Performance analysis of LDPC and Polar codes for message transmissions over different channel models

Darija Čarapić, Mirjana Maksimović and Miodrag Forcan

***Abstract*— The realization of a wireless communication system that will meet the demands of the modern world in terms of fast, secure, reliable, and cost-effective information exchange, is a challenging task. Having in mind that the transmission of data takes place in an imperfect channel environment where noise, fading, and interference are present, the achievement of timely communication with a minimum of errors during data transfer requires the right choice of the channel coding scheme. Channel coding is a fundamental component of the communication system and is intended to ensure that the information received is the same as the sent one. Two coding schemes are available in the fifth generation of mobile communications (5G): Low-Density Parity-Check (LDPC) codes for coding user information and Polar codes for coding control information. This paper presents a comparative simulation study of LDPC and Polar codes for message transmissions over different channel models (Additive White Gaussian Noise (AWGN), Rician, and Rayleigh). The Bit Error Rate (BER) performance of these codes was reviewed for all three channel models. The simulations considered variable message sizes and code rates for LDPC and Polar codes, different modulation patterns for LDPC codes, and different decoding schemes for Polar codes. The results of the simulations showed the performances of the LDPC and Polar codes in the case of channel models: AWGN with no fading and AWGN with fading. The LDPC codes have been superior in the case of long messages and the Polar codes have been more efficient in the case of short messages, hence justifying the use of both LDPC and Polar codes within the 5G.**

***Index Terms*— LDPC, Polar, BER, AWGN, Rician, Rayleigh**

I. Introduction

A communication medium is prone to errors due to random noise, interference, fading, device impairments, etc. Channel impairments lead to the corruption of the original data flow, so the data on the receiving side is not the same as the data that was sent. To correct the errors made during data transmission, channel coding is applied. This means that on the transmitter side, the original data flow is subjected to a series of algorithmic operations (channel encoding). On the receiver side, channel decoding is done by applying other operations set to correct errors. It is obvious that the choice of an adequate coding scheme is of paramount importance for the rapid and reliable transmission of data. Enhanced flexibility, low computation complexity, low latency, low cost, and high reliability are desired features for the coding scheme [1, 2].

In contrast to the previous generations of mobile communication systems (3G and 4G), which used Turbo code as a channel coding technique, the fifth generation of mobile communications (5G) introduces two coding techniques: Low-Density Parity-Check (LDPC) and Polar codes. The reasons Turbo code is not chosen for the 5G are numerous iterations and a significant delay in decoding. As such, Turbo codes are unable to meet the demands of 5G networks in terms of high speed and low delay. LDPC and Polar codes are chosen as 5G channel coding standards due to their features and because the unique coding technology can no meet the needs of all scenarios and users in 5G. LDPC codes have better band utilization, and they perform better for longer block lengths in comparison with Polar codes that are superior for shorter block lengths. Furthermore, compared to other codes, LDPC codes have better decoding latency, throughput, and implementation while Polar codes are simple to implement, can reach the channel capacity and have low encoding and decoding complexity [3]. According to 3rd Generation Partnership Project (3GPP) 5G New Radio (NR) standardization, LDPC coding scheme is proposed for use in data channels while Polar codes are applied in control channels [4].

This paper presents an attempt to simulate the performances of LDPC and Polar codes in the case of different channel models (Additive White Gaussian Noise (AWGN), Rician fading + AWGN, and Rayleigh fading + AWGN) in order to summarize the advantages and disadvantages of 5G channel coding techniques. A comparative simulation study is performed for variable message sizes and code rates. Moreover, different modulation schemes were analyzed in the case of LDPC codes as well as different decoding schemes for Polar codes.

Therefore, the paper is organized in the following manner. A short overview of communication channel models is presented in Section II. Section III presents 5G channel coding schemes while the results of simulations (Bit Error Rate (BER) vs Signal-to-Noise Ratio (SNR) graphs) are given in Section IV. A summary of the performed research and directions for future research are provided in the Conclusion.

II. Communication channel models

The theory of communication is often based on the assumption that the transmitted signals are distorted by a certain noise. The most commonly used noise assumption is additive, white, with Gaussian-distributed values. The

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model of AWGN channel is used to simulate the influence of naturally occurring random signals on wireless signals. It typically represents the background noise, amplifier noise in the transceivers, and signals from other communication systems in the frequency bands [5].

It is important to highlight that fading, frequency selectivity, interference, non-linearity, or dispersion are not considered in the AWGN channel model what makes it unrepresentative for most wireless connections. A more realistic scenario of wireless channels is the availability of multiple paths between transmitters and receivers. These routes can be direct or formed through reflection, diffraction, or scattering. In this case, the receiver receives distinct copies of the sent signal (with variable attenuation, delay, or phase shift) [6, 7]. Rayleigh distribution (for the scenario when no Line of Sight (LoS) component is present) and Rician distribution (when LoS component is present) are often used to represent multipath fading in wireless communication systems. In the Rician channel model, a receiver receives a direct LoS signal from the source in addition to the other non-LOS components. Rayleigh fading is considered as a special case of Rician. The receiver cannot receive any LoS signal directly from the source. All incoming signals are diffracted, reflected, or diffused. Rayleigh fading channel model is the right choice when there are several objects in the surroundings that scatter the signal before it reaches the receiver [8].

III. 5G Channel coding schemes

Data transmission over the wireless communication link that is subject to interference and fading can result in the data received is different than the data sent. In order to overcome this problem, additional information is added to the data sent by the transmitter. At the receiver side, complex schemes that need sophisticated algorithms decode this information and retrieve the original data. This process is called Forward Error Correction (FEC) or channel coding and has an immense role in increasing the performance of wireless communication systems.

3GPP 5G NR brings requirements to channel coding at a completely new level. 5G is designed to serve a wide range of applications: enhanced mobile broadband (eMBB), ultra-reliable and low-latency communication (URLLC), and massive machine-type communication (mMTC) [9].

5G introduces the two capacity-achieving channel coding schemes, LDPC and Polar codes, not used in earlier generations of mobile communication systems. Hence, in the 5G communication systems, the channel coding has been separated into channel coding of user information (LDPC coding) and channel coding of control information (Polar coding).

A. LDPC codes

LDPC codes are a sort of linear block code first proposed by Gallager in the early 1960s [10] and rediscovered in the late 1990s thanks to MacKay [11, 12]. The name of these codes comes from the fact that their parity-check matrix is largely zeros (0s) with a minor number of ones (1s). LDPC codes can be described via matrices or represented graphically (Tanner graphs). There are two basic graphs and eight sets of lifting sizes in the 5G NR, hence allowing a variety of block lengths and coding rates. Graph structure sparsity has a strong influence on the algorithmic efficiency of LDPC codes. According to [13], it is not difficult to construct effective LDPC codes. Actually, the random codes have a high probability of success. The issue is that the encoding complexity of these codes is typically quite high. Decoding algorithms for LDPC codes are relatively simple and practical. The belief propagation algorithm, the message passing algorithm, and the sum-product algorithm are the most commonly used [13, 14]. The main advantages of LDPC codes are good block error performance, error floors in much lower BER values, the ability to achieve good error performance without requiring interleavers, and an iterative-based decoding process [15]. Because LDPC codes perform close to a channel's Shannon limit only for long block lengths, they are well suited for use in 5G NR for user data transmission.

3GPP specifies LDPC coding chains for the 5G NR downlink shared transport channels (DL-SCH) and uplink shared transport channels (UL-SCH) [4]. In 5G NR, data are transmitted in units referred to as transport blocks. The term "transport blocks" refers to data sent from the Medium Access Control (MAC) layer to the physical layer. A transport block goes through the processing steps shown in Fig. 1 before transmitting to the Physical Downlink Shared Channel (PDSCH) for scrambling, modulation, layer mapping, and resource/antenna mapping.

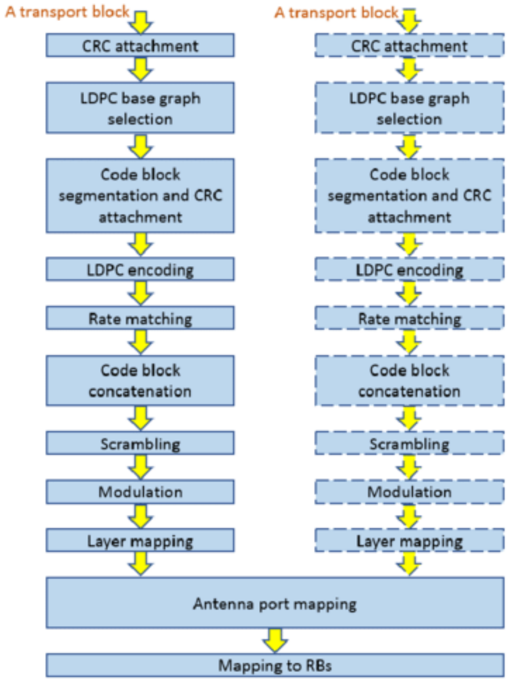


Fig. 1. 5G NR PDSCH physical layer processing [16]

PDSCH is used for a variety of data transmissions, including downlink user data, user equipment specific higher layer information, system information blocks, and paging [16]. Depending on the link conditions, the PDSCH employs an adaptive modulation format (QPSK, 16-QAM, 64-QAM, and 256-QAM). It also employs a flexible coding scheme. When these elements are combined, it results in a flexible coding and data rate [17]. The Physical Uplink Shared Channel (PUSCH) is the PDSCH's counterpart. PUSCH transmits an uplink shared channel (UL-SCH) and its higher mapped channel data. The physical layer of an uplinked transport block is processed similarly to that of a downlinked transport block (Fig. 2). PUSCH also has a very adaptable format. Frequency resources are allocated using blocks of resources as well as a flexible modulation (pi/2-BPSK, QPSK, 16-QAM, 64-QAM, and 256-QAM) and coding scheme depending on the link conditions [16, 17].

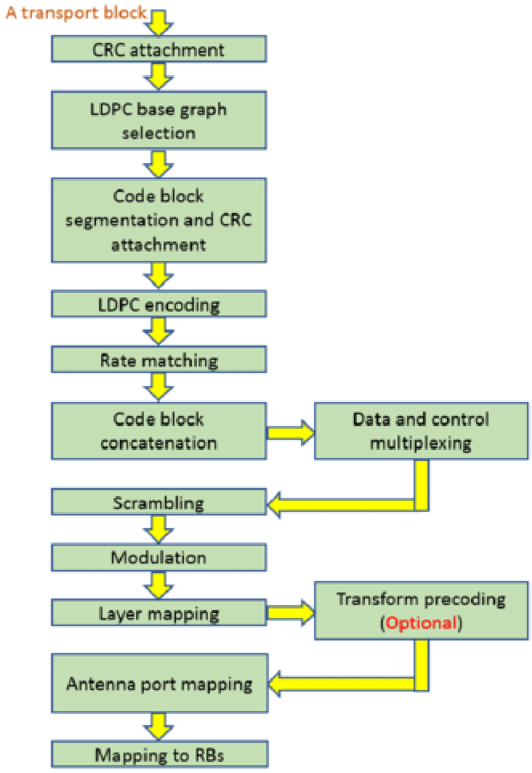


Fig. 1. 5G NR PUSCH physical layer processing [16]

B. Polar codes

Polar codes are another official channel coding scheme accepted in 5G standardization. The idea behind Polar codes, introduced by Arikan [18] in 2009, is to subdivide the original channel into a number of virtual channels, each of which is purely noisy or noiseless. By sending data over noise-free channels while the fixed bits, which are known at both the encoder and decoder, are sent over noisy channels, nearly error-free transmission is possible [19]. Polar codes are applied as channel codes for 5G NR control channels (Physical Downlink Control Channel (PDCCH) and Physical Uplink Control Channel (PUCCH)) where blocks of information are small, and the Hybrid Automatic Repeat Request (HARQ) is not used [14].

As indicated by the name, the 5G PDCCH transports downlink control information (DCI). Its main function is to schedule downlinking transmissions on the PDSCH as well as uplinking data transmissions on the PUSCH. With the exception of small data packets, the PDCCH employs QPSK as a modulation format and Polar coding as a coding scheme [17]. 5G NR PDCCH physical layer processing steps are shown in Fig. 3. It is important to point out that for downlink transmission, the size of the transport block is limited to 36-164 bits (interleaver limit).

The main purpose of PUCCH is to carry Uplink Control Information (UCI) such as HARQ feedback, channel state information, and scheduling request. The PUCCH employs BPSK or QPSK as a modulation format. As a coding scheme, PUCCH uses Polar coding. In the uplink transmission, the size of the transport block is limited to 31-1024 bits. If the payload size is greater than or equal to 1013 bits, code block segmentation for uplink is carried out [16].

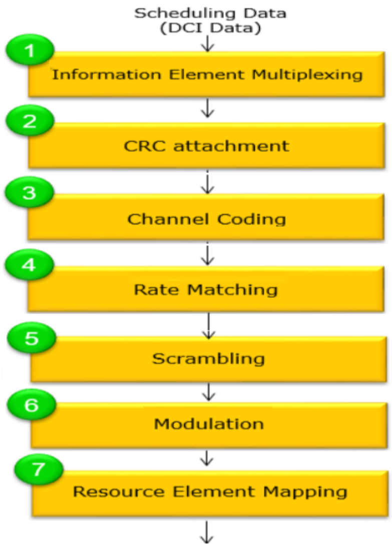


Fig. 3. 5G NR PDCCH physical layer processing [20]

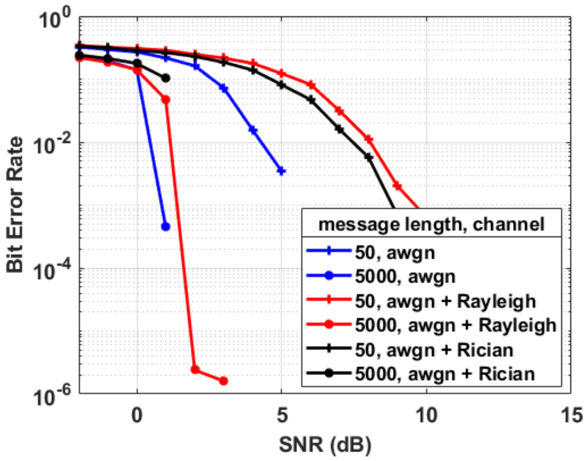
As a starting point for Polar decoding, Arikan proposed decoding using successive cancellation (SC). Despite the advantage of low complexity, it is not adequate for block lengths ranging from short to medium. This problem can be solved by using the successive cancellation list (SCL) decoding algorithm. The SCL decoder uses a list size parameter L (the number of decoding paths that are most likely to be retained) to decode the input bits one by one. In 5G error-correction performance evaluations, Cyclic Redundancy Check (CRC)-aided SCL has been used. Although SCL's effectiveness increases as the list size parameter L increases, so does its implementation complexity. SCL becomes SC when L is set to 1 [14, 21].

IV. 5G Channel Coding Schemes' BER Performance

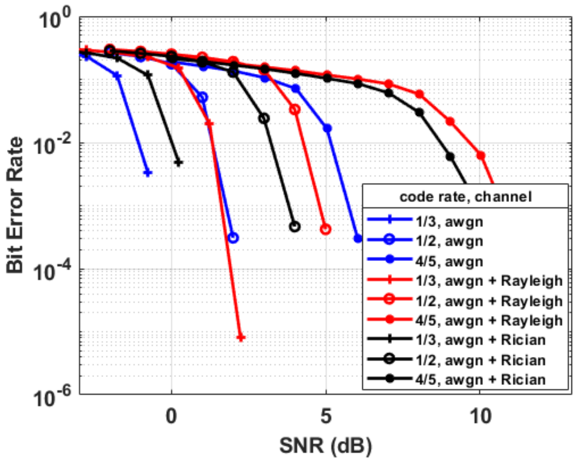
The MATLAB R2020a software package [22] was used to simulate the 5G physical communication layer with LDPC and Polar coding schemes. The downlink and uplink coding schemes are implemented in accordance with 3GPP regulations [4]. The performance of BER is analyzed for different message lengths (50, 500, 5000, and 50000 bits) and variable code rates using different communication channels: AWGN, Rician, and Rayleigh. The variances of AWGN channel model are estimated using SNR values. In the case of fading presence, a fading channel block was accompanied by the AWGN channel block that had previously been used. Fading channel property values used in simulations are: sampling rate: 10^5 [s]; path delays: 0, 10^{-7} and 10^{-5} [s] (for the outdoor environment); average path gains: 0, -3, and -3 [dB]; a maximum Doppler shift of 0; and the Rician K factor is set to 3 (K is the power of the LoS component divided by the power of the scattered components) [14, 23]. BER is calculated and plotted against the SNR. Each simulation was performed for 500 frames and continued until the BER of 10^{-6} is achieved. QPSK has been used in all simulations [23].

A. LDPC codes

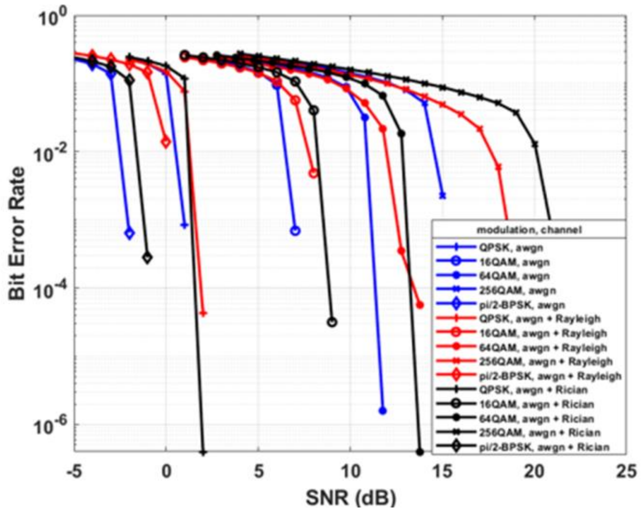
Fig. 4 shows BER vs SNR graph for LDPC coded uplink transmission (quite similar simulation results are obtained for downlink transmission). Fig. 4. a) presents BER performance for messages of different lengths (50 bits and 5000 bits). The selected code rate is ½. As can be seen, for the longer message LDPC shows better performance. BER performance for different code rates is given in Fig. 4. b). The simulation is performed for 500 bits long message in the uplink direction. Simulation results demonstrate that the lowest code rate means the longest coded word and better BER performance. Since LDPC codes show better performance for longer words, Fig. 4. c) presents BER vs SNR graph for 5000 bits long message in case of different modulation techniques. In uplink directions, pi/2-BPSK, QPSK, 16-QAM, 64-QAM, and 256-QAM modulation schemes are supported while the opposite direction supports QPSK, 16-QAM, 64-QAM, and 256-QAM modulation schemes. Obtained results show the best performance for pi/2-BPSK and QPSK modulation schemes. Since pi/2-BPSK is not supported in both directions, all other simulations have been performed using QPSK modulation scheme.



a) variable message length (code rate=1/2);



b) variable code rates (message length =500 bits);



c) different modulation techniques (message length =5000 bits)

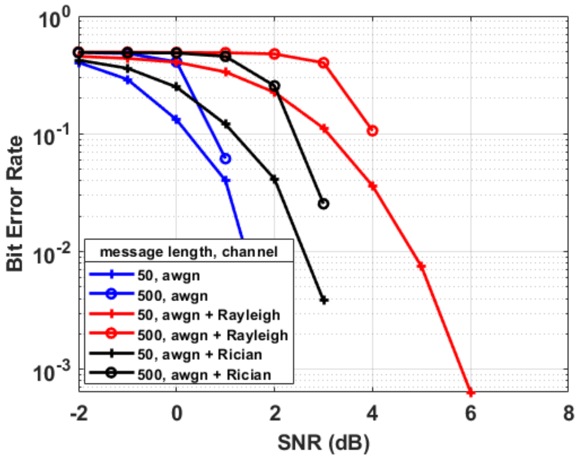
Fig. 4. BER performance for LDPC coded uplink data transmission

The common feature of all three graphs in Fig. 4 is that the AWGN channel model achieves the best performance, and the Rayleigh channel model achieves the worst. This is because the performance of the BER is considerably improved in the case of low SNR, but not in the case of high SNR. White Gaussian noise dominates the BER error when SNR is low. In this case BER performance can be improved by increasing SNR. However, when the SNR is high, the phase estimation error dominates the BER error. Simply increasing the SNR will not improve BER performance in this case [8].

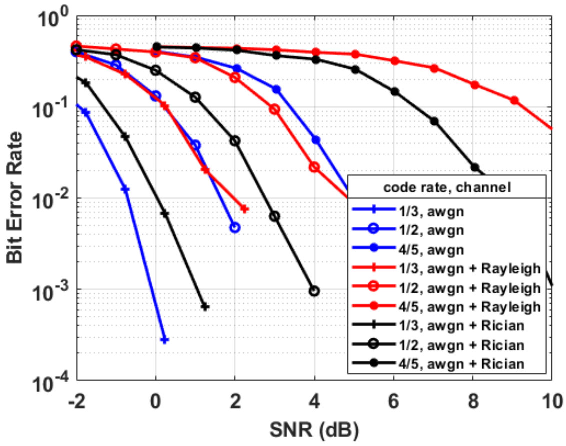
B. Polar codes

A similar simulation study was also conducted in the case of Polar codes. Fig. 5 shows the BER vs SNR graphs for uplink transmission of Polar coded messages. Fig 5. a) considers different message lengths (50 bits and 500 bits). Uplink transmission of a longer message is not supported according to 3GPP (the maximum size of input length is 1023 bits). Among selected message lengths, BER performance simulation in downlink directions can be done only for a 50 bits long information message since the maximum input length is 164 bits. Fig. 5. a) results have been achieved for code rate = 1/2. As can be seen, opposite to LDPC, Polar codes show better performance for shorter messages. Since Polar codes show better performances for a shorter message, Fig. 5. b) shows the BER performance for 50 bits long message in case of different code rate values. The best results are achieved for the lowest code rate. Fig. 5 c) shows the simulation results for the CRC-aided SCL decoding algorithm. Variable list sizes *L* (4, 16) have been considered for code rate = 1/2. Results confirm that the larger list size *L* means enhanced Polar coding performance (lower error rate), but implementation complexity increases with higher *L* values.

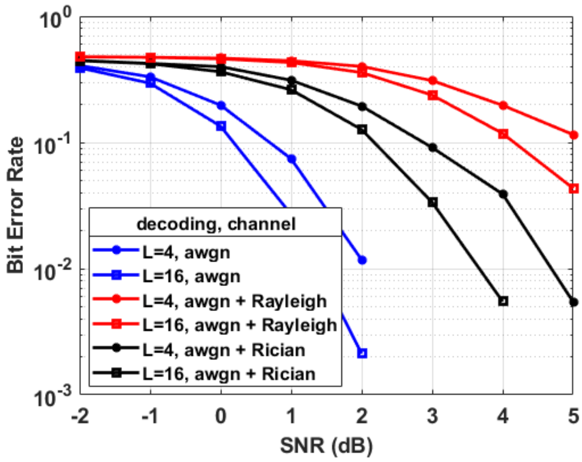
The same as in the LDPC case, the best simulation results are achieved for the AWGN channel. The Rician channel model outperforms the Rayleigh use case in terms of BER.



a) variable message length (code rate=1/2);



b) variable code rates (message length =500 bits);



c) different *L* values (message length =50 bits)

Fig. 5. BER performance for Polar coded uplink data transmission

C. LDPC vs Polar codes

Fig. 6 demonstrates a comparison of LDPC and Polar coding techniques in both directions. Fig 6. a) shows BER vs SNR graph for uplink data transmission of 50- and 500 bits messages. Simulation results are achieved for code rate = 1/2, and show that LDPC codes have better performances for longer messages while Polar codes are superior in the case of short messages. Fig. 6 c) considers downlink transmission and knowing that the information message length, in this case, is limited to 164 bits, comparative analysis has been performed only for 50 bits long message. Polar codes outperform LDPC codes because messages are shorter. Fig 6. b), and d) present BER performance for 50 bits long message in case of variable code rates in both directions. For 50 bits long message, Polar codes are better than LDPC in both uplink and downlink directions and at lower code rates show better performance. Following the results from Fig. 6 a), it is evident that the LDPC would have better performance in the uplink transmission of a longer message. In all simulations, the best results are achieved for the AWGN channel model. When comparing fading channel models, the Rician channel model shows better performance in comparison with the Rayleigh channel model.

V. CONCLUSION

Recognizing the importance of selecting the right channel coding scheme to ensure fast and error-free transmission of data, this paper presents an attempt to conduct a comparative simulation study of 5G channel coding techniques. The performance of the LDPC and Polar codes is studied for three channel models (AWGN, Rician, and Rayleigh) taking into consideration the size of the messages and variable code rates. Performance of 5G channel coding techniques is measured by their ability to correct errors at a given SNR. The results have confirmed LDPC codes' superiority for longer messages and Polar codes' superiority for short messages. In this way, using LDPC codes in data channels and Polar codes in control channels is justified. In addition, for lower SNR values, Gaussian noise dominates the BER error and just improving the SNR, BER error can be improved. For higher SNR values, this cannot be performed as the phase estimation error dominates the BER error. That is why the simulation results have shown that BER performance of the AWGN channel model is better than for fading channel models. Apart from measuring the performance of a channel coding techniques via BER vs SNR graphs, it is also important to analyze the maximum possible throughput, latency and the resources and power consumption. This is the direction of our future research.

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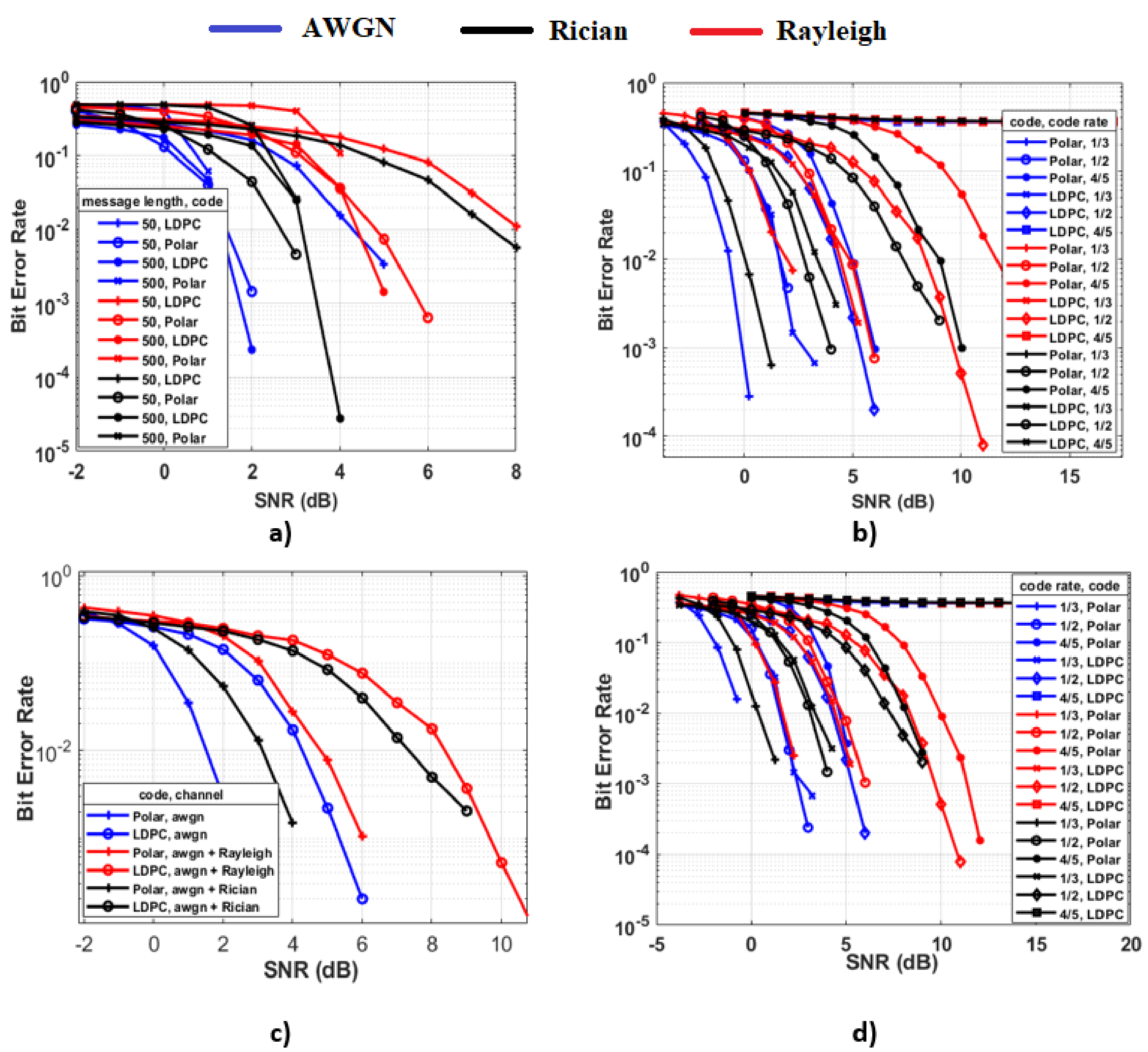

Fig. 6. BER performance – LDPC vs. Polar codes: a) variable message length (code rate=1/2) - uplink; b) variable code rates (message length =50 bits) - uplink; c) message length 50 bits (code rate=1/2) - downlink; d) variable code rates (message length =50 bits) – downlink.

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