Low Complexity High Throughput Low Density Parity Check Code Based on Compromised Iteration over 5G Out Door Channel

Walled Khalid Abdulwahab[1,*], Sarmad Mahmood Hadi[2]

[1]Computer Science Department; College of Computer Science and Information Technology, University of Kirkuk, Kirkuk, Iraq

[2]Department of Computer Network Engineering; College of Information Engineering, Al-Nahrain University, Baghdad, Iraq

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Abstract

This paper presents a framework for determining an optimized decoding iteration value for low-density parity-check (LDPC) decoders, considering factors such as error rate performance, complexity, throughput, and latency. The compromised iteration is calculated at a specific signal-to-noise ratio (SNR). At this SNR, the error rate performance of the LDPC code meets the requirement for 5G by achieving a Bit Error Rate (BER) less than 10^{-4}. The optimized decoding iteration value is determined for a given coding length, rate, and communication channel. The system has been evaluated using two channel models, additive white Gaussian noise and 5G channels. The results show that the proposed approach reduces the overall complexity and latency of the decoder by up to 50%, and enhances the decoder throughput by up to 99%. However, this improvement comes at the cost of a bit error rate degradation in a range between 0.1 and 0.6 dB.

Keywords: 5G, low-density parity-check (LDPC), error rate, complexity, throughput

1. Introduction

Low-density parity-check (LDPC) codes are linear block codes introduced in the early 1960s by R. Gallager. However, they were initially considered impractical to implement. They were omitted until 1996 when MacKay and Neal rediscovered them [1]. The codes are constructed using sparse Tanner graphs. The decoding process is generally based on an iterative message-passing algorithm [2]. This iterative message-passing algorithm can be classified into two node types, variable nodes and check nodes. These nodes can exchange messages iteratively until they get the correct decoded message or reach the maximum number of iterations [1].

Increasing attention has been given to LDPC codes due to their excellent characteristics in error correction performance and highly parallel implementation. In the last decades, these codes have been considered one of the most popular forward error correction codes, achieving error correction capabilities close to the Shannon limit [2] . Therefore, LDPC codes have been adopted by modern communication systems such as digital video broadcasting - satellite - second generation (DVB-S2, Wi-Fi, and WiMAX because of their near-optimal performance. Furthermore, the codes have been approved by the third generation partnership project (3GPP) as the standard for the data channel in enhanced mobile broadband (eMBB), which is a use case for 5G mobile communications [3].

The performance of LDPC codes mainly depends on the number of decoding iterations. As the number of iterations increases the bit-error-rate (BER) performance of the decoder improves [1-2]. Often, a relatively high number of decoding iteration is used to provide the level of error rate required by the communication standard such as 5G [4]. On the other hand,

* Corresponding author. E-mail address: walled.khalid@uokirkuk.edu.iq

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the increase in the decoding iteration causes an increase in the decoding complexity, latency, and a reduction in the overall throughput which are critical parameters. Therefore, based on the requirements of the provided application, the communication system selects a proper value for decoding iteration [2-3].

Roberts [5] introduces a low-complexity multi-mode decoder design using a modified optimally quantized offset min-sum decoding for superior error correction and stability. It uses an advanced quasi-cyclic low-density parity-check code (QC-LDPC)and a layered decoding technique for flexibility and convergence speed. The multi-rate decoder is developed using 65 nm complementary metal-oxide-semiconductor (CMOS) technology. The implementation results show a good throughput-to-area ratio and reduced consumed power.

Nguyen et. al. [6] proposed a combination of min-sum and offset min-sum decoding algorithms with pipelined layered decoder architecture resulting in a low complexity and a high throughput decoder for the 5G new radio (NR) wireless standards. Ren et. al.[7] provided a decoder that balances the hardware complexity and error rate by extending the min-sum decoding algorithm, achieving flexible truncation for the messages incoming to the check node level, and carefully approximating the non-linear functions in the back-propagation decoder. A combination of the modified weighted bit-flipping decoding algorithm and the logarithmic likelihood ratio algorithm was proposed by Chang et. al. [8]. This work introduced a low-complexity LDPC decoder that avoids the traditional bit-flipping decoding algorithm. A simplified version of the offset min-sum decoding algorithm was proposed by Verma and Shrestha [9] utilizing a new logarithmic-likelihood-ratio technique to reduce the computational complexity of the QC-LDPC decoder and introduce an efficient and parallel hardware decoder architecture.

Mejmaa et. al. [10] modified the QC-LDPC architecture to meet the high throughput demands of improved Mobile Broadband applications. They used the sub-optimal low-latency (SOLL) method to enhance the essential check node procedure, significantly improving ultra-reliable low-latency communications (URLLC) situations. Konfé et. al [11] proposed a new design of LDPC codes and the number of decoding iterations of LDPC codes required for sliding windows is optimized to reduce decoding complexity and solve the decoder blocking issue. Simulation results showed that the proposed approach achieved a 30% reduction in decoding complexity with unpretentious degradation in decoding performance. Ren et. al.[12]. proposed a low complexity and a high performance LDPC decoder. An extension of adjusted min-sum decoding is suggested and then implemented. The results indicate that the memory overhead is reduced by about 42% and the throughput reached peak values at the cost of a slight loss in decoding performance.

These studies focus on reducing complexity and improving throughput in LDPC decoders by optimizing decoding algorithms or enhancing hardware implementations. On the other hand, the values of decoding iteration used in these works are the common values. No attempts have been made to determine specific decoding iteration counts that can further decoding performance.

This paper develops an approach to determine a value for decoding iteration based on the main parameters for the decoding process including error rate, computational complexity, throughput, and latency. This determined value for decoding iteration is referred to as compromised decoding iteration. The proposed approach is a pre-coding process and can be considered as a framework that can be applied to any type of LDPC decoder to determine a compromised decoding iteration value after assuming the required parameters. Instead of the traditional iteration, the compromised decoding iteration value in the decoding process is used for two purposes. First, the computational complexity and latency of the LDPC decoder can be thenceforth reduced. Second, the decoder throughput can thereby be increased at the cost of slight degradation in error performance.

The remainder of this paper is organized as follows. Section 2 presents the approach of compromised decoding iteration. Section 3 describes the channel model and the 5G environment used to evaluate the proposed system. Section 4 illustrates the simulation results of the proposed work and discusses these results. Finally, section 5 presents the conclusion.

2. Creative Compromised Iteration LDPC (CI-LDPC)

LDPC codes have a relationship between decoding iteration, BER, complexity, throughput, and latency. The LDPC decoding process is an iterative process, where increasing the number of iterations reduces the BER. On the other side, the complexity of LDPC decoding is influenced by factors such as code size, and the number of iterations. Increasing the number of decoding iterations generally increases computational complexity and vice versa. The formula for the computational complexity is displayed in Eq. (1) [13-15].

$$cc_{mp} = \frac{N \times \left[6 \times mean(dv) - 9\right] \times I_{\max}}{R + 6} \tag{1}$$

CCmp represents the computational complexity of maximum, minimum, and addition operations. N, R, and *Imax* denote code length, code rate, and maximum value for decoding iteration. Finally, *mean(dv)*, is the mean value of the variable node distributions of the H-matrix.

In addition, throughput is defined as the rate of data processing in a system. In LDPC decoding, increasing the number of iterations can decrease throughput as a consequence of adding computational overhead. The dependence of the LDPC throughput on the number of decoding iterations is illustrated in Eq. (2) [6].

$$Th_r = \frac{N \times f_{\max}}{I_{\max} \times 2 \times l + 2} \tag{2}$$

where *Thr* is the throughput, f_{max} is the maximum operating frequency and *l* is the decoding block layers [6].

The time delay between the system input and output is called latency. In LDPC decoding, latency is influenced by the number of decoding iterations. As the number of iterations rises, the processing time for the decoder also increases. Eq. (3) clarifies the formula of latency in the LDPC decoder [13-15].

$$Lt_n = \frac{N \times R}{Th_r} \tag{3}$$

where Lt_n, *N*, and *R* are the decoding latency, code length, and code rate, respectively. Based on equations 1, 2, and 3, there is a dependency of the complexity, throughput, and latency in addition to the error rate on the value of iteration used in the decoding process. It is possible to say that, based on decoding iteration, there is a trade-off between LDPC BER, complexity, throughput, and latency. As decoding iteration increases, an advantage is obtained by reducing the error rate of the code but at the cost of increasing computational complexity, latency, and the reduction of overall throughput. Thus, there is a need to achieve a compromise between these factors to attain the required BER level while meeting constraints on computational complexity, throughput, and latency.

In this work, a pre-processing approach, named Compromised Iteration LDPC (CI-LDPC), is developed to find a compromised value for the decoding iteration for a given maximum number of iterations while taking into consideration the error rate performance, computational complexity, throughput, and latency. The compromised iteration is the value of decoding iteration that achieves the minimum possible complexity and latency along with maximum throughput for the LDPC decoder at the best possible BER. This pre-processing is conducted at a specific SNR, referred to as the *required-SNR*. At this SNR, the BER of the decoder is less than 10^{-4}. This error rate is among the requirements for the new radio (NR) 5G communication system. The compromised iteration value is determined for a given code length, code, rate, and channel parameters.

After specifying the coding length, coding rate, maximum iteration value, and channel parameters, the *required-SNR* is determined. Later, at this SNR, the BER performance, computational complexity, throughput, and latency are analyzed as functions of the decoding iteration. The iteration count varies from one to its maximum value. Four curves for the mentioned parameters are obtained. Two of these curves, complexity and latency, are directly proportional to the value of decoding iteration while the other two curves, BER and throughput, are inversely proportional to it. Four points resulted from the intersection between these curves. The values of decoding iteration at these intersection points are used to determine the average iteration, as shown in Eq. (4).

$$I_{av} = \frac{\delta_1 I_1 + \delta_2 I_2 + \delta_3 I_3 + \delta_4 I_4}{4} \tag{4}$$

where:

$$\delta_1 + \delta_2 + \delta_3 + \delta_4 = 4,\ \delta_i > 0,\ i = 1,2,3,\ or\ 4$$

The value I_{av} is the average iteration count, I_1 is the iteration value for the intersection point between BER and complexity curves, and the curves of error rate performance and latency intersect at decoding iteration value I_2. Additionally, I_3 is the decoding iteration value for the intersection between throughput and complexity, and finally, I_4 represents the iteration value at the intersection between throughput and latency curves. Furthermore, δ_i, where i=1, 2, 3, or 4, is a coefficient that scales intersection iteration values (I_1, I_2, I_3, and I_4). This can be used if there is a need to give specific performance parameters a weight higher than others.

After determining I_{av}, another factor, Zeta (ζ), needs to be computed at the given required-SNR and I_{av} which are specified earlier. Eq. (5) introduces a formula to determine current values for decoding iteration for evaluating error rate performance, computational complexity, throughput, and latency over a range of ζ. As a result, four curves represent these factors.

$$I_{current} = \zeta \times I_{av},\ \zeta \geq 1, and\ I_{current} \leq I_{\max} \tag{5}$$

$I_{current}$ represents the current iteration count used to determine the error rate, complexity, throughput, and latency. Furthermore, is a factor with a specific range that is multiplied by Iav to get the current value of decoding iteration. The same approach is used to determine Iav, which is utilized to locate the value based on the intersection points of the performance parameter curves, as clarified by Eq. (6).

$$\zeta_{av} = \frac{\zeta_1 \delta_1 + \zeta_2 \delta_2 + \zeta_3 \delta_3 + \zeta_4 \delta_4}{4} \tag{6}$$

where:

$$\delta_1 + \delta_2 + \delta_3 + \delta_4 = 4,\ \delta_i > 0,\ and\ i = 1,2,3\ or\ 4$$

The value ζ_{av} is the average value of ζ , ζ_1 is the zeta value at the intersection of the error rate performance curve, and complexity curve intersect. Meanwhile, the error rate performance and latency curves intersect at ζ_2. The symbol ζ_3 is the zeta value for the intersection between the throughput curve and complexity curve and ζ_4 is the value at the zeta axis for intersecting between the throughput curve and latency curve. Further, δ_i, i=1, 2, 3, or 4 is a coefficient that multiplies with zeta parameters. This can be used if there is a need to give specific performance parameters higher weights than others. The similar coefficients δ_i in Eqs. (4) and (6) hold the same values.

Finally, the compromised iteration value is determined as presented in Eq. (7)

$$I_{cmpr} = round(I_{av} \times \zeta_{av}) \tag{7}$$

I_{Cmpr} represents the compromised value of decoding iteration, which is used in the decoding process. In summary, this approach consists of four stages: finding the required-SNR, determining the I_{av}, finding ζ_{av}, and finally, obtaining I_{Cmpr}. A visual example for determining I_{av}, ζ_{av}, I_{Cmpr}, and other parameters can be found in subsection 4.1. Algorithm (1) summarizes the steps for this process.

Algorithm (1); C-I LDPC process

Step 1: Specify parameters N, R, I_{max}, and Channel.

Step 2: Specify required-SNR.

Step 3: for I=1,.., I_{max}. determine BER, Complexity, Throughput, and Latency.

Step 4: Find ζ_{av} $I_1, I_2, I_3,$ and I_4.

Step 5: Find I_{av} based on Eq. (4).

Step 6: For $\zeta \geq 1$, determine BER, Complexity, Throughput, and Latency based on Eq. (5).

Step 7: Find ζ_1, ζ_2, ζ_3 and ζ_4.

Step 8: Determine ζ_{av} based on Eq. (6).

Step 9: Determine I_{Cmpr} based on Eq. (7).

3. 5G Environment and Channel Model

In this work, two channels are employed to evaluate the proposed CI-LDPC code and the original LDPC code. The first channel used quadrature phase shift keying (QPSK) as its modulation scheme with the additive white gaussian noise (AWGN) [16].

The 5G umi outdoor channel model is the second channel model. The following elements are part of this model: First, to attain spectral efficiency, signals are modulated and demodulated using quadrature phase shift keying (QPSK) [17-18]. Second, signal mapping is performed using orthogonal frequency division multiplexing (OFDM), which has a length of 512 and a cyclic prefix of length 36 with a subcarrier spacing of 120 kHz [19-20]. Third: Space-Time Block Coding (STBC) is implemented to form a 4x4 dimensional multiple-input multiple-output (MIMO) antenna [17]. Fourth: A 3GPP-approved fading channel model for the 5G scenario is considered.

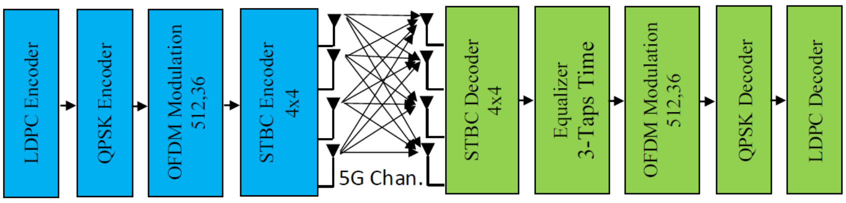

Fig. 1 5G channel model

The utilized channel operates over a frequency range of 0.5 to 100 GHz, with a maximum bandwidth of 2 GHz [21]. This channel model represents the tapped delay line E-channel for the umi-street canyon. The proposed channel includes three taps and operates at a carrier frequency of 39 GHZ. This frequency is in the (mmWave) range of frequencies. The path gains expressed in dB are [-0.03 -15.8 -18.1]. The normalized delays of taps, with a delay spread of 30 ns, are [0 0.5133 0.5440]. For this model, the K-factor is 22 dB [21]. Considered is a maximum Doppler shift of 77.784 Hz for a relative velocity of 3 km/h between the transmitting and receiving nodes. The proposed channel has a bandwidth of 100 MHz [19,22-23]. Lastly, to mitigate the effects of the suggested fading channel, a three-tap MIMO time domain equalizer is offered [24-25]. The 5G channel model can be clarified in Fig. 1.

4. CI-LDPC Performance Evaluation

The proposed CI-LDPC decoder is applied to LDPC code with two coding cases; the first scenario has a coding length (N) of 3808 and a coding rate (R) of 1/3. The second case involved N of 2304 and R equal to ½. Three iteration values are used to evaluate this approach which are 10, 20, and 30. The values used for f_{max} and l are 750 MHz and 16, respectively [6,26] . The selected block lengths and iterations for the LDPC codes are among the interesting parameters in 5G. CI-LDPC and the original LDPC codes are simulated using QPSK, OFDM modulation, and 4x4 MIMO with the related transmission parameters, as shown in section 3. Two channel models are used: the AWGN channel and a fading channel model in the mmWave frequency band related specifications. The proposed CI-LDPC decoder together with the conventional LDPC decoder is simulated by using Matlab R2022b version 9.13.0. The results of the simulation and the discussions related to the achieved gain in computational complexity, throughput, and latency by CI-LDPC compared to the traditional LDPC are presented in this section.

4.1. CI-LDPC and LDPC Simulations

The simulation tests in this subsection include the determination of the compromised parameters for each channel model and the performance evaluation of the proposed CI-LDPC decoder alongside the standard LDPC decoder for the comparison analysis. In the case of the AWGN channel, for LDPC code with a coding length of 3808 and coding rate of 1/3, the required-SNR is 0.1 dB with a value for maximum decoding iteration of 10. This SNR value is utilized to determine the compromised iteration parameters. In this work, the values for the factors δ are set to one in all equations and all considered cases. The estimation of the compromised parameters begins with determining I_1, I_2, I_3, and I_4, where error rate, performance complexity, throughput, and latency are calculated as functions of decoding iteration, as shown in Fig. 2. The values of complexity, throughput, and latency are normalized in the range between 0 and 1 in Figs. 2-3.

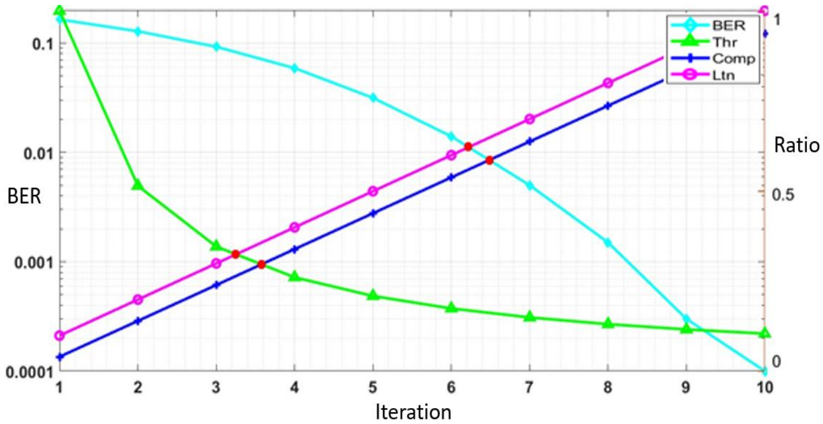

Fig. 2 Determining I_1, I_2, I_3, and I_4

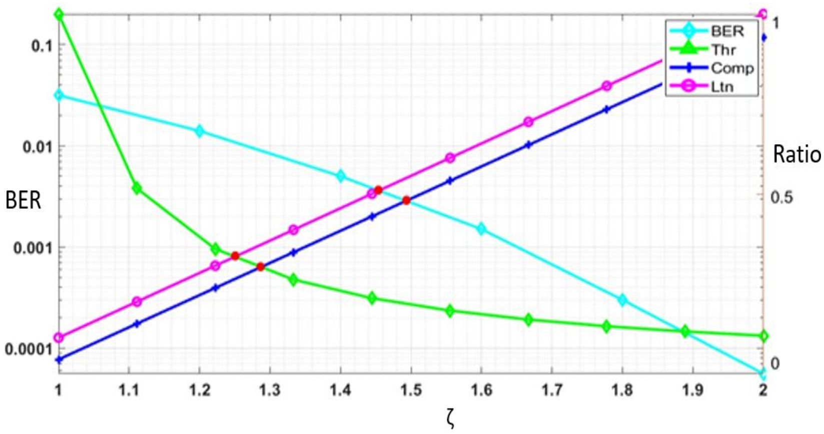

Fig. 3 Determining ζ_1, ζ_2, ζ_3, and ζ_4

Four intersection points between the performance curves yield four points on the iteration axis denoted as I_1, I_2, I_3, and I_4. The values for these points are 6.2, 6.5, 3.25, and 3.6, respectively. Based on Eq. 4 the value of I_{av} is determined to be 4.8875. Then by using Eq. 5, the performance concerning error rate, complexity, throughput, and latency is evaluated as a function of ζ. As shown in Fig. 3, the intersections of the performance curves yield four points on the ζ axes, which are ζ_1, ζ_2, ζ_3, and ζ_4, their values are 1.455, 1.495, 1.25, and 1.288, respectively. Using Eqs. 6-7, ζ_{av} and I_{Cmpr} are calculated where their values are 1.372, and 7, respectively.

Using the same approach, the values of I_{cmpr} for other iteration values with the same code, for all considered decoding iterations with other codes, and across all considered channels are determined. Table 1 summarizes all compromised parameters and the corresponding compromised iterations of the considered codes over the AWGN and 5G channels. The BER performance for the CI-LDPC and the original LDPC decoders for the considered codes, iterations, and channels is shown in Figs. 4-7.

Table 1 Compromised parameters and compromised iterations

LDPC (N, K)	Channel	Iteration	Required-SNR in dB	I_1, I_2, I_3, I_4	I_{av}	ζ_1, ζ_2, ζ_3, and ζ_4	ζ_{av}	I_{Cmpr}
LDPC (3808,1269)	AWGN	10	0.1	6.2, 6.5, 3.25, 3.6	4.8875	1.455, 1.495, 1.25, 1.288	1.372	7
LDPC (3808,1269)	AWGN	20	-0.8	11.4, 11.7, 4.6, 4.9	8.15	1.63, 1.66, 1.33, 1.36	1.495	12
LDPC (3808,1269)	AWGN	30	-1	15.1, 15.4, 5.6, 5.9	10.5	1.7, 1.72, 1.375, 1.4	1.54875	16
LDPC (2304,1152)	AWGN	10	2.4	6.25, 6.55, 3.4, 3.72	4.9852	1.47, 1.51, 1.25, 1.29	1.38	7
LDPC (2304,1152)	AWGN	20	1.6	10.5, 10.75, 4.6, 4.9	7.6875	1.65, 1.675, 1.375, 1.42	1.53	12
LDPC (2304,1152)	AWGN	30	1.4	13.75, 14, 5.7, 5.95	9.85	1.66, 1.68, 1.375, 1.4	1.52875	15
LDPC (3808,1269)	5G	10	-0.45	6.42, 6.75, 3.25, 3.6	5.005	1.439, 1.476, 1.274,1.308	1.37425	7
LDPC (3808,1269)	5G	20	-0.725	12.2, 12.5, 4.6, 4.9	8.55	1.63, 1.67, 1.33, 1.35	1.495	13
LDPC (3808,1269)	5G	30	-0.775	16.4, 16.75, 5.7, 5.95	11.2	1.8, 1.82, 1.32,1.34	1.57	18
LDPC (2304,1152)	5G	10	1.65	6.07, 6.39, 3.25, 3.6	4.8275	1.421, 1.46, 1.25, 1.287	1.3545	7
LDPC (2304,1152)	5G	20	1.35	11.3, 11.7, 4.6, 4.9	8.125	1.64, 1.67, 1.33, 1.36	1.5	12
LDPC (2304,1152)	5G	30	1.3	14.8, 15.05, 5.7, 5.95	10.375	1.68, 1.71, 1.375, 1.4	1.54125	16

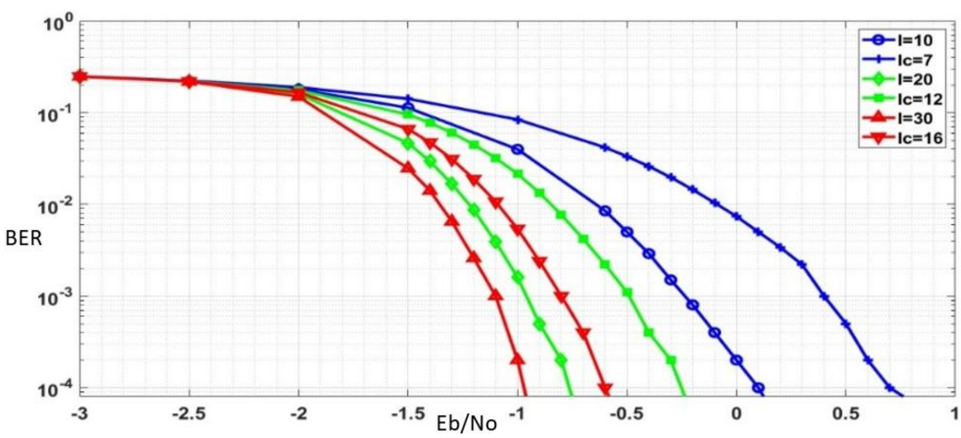

Fig. 4 BER performance for CI-LDPC & LDPC with N=3808 & R=1/3 over AWGN channel

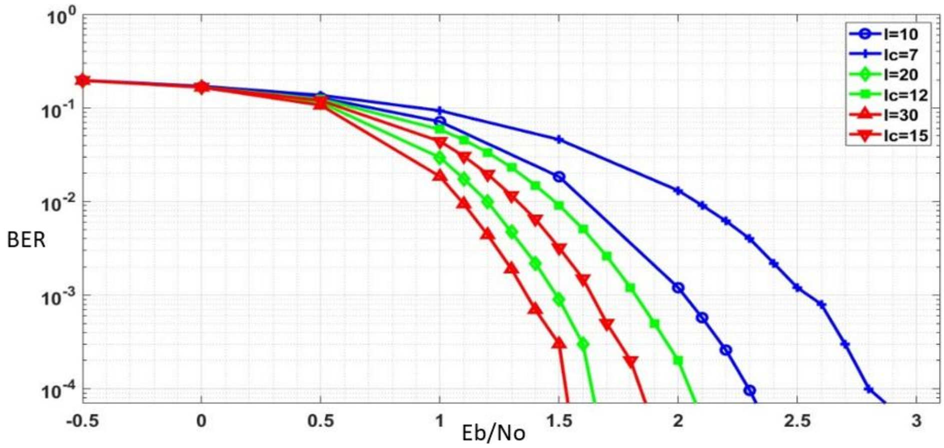

Fig. 5 BER performance for CI-LDPC & LDPC with N=2304 & R=1/2 over AWGN channel

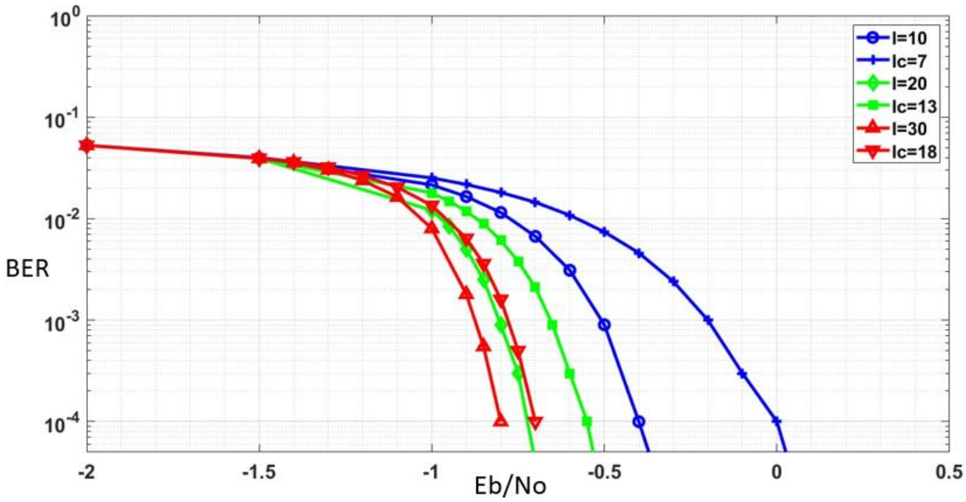

Fig. 6 BER performance for CI-LDPC & LDPC with N=3808 & R=1/3 over 5G channel

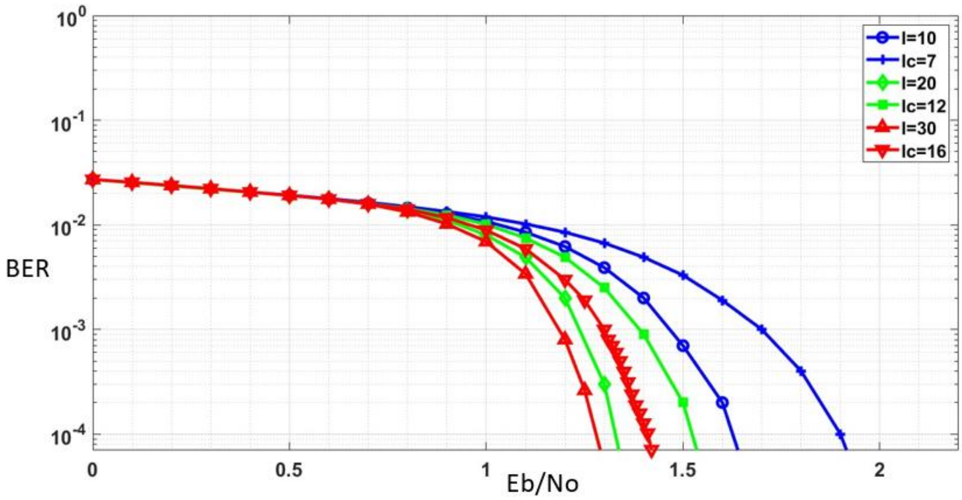

Fig. 7 BER performance for CI-LDPC & LDPC with N=2304 & R=1/2 over 5G channel

4.2. Results and discussions

In the last subsection, the compromised decoding iteration for each considered case with its related parameters was presented along with the BER performance of CI-LDPC and original LDPC. In this subsection, the effect of each I_{cmpr} value in CI-LDPC is compared with its corresponding I_{max} in the original LDPC in terms of computational complexity, throughput, latency, and BER performance. These effects are summarized in Table 2. The values of complexity, throughput, and latency for both CI-LDPC and LDPC are determined based on Eq. (1), Eq. (2), and Eq. (3), respectively. The improved percentages for decoding complexity, throughput, and latency are determined based on Eq. (8), Eq. (9), and Eq. (10), respectively.

Table 2 Gains & BER loss for CI-LDPC

code	channel	I	I_{Cmpr}	Parameters	I	I_{Cmpr}	Improved Percentage	SNR loss(dB) at BER 10^{-4}
N=3808 K=1269	AWGN	10	7	Complexity	$1.6029*10^4$	$1.1221*10^4$	30%	0.6 dB
				Throughput	$0.9852*10^9$	$1.4038*10^9$	42%	
				Latency	$0.1288*10^{-5}$	$0.0904*10^{-5}$	30%	
N=3808 K=1269	AWGN	20	12	Complexity	$3.2059*10^4$	$1.9235*10^4$	40%	0.5 dB
				Throughput	$0.4942*10^9$	$0.8219*10^9$	66%	
				Latency	$0.2568*10^{-5}$	$0.1544*10^{-5}$	40%	
N=3808 K=1269	AWGN	30	16	Complexity	$4.8088*10^4$	$2.5647*10^4$	47%	0.3 dB
				Throughput	$0.3298*10^9$	$0.6172*10^9$	87%	
				Latency	$0.3848*10^{-5}$	$0.2056*10^{-5}$	47%	
N=2304 K=1152	AWGN	10	7	Complexity	$1.1522*10^4$	$0.8065*10^4$	30%	0.5 dB
				Throughput	$0.1342*10^{10}$	$0.1912*10^{10}$	42%	
				Latency	$0.8587*10^{-6}$	$0.6027*10^{-6}$	30%	
N=2304 K=1152	AWGN	20	12	Complexity	$2.3044*10^4$	$1.3826*10^4$	40%	0.4 dB
				Throughput	$0.0673*10^{10}$	$0.1119*10^{10}$	66%	
				Latency	$0.1712*10^{-5}$	$0.1029*10^{-5}$	40%	
N=2304 K=1152	AWGN	30	15	Complexity	$3.4565*10^4$	$1.7283*10^4$	50%	0.3 dB
				Throughput	$0.0449*10^{10}$	$0.0896*10^{10}$	99%	
				Latency	$0.2565*10^{-5}$	$0.1285*10^{-5}$	50%	
N=3808 K=1269	5G	10	7	Complexity	$1.6029*10^4$	$1.1221*10^4$	30%	0.4 dB
				Throughput	$0.9852*10^9$	$1.4038*10^9$	42%	
				Latency	$0.1288*10^{-5}$	$0.0904*10^{-5}$	30%	
N=3808 K=1269	5G	20	13	Complexity	$3.2059*10^4$	$2.0838*10^4$	35%	0.18 dB
				Throughput	$0.4942*10^9$	$0.7590*10^9$	54%	
				Latency	$0.2568*10^{-5}$	$0.1672*10^{-5}$	35%	
N=3808 K=1269	5G	30	18	Complexity	$4.8088*10^4$	$2.8853*10^4$	40%	0.1 dB
				Throughput	$0.3298*10^9$	$0.5489*10^9$	66%	
				Latency	$0.3848*10^{-5}$	$0.2312*10^{-5}$	40%	
N=2304 K=1152	5G	10	7	Complexity	$1.1522*10^4$	$0.8065*10^4$	30%	0.28 dB
				Throughput	$0.1342*10^{10}$	$0.1912*10^{10}$	42%	
				Latency	$0.8587*10^{-6}$	$0.6027*10^{-6}$	30%	
N=2304 K=1152	5G	20	12	Complexity	$2.3044*10^4$	$1.3826*10^4$	40%	0.2 dB
				Throughput	$0.0673*10^{10}$	$0.1119*10^{10}$	66%	
				Latency	$0.1712*10^{-5}$	$0.1029*10^{-5}$	40%	
N=2304 K=1152	5G	30	16	Complexity	$3.4565*10^4$	$1.8435*10^4$	47%	0.12 dB
				Throughput	$0.0449*10^{10}$	$0.0840*10^{10}$	87%	
				Latency	$0.2565*10^{-5}$	$0.1371*10^{-5}$	47%	

IP_{cmp}, IP_{thr}, and IP_{ltn} are the improved percentages achieved by CI-LDPC over LDPC in terms of decoding complexity, throughput, and latency, respectively. Further, C_{ldpc}, Thr_{ldpc}, and Ltn_{ldpc} are the decoding complexity, throughput, and latency at I_{max}. $C_{ci\text{-}ldpc}$, $Thr_{ci\text{-}ldpc}$, and $Ltn_{ci\text{-}ldpc}$ represent the decoding complexity, throughput, and latency at I_{cmpr}.

$$IP_{Cmp} = \frac{C_{ldpc} - C_{ci-ldpc}}{C_{ldpc}} \times 100\% \tag{8}$$

$$IP_{thr} = \frac{Thr_{ci-ldpc} - Thr_{ldpc}}{Thr_{ldpc}} \times 100\% \tag{9}$$

$$IP_{Ltn} = \frac{Ltn_{ldpc} - Ltn_{ci-ldpc}}{Ltn_{ldpc}} \times 100\% \tag{10}$$

The reduction ratio in decoder complexity and latency ranged from 30% to 50% across the considered cases. All considered cases exhibited a 30% gain at a decoding iteration 10. At the iteration of 20, the reduction ratio increased to 35% and 40%. The maximum reduction in computational complexity and decoding latency is achieved at a decoding iteration value of 30 where the reduction falls within the range of 46% to 50% across the considered case, as shown in Figs. 8-9.

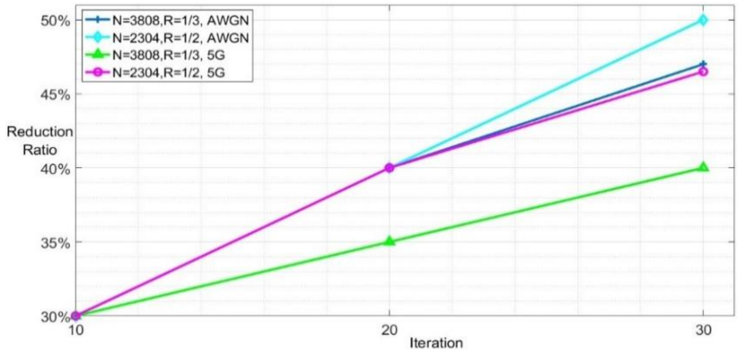

Fig. 8 Reduction ratio in decoder complexity for CI-LDPC

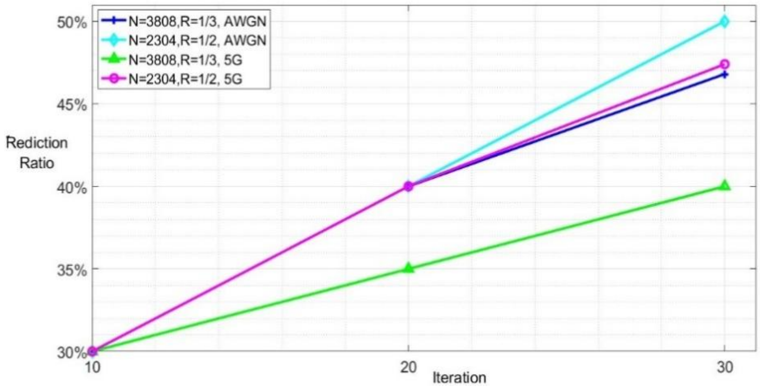

Fig. 9 Reduction ratio in decoder latency for CI-LDPC

The proposed approach realizes an increase in the throughput ranging from 40% and 99%. At a decoding iteration of 10, a 40% increase in decoder throughput is achieved in all considered cases. This improvement increased at the decoding iteration of 20 to between 54% and 66%. At decoding iteration of 30, the gains in throughput range from 66% and 99%. Fig. 10 illustrates the gains fulfilled in throughput.

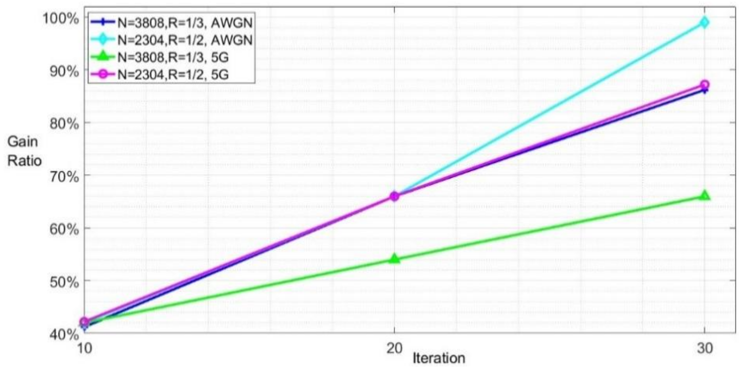

Fig. 10 Increasing ratio in decoder throughput for CI-LDPC

The mentioned advantage achieved by CI-LDPC is accompanied by a degradation in BER performance between 0.6 and 0.1 dB compared to the original LDPC. At a decoding iteration value of 10, the loss in BER performance is from 0.28 to 0.6 dB in the considered cases. At an iteration of 20, this range narrows to 0.18 and 0.5 dB. The minimum BER loss occurs at the decoding iteration of 30, ranging from 0.1 and 0.3 dB. The losses in BER performance for all considered cases are illustrated in Fig. 11. Although these losses are considerable in some cases, they are common in literature as a price for reducing decoding complexity and improving other decoding factors in LDPC for 5G [26-27].

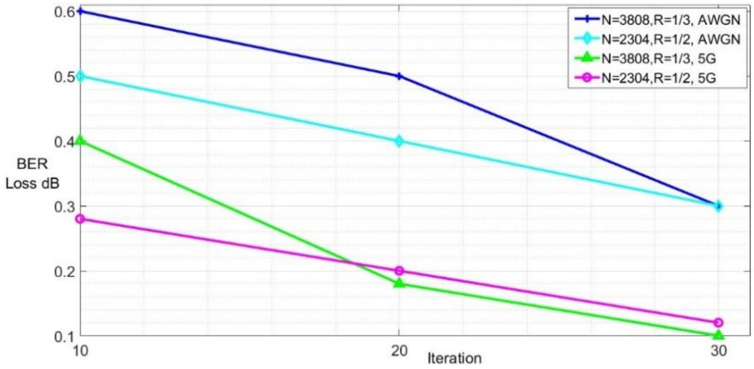

Fig. 11 BER losses in CI-LDPC

The proposed decoding approach meets the requirements of various services and applications in 5G. The reduction in decoding complexity achieved by CI-LDPC satisfies key requirements for massive machine-type communication (mMTC) use cases and their applications such as smart city healthcare, manufacturing, and smart agriculture. These applications mainly utilize devices that depend on batteries in their work. Furthermore, the reduction in latency and the improvement in decoding throughput are highly demanded by ultra reliable low latency communication (URLLC) 5G use cases and their applications like assisted and automated driving, industrial robotics, vehicle-to-vehicle communications, wirelessly controlled manufacturing, remote medical, and others. [28-29]

The proposed CI-LDPC has some limitations. First, there is a considerable degradation in BER performance in certain cases. Further, optimal values should be assigned to the parameters δ_i, i=1, 2, 3, or 4, instead of assigning the value 1 for all parameters. Finally, the use of multiple SNR values instead of a single SNR value, required-SNR, in determining the compromised iteration may provide better results.

Based on the above findings, it is clear that CI-LDPC has achieved important gains in the three decoding parameters: complexity, throughput, and latency at the cost of a BER degradation that does not exceed 0.6 dB. Furthermore, the improvement in these parameters increased and the degradation in BER performance decreased as the number of decoding iterations grew. The values of the determined compromised iteration in the considered cases indicate that they are generally confined within specific ranges, as defined by Eq. (11).

$$I_c = \begin{cases} f_1 \times I_{max} & f_1 = 0.75 \; as \; I_{max} = 10 \\ f_2 \times I_{max} & 0.6 \le f_2 \le 0.65 \; as \; I_{max} = 20 \\ f_3 \times I_{max} & 0.5 \le f_3 \le 0.6 \; as \; I_{max} = 30 \end{cases} \tag{11}$$

5. Conclusions

This work develops a general framework to find a compromised value for decoding iterations in the LDPC code. The determination of this iteration value considers multiple LDPC decoder parameters, including error performance, computational complexity, throughput, and latency. The compromised decoding iteration successfully achieves gains in the decoder complexity, throughput, and latency with values reaching up to 50%, 99%, and 50%, respectively, compared to the original case for the considered LDPC decoder. This improvement is at the price of a degradation in the bit error rate between 0.1 dB and 0.6 dB. CI-LDPC shows better performance at a high value of decoding iteration in terms of achieved gains and BER losses. Further, the rather best results are obtained by CI-LDPC with the higher coding rate. The proposed approach applies to multiple applications within URLLC and mMTC 5G use cases.

Finally, several aspects of the proposed work need further in-depth study, including the considerable degradation in error performance in some considered cases, the optimal values for δ_i, and the use of multiple required-SNR in determining the compromised iteration parameters. These issues can be addressed in future works.

Conflicts of Interest

The authors declare no conflict of interest.

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