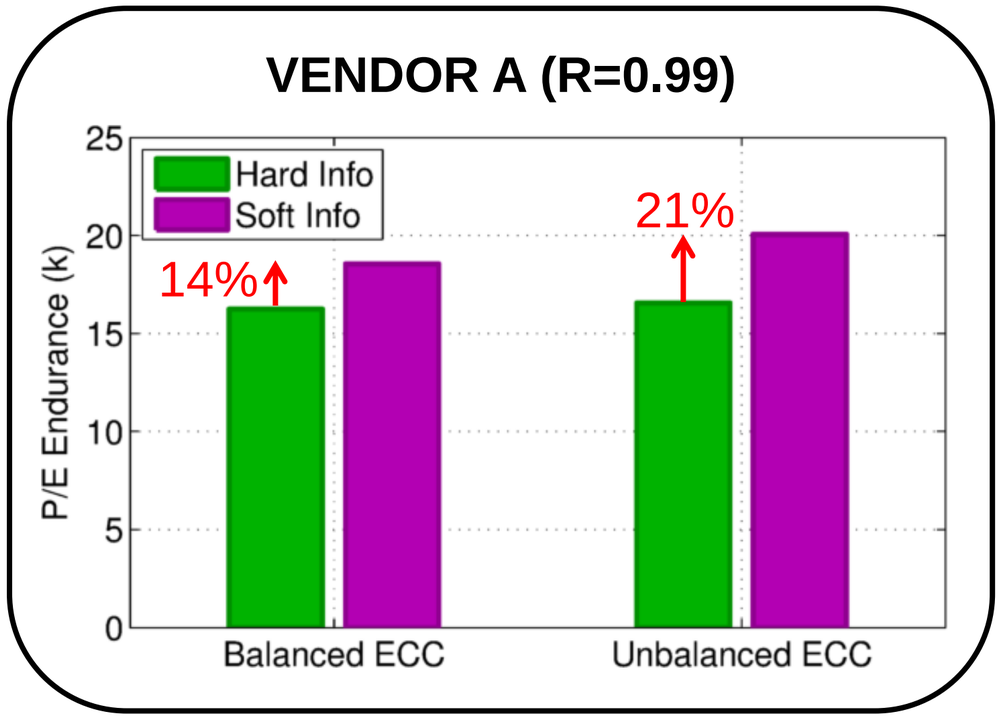
Same ECC rate in upper/lower page:

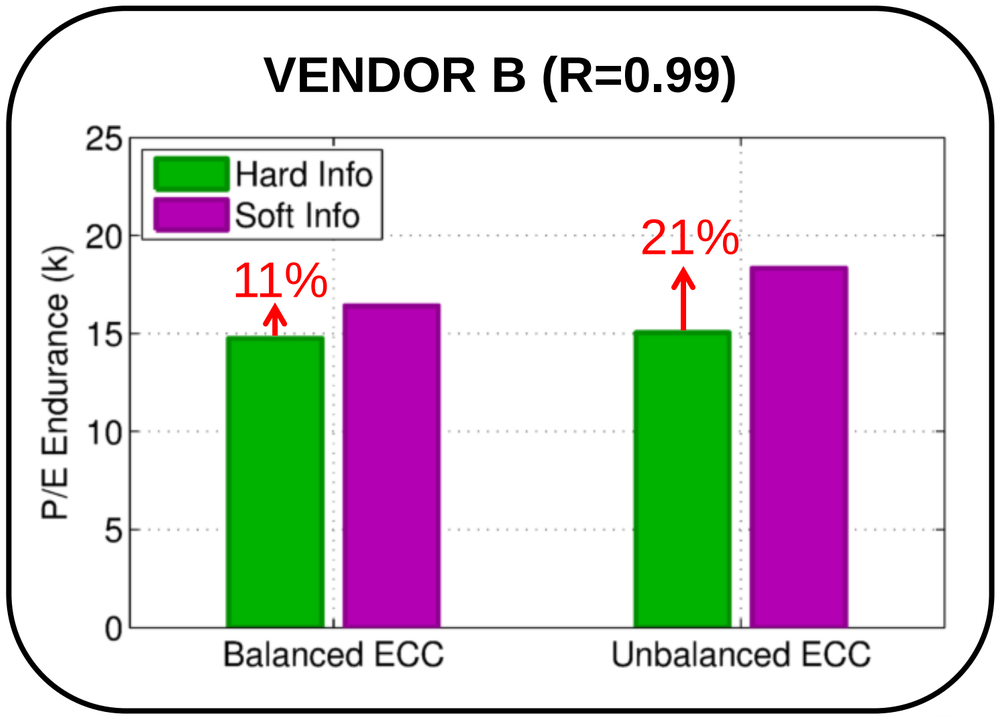
$$\mathrm{PEC}(R) = \min(\mathrm{PEC}_{\mathrm{L}}(R), \mathrm{PEC}_{\mathrm{U}}(R))$$

Endurance (Unbalanced ECC)

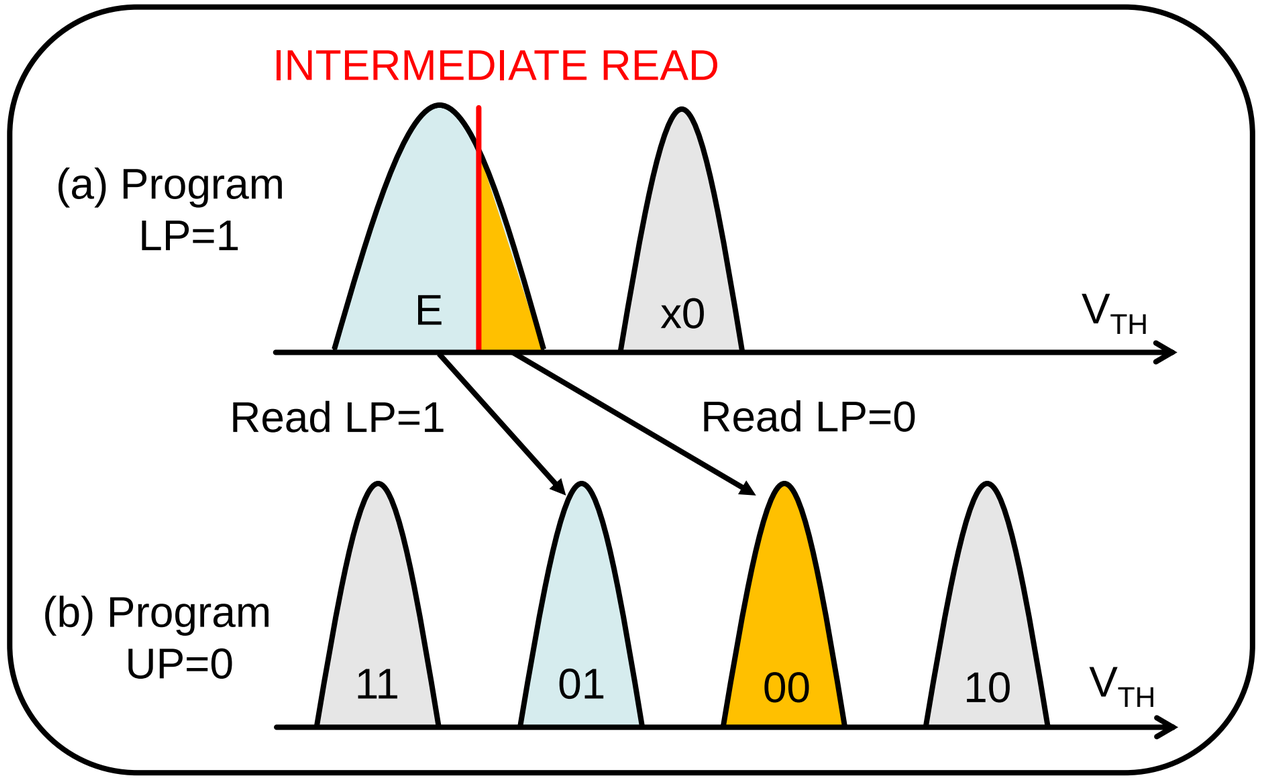
Different ECC rate in upper/lower page:

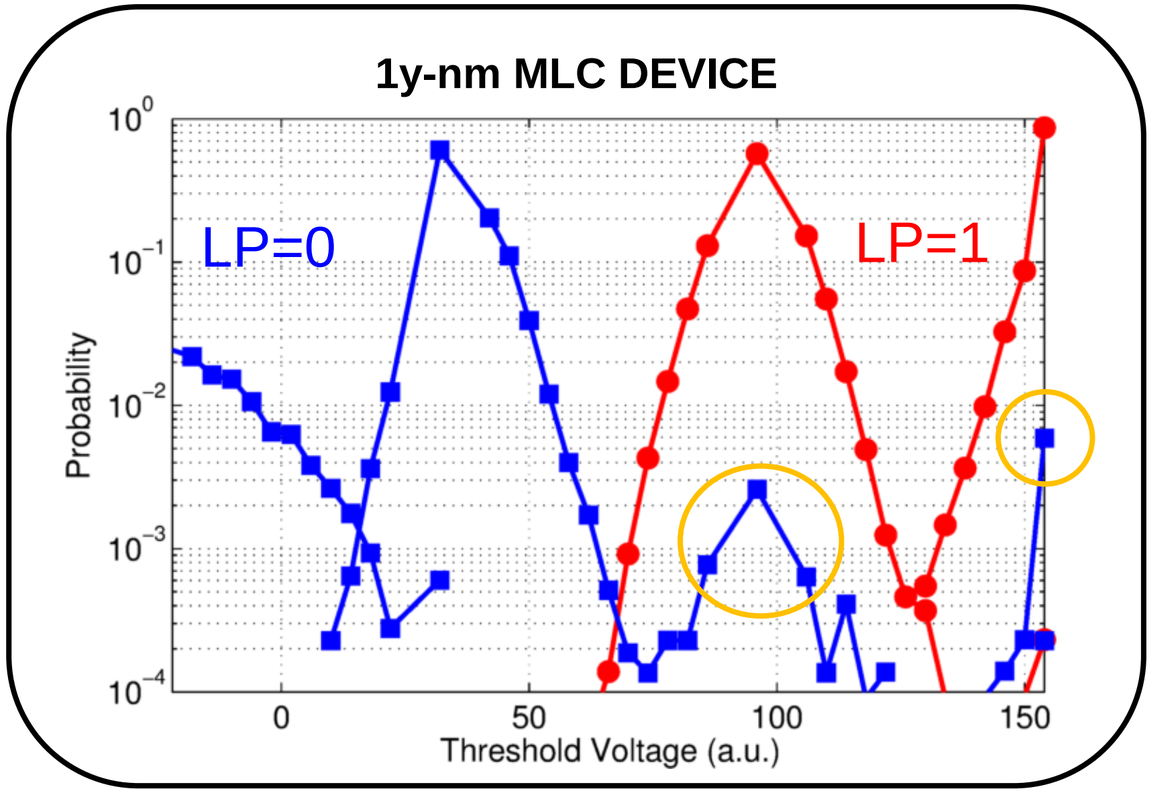
$$\mathrm{PEC}(R) = \max_{R_L + R_U = 2R} \min(\mathrm{PEC}_{\mathrm{L}}(R_L), \mathrm{PEC}_{\mathrm{U}}(R_U))$$





Why do we only see a small increase in capacity for lower pages?



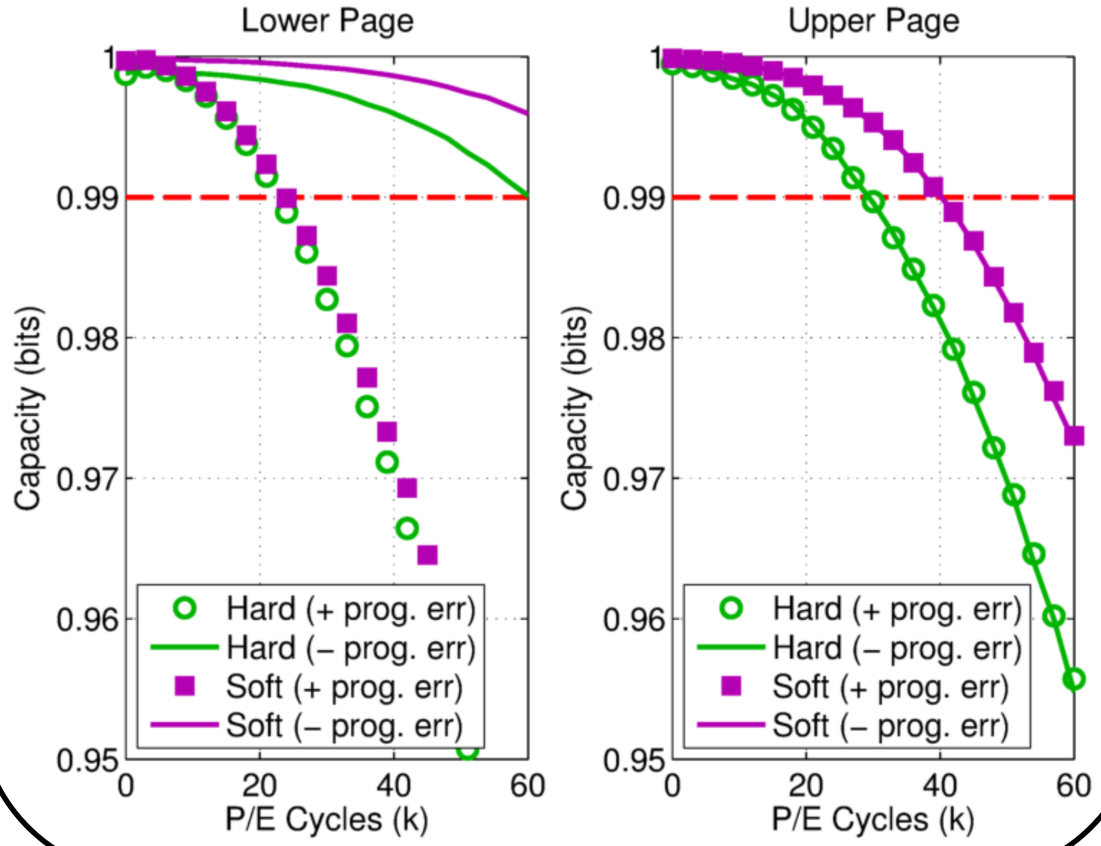


Degradation of the erase state can lead to error-propagation during two-stage MLC programming

Programming errors are present for the lower page that are difficult to correct even with soft information

What if we can prevent programming errors?

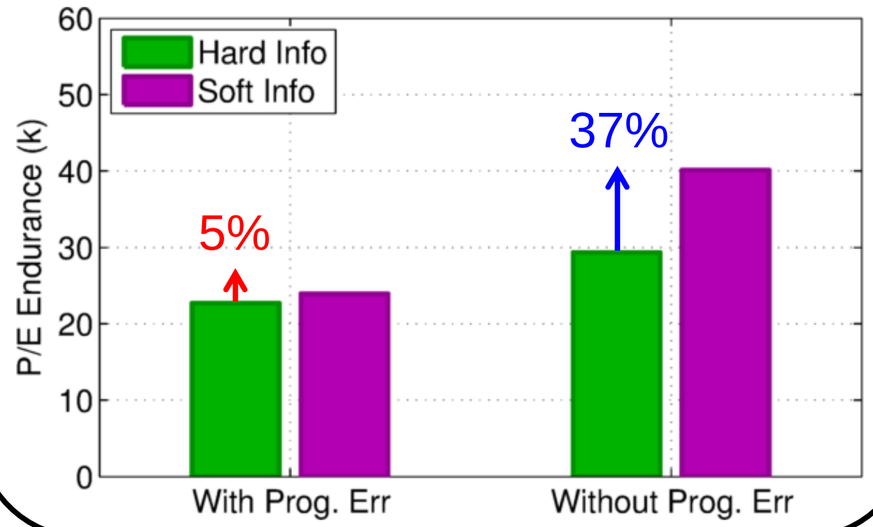
1x-nm MLC MODEL [ICC2015]



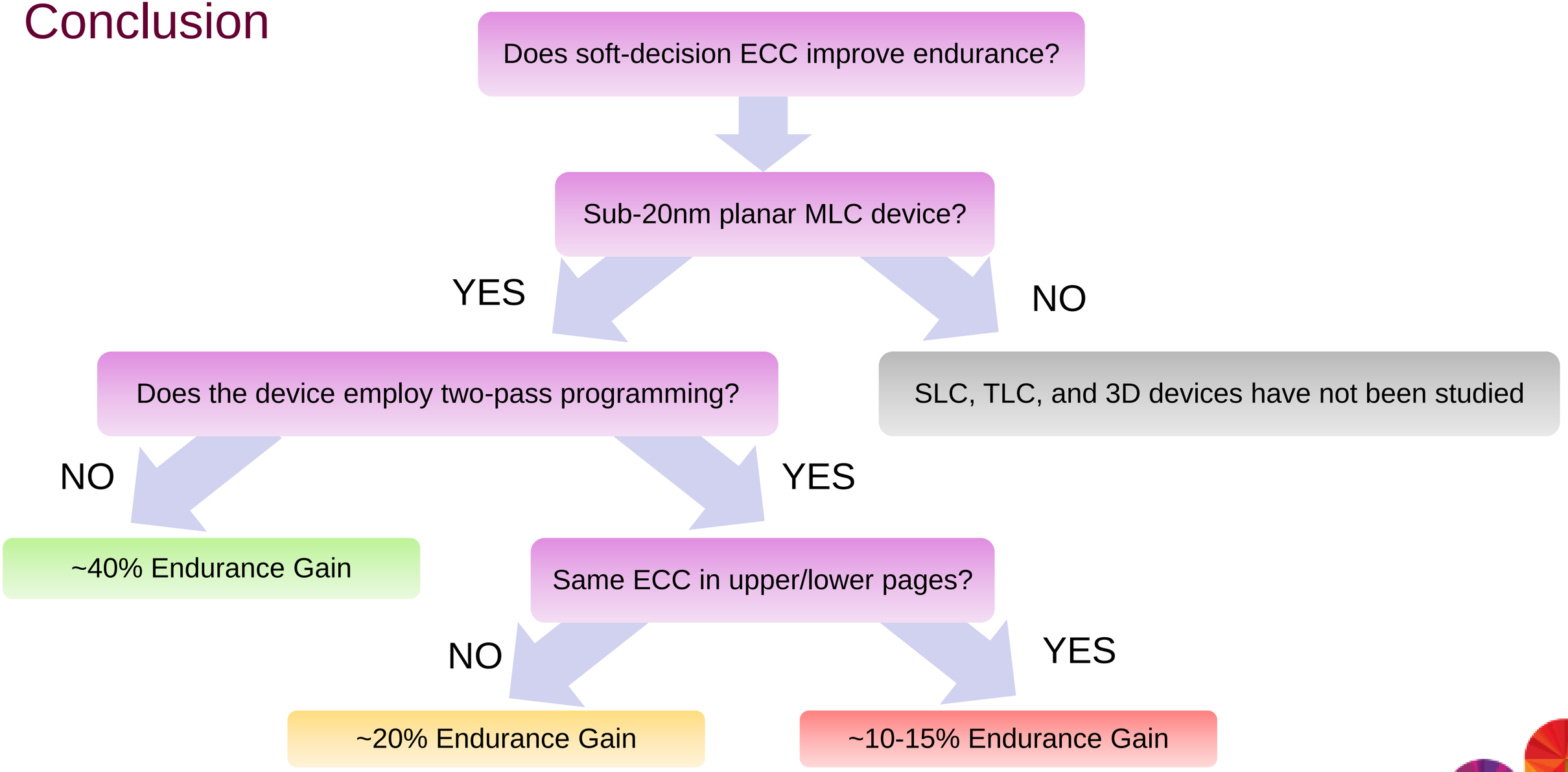
Removing programming errors dramatically improves the lower page capacity

~40% endurance gain due to soft information

BALANCED ECC (R=0.99)



Conclusion



Acknowledgements

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