LDPC Codes for 5G: An Empirical Analysis for Wireless Communication System Advances

Amaad Khalil[1], Mahmood Ul Haq[1], Ishtiaque Ahmed[2], M. Abeer Irfan[1], Muhammad Bilal Rafaqat[3], Abid Iqbal[4]

[1] Department of Computer Systems Engineering – University of Engineering & Technology, Peshawar, 25000, Pakistan
[2]National center of Big Data and Cloud Computing – University of Engineering & Technology, Peshawar, 25000, Pakistan
[3]School of ICT, University of Tasmania, Hobart, TAS 7000 Australia
[4]Department of Computer Engineering, King Faisal University Al Ahsa, Saudi Arabia

Abstract With advancements and new proposals in wireless communication standards, there is an increase in the demand for band-width-efficient wireless transmission mechanisms. The 5G networks will also enable the Internet of Things (IoT) by creating more efficient and reliable networks for billions of connected devices. Error-Correction Coding (ECC) is a powerful technique to ensure reliable and secure communication in wireless multimedia systems. ECCs are essential for modern wireless communication as they help reduce the amount of data lost during transmission due to errors and noise in the channel. Recent research has demonstrated the usefulness of Low-Density Parity-Check (LDPC) codes for 5G and beyond communication. This paper compares LDPC with polar, Reed-Muller, and convolutional codes, along with a motivation for their application in wireless multimedia communication. Simulation results show that the LDPC outperforms Reed-Muller, polar, and convolutional codes for larger block length codes. Thus, two sub-classes of LDPC codes, AR4JA and AR3A, with different decoding algorithms, are presented for possible adoption in next-generation reliable communication. The performance is evaluated in terms of the Bit Error Rate (BER) and code rate. The paper also highlights the importance of using ECCs in wireless multimedia communication to improve data transmission reliability and reduce channel impairments' impact. More specifically, the AR4JA exceeds the AR3A by a factor of 0.5 dB SNR at the BER degradation point of 10-8 and attains the error floor level of 10-9.

Keywords 5G LDPC, Error-Correction Coding (ECC), the Bit Error Rate (BER)

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1. Introduction

Wireless technology has grown exponentially over the last few decades [1]. The recent advancement in wireless technology has boosted the potential capabilities of the Internet of Things (IOT), increased data capacity by 30–40% , and resulted in high bit rate transmission [2]. Researchers have significantly developed in resolving constraints related to low bandwidth, high-data-rate transmission, and service cost [3].

Although wireless communication networks provide high-speed data transmission, low-cost maintenance, and ease of installation [4]. However, the rising demand for high-data-rate transmission in wireless technology has brought new challenges to communication systems. These challenges are security and Privacy, portability [5], communication infrastructure [6], mobility, coding, limited bandwidth, and wireless access techniques [7].

In wireless communication, the transmission of multimedia contents is supported by source and channel coding techniques [8]. For efficient multimedia data compression, source encoding has received much attention [9, 10]. Error-correction coding is a technique used to describe a series of numbers in a form that allows errors to be found and fixed, subject to constraints imposed on the remaining numbers. The main focus of channel coding is to reduce the effect of errors in a communication link and the system's complexity, allowing for practical implementation. Massive machine-type communications (mMTC), enhanced mobile broadband, and ultra-reliable and low latency communications (URLLC) (eMBB) are three scenarios supported by the next-generation communication network, 5G NR, beyond 4G LTE [11-13]

These scenarios require reliability, low latency, less computational cost, and improved throughput compared to 4G LTE [14]. Considering these requirements, low-density parity check (LDPC) codes were implemented for the 5G standard for data channels [15, 16]. During the 5G standardization study phase, several coding schemes were tested based on the mentioned requirements and adopted polar coding for eMBB scenario control information and LDPC coding for user data.

Following are some of the significant contributions of this treatise:

- Comparison of LDPC codes with different FEC for performance estimation.
- Effect of variation in the block length of LDPC codes on error-resiliency.
- Investigation of the types of LDPC for deployment in 5G communication setupTop of Form.

In Section II, we describe some of the related work in modern wireless communication. Sections III, IV, V, and VI discuss basic LDPC coding, Polar codes, advanced 5G LDPC coding, and 5G polar coding. Section VII covers Reed-Muller codes, while Section VIII elaborates on convolutional codes. Experimental results are given in Section IX. Finally, Section X briefly concludes the article along with future research directions.

2. Related Work

Gallager developed LDPC codes during his Ph.D. studies, and it was established that the results of communication systems could approach the Shannon capacity when LDPC codes are used for channel encoding [19]. Soft-in and soft-out information is utilized for LDPC codes to enhance diversity and reduce complexity. Multiple nodes transmit the code-words along a shared path. Due to the random nature of LDPC codes, there is no need for an interleaved [19]. Using LDPC codes allows for exchanging external and internal information, facilitating cooperation and suggesting that cooperative decoding is superior to other methods. A study [20] combines JSCC and LDPC for increased effectiveness. Iterative decoding requires Tanner-graph mapping of the source and channel coding using a message-based approach. In [21], the authors propose using superposition-coded modulation for wireless channel video transmission. LDPC codes are employed for encoding videos, resulting in higher-quality videos. The authors suggest reducing complexity through repeated decoding, achieving a 67% decoding success rate. The concept of using path sharing to create a multicast system while utilizing the same media is presented in [22]. Polar codes, invented by Turkish scientist Arikan [23], are error correction codes used in communication systems. They serve as a reliable channel encoding scheme and are employed as coding schemes in fifth-generation networks for error correction [24].

3. LDPC Codes

LDPC codes are a valuable class of error-correction codes for efficiently improving the above parameters. LDPC provides practical implementation near Shannon channel capacity and greater speed and accuracy with less complex algorithms. LPDC codes are specified by a parity check matrix containing a few ones and primarily zeros. LDPC codes can be represented in two ways: in matrix form and graphical representation. In LDPC codes, the sparse parity check matrix ((n-k) × n dimension) represents the parity check sets. Sparse means that the condition (w_c and $w_r << n\times(n-k)$ should be satisfied, where n represents the coded length, w_r, and w_c represent the number of ones in a row and column, respectively [19].

A sparse parity check matrix of ($n = 8$, $w_c = 4$, $w_c = 2$) is presented in equation 1, where each row appears to be a check node and each column is a variable node [19].

$$H=\begin{bmatrix} 0 & 1 & 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 1 & 1 \\ 1 & 0 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \quad (1)$$

The 1's in the H matrix represent the connection between the variable node and the check node. The parity check matrix can be categorized into two types. The codeword of any linear block code associated with LDPC codes, including message and parity bits, can be described in Equation 2.

$$C = [m_{1\times k} \quad P_{1\times n-k}] \quad (2)$$

Where p represents the parity vector and m represents the message vector. Figure 1 shows the 5G LDPC codes encoding procedure [19].

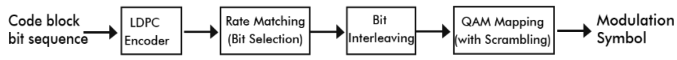

Figure 1. Encoding process timof 5G LDPC codes.

4. Polar Codes

Polar codes were initially presented in 2009 by Erdal Arıkan [17]. The first linear code achieved the Shannon channel capacity. Polar codes have an excellent structure with efficient and less complex encoding and decoding operations. The LDPC relies on ensemble performance levels, whereas the polar codes can be confirmed using a specific realization. Identifying frozen bit positions and information is another crucial aspect of polar codes [18-20].

Although the achievable polar code capacity with SC decoding is impressive, its finite length capacity, compared to other channel coding, is even worse. List decoding is a well-known solution for this matter [21]. Successive cancellation list (SCL) decoding keeps multiple decision candidates during successive cancellation (SC) decoding to overcome the premature decision drawback of SC decoding. Moreover, CRC-aided (CA) SCL is considered for error detection and correction to enhance the block-error rate (BLER) performance of SCL decoding. Furthermore, several solutions were presented in previous literature to overcome the latency issue of SC decoding [22-24]. The 5G polar transmitting processing chain is present-ed in Figure 2.

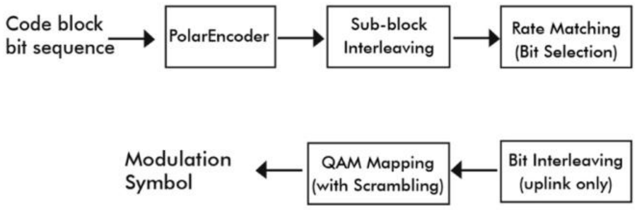

Figure 2. 5G polar codes transmitter processing chain

5. 5G LDPC Codes

The main features of 5G LDPC codes are briefly described in this section. QC-LDPC codes are 5G LDPC codes related to the protograph code family. This section explains the design of a permutation matrix and a photograph, two crucial components of the protograph code. Moreover, rate matching procedures and IR-HARQ support, are also described.

5.1. Protograph codes

The fifth-generation LDPC codes are QC-LDPC codes [25]. The concept of protograph codes will help explain QC-LDPC codes. The graphic representation of protograph codes can be obtained by affixing numerous protograph copies and rearranging the borders between them. The check nodes and variables are initially identified from each protograph copy in the edge permutation process. The local connection between check nodes and variables is vital for better performance. It is important to design a better permutation pattern with efficient cycle properties for better performance of protograph codes. Several observations have been presented in the literature showing the better finite-length performance of protograph codes in various environments [25].

Table 1: Shift-value sets and lifting sizes set for 5G LDPC codes with their relation.

Index of Shif-value set	Lifting sizes (Z) set							
0	2	4	8	16	32	64	128	256
1	3	6	12	24	48	96	192	389
2	5	10	20	40	80	160	320	
3	7	14	28	56	112	224		
4	9	18	36	72	144	288		
5	11	22	44	88	176	352		
6	13	26	52	104	208			
7	15	30	60	120	240			

Moreover, protograph codes allow parallelism in the encoding and decoding processes [26], which is advantageous in the case of layered decoding [27]. In the 5G specification [28], a photograph is formally known as a base graph. The base graph has two types whose usage is determined by the size of the code rate or information bit. The parity check matrix can be constructed through the base graph by replacing the nonzero entries with a Z × Z permutation matrix and the zero entries with a Z × Z zero matrix. During each cycle of decoding the layer, each check/variable node is evaluated sequentially.

Contrarily, the flooding schedule updates messages for all check nodes concurrently (in parallel) during the first half of the decoding process and the opposite for all variable nodes simultaneously during the second half. Although it is not parallelized as a flooding schedule, layered decoding often speeds up convergence in terms of iterations of decoding. The like nodes from each protograph copy can be processed simultaneously without affecting the layered decoding performance. Such types of parallelism have a critical effect on high throughput. In addition, the identity matrix of the QC-LDPC code permutation is circularly shifted. A single number can represent each permutation when a permutation matrix with a circularly shifted identity matrix is used. This will make employing a straightforward switch network easier for the encoding and decoding process and decrease the amount of RAM needed to implement it [29]. About 51 lifting sizes (Z) are included in the 5G specification, with eight permutation matrices per base graph. These lifting sizes and permutation matrix designs are presented in Table 1.

5.2. Base graph Design

To ensure that LDPC codes function better, base graph design is similarly as essential as shift values. The base graph regulates the improved local connection between check nodes and variables. We need to discuss the LDPC codes' capacity and achievability before going into the detail of the base graph design of 5G LDPC codes. However, these codes promised to improve the capacity of MBIOS channels. The variable ($\lambda(x)$) degree distribution and check nodes ($\rho(x)$) are shown in Equation 4 and Equation 5, respectively.

$$\lambda(x) = \sum_i \lambda_i \times x^{i-1} \quad (4)$$

$$\rho(x) = \sum_i \rho_i \times x^{i-1} \quad (5)$$

The edges' fraction linked to the variable or check node is represented by $\lambda_i(\rho_i)$ with i degrees. The $\lambda(x)$ and $\rho(x)$ defined the standard ensemble as the LDPC code ensemble. If they contain a single term, it is referred to as regular and it is referred to as irregular otherwise. Unfortunately, a traditional ensemble cannot attain the MBIOS channel capacity until the parity check matrix density increases to infinity compared to code length. However, such an unfavorable finding does not always true when the standard ensemble is modified. By inserting punctured variable nodes or various edge types, such as the proportion of accumulator in IRA codes [30], several LDPC codes [31, 32] are proposed to provide MBIOS channel capacity with finite density.

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5.3. Quasi-cyclic Low-density Parity-check (QC-LDPC) codes

QC-LDPC codes are the enhanced standard 5G codes for mobile broadband data channels [33]. These codes support rate-compatible properties [34] and multiple lifting sizes and have adapted well to the various code rates and information lengths. QC LDPC codes. These codes are investigated extensively and are used in numerous applications in storage systems and digital communications [35-37] because of their simple hardware implementation, lower error floor, and fast decoding convergence. The channel coding strategy for 5G eMBB data channel communication is considered QC-LDPC codes [38].

5.4. AR3A and AR4JA Codes

Abbasfar introduced the Accumulate Repeat and Accumulate (ARA) codes, a subclass of LDPC codes [39, 40]. These codes were proposed because of their simple encoder sub-structures and efficient decoding performance. AR3A codes use repetition-3 and are suitable for LDPC structures. From the AR3A protograph, it can be seen that the variable nodes of degree 1 are introduced by means of an inner accumulator. AR4JA codes are ARA codes with repetition 4 in them. AR4JA codes should achieve better error floor performance and a higher minimum distance. The experimental section will present a comparison of performance between regular LDPC codes, AR3A codes, and AR4JA codes.

6. 5G Polar Codes

A polar code (represented by (N, K)) has K (NR) no of inputs and N number of outputs with code rate R. An encoder of length N will be used for encoding the 5G polar codes, While the remaining inputs (N-K) Consider a polar code (represent-ed by (N, K)) with K (NR) inputs and N outputs and a code rate of R. An encoder of length N will be used for encoding the 5G polar codes. In contrast, the remaining inputs (N–K) are held constant (frozen). By selecting A for any subset of k, where k = 1, 2,..., N, a polar code (N, K) can be generated. However, to get an efficient code, we must choose A carefully. In order to select option A, all GN inputs without frozen bits will be imagined, and the probability of a decoding error will be determined for each input. The input set with the lowest error probability, A, will be selected as the input set for optimizing the polar code for W. 5G polar codes can have code lengths of 2n for $5 \leq n \leq 10$ for uplink. While $7 \leq n \leq 9$ for downlink. For the uplink, 5G polar codes can have code lengths of 2n for $5 \leq n \leq 10$, while $7 \leq n \leq 9$ is often used for downlink. We have attained the MBIOS channel capacity using SC decoding polar codes [41]. For decoding polar codes, use the Successive Cancellation (SC) decoder. For each encoder, the input bit u_i with polar codes [41].

7. Reed-Muller Codes

The Reed-Muller (RM) codes were initially introduced in 1956 by Muller [42] and are mainly used in deep-space commu-nication. Assume G represents the nth order generator matrix for RM codes with N = 2n blocks as shown in equation 8.

$$G(n, n) = F\oplus n \tag{8}$$

where,

$$F = \begin{vmatrix} 1 & 0 \\ 1 & 1 \end{vmatrix} \tag{9}$$

Where F⊕n represents the nth tensor power of F, as shown in equation 9. The RM code (r^{th} order) can be obtained as a linear code with the generator matrix G(r,n) [51,52]. The G(r,n) matrix can be calculated by taking the rows of G(n,n) and $2^{n-r} \leq$ Hamming weights, as shown in equation 10.

$$G(3,3) = \begin{vmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{vmatrix} \tag{10}$$

While RM (1,3) is a reed muller code with the generator matrix G(1,3) as shown in equation 11.

$$G(1,3) = \begin{bmatrix} 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \tag{11}$$

RM decoders are categorized into two parts: non-iterative and iterative decoders. The Dumer recursive list decoding algorithm [43], known as SCL decoding, is the most well-known RM decoder for an additive white Gaussian noise channel. Recently, a new decoding algorithm, Recursive Projection Aggregation (RPA) decoding, was proposed in [44].

8. Convolutional Codes

Convolutional codes are error-correction code in which output bits are determined by performing a logical operation on the present bitstream with the previous bits. This code uses A shift register to temporarily store the bits with shifting operations and an XOR logic circuit. The two main parameters of convolutional coding are constraint length and code rate. The constraint length is the window size (in bits) inside the shift register or the encoder's length. However, equation 12 gives the code rate (r_c) while code rate is the proportion of bits in the encoded bitstream to bits shifted all at once in the shift register (k)/(n).

$$r_c = \frac{k}{n} \tag{12}$$

In a convolutional encoder, there are two states, x[n-1] and x[n-2], and the input bit x[n]. The encoder bits X_1 and X_2 are obtained from an XOR operation and shown in Equation 13 and Equation 14.

$$X_1 = x[n] \oplus x[n-1] \oplus x[n-2] \quad (13)$$

$$X_2 = x[n] \oplus x[n-2] \quad (14)$$

Convolution codes are a coding error technique commonly used in communication systems. It encodes certain replicated data into messages and enhances the efficiency of the network's data. Furthermore, it is a fast-coding technique with good results and limited integration costs [55]. However, this technique is computationally intensive and fails to fix explosion errors without interleaving. The complexity and performance of convolutional codes were compared in the literature [45-47]. However, literature [48, 49] investigated convolutional code applications.

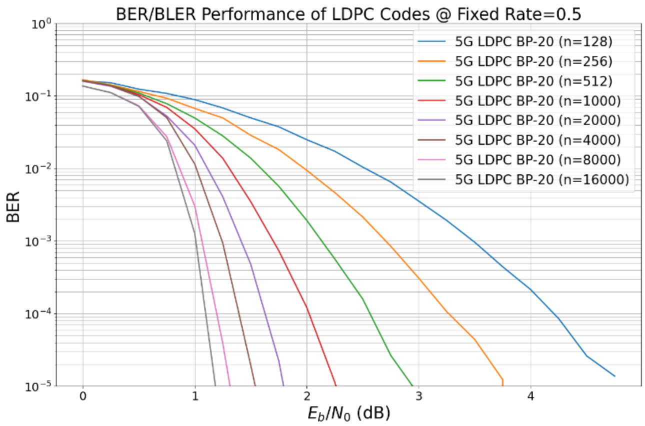

Figure 3. BER/BELR Performance of LDPC codes @ Fixed Rate = 0.5.

9. Experimental Results

This section offers a comparative study of these codes to highlight the justifications for choosing LDPC, polar, Reed-Muller, and/or convolutional codes. The BER performance for a fixed half-rate LDPC code with a varying number (n) of inputs is presented in Figure 3. It is plausible that the larger the number of input bits to the LDPC encoder, the better the performance of that variant in terms of BER. Figure 4 gives the performance of the bit error rate of LDPC codes on an AWGN channel with a fixed rate of 0.5 for different code length values (n).

Figure 5 presents an EXIT chart analysis of LDPC codes. It is viable that the EXIT curves meet after a few iterations at the point of convergence, showing that the LDPC codes can attain an infinitesimal BER. Figure 6 compares the BER curves of LDPC with those of polar SC and SCL-8+CRC, Reed-Muller, and convolutional codes. The evaluation is performed regarding BER vs. SNR for larger block codes. The simulation results show that 5G LDPC codes provide better BER than polar, Reed-Muller, and convolutional codes.

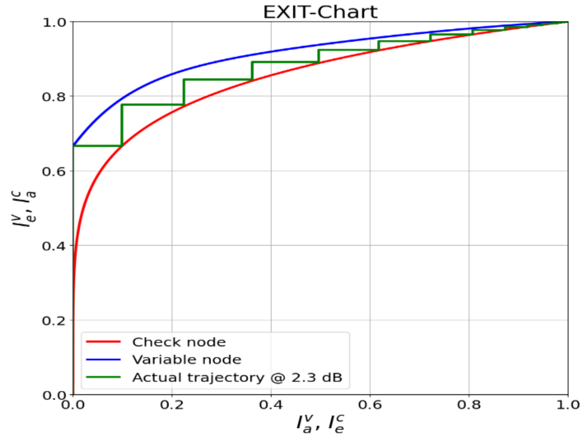

Figure 4. EXIT Chart Analysis of LDPC Codes

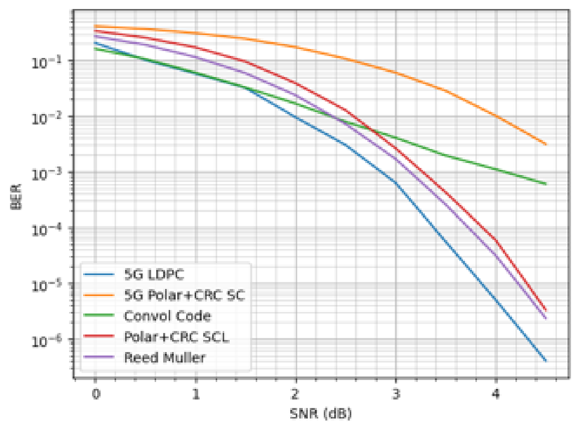

Figure 5. BER/BLER Performance of Larger Length Codes.

The result shows that the AR4JA for different decoding algorithms provided better performance and attained the error floor as compared to AR3A. Figure 7 presents the performance of Regular LDPC, AR3A, and AR4JA codes with family rates of 1/2 and 2/3 over the AWGN channel. It can be seen that the AR4JA sub-class outperforms the AR3A and regular LDPC codes for both 1/2 and 2/3 overall code rates.

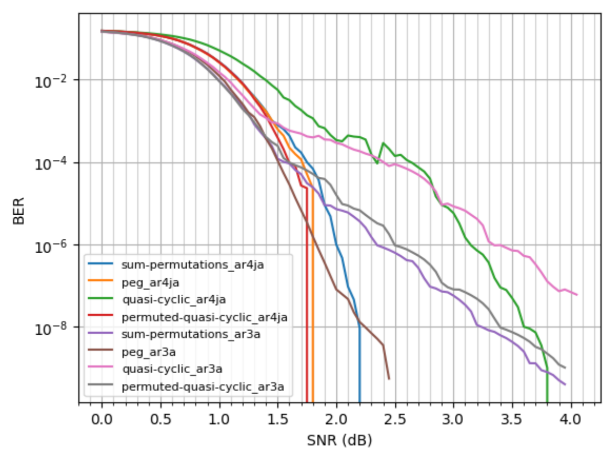

Figure 6. Comparison of Performance of PEG AR3A, PEG AR4JA, Quasi cyclic AR3A, Quasi cyclic AR4JA, Permuted quasi-cyclic AR3A, and Permuted quasi-cyclic AR4JA.

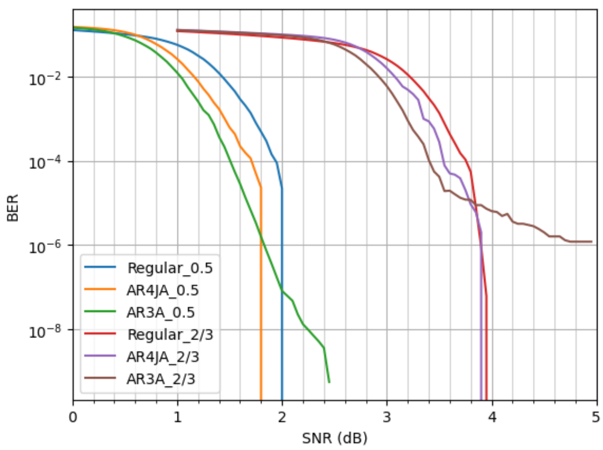

Figure 7. Performance of Regular LDPC, AR3A, and AR4JA codes family over AWGN channel.

9. Conclusion

The results of this paper shed light on the trade-offs between different codes for 5G wireless communication, aiming to enhance the speed, capacity, and reliability of wireless networks and enable a higher number of devices to connect to the internet. The paper evaluates the performance of 5G LDPC codes and compares them with various error-correction coding schemes such as convolutional, Reed-Muller, and polar codes (SC and SCL). The experiment considers state-of-the-art codes.

The efficiency of a coding scheme in correcting a maximum number of errors in a wireless communication setup determines its effectiveness. The tested coding schemes show comparable performance. However, the simulation results demonstrate that LDPC codes outperform convolutional, polar, and Reed-Muller coding schemes for larger block-length codes. Additionally, it is observed that a subclass of LDPC codes, specifically AR4JA, performs better than regular AR3A codes. All the decoding algorithms for ARJ4A achieve a bit error rate (BER) floor level of 10-9.

In conclusion, the comparison of error correction codes (ECCs) in this study highlights that while all codes offer some level of error protection, their effectiveness varies depending on different circumstances. Therefore, selecting the most suit-able code for a specific application is crucial based on its ability to detect and correct errors. Future work could explore further optimizations and advancements in 5G wireless communication error-correction coding schemes.

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