Fast SC-Flip Decoding of Polar Codes with Reinforcement Learning

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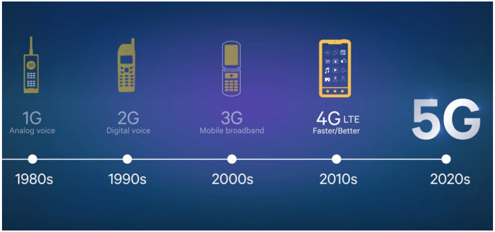
Preliminaries & Problem Statements

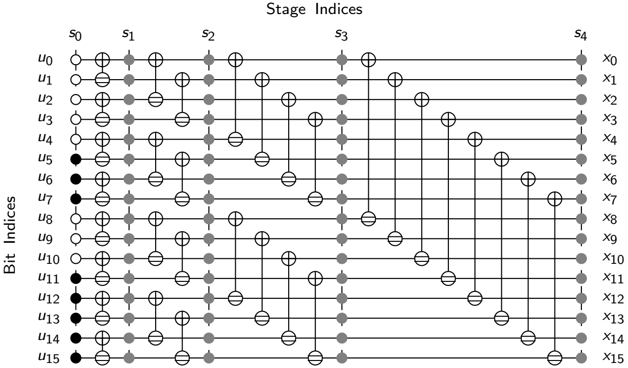
Background



- Polar codes: selected for the eMBB control channel in 5G
- Cyclic redundancy check (CRC) is concatenated with polar codes in 5G for error detection
- CRC-polar concatenated codes are decoded using Successive-Cancellation (SC) based decoding algorithms

Polar codes

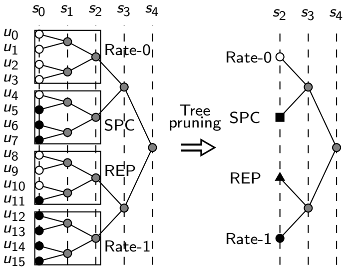
- Introduced by Arıkan in 2009 [Arıkan'09]
- $\mathcal{P}(N, K)$, N: code length, K: message length
- $\mathcal{A}$: information-bit set, $|\mathcal{A}| = K$, contains the reliable channels
- $\mathcal{A}^c$: frozen-bit set, $|\mathcal{A}^c| = N - K$, contains the noisy channels



E. Arıkan, "Channel Polarization: A Method for Constructing Capacity-Achieving Codes for Symmetric Binary-Input Memoryless Channels", IEEE Trans. on Info. Theory, vol. 55, no. 7, pp. 30513073, July 2009.

SC and Fast-SC Decoding

- SC decoding traverses all the nodes under the binary-tree representation of the code, rendering a high decoding latency
- Fast-SC decoding performs the decoding at the parent-node level of some special nodes → reduce the decoding latency [Sarkis'14]



(a) SC decoding (b) Fast-SC decoding

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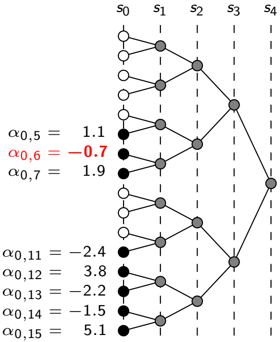
G. Sarkis, P. Giard, A. Vardy, C. Thibeault, and W. J. Gross, Fast polar decoders: Algorithm and implementation, IEEE J. Sel. Areas Commun., 2014.

SC-Flip (SCF) Decoding

- Given that the first SC decoding is not successful
- Estimation of the first error bit: $i_e^* = \arg\min_{\forall i \in \mathcal{A}} |\alpha_{0,i}|$
- E.g., $i_e^* = 6$, thus $\hat{u}_6$ is flipped from 1 to 0 in the second SC decoding attempt



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Dynamic SC-Flip (DSCF) Decoding

- Estimation of the first error bit: $i_e^* = \arg\min_{\forall i \in \mathcal{A}} Q_i$, where

$$Q_i = |\alpha_{0,i}| + \sum_{\substack{\forall j \in \mathcal{A} \\ j \leq i}} \frac{1}{\delta} \ln\left[1 + \exp\left(-\delta|\alpha_{0,j}|\right)\right],$$

and $\delta = 0.3$ is a perturbation parameter.

- E.g., $i_e^* = 5$, thus $\hat{u}_1$ is flipped in the second SC decoding attempt

$i \in \mathcal{A}$	5	6	7	11	12	13	14	15
$\lvert\alpha_{0,i}\rvert$	1.1	0.7	1.9	2.4	3.8	2.2	1.5	5.1
Q_i	2.9	4.5	7.2	9.0	11.3	11.1	12.1	16.3

- **DSCF requires costly computations and the decoding is performed at the leaf-node level, which results in a high decoding latency.**

L. Chandesris, V. Savin and D. Declercq, "Dynamic-SC Flip Decoding of Polar Codes," in IEEE Transactions on Communications, 2018.

Contributions

- Propose a novel bit-flipping algorithm tailored to Fast-SC decoding.
- Use a parameterized model, which is optimized using reinforcement learning (RL).
- Has a similar or better error-bit prediction accuracy when compared with the state-of-the-art SCF-based algorithms.

The Proposed Algorithm

Construction of the LLR vector γ

- γ: a vector of LLR values of the visited nodes under Fast-SC decoding.

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  - Parity check condition: $0 = \bigoplus_{i=i_{\min\,\nu}}^{i_{\max\,\nu}} \beta_{s,i} \rightarrow \beta_{s,i_{\min\,\nu}} = \bigoplus_{i=i_{\min\,\nu}+1}^{i_{\max\,\nu}} \beta_{s,i} \rightarrow$ only flip $\beta_{s,i}$ where $i_{\min\,\nu} < i \leq i_{\max\,\nu}$

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  - Update $\gamma \leftarrow \gamma \cup \alpha_{s,i}$ for all $i_{\min_\nu} < i \leq i_{\max_\nu}$

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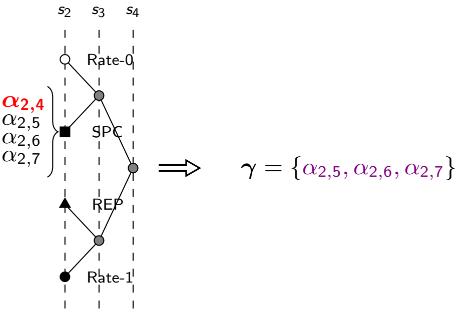
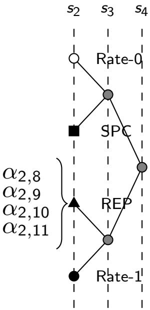


Construction of the LLR vector γ

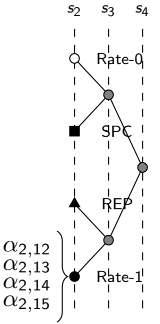
- ν: REP node
  - Update $\boldsymbol{\gamma} \leftarrow \boldsymbol{\gamma} \cup \alpha_{0,i_{\max\,\nu}}$, where $\alpha_{0,i_{\max\,\nu}} = \sum_{i=i_{\min\,\nu}}^{i_{\max\,\nu}} \alpha_{s,i}$



$\Longrightarrow \boldsymbol{\gamma} = \{\alpha_{2,5}, \alpha_{2,6}, \alpha_{2,7}, \alpha_{0,11} = \sum_{i=8}^{11} \alpha_{2,i}\}$

Construction of the LLR vector γ

- ν: Rate-1 node
  - Update $\boldsymbol{\gamma} \leftarrow \boldsymbol{\gamma} \cup \alpha_{,i}$ for all $i_{\min_\nu} \leq i \leq i_{\max_\nu}$



$\Longrightarrow \boldsymbol{\gamma} = \{\alpha_{2,4}, \alpha_{2,5}, \alpha_{2,7}, \alpha_{0,11}, \alpha_{2,12}, \alpha_{2,13}, \alpha_{2,14}, \alpha_{2,15}\}$

- If the i-th bit of γ is an error bit $\rightarrow$ flip the hard decision corresponding to the i-th bit of γ

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- The bit-error metric M_i of the i-th element of $\boldsymbol{\gamma}$:

$$M_i=\sum_{0\le j<K+C}\theta_{i,j}|\gamma_j|. \tag{1}$$

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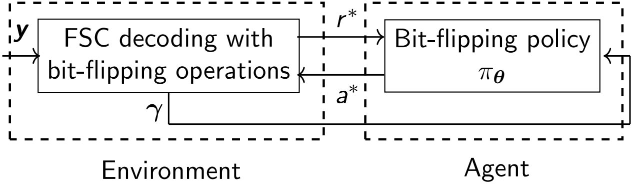
- The bit-error metric M_i of the i-th element of γ:

$$M_i = \sum_{0 \leq j < K+C} \theta_{i,j} |\gamma_j|. \quad (1)$$

- The most probable error index: $i_e^* = \arg\min_{0 \leq i < K+C} M_i$.

Optimzation of $\boldsymbol{\theta}$ using a RL setup

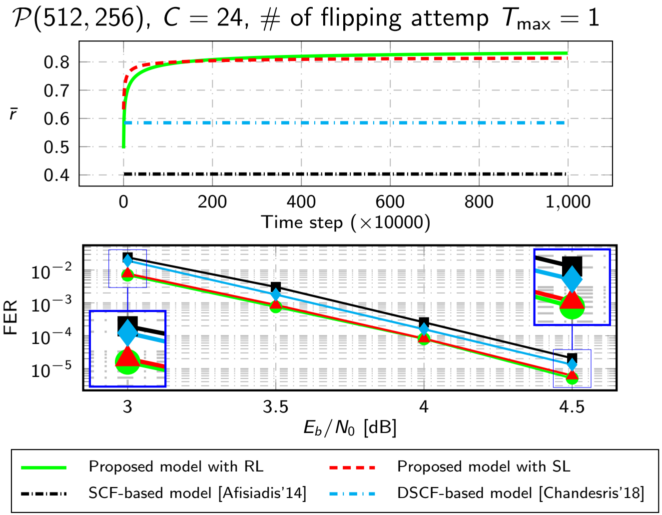


- If flipping the bit associated with the a^*-th element of $\boldsymbol{\gamma}$ results in a CRC pass $\rightarrow$ $r^* = 1$, otherwise $r^* = 0$.
- Update $\boldsymbol{\theta}$ using the gradient ascent technique

$$\boldsymbol{\theta} \leftarrow \boldsymbol{\theta} + \frac{\mathrm{d} \ln p_{a^*}}{\mathrm{d}\boldsymbol{\theta}}(r^* - \bar{r}), \quad (2)$$

where $\bar{r}$ is the cumulative average reward.

Performance Evaluation



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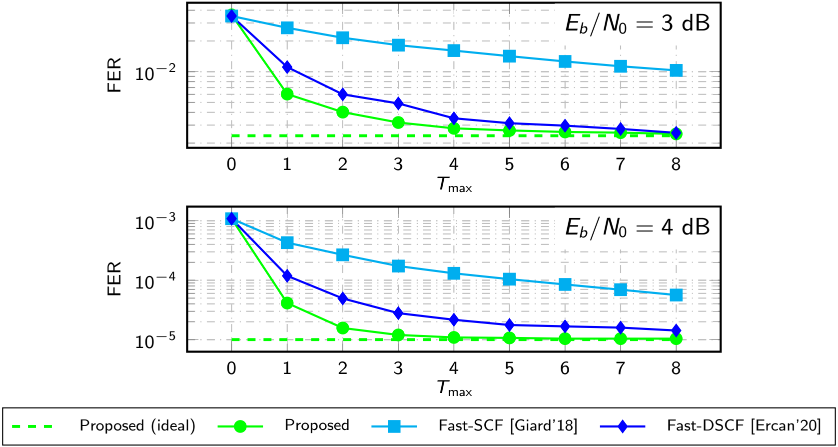
Performance Evaluation

The FERs of various fast SCF decoding algorithms as a function of $T_{\max}$.



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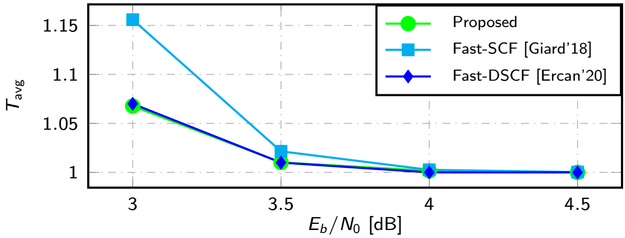
Performance Evaluation

Average number of decoding attempts T_{avg} of various fast SCF decoding algorithms with $T_{\max} = 8$.



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Conclusion

- Proposed a novel bit-flipping algorithm for Fast-SC decoding
- Better error-bit estimation accuracy compared to that of state-of-the-art Fast-SCF decoding algorithms, given a small number of flipping-attempts.
- Using RL technique to optimize the parameters, which can be carried out at the decoder side and does not require pilot signals.

Thank You!