Decoding Complexity of Long Polar and LDPC Codes

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2nd March 2026

University of Stuttgart
Institute of Telecommunications
Prof. Dr. Ing. Stephan ten Brink

Outline

Agenda

Basis of This Work

- Coding group at INUE, working on, e.g.,
  - Polar & LDPC Coding for Wireless
  - Staircase-like/Spatially Coupled Codes for Optical
  - Ensemble Decoding
  - Expectation Propagation
- Material taken from our recent Globecom-paper
  - Krieg et al., "Long Polar vs. LDPC Codes under Complexity-Constrained Decoding," IEEE Globecom 2025 Workshop on Channel Coding beyond 5G, Taiwan, December 2025 [2508.05485]; not yet on IEEE Xplore...
- Contact the authors
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Motivation

New design goals in 6G: **sustainability** and **efficiency**
The new standards aim to include even more device types

➜ Redcap devices

With FEC as the workhorse of the physical layer, new challenges arise:

- Reduced chip area
- Low energy consumption of the decoder

➜ Powerful yet simple decoders will be required

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Possible Code Families

The codes also should be easy to standardize:

- We don't expect any major inventions, such as a new family of codes, for 6G
- Rely on the trusted 5G codes:

➜ LDPC codes, and/or

➜ Polar codes

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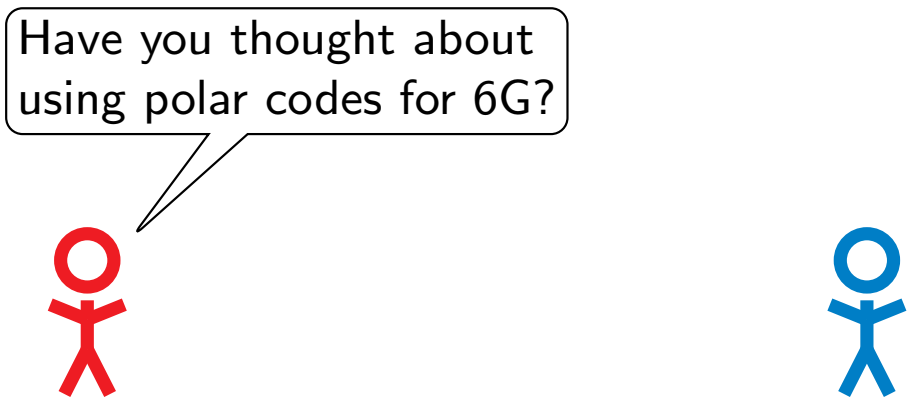
The Common Conception



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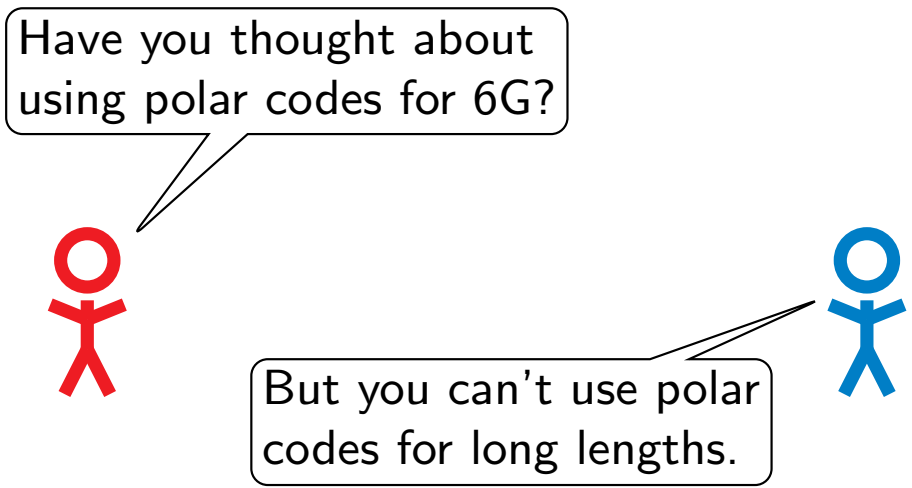

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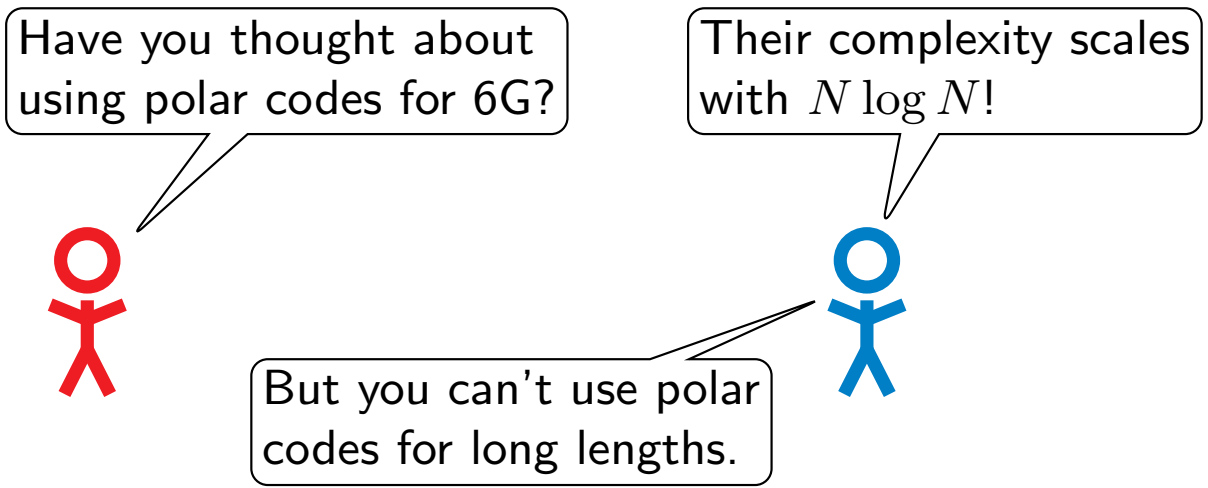

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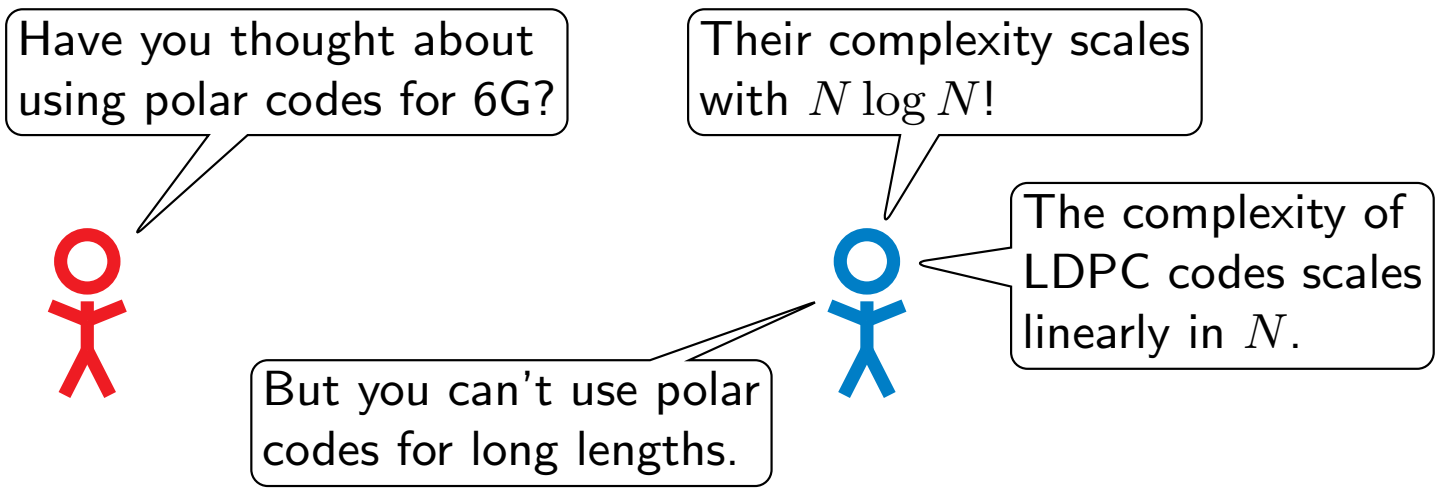

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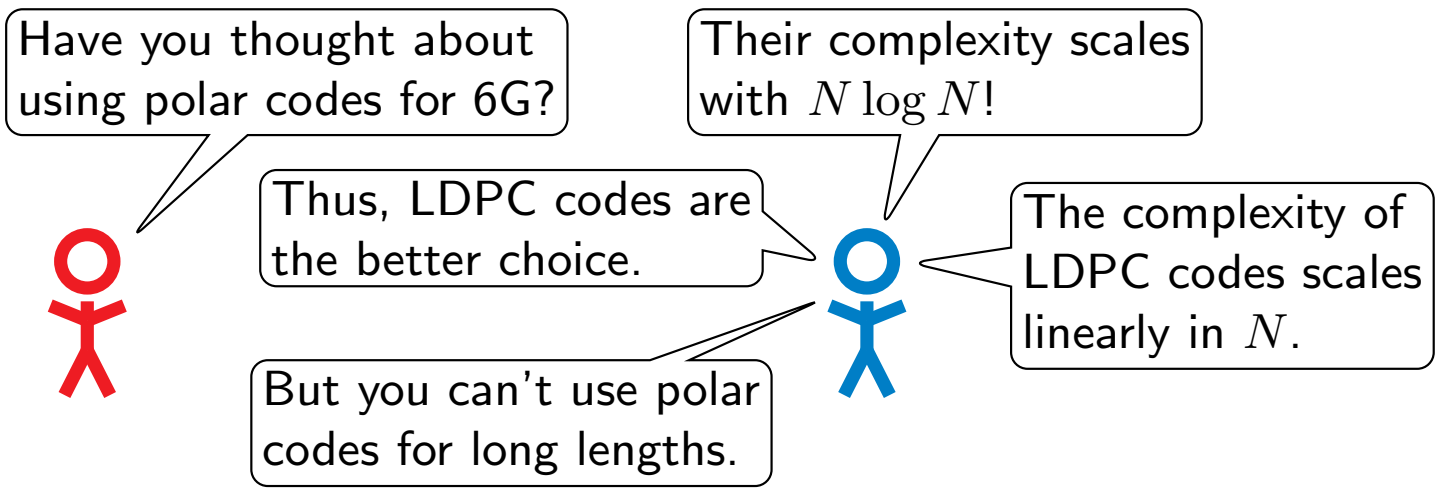

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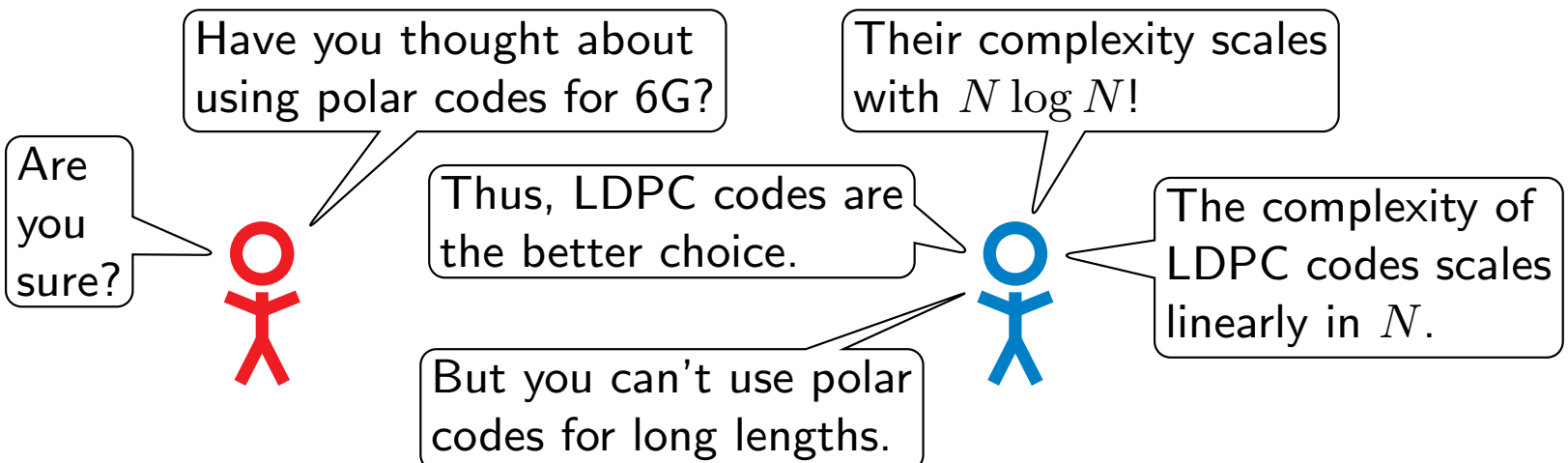

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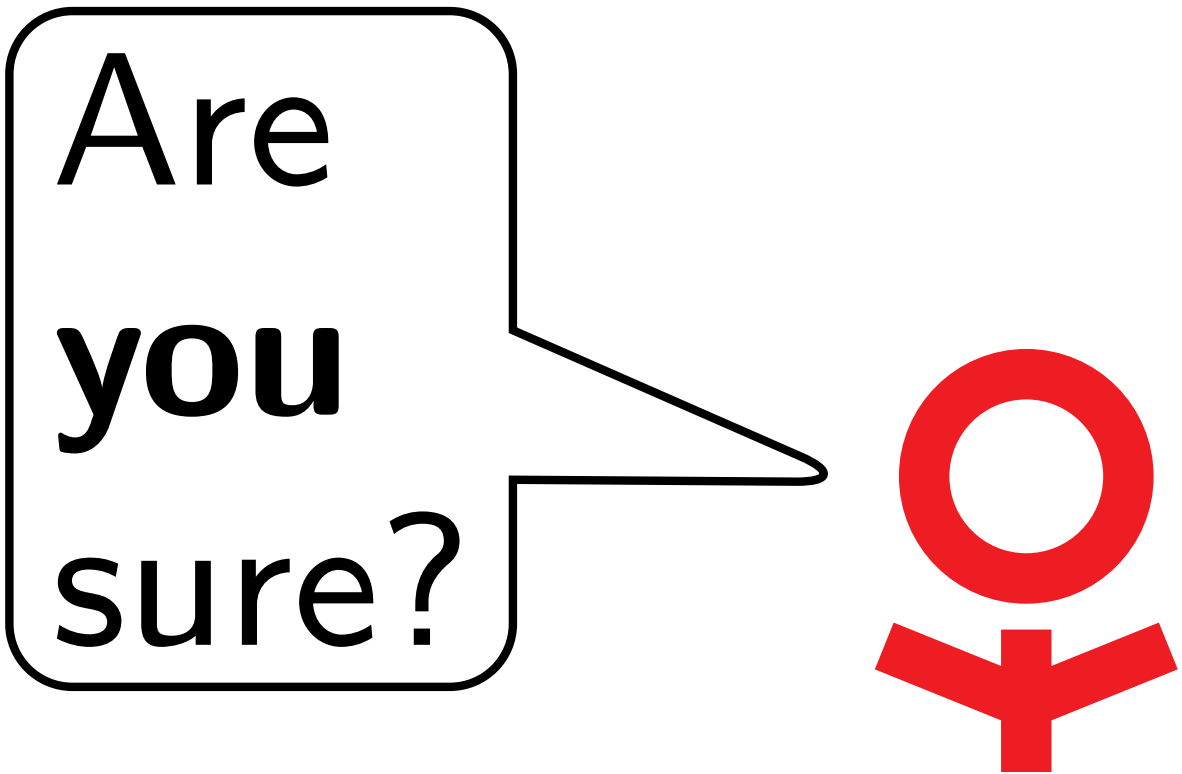


Goal

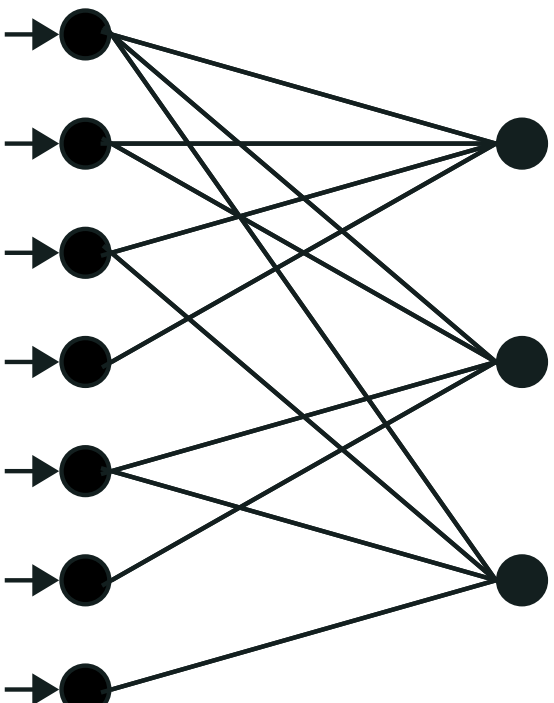
- There is an overwhelming consensus that polar codes do not scale well to longer lengths

➜ Let's make a fair comparison!

Agenda

LDPC Codes & BP Decoding

- Represent $\boldsymbol{H}$ as a bipartite graph
- Constraints between variable nodes are considered in check nodes
- Focusing on one check node $j = 3$:
  - The variable nodes V_j propagate their reliabilites to the check node
  - The check node calculates $r_{i \leftarrow j} = \boxplus_{i' \in V_j \setminus i} q_{i' \rightarrow j}$ and propagates back to the variable nodes
  - The check node update can be approximated



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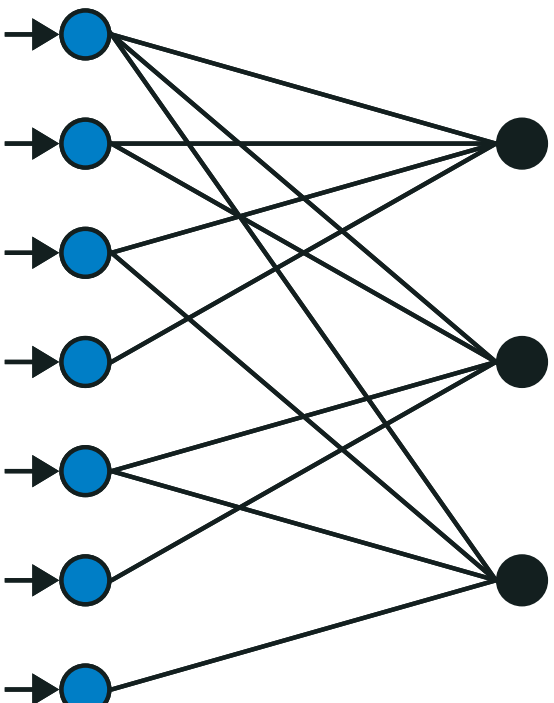

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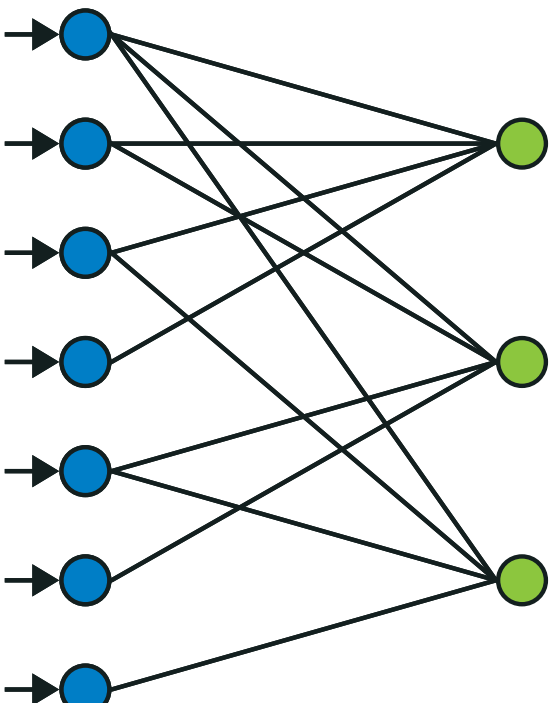

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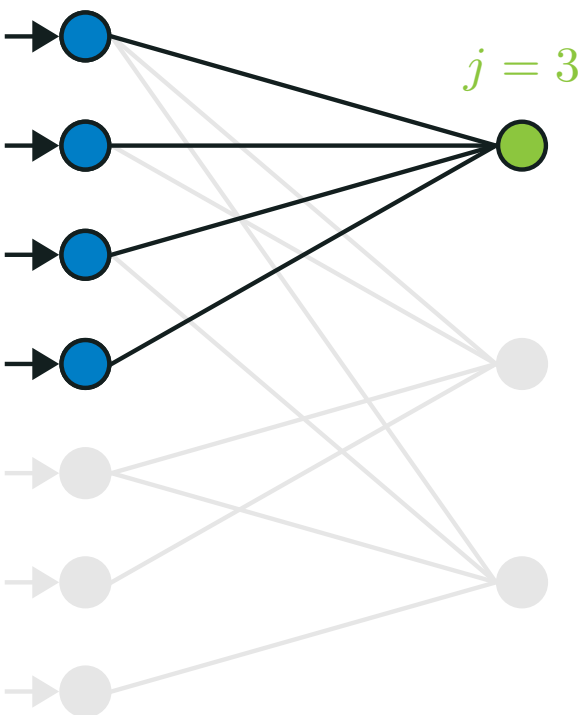

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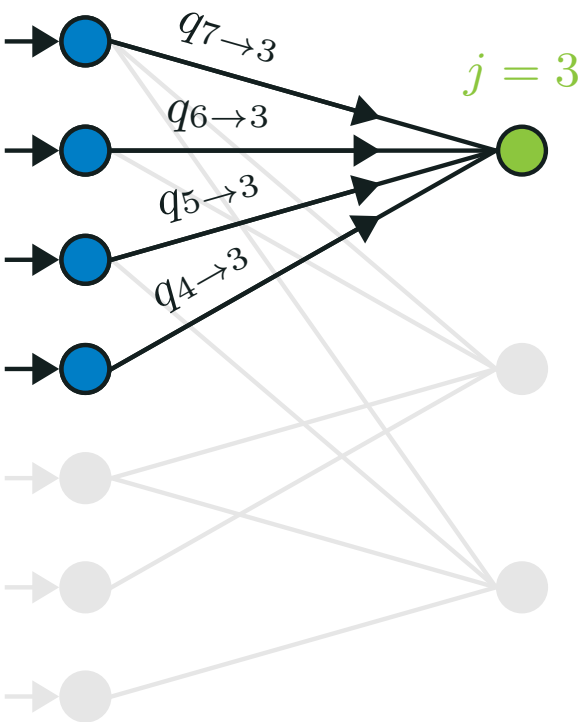

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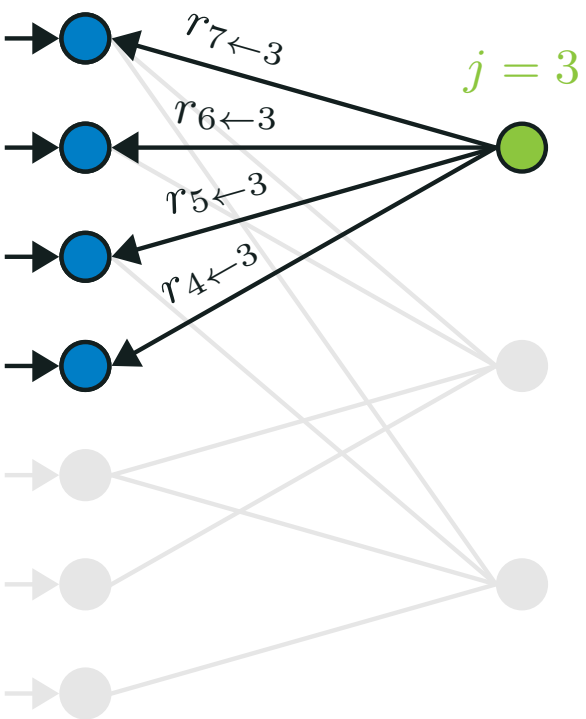

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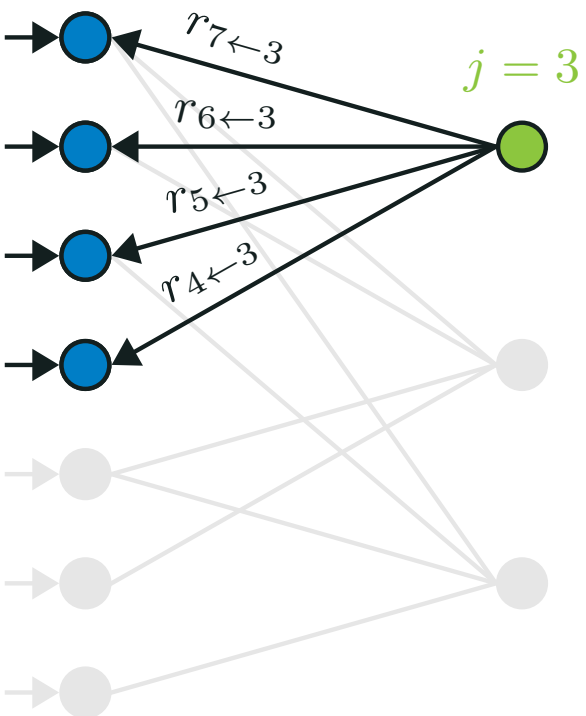

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LDPC Codes & BP Decoding (cont.)

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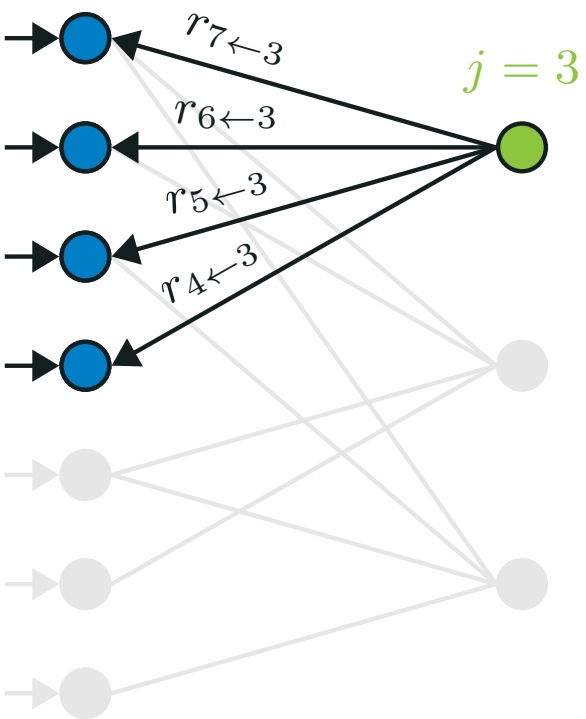

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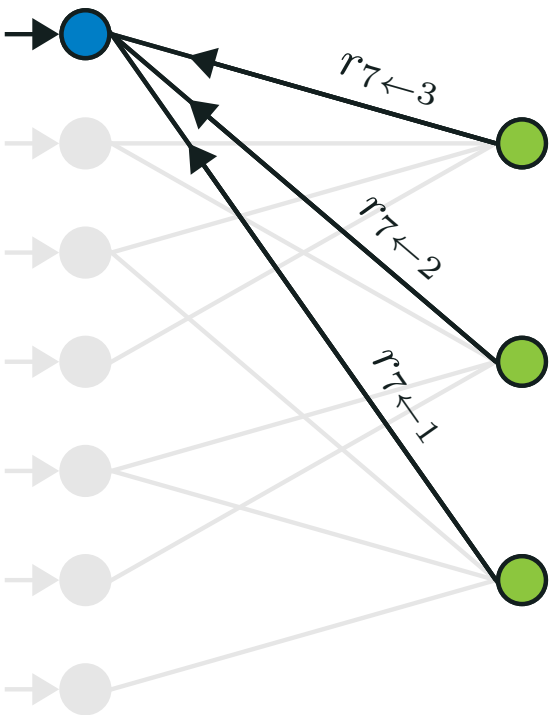

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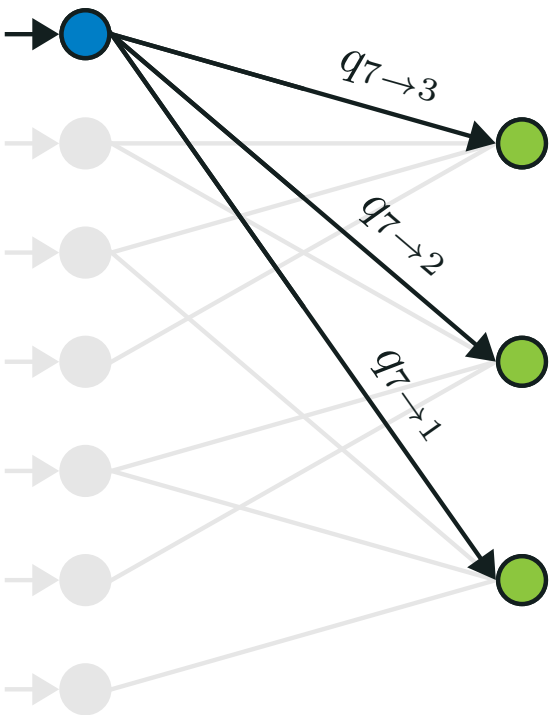

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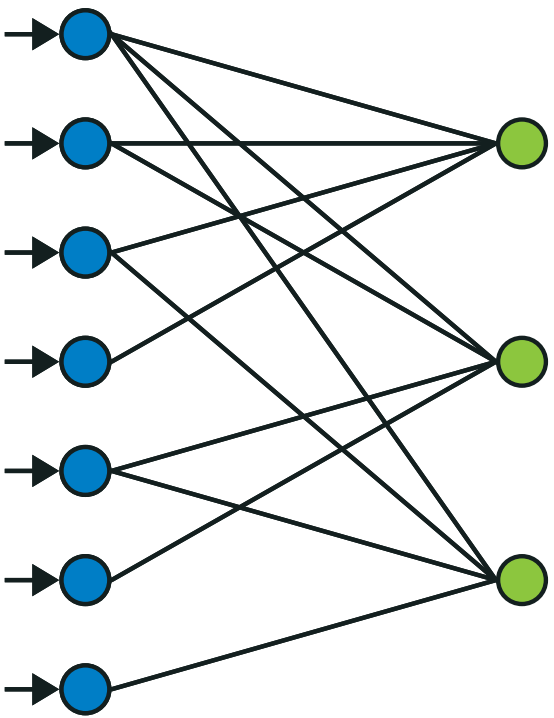

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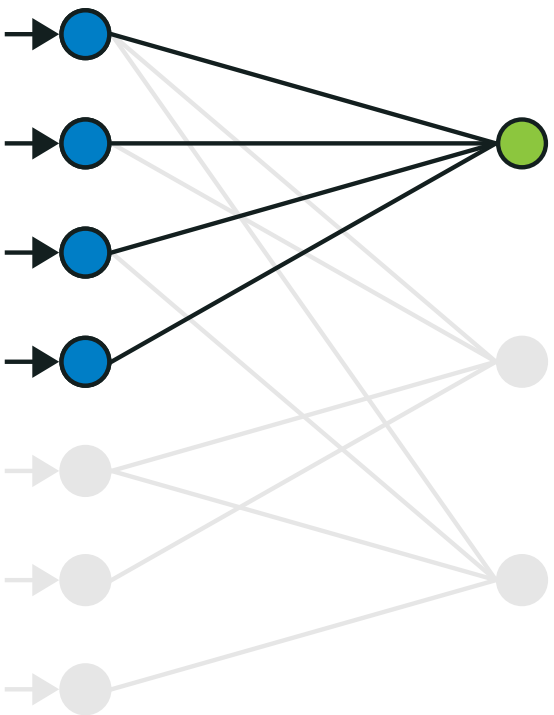

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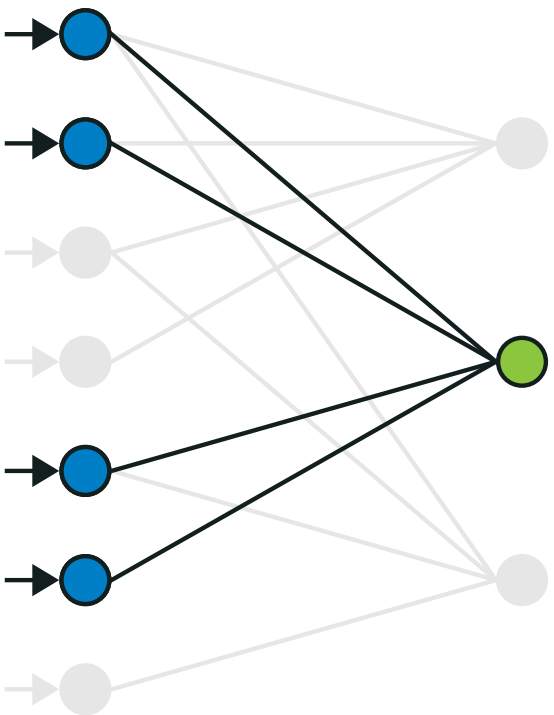

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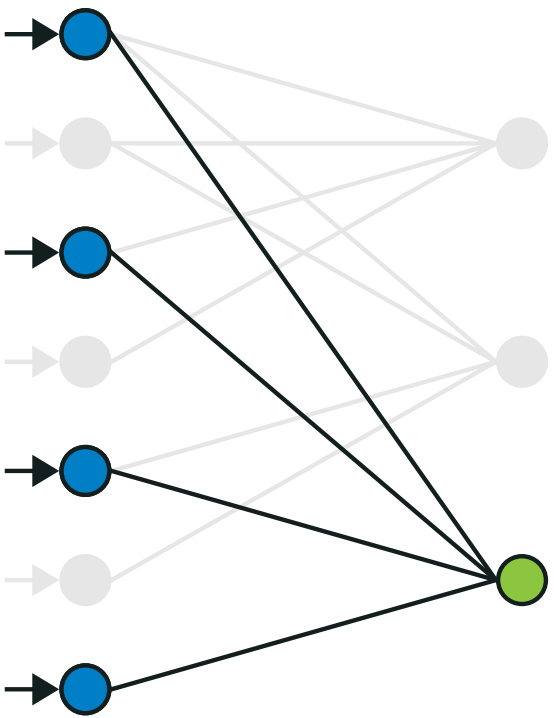

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Polar Codes & SC Decoding

- Main building block: 2×2 kernel
- Frozen bits $(N - K)$ are always 0
- Remaining bits carry information
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  - Decode first channel(s)
  - Decide at the message side
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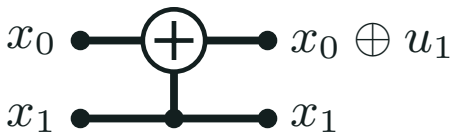

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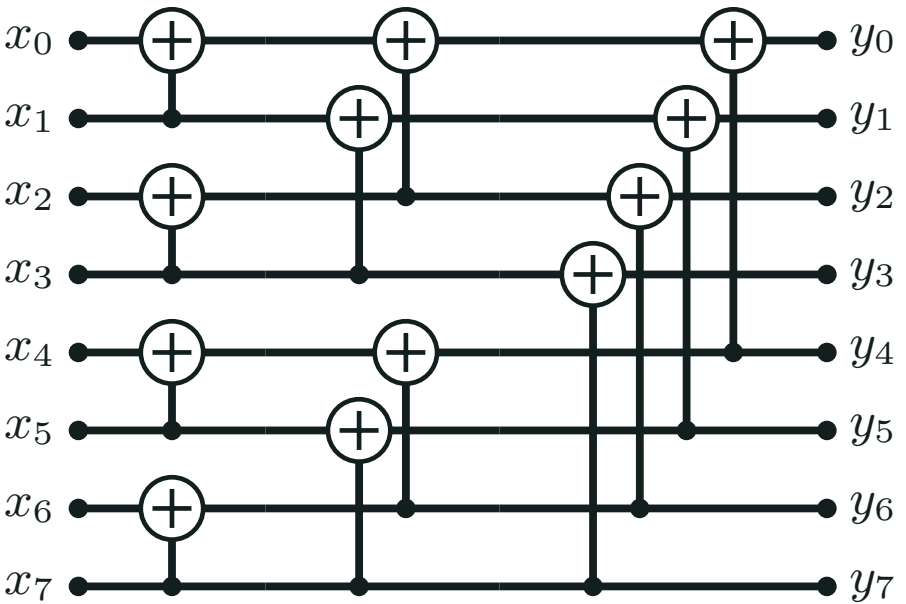

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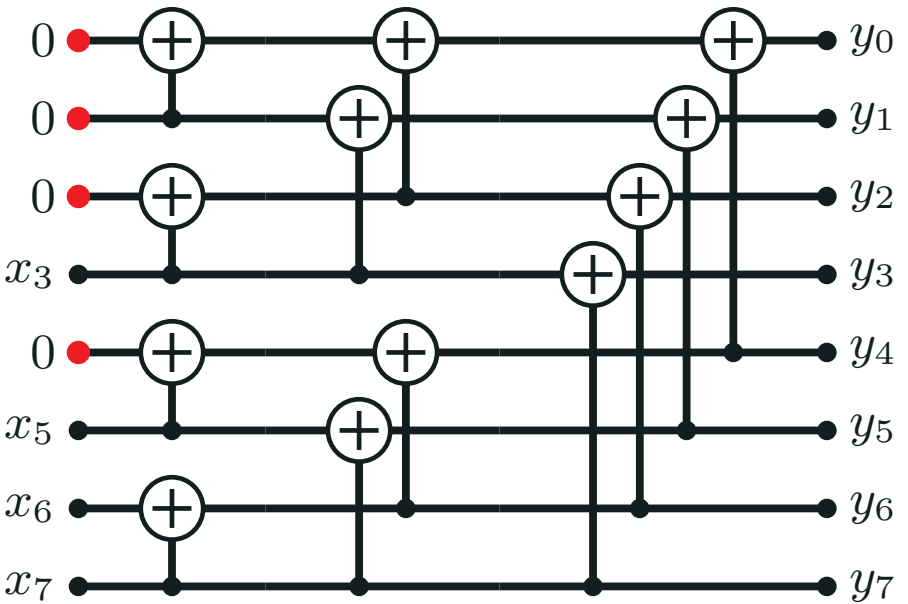

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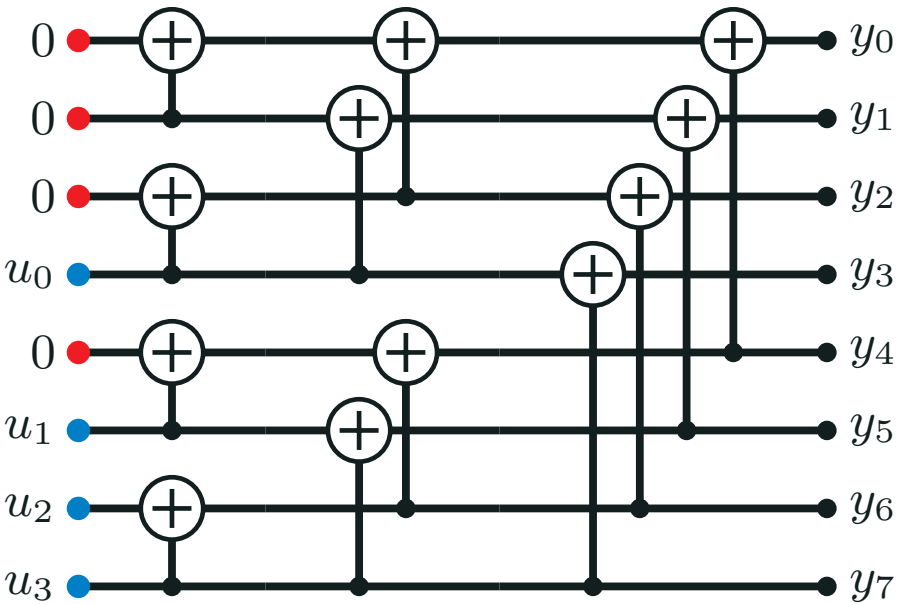

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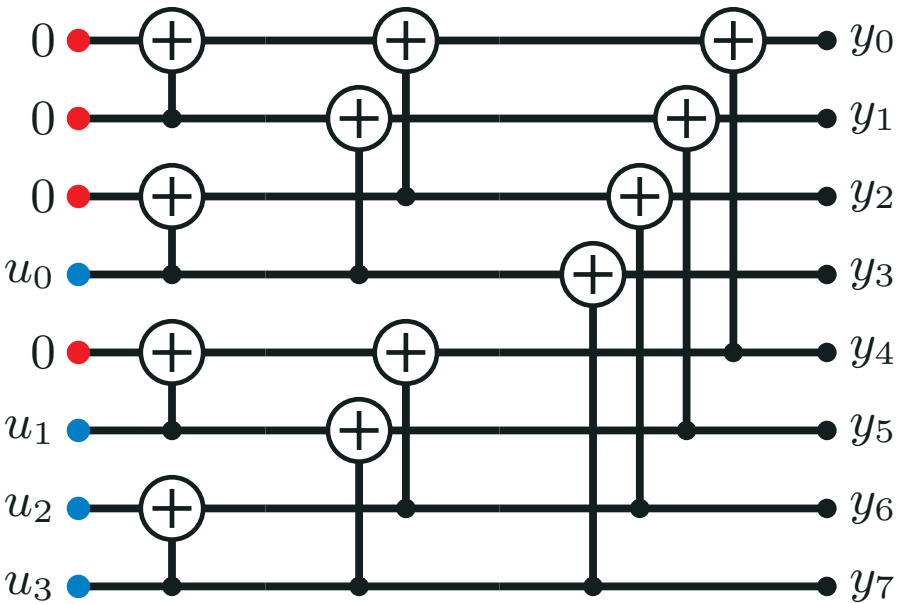

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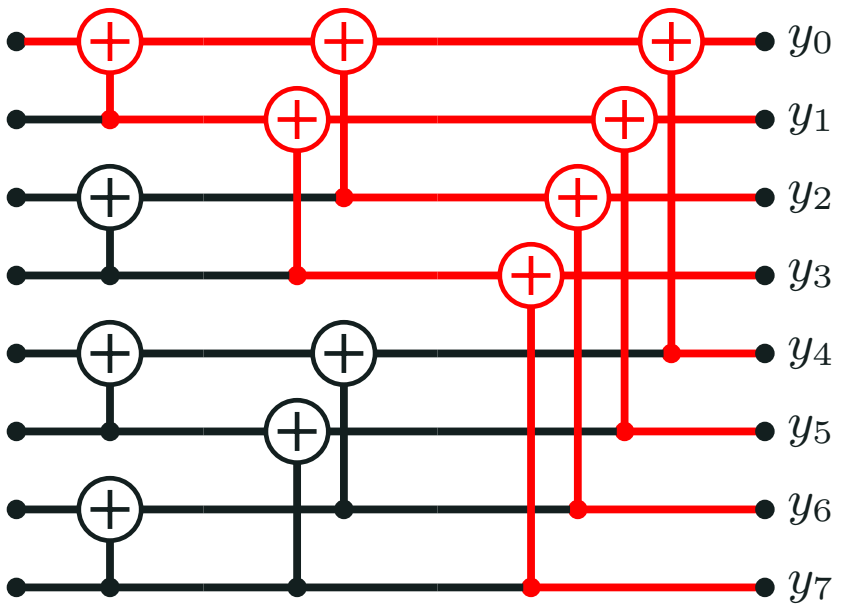

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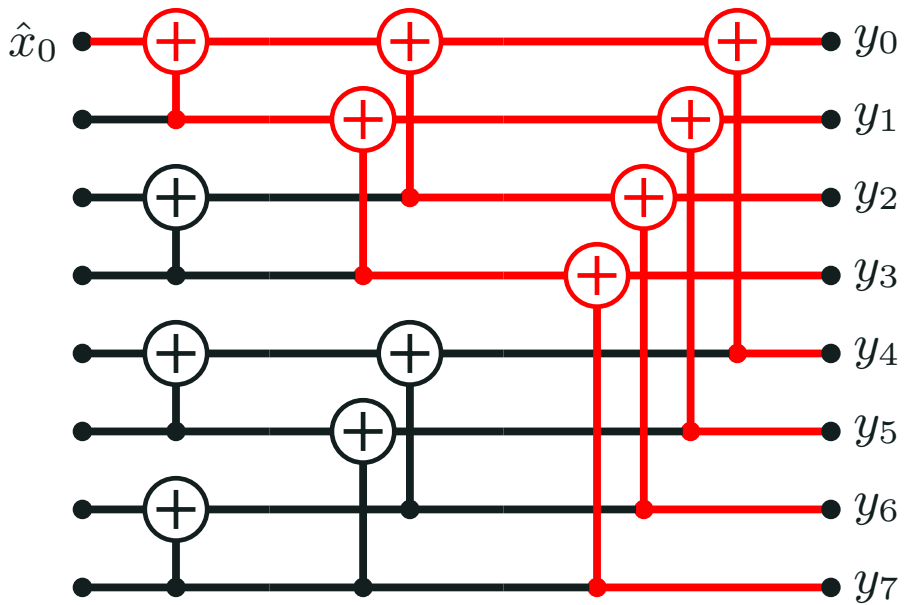

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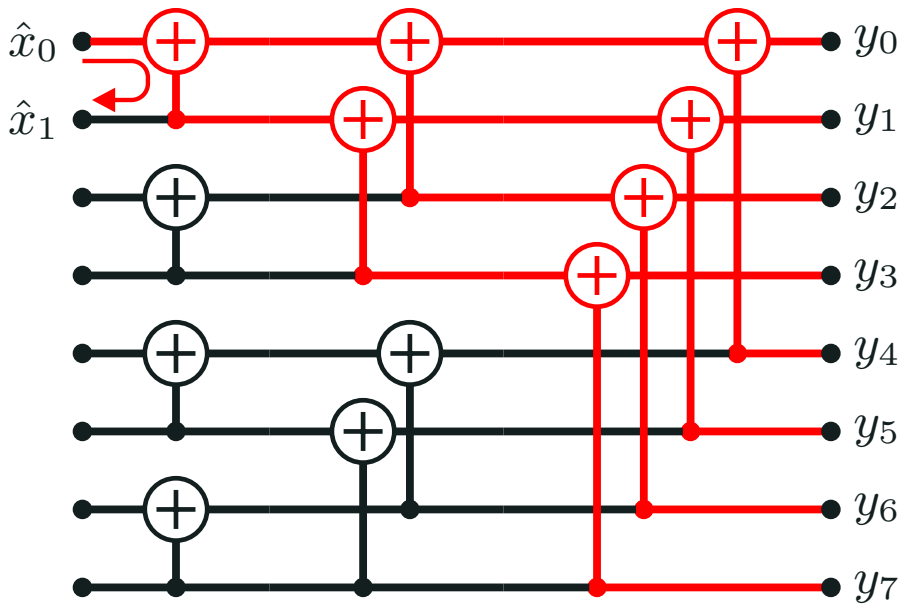

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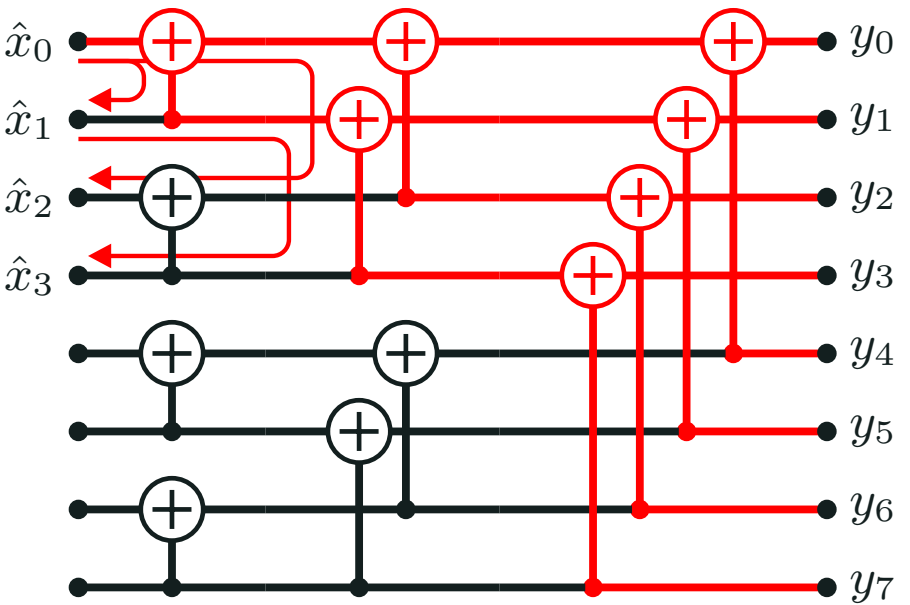

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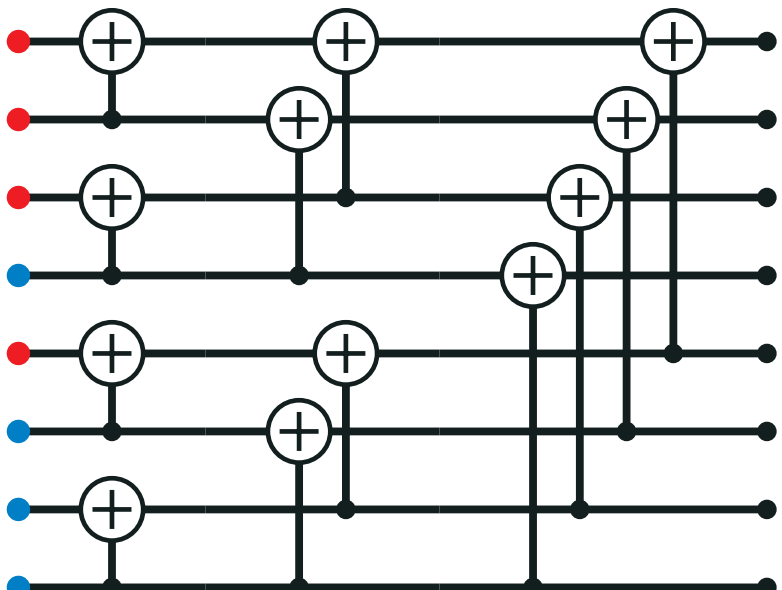
Simplified SC Decoding

- Certain combinations of frozen and information bits lead to known subcodes
  - Repetition codes
  - Single parity check codes
  - Rate-0 and rate-1 codes
- These codes can be decoded in one operation
- Simplified SC decoding leverages this to reduce the complexity

➜ This does not degrade decoding performance!



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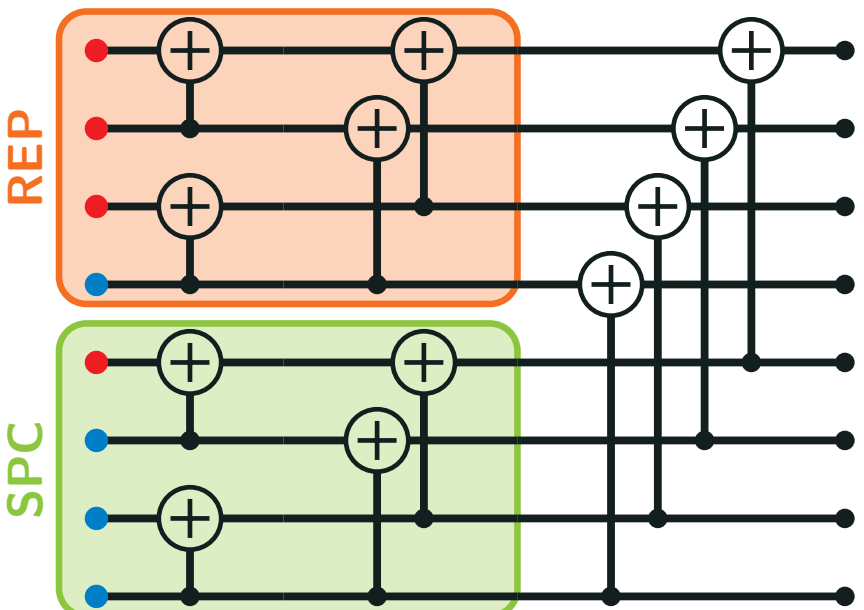

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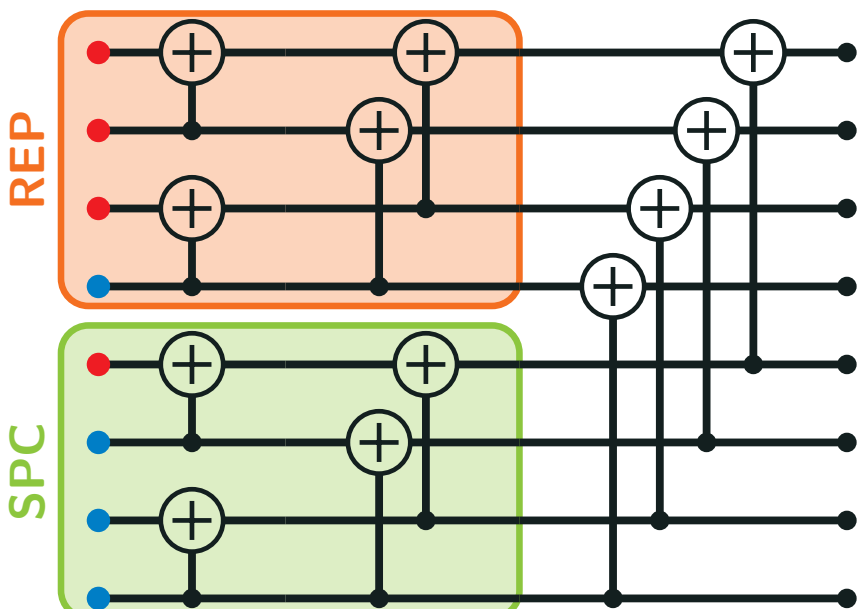

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Simplified SC Decoding

- Certain combinations of frozen and information bits lead to known subcodes
  - Repetition codes
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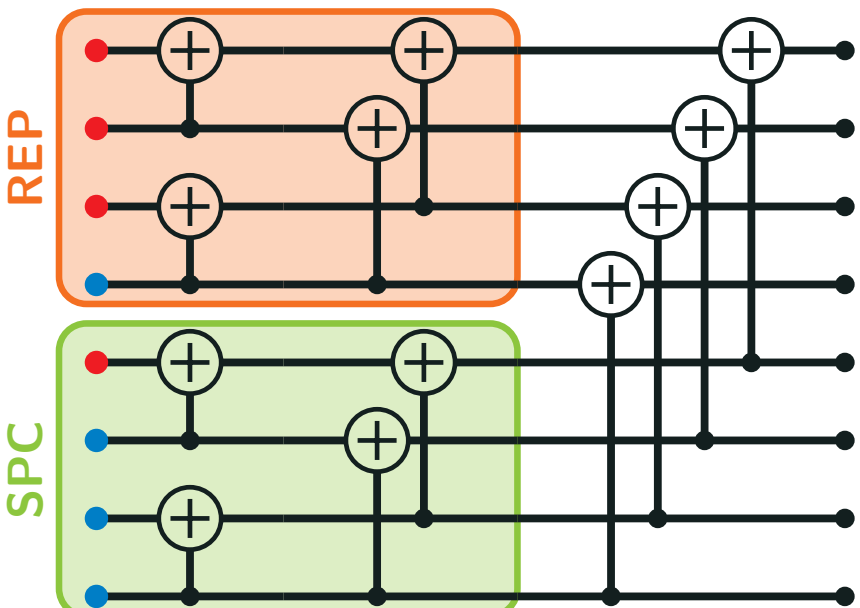

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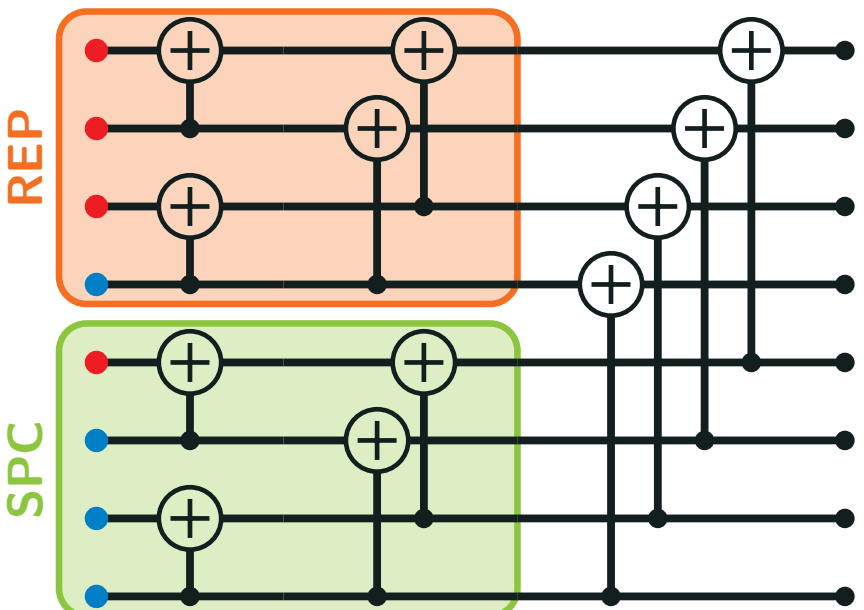

Agenda

How to Approximate the Complexity?

- Both polar and LDPC codes need to evaluate the boxplus-function
- For both codes: approximate this function as

$$\boxplus_{x\in\mathcal{X}} x \approx \underbrace{\prod_{x\in\mathcal{X}} \operatorname{sgn}(x)}_{1 \text{ bit op.}} \cdot \underbrace{\alpha \cdot \min_{x\in\mathcal{X}} |x|}_{\geqslant 4 \text{ bit op.}} \tag{1}$$

➜ Complexity dominated by operations of higher bit-width
  - Binary additions of LLRs
  - MIN-operation on a list of LLRs (also an addition)

$$\min(x_1, x_2) = \begin{cases} x_1 & \text{if } x_1 - x_2 \leqslant 0 \\ x_2 & \text{otherwise} \end{cases} \tag{2}$$

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Operations in BP decoding

- For the i-th CN update, we need to compute
  - $2\deg_{\mathrm{CN}}(i) - 3$ comparisons to find the two smallest magnitudes
  - $\deg_{\mathrm{CN}}(i)$ additions to make the belief extrinsic
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- For the j-th VN update, we need to compute
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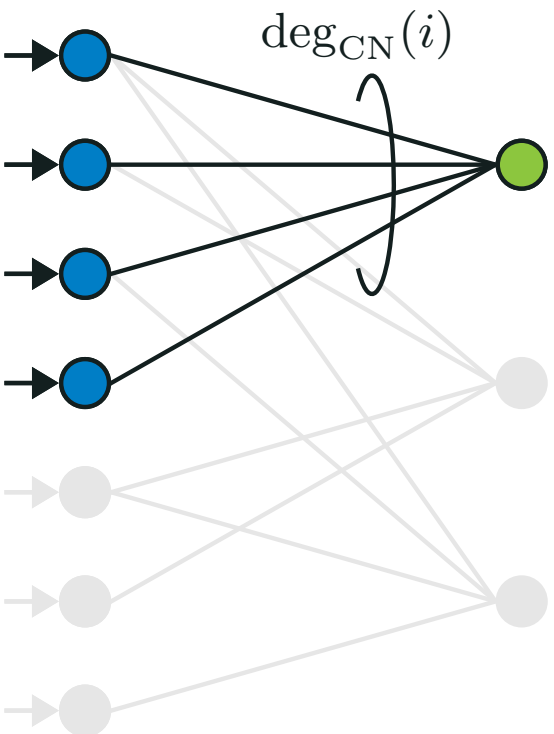
- In total: $5 \cdot \sum_{i,j} h_{i,j} - 3M$ additions per iteration, depends on code design



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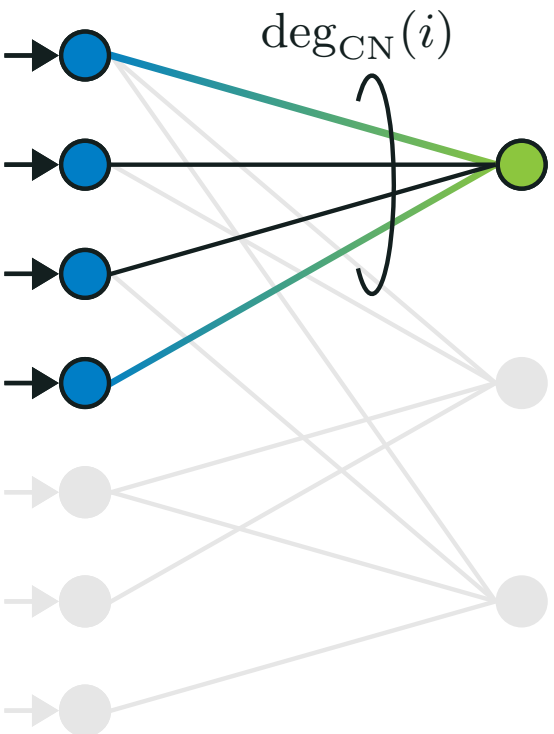

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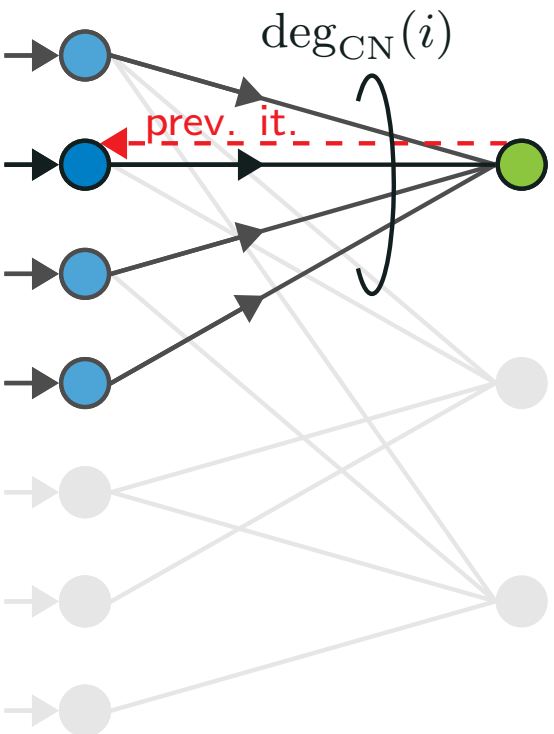

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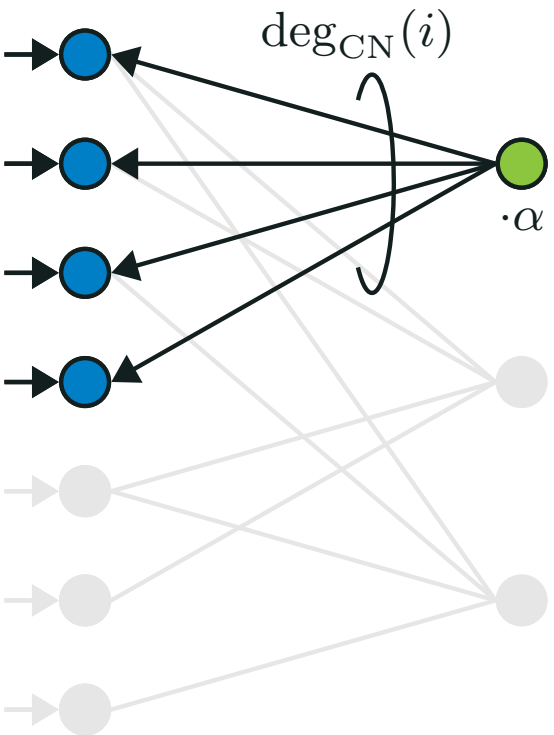

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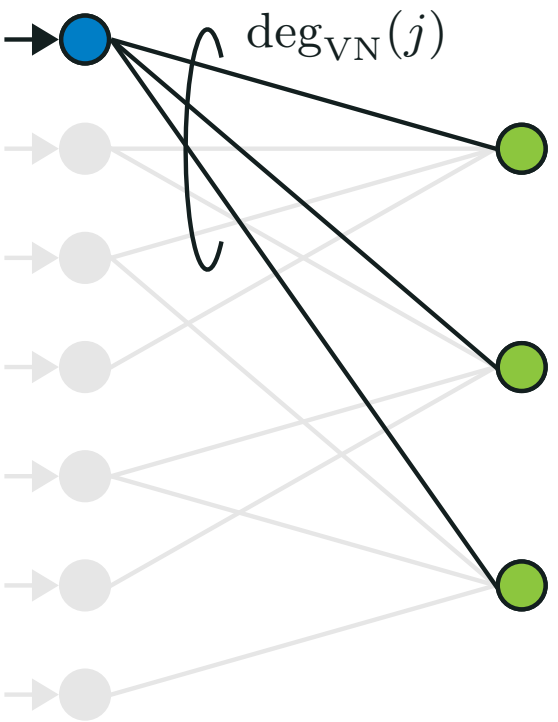

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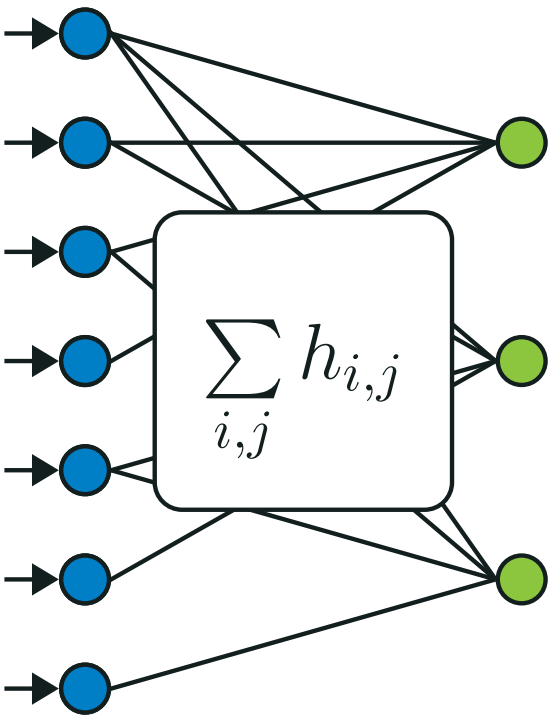

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Operations in (S)SC decoding

- Plain SC: $\log N$ stages
- Per stage:
  - $N/2$ additions
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- SSC reduces the number of operations
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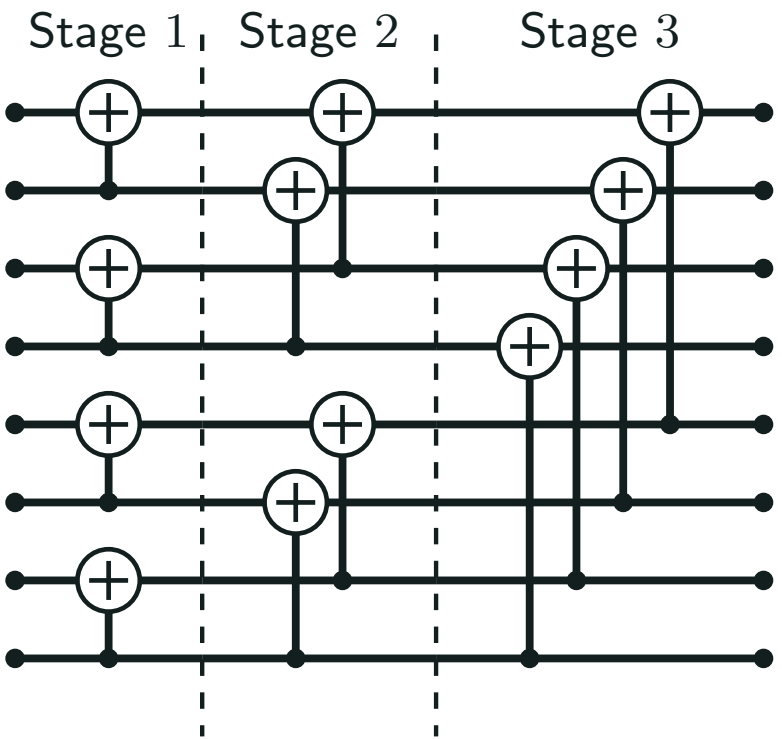

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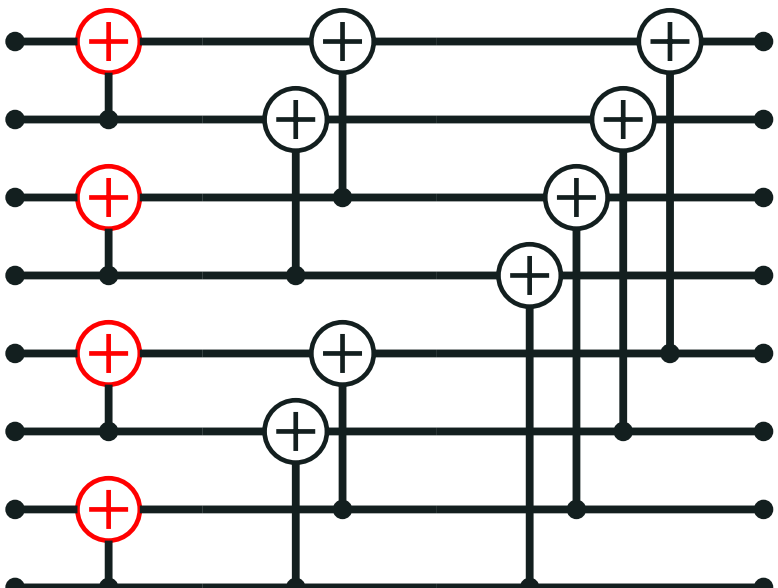

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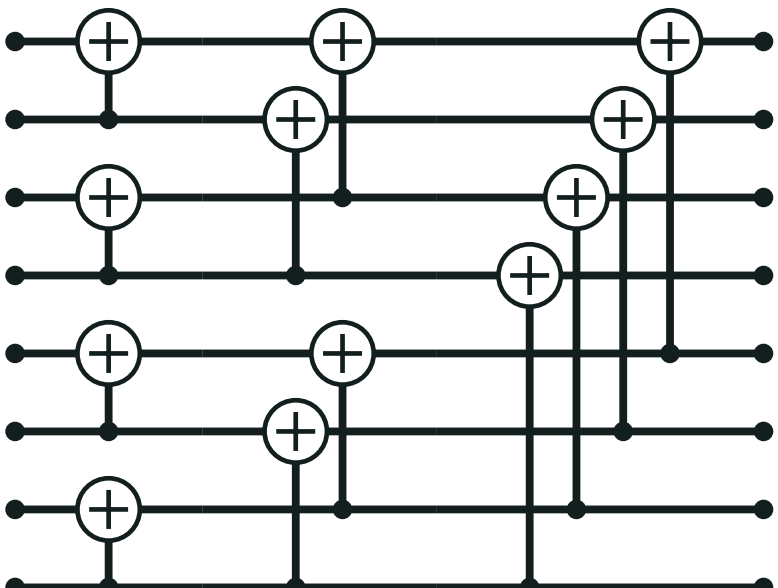

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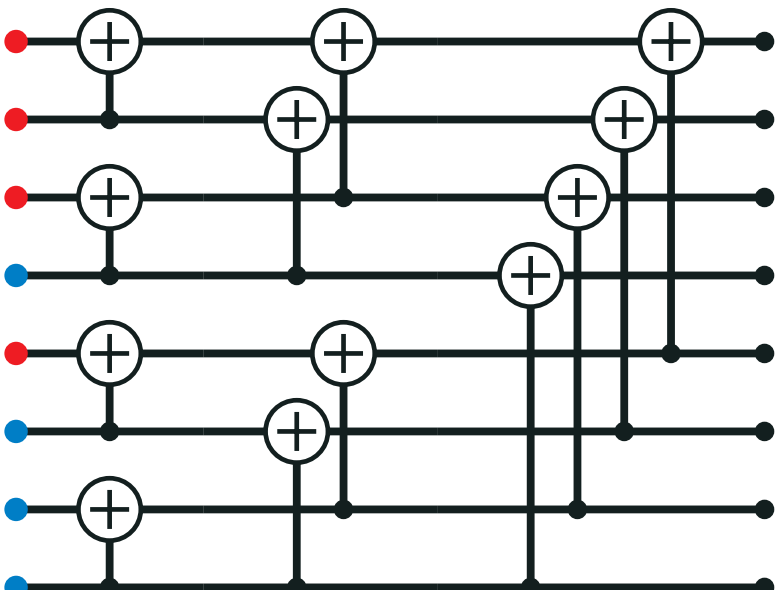

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Considered Codes

Polar design	Density evolution @ BLER 10^{-6}			
LDPC design	CCSDS			DVB-S2
Dimension K	1 024	4 096	16 384	$N \cdot R$
Length N		K/R		64 800
Code Rate R	$1/2$, $2/3$, $4/5$			

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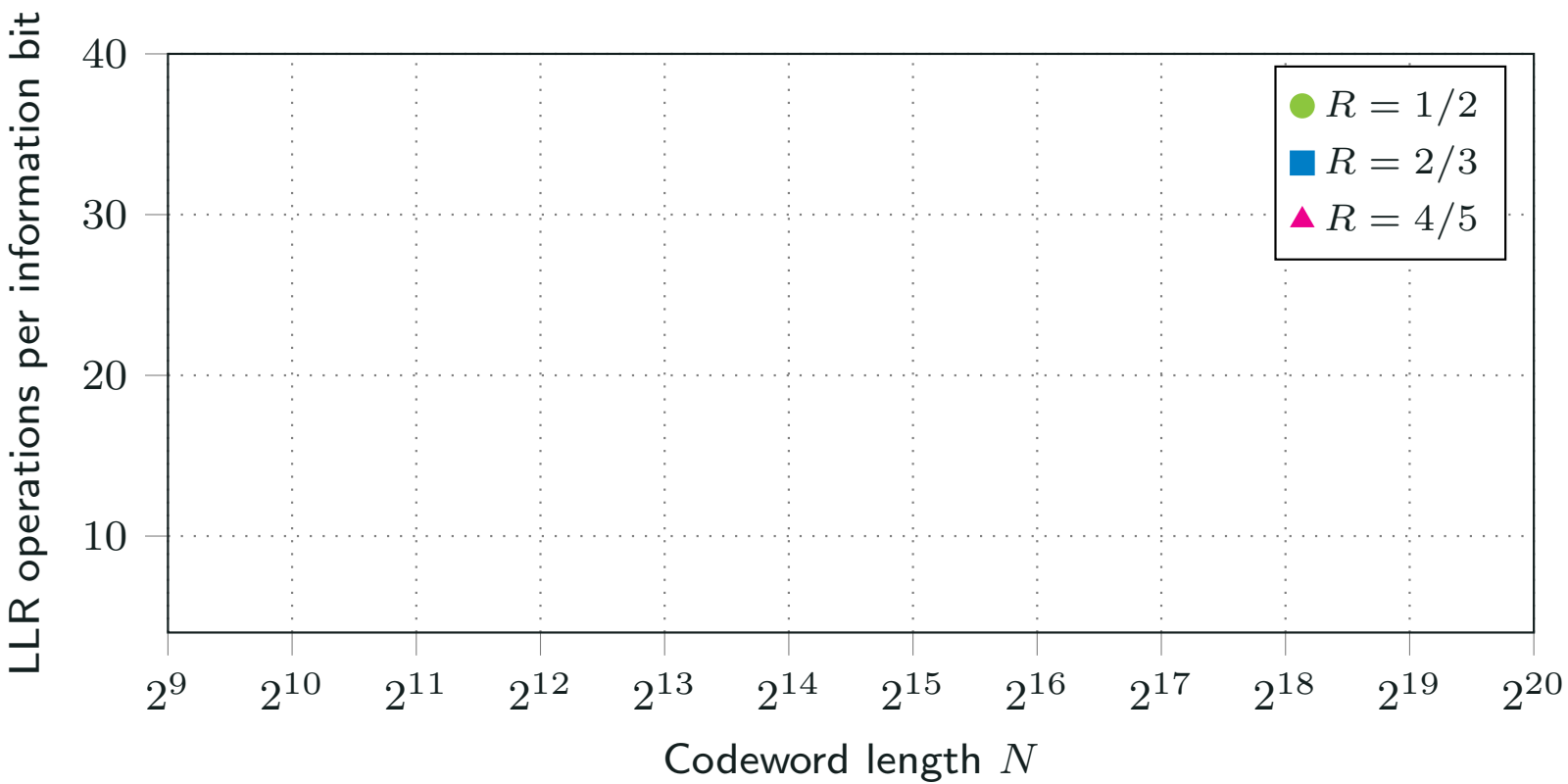
Complexity of the Considered Codes



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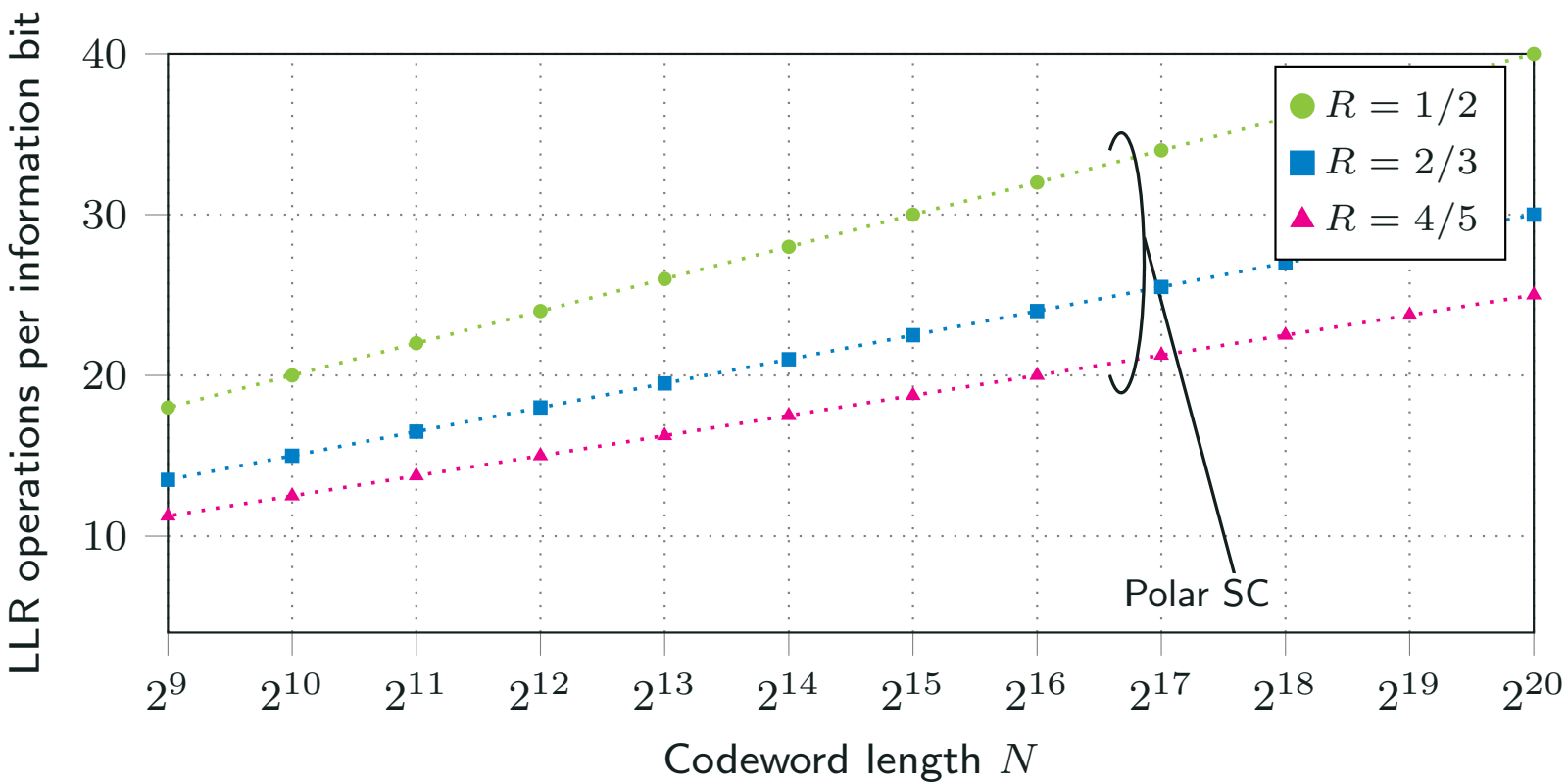

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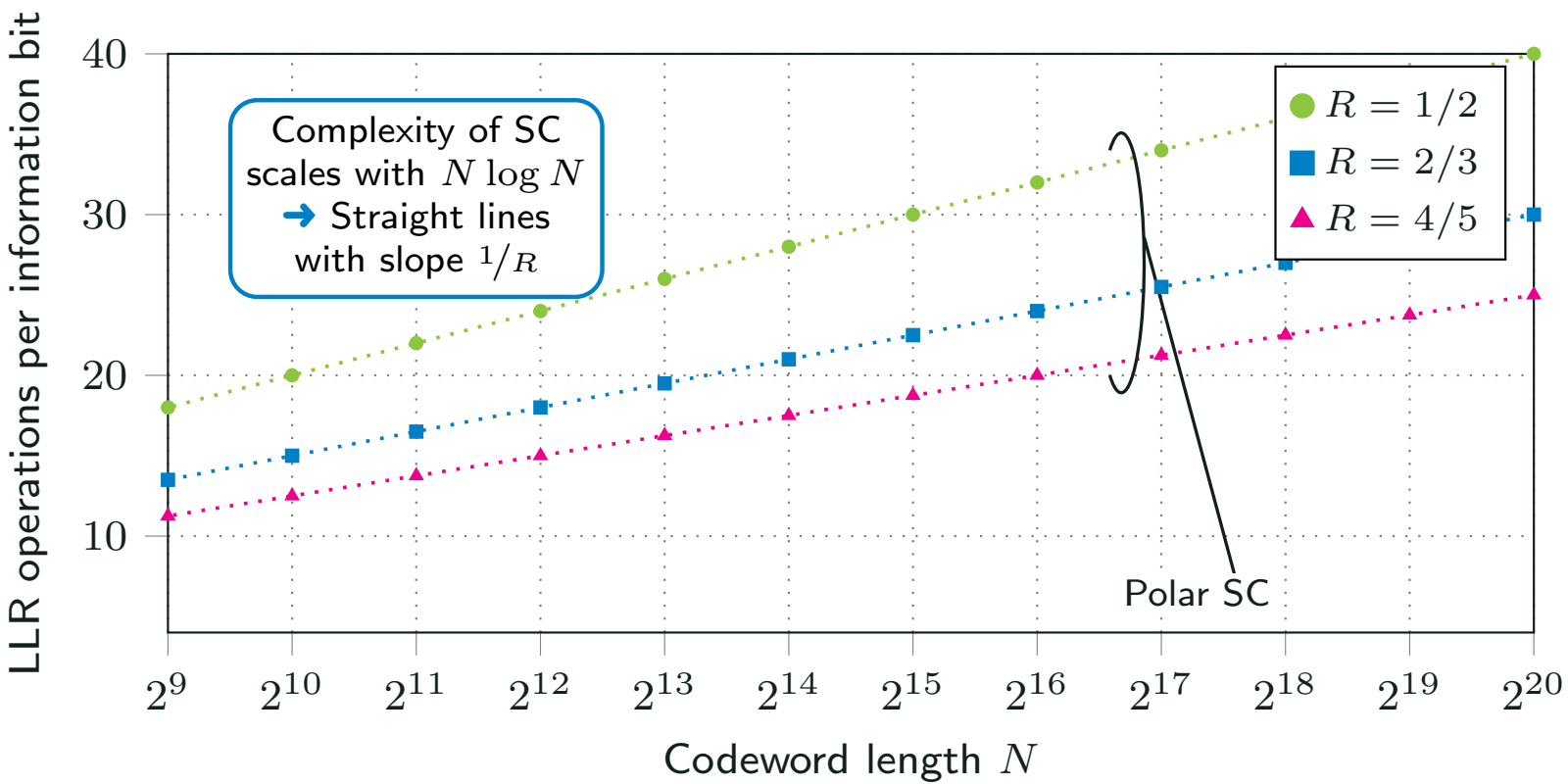

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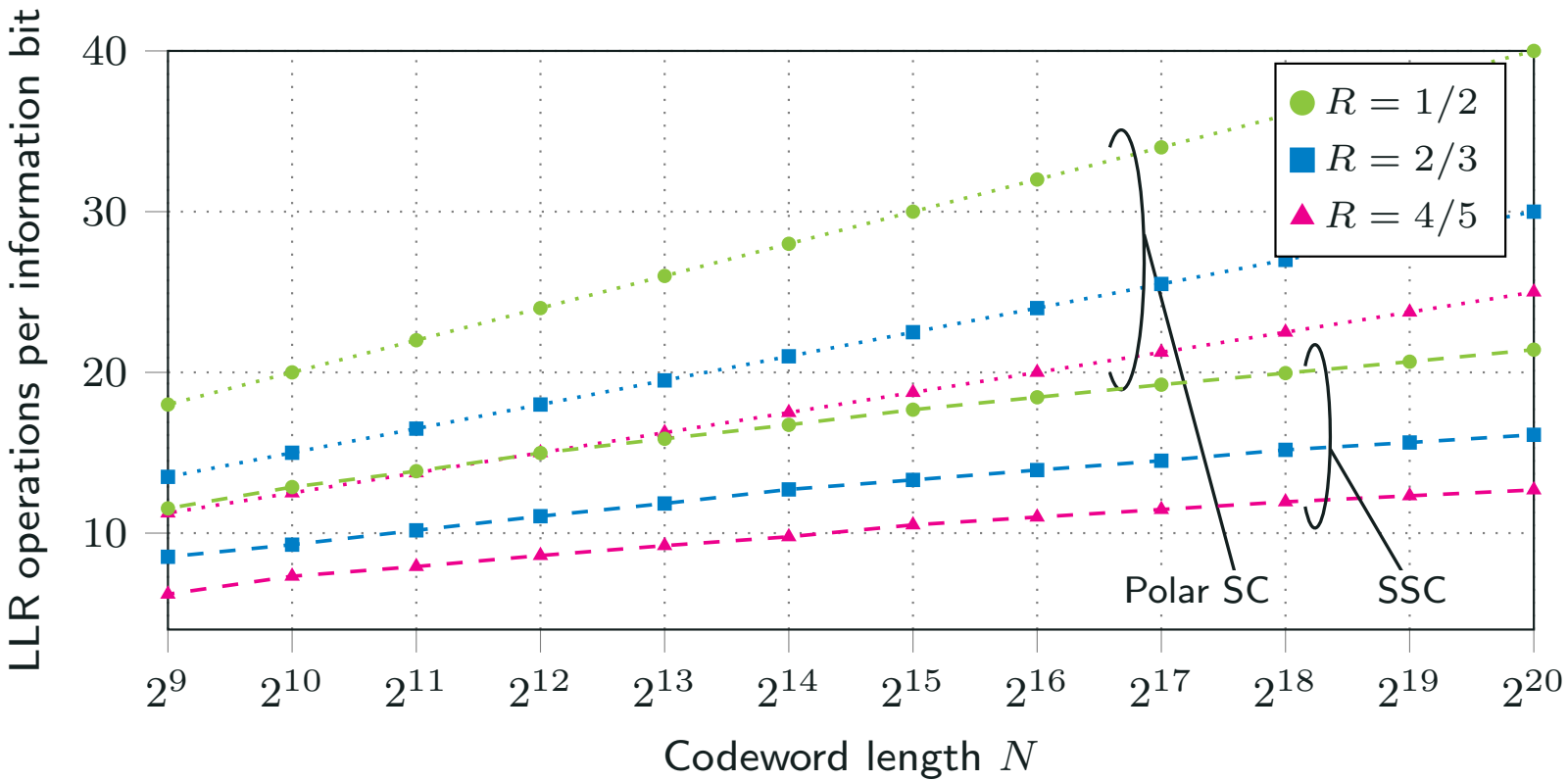

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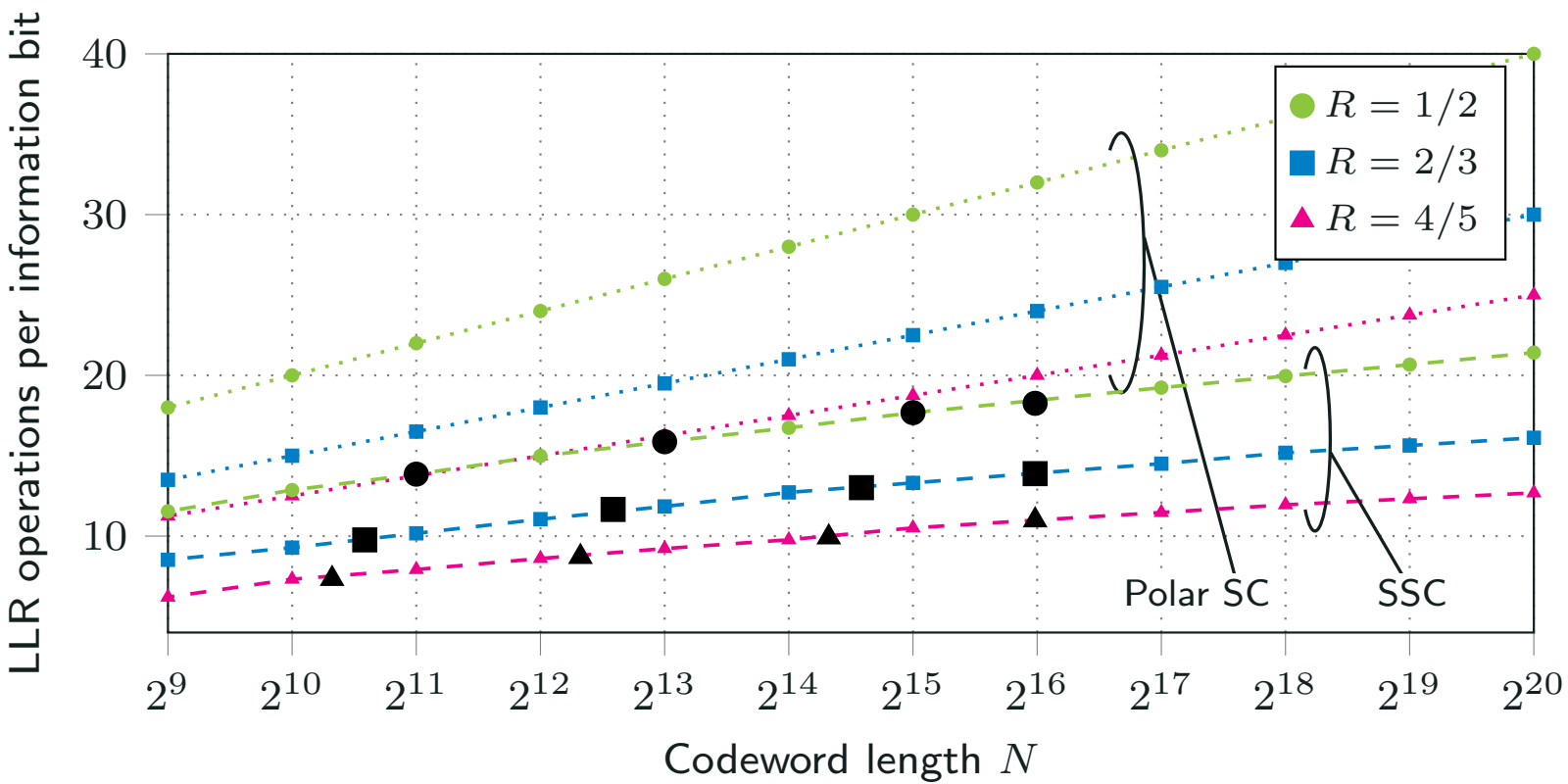

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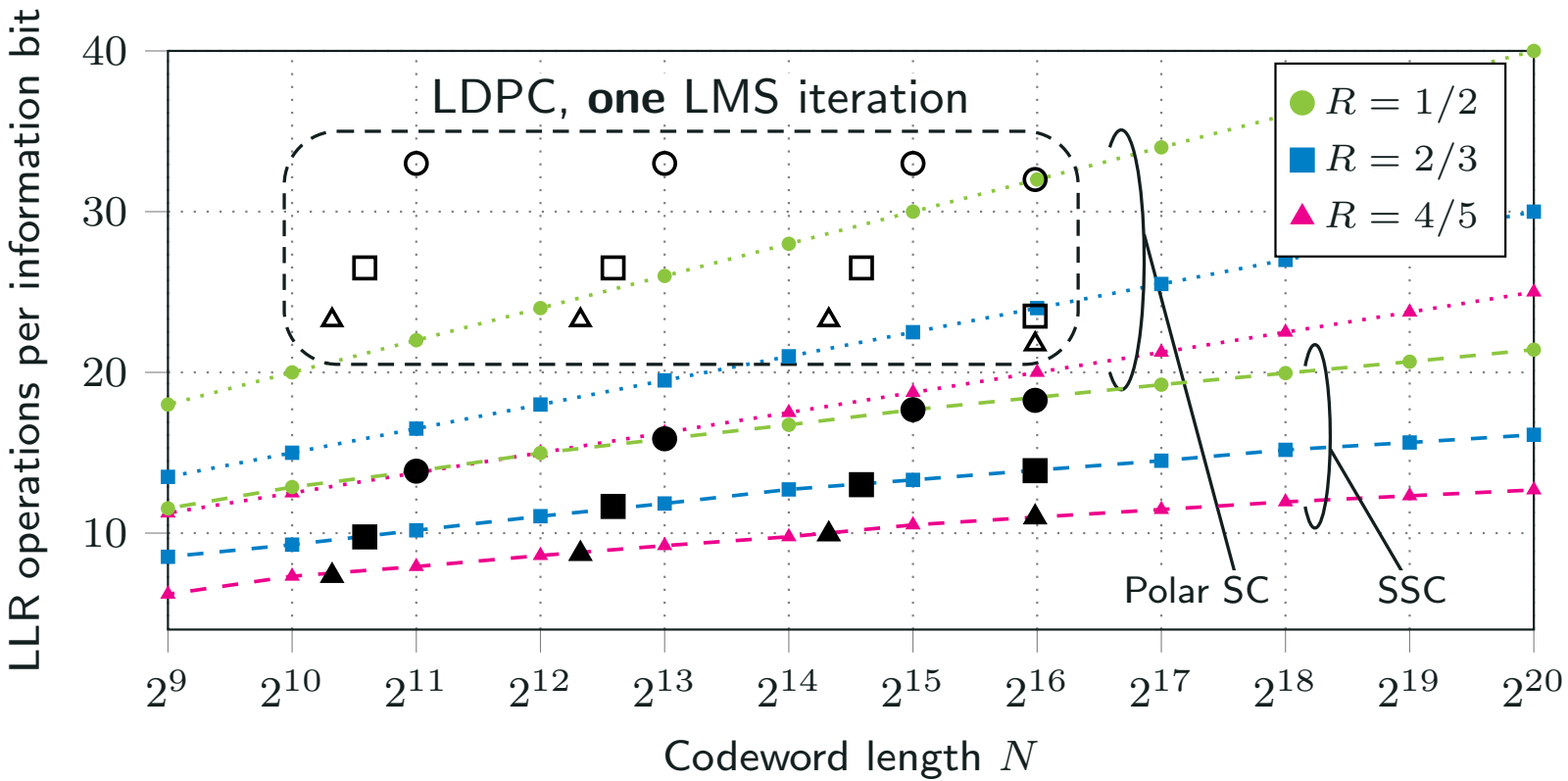

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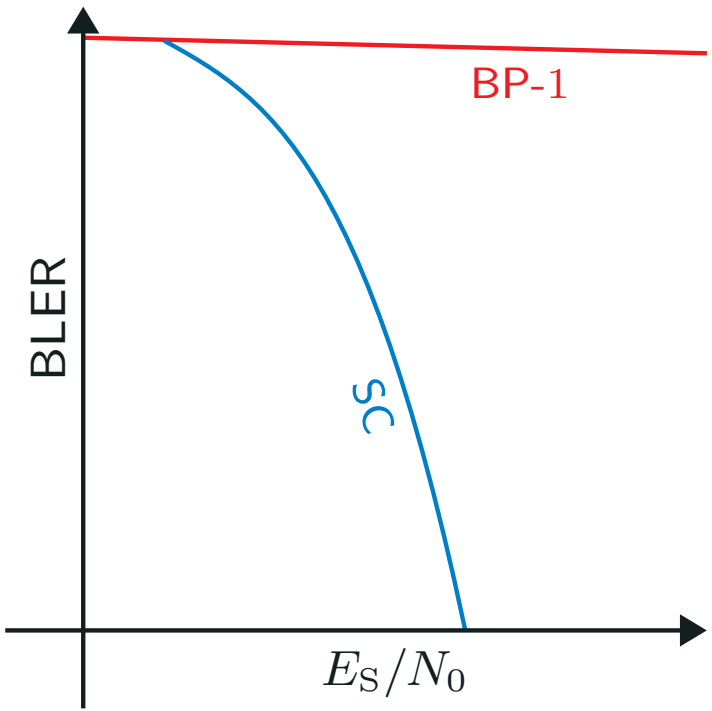
Fixing the Performance

- BP decoding requires multiple iterations
- Iteration control allows to adjust performance
- We matched the performance by adjusting the max. number of BP iterations

➜ Goal: Similar SNR for BLER of 10^{-4}



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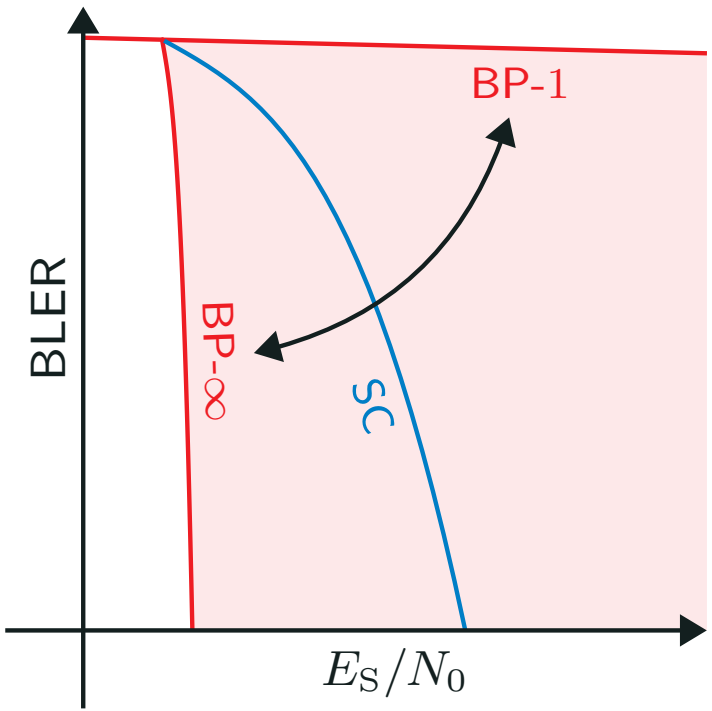

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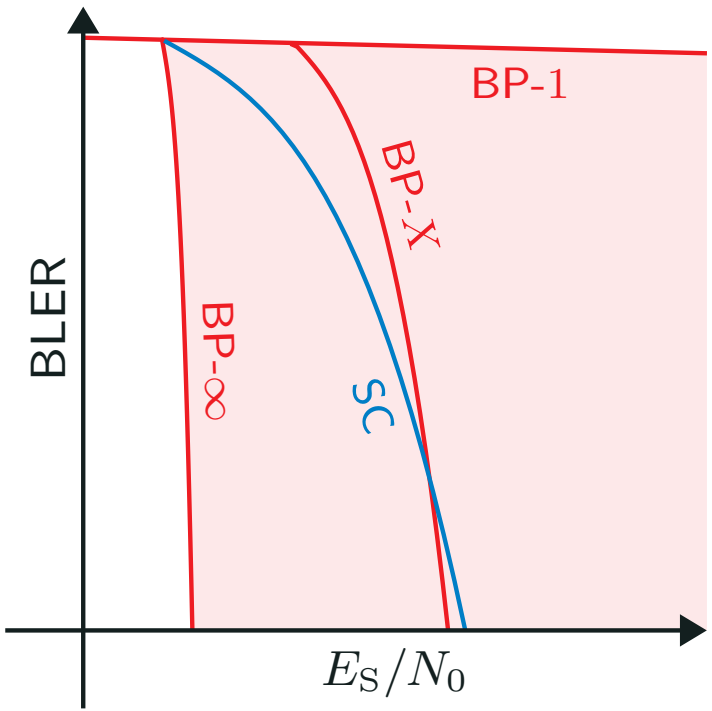

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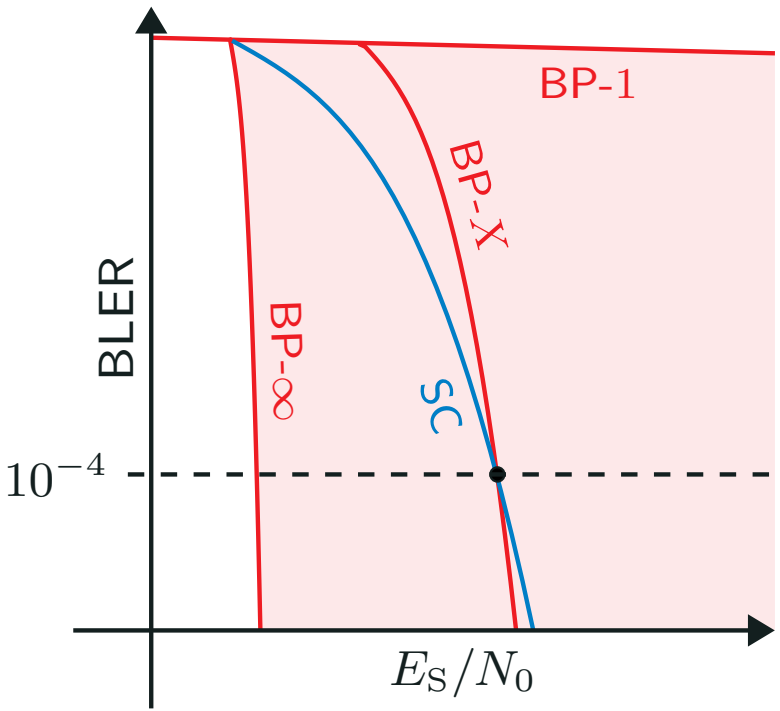

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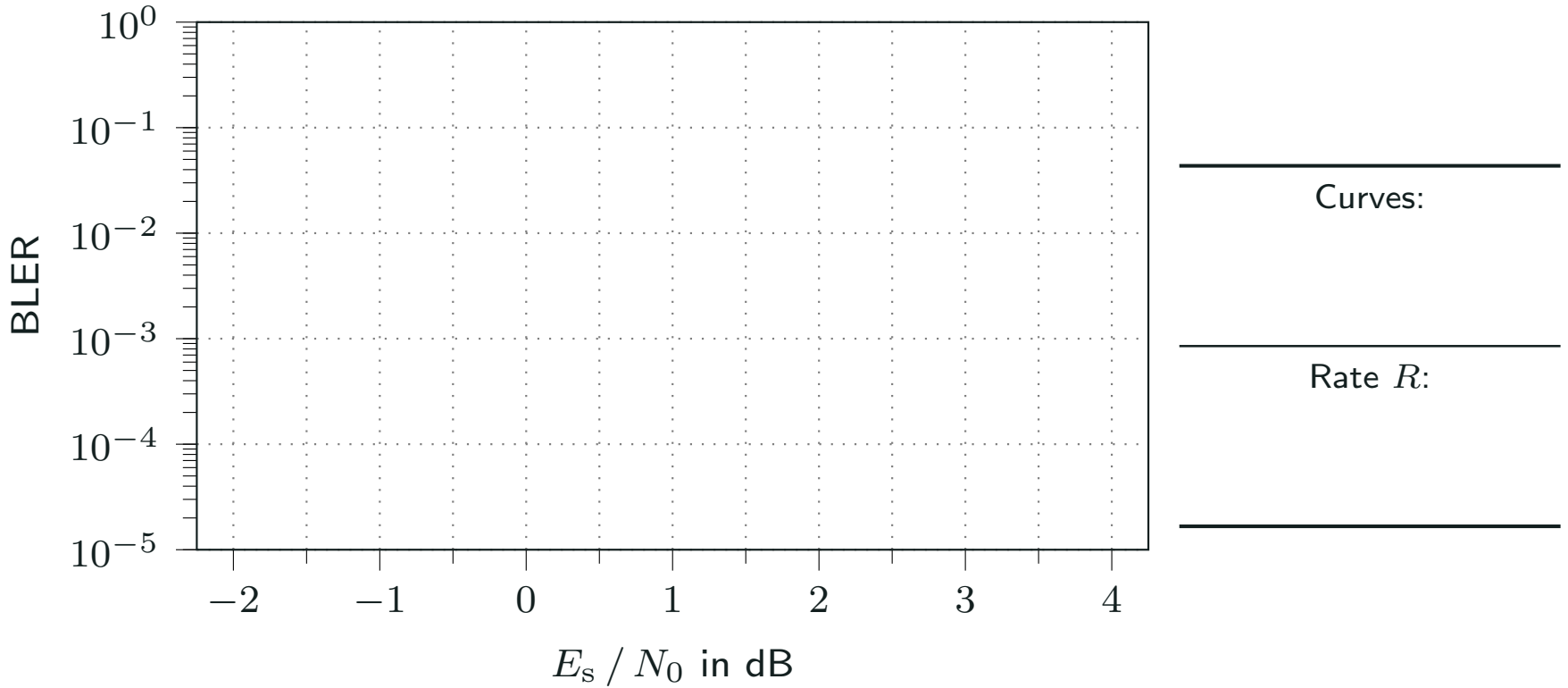

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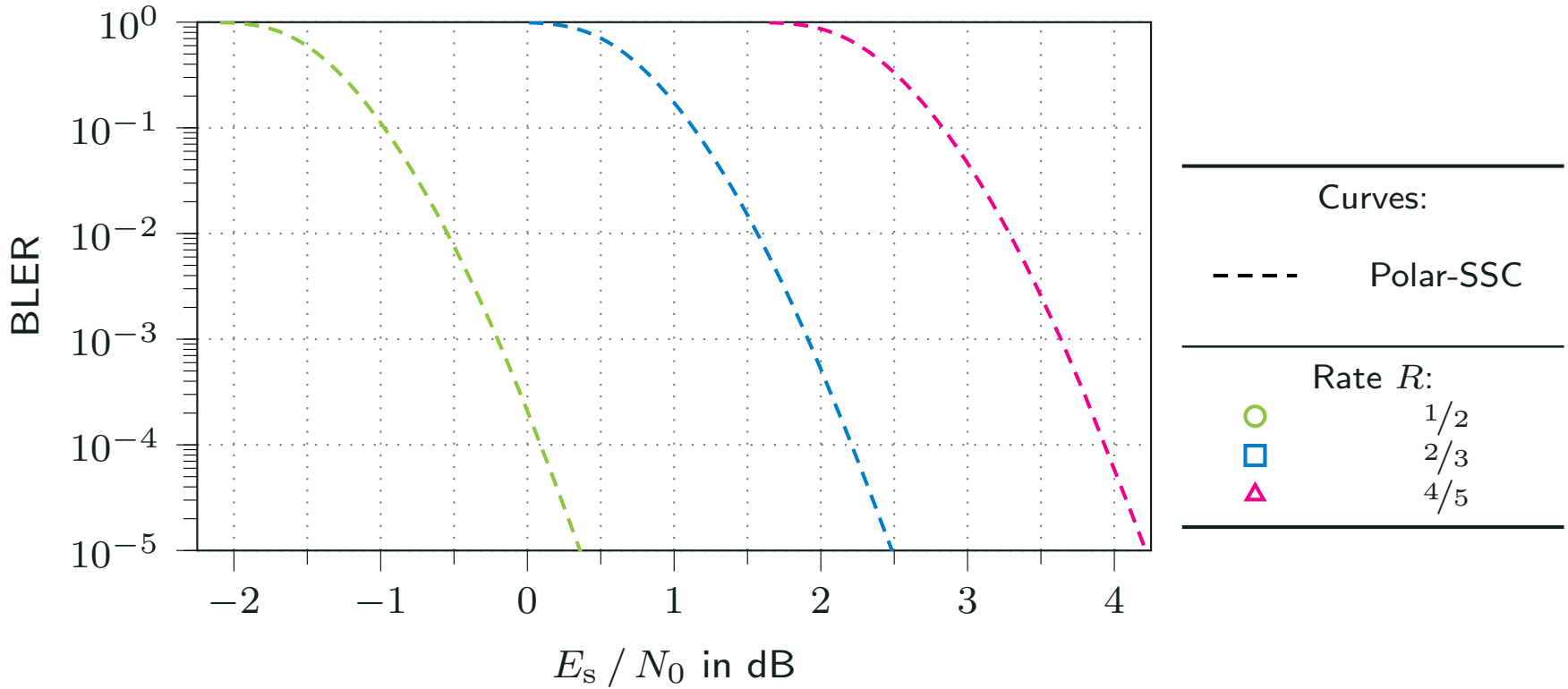

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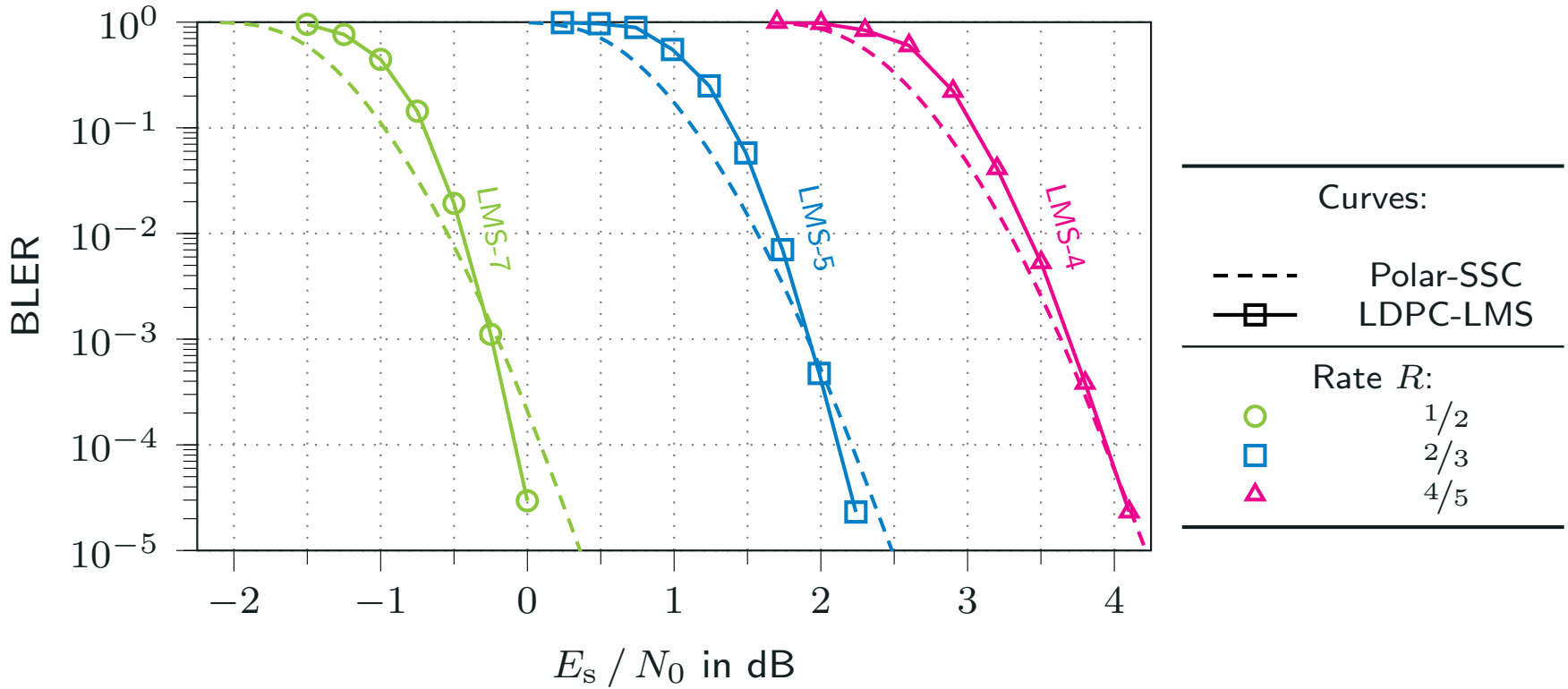

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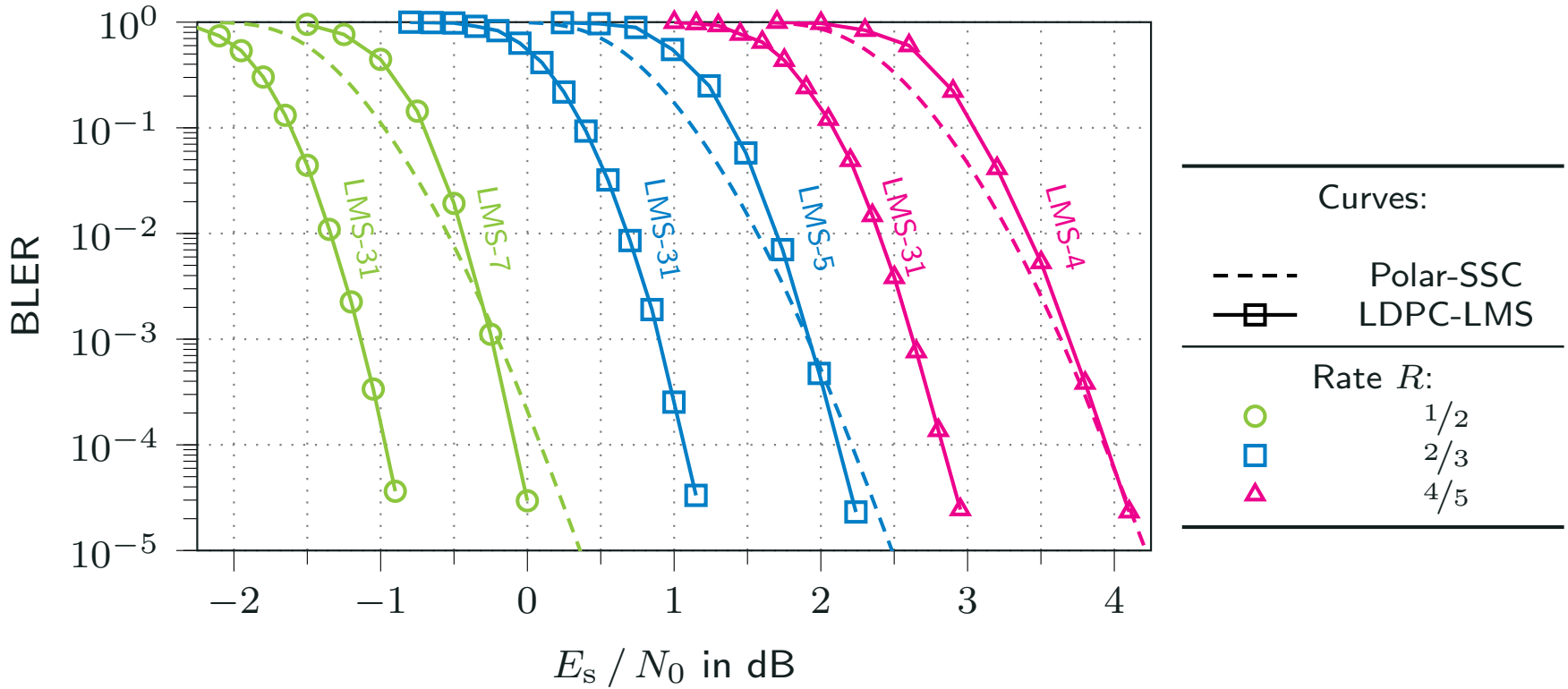
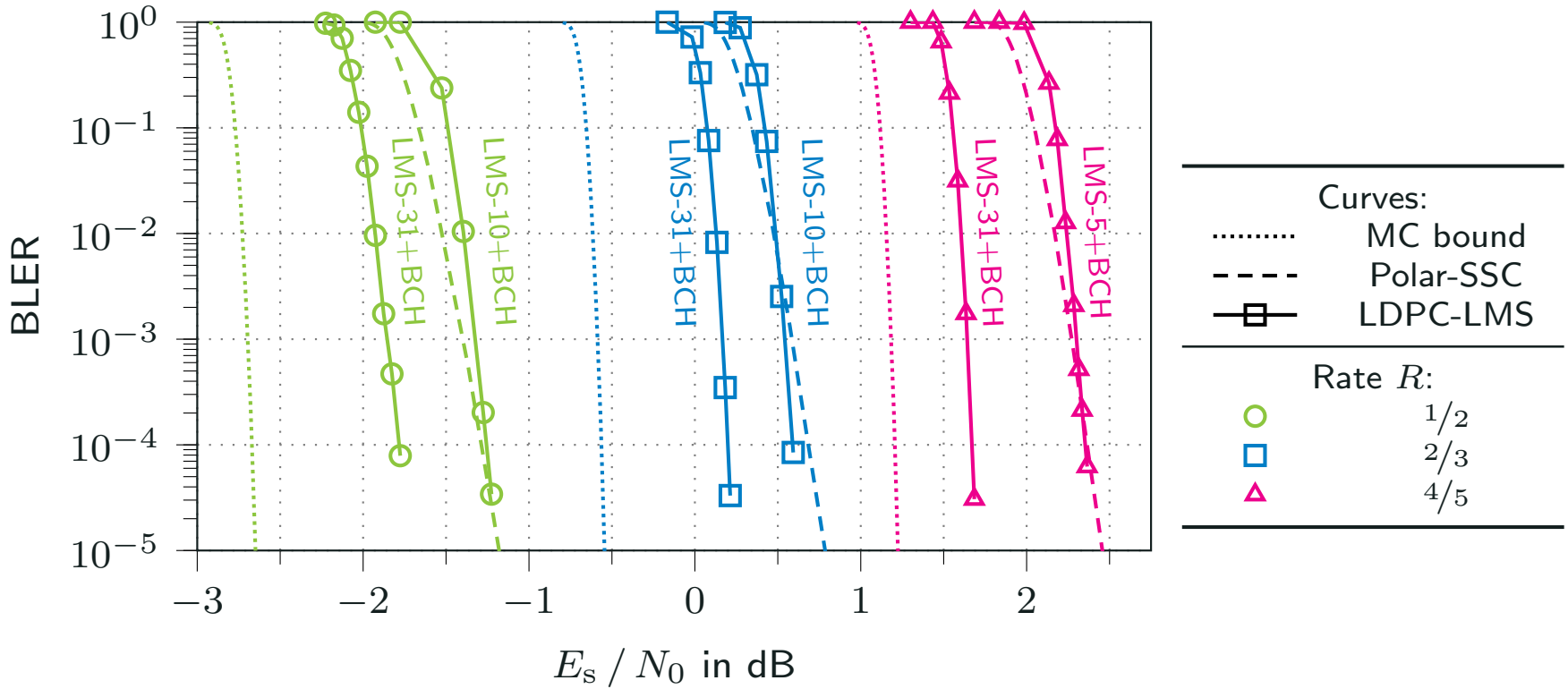


Example 2: $N = 64800$



Required Complexity for Matched Performance

	$K = 1024$ (CCSDS)			$N = 64800$ (DVB-S2)		
Code rate R	$1/2$	$2/3$	$4/5$	$1/2$	$2/3$	$4/5$
Polar SSC $N_{\mathrm{Ops,SSC}}/K$	13.85	9.76	7.34	18.26	13.88	10.99
LDPC LMS $N_{\mathrm{Ops,LMS}}/K$	191.40	94.34	75.35	320.00	234.26	108.75
Ratio $N_{\mathrm{Ops,LMS}}/N_{\mathrm{Ops,SSC}}$	13.82	9.67	10.27	17.52	16.88	9.9

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Conclusion

- We compared the decoding complexity of LDPC and polar codes
- ➜ Hard for LDPC codes to match performance of polar codes at *similar computational complexity*
- At *similar decoding performance* LDPC codes require $\geqslant 17$ times more LLR operations
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- ➜ If we are willing to invest into more complexity, LDPC codes still reign supreme

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Thank you for your attention!

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Backup 1: Polar SSC Scales Better Than $N \log N$