Next Generation ECC Schemes for High-Endurance SSDs

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Presentation Outline

- History of Modern Codes
- ECC Evolution in Storage
- **Non-Binary LDPC codes**
- **Polar Codes**
  - Reed-Muller Codes (1954)
  - Recursion, Rate of Polarization
  - Decoding polar codes
- Conclusions

History of Modern Codes

- Turbo Codes (1993)
- LDPC Codes (1996)
  - Developed by Gallager in 1960
  - PhD Thesis at MIT
  - http://www.rle.mit.edu/rgallager/documents/ldpc.pdf
- LDPC Code Implementation
  - Accepted for DVB-S2 in 2003
  - Part of Wi-Fi 802.11n (optional) in 2009
  - HDD- Marvel, LSI, BRCM etc put ASIC efforts in 2008
    - Drives with LDPC codes shipped couple years later
    - LDPC codes with 512B information size
    - Marvel, LSI make channels with non-binary LDPC codes

ECC Evolution in Storage

- Hard Disk Drives
  - Reed Solomon Codes
    - – Viterbi detector and burst errors due to defects
  - Binary LDPC Codes
    - – Soft information comes from SOVA
    - – Erasure decoding from media defects
  - Non-Binary LDPC Codes
    - – GF(4), GF(8), GF(16)
- Solid State Drives
  - Algebraic code
    - – BCH codes
  - LDPC codes
    - – Binary LDPC codes
      - – Soft information limited by trigger rate

ECC Evolution in SSDs

- What's next?

- Non-Binary LDPC Codes
  - For HDD, there is inter-symbol-interference (ISI)
  - ISI makes non-Binary LDPC codes suitable for HDD

- Polar Codes
  - Recent results show they have potential

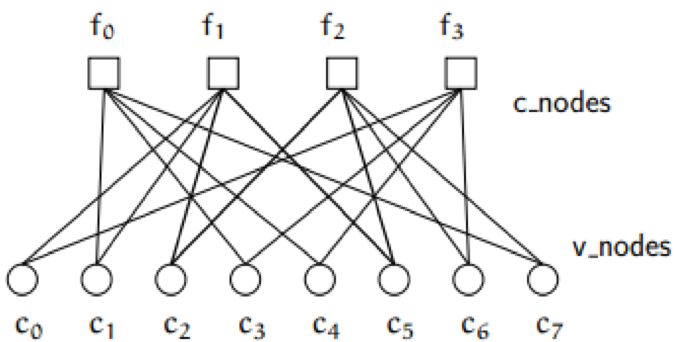
Non-Binary LDPC codes

- Instead of working on bits, non-binary LDPC codes work on groups of bits (called symbols)
- Symbols can be a set of $1,2,\ldots q$ bits
- Galois fields- $GF(2^2), GF(2^4),$ …… $GF(2^q)$

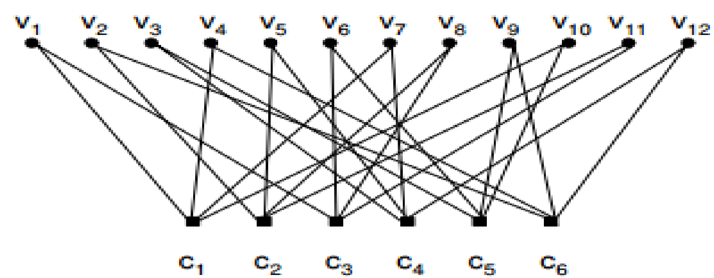
Parity check matrix

- H-matrix of a binary vs non-binary LDPC code over GF(8)

$$H = \begin{bmatrix} 0 & 1 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 1 & 1 \\ 1 & 0 & 0 & 1 & 1 & 0 & 1 & 0 \end{bmatrix}$$



$$H = \begin{bmatrix} 5 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 2 & 0 & 0 \\ 0 & 3 & 0 & 0 & 3 & 0 & 0 & 5 & 0 & 0 & 3 & 0 \\ 1 & 0 & 0 & 0 & 0 & 5 & 0 & 2 & 0 & 0 & 7 & 0 \\ 0 & 0 & 5 & 0 & 6 & 0 & 3 & 0 & 0 & 0 & 0 & 7 \\ 0 & 0 & 2 & 0 & 0 & 3 & 0 & 0 & 1 & 5 & 0 & 0 \\ 0 & 2 & 0 & 4 & 0 & 0 & 0 & 0 & 2 & 0 & 0 & 4 \end{bmatrix}$$



All operations are over $GF(2^q)$

Non-Binary LDPC code and its binary representation

- Any non-binary LDPC code can be represented by its binary equivalent

$$H = \begin{bmatrix} 5 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 2 & 0 & 0 \\ 0 & 3 & 0 & 0 & 3 & 0 & 0 & 5 & 0 & 0 & 3 & 0 \\ 1 & 0 & 0 & 0 & 0 & 5 & 0 & 2 & 0 & 0 & 7 & 0 \\ 0 & 0 & 5 & 0 & 6 & 0 & 3 & 0 & 0 & 0 & 0 & 7 \\ 0 & 0 & 2 & 0 & 0 & 3 & 0 & 0 & 1 & 5 & 0 & 0 \\ 0 & 2 & 0 & 4 & 0 & 0 & 0 & 0 & 2 & 0 & 0 & 4 \end{bmatrix}$$

- Replace all the $GF(2^3)$ entries by their 3 x 3 binary equivalents

Why the difference then?

- Encoding/Decoding done in $GF(2^q)$
- Message passing works on symbol basis
- All properties of the code are in that space
- Girth, distance properties
  - Typically large girths with small column weights
- Binary representation helps with code construction

Why non-binary LDPC should perform better for SDD

- Hard disk drives
  - Have ISI
- Even for AWGN channels, literature on non-binary LDPC codes shows improved performance

Decoding non-binary LDPC codes

- Binary LDPC codes
  - Min-Sum Decoder, 2-D Min-Sum Decoder
- Non-Binary LDPC codes
  - Extended Min-Sum (EMS) decoder
- Message Passing Algorithms
  - Probability domain
    - Check node update in Fourier domain- FFT
  - Log domain

Decoding non-binary LDPC codes

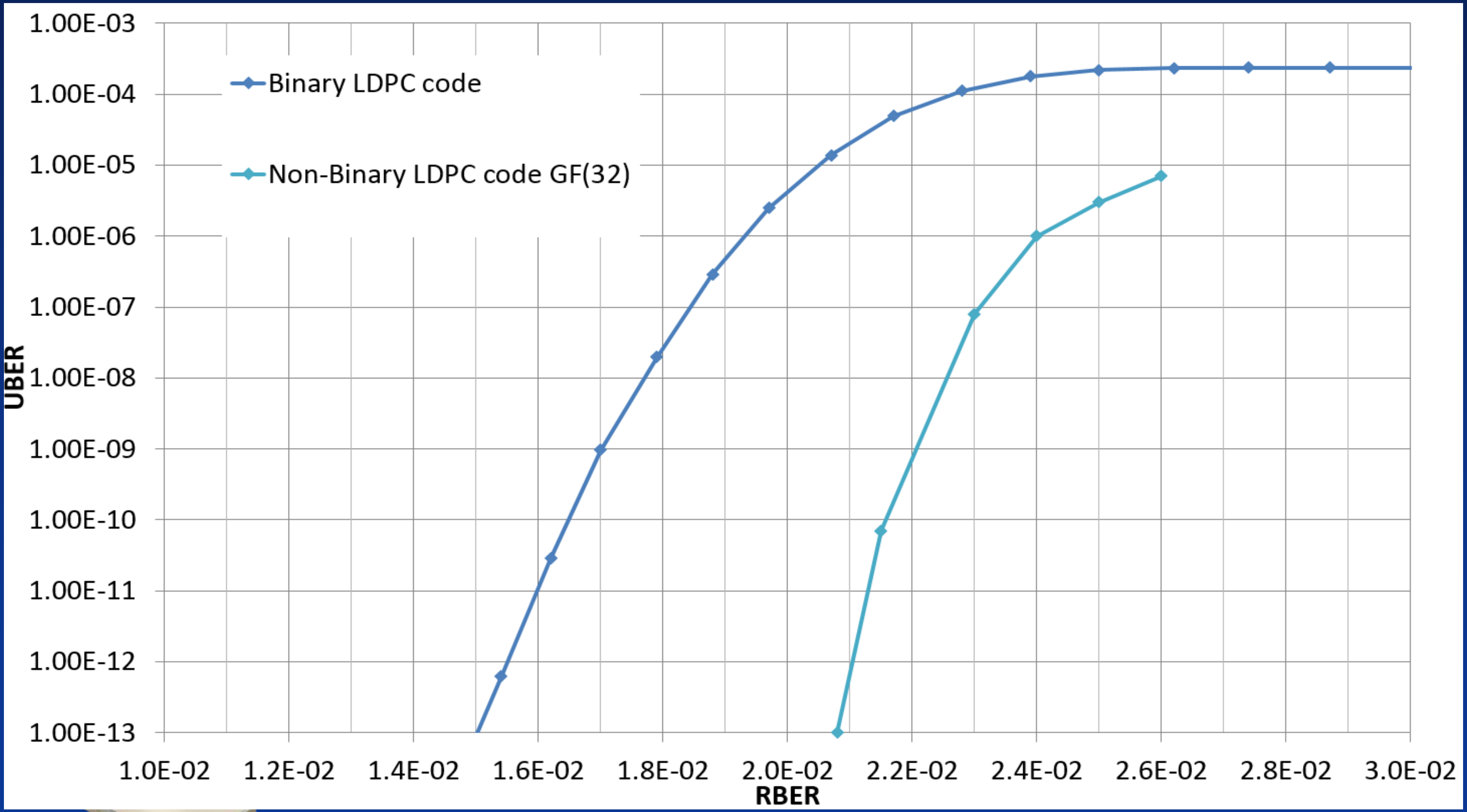
- Log-density-ratios (LDR)
- $LDR(s) = \log \frac{p(r|s)}{p(r|0)}, s = 0,1,..2^q - 1$
- From r, compute the $LDR(s)$
- Message passing consists of updating the LDRs at the check and symbol nodes
- Introduce permutation nodes

Decoding Non-Binary LDPC codes

- Symbol flipping algorithm
  - Bit flipping decoding for binary LDPC codes
- Min-max decoding
  - Simplified decoding
- Trellis EMS algorithm
  - Ideal for high throughput, high rate applications
  - Memory requirements are huge

Simulation Results

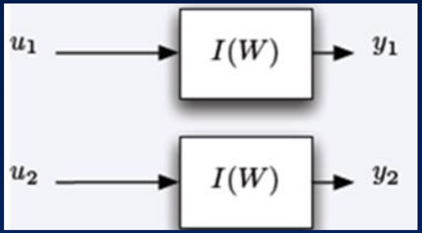
- 1KB LDPC codewords, soft decision decoding, simulation results at Intel- 1.53x RBER gain



Polar Codes- History

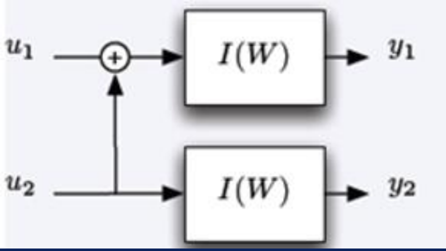
- Erdal Arikan- 2008
- Binary discrete memory-less channels (B-DMC)
- Capacity achieving codes with low encoding and decoding complexity- $O(N\ logN)$
- Minimum codeword size for channels to polarize
  - 2K bits
- Successive cancellation decoding algorithm
- List Decoding with CRC- Tal & Vardy

Channel Polarization



- $I(u_1, u_2; y_1, y_2) = I(u_1; y_1, y_2) + I(u_2; y_1, y_2 | u_1)$
  $= I(u_1; y_1) + I(u_2; y_2)$
  $= I(W) + I(W) = 2I(W)$
- Synthesize two channels from two independent copies of DMC channels *W*
- The two channels have same symmetric capacity

Channel Polarization



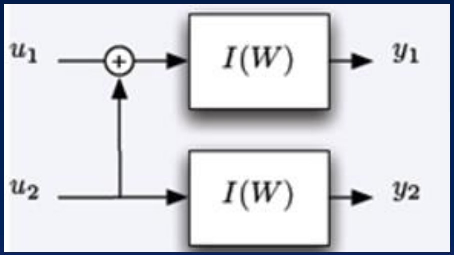
- $I(u_1, u_2; y_1, y_2) = I(u_1; y_1, y_2) + I(u_2; y_1, y_2 | u_1)$

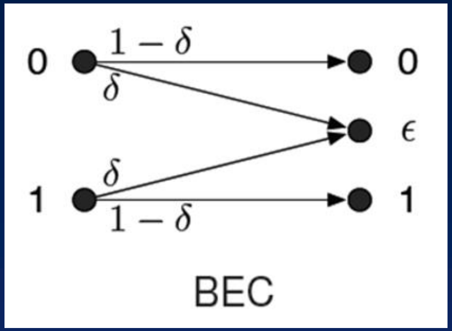
$$= I(W') + I(W'') = 2I(W)$$

$$I(W') \le I(W) \le I(W'')$$

- Created two channels
- One channel can have higher capacity than the other
- Total capacity of the two channels is unchanged

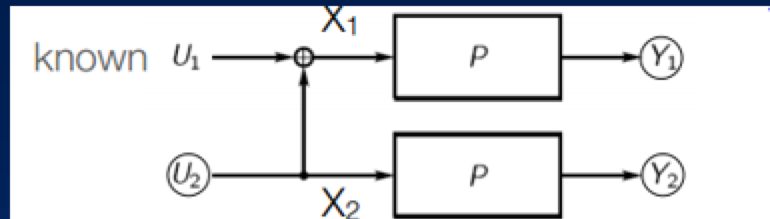
Channel Polarization- BEC



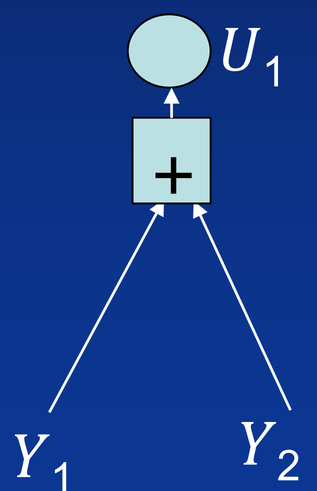


- u_1 is erased if either y_1 or y_2 is erased
- u_2 is erased if both y_1 or y_2 are erased
- Probability of u_1 erased is $2\delta(1-\delta)+\delta^2$
- Probability of u_2 erased is δ^2
- δ=0.4, $I(W)$ =0.6
- P(u_1 erased)=0.64, $I(W')$= 0.36 $< I(W)$
- P(u_2 erased)=0.16, $I(W'')$=0.84 $> I(W)$

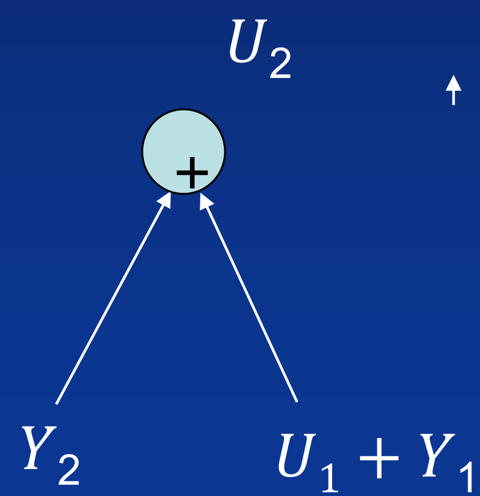
Why channels polarize?



- $Observe \;\; Y_1, Y_2$
- $U_1 = X_1 + X_2$
- $U_2 = X_2; U_2 = X_1 + U_1$



Parity check node



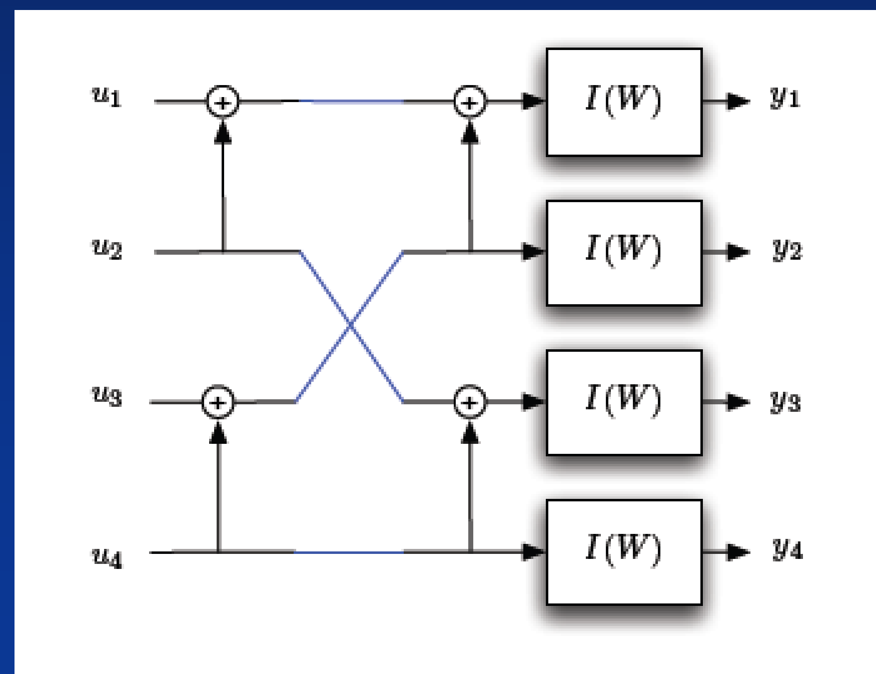
Variable node
Repitition code

Polar Codes

- $m = 2$
- Recursive code construction
- Kronecker Product to get $N = 4$

$$G_2 = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix}$$

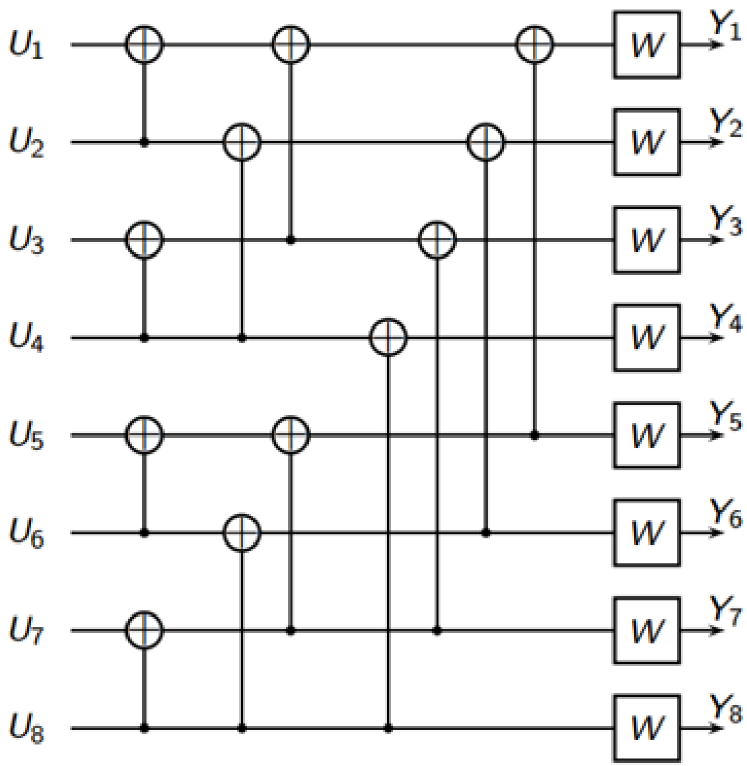
$$G_2^{\otimes 2} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 \end{bmatrix}$$



Codes from Kronecker Products of G_2

length $N = 2^m$, $m \in \mathbb{N}$

generator matrix: rows of $G_2^{\otimes m}$



$$G^{\otimes 3} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}$$

Reed-Muller Codes

length $N = 2^m$, $m \in \mathbb{N}$

generator matrix: rows of $G_2^{\otimes m}$

How to choose the rows?

$$G_2^{\otimes 3} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}$$

choose rows of largest weight

$$\mathbf{u} = (0, 0, 0, u_4, 0, u_6, u_7, u_8)$$

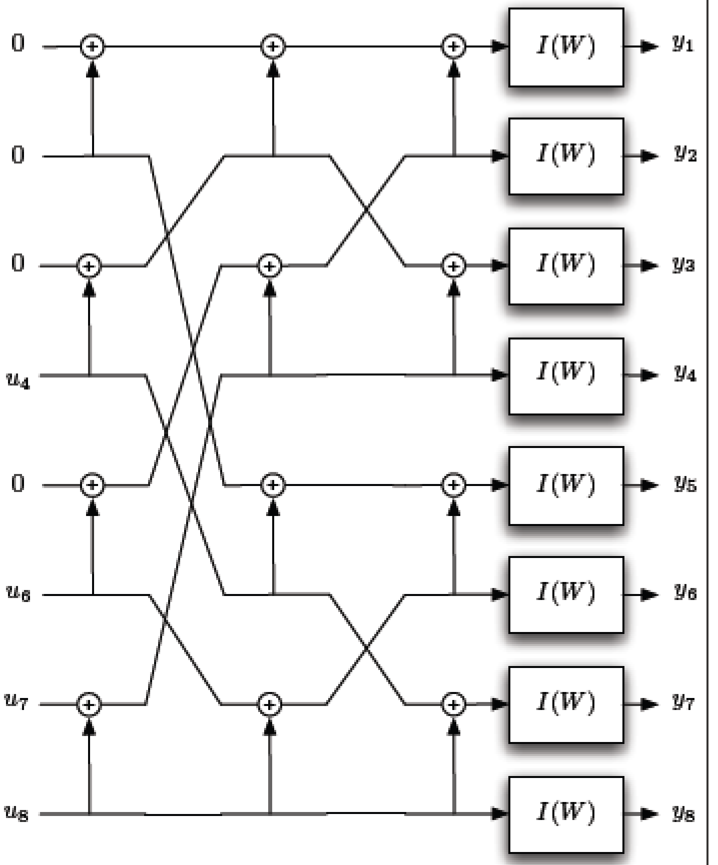
Polar Codes

length $N = 2^m$, $m \in \mathbb{N}$

generator matrix: rows of $G_2^{\otimes m}$

$$G_2^{\otimes 3} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}$$

$$\bar{x} = (0, 0, 0, u_4, 0, u_6, u_7, u_8)\ G_2^{\otimes 3}$$



Frozen set

- Freeze the bits on the bad channel- Frozen set
- Useless Channels, asymptotically $W_N^{(i)}\left(y_1{}^N, u_1{}^{i-1} \middle| u_i\right) = 0.5, u_i = 0,1$
- These indices i are the ones which are channels with capacity 0

Polar Codes

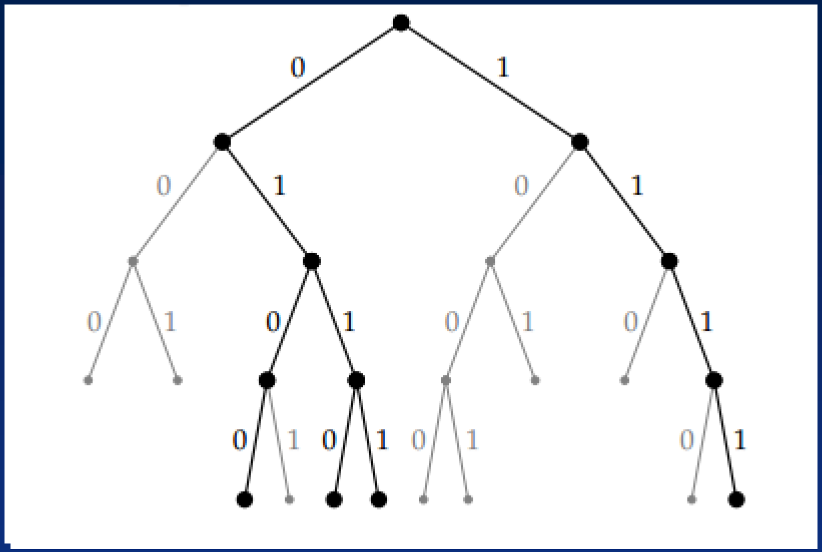
- Choice of frozen set
  - RM- Choose the rows with maximum Hamming weight
  - Bhattacharya parameter
- Only for code lengths which are powers of 2
  - Shortening
  - Other base matrices or combinations
- Decoding
  - Successive Cancellation Decoding
  - List Decoding + CRC
- Non-systematic codes
  - Can we do systematic constructs?

Shortening Polar Codes

- Default length of polar codes is 2^q, for some integer q
- Is shortening possible*?
- Yes, since the generator matrix is a lower triangular matrix
- Hard decision decoding shows RBER advantage and quite some endurance benefit *

- * Yue Li et al, “The performance of Polar Codes for Multi-level Flash Memories,” NVM Workshop 2014

List Decoding of Polar Codes with CRC



- List size has to be at least 32 or more
- Decoder memory impact since we need to store n codewords in the list
- Not as amenable to decoding as LDPC codes
- Multiple rate constructs difficult

Conclusions

- Non-Binary LDPC codes are an appropriate future generation choice
- Polar codes competing with non-binary LDPC codes?
  - Not beating non-binary LDPC codes on RBER
  - Polar codes not as amenable to decoding as non-binary LDPC codes
  - Variable rate constructs not as easy as LDPC
  - List size is large which has SRAM cost downsides