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Simplified Early Stopping Criterion for Belief-Propagation Polar Code Decoder Based on Frozen Bits

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ABSTRACT Polar codes were first proposed by E. Arıkan in 2009 and have received significant attention in recent years. Successive-cancellation (SC) and belief-propagation (BP) decoding algorithms have been applied by some researchers to polar codes. However, unlike SC-based decoders, the performance optimization of BP-based decoders has not been fully explored yet, especially in regard to the impact of the number of iterations on the decoding complexity. In this paper, a novel early stopping criterion based on partial frozen bits for belief-propagation polar code decoders is designed. The proposed criterion is based on the fact that some of the frozen bits that are known to the decoders have a higher average error probability than the information bits and can be used to terminate the decoding. Furthermore, the hardware architecture of the BP-based polar code decoder with the proposed stopping criterion is presented. The simulation results show that the proposed early stopping criterion greatly reduces the number of iterations of BP-based polar code decoders without any performance loss and reduces the hardware complexity from $O(NlogN)$ to $O(N)$ compared with state-of-the-art design.

INDEX TERMS Polar codes, belief-propagation, early stopping, frozen bits.

I. INTRODUCTION

The polar codes were proposed by E. Arıkan according to the polarization theory, and it was the first coding scheme that has been theoretically proven to reach the Shannon limit [1]. The classical decoding algorithm of the polar codes is also proposed by E. Arıkan, which is called the successive-cancellation (SC) decoding algorithm [1]. As an improved version of SC, the successive-cancellation list (SCL) [2], successive cancellation stack (SCS) [3] and CRC-Aided successive cancellation list (CA-SCL) [4] have been introduced to approach the performance of maximum-likelihood decoding. In addition, the belief-propagation (BP) algorithm was also used for the decoding of polar codes [5]–[7]. The BP decoding algorithm has the advantages of high computational parallelism and low decoding latency, which are essentially different from the serial decoding manner of the SC. However, a major shortcoming with BP is that it is difficult to achieve the best error performance and decoding complexity due to the ambiguous stopping conditions.

Several early stopping criteria have been proposed for BP-based polar code decoders in [8]–[10], with the aim of reducing the redundant iterations and computational complexity. In [8], the G-Matrix and minimum magnitude LLR (minLLR) criteria are designed to early stop the belief-propagation decoding of polar codes. Since the G-Matrix method requires re-encoding after each iteration, the decoding complexity is relatively high, although the number of iterations can be effectively reduced. In addition, the minLLR method is not very effective at reducing the number of iterations. To further reduce the decoding complexity, the WIB (worst information bits) method was proposed in [9] to early stop the BP decoder. However, the average number of iterations is much higher than that in the G-Matrix. In [10], the FBER (Frozen BER) criterion was designed for the BP decoding algorithm with a slight reduction in the number of iterations compared to the WIB method. However, none of the above papers consider the fact that the frozen bits are known to the decoders, which can be used to design early

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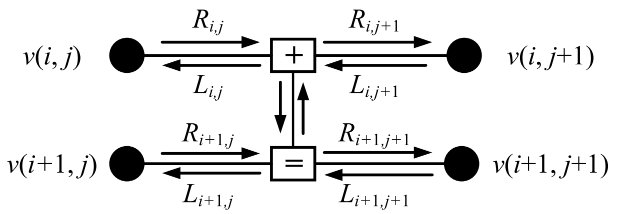

FIGURE 1. Basic process elements of the BP decoder.

stopping criteria for BP decoding algorithms for polar codes and reduce the computational complexity.

In this paper, a novel early stopping criterion based on the channel polarization phenomena is designed for BP-based polar code decoders. The theory of channel polarization tells us that the frozen bits have higher error probabilities than the information bits [1]. Based on this fact, we observe that some of the frozen bits with the lowest error probabilities have higher average error probabilities than the information bits, which can be used to terminate the decoding. We call these partial frozen bits as the best frozen bits (BFBs). Simulation results show that the proposed early stopping criterion greatly reduces the decoding complexity of BP-based polar code decoders with no performance loss.

The rest of this paper starts with a review of the BP decoding algorithm for polar codes. A new early stopping criterion for BP-based polar code decoders is introduced in Section III, and the simulation results and comparisons are given in Section IV. Finally, Section V summarizes the paper.

II. REVIEW OF BP DECODING ALGORITHM FOR POLAR CODES

Similar to the low-density parity-check code, the message propagation of the polar code BP decoder can also be represented by the factor graph [5]. The basic information processing module in the factor graph is called process elements (PEs), as shown in Figure 1. For a polar code with a block length of $N = 2^n$, its factor graph is divided into n stages, and each stage has $N/2$ bidirectional PEs. In addition, node $v(i, j)$ in the PEs is associated with two types of log-likelihood ratio (LLR) messages, which are the left-to-right message $R_{i,j}$ and the right-to-left message $L_{i,j}$ in Figure 1.

The LLR messages are propagated in a round-trip manner in the factor graph. First, the LLR messages of the right-most nodes pass through the PEs to the left-most nodes, and its update rules are as shown in (1).

$$\begin{cases} L_{i,j} = G\left(L_{i,j+1}, R_{i+1,j} + L_{i+1,j+1}\right) \\ L_{i+1,j} = G\left(L_{i,j+1}, R_{i,j}\right) + L_{i+1,j+1} \end{cases} \tag{1}$$

Secondly, the LLR messages of the left-most nodes pass through the PEs to the right-most nodes, and its update rules are as shown in (2).

$$\begin{cases} R_{i,j+1} = G\left(R_{i,j}, R_{i+1,j} + L_{i+1,j+1}\right) \\ R_{i+1,j+1} = G\left(R_{i,j}, L_{i,j+1}\right) + R_{i+1,j} \end{cases} \tag{2}$$

where, $G(\alpha, \beta) = 2tanh^{-1}\left(tanh\left(\alpha/2\right) tanh\left(\beta/2\right)\right)$.

The LLR updating rules (1) and (2) contain a large number of hyperbolic operations, which increases the complexity of the BP decoding algorithm. The min-sum (MS) approximation proposed in [11] greatly reduces the computational complexity of the BP algorithm but incurs a degradation in error performance. In [7], a scale factor is introduced to reduce the approximation error, called scaled min-sum (SMS) approximation. The simplified LLR updating rules provided in [7] are

$$\begin{cases} L_{i,j} = \lambda \times g\left(L_{i,j+1}, R_{i+1,j} + L_{i+1,j+1}\right) \\ L_{i+1,j} = \lambda \times g\left(L_{i,j+1}, R_{i,j}\right) + L_{i+1,j+1} \end{cases} \tag{3}$$

$$\begin{cases} R_{i,j+1} = \lambda \times g\left(R_{i,j}, R_{i+1,j} + L_{i+1,j+1}\right) \\ R_{i+1,j+1} = \lambda \times g\left(R_{i,j}, L_{i,j+1}\right) + R_{i+1,j} \end{cases} \tag{4}$$

where, $g(\alpha, \beta) = sign(\alpha)\, sign(\beta)\, min(|\alpha|, |\beta|)$, λ is the scale factor.

In general, when the channel has a high signal to noise ratio (SNR), the LLR of each node converges quickly in the process of message propagation, so an effective decoded output can be obtained before the maximum number of iterations is reached. Therefore, a criterion is needed to early terminate the BP decoding process without adding too much hardware overhead.

III. PROPOSED BFB-BASED EARLY STOPPING CRITERION

As a class of linear block error correcting code, polar codes can be identified as a parameter vector (N, K, A, A^c), where N is the block length, K is the information size, A is an arbitrary subset of $(1, 2, \cdots, N)$ which is called the information bits set, A^c is the complementary set of A in $(1, 2, \cdots, N)$ which is called the frozen bits set. According to the theory of channel polarization [1], assuming that $A^c = \{f_1, f_2, \cdots, f_{N-K}\}$, and the error probabilities of the frozen bits satisfy $P_e(f_1) < P_e(f_2) < \cdots < P_e(f_{N-K})$, then the N_{BFB} frozen bits with the lowest error probabilities in A^c are called the best frozen bits.

According to the theory of channel polarization [1], sub channels with higher error probabilities are used to transmit the fixed bits, which are known to the receiver. While performing the BP decoding algorithm, since the error probabilities of the frozen bits are higher than those of the information bits, if the BFBs are successfully decoded, it can be assumed that the information bits are successfully decoded too. Therefore, the decoded values of the frozen bits can be used as a trigger to end the decoding. The method based on this idea is called the BFB early stopping criterion.

To further explain our criterion, we define a simple parameter called the proportion of average error probability (PEP), which is based on the Bhattacharyya method [1], as follows:

$$PEP = \frac{\frac{1}{N_{BFB}} \sum_{i \in BFB} Z(W_i)}{\frac{1}{N_{INFO}} \sum_{i \in INFO} Z(W_i)} \tag{5}$$

where, N_{BFB} and N_{INFO} are the numbers of best frozen bits and information bits, respectively. The Bhattacharyya

TABLE 1. PEP values for (N = 1024, K = 512) polar codes.

	N_{BFB}			
W	16	32	64	128
0.5	$1.3*10^{1}$	$1.4*10^{1}$	$1.6*10^{1}$	$1.9*10^{1}$
0.6	$3.2*10^{1}$	$4.5*10^{1}$	$8.1*10^{1}$	$2.1*10^{2}$
0.7	$7.2*10^{1}$	$1.2*10^{2}$	$4.4*10^{2}$	$4.6*10^{3}$
0.8	$1.2*10^{2}$	$3.5*10^{2}$	$3.1*10^{3}$	$1.7*10^{5}$
0.9	$4.8*10^{2}$	$6.0*10^{3}$	$6.9*10^{5}$	$6.0*10^{8}$

parameter $Z(W)$, as an upper bound of the maximum-likelihood decision error, was introduced in [1]. W is the transition probability of the binary-input discrete memoryless channels (B-DMCs) [1].

Table 1 provides the PEP values under various $N_{BFB}s$ and Ws over B-DMCs. As seen from Table 1, as the transition probability W increases, the average error probability of the BFBs increases rapidly with respect to the average error probability of the information bits for the ($N = 1024, K = 512$) polar codes. Therefore, the BFBs require more iterations than the information bits for successful decoding.

The indices of BFBs are determined using the selected construction method. The bit estimation of the frozen bits is made according to the sign of the left-most LLRs, as shown in (6).

$$\hat{u}_i = \begin{cases} 1, & L_{i,1} < 0 \\ 0, & L_{i,1} \geq 0 \end{cases} \tag{6}$$

It can be seen from (6) that the hard decision rule only utilizes the sign of the LLR message and ignores the magnitude part. However, the magnitude of the $L_{i,1}$ is more likely to indicate the probability that u_i being 0 or 1. The definition of $L_{i,1}$ is given by (7). Therefore, the larger the magnitude of $L_{i,1}$, the greater the probability that the u_i is zero (that is, it assumes that all frozen bits are zero, $L_{i,1} \geq 0$).

$$L_{i,1} = ln\left(\frac{P(u_i = 0)}{P(u_i = 1)}\right) \tag{7}$$

Here, we introduce two parameters to describe the BFB early stopping criterion: the minimum number of iterations M and the positive minimum threshold Θ. That is, after a minimum of M iterations, the magnitudes of the BFBs are evaluated. If the magnitudes of all BFBs are not less than Θ, the iteration is terminated.

$$C_i^t = \begin{cases} 0, & L_{i,1}^t \geq \Theta \\ 1, & L_{i,1}^t < \Theta, \end{cases} \quad L_{i,1} \in BFBs \tag{8}$$

For the t-th iteration, the magnitudes of the BFBs are evaluated by (8). After the evaluation is completed, the sum of the comparison results (SCR) is computed according to (9).

$$SCR = \sum_{i \in BFBs, t \geq M} C_i^t \tag{9}$$

If the result of (9) is equal to zero, the BFB method considers that the decoding is complete. Algorithm 1 provides the pseudocode of the proposed BFB early stopping criterion for BP-based polar code decoders.

Algorithm 1 Pseudocode of the BP Polar Code Decoder With the BFB Method

1 **Input**:
2 Log-likelihood ratio (LLRs) from channel output
3 Frozen bits set: $f = \{f_1, f_2, \cdots, f_{N-K}\}$
4 Minimum number of iterations: M
5 Maximum number of iterations: I_{max}
6 Number of BFBs: N_{BFB}
7 Positive minimum threshold: Θ
8 **Initialization**:
9 **if** $i \in f$ **then**
10 $R_{i,1} = \infty$
11 **else**
12 $R_{i,1} = 0$
13 $L_{i,n+1} = LLRs$
14 **Iteration process**:
15 $t = 1$
16 **while** $t \leq I_{max}$ **do**
17 *Update* $L_{i,j}$ *and* $R_{i,j}$ *according to Eq.* $(1-2)$
18 **BFB early stopping criterion process:**
19 **if** $t \geq M$ **AND** $Eq. (9) \equiv 0$ **then**
20 *Stop iteration*
21 **else**
22 $t = t + 1$
23 **Output:**
24 $\hat{u}_i = (L_{i,1} + R_{i,1}) < 0$

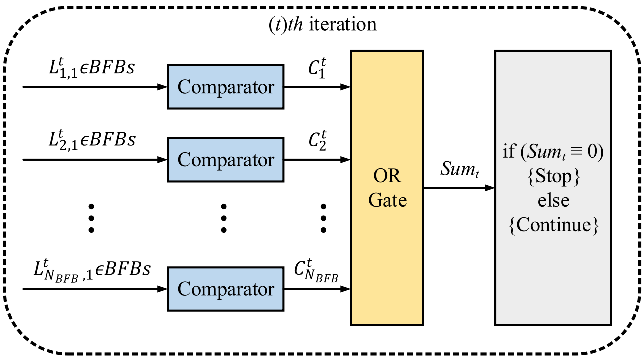

FIGURE 2. Hardware architecture of the proposed BFB early stopping criterion.

Figure 2 shows the hardware architecture of the proposed BFB early stopping criterion. To gain an intuitive understanding of the hardware architecture in Figure 2, consider a multiple-input OR gate in which its output is zero only when the inputs are all zeros. Therefore, the OR gate is well suited for the nonzero detection in the hardware design. The hardware architecture shown in Figure 2 corresponds to lines 18 $\sim$ 22 in algorithm 1. First, the comparisons are applied to the LLRs of the best frozen bits according to (8) (corresponding to the blue block in Figure 2). Then, the sum of the comparison results is calculated by an N_{BFB}-input OR

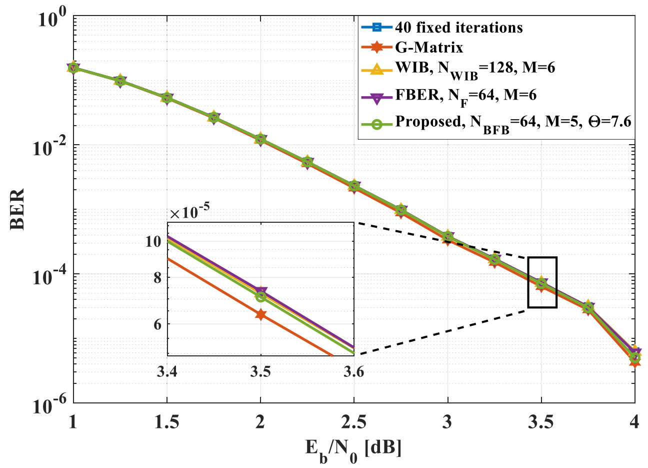

FIGURE 3. BER comparisons of the (N = 1024, K = 512) polar codes using different criteria.

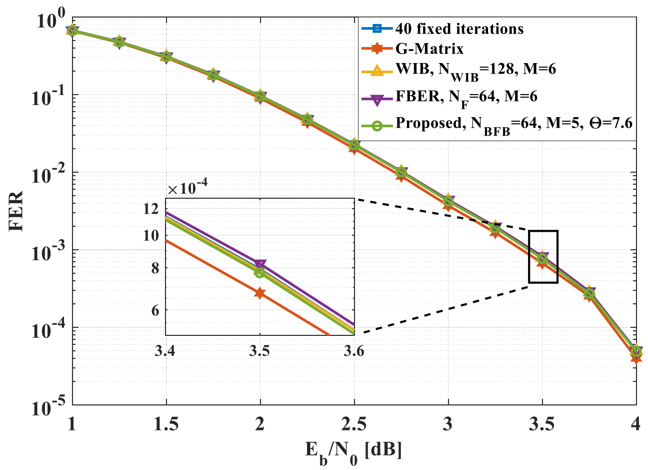

FIGURE 4. FER comparisons of the (N = 1024, K = 512) polar codes using different criterion.

gate (corresponding to the yellow block in Figure 2). Once the accumulated result is zero, the iteration is stopped.

IV. SIMULATION RESULTS AND COMPARISONS

This section will provide the comparisons of the error performance and the average iteration reductions for the G-Matrix, WIB, FBER and proposed BFB early stopping criteria. Here, the additive white Gaussian noise channel is assumed, the block length and code rate of the polar codes are 1024 and 1/2, respectively. The upper limit of the number of iterations of the BP decoder is set to forty. The Bhattacharyya method is adopted to determine the indices of information bits and frozen bits.

Figure 3 and Figure 4 show the BER (Bit Error Rate) and FER (Frame Error Rate) performances of the G-Matrix, WIB, FBER, proposed BFB and original BP decoding without early stopping methods, respectively. As illustrated, there is no performance loss when N_{BFB} equals 64, M is 5 and Θ is 7.6. However, small N_{BFB} and Θ can cause performance degradation. It is easy to understand since lower N_{BFB} makes

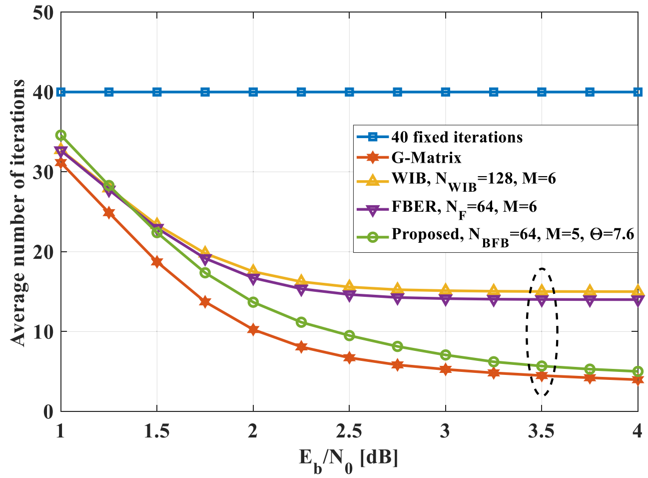

FIGURE 5. Average iteration number comparisons of the (N = 1024, K = 512) polar codes using different criteria.

the PEP smaller and a smaller Θ will cause the iteration to be terminated before the LLRs have not fully converged. Simulation results show that $N_{BFB} = N/16$ is enough to ensure there is no performance loss while those for the WIB and FBER methods are $N/8$ and $N/16$, respectively.

Figure 5 shows the average number of iterations of different early stopping criteria under various SNRs. As shown, the average iteration reductions of the proposed BFB method is between the G-Matrix and FBER methods while it has the lowest decoding complexity. This is because re-encoding provides a good basis for the G-Matrix method to stop the iterations while causing high complexity and the FBER method needs to wait until the BER of the frozen bits is stable. In addition, as the SNR increases, the number of iterations required by the BFB method gradually approaches G-Matrix. This is because high SNR accelerates the convergence speed of the LLRs of the best frozen bits. The detailed average iteration reductions for different early stopping criteria under various SNRs are presented in Table 2. Table 2 shows that when the channel has a low noise level, the proposed BFB method reduces the number of iterations by more than 80 percent, which helps to greatly reduce the decoding delay.

Before we analyze the hardware complexity of the BFB method, the equivalent circuit for the multiple-input OR gate needs to be discussed. For a Q-input OR gate, its equivalent circuit with 2-input OR gate is shown in Figure 6. It can be proved that for any $Q \geq 2$, the number of equivalent 2-input OR gates sum satisfies $sum \leq 2^{\lceil log_2(Q) \rceil} - 1$ (the sum of the geometric sequences with $2^{\lceil log_2(Q) \rceil}$ terms, the first term $\alpha = 1$, common ratio $\gamma = 2$). In particular, when Q is a power of two, $sum = Q - 1$. The proposed BFB method requires an $N/16$-input OR gate for nonzero detection. Therefore, $2^{\lceil log_2(N/16) \rceil} - 1$ can be used as an upper limit of the number of equivalent 2-input OR gate.

Table 3 provides a comparison of the hardware complexity between different early stopping criteria for a single iteration, where $f(x) = 2^{\lceil log_2(x) \rceil} - 1$. As is shown, the hardware

TABLE 2. Iteration reductions based on 40 fixed iterations for the ($N = 1024, K = 512$) polar code BP decoder.

Early Stopping Criterion	G-Matrix		WIB		FBER		Proposed BFB	
			$N_{WIB} = 128, M = 6$		$N_F = 64, M = 6$		$N_{BFB} = 64, M = 5, \Theta = 7.6$	
E_b/N_0(dB)	Average Iteration	Iteration Reduction (%)	Average Iteration	Iteration Reduction (%)	Average Iteration	Iteration Reduction (%)	Average Iteration	Iteration Reduction (%)
1.0	31.16	22.09	32.75	18.13	32.67	18.33	34.60	13.50
1.5	18.73	53.18	23.36	41.60	22.96	42.61	22.39	44.02
2.0	10.25	74.37	17.51	56.23	16.72	58.20	13.68	65.80
2.5	6.72	83.19	15.58	61.04	14.64	63.40	9.50	76.25
3.0	5.26	86.84	15.12	62.20	14.13	64.67	7.07	82.32
3.5	4.49	88.78	15.02	62.45	14.02	64.95	5.68	85.79
4.0	3.97	90.07	15.00	62.49	14.00	64.99	5.01	87.47

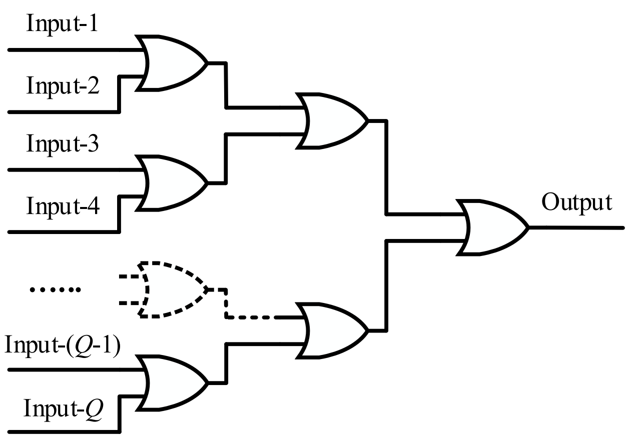

FIGURE 6. The equivalent circuit of the Q-input OR gate.

TABLE 3. Hardware complexities of the early stopping criterion for a single iteration.

	G-Matrix	WIB	FBER	Proposed
Adder	$2N$	$M + 2N/8$	$M + N/16$	–
OR	–	–	–	$f(N/16)$
XOR	$NlogN$	$N/8$	$N/16$	–
Comparator	$3N$	–	–	$N/16$
Hardware Complexity	$O(NlogN)$	$O(M + N)$	$O(M + N)$	$O(N)$

resource costs of the proposed method are much lower than those of the others, which is beneficial to reduce power consumption.

The register transfer level models of SMS-BP decoder with different early stopping criteria are developed with Verilog HDL and synthesized by Synopsys Design Compiler with Semiconductor Manufacturing International Corporation 55nm CMOS library. The worst timing model in the standard library is selected with a supply voltage of 1.08 volts and a temperature of 125°. Table 4 lists the synthesis results of different designs. Here, the value of energy per bit (EPB) is calculated according to (10).

$$EPB = \frac{Power \times DecodingLatency}{ClockFrequency \times N} \tag{10}$$

TABLE 4. Hardware comparisons for ($N = 1024, K = 512$) polar code BP decoder.

Design (7-bit Quantization)	SMS-BP Decoder	Decoder with G-Matrix	Decoder with BFB $\left(\begin{matrix} N_{BFB} = 64, \\ M = 5, \Theta = 7.6 \end{matrix}\right)$
CMOS Technology	55nm	55nm	55nm
Maximum Clock Frequency (MHz)	400	400	400
Total Gate Counts	2148935	2198726	2149162
Average Number of Iterations @4.0dB	40	3.97	5.01
Average Latency (Cycles) @4.0dB	400	43.7	52.1
Energy Per Bit (pJ/bit) @4.0dB	426.8	56.4	55.6

where, the power is reported by Synopsys Design Compiler, N is the block length and the unit of decoding latency is clock cycle.

For a polar code BP decoder with block length N, it takes $logN$ clock cycles to complete a single iteration [7]. In addition, using the G-Matrix and BFB early stop criteria will result in additional decoding delays of four and two clock cycles, respectively. As shown in Table 4, the hardware resource cost of the proposed BFB method is lower than that of G-Matrix, and the hardware overhead of the G-Matrix and the proposed BFB are 2.32% and 0.01%, respectively. In this design, the decoding latency of G-Matrix is lower than that of BFB, which means that the proposed criterion sacrifices the decoding latency in exchange for hardware complexity. On the other hand, thanks to the lower hardware complexity of the BFB method, the EPB of BFB is lower than that of G-Matrix.

As seen from Tables 3 and 4, the proposed BFB method can achieve a better trade-off between decoding performance and hardware complexity compared to the G-Matrix method while achieving better performance with lower complexity compared to the WIB and FBER methods.

V. CONCLUSION

In this paper, the principle of belief-propagation decoding algorithms and previous early stopping criteria for polar codes are explored. A novel early stopping criterion with reduced complexity based on partial frozen bits is designed for BP-based polar code decoders. The proposed BFB early stopping criterion not only helps to make the decoding converge faster, but also reduces the hardware complexity from $O(NlogN)$ to $O(N)$ compared with G-Matrix method.

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