Soft-aided Decoding of Product Codes for Optical Communications

Laurent Schmalen, **Sisi Miao**, Lukas Rapp

Overview

- Motivation
- Iterative Bounded Distance Decoding of PCs
- Decoder with Dynamic Reliability Scores
- List-Based Decoder with Dynamic Reliability Scores

Motivation

- Product codes (PCs) **[Eli55]** are powerful code construction for high speed optical communication systems
- Conventional decoding of PCs

- **Soft-decision decoding (SDD)**
  e.g.: turbo product decoding (TPD) **[Pyn98]**
  ✓ large decoding gain
  ✗ high complexity
  ✗ high internal decoder data flow

- **Hard-decision decoding (HDD)**
  e.g.: iterative bounded distance decoding (iBDD)
  ✗ small decoding gain
  ✓ low complexity
  ✓ low internal decoder data flow

[Eli55] P. Elias, "Coding for noisy channels," in *IRE Convention Record, Part IV*, Mar. 1955.
[Pyn98] R. M. Pyndiah, "Near-optimum decoding of product codes: Block turbo codes, "*IEEE Trans. Commun.*, vol. 46, no. 8, 1998.
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- This work: **soft-aided HDD** with
  ✓ low complexity and reduced internal decoder data flow with hard message passing
  ✓ provide largest decoding gain among existing soft-aided algorithms **[LSA19]**,**[SAA21]**,**[MRS22]**

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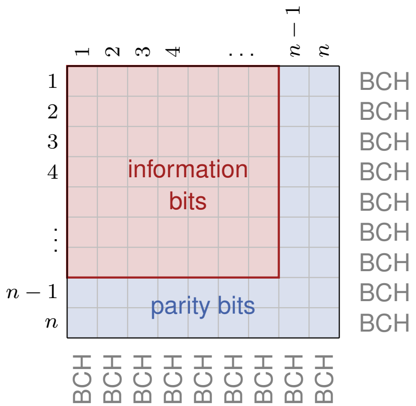
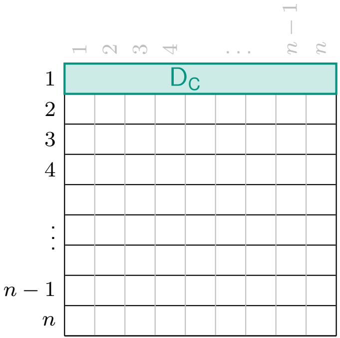


Iterative Bounded Distance Decoding of PCs

- PC of rate $r = k^2/n^2$ with (n, k, t) component codes, typically being BCH/RS codes
- Rows and columns of a PC block are decoded alternately with a **component code decoder** $\mathrm{D_C}$



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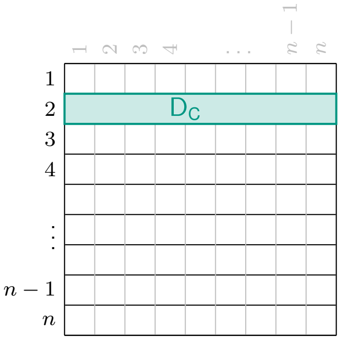

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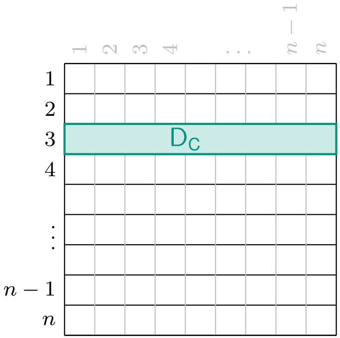

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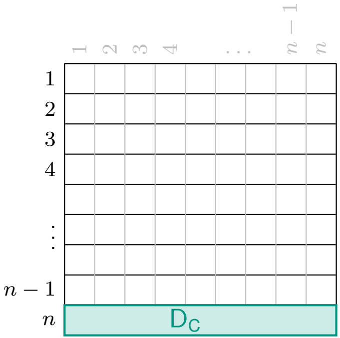

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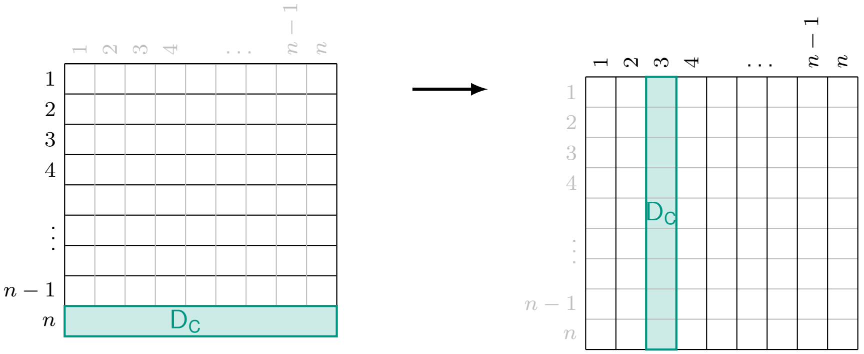

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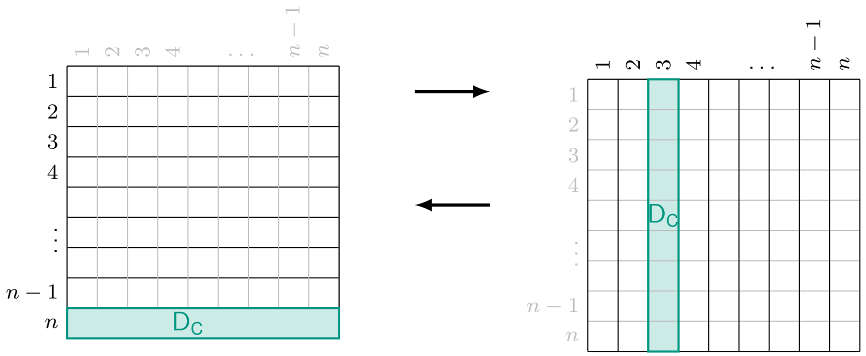

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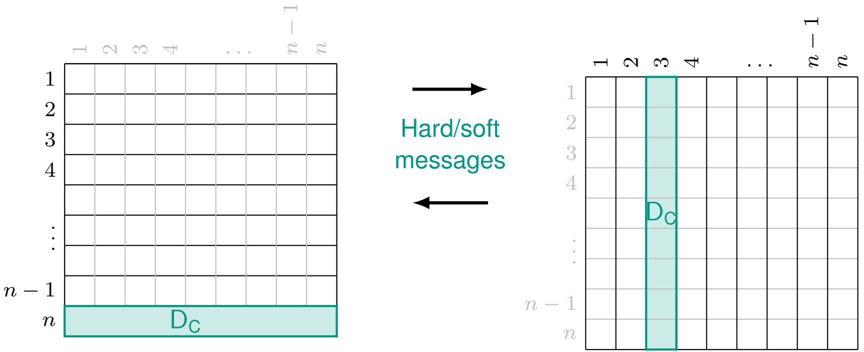

- **iBDD**: D_C is a simple BDD decoder
- **TPD**: D_C is a list-based soft decision decoder [Pyn98]

Improving iBDD: Problem and Solution

- **Problem**: What degrades the performance of iBDD?

Improving iBDD: Problem and Solution

- **Problem**: What degrades the performance of iBDD?
  - High **miscorrection** rate and error propagation
    - A miscorrection of $\boldsymbol{y}$ happens when $\mathrm{D_C}(\boldsymbol{y}) = \boldsymbol{c} \in \mathcal{C}$ but $\boldsymbol{c} \neq \boldsymbol{x}$, the transmitted codeword
    - PCs for optical communication consist of high rate BCH/RS codes which entails high miscorrection rate **[MS86][Jus11]**

[MS86] R. McEliece and L. Swanson, "On the decoder error probability for Reed - Solomon codes (Corresp.)," *IEEE Trans. Inf. Theory*, vol. 32, no. 5, 1986.

[Jus11] J. Justesen, Performance of Product Codes and Related Structures with Iterated Decoding," *IEEE Trans. Commun.*, vol. 59, no. 2, 2011.

Improving iBDD: Problem and Solution

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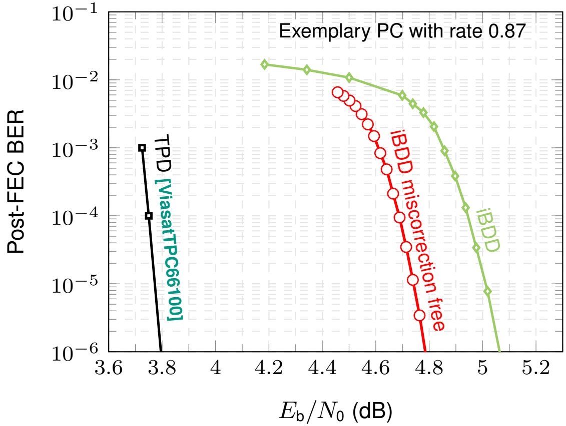

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  - High **miscorrection** rate and error propagation
  - Component code decoder D_C limited to bounded distance, **small number of correctable errors**
- **Our solution**:
  - Introduce **dynamic reliability score (DRS)** to ensure near miscorrection free decoding
  - **Enhance** D_C to have large decoding radius as BDD is not enough
  - Find **trade-off** between decoding radius and miscorrection rate

Miscorrection Detection

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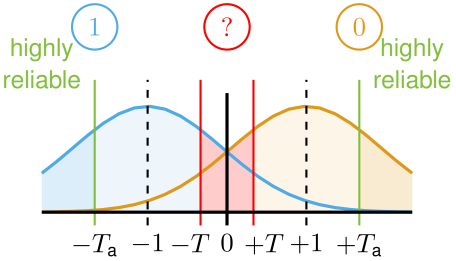

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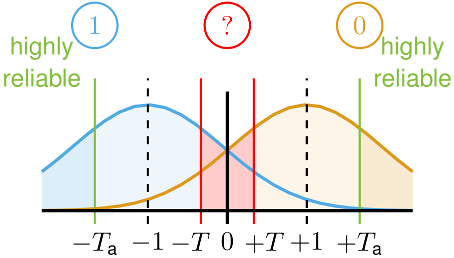

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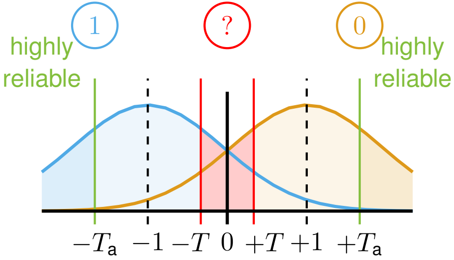
  - Successfully decoded bits that rarely conflict with later component code decoding decisions, as in **anchor decoding (AD)** [HP18]
- We introduce a **dynamic reliability score (DRS)** which reflect the overall reliability of a bit from both aspects



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Dynamic Reliability Score (DRS) [MRS22]

- **Channel model**:
  - BPSK signal $\tilde{x}_i \in \{0, 1\}$ transmitted over binary input AWGN channel.
  - Channel output $\tilde{y}_i = (-1)^{\tilde{x}_i} + n_i$

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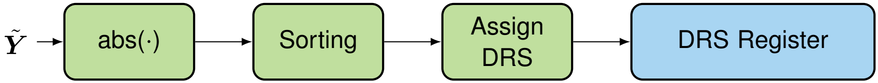
- DRSs Reflect the reliability of the bits in a PC codeword
- Represented with 5 bit integers, i.e., range $[0, 31]$
- Initialized with soft channel information
  - Sort and divide channel outputs into even groups
  - Assign high DRS to the bits with high channel outputs



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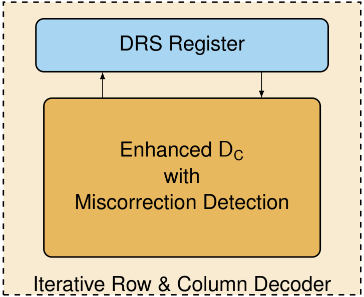
Updating DRS

- Updated with **hard messages**
  - DRSs are increased $(+1)$ for bits that stay constant during the decoding
  - DRSs are decreased (-1) for bits where row and column decoder disagrees
  - Clip to $[0, 31]$

Miscorrection Detection with DRSs

- Used to identify miscorrections at the output of the component decoder
  - The decision should not conflict with bits with high DRS (similar idea used in [HP18][LSA19])
  - The sum of the DRSs of the bits that are flipped should be small



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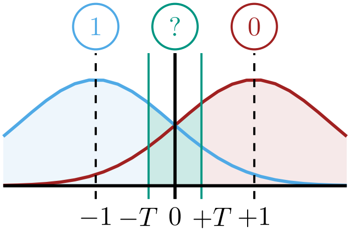
[LSA19] G. Liga, A. Sheikh, and A. Alvarado, “A novel soft-aided bit-marking decoder for product codes,” in *Proc. ECOC.* 2019.

Enhanced Component Decoder D_C

- Step 1: Introduce erasures (Ternary decision):

$$y_i = \begin{cases} ? \text{ (\textbf{erasure})} & \text{if } |\tilde{y}_i| < T \\ \text{sign}(\tilde{y}_i) & \text{if } |\tilde{y}_i| \geq T \end{cases}$$



Error-and-Erasure Decoding

- Classical bounded distance error-and-erasure decoding of BCH codes by extending Gorenstein-Zierler decoding [For65]
- Can decode if D errors and E erasures if $2D + E < d_{\min}$
- **Example:** Decoding success rate of code with $d_{\min} = 6$ (BCH even-weight subcode)

D \ E	0	1	2	3	4	5
0	1.000	1.000	1.000	1.000	1.000	1.000
1	1.000	1.000	1.000	1.000	0	0
2	1.000	1.000	0	0	0	0

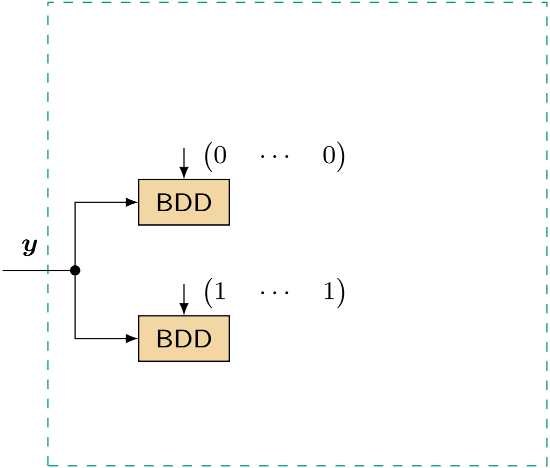
[For65] G. Forney, “On decoding BCH codes,” *IEEE Trans. Inf. Theory*, vol. 11, no. 4, pp. 549–557, 1965.

Textbook Error-and-Erasure Decoding

- **Step 1**: Introduce erasures

$$y_i = \begin{cases} ?\ (\textbf{erasure}) & \text{if } |\tilde{y}_i| < T \\ \text{sign}(\tilde{y}_i) & \text{if } |\tilde{y}_i| \geq T \end{cases}$$

- **Step 2**: Replace the erasures with complementary binary values to generate test patterns $(\boldsymbol{p}^{(1)}, \boldsymbol{p}^{(2)})$
  - Typically $\boldsymbol{p}^{(1)} = \begin{pmatrix} 0 & \cdots & 0 \end{pmatrix}$, $\boldsymbol{p}^{(2)} = \begin{pmatrix} 1 & \cdots & 1 \end{pmatrix}$



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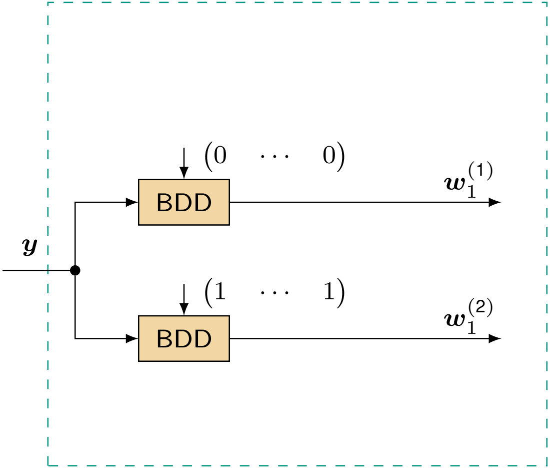
- **Step 3**:
  - Decode the test patterns with BDD



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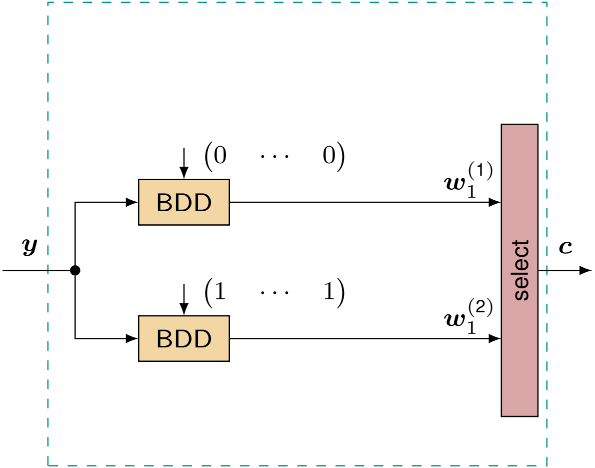
  - Select the decoding results



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Textbook Error-and-Erasure Decoding

- Textbook-style list decoding **[Moo05]**
- Can decode some patterns with D errors and E erasures when $2D + E \geq d_{\min}$
- **Example:** Decoding success rate of code with $d_{\min} = 6$ (BCH even-weight subcode)

D \ E	0	1	2	3	4	5
0	1.000	1.000	1.000	1.000	1.000	1.000
1	1.000	1.000	1.000	1.000	0.625	0.375
2	1.000	1.000	0.500	0.250	0.125	0.063

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Modified Textbook Error-and-Erasure Decoding

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- **Modified Step 2**: Replace the erasures with complementary binary **random** values to generate test patterns $(\boldsymbol{p}_1^{(1)}, \boldsymbol{p}_1^{(2)})$
  - Each decoding iteration, use **different random** patterns $(\boldsymbol{p}_1^{(1)}, \boldsymbol{p}_1^{(2)})$
- Step 3:
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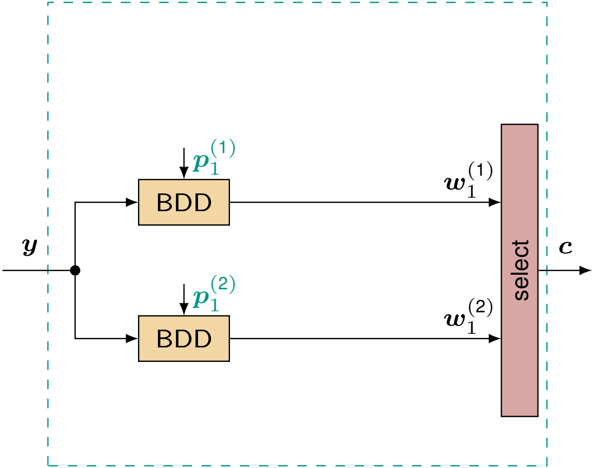

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- **Example:** Decoding success rate of code with $d_{\min} = 6$ (BCH even-weight subcode) after $\ell = 5$ **decoding trials**

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0	1.000	1.000	1.000	1.000	1.000	1.000
1	1.000	1.000	1.000	1.000	0.993	0.905
2	1.000	1.000	0.969	0.762	0.487	0.276

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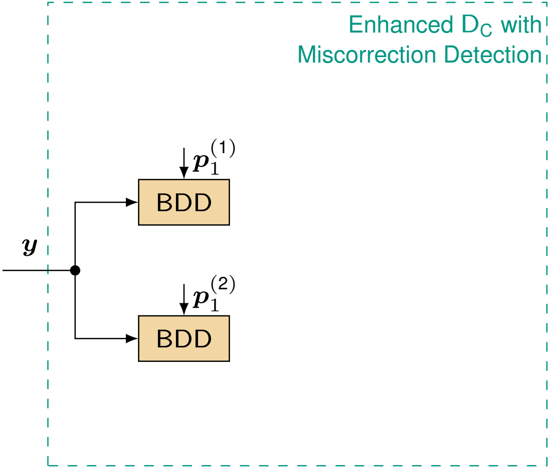

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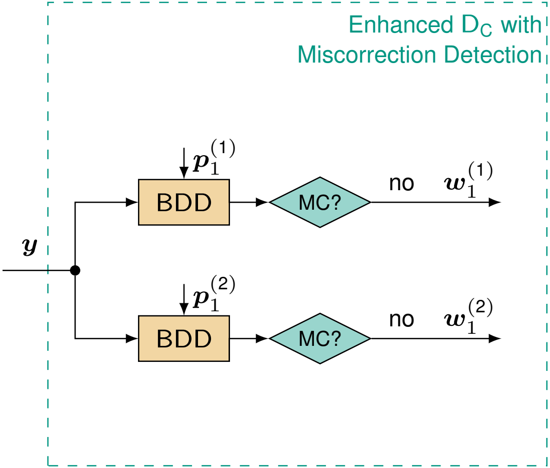

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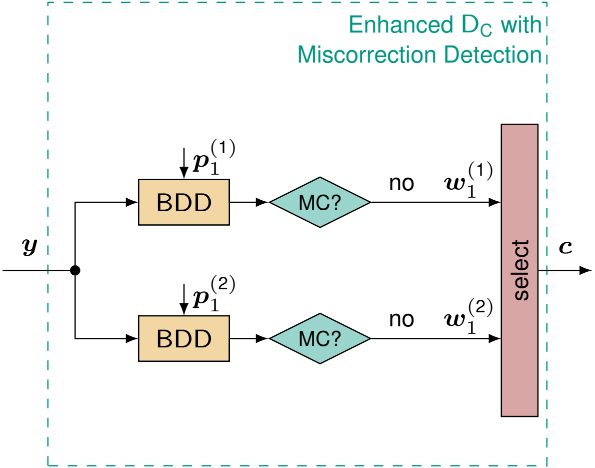
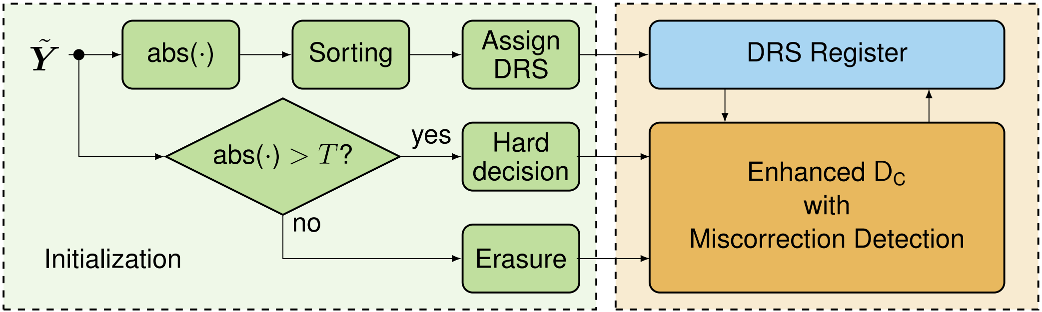


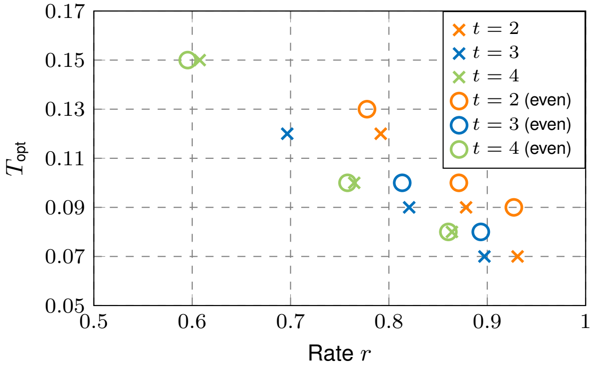
[Moo05] T. K. Moon, *Error Correction Coding - Mathematical Methods and Algorithms*. John Wiley & Sons, Inc., 2005.

Flow Chart of the Proposed Algorithm



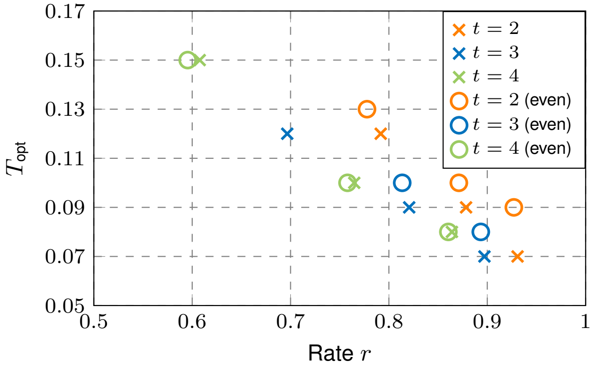
Parameter Analysis – Simulation Results

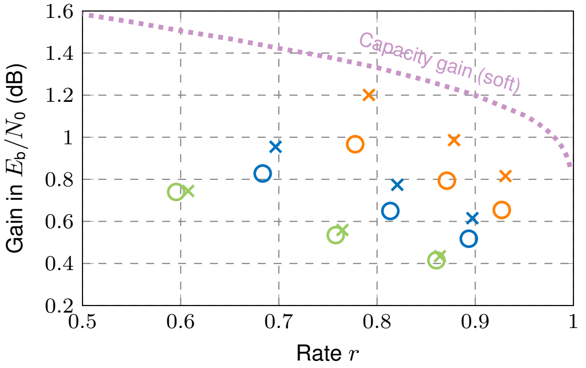
- Optimized **erasure threshold** T_{opt} for different PCs with BCH component codes (different t and even-weight subcodes)



Parameter Analysis – Simulation Results

- Optimized **erasure threshold** T_{opt} for different PCs with BCH component codes (different t and even-weight subcodes)
- **Threshold gains** compared to iBDD with 20 iterations





Numerical Simulation Results (1)

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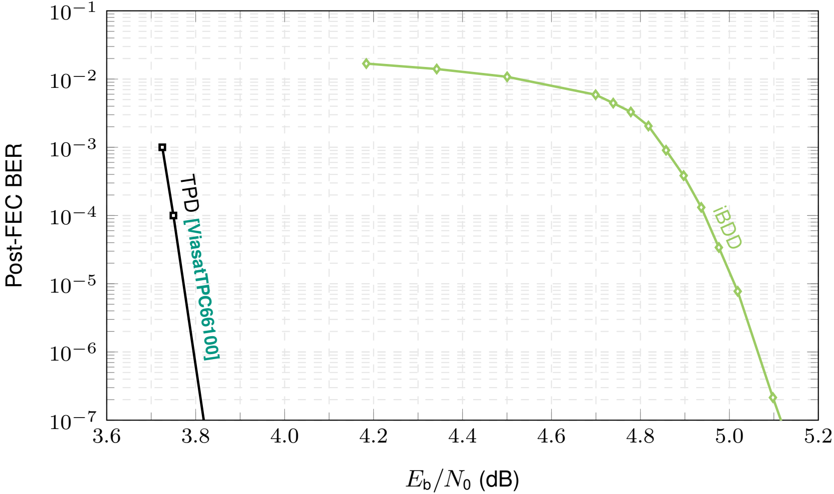
- PC of **rate 0.87**, component code **[255, 238, 2]** even weight subcode of BCH code



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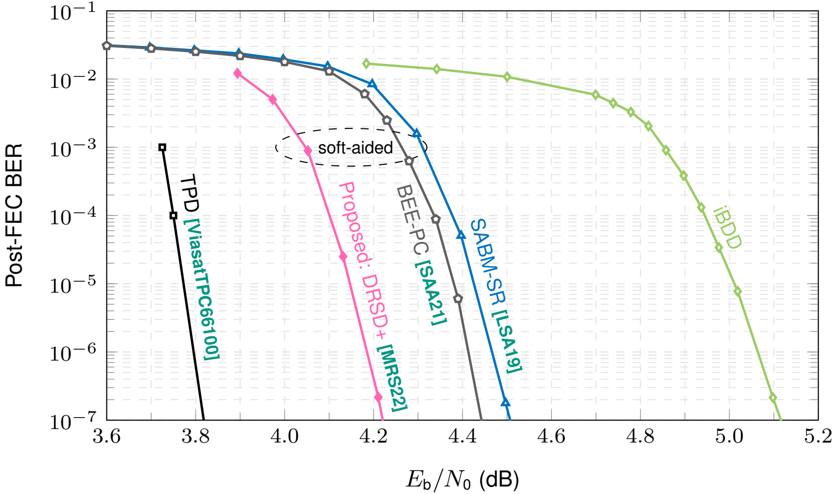

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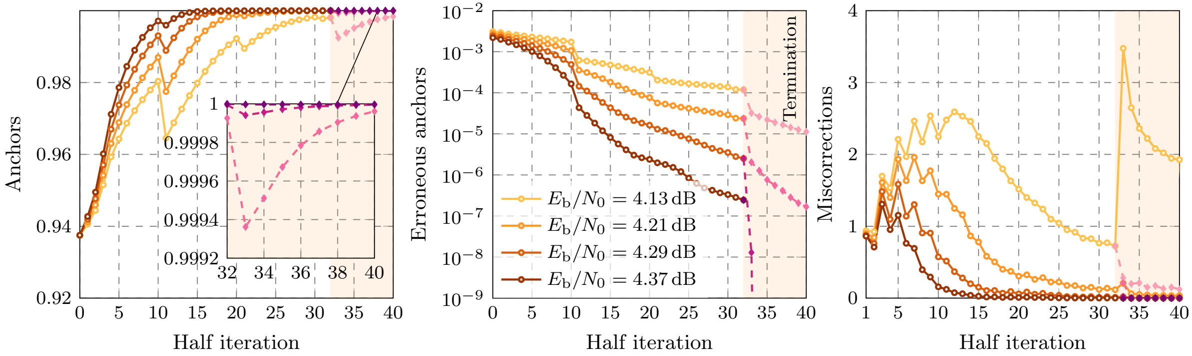
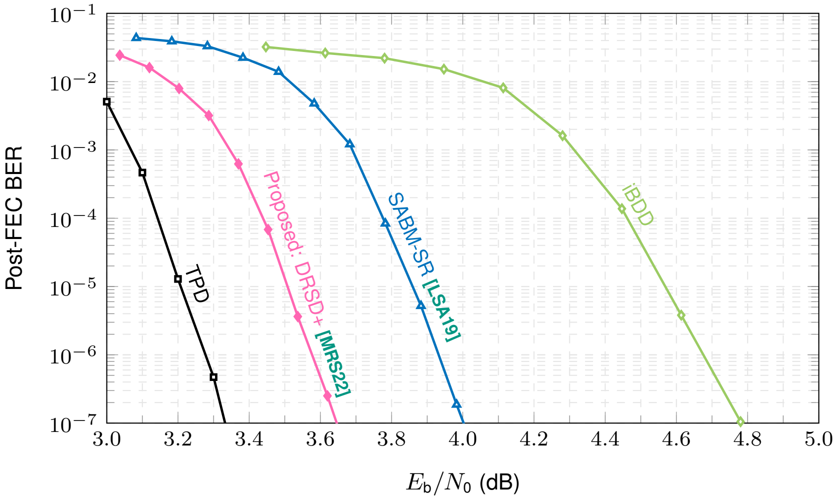
- Percentage of marked anchor bits, percentage of wrongly marked anchor bits, and average number of miscorrections in every iteration



Numerical Simulation Results (2)

- PC of **rate 0.78**, component code **[127, 112, 2]** even weight subcode of BCH code



Overview

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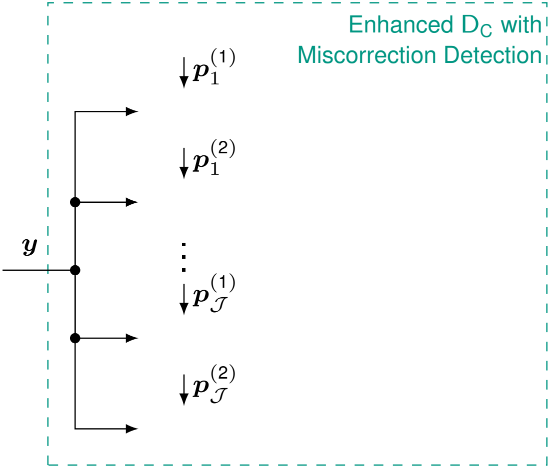
- Motivation
- Iterative Bounded Distance Decoding of PCs
- Decoder with Dynamic Reliability Scores
- List-Based Decoder with Dynamic Reliability Scores

Enhanced Component Decoder

- Step 1: Introduce erasures

$$y_i = \begin{cases} ?\ (\textbf{erasure}) & \text{if } |\tilde{y}_i| < T \\ \text{sign}(\tilde{y}_i) & \text{if } |\tilde{y}_i| \geq T \end{cases}$$

- Step 2: Replace the erasures with $\mathcal{J}$ pairs of complementary binary random values to generate test patterns $(\boldsymbol{p}_i^{(1)}, \boldsymbol{p}_i^{(2)})$
  - $\mathcal{J}$ is a configurable parameter for complexity-performance trade-off



[MRS22b] S. Miao, L. Rapp, and L. S., "Improved soft-aided decoding of product codes with adaptive performance-complexity trade-off," *Proc. ECOC*, Basel, CH, 2022.

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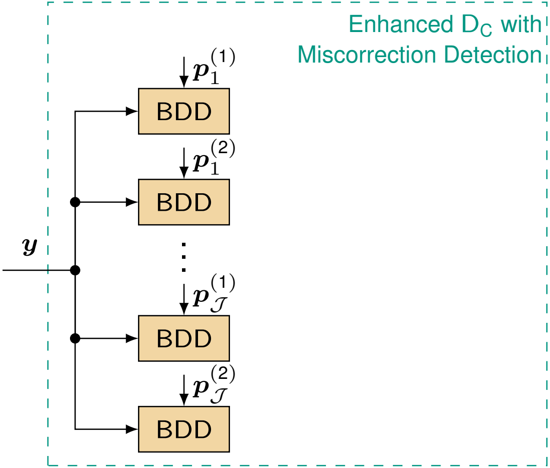

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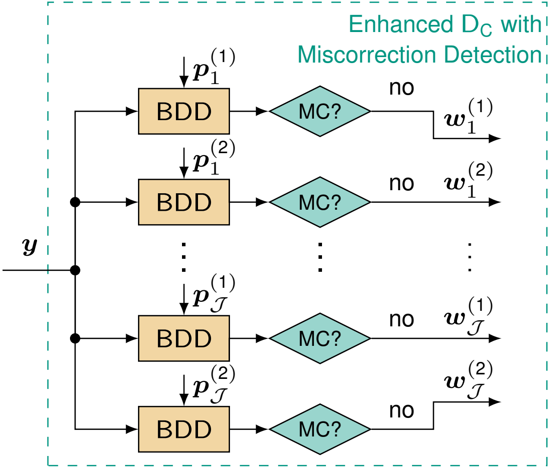

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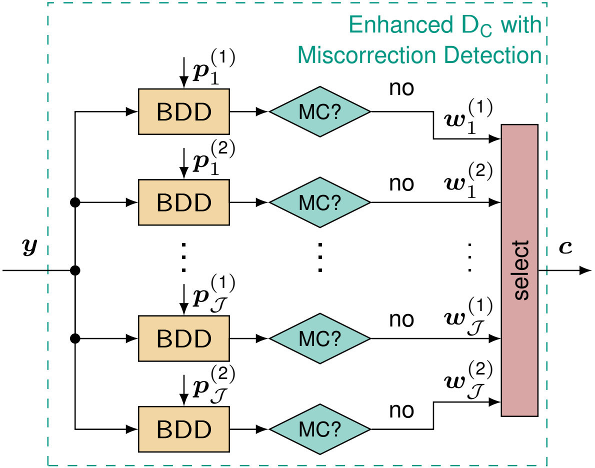

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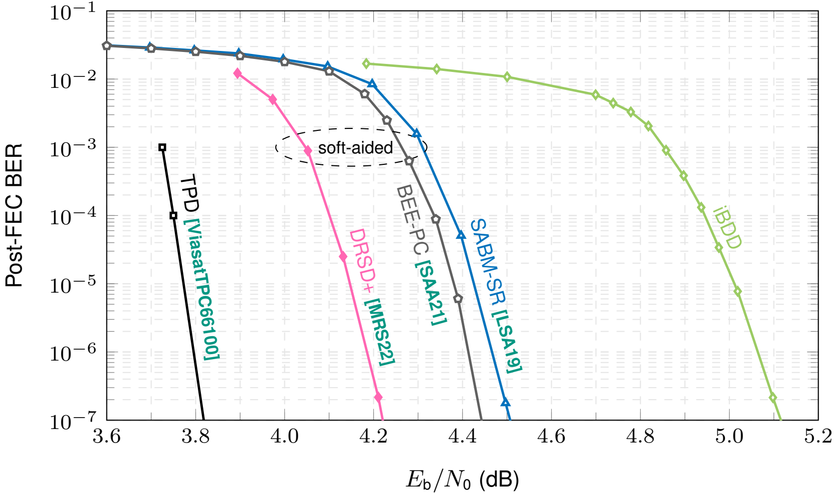

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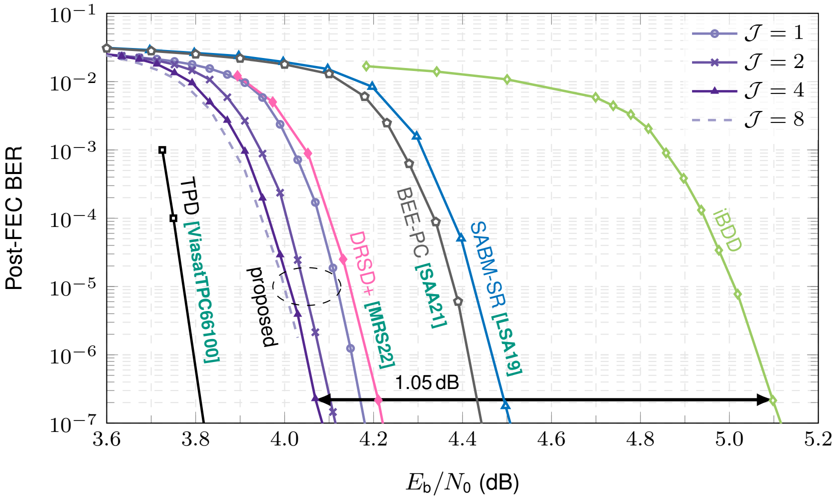

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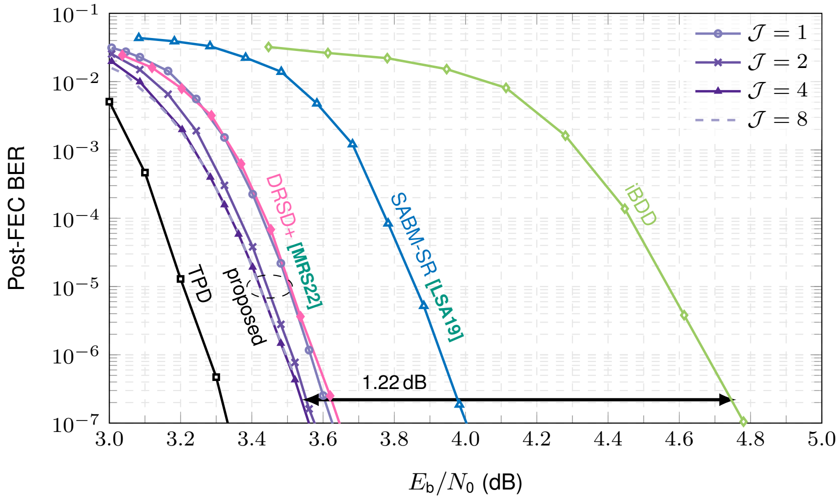

Conclusions & Outlook

- Proposed a novel soft-aided HDD algorithm with increased number of correctable errors with additional miscorrection control
- Provides comparable decoding performance with soft decision decoding
- Low complexity and internal decoder data flow

- Analysis and extension to generalized PCs and zipper codes **[MMR+24]**

[MMR+24] S. Miao, J. Mandelbaum, L. Rapp, H. Jäkel, L. S., “Performance analysis of generalized product codes with irregular degree distribution ,” submitted to *ISIT*, `https://arxiv.org/abs/2401.16977`

[MRS22a] S. Miao, L. Rapp, and L. S., “Improved soft-aided decoding of product codes with dynamic reliability scores,” *J. Lightw. Technol.*, vol. 40, no. 22, pp. 7279-7288, 2022.

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Questions?

European Research Council
Established by the European Commission

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