Partitioned Successive-Cancellation Flip Decoding of Polar Codes

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Abstract—Polar codes are a class of channel capacity achieving codes that has been selected for the next generation of wireless communication standards. Successive-cancellation (SC) is the first proposed decoding algorithm, suffering from mediocre error-correction performance at moderate code lengths. In order to improve the error-correction performance of SC, two approaches are available: (i) SC-List decoding which keeps a list of candidates by running a number of SC decoders in parallel, thus increasing the implementation complexity, and (ii) SC-Flip decoding that relies on a single SC module, and keeps the computational complexity close to SC. In this work, we propose the partitioned SC-Flip (PSCF) decoding algorithm, which outperforms SC-Flip in terms of error-correction performance and average computational complexity, leading to higher throughput and reduced energy consumption per codeword. We also introduce a partitioning scheme that best suits our PSCF decoder. Simulation results show that at equivalent frame error rate, PSCF has up to 4.1× less computational complexity than the SC-Flip decoder. At equivalent average number of iterations, the error-correction performance of PSCF outperforms SC-Flip by up to 0.26 dB at frame error rate of $10^{-4}$.

I. INTRODUCTION

Polar codes, introduced by Arıkan in [1], are a class of error-correcting codes that provably achieves channel capacity when the code length approaches infinity. They have been selected for the control channel of the enhanced mobile broadband (eMBB) scenario of the 5th generation wireless systems standards (5G) [2]. The standardization procedure is currently ongoing for other communication scenarios, such as massive machine type communications (mMTC). The mMTC communication scenario sees a large number of devices connected to each other, targeting low power/energy consumption, and improved error-correction performance [3]. Therefore, practical algorithms for polar codes that would meet these requirements must be addressed.

Successive-cancellation (SC) decoding of polar codes was introduced in [1]: its error-correction performance approaches channel capacity at infinite code length, but it degrades significantly at moderate to short code lengths. SC-List decoding [4] improves the error-correction performance of polar codes significantly, at the cost of higher decoding latency and implementation complexity [5]. On the other hand, successive-cancellation flip (SC-Flip) decoding [6] keeps the computational complexity close to that of SC, while providing error-correction performance close to that of SC-List.

Prior results in the literature about SC-Flip decoding target the correction of a single wrong decision in SC decoding [6]. If more errors are to be corrected, the decoding complexity grows linearly with the number of erroneous decisions that are targeted [7]. In this work, we propose the partitioned SC-Flip (PSCF) decoding algorithm: it subdivides the codeword into partitions, on which SC-Flip is run. PSCF targets the correction of at least a single wrong decision, with lower computational complexity than SC-Flip. We also present a codeword partitioning scheme that best suits our PSCF decoder, and aims at maximizing the error-correction performance of PSCF, while keeping the average computational complexity of it as close to that of SC as possible.

The remainder of this work is organized as follows: in Section II an overview of polar codes and their decoding algorithms is presented. In Section III the PSCF decoding algorithm is detailed, while Section IV describes a partitioning scheme based on the error observations obtained from SC decoding. Section V reports simulation results, and conclusions are drawn in Section VI.

II. PRELIMINARIES

A. Polar Codes

A polar code $PC(N, K)$ is a linear block code that can achieve channel capacity via channel polarization, that splits $N = 2^n, n \in \mathbb{Z}^+$ channel utilizations into $K$ reliable ones and $N-K$ unreliable ones. The reliable channels are used to transmit the information bits, while the unreliable channels are frozen to a known value, usually zero, leading to a code rate $R = K/N$.

The encoding process of a polar code can be represented with the following matrix multiplication:

$$x_0^{N-1} = u_0^{N-1}G^\otimes n,$$  \hspace{1cm} (1)

where $x_0^{N-1} = \{x_0, x_1, \ldots, x_{N-1}\}$ is the encoded vector, $u_0^{N-1} = \{u_0, u_1, \ldots, u_{N-1}\}$ is the input vector, and the generator matrix $G^\otimes n$ is the $n$-th Kronecker product of the base polar code matrix $G = [1 \ 0]$. Thus, a polar code of length $N$ can be seen as the concatenation of two polar codes of length $N/2$. The encoding operation in (1) for polar code $PC(8, 5)$ is portrayed in Fig.1 gray indices represent the frozen bits whereas the black indices indicate the information bits.

The decoding process of the SC algorithm can be interpreted as a binary tree search: the tree is explored depth-first, with priority given to the left branch, with a complexity of $O(N \log N)$, and produces an estimated bit vec-
tor \( \hat{u}_0^{N-1} \). The SC decoding tree for PC(8, 5) is depicted in Fig 2. Each parent node contains logarithmic likelihood ratio (LLR) values \( \alpha = \{\alpha_0, \alpha_1, \ldots, \alpha_{2^{S-1}}\} \), which are passed to the child nodes via left and right operations recursively. From a parent node at stage \( S \), the LLR values passed to left \( \alpha^l = \{\alpha_0^l, \alpha_1^l, \ldots, \alpha_{2^{S-1}}^l\} \) and right \( \alpha^r = \{\alpha_0^r, \alpha_1^r, \ldots, \alpha_{2^{S-1}}^r\} \) child nodes are approximated as

\[
\alpha_i^l = \text{sgn}(\alpha_i) \text{sgn}(\alpha_{i+2^{S-1}}) \min(|\alpha_i|, |\alpha_{i+2^{S-1}}|),
\]

\[
\alpha_i^r = \alpha_{i+2^{S-1}} + (1 - 2\beta_i^r)\alpha_i.
\]

The LLRs at the root node are initialized with the channel LLR values \( y_0^{N-1} \). The partial sums \( \beta \) observed from the left \( \beta^l = \{\beta_0^l, \beta_1^l, \ldots, \beta_{2^{S-1}}^l\} \) and right \( \beta^r = \{\beta_0^r, \beta_1^r, \ldots, \beta_{2^{S-1}}^r\} \) child nodes are passed to their parent nodes as

\[
\beta_i = \begin{cases} 
\beta_i^l \oplus \beta_i^r, & \text{if } i \leq 2^{S-1} \\
\beta_i^l, & \text{otherwise.}
\end{cases}
\]

where \( \oplus \) denotes bitwise XOR operation, and \( 0 \leq i < 2^S \).

The \( \beta \) value at leaf nodes is calculated as

\[
\beta_i = \begin{cases} 
0, & \text{when } \alpha_i \geq 0 \text{ or } i \in \Phi; \\
1, & \text{otherwise.}
\end{cases}
\]

where \( \Phi \) denotes the set of frozen indices.

SC-List decoding algorithm [4] creates \( L \) distinct SC decoding paths working in parallel to have an improved error-correction performance. A path metric associated with each decoding path indicates the likelihood of the correct codeword. An outer cyclic-redundancy check (CRC) code improves the error-correction performance of SC-List decoding significantly. The computational complexity of the SC-List decoder is \( O(LN \log N) \).

### B. Successive-Cancellation Flip Decoding

In [6], the SC-Flip decoding algorithm was introduced. It was observed that, when an SC decoder fails to estimate the correct codeword, it is either due to a wrong decision that is caused by the channel noise, or due to a prior wrong decision that was made earlier in the SC tree. It was also explained that the first wrong decision that occurs while decoding is always due to channel noise. Moreover, experiments show when SC decoding fails, it is mostly due to a single wrong decision caused by the channel which is potentially followed by propagated wrong decisions. A hypothetical decoder, called SC-Oracle decoder, was created to show that if all first wrong decisions are avoided, the error-correction performance of SC decoding would improve significantly.

The SC-Flip algorithm attempts to identify and correct the first error due to channel noise that the SC algorithm would incur. To do so, a CRC outer code with a remainder of \( C \) bits is used to encode the information bits. At the end of a SC decoding phase, if the CRC does not detect any error, the estimated codeword with a correct CRC check still contains errors, or the decoding stopped after a maximum number of iterations \( T_{\text{max}} \).

The computational complexity of SC-Flip decoding is \( O(N \log N[1 + T_{\text{max}} \times \Pr(R, \text{SNR})])\) [6], where \( \Pr(R, \text{SNR}) \) denotes the frame error rate (FER) of a polar code of rate \( R \) at given signal-to-noise ratio (SNR) under SC decoding. Consequently, the average computational complexity of SC-Flip decoding is directly proportional to the average number of iterations, that depends on both \( T_{\text{max}} \) and \( \Pr(R, \text{SNR}) \).

Fig. [3] presents the performance of SC-Flip compared to SC, SC-Oracle and SC-List for PC(1024, 512) constructed for a signal-to-noise ratio of 2.5 dB. Both SC-Flip and SC-Oracle outperform SC and SC-List with list size \( L = 2 \), and SC-Oracle has the same FER of SC-List with \( L = 4 \). The performance gap between SC-Flip and SC-Oracle is due to two reasons: either the estimated codeword with a correct CRC check still contains errors, or the decoding stopped after reaching the maximum number of iterations without being successful. Note that adding CRC bits to a polar code affects its error-correction performance, as it is effectively adding more non-frozen bits.

Further improvements for SC-Flip decoding algorithm have been recently proposed in [8] and [7]: a generalized SC-Flip decoder algorithm uses nested flips to correct more than one erroneous decision with a single CRC. They also introduce a metric that helps the SC-Flip decoder to detect the erroneous bit indices more accurately. Their simulation results show upto 0.8 dB improvement over the
error-correction performance of SC-Flip. On the other hand, the implementation requires parallel decoders similar to SC-List.

III. PARTITIONED SC-FLIP DECODING

Let Pr(\(E_i\)) denote the probability of failed decoding for an SC decoder, where \(E_i\) represents the number of channel-induced errors with \(0 < i < K + C\), and let Pr(\(E_0\)) denote the probability of a successful decoding. Thus:

\[
\Pr(E_0) + \Pr(E_1) + \sum_{i=2}^{K+C} \Pr(E_i) = 1 \tag{6}
\]

SC-Flip attempts to minimize \(\Pr(E_1)\) within a maximum number of iterations, but it cannot help with \(\Pr(E_i)\) when \(i > 1\). The ability to detect and correct more than a single error in a codeword would improve the error-correction performance significantly. We propose a partitioned SC-Flip (PSCF) decoding algorithm, where the estimated codeword is divided into sub-blocks, with a partitioning factor \(P\). Each partition is protected with its own CRC, all of which are independent from each other.

**Example 1:** To have a better understanding of how PSCF helps minimizing erroneous decisions, with a partitioning factor of \(P = 2\), the error probabilities \(\Pr(E_1)\) and \(\Pr(E_2)\) in (6) can be reinterpreted as:

\[
\begin{align*}
\Pr(E_1) &= \Pr(e_0 \in p_1) \times \Pr(e_1 \in p_2) + \\
& \quad \Pr(e_1 \in p_1) \times \Pr(e_0 \in p_2) \tag{7}
\end{align*}
\]

and

\[
\begin{align*}
\Pr(E_2) &= \Pr(e_0 \in p_1) \times \Pr(e_2 \in p_2) + \\
& \quad \Pr(e_1 \in p_1) \times \Pr(e_1 \in p_2) + \\
& \quad \Pr(e_2 \in p_1) \times \Pr(e_0 \in p_2) \tag{8}
\end{align*}
\]

where \(e_i \in p_j\) indicates that \(i\) errors are present in partition \(p_j\), with \(0 \leq i \leq 2\) and \(0 < j < 2\).

In SC-Flip, the CRC enables the algorithm to correct a single error. Dividing the codeword in two partitions, each protected by its own CRC, allows to correct up to one error in each partition, as expressed by the following error probability:

\[
\begin{align*}
\Pr(e_0 \in p_1) \times \Pr(e_1 \in p_2) + \\
\Pr(e_1 \in p_1) \times \Pr(e_0 \in p_2) + \\
\Pr(e_1 \in p_1) \times \Pr(e_1 \in p_2)
\end{align*}
\]

Note that if multiple channel errors occur in a single partition, a successful decoding is not possible with PSCF. As a result, PSCF can detect and correct more than one error if each error resides in a different partition.

The PSCF decoding process is described in Algorithm 1.

**Algorithm 1:** Partitioned SC-Flip Algorithm

```plaintext
input : \(y_0^{N-1}, T_{max}, \rho_1, I\)
output: \(\hat{u}_0^{N-1}\)
1 \(\rho[0] = 0\)
2 for \(j = 1\) to \(P\) do
   3 for \(i = \rho[j-1]\) to \(\rho[j]\) do
      4 \((\hat{u}_k^\rho[j-1]_{\rho[j]}, \alpha_{\hat{u}_k}) \leftarrow \text{SC}(y_0^{N-1}, I, O)\)
      5 if \(T_{max} > 1\) and CRC(\(\hat{u}_k^\rho[j-1]_{\rho[j]}\)) fails then
         6 \(\alpha_{\text{sort}} = \text{sort}(\alpha_{\hat{u}_k}), i \in I\)
         7 \(U = \text{first} \ T_{max} \text{ indices of } \alpha_{\text{sort}}\)
         8 \(t = 1\)
         9 while \(t \leq T_{max}\) and CRC(\(\hat{u}_k^\rho[j-1]_{\rho[j]}\)) fails do
            10 \((\hat{u}_k^\rho[j-1]_{\rho[j]}, \alpha_{\hat{u}_k}) \leftarrow \text{SC}(y_0^{N-1}, I, U[t])\)
            11 \(t = t + 1\)
      12 if CRC(\(\hat{u}_k^\rho[j-1]_{\rho[j]}\)) fails then
         13 terminate process
   14 end
3 end
1 end
```

The information bit indices \(I\) and partitioning indices \(\rho\) are predetermined and known by the decoder. For each partition, the SC algorithm is executed first, followed by the computation of the CRC remainder (lines 4-5). If the CRC detects an error for the first time, then the indices of the \(T_{max}\) information bits that have the least reliable LLRs are identified (line 7). For a maximum of \(T_{max}\) iterations, the SC algorithm is executed: at each iteration \(t\), the information bit with the \(t^{th}\) least reliable LLR is flipped, until the CRC does not detect an error anymore (lines 9 to 11). If after \(T_{max}\) iterations the CRC still detects an error, then the decoding process is terminated.

In order for the code rate to remain the same when either PSCF or SC-Flip are applied, the total number of information
and CRC bits are unchanged, such that

\[ R = \frac{K + C}{N}, \quad (10) \]

\[ \sum_{i=0}^{P-1} K_{p_i} = K_{SCF}, \quad (11) \]

\[ P \times C_{p_i} = C_{SCF} \quad (12) \]

where \( K_{p_i} \) (\( C_{p_i} \)) is the total number of information (CRC) bits in partition \( p_i \) of PSCF, and \( K_{SCF} \) (\( C_{SCF} \)) is the total number of information (CRC) bits in SC-Flip. In order to keep the effective rate of PSCF equal to that of SC-Flip, the number of CRC bits in both cases have to be the same. The most straightforward method to keep the same effective rate is to distribute the CRC bits equally among the partitions as suggested in (12).

Depending on the number of partitions and their position, the number of information bits included in each partition might be different. After the information bits, each partition reserves the following \( C_{SCF}/P \) most reliable position to the CRC remainder bits. As a result, the bits assigned to the CRC in SC-Flip and PSCF are different, while the locations of the information bits are the same under both algorithms.

Note that the idea of partitioning was also used in SC-List decoders in [9]–[11]: nevertheless, SC-List partitioning involves a completely different process, and aims at a different outcome. Partitioned SC-List (PSCL) divides the SC decoding tree in upper and lower tree, using a lower list size in the upper part to minimize memory requirements without degrading the error-correction performance. On the other hand, the PSCF algorithm loops SC-Flip over different portions of the codeword, reducing the average number of iterations and improving error-correction performance.

IV. CODEWORD PARTITIONING

Careful partitioning of the SC-Flip decoding process can significantly reduce the average number of performed iterations, and improve the error-correction performance. As mentioned in Section III with partitioning factor \( P \), PSCF can identify and correct up to \( P \) errors. In this Section, we refer to an error pattern of \( \rho \)th order when \( \rho \) errors occur in the codeword, and represent it with \( E_\rho \).

Fig. 4 depicts the distribution of errors according to their order, for \( PC(1024, 512) \), under SC decoding. The probability of a failed decoding being due to \( E_1 \) increases with \( E_b/N_0 \). For example, at \( E_b/N_0 = 2.5 \text{ dB} \), 95.3% of decoding failures are due to \( E_1 \). Therefore, at high \( E_b/N_0 \), the ability to correct error orders higher than \( E_1 \) becomes an advantage for PSCF only when the proposed algorithm is as effective as SC-Flip in correcting failures due to \( E_1 \).

In general, the ability to identify and correct errors in the codeword improves with the CRC size. As mentioned in Section III, the CRC bits for each partition are uniformly distributed over partitions for PSCF decoding. As a result, each partition should cover an equal probability of error occurrences. Since \( E_1 \) dominates the probability of error occurrence at medium and high \( E_b/N_0 \) values, we can approximate an equal error probability partitioning method by dividing the codeword with respect to \( E_1 \). In order to distribute the partitions, given the length and rate of a polar code, a map of error distribution is required.

Fig. 5 portrays the cumulative probability of \( E_1 \) occurrence over a set of polar codes where \( N = 1024 \) and rates \( R \in \{ \frac{1}{4}, \frac{1}{2}, \frac{3}{4} \} \), under SC decoding, at \( E_b/N_0 = 2.5 \text{ dB} \). These curves have been obtained through SC-Oracle decoding, storing the error indices for failed decoding due to a single error. The partitioning indices \( \rho \) should be placed according to \( E_1 \) distribution, given that each partition should cover \( 1/P \) of the \( E_1 \) errors. Note that the partitioning index refers to the last bit of the partition. It can be seen in Fig. 5 that the partitioning index \( \rho \) does not only change with \( P \) but also with rate \( R \). For example, for a partitioning factor of \( P = 2 \), the first partitioning index \( \rho_1 \) for \( PC(1024, 512) \) should correspond to first the 50% of \( E_1 \) distribution and thus should be located around \( N/2 \), while for \( PC(1024, 768) \) the 50% mark is reached at \( \approx N/5 \).

If a consecutive series of bits have zero error probability, they are represented by a horizontal flat line in the corresponding cumulative error distribution. These bits correspond to either frozen channels or extremely reliable information channels. If a partitioning index corresponds to such a flat line, \( \rho_1 \) can be placed anywhere within the set of bits without affecting the error-correction performance of PSCF. If \( \rho_1 \) is placed at the highest bit index in the set, when the partition is reiterated, operations for the complete set have to be repeated. On the other hand, if \( \rho_1 \) is placed at the lowest bit index in the set, the flat line is included at the beginning of the following partition, and never reiterated. Such an example can be found for \( PC(1024, 512) \), where the 50% mark of \( E_1 \) corresponds to a flat line for \( P = 2 \) in Fig. 5.

Fig. 6 shows how the cumulative \( E_1 \) distribution changes...
probability of $E_1$ occurring. In this context, the computational complexity of PSCF is also related to its average number of iterations. In this context, the computational complexity of PSCF is also related to its average number of iterations. In this context, the computational complexity of PSCF is also related to its average number of iterations. In this context, the computational complexity of PSCF is also related to its average number of iterations.

V. Simulation Results

As mentioned in Section II, the average computational complexity of SC-Flip decoder, and thus its latency, is directly proportional to the average number of iterations. In this context, the computational complexity of PSCF is also related to its average number of iterations. In this context, the computational complexity of PSCF is also related to its average number of iterations. In this context, the computational complexity of PSCF is also related to its average number of iterations. In this context, the computational complexity of PSCF is also related to its average number of iterations.

Fig. 6. Cumulative error distribution for $E_1$ for $PC(1024, 512)$ at various $E_b/N_0$ points.

Fig. 7. Normalized average computational complexity of PSCF ($P \in \{2, 4\}$) and SC-Flip for $PC(1024, 512)$ at matched error-correction performance ($C = 32, T_{\text{max}} = 10$).

On the other hand, the worst case computational complexity of PSCF with $P = 2$ is only 20% above that of SC. At low $E_b/N_0$ values, the complexity of PSCF with $P = 4$ is less than that of SC: this is due to the early termination of decoding in case a partition fails after $T_{\text{max}}$ iterations. At higher $E_b/N_0$, it converges to the complexity of SC. From Fig. 7 it can be seen that, compared to SC-Flip, PSCF is up to $3.2 \times$ faster with $P = 2$, and up to $4.1 \times$ faster with $P = 4$.

The error-correction performance of PSCF with different numbers of partitions is depicted in Fig. 8 and Fig. 9. The curves have been obtained by matching the average number of iterations at the $E_b/N_0$ point $M$. The partitioning indices $\rho$ are selected based on the partitioning scheme described in Section IV. It can be observed that at low $E_b/N_0$ points, PSCF outperforms SC-Oracle, as it can correct more than a single error. The advantage of PSCF over SC-Oracle reduces as $E_b/N_0$ increases. This can be explained observing Fig. 4 where the probability of a single error causing a failed decoding increases with respect to higher error orders.
Compared to SC-Flip, PSCF has better error-correction performance in almost all cases. At low $E_b/N_0$, PSCF has a lower FER because of its ability to correct higher-order errors. As $E_b/N_0$ grows, the impact of higher-order error correction begins to decrease; however, PSCF performs better than SC-Flip in terms of correcting single errors. This is due to the fact that PSCF has, overall, the ability to flip up to $P \times T_{\text{max}}$ bits, increasing the probability of identifying the wrong decision. As $E_b/N_0$ grows further, SC-Flip begins to gain advantage over PSCF. The reason is that at high $E_b/N_0$ values, as mentioned in Section III, the sub-optimal CRC placement of PSCF due to partitioning makes PSCF more vulnerable to errors than SC-Flip. With increasing partitioning factor $P$, CRC distribution gets more sub-optimal (see Fig. 9). Nevertheless, the performance of PSCF is better than SC-Flip at practical FER region of $[10^{-3}, 10^{-4}]$. With $C = 32$ bits for $PC(1024, 512)$, PSCF algorithm outperforms SC-Flip by up to 0.26 dB with $P = 2$ and 0.2 dB with $P = 4$ in the target FER region. SC-List with list size $L = 4$ has the same FER as SC-Oracle, that is comparable to that of PSCF.

VI. CONCLUSION

In this work, we present the partitioned successive-cancellation flip (PSCF) decoding algorithm, that divides the polar code decoding tree into $P$ partitions, and applies the successive-cancellation flip (SC-Flip) algorithm to each partition separately. We show that with partitioning, unlike with SC-Flip, it is possible to correct more than one erroneous bit estimation, as long as the wrong decisions take place in separate partitions. We also show that the average number of iterations can be reduced significantly with partitioning. Then, we present a partitioning scheme for PSCF based on the probability of error distribution for a given codeword. At equivalent number of iterations, our approach demonstrates an improved error-correction performance of up to 0.26 dB with a partitioning factor of $P = 2$, and up to 0.2 dB with $P = 4$

compared to SC-Flip decoding. At equivalent error-correction performance, PSCF shows an average computational complexity reduction of $3.2 \times P = 2$, and of $4.1 \times P = 4$ compared to SC-Flip. In case of $P = 4$, the overall average computational complexity is equivalent to that of a single SC decoder. This leads to increased average throughput and reduced energy consumption for the PSCF decoder.

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