Performance Evaluation of Polar Coding Schemes for 5G Wireless Communication Networks

Genet Gebretsadik Gebrealif

A Thesis Submitted to

The Department of Electronics and Communication Engineering
School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Electronics and Communication Engineering

(Communication engineering)

Office of Graduate Studies
Adama Science and Technology University

June 2023

Adama, Ethiopia

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DECLARATION

I declare that this thesis entitled **"Performance Evaluation of Polar Coding Schemes for 5G Wireless Communication Networks"** is my own work and has not been submitted to any university for a similar purpose. The references used in this thesis are duly recognized by proper citations.

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LIST OF ACRONYMS

5G	5 Generation
AWGN	Additive White Gaussian Noise
ARQ	Automatic Repeat Request
B-DMC	Binary Discrete Memoryless Channel
BER	Bit Error Rate
BPSK	Binary Phase Modulation
CRC	Cyclic Redundancy Check
CRC-A-SCL	Cyclic Redundancy Check Aided Successive Cancellation List
CRC-A-I-SCL	Cyclic Redundancy Check Aided Interleaved Successive Cancellation list
DCA	Distributed Cyclic Redundancy Check Assisted
eMBB	Enhanced Mobile Broadband
FAR	False Alarm Rate
FECC	Forward Error Control Coding
FER	Frame Error Rate
I-CRC-A-SCL	Interleaved Cyclic Redundancy Check Aided Successive Cancellation list
I-CRC-A-I-SCL	Interleaved Cyclic Redundancy Check Aided Interleaved Successive Cancellation list
I-SC	Interleaved-Successive Cancellation
LDPC	Low-Density Parity Check
LLRs	Logarithmic Likelihood Ratios
LTE	Long Term Evolution
mMTC	Massive Machine Type Communication
NR	New Radio
PCC	Parity Check Concatenated
SC	Successive Cancellation
SCL	Successive Cancellation List
SNR	Signal To Noise Ratio
URLLC	Ultra-Reliable Low Latency Communication
UMTS	Universal Mobile Telecommunication System

ABSTRACT

Today's technology for 5G wireless connectivity is expanding quickly. Due to randomly occurring noise, interference, fading, device limitations, and other factors, the data delivered by the 5G wireless communication channel is vulnerable to error. Channel coding is an essential element for 5G wireless communication networks since it is used to address issues that arise during data transmission and reception in these networks. With outstanding error-correcting performance, polar coding is one of the best channel coding systems for 5G wireless communication networks. It can operate on binary memoryless symmetric channels. Successive cancellation (SC), successive cancellation list (SCL), and their modification are the most known polar decoding algorithms. In this work we have considered parameters such as bit error rate (BER) and frame error rate (FER) for different values of bit energy to noise spectral ratio (Eb/No), code rate, and list size to compare the performance of polar code with SC decoding, interleaving polar code with SC decoding (I-SC), cyclic redundancy check aided polar code with SCL decoding (CRC-A-SCL), interleaved cyclic redundancy check aided polar code with SCL decoding (I-CRC-A-SCL), cyclic redundancy check aided interleaved polar code with SCL decoding (CRC-A-I-SCL) and interleaved cyclic redundancy check aided interleaved polar code with SCL decoding (I-CRC-A-I-SCL) under BPSK modulation and AWGN channel model. We have also identified the most performance-affecting parameters such as code rate, CRC length, and list size by comparing the BER and FER. From the result of our work, CRC-A-SCL polar coding scheme has a BER value of 0.94%, I-CRC-A-SCL polar coding scheme has 0.45%, CRC-A-I-SCL polar coding scheme has 0.14%, and I-CRC-A-I-SCL polar coding scheme has 0.03% at Eb/No of 2.4dB, list size 8 and CRC length 16 over AWGN channel and BPSK modulation. From this result, I-CRC-A-I-SCL polar coding scheme has better performance and it is the best polar coding scheme for 5G wireless communication networks.

Keywords: Polar coding, BER, FER, 5G wireless communication networks

CHAPTER ONE

1. INTRODUCTION

1.1 Background of the Study

Nowadays 5G wireless communication is a fast-growing technology. The data transmitted over a 5G wireless communication channel is exposed to error due to unpredictable noise, interference, fading, device limitations, and other factors. This means data on the receiving side is not the same as the data that was delivered due to channel impairments that affect the original data flow. Channel coding is used to fix those problems produced during data transmission and reception in 5G wireless communication networks (Čarapić et al., 2021). Channel coding happens both at the transmitter side and receiver side. Channel coding at the transmitter side is known as the encoder and at the receiver side is known as the decoder. Shannon demonstrated in 1948 that error-free information can be transmitted over a noisy medium (channel) if the channel rate is less than or equal to the channel capacity. To develop the capacity for trustworthy codes that may be utilized in current communication technology, a significant amount of research has been done in the field of channel coding (Channels et al., 2023). The targeted characteristics of the channel coding include increased flexibility, reduced computation complexity, low latency, cheap cost, and high reliability (Čarapić et al., 2021). Polar code is one of the most powerful channel coding techniques that is chosen for 5G wireless communication networks due to its low encoding and decoding complexity, simplicity of implementation, and can extend the channel capacity (Čarapić et al., 2021). The polar coding scheme works based on the concept of channel polarization. Channel polarization divides the channel into two sets: one set, known as reliable channels, allows for the transmission of information bits; the other set, known as unreliable channels, allows for the transmission of frozen bits (Channels et al., 2023). The bit error rate, frame error rate, computational complexity, and delay at a specific signal-to-noise ratio all affect how well wireless communications work. The capacity of a channel coding solution to rectify errors at a specific Eb/No is what matters most. In this thesis, we have focused on the performance of evaluation of polar coding schemes for 5G wireless communication networks.

Channel coding aims to improve the performance of communication systems by using redundancy to reduce the impact of various channel impairments, such as noise and fading.

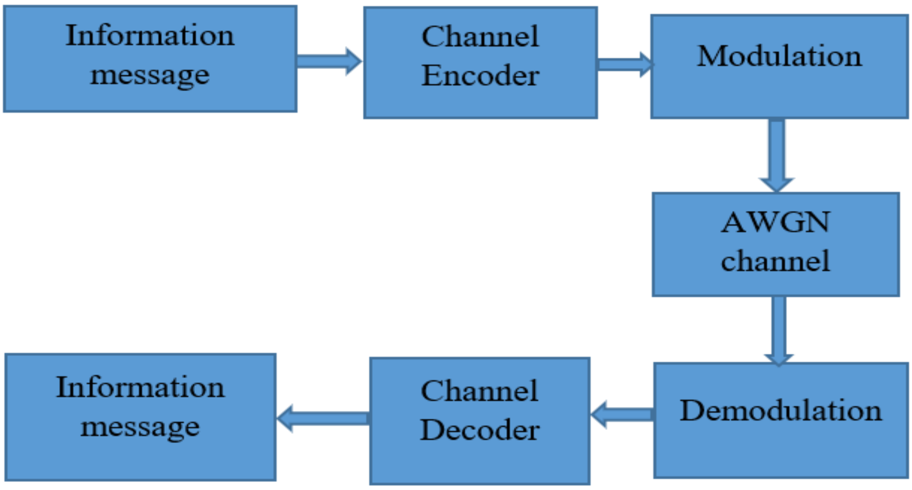

Figure 1.1 Digital communication model (Khan & Zhang, 2020)

To improve the performance of a communication system the main objective is the implementation cost. As the size and speed of digital data networks increase, bandwidth efficiency is important. This is the main goal of 5G wireless communication networks, where digital signal processing is evaluated by considering the bandwidth resources. In 5G wireless communication, polar coding forms a very valuable preprocessing step in the transmission of a digital bit stream. Because bandwidth is scarce and expensive, a coding technique that needs fewer redundant bits with better error correction and detection performance is highly preferred in 5G wireless communication networks. Channel coding eliminates channel errors based on the addition of redundancy bits. Redundancy can be used in two fundamental ways to manage errors (Faruque, 2016). Those are

- Automatic repeat request (ARQ)
- Forward error control coding (FECC)

In the ARQ method parity bits or redundant bits to the transmitted data stream to find errors in the data it receives. When the receiver notices an error, it asks for retransmission of the data. This keeps happening until the message is properly received. But this method of error detection needs a lot of bandwidth and also it cannot correct errors but only detection of errors (Faruque, 2016).

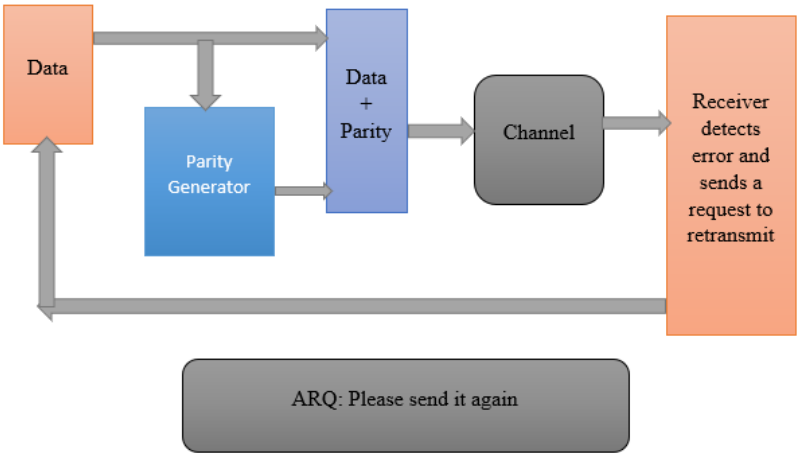

Figure 1.2 ARQ technique (Faruque, 2016)

In FECC codes, to enable the receiver to detect and fix errors, the data are encoded using redundant bits. Because these techniques are frequently employed to repair errors that are brought on by channel noise, this sort of error correction is sometimes referred to as "channel coding". All FECC methods aim to find and fix as many faults as they can without significantly affecting the data rate or bandwidth (Faruque, 2016). The redundant bits in polar coding are zero bits, but the main concern is the position of these bits. The position of these redundant bits is known by the transmitter side and receiver side.

1.2 Statement of the Problem

Wireless communication in a radio link or wireless channel is used to transfer bits of information among transmitters and receivers in communication systems. Due to some channel impairments such as interference, noise, and fading the received bits are in error compared to the transmitted bits. The received bits are subject to communication errors due to channel impairments. The primary objective of the 5G wireless communication networks is to transmit a low error bit for reliable communication. To improve the reliability of wireless communication systems channel coding plays a big role by reducing the bit errors formed during communication. The coming new generation is expanding to further improve the quality of 5G wireless communication networks by using channel coding. So, to improve the performance of 5G wireless communication networks polar coding plays an exceptionally large role with low encoding and decoding complexity. So, due to this, we are excited to work on the performance evaluation of polar coding schemes for 5G wireless communication networks by using comparative parameters like BER and FER.

1.3 Objectives

1.3.1 General Objective

The main objective of this thesis is the Performance Evaluation of Polar Coding Schemes for 5G Wireless Communication Networks.

1.3.2 Specific Objectives

- To compare and evaluate Successive Canceling (SC) polar coding schemes and Interleaved-Successive Canceling (I-SC) polar coding schemes.
- To analyze and compare Cyclic Redundancy Check (CRC)-Aided-Successive Cancellation List (CRC-A-SCL) polar coding schemes and Interleaved-CRC-Aided-Successive Cancellation List (I-CRC-A-SCL) polar coding schemes.
- To evaluate and compare Interleaved-CRC-Aided-Successive Cancellation List (I-CRC-A-SCL) polar coding schemes and Interleaved-CRC-Aided-Interleaved-Successive Cancellation List (I-CRC-A-I-SCL) polar coding schemes.
- To compare and analyze CRC-Aided-Interleaved-Successive cancellation List (CRC-A-I-SCL) polar coding schemes and Interleaved-CRC-Aided-Interleaved-Successive cancellation List (I-CRC-A-I-SCL) Polar coding schemes.

1.4 Significance of this Thesis Work

A key technological element of any wireless communication system is channel coding. Channel coding allows for the controlled addition of redundancies to the information bits on the transmitter side via an encoder and the exploitation of those added bits with the help of the decoder on the receiver side, allowing for the control and reduction of transmission errors. This study will be very useful for finding appropriate polar coding schemes for 5G wireless communication networks. And also, it will be useful for evaluating and comparing the error correction performance of Polar coding Schemes.

1.5 Scope of the Study

The scope of our work is confined to only analyzing the performance of polar coding schemes. Additionally, a comparison of the performance of the Polar coding schemes used in the 5G NR standard will be made to assess the performance of the Bit error rate and Frame error rate only. We have tried to compare the performance of six polar coding schemes depending on BER and FER only.

1.6 Main Contributions of this Thesis Work

This thesis is focused on the performance evaluation of polar coding schemes for 5G wireless communication networks. The performance metric parameters such as bit error rate and frame error rate for different values of Eb/No, code rate and list size are compared and evaluated for 5G wireless communication networks. The performance evaluation of the SC polar coding scheme, Interleaved-SC polar coding scheme, CRC-A-SCL polar coding scheme, interleaved-CRC-A-SCL polar coding scheme, CRC-A-Interleaved-SCL polar coding scheme, and Interleaved-CRC-A-Interleaved-SCL polar coding schemes is considered in this work.

1.7 Limitation of Our Thesis Work

In our thesis work the performance of polar coding schemes is evaluated and compared over AWGN channel and BPSK modulation. Our work is limited to only simulation-based study and also, we have used the parameters BER and FER only to evaluate the performance of polar coding schemes for error correcting capability and we have not considered how to error detection in our work.

1.8 Thesis Organization

This thesis is organized as follows; Chapter 2 presents the literature review and related works on the subject matter of our study. It provides a whole overview of the problems of the background. It refers to what research has already been done by others and has relevance to the present day. In chapter 3 materials and methods followed in this thesis research are described and at the last chapter 4, results and discussions are briefly presented. Finally Conclusions and recommendations for research work directions are offered in chapter 5 of the paper.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Channel Coding

Channel coding, also known as forward error control coding (FECC), is a mechanism for detecting and correcting bit errors in digital communication systems. Channel coding is performed both at the transmitter side and receiver side. Channel coding is known as an encoder on the transmitter side, where extra bits (parity bits) are added to the raw data before modulation and it is referred to as a decoder at the receiver end. This makes it possible for the receiver to identify and fix any transmission errors caused by noise, interference, or fading. Transmission of coded information requires more bandwidth because error control coding involves the addition of extra bits to detect and correct errors. The importance of bandwidth efficiency is growing as the size and speed of digital data networks increase. This is especially true for broadband communication, where digital signal processing is done keeping in mind the available bandwidth resources. Channel coding is a crucial preprocessing step in the transmission of digital data as a result (bit-stream). A coding method that uses fewer redundant bits without compromising error performance is greatly desired because bandwidth is expensive and in short supply (Faruque, 2016).

2.2 Channel Coding Techniques

2.2.1 Polar codes

Polar code was introduced by Arikan in 2008, it is a special class of error-correcting codes that can provably achieve channel capacity (Belhadj et al., 2021). The code belongs to the first family that can work with low decoding complexity O(NlogN), where N stands for the block length, to achieve maximum channel capacity on any symmetric binary-input discrete memory-less channel (B-DMC). Recursion is the basis of Polar Codes, which divide the primary channel Wn into virtual channels W1 and W2. Arikan demonstrated that the virtual channels tend to have either high or low reliability, with sufficient division recursion the cut-off rate would be higher on the virtual channel than the original channel. This indicates that the channels are either entirely noisy or noiseless, and data transmission should take place on the noiseless channels (Rosenqvist et al., 2019).

2.2.2 Low-Density Parity Check (LDPC) Codes

Low-density parity check (LDPC) codes are a family of error-correcting correcting codes that were introduced by R. Gallager in 1962 (Belhadj et al., 2021). Due to its practical implementation almost achieving the Shannon channel capacity of reliable transmission, LDPC codes are particularly effective codes. According to the Shannon channel capacity rule, as block length is increased, codes with code rates close to the capacity number result in errors going to zero when decoded using the maximum likelihood decoder. By employing random linear block codes that are represented as polynomials of time, this criterion can be satisfied. The problem of complicated calculation algorithms for encoding and decoding arises as we raise the block length for error near zero, and this ultimately forces us to compromise on performance. Hence, in this case, LDPC code successfully implements LDPC code at the Shannon limit with extended block lengths and also offers the additional benefits of simpler algorithms, faster processing, and higher accuracy (Pregara & Saigh, 2013).

2.2.3 Turbo Codes

A turbo code is a kind of channel coding method that was first developed by Berrou in 1993 for burst errors and is also intended for error correction. One of the greatest methods for channel coding error correction is turbo coding. This has resulted in a significant impact. Turbo codes are used to improve communication systems data transmission efficiency. Several space crafts use turbo codes, and universal mobile telecommunication systems (UMTS) and long-term evolutions (LTE) use them as well for high-speed communication. In the power-controlled system, communication channels are close to Shannon's limit, and effective communication is achievable. The purpose of channel coding is to transform data into code, allowing for the transmission of information via a communication channel. Even in the presence of noise, errors are identified and corrected (Pregara & Saigh, 2013). Turbo code is used in 3G and 4G systems. The reasons why Turbo code is not selected for 5G wireless communication networks due to more number of iterations and high decoding latency (Čarapić et al., 2021).

2.3 Channel Coding Overview for 5G Use Case Aspect

The next generation of mobile communication networks, known as 5G New Radio (NR), is anticipated to meet the growing demand for improved mobile connectivity and open the door for a wide range of new mobile services. According to its specifications, 5G NR should be able to provide data transfer with a latency of less than 1 microsecond and peak download speeds of 20 Gbps (Indoonundon & Pawan Fowdur, 2021).

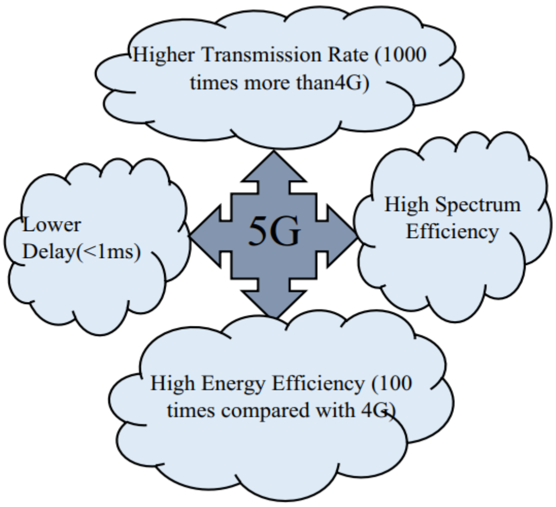

Figure 2.1 5G requirements (Arora et al., 2020)

2.4 Channel Coding Challenges of 5G Networks

The selection of channel codes for 5G has been the subject of extensive research over the past ten years. LDPC for the data channel and polar codes for the control channel has already been chosen as the channel codes for eMBB (Zhu et al., 2018). Those are some challenges of 5G channel coding schemes Throughput, Latency, Error correction capabilities, Flexibility, and Computational Complexity.

2.6 Polar Encoding

Arikan has discovered a completely new effect called channel polarization. The so-called polar transform, also known as the Arikan transforms, is the most fundamental component of the polar code and is used to characterize it in information-theoretic terms. The polar encoding uses a polarization matrix or transform kernel (Condo et al., 2018).

2.7 Interleaved CRC for polar codes

Interleaved CRC for polar code is formed by inserting interleaved between The CRC bits and the polar encoder. Interleave CRC bits before the polar encoder is used to distribute the CRC bits between the information bits and frozen bits before the encoding process happens. Distributing the CRC bits between the information and frozen bits helps CRC checks to perform earlier in the decoding process due to this the list decoding process can end when the CRC checks of all competitor paths in the list fail. These interleaved CRC bits have the ability for both early error detection and to improve the performance of error correction (Hui & Breschel, 2018).

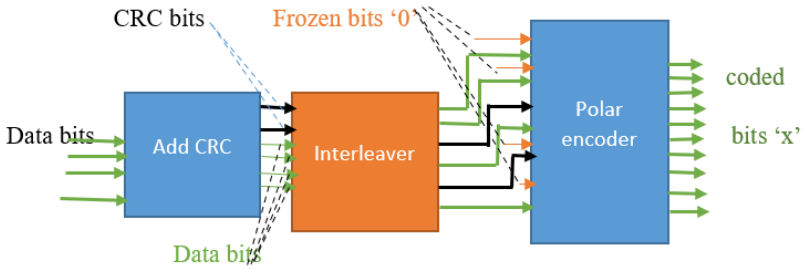

Figure 2.2 Interleaved CRC for Polar codes (Hui & Breschel, 2018)

2.8 Polar Decoding

The polar decoder receives a polar encoded message that has been transmitted over an AWGN channel (Albert Raj et al., 2021). It is also thought of as a binary tree search, where each node at stage t receives soft information from its parent node in the form of logarithmic likelihood ratios (LLRs) from its parent node vector and then returns the hard decision vector β. The depth of the tree is first investigated, with priority on the left branches after that it will pass to the right branches (Condo et al., 2018).

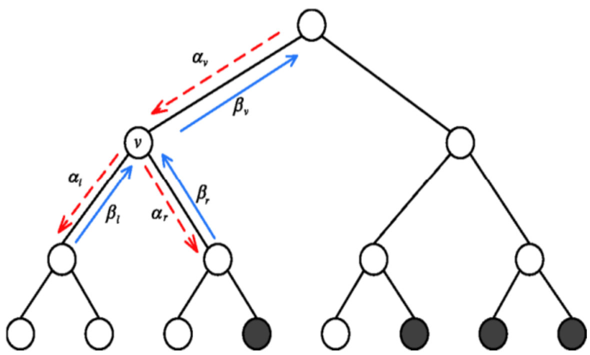

Figure 2.3 Polar decoder (Albert Raj et al., 2021)

2.9 Polar Coding Schemes and their Decoding Techniques

The mapping of the information bits to the input bits for the polar encoder kernel determines the design of a successful polar code. The K best (or most dependable) bit channels should be used for the information bits. Frozen bits are the leftover $N - K$ input bits that are not taken from the information bits. The frozen bits are often set to 0. The set of positions for information bits is known as the information bits set, while the set of positions for frozen bits is known as the frozen set. Several methods are used in polar coding schemes. A polar code is a linear block error-correcting code in information theory. The short kernel code that converts the physical channel into virtual outer channels is the foundation of the code construction, which is built on successive recursive concatenations of the code (Xi et al., 2018).

2.9.1 Polar Codes with Successive Cancellation (SC) Decoding

Successive cancellation decoding is a decoding technique that works sequentially. Using soft input and soft output, SC decoding is a very effective decoding technique and it has low decoding complexity $O(NlogN)$. We also ignore the soft results and choose the hard decision. The decoder typically sends out one code word after receiving the vectors (Albert Raj et al., 2021). Due to its innate serial nature, SC produces a high decoding latency (Xi et al., 2018). The decoding sequence of SC decoding.

- First, send information to the left child and receive some beliefs from the parent node
- After it receives the decision from the left child, then it can send some beliefs to the right child.
- Once it receives the decision from the right child, it combines them and sends them to the parent node. These three distinct tasks will be carried out by these nodes. Let's begin with the internal node action (the nodes other than leaf nodes in the binary node). These internal nodes perform three distinct operations (Albert Raj et al., 2021) as shown in figure 2.4.

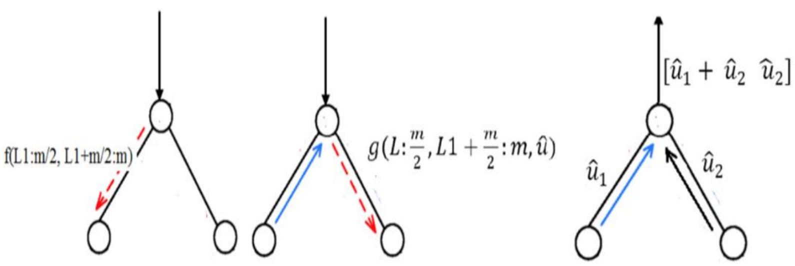

Figure 2.4 Interior node operation of polar codes (Albert Raj et al., 2021)

Figure 2.5 shows how to get back the information bit from the received bits.

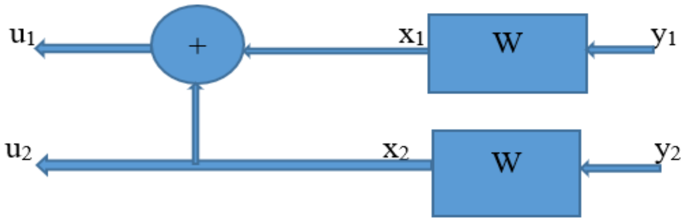

Figure 2.5 Sample decoding circuit of polar codes (Albert Raj et al., 2021)

2.9.2 Polar Codes with Successive Cancellation List (SCL) Decoding

The SC decoder frequently is unable to discover the ideal decoding path due to the local optimum search limit. The SCL algorithm was suggested as a solution to this issue. Finding the right decoding path is much more likely when many SC decoders are applied to the same code tree. List size L refers to the quantity of SC component decoders in this context (Yuan & Parhi, 2012). Similar to SC decoding, SCL decoding proceeds sequentially as each bits decision is dependent on that of the bits that have come before it. However, SCL maintains a list of $L(L > 1)$ potential bit combinations in the sequential decoding, as opposed to SC decoding, which only stores one decision per bit. The list of L candidates is updated for each new bit that is decoded (Tao et al., 2021). But as the list size increases further SCL decoding becomes more complex and it is the problem of SCL decoding.

2.9.3 Polar Codes with Cyclic Redundancy Check Aided Successive Cancellation List (CRC-A-SCL) Polar decoding

More accuracy is achieved with bigger list sizes L, but complexity increases exponentially with L. Adding a cyclic redundancy check (CRC) to the process of choosing the final decoding option from the list of L candidates can also increase accuracy. Polar codes with CRC-A-SCL decoding can outperform SC polar decoding in error correction but it is more complex than SC decoding because of the addition of CRC (Tao et al., 2021).

2.9.4 Interleaving Polar Codes with SC Decoding

polar code encoder incorporates interleaves between the intermediate stages. Interleaved polar (I-polar) codes are those created based on this concept. All potential interleaves are taken into account when creating the ensemble of I-polar codes.

One realization of the ensemble of I-polar codes is the regular polar code. I-Polar codes are also decoded using interleaved polar codes with SC decoding (Chiu, 2020).

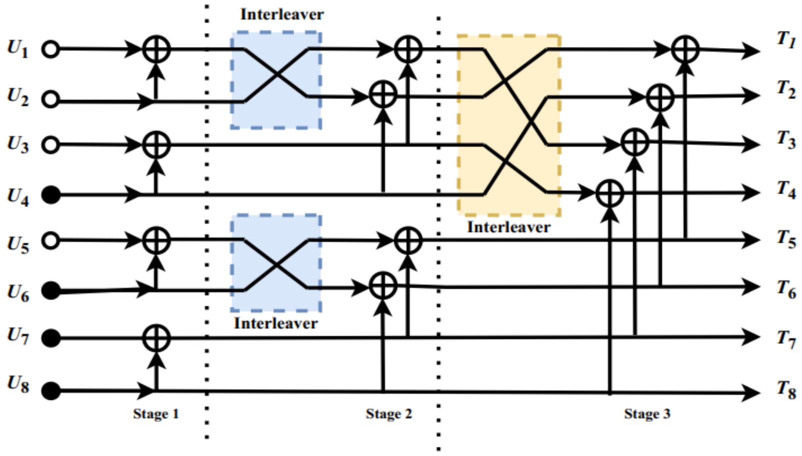

Figure 2.6 I-Polar encoder (Jali et al., 2022)

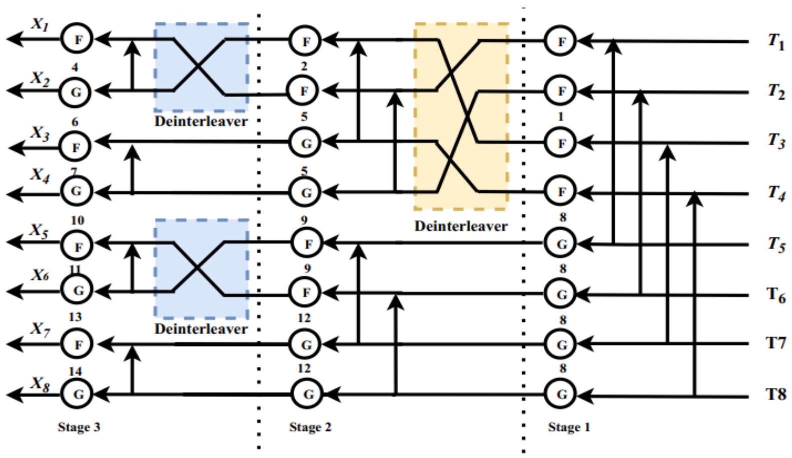

Figure 2.7 I-Polar Decoder (Jali et al., 2022)

2.9.5 Interleaving Polar Codes with SCL Decoding

Interleaved Polar codes intended to correct burst errors that would happen randomly. This type of polar code also uses different types of decoding algorithms to recover the original message. SCL decoding is an example of a decoding technique that is used in I-polar codes.

2.9.6 Interleaving Polar Codes with Cyclic Redundancy Check Aided Successive Cancellation List (CRC-A-I-SCL) Polar Decoding Schemes

Interleaving is a technique intended to lessen burst errors that could happen randomly. to enhance the currently used error control codes to enable the recovery of the original message bits. Before transmission, the data bits are distributed, and if any of the information is altered while being transmitted across the channel, it can be recovered by rearrangement of the data after recovery.

2.9.7 Interleaved Cyclic Redundancy Check Aided Successive Cancellation List (I-CRC-A-SCL) Polar Coding Schemes

This polar decoding scheme is a type of decoding scheme that uses interleaved CRC bits instead of normal CRC bits. These interleaved CRC bits are distributed to the information block. This distribution of CRC bits along with the information block helps early error detection and correction in the list decoding process. This improves the performance of error correction and reduces the decoding latency (Hui & Breschel, 2018). This decoding type of polar code is the same as that of the CRC-A-SCL polar decoding technique but it uses Interleaved CRC (I-CRC).

2.9.8 Interleaved Cyclic Redundancy Check Aided Interleaved Successive Cancellation List (I-CRC-A-I-SCL) Polar Coding Schemes

Interleaved CRC-aided interleaved polar decoding is a polar decoding scheme that is used to improve the performance of polar codes. Interleaved CRC-aided interleaved polar decoding involves interleaving the information bits of the polar code before encoding, and then encoding the interleaved sequence with a CRC code. The codeword is then again interleaved before transmission, and at the receiver, the interleaving is reversed and SCL decoding with CRC checking is performed. The interleaving can help to spread out errors due to noise, making the CRC code more effective in detecting and correcting errors. Additionally, the interleaving can help to mitigate any burst errors that may occur. This polar coding schemes works on both early error detection and mitigating the burst error.

2.10 BPSK in AWGN Channel Transmission and Reception

An information transmission means that it physically transmits data from one place to another place. It is referred to as a communication channel, or simply a channel. The additive white Gaussian noise channel (AWGN), which transmits signals while introducing white noise, (Suman, 2017) is used in this study. Information is encoded and modulated before transmission then after that, it is transmitted through the AWGN channel then after reception the information is demodulated. We have used Binary Phase Shift Keying (BPSK)

Modulation in our study. In figure 2.8 s(t) is the modulated input signal, n(t) is the noise added and r(t) is the received signal.

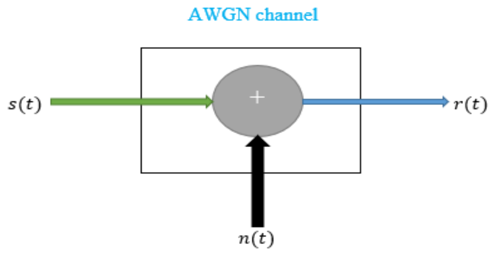

Figure 2.8 AWGN channel (Suman, 2017)

$$r(t) = s(t) + n(t) \quad (2.1)$$

2.11 Related Work

(Hashemi et al., 2018) examined polar codes with brief lengths and various coding rates. They demonstrate that there exists an ideal code rate at which SC and SCL decoders can achieve a fixed goal frame error rate (FER) while utilizing the least amount of power. They get the E_b/N_o value for each code rate to begin analyzing the power efficiency of the codes in the 5G eMBB control channel. Based on the decoder used, they demonstrate that polar codes exhibit their highest level of power efficiency at a particular rate. They also examined the impact of CRC length on SCL decoding speed and error-correction performance. To increase the decoding speed and achieve the highest error correction performance, they offer a CRC selection technique. They demonstrated the usefulness of CRC for codes with longer lengths and greater rates. SCL without CRC offers adequate error-correction performance for short codes and low speeds. They also proved that CRC affects the speed of the decoders for polar codes but they only consider the simulation of FER versus Eb/No.

(Čarapić et al., 2021) Studied the benefits and drawbacks of 5G channel coding schemes, they evaluate both LDPC and Polar codes in their work. They consider several channel models (Additive White Gaussian Noise (AWGN), Rician fading + AWGN, and Rayleigh fading + AWGN). They compare the effects of different message sizes and coding rates. Also, various decoding strategies for Polar codes and various modulation schemes for LDPC codes were examined in this study. The studies have proved that Polar codes were best for short messages and LDPC codes for longer messages. This justifies the use of Polar codes for control channels and LDPC codes for data channels. They consider the performance of

BER by changing the code rate and message length. In this study, they only compare depending on the BER on different channels but they cannot further compare other parameters like latency, complexity, and BLER.

(Belhadj et al., 2021) studied on the selection of the best channel coding method for the 5G-mMTC scenario, this study examines the performance of various coding schemes, including tail-biting convolutional code (TBCC), low-density parity-check codes (LDPC), Turbo code, and Polar codes. For short information block lengths, the considered codes were assessed in terms of bit error rate (BER) and block error rate (BLER). Researchers also look at the complexity of their algorithms in terms of how many fundamental operations there are. The findings show that although the polar code with SC algorithms has very low computational complexity, its performance is lower compared to other coding schemes. In terms of error correction performance and computational complexity, polar code with CRC-SCL decoding algorithm performs better than TBCC, LDPC, and Turbo codes. Concerning the trade-off between computational complexity and performance in 5G mMTC, it is, therefore, reasonable to assume that polar code (CRC-SCL) is more flexible than other channel coding schemes. They conclude that Polar codes with CRC-A-SCL decoding appear to be the best option for 5G mMTC. Those researchers were able to go further on the performance of polar coding by considering different polar coding schemes but they don't compare those polar codes.

(Khan & Zhang, 2020) The potential coding system for the 5g network was evaluated in this research, although their work was focused on the mMTC use case only. Information sharing across billions of intelligent devices without human intervention is a key feature of mMTC. Despite offering many benefits, mMTC also presented several difficulties. First off, as the uplink dominates the traffic coming from many mMTC devices, it is crucial to reduce uplink traffic congestion. Second, a lot of mMTC applications for emergency monitoring demanded incredibly fast response times and minimal latency. Furthermore, they must assure energy-efficient device operation because mMTC devices have limited resources, mostly due to battery limitations. Designing a suitable channel coding scheme for small packet length that satisfies the downlink and uplink-dominated traffic of mMTC applications and meets additional requirements such as low latency, low complexity, and ultra-low energy consumption is an efficient solution to tackle these difficulties. Nevertheless, due to a higher uplink-to-downlink traffic ratio than the traditional cellular system, design channel codes for mMTC applications increase implementation difficulties. The main driving force behind this effort is the need to identify the most reliable channel coding for mMTC applications. It should be noted that the scope of their work is restricted to the evaluation of dependability performance; nevertheless, to choose appropriate channel coding schemes, other factors such as computational complexity, flexibility, cost, and decoding latency must also be taken into account. By comparing those channel codes, they conclude that the best channel code for mMTC is the polar code with CRC-A-SCL.

(Sinha & Bhaumik, 2021) proposed Distributed Cyclic Redundancy Check Assisted Polar (DCA-polar) coding algorithm is suggested and used in this study along with Cyclic Redundancy Check Aided Polar (CA-polar) codes to create a novel polar coding technique. This work's primary addition, in contrast to earlier works, is to provide an examination of the polar codes operation and error performance (SNR and False Alarm Rate (FAR)) for short block lengths for the NR control channel (specifically in uplink and downlink control channels). The performance of the polar codes for error detection and correction is then thoroughly evaluated for 5G NR control channels using SNR and FAR analysis. In this study, they were able to compare polar coding schemes for short information block length by changing the list size. They considered a few polar decoding algorithms only.

(Hui & Breschel, 2018) proposed a CRC code, which has a low implementation complexity and is typically primarily used for error detection, is the focus of this paper. Here, both error detection and correction are accomplished with a single CRC code. In this study, they also consider various applications of a single CRC outer code to enhance polar codes. They demonstrate how the CRC bits can be dispersed throughout the information block so that no information bit that a CRC bit depends on is behind it in the subsequent decoding order by applying an inter-leaver between a polar encoder and a CRC encoder. So, similar to Parity-Check-Concatenated (PCC) polar codes that improve the performance of combined codes concerning block errors. These CRC bits can be employed to increase the concatenated code's error-correction capability in addition to being used for early error detection. The average decoding delay is decreased by distributing the CRC bits more uniformly via the inter-leaver, which also enables early list decoding process termination. In their simulation result, they conclude that interleaving the CRC bits with the information bits improves early decoder termination by a small-to-moderate amount without degrading the error rate performance. But in this paper, they only consider Interleaved CRC.

(Vaz et al., 2019) considered the BER comparison and evaluation of Turbo and Polar codes by varying code rates and block lengths. In this research work the information bits are modulated using BPSK and also the channel used for data transmission or communication channel is the AWGN channel. These coding schemes are selected for 4G/5G services and satellite communication systems. As we have tried to understand from the simulation result the performance of turbo codes are decreased as the code rate increases and increases as the block length increases. In this research work, we have shown that turbo codes with greater block length and smaller code rates create a good performance.

(Tahir et al., 2017) studied the bit error rate (BER) performance for different information block lengths and code rates for convolutional, turbo, low-density parity check (LDPC), and polar codes. Further research was done on how their performance is affected by the approximation decoding algorithms, as well as on their convergence behavior concerning list size (polar) and iteration number (turbo and LDPC). The information bits are modulated by using a BPSK modulator and sent over the AWGN channel. The iterations (list size) of 32,16,8,4,1 is used in this research. Turbo codes do not give much gain if the iteration goes beyond 8. 16 number of iterations is sufficient for LDPC codes and if the iteration increases to 32 and there is very little gain. For polar codes, better performance is obtained for larger list sizes.

(Cuc et al., 2023) studied the performances of turbo codes, low-density parity check (LDPC) codes, and polar codes over an additive white Gaussian noise (AWGN) channel in the presence of inter-symbol interference at a code rate of 1/3, denoting the disturbances that altered the original signal. They were used as equalizers at the level of the receiver to eliminate the negative effects of inter-symbol interference (ISI). In this research transmitted bits are modulated by using BPSK modulation. The performance of these codes becomes better as the length of the information bit becomes longer. In this research, they used five iterations for turbo codes and ten iterations for LDPC codes. In this research, they use equalization before decoding the three codes. MMSE and ZF equalizers are used in this research. At the same level of signal-to-noise ratio, turbo codes offer a lower level of BER since they perform better than LDPC codes for both MMSE and ZF equalization.

Table 2.1 Summary of related works

Author(s), year	Title	Methodology used	Contributions	Gap
Hashemi et al., (2018)	On the Performance of Polar Codes for 5G eMBB Control Channel	SC and SCL decoders and their modification	Analyze the power efficiency of the codes in the 5G eMBB control channel by finding the Eb/No value for different code rates and also an effect of CRC length on the SCL decoding speed and error-correction performance.	Only CRC length and code rate are considered
Čarapić et al., (2021)	Performance analysis of LDPC and Polar codes for message transmissions over different channel models	Different channel models	Compared the BER performance for three channel models at different message lengths and code rates and showed that LDP code is good for long block length and polar for short	only Compared BER by varying the message length and code rate
Belhadj et al., (2021)	Performance comparison of channel coding schemes for 5G massive machine-	Viterbi algorithm, sub-optimal max-log-MAP, Min-sum, SC	Compared the coding schemes of 4G LTE and 5G in terms of BLER and BER and also	Compare the BER and BLER only by varying the message length

	type communications	and CRC-A-SCL	consider the decoding complexity	
Khan & Zhang, (2020)	Evaluation of Channel Coding Techniques for Massive Machine-Type Communication in 5G Cellular Network	SC, CRC-A-SCL, and iterative message-passing layered	Compared the coding scheme in terms of FER for small and moderate length message	Limited only to evaluate the reliability performance at code rate 1/2
Sinha & Bhaumik, (2021)	Performance analysis of NR Polar Codes at short information blocks for control channels	Distributed Cyclic Redundancy Check Aided-SCL and CRC-A-SCL	Evaluated the performance of the coding schemes in terms of False alarm rate (FER) and SNR	Interleaving is applied to the CRC bits only and Limited parameters are used
Hui & Breschel, (2018)	Interleaved CRC for Polar Codes	Interleaving CRC bits	Evaluate the performance in terms of BLER and early termination gain for different code rate	Only compare the two coding schemes I-CRC-A-SCL and CRC-A-SCL
Vaz et al., (2019)	Performance Comparison between Turbo and Polar Codes	Max-Log-MAP decoding for turbo and SC for polar codes	Compared the BER Turbo with polar codes	Only code rate and code length are considered
Tahir et al., (2017)	BER Comparison Between Convolutional,	Maximum A Posteriori (MAP) decoder	Evaluate the coding schemes in terms of BER with different code rates	Limited only on the BER comparison of

	Turbo, LDPC, and Polar Codes	For convolutional, iterative decoding for turbo codes, message passing on Tanner graph for LDPC and SC for polar codes	and information block length	the coding schemes
Cuc et al., (2023)	Performance Analysis of Turbo Codes, LDPC Codes, and Polar Codes over an AWGN Channel in the Presence of Inter Symbol Interference	Used equalization before decoding at the receiver side	Compare turbo, LDPC, and polar codes in the presence of ISI by using an equalizer at the level of the receiver side	Only consider the BER of those channel coding schemes and also they do not consider Interleaving polar codes

CHAPTER THREE

3. MATERIALS AND METHODS

3.1 Materials

In this research work, software such as MATLAB/R2020a is used. MATLAB is computing software that runs on a computer and consists of technical toolboxes and Simulink.

3.2 Methods

- Generating input data
- Prepare the proposed system model
- Prepare mathematical modeling for the channel encoding and decoding process
- Preparing the mathematical modeling to calculate the bit error rate

3.3 Data Generation

To analyze the performance under the parameters BER and FER random data is generated in MATLAB. To prevent bias in the performance comparison, data generation is based on the necessary block length and code rate.

3.4 General Block Diagram of Polar Coding Schemes

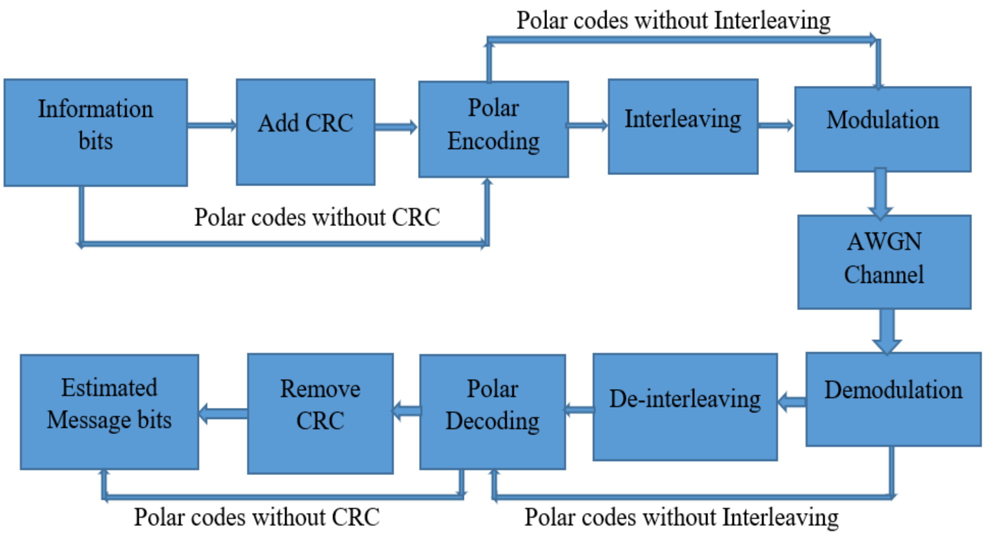

Figure 3.1 General Block Diagram of Polar Coding Schemes

3.5 Polar Encoding and Channel Polarization

A role of an encoder is to convert data from a sender into a code word that is subsequently sent to the receiver. The encoder must also add security to the message so that the decoder can still restore the message even if some bits are reversed during transmission because the noise might damage the transmission and interrupt the signal. To do this polar coding scheme uses Binary Discrete Memory-less Channels (B-DMC) (Rosenqvist et al., 2019),

$$P_r(X = x, Y = y) \tag{3.1}$$

where x and y are discrete values, in this context $x = \{0,1\}$and $y = \{0,1\}$, B-DMC represents binary bits which means 0 or 1. X and Y represent input value and output value respectively where X is a random value in x and Y is a random value in y. As (Rosenqvist et al., 2019) concluded in their thesis work equation 3.2 was described as follows,

$$W : P_r\{X = x, Y = y\} = P_r\{X = x\} p(Y / X) \, . \tag{3.2}$$

In Polar encoding, W is used and N copies are made, concatenated, and divided into several virtual channels. The virtual channels might be fully "noiseless" or entirely "noisy." The information from other channels that is added is what is meant by the term "noise”. There are perfect and imperfect channels in binary input communication channels. In perfect channels, the capacity means if zero bit is sent some output y_0 will be received and if bit one is sent some output y_1 will be received. In another case for channel transition probability W

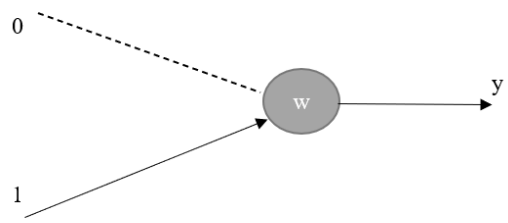

Figure 3.2 Simple binary channel (Kaime et al., 2019)

$$W(y/0) = W(y/1) \tag{3.3}$$

Figure 3.3 Single B-DMC channel (Rosenqvist et al., 2019)

If the channel transition probability is given by equation 3.3. In this case, the capacity is zero and coding is not necessary and this channel is useless. If two copies of the original channel W are created the capacity occurs in the middle between the perfect and zero capacity channel and channel W is a binary input channel by using the channel multiple times.

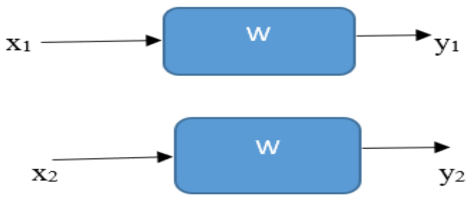

Figure 3.4 Two identical channels having equal capacity

In figure 3.4, one channel is used two times with inputs x_1 and x_2 to get outputs y_0 and y_1 respectively. If we consider the dependence between the inputs x_1 and x_2 systematically we gate figure 3.5; in this case we can able to relate the inputs x_1 and x_2 of both channels by using the new binary inputs u_1 and u_2.

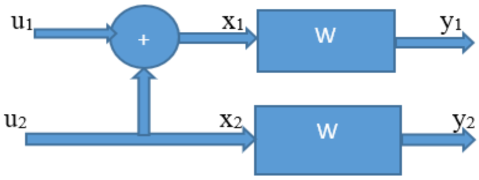

Figure 3.5 Systematically arranged inputs of polar code (Mude, 2018)

$$x_1 = u_1 + u_2 \tag{3.4}$$

$$x_2 = u_2 \tag{3.5}$$

When we define two channels W^- and W^+

$$W^- : u_1 \rightarrow y_1, y_2 \tag{3.6}$$

$$W^+ : u_2 \rightarrow y_1, y_2, u_1 \tag{3.7}$$

The channels in polar coding are splitted into N virtual channels. When the number of recursions becomes large, the virtual channels tend to polarize and the data bits take position to the most reliable channels and frozen bits to the unreliable channels. The polarization effect divides the N bit input vector ‘u’ between reliable and unreliable channels.

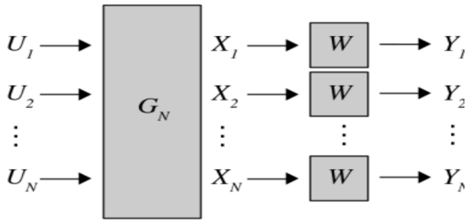

Figure 3.6 Polarization of W into N virtual channels (Rosenqvist et al., 2019)

The virtual channels are combined by using a Kronecker product of G_2 as shown in the equations below. The codeword C is found by matrix multiplication of information bit and polarization matrix G_N.

$$C = UG_N \tag{3.8}$$

where C is the length of the codeword and U is the length of the information bit or message bit. The encoding is performed by kernel matrix G_N. The kernel matrix for $N = 2$ is given as follows;

$$G_2 = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix} \tag{3.9}$$

the kernel matrix for $N = 4$ is given also as follows;

$$G_4 = G_2 \otimes G_2 \tag{3.10}$$

$$G_4 = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix} \otimes \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 \end{bmatrix} \tag{3.11}$$

$$G_N = \left[G_{N/2}\right]^{\otimes n} \tag{3.12}$$

where n is given by $\log_2 N$ given that N is the length of the information bits. Figure 3.7 shows how polar codes are encoded starting from the child node to the parent node.

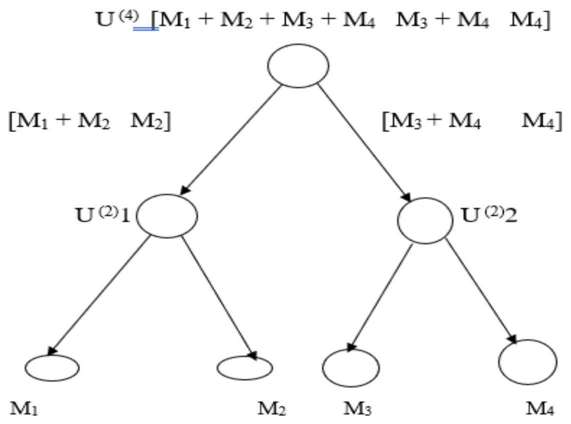

Figure 3.7 Binary tree representation of Polar encoder for N = 4 (Rosenqvist et al., 2019)

3.6 Interleaving Polar Codes

Interleaved polar codes (I-Polar) are a new variant of polar codes devised by putting the inter-leavers between the intermediate phases of the polar codes. Inter-leaver is used in conjunction with error-correcting code to reduce errors or mitigate the burst errors. Symbols are redistributed depending on a mapping technique (Jali et al., 2022).

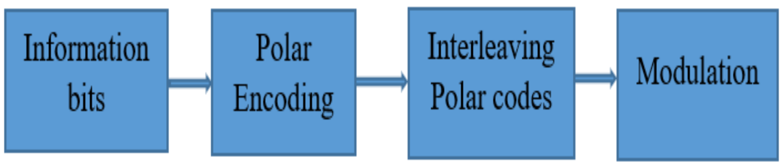

Figure 3.8 Inserting of interleaved to polar codes

Interleaving means the coded information bits or codeword which get by encoding c_1, c_2, c_3,…….c_N is changed to c'_1, c'_2, c'_3,…………c'_N which are the interleaved bits.

3.7 Modulation

This is the technique of altering a high-frequency carrier signals parameter concerning the same parameter of an incoming digital message signal (analog message must be converted into digital before digital modulation) (Chirag B, 2017). There are different types of digital modulation techniques Binary Phase Shift Keying (BPSK), QPSK, QAM, etc. In our thesis work, we have considered BPSK modulation technique which maps 0 to 1 and 1 to -1.

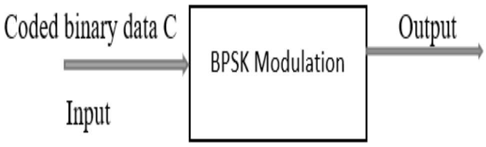

Figure 3.9 BPSK modulation of coded binary data

$$output = s(t) = 1 - 2C \tag{3.13}$$

3.8 De-interleaving

De-interleaving is accomplished by reordering the bits as they were before the interleaving operation. An interleaver is defined as a device that reads the symbols from an input vector. Rearranging is done following the index's inverted interleaved pattern. This de-interleaving process is the opposite of interleaving and it is inserted after reception of the information after decoding. It is the recovery of the original code word or information bits from the interleaved received data.

3.9 Channel Modelling

The impacts of the atmosphere are modeled and examined via channel modeling (Anandkumar & Sangeetha, 2021). Several channel models have been investigated. To build and develop a wireless communication system, considerable familiarity with various channel model types and their characteristics is required. While modeling networks, channel models are employed to examine how the system architecture performs in various states and circumstances. The signal passing through the AWGN Channel receives the addition of white Gaussian noise. AWGN produces modulated signals with no amplitude loss or phase distortion since the channel's amplitude frequency response is flat (resulting in an unlimited or limitless bandwidth) and its phase frequency response is flat for all frequencies. The performance and analysis of the polar coding schemes are compared in this thesis work by using the AWGN channel model. The received signal $r(t)$ is given by the transmitted signal $s(t)$ and the noise added to the signal $n(t)$ in equation 3.9.

$$r(t) = s(t) + n(t) \tag{3.14}$$

3.10 Polar Decoding Schemes

3.10.1 Polar Code with Successive Cancellation Decoding

Successive cancellation (SC) decoding is a polar decoding technique that decodes the received bits sequentially (Jali et al., 2022). Due to sequential cases, it has high decoding latency but low complexity. As the name suggests, the SC decoding makes decisions on the information bits in sequence. In this scenario, the receiver examines the channel output vector while successively estimating the input vectors constituents. This decoding algorithm's primary objective is to provide an estimated vector rather than the real vector that corresponds to the input vector. The receiver's decoder can decode the frozen bits as 0 with error zero because it knows of them according to the reliability sequence. The soft in-soft out decoder will decode the message bits if the bit position contains them. The likelihood-ratio test measures the goodness of fit of two statistical models that compete based on the ratio of their likelihoods, specifically the likelihood obtained by maximizing over all possible parameter combinations.

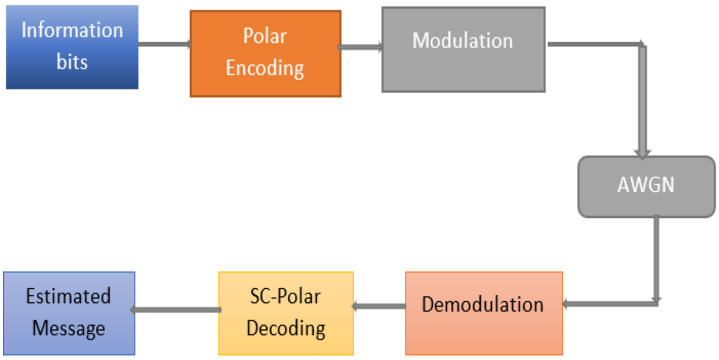

Figure 3.10 Polar coding with SC decoding block diagram

SC decoder operation in the interior node

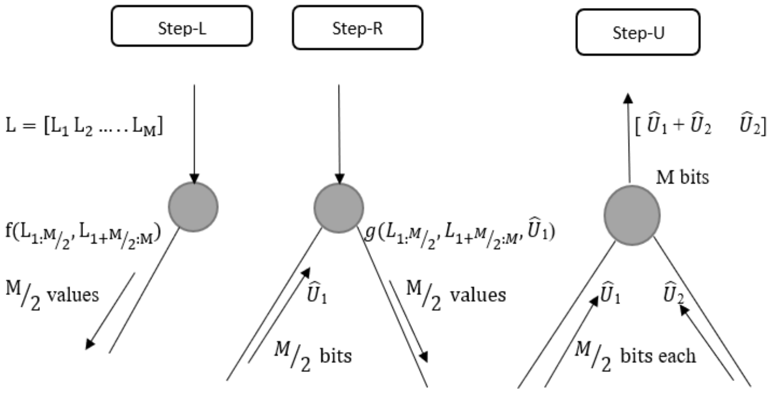

Figure 3. 11 Binary tree representation of interior node operation (Albert Raj et al., 2021)

The above two functions f and g are calculated by using the equation 3.15 and equation 3.16.

$$f(L_{1:M/2}, L_{1+M/2:M}) = f(r_1, r_2) = \text{sgn}(r_1)\,\text{sgn}(r_2)\min(|r_1|, |r_2|) \qquad (3.15)$$

$$g(L_{1:M/2}, L_{1+M/2:M}, U_1) = g(r_1, r_2, b) = r_2 + (1-2b)r_1 \qquad (3.16)$$

where b represents bits and r_1 and r_2 represents received values.

SC decoder leaf node operation

The leaf node does not have any children as shown in the figure below. Simply it receives $L(u_i)$ From the parent node and sends $\hat{u}_i$ to the left child. If i is frozen position: $\hat{u}_i = 0$. If i is a message position: $\hat{u}_i = 0$, if $L(u_i) \geq 0$; $\hat{u}_i = 1$, if $L(u_i) < 0$.

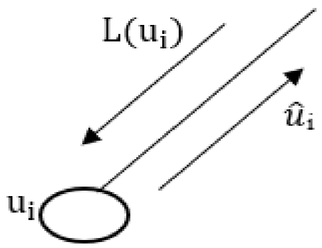

Figure 3.12 Binary tree representation of leaf node

Generally, successive cancellation decoders of polar codes can be decoded bit by bit successively by combining the above steps at the same time the decoding tree is given in figure 3.13. The sequence of the SC decoder operation step by step is listed below;

1. At every node (if not leaf) do step L and go to the left child and perform the min-sum operation
2. When decisions are received from the left child, do step G (repetitive operations) and go to the right child
3. When the decision is received from the right child do step $U(\hat{u}_1 + \hat{u}_2, \hat{u}_2)$ and go to the parent.

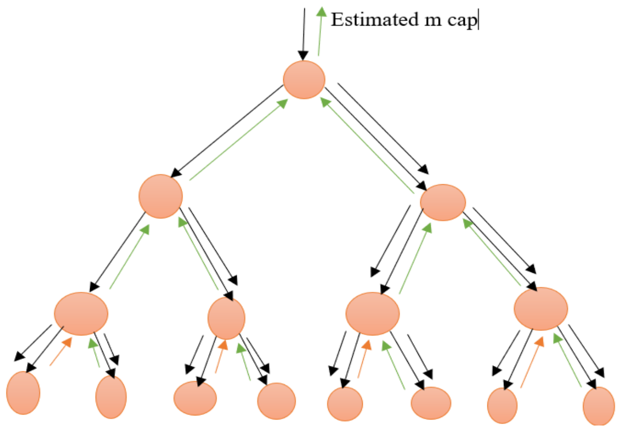

Figure 3.13 Binary tree representation of SC polar decoder with N=8 (Zheng et al., 2021)

The single decoding circuit of the SC polar decoder is also given in figure 3.14.

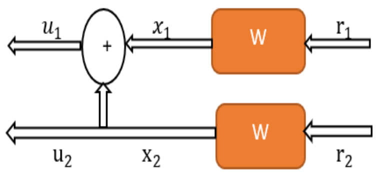

Figure 3.14 Sample decoding circuit of SC polar decoder (Albert Raj et al., 2021)

On the receiver side, the decoder gets the information with the help of a reliability sequence about the frozen bits and can decode these bits as 0 with error zero or there is no need to decode if it is a frozen bit. If a bit position is message bits these will be decoded by soft in soft out decoder successively. The likelihood-ratio test assesses the goodness of fit of two competing statistical models based on the ratio of their likelihoods, specifically one found by maximization over the entire parameter space. In the decoding of the successive cancellation of polar codes, we can compute the probability of the likelihood ratio as follows. According to the decoding of polar codes successively we can calculate the probability in the following way as described in (Albert Raj et al., 2021).

$$P_r(c_i = 0 / r_i) = \frac{f(r_i / c_i = 0)\, p_r(c_i = 0)}{f(r_i)} \tag{3.17}$$

$$P_r(c_i = 1 / r_i) = \frac{f(r_i / c_i = 1)\, p_r(c_i = 1)}{f(r_i)} \tag{3.18}$$

It is known that the probability of either 0 or 1 is ½ this expression is shown in equation 3.19.

$$p_r(c_i = 0) = p_r(c_i = 1) = 1/2 \tag{3.19}$$

The likelihood ratio is calculated in equation 3.20.

$$\frac{P_r(c_i = 0 / r_i)}{P_r(c_i = 1 / r_i)} = \frac{f(r_i / c_i = 0)}{f(r_i / c_i = 1)} \tag{3.20}$$

Equation 3.21 is the simplified form of equation 3.20.

$$= \frac{\frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(r_i - 1)^2}{2\sigma^2}}}{\frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(r_i + 1)^2}{2\sigma^2}}} \tag{3.21}$$

When we estimate the above equation using the rule of logarithm what we called the log-likelihood ratio is shown in equation 3.22.

$$\log \frac{P_r(c_i = 0 / r_i)}{P_r(c_i = 1 / r_i)} = \frac{2}{\sigma^2} r_i \tag{3.22}$$

$$r_i = r_1 + r_2 + r_3 + r_4 ... r_N \tag{3.23}$$

By substituting equation 3.23 for equation 3.22 the equation will be 3.24.

$$\log \frac{P_r(c_i = 0 / r_1, r_2, r_3, r_4, ..., r_N)}{P_r(c_i = 1 / r_1, r_2, r_3, r_4, ..., r_N)} = \frac{2}{\sigma^2}(r_1 + r_2 + r_3 + r_4 + ... + r_N) \tag{3.24}$$

3.10.2 Interleaved Successive Cancellation (I-SC) Polar Coding Scheme

Polar codes are designed to correct random errors, but they may perform poorly in the presence of burst errors, where multiple bits are corrupted in a short interval of time. Interleaving helps to spread out the burst errors across multiple codewords, making them easier to correct the error. In an interleaved SC polar coding scheme, the input data is first divided into a series of smaller blocks, each of which is independently encoded using a polar code. The resulting codewords are then interleaved to spread out any errors that may occur during transmission. In an interleaved SC polar coding scheme, the interleaving is done to ensure that errors are spread out across the entire data stream, rather than being concentrated in one or a few blocks. This helps to ensure that the maximum number of errors that can be corrected by the error-correcting code is achieved, which in turn increases the overall reliability of the communication system. It is used to mitigate burst errors which are not able to correct by error correcting codes.

3.10.3 Cyclic Redundancy Check Aided Successive Cancellation List (CRC-A-SCL) Polar Coding Schemes

CRC-aided SCL (Successive Cancellation List) polar coding is a technique used to improve the error correction capability of polar codes in communication systems. It involves adding a Cyclic Redundancy Check (CRC) code to the transmitted data and using an SCL decoder to decode the polar code. The CRC code is used to detect errors in the received data before the polar code is decoded. If the CRC check fails, the decoder discards the received data and tries the next candidate codeword in the SCL list. By using the CRC code to detect errors early in the decoding process, CRC-aided SCL polar decoding can improve the error correction capability of polar codes, especially in noisy communication channels. The SCL decoder used in CRC-aided SCL polar decoding is similar to the standard SCL decoder used for polar codes. The main difference is that the decoder considers multiple candidate codewords instead of just one. The candidate codewords are ranked based on their likelihood of being the correct codeword, and the decoder keeps track of the top-ranked codewords as it proceeds through the decoding process. The addition of CRC adds more complexity but it provides vital improvement in performance.

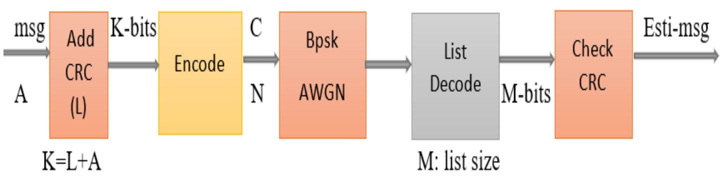

Figure 3.15 Addition of CRC to the SCL polar coding

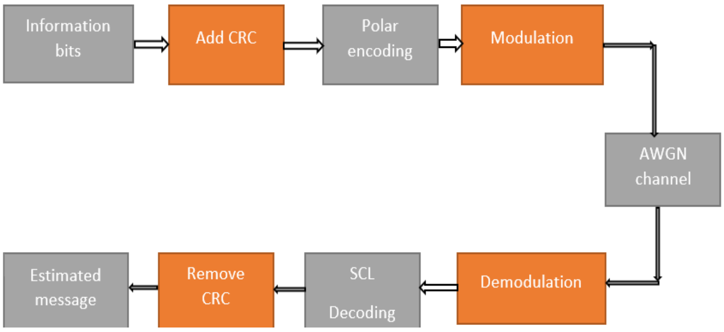

Figure 3.16 SCL polar coding with CRC

Figure 3.15 indicates we have 'A' message block that is given as $m_0, m_1, m_2, m_3, \ldots . m_A$ and CRC bits with length 'L' parity bits $p_0, p_1, p_2, p_3, \ldots p_{L-1}$ where A is the size of the input sequence and L is the length of the CRC bits which are added to the information bit or message bit to detect and correct errors. The parity bits are generated or produced using the CRC generator polynomials. The combination of message bits and CRC bits becomes K bits. The K-bits are encoded using the polar encoder and give N-bits of a codeword. The codeword is modulated using BPSK modulation and transmitted through the AWGN channel. The list decoder will pass the M-list codewords and those M-list code words are checked if the CRC is satisfied or not. The code word or the message word which passes the CRC is put out as the message estimate. If more than one codeword passes the CRC, we have to pick one code word by using path-metric because each of these candidates has a metric associated with them which is called path-metric. Path metric is an important notation in this list decoding. It serves multiple purposes; it keeps an indication of how good a particular candidate code word is. This path metric works depending on the decision metric (DM). It is the sum of decision metrics on a path choice.

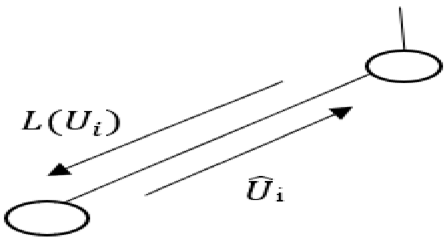

Figure 3.17 Belief flow structure for SCL decoding for N codewords

If $L(u_i) \geq 0$: $\hat{u}_i$ have $DM_i = 0, \hat{u}_i = 1$ has $DM_i = |L(u_i)|$

If $L(u_i) < 0$: $u_i = 1$ *has* $DM_i = 0, \hat{u}_i = 0$ has $DM_i = |L(u_i)|$

Figure 3.18 show the successive cancellation list decoder of polar codes depending on the decision metric and path metric.

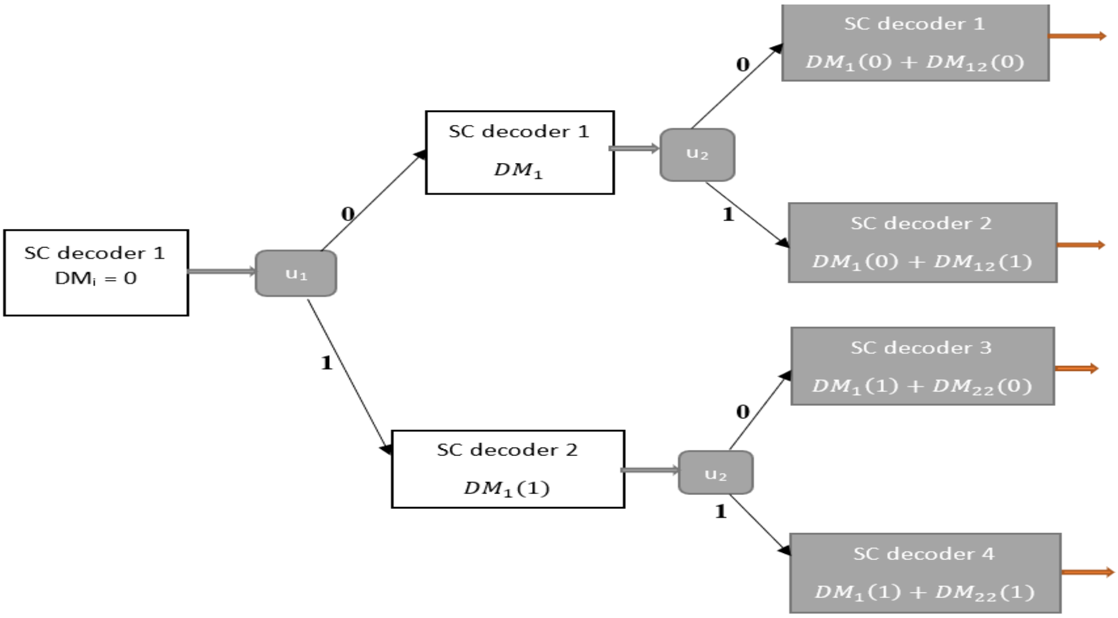

Figure 3.18 SCL decoder with L=4

3.10.4 Interleaved-CRC Aided Successive Cancellation List (I-CRC-A-SCL) Polar Coding Schemes

Interleaved CRC-aided successive cancellation list polar coding scheme is a type of polar code that inserts interleaver between the CRC encoder and polar encoder to early detect the error and mitigate burst errors. In this polar decoding scheme, the CRC and information bits are interleaved before encoding.

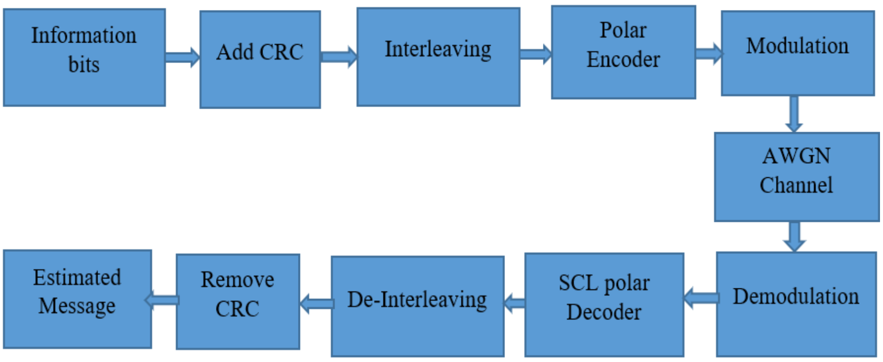

Figure 3.19 Block diagram of I-CRC-A-SCL polar coding scheme

3.10.5 CRC-Aided Interleaved Successive Cancellation List (CRC-A-I-SCL) Polar Coding Schemes

CRC-aided interleaved SCL (Successive Cancellation List) polar decoding is a technique used to further improve the error correction capability of polar codes in communication systems by spread out errors throughout the information bits and by mitigating burst errors which damages multiple bits are corrupted at the same time. It combines the benefits of both interleaving and CRC-aided SCL polar decoding. In CRC-aided interleaved SCL polar decoding, the transmitted data is first interleaved to spread out errors and reduce the impact of burst errors and other channel impairments. The interleaved and CRC-encoded data is then decoded using an SCL decoder. The SCL decoder used in CRC-aided interleaved SCL polar decoding is similar to the one used in CRC-aided SCL polar decoding. It considers multiple candidate codewords and keeps track of the top-ranked codewords as it proceeds through the decoding process. The interleaved CRC-aided SCL decoder improves the error correction capability of polar codes in several ways. First, the interleaving operation spreads out errors, making them easier to correct. Second, the CRC code detects errors early in the decoding process, allowing the decoder to discard candidate codewords that are unlikely to be correct. Finally, the SCL decoder considers multiple candidate codewords, increasing the likelihood of finding the correct codeword.

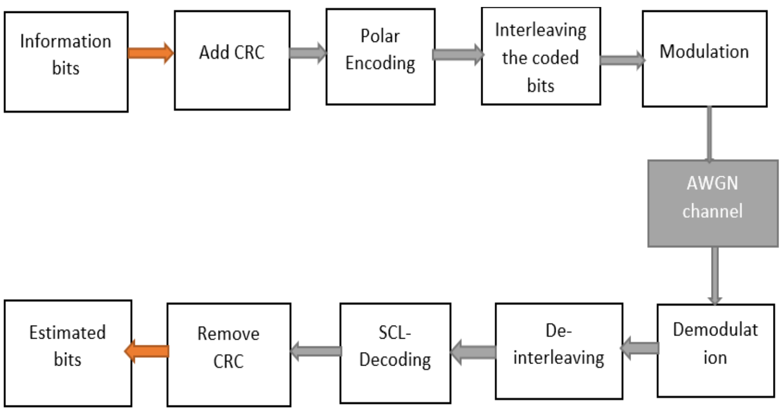

Figure 3.20 CRC-A-I-SCL polar coding block diagram

3.10.6 Interleaved-CRC-Aided-Interleaved-Successive Cancellation List (I-CRC-A-I-SCL) Polar coding schemes

Interleaved-CRC-aided-interleaved SCL polar decoding is a decoding scheme used for polar codes, a type of error-correcting code used in communication systems. This technique involves interleaving the information bits and CRC bits. Interleaving is a technique used to randomize the order of the code bits to improve the performance of the code. In interleaved-CRC-aided-interleaved SCL polar decoding, the interleaving is done twice: once before the CRC application and once after the CRC application. The CRC helps to early detect errors in the decoded bits and can be used to improve the decoding performance. Interleaved-CRC-aided-interleaved SCL polar decoding combines the interleaving, CRC, and SCL decoding techniques to improve the error-correction performance of polar codes. It is an effective technique for decoding polar codes in practical communication systems.

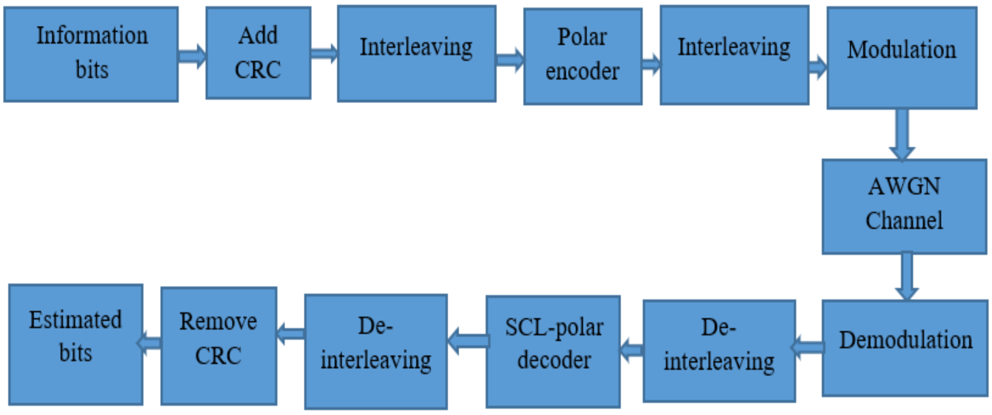

Figure 3.21 I-CRC-A-I-SCL polar coding scheme

3.11 Mathematical Model of Bit Error Rate (BER) and Frame Error Rate (FER)

The bit error rate (BER), or perhaps more appropriately the bit error ratio, is the number of bits received in error divided by the total number of bits transferred. We can estimate the BER by calculating the probability that a bit will be incorrectly received due to noise or interference.

$$BER = \frac{N_e}{N_T} \tag{3.25}$$

Where N_e total number of bits in error and N_T is the total number of transmitted bits

The code rate of in-polar coding can be calculated as follows in equation 3.26. Which means the ratio of information bit K to the code word or coded bit N.

$$R = \frac{K}{N} \tag{3.26}$$

The Rate R can be also calculated as the ratio of signal energy E_s to the information bit energy E_b.

$$R = \frac{E_s}{E_b} \tag{3.27}$$

From equation 3.27 signal bit energy is calculated in equation 3.28.

$$E_s = RE_b \tag{3.28}$$

Signal to noise ratio (SNR) can be calculated as follows in equation 3.29.

$$SNR = \frac{E_s}{\sigma^2} = \frac{RE_b}{N_o / 2} \tag{3.29}$$

Where $\sigma^2 = \frac{N_o}{2}$ Which is called noise power and $RE_b = E_s$ given in equation 3.28

$$SNR = 2R(E_b / N_o) \tag{3.30}$$

$$BER = Q(1/\sigma) \tag{3.31}$$

$$\frac{1}{\sigma} = \sqrt{SNR} \tag{3.32}$$

Then

$$BER = Q(\sqrt{SNR}) \tag{3.33}$$

$$BER = Q((\sqrt{RE_b / N_o})) \tag{3.34}$$

FER is a measure of the percentage of frames or packets that contain at least one-bit error. A frame or packet is considered erroneous if one or more bits in the frame are in error. FER is typically used to evaluate the error performance of systems that transmit data in frames or packets, such as wireless systems or network protocols. The main difference between FER and BER is their scope. FER measures the error rate at the frame or packet level, while BER measures the error rate at the bit level. FER is more appropriate for evaluating the performance of systems that transmit data in frames or packets, and it provides a more accurate representation of the error performance of the system. BER is more appropriate for evaluating the performance of digital communication systems that transmit data at the bit level, and it provides a more accurate representation of the error performance of the channel or transmission medium.

$$FER = \frac{F_e}{F_T} \tag{3.35}$$

where F_e is the number of received frames in error and F_T is the total number of transmitted frames.

CHAPTER FOUR

4. RESULT AND DISCUSSION

4.1 Introduction

This chapter contains the main body of our work and it contains simulation results and discussions. The simulations are based on the concepts of the previous chapters. To combatively study the performance of polar coding schemes based on the bit error rate and frame error rate by specifying simulation parameters in each section. Based on the result obtained interpretations are made and also, and we have analyzed the result further. The simulations are done using MATLAB R2020a software package. The parameters of interest for our work are limited to codeword size, Message frame size, Eb/No, Noise, BER, FER, CRC length, List size, and Code rate. In this work, we have understood the effect of code rate, list size, and CRC length on the performance of different polar coding schemes.

4.2 BER and FER Analysis and Comparison of SC and Interleaved-SC (I-SC) Polar Coding Schemes

To evaluate and compare SC and Interleaved-SC polar coding schemes at code rates of 1/4 and 1/2 we have used the parameters listed in table 4.1. In this simulation, we compare polar codes with SC and interleaved SC polar decoding algorithms by changing the code rate. Through this simulation, we understood the effect of code rate on the performance of both SC polar codes and I-SC polar codes under the AWGN channel and BPSK modulation schemes. From this simulation, we have plotted BER versus Eb/No at different code rates and we have tabulated in table 4.2. Additionally, we have plotted FER versus Eb/No in figure 4.2 and the result is tabulated in table 4.3. As we have understood from this simulation when the code rate increases the performance of each decoding algorithm decreases this means the BER and FER value increases with increasing in code rate. When we compare the performance of both decoding algorithms the I-SC polar decoder has better performance as we have understood from the result of our simulation; but when we see both coding schemes as the code rate increases their performance degrades.

Table 4. 1 Simulation parameters for comparison of SC polar and I-SC polar

Polar size and codeword size	(32,128), (64,128)
Code Rate	1/4 and 1/2
Frames size	1000
Eb/No in dB	0.4-3.6dB

For a code rate of 1/4 with an information bit size of 32 and a code rate of 1/2 with an information bit size of 64 with a polar size of 128, the BER and FER with 1000 frame size are tabulated in tables 4.2 and 4.3 respectively as shown below. As we can see from the result of our simulation from table 4.2 and figure 4.1 at Eb/No of 3.6dB for a code rate of 1/2 1.19% of bits are in error; when we reduce the code rate to 1/4 0.93% of bits are in error in SC polar coding schemes. When we see the I-SC polar coding scheme at the same Eb/No of 3.6dB for code rate 1/2 1.19% bits are in error when we reduce the code rate to 1/4 the bit error rate is reduced to 0.7%. Generally, when we compare the SC polar and I-SC polar at both code rates the bit error rate in the I-SC polar is less than the bit error rate in the SC polar. At smaller Eb/No value the BER and FER value of both coding schemes is almost equal but when the Eb/No value increases the performance of the I-SC polar coding scheme becomes better than SC polar coding scheme. Interleaved SC polar coding scheme is used in 5G wireless communication networks because it has high performance when compared with SC polar coding scheme. It is recommended for data channels in 5G wireless communication systems. These data channels are used for transmitting high-speed data, such as video and multimedia content. Interleaved SC polar coding can provide high reliability and low latency for these data channels; and also, it can be used to improve the reliability of satellite communication systems. The interleaving process can help to distribute errors caused by atmospheric effects and other sources of interference.

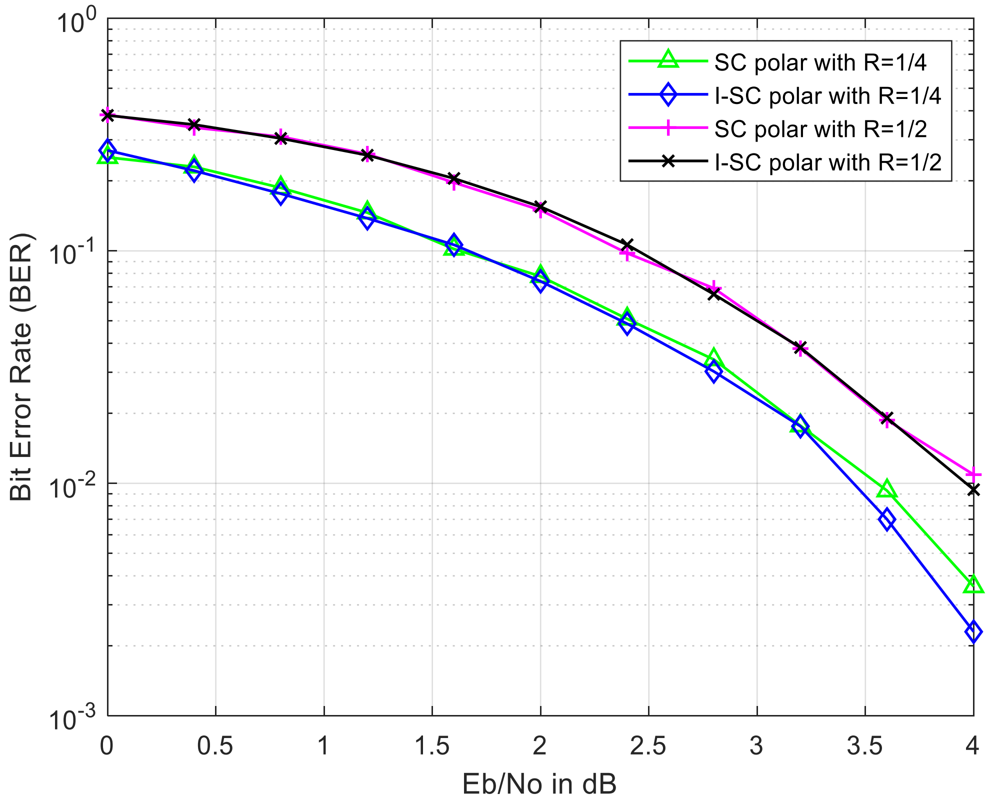

Figure 4.1 BER versus Eb/No of SC-polar and I-SC polar coding schemes at code rates of 1/4 and 1/2

Table 4. 2 BER for the comparison and analysis of polar SC and polar I-SC

Eb/No dB	BER			
	SC-polar decoder		I-SC polar decoder	
	Code Rate		Code Rate	
	1/4	1/2	1/4	1/2
0.4	0.23	0.3494	0.2214	0.3494
0.8	0.1868	0.3047	0.1763	0.3047
1.2	0.146	0.2579	0.1381	0.2579
1.6	0.1019	0.1968	0.1062	0.2050
2	0.0777	0.1497	0.074	0.1549
2.4	0.051	0.0977	0.0486	0.1063

2.8	0.0341	0.0691	0.0308	0.0651
3.2	0.0176	0.0384	0.0176	0.0384
3.6	0.0093	0.0191	0.007	0.0191

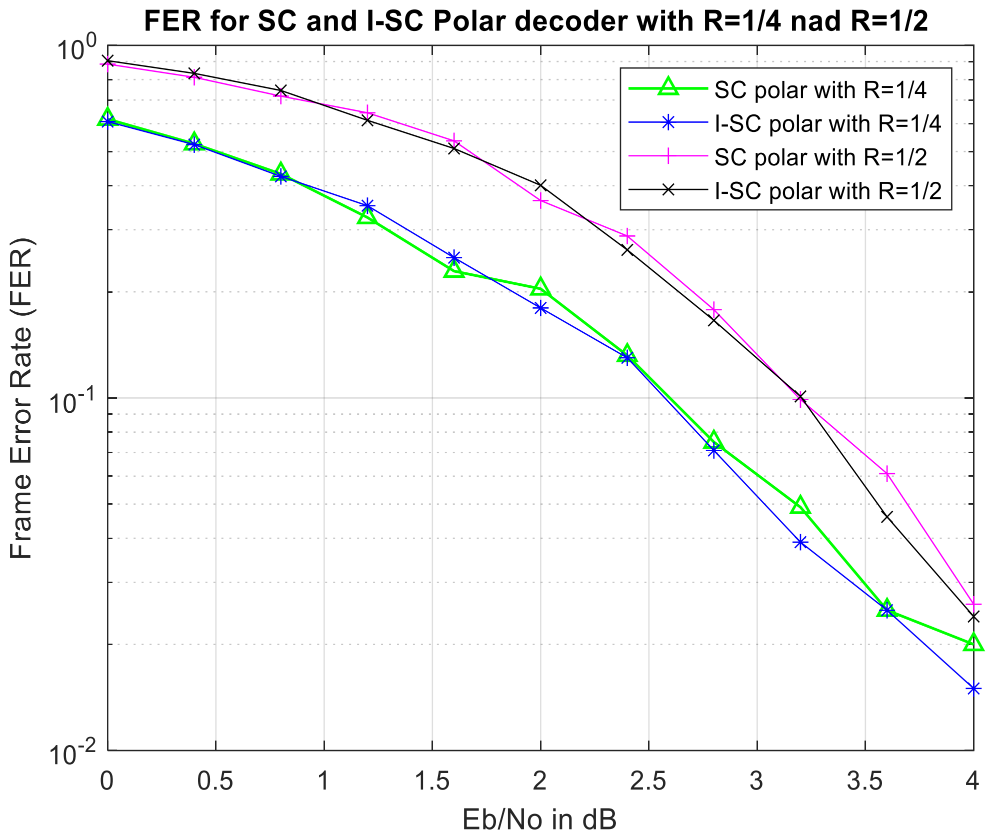

Figure 4.2 FER versus Eb/No of SC-polar code and I-SC polar code at code rate 1/4 and 1/2

As we can see in table 4.3 which shows the frame error rate analysis at a code rate of 1/4 and 1/2 similar to the simulation of BER versus Eb/No as the code rate increases the performance of both coding schemes reduces. When we see the FER value of both the SC polar coding scheme and I-SC polar coding scheme at a code rate of 1/2 and Eb/No of 2dB; 363 frames out of 1000 are in error for SC polar and 263 out of 1000 frames are in error at the same Eb/No value from this FER value of I-SC polar coding scheme is less than the FER value of SC polar coding scheme. When we reduce the code rate from 1/2 to 1/4 there are 204 frames in error out of 1000 frames for SC polar coding scheme and 180 frames are in error out of 1000 frames for I-SC polar coding scheme. When we compare both SC polar coding scheme and I-SC polar coding scheme fewer frames are in error for I-SC polar coding scheme than

SC polar coding scheme. Therefore, when we compare both these polar codes the interleaved polar with SC decoding has high performance than the polar code with SC decoding. By comparing these two codes I-SC polar coding scheme is better than SC polar coding scheme. In this scenario, the I-SC polar coding scheme has better performance due to the insertion of interleaving before the information is transmitted through the AWGN channel. This insertion of interleaving before the transmission helps to reduce the burst errors which are happened in the transmitted bits. Interleaving is a technique used in many communication systems to mitigate burst errors and improve error correction performance. In the context of the polar coding scheme, interleaving can be used to improve the performance of successive cancellation decoding, which is the most commonly used decoding algorithm for polar codes. Interleaving can help to spread out any burst errors that may occur during transmission, making them less likely to affect consecutive bits in the decoded sequence. In addition, interleaving can help to mitigate the effects of channel fading and other time-varying channel impairments. That is why interleaved SC polar coding scheme has better performance.

Table 4.3 FER analysis of SC polar coding scheme and I-SC polar coding scheme

Eb/No dB	FER			
	SC polar decoder		I-SC polar decoder	
	Code Rate		Code Rate	
	1/4	1/2	1/4	½
0.4	0.523	0.812	0.523	0.833
0.8	0.432	0.718	0.425	0.745
1.2	0.325	0.644	0.351	0.613
1.6	0.229	0.536	0.25	0.51
2	0.204	0.363	0.18	0.401
2.4	0.132	0.288	0.13	0.263
2.8	0.075	0.178	0.071	0.166
3.2	0.049	0.099	0.039	0.101
3.6	0.025	0.061	0.025	0.046

From tables 4.3 and 4.2 the analysis of frame error rate and bit error rate is tabulated respectively. If we take a 0.0341-bit error rate for SC polar and 0.0308 for I-SC polar at a code rate of 1/4 and also if we take a 0.075 frame error rate for SC polar and 0.071 frames error rate at a code rate of 1/4 and Eb/No of 2.8dB for BPSK modulation over AWGN channel; when the code rate is increased to 1/2 the bit error rate is increased to 0.0691 for SC polar and 0.0651 for I-SC polar and also its frame error rate is increased to 0.178 for SC polar coding scheme and 0.166 for I-SC polar coding scheme at same Eb/No value. When we see the whole performance by increasing the code rate from 1/4 to 1/2 the performance of both SC polar and I-SC polar coding scheme degrades. Degradation of performance means that there is a loss in Eb/No. If the BER and FER value increases the performance of the polar coding scheme decreases.

4.3 BER and FER Comparison of CRC-A-SCL Polar Coding Scheme and Interleaved (I)-CRC-A-SCL Polar Coding Scheme by Varying Code Rate

In this simulation, CRC-A-SCL polar coding scheme and Interleaved-CRC-A-SCL polar coding scheme are considered and compared. The performance of the two coding schemes is compared and analyzed at different code rates for the parameters listed in table 4.4. In this simulation BER versus Eb/No and FER versus Eb/No are plotted in figure 4.3 and figure 4.4 respectively at different code rates, CRC length 4, and list size 8 with BPSK modulation scheme under AWGN channel.

Table 4.4 Simulation parameters for comparison of CRC-A-SCL and I-CRC-A-SCL by varying code rate

Polar Block size	(32,128), (64,128)
Code rate	1/4 and 1/2
No of frames	1000
CRC length	4
Eb/No	0.4-3.6dB
List size	8

In this simulation, we compare the performance of both CRC-A-SCL and I-CRC-A-SCL polar coding schemes at different code rates by plotting bit error rate versus Eb/No and frame error rate versus Eb/No. When we see from the plotted result the performance of both polar coding schemes decreases with increasing code rate. But when we compare both coding schemes at different code rates the performance of interleaved CRC-aided SCL (I-CRC-A-SCL) polar coding scheme is better than CRC-A-SCL polar coding scheme. Let us see the bit error rate of both coding schemes at Eb/No of 2.4dB and code rate of 1/4; when we look in table 4.4 which is shown below the bit error rate of CRC-A-SCL polar coding scheme at a code rate of 1/4 is 0.0005 and the bit error rate of I-CRC-A-SCL polar coding scheme at code rate of 1/4 is also 0.0004. by looking at these results the performance of the I-CRC-A-SCL coding scheme is better than CRC-A-SCL polar coding scheme.

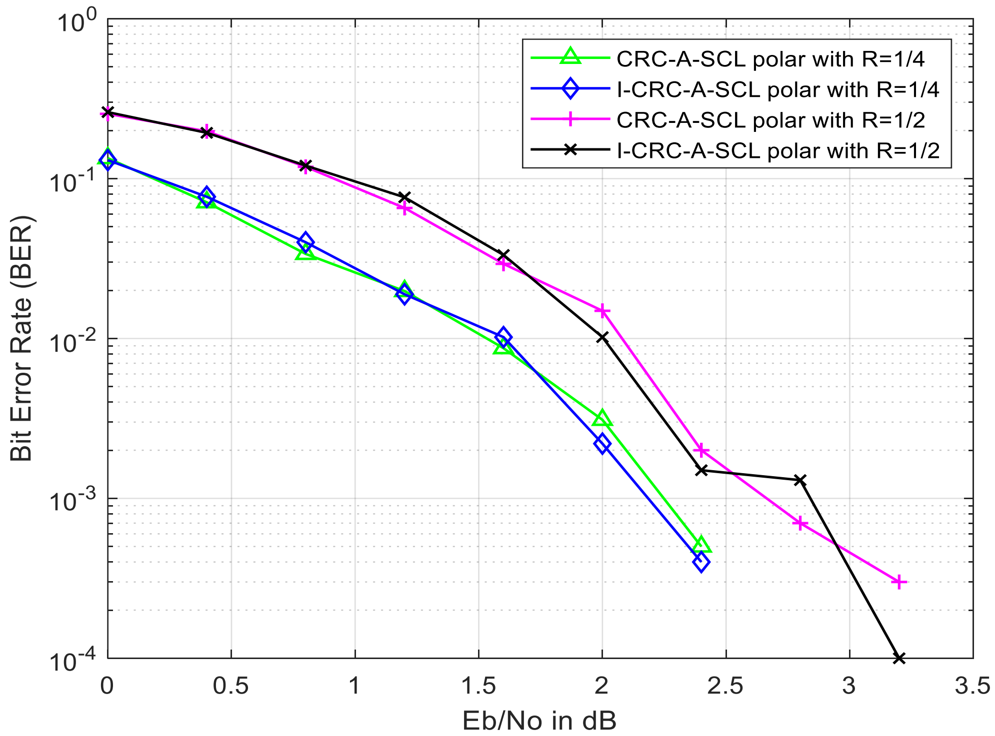

Figure 4.3 BER versus Eb/No of CRC-A-SCL code and I-CRC-A-SCL code with list size 8 and CRC length 4

Table 4.5 BER for the comparison and analysis of CRC-A-SCL and I-CRC-A-SCL polar coding schemes

Eb/No in dB	BER			
	CRC-A-SCL polar decoder		I-CRC-A-SCL polar decoder	
	Code Rate		Code Rate	
	1/4	1/2	1/4	1/2
0.4	0.0711	0.1976	0.077	0.1934
0.8	0.0338	0.1206	0.04	0.1185

1.2	0.0198	0.0655	0.0189	0.0764
1.6	0.0087	0.0293	0.0102	0.0333
2	0.0031	0.0149	0.0022	0.0102
2.4	0.0005	0.0020	0.0004	0.0015
2.8	0	0.0007	0	0.0013
3.2	0	0.0003	0	0.0001
3.6	0	0	0	0

In figure 4.4 which is shown below we plot the FER versus Eb/No for both polar coding schemes at different code rates. In this simulation, we have looked at the performance of both coding schemes. As we have shown in figure 4.4 and table 4.6. We have understood that the performance of I-CRC-A-SCL polar coding is better than CRC-A-SCL polar coding schemes.

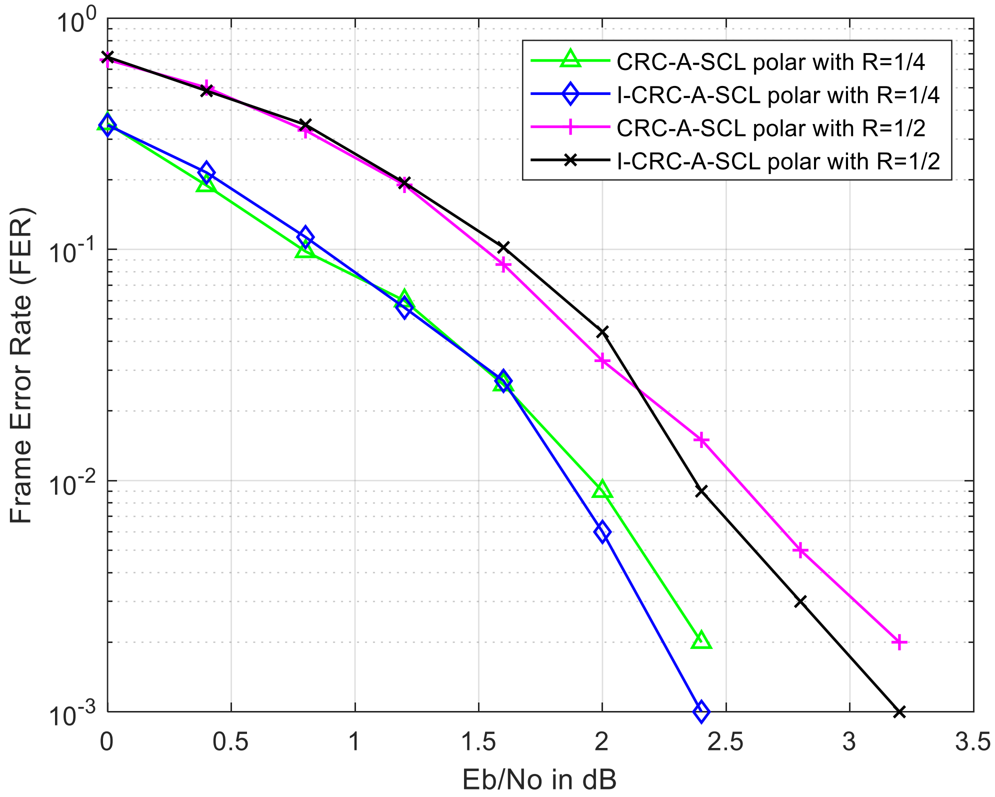

Figure 4.4 FER versus Eb/No for CRC-A-SCL and I-CRC-A-SCL polar coding schemes at list size 8 and CRC length 4 at different code rate

In table 4.6 the FER value of both CRC-A-SCL and I-CRC-A-SCL is tabulated from figure 4.4. In this simulation, we have used different code rates for both coding schemes. When we take Eb/No of 2.4dB the FER value at a code rate of 1/4 is 0.002 and 0.001 frames are in error for CRC-A-SCL and I-CRC-A-SCL polar coding schemes respectively. When we increase the code rate to 1/2 the FER value is 0.015 and 0.009 respectively at Eb/No of 2.4dB. In this case when the code rate increases the performance of both coding schemes degrades.

Table 4.6 FER for the comparison and analysis of CRC-A-SCL and I-CRC-A-SCL polar coding schemes

Eb/No in dB	FER			
	CRC-A-SCL polar		I-CRC-A-SCL polar	
	Code Rate		Code Rate	
	1/4	1/2	1/4	1/2
0.4	0.189	0.501	0.215	0.485
0.8	0.098	0.327	0.113	0.346
1.2	0.06	0.19	0.056	0.194
1.6	0.026	0.086	0.027	0.102
2	0.009	0.033	0.006	0.044
2.4	0.002	0.015	0.001	0.009
2.8	0	0.005	0	0.003
3.2	0	0.002	0	0.001
3.6	0	0	0	0

4.4 BER and FER Analysis and Comparison of CRC-A-SCL and I-CRC-A-SCL Polar Coding Schemes by Varying List Size

To compare and analyze the performance of the CRC-A-SCL polar coding scheme and I-CRC-A-SCL polar coding scheme at different list sizes we have used the parameters listed in table 4.7. In this simulation, we have studied the effect of increasing the list size on both polar coding schemes under the AWGN channel and the BPSK modulation scheme. In this part of our simulation, we have considered the CRC length and code rate 16 and 1/2 respectively and also, we have changed the list size. We have considered list sizes 8 and 16 to see the effect.

Table 4.7 Simulation parameters for comparison of CRC-A-SCL and I-CRC-A-SCL by varying list size

Polar size	(64,128)
Code rate	1/2
Frame number	1000
List size	8,16
CRC length	16
Eb/No	0.4-3.6dB

In figure 4.5 we have plotted the BER versus Eb/No of CRC-A-SCL and I-CRC-A-SCL polar coding schemes at a fixed code rate by varying list size. In general, as the list size increases the performance of both coding schemes increases by making the code rate constant. In this simulation, we have used code rate 1/2 and list sizes 8 &16. When we compare both polar coding schemes at different list sizes the performance of the I-CRC-A-SCL polar coding scheme has better performance than CRC-A-SCL polar coding scheme. When we plot the BER by keeping the code rate increasing the performance of both polar coding schemes degrades but when we consider the list size increasing the performance of these polar coding schemes increases as we compared with the previous simulation results which means what we plotted the BER versus Eb/No and FER versus Eb/No at different code rates. The list size determines the number of candidate solutions considered by the decoder, and a larger list size means that more candidate solutions are considered. If the list size is small, each polar decoder considers only a few candidate solutions, which may not include the correct solution. As a result, the error correction performance of both polar codes is limited. However, if the list size is increased, each decoder considers more candidate solutions, including the correct solution, which improves the error correction performance of both polar codes.

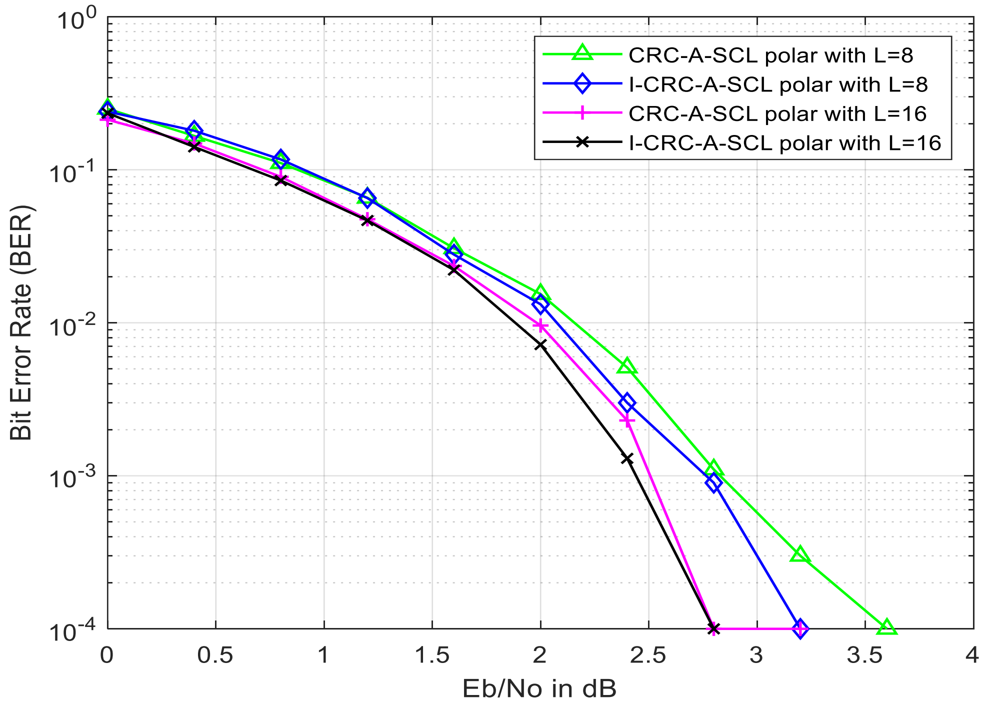

Figure 4.5 BER versus Eb/No for CRC-A-SCL and I-CRC-A-SCL polar coding schemes by varying list size at code rate 1/2 and CRC length 16

We have plotted both BER versus Eb/No and FER versus Eb/No by changing the list size from 8 to 16 at a code rate of 1/2 and CRC length of 16. In figure 4.6 the FER versus Eb/No for CRC-A-SCL and I-CRC-SCL polar coding scheme is plotted at code rate 1/2, CRC length 16, and list size 8 and 16. In this simulation, from figure 4.6 we have understood the effect of the list size on the FER value. In figure 4.5 we have understood the effect of increasing list size on BER value. In the case of figure 4.5 as the list size changes from 8 to 16 the value of the BER of both polar coding schemes reduces means at a list size of 8 the number of candidate solutions is less or limited but at a list size of 16 there are more candidate solutions than at list size 8 due to this we have a chance to get the correct solution with less BER value and higher performance. At list size 8 both polar decoders consider only a few candidate solutions, which may not include the correct solution compared to the list size 16.

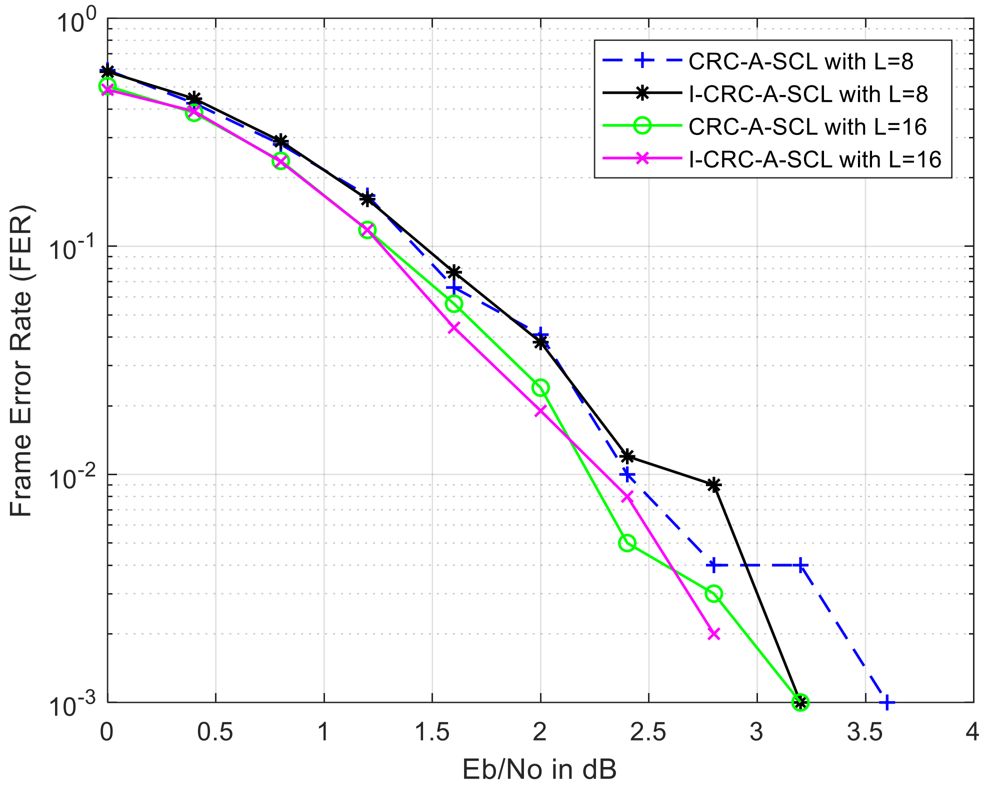

Figure 4.6 FER versus Eb/No for CRC-A-SCL and I-CRC-A-SCL polar coding scheme by varying list size at code rate1/2 and CRC length 16

As we have shown in figure 4.6 increasing list size has a positive effect on the performance of the CRC-A-SCL polar coding scheme and I-CRC-A-SCL polar coding scheme. The performance of the polar coding schemes increases as the list size increases but increasing the list size. The FER value of the I-CRC-A-SCL polar coding scheme at list size 16 is less than the FER value of the I-CRC-A-SCL polar coding scheme at list size 8 and CRC-A-SCL polar coding scheme at list size 8 and 16. The performance of I-CRC-A-SCL polar coding scheme at list size 16 has better performance than I-CRC-A-SCL polar coding scheme at list size 8.

4.5 BER and FER Analysis and Comparison of I-CRC-A-SCL and I-CRC-A-I-SCL Polar Coding Schemes by Varying Code Rate

To compare and analyze the performance of I-CRC-A-SCL and I-CRC-A-I-SCL polar coding schemes we have used the parameters listed in table 4.8. In this simulation, we have considered the effect of changing code rate on both polar coding schemes at list size 8, CRC length 4, and frame size 1000. In this part of our simulation, the performance of both coding schemes degrades with increasing code rates by keeping the list size and CRC length constant.

Table 4.8 Simulation parameters to compare and analyze I-CRC-A-SCL and I-CRC-A-I-SCL polar coding schemes by varying code rate

Polar block size	(32,128), (64,128)
Code rate	1/4, 1/2
Frame size	1000
Eb/No	0.4-3.6dB
List size	8
CRC-length	4

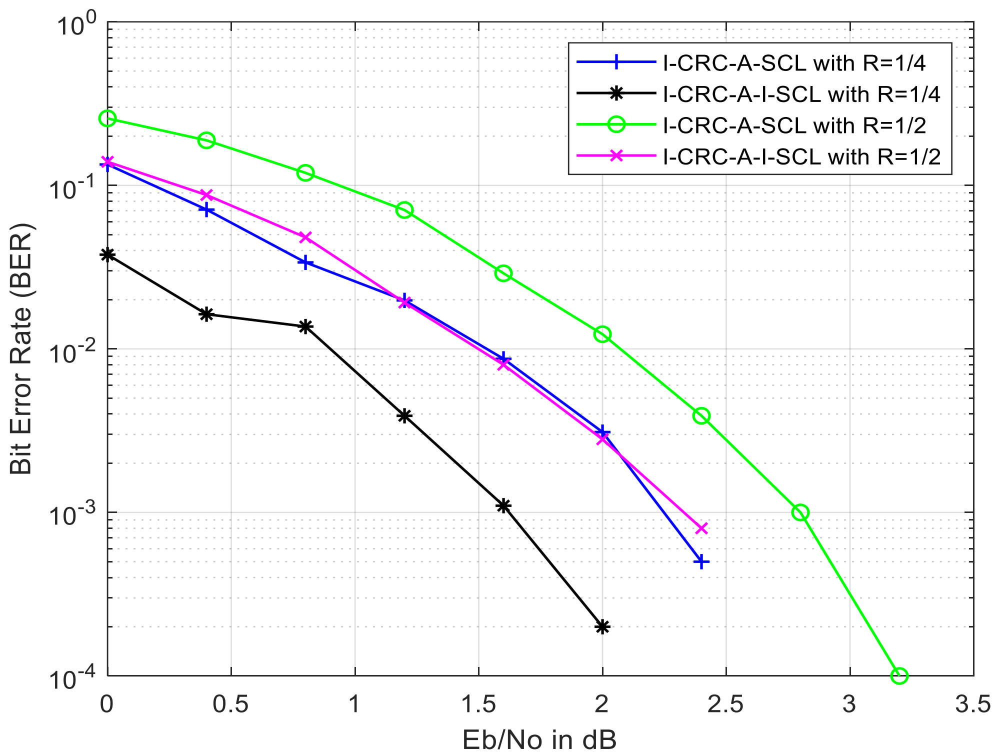

Figure 4.7 BER versus Eb/No for I-CRC-A-SCL and I-CRC-A-I-SCL polar coding schemes by varying code rate at list size 8 and CRC length 4

In figure 4.7 the BER versus Eb/No for I-CRC-A-SCL and I-CRC-A-I-SCL polar coding schemes is plotted by varying the code rate. In this simulation, we consider two code rates 1/4 and 1/2 at list size 8 and CRC length 4. When we see the simulation result the BER value of both coding schemes increases as the code rate increases from 1/4 to 1/2 this means the performance of both coding schemes decreases as the code rate increases. When we compare the performance of the two polar coding schemes as shown in figure 4.7; the performance of I-CRC-A-I-SCL polar coding schemes at a code rate of 1/4 performs better than I-CRC-A-SCL polar coding schemes at the same code rate. When we increase the code rate from 1/4 to 1/2 the performance of both coding schemes degrades but I-CRC-A-I-SCL polar coding scheme still performs better than I-CRC-A-SCL at a code rate of 1/2. The performance of I-CRC-A-I-SCL at a code rate of 1/2 and I-CRC-A-SCL polar coding scheme at a code rate of 1/4 have almost the same performance as we see in figure 4.7; but not exactly equal value.

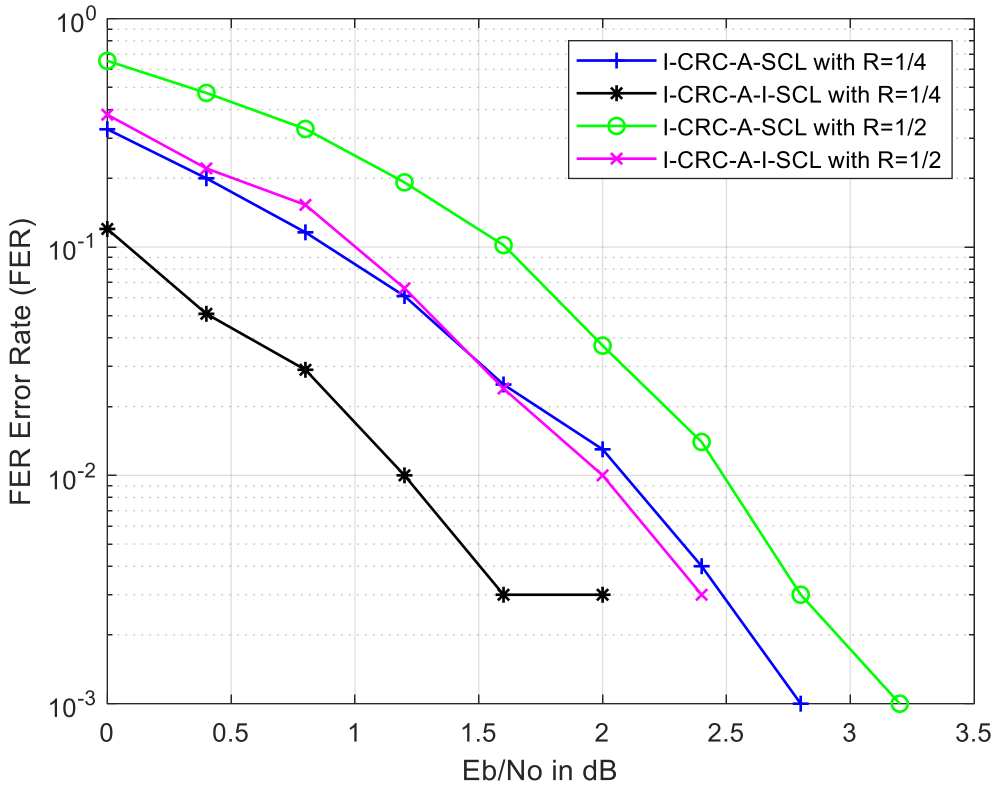

Figure 4.8 FER versus Eb/No for I-CRC-A-SCL and I-CRC-A-I-SCL polar coding schemes by varying code rate at list size 8 and CRC length 4

As we have shown again in figure 4.8 FER versus Eb/No is plotted at a code rate of 1/4 and 1/2 and we have understood the performance of both coding schemes in terms of FER at different code rate. In this case, the FER value increases with increasing code rate as we have understood in figure 4.8. When we compare both coding schemes in terms of FER the performance of I-CRC-A-I-SCL polar coding scheme at a code rate of 1/4 performs better than I-CRC-A-SCL polar coding scheme at a code rate of 1/4 and 1/2. The performance of the I-CRC-A-I-SCL polar coding scheme at a code rate of 1/2 has better error correction performance than the I-CRC-A-SCL polar coding scheme at a code rate of 1/4 and 1/2.

4.6 BER and FER Analysis and Comparison of I-CRC-A-SCL and I-CRC-A-I-SCL Polar Codes by Varying List Size

In this part of our simulation, we have compared the performance of the I-CRC-A-SCL polar coding scheme and the I-CRC-A-I-SCL polar coding scheme by plotting like BER versus Eb/No and FER versus Eb/No value at different list sizes by keeping the code rate 1/2 and increasing the CRC length from 4 to 16 from a previous simulation. In this simulation, we have used the parameters listed in table 4.9 to plot this part of our simulation result.

Table 4.9 Simulation parameters for comparison and analysis of I-CRC-A-SCL and I-CRC-A-I-SCL by varying list size

Polar block size	(64,128)
Code rate	1/2
Block Size/Frame size	1000
Eb/No	0.4-3.6dB
List size	8,16
CRC-length	16

In this simulation, we have plotted both BER versus Eb/No and FER versus Eb/No by changing the list size from 8 to 16 and increasing the CRC length from 4 to 16, and keeping the code rate 1/2 relative to the previous simulation. In this simulation, we have studied the effect of increasing the list size at both I-CRC-A-SCL and I-CRC-A-I-SCL polar coding schemes. As we have understood from both figures 4.9 and 4.10. The performance of the I-CRC-A-I-SCL polar coding scheme is better than I-CRC-A-SCL polar coding scheme. In this simulation, we have understood that the performance of both coding schemes increases as the list size of the decoder increases but a further increase in list size is not good as we have tried to mention in another simulation.

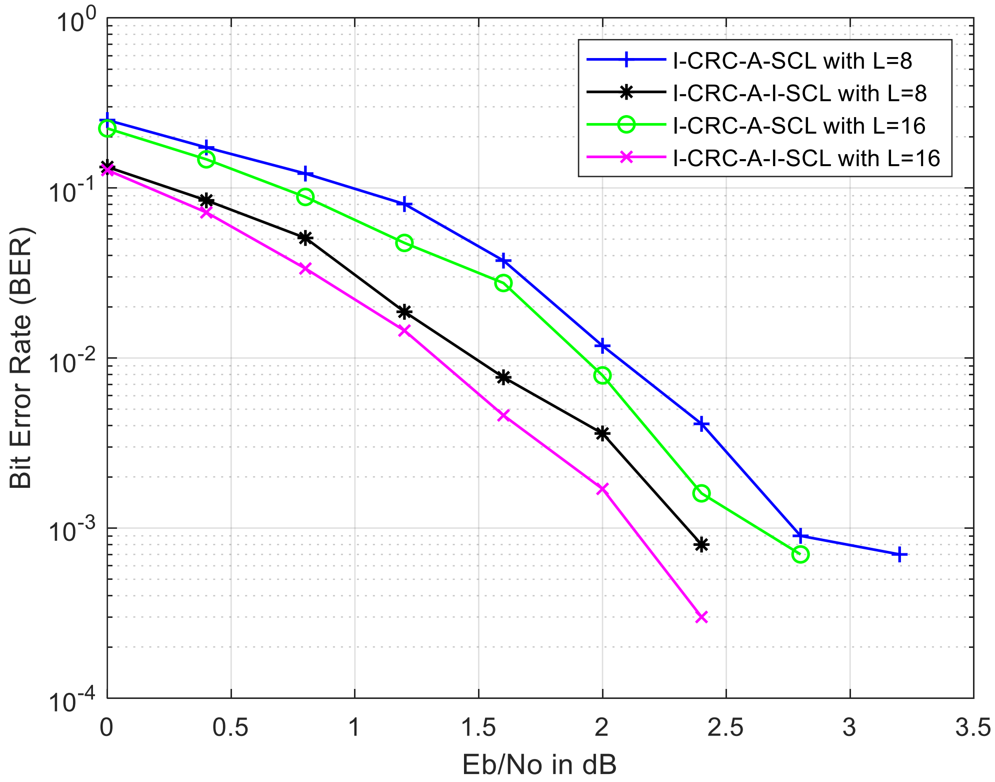

Figure 4.9 BER versus Eb/No for I-CRC-A-SCL and I-CRC-A-I-SCL polar coding by varying list size at code rate 1/2 and CRC length 16

In figure 4.9 we have plotted BER versus Eb/No for both polar coding schemes by increasing the list size from 8 to 16 and CRC length to 16 at a code rate of 1/2 and we have tried to understand the effect of changing the list size on those polar coding schemes. As shown in figure 4.9 the performance of both coding schemes increases with increasing the list size means the BER value decreases as the list size increases. The performance of the I-CRC-A-I-SCL polar coding scheme at list size 16 has better performance relative to I-CRC-A-SCL polar coding scheme at list sizes 16, 8, and I-CRC-A-I-SCL at list size 8. In general, I-CRC-A-I-SCL at both list sizes has better performance than I-CRC-A-SCL at list sizes 8 and 16. When we compare the performance of I-CRC-A-SCL at list sizes 8 and 16; the performance of the I-CRC-A-SCL polar coding scheme at list size 16 has better performance than at list size 8. I-CRC-A-I-SCL polar coding scheme forms by inserting interleaving before encoding and after encoding at CRC-A-SCL. It works both on early error detection and mitigating burst errors effectively. Therefore I-CRC-A-I-SCL polar coding schemes have better performance than I-CRC-A-SCL polar coding schemes.

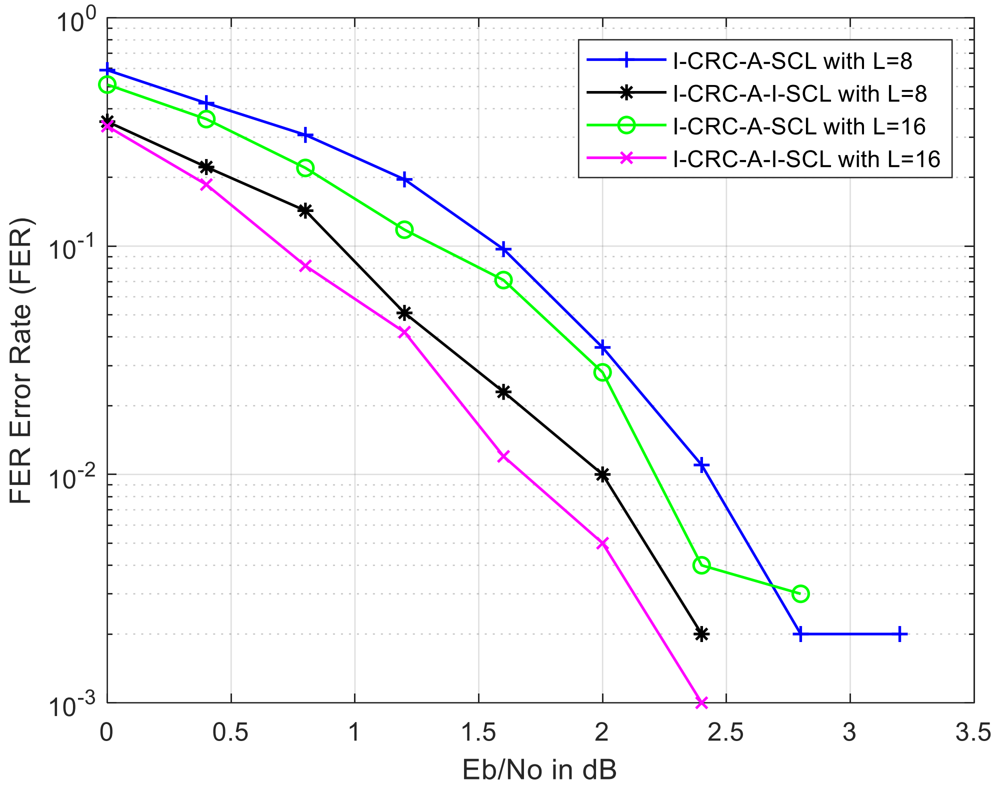

Figure 4.10 FER versus Eb/No for I-CRC-A-SCL and I-CRC-A-I-SCL polar coding schemes by varying list size

In figure 4.10 the performance of both coding schemes is tested by plotting FER versus Eb/No at different list sizes and fixed code rates. When we see the performance of these two codes; I-CRC-A-I-SCL polar coding scheme has better performance when we test in terms of FER. The FER value of the I-CRC-A-I-SCL polar coding scheme is lower at list size 16. This means at list size 16 the performance of the I-CRC-A-I-SCL polar coding scheme performs better than I-CRC-A-I-SCL at list size 8, and I-CRC-A-SCL at list sizes 8 and 16.

4.7 BER and FER Analysis and Comparison of I-CRC-A-SCL and I-CRC-A-I-SCL Polar Codes by Varying CRC Length

In this simulation, we have compared both I-CRC-A-SCL and I-CRC-A-I-SCL by varying the CRC length at a code rate of 1/2 and list size 16 for 1000 frames. The parameters used in this part of our simulation are listed in Table 4.10. When we compare the performance of these codes by varying the CRC length from 8 to 16, we have considered both BER and FER at a polar block size of (64,128) means at a code rate of 1/2.

Table 4.10 Simulation parameters to compare I-CRC-A-SCL and I-CRC-A-I-SCL polar coding schemes by varying CRC-length

Polar block size	(64,128)
Code rate	1/2
Block Size/Frame size	1000
Eb/No	0.4-3.6dB
List size	16
CRC-length	8,16

By using the parameters listed in table 4.10 we have plotted both BER versus Eb/No and FER versus Eb/No and we have tried to see the effect of variation in CRC length in I-CRC-A-SCL and I-CRC-A-I-SCL polar coding schemes.

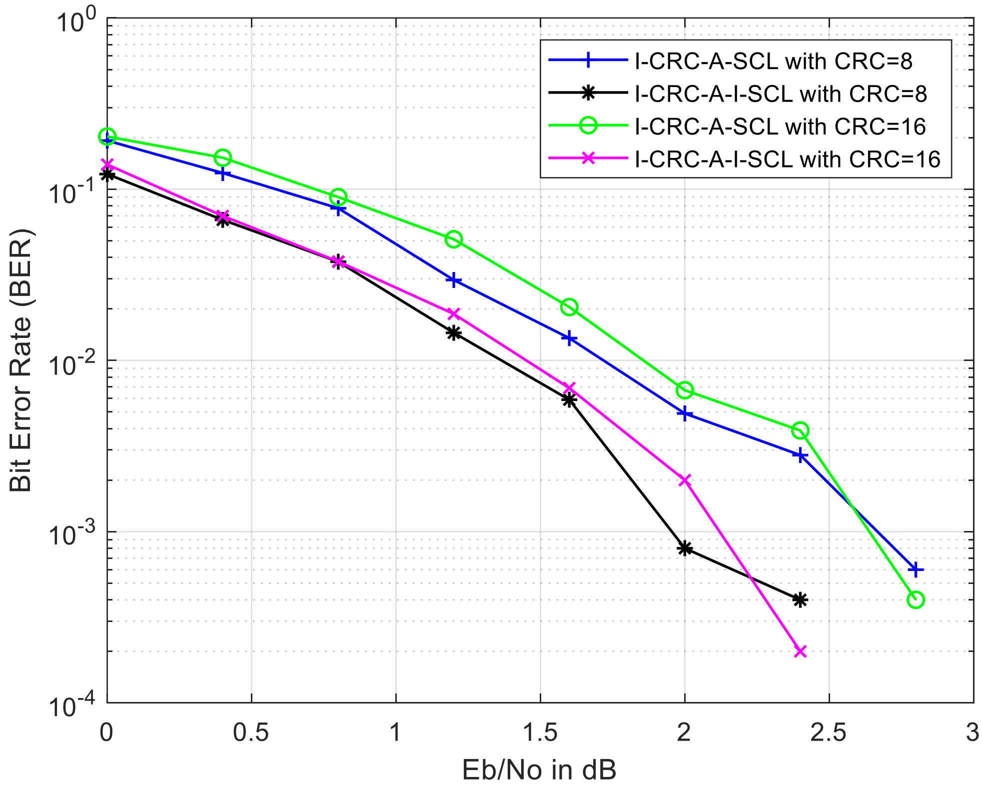

Figure 4.11 BER versus Eb/No for I-CRC-A-SCL and I-CRC-A-I-SCL polar coding schemes by varying CRC length

In figure 4.11 we have plotted the BER versus Eb/No for both polar coding schemes at CRC-length 8 and 16. As we have shown in the figure the performance of the I-CRC-A-I-SCL polar coding scheme at CRC length 16 has better performance than the I-CRC-A-I-SCL at CRC length of 8 and I-CRC-A-SCL polar coding scheme at CRC length of 8 and 16. The performance of the I-CRC-A-SCL polar coding scheme at CRC length 16 is also better than the I-CRC-A-SCL polar coding scheme at CRC length of 8. But further increasing the CRC length is no more important in polar coding schemes.

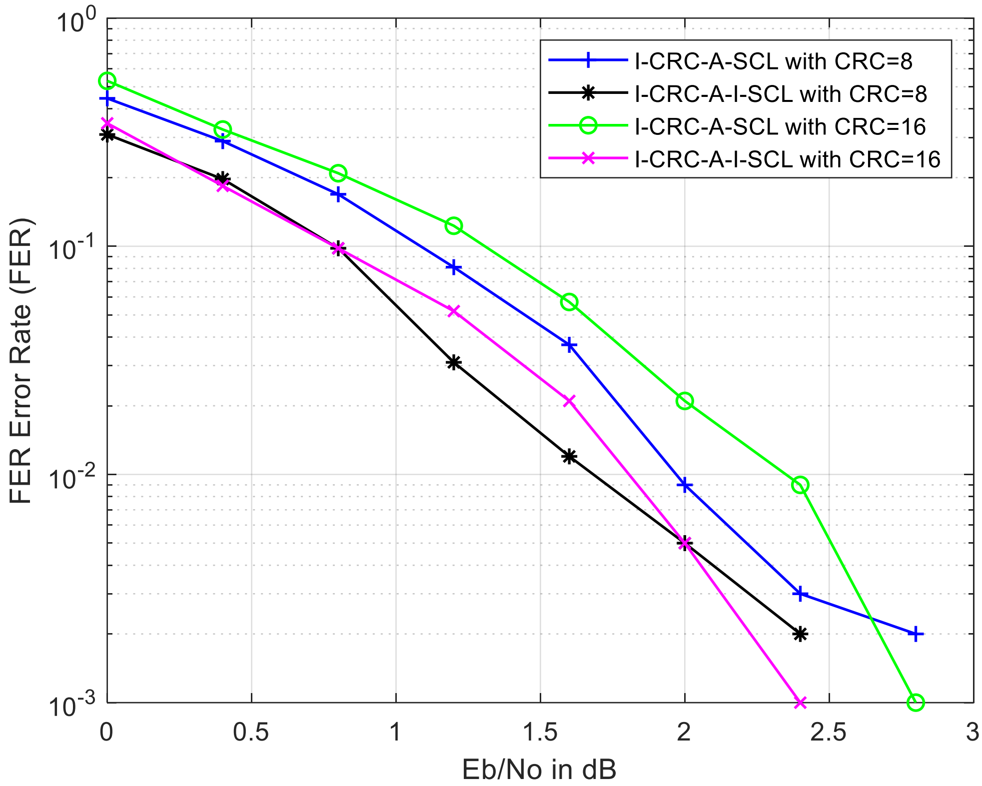

Figure 4.12 FER versus Eb/No for I-CRC-A-SCL and I-CRC-A-I-SCL polar coding schemes by varying CRC length

In figure 4.12 we have plotted FER versus Eb/No for I-CRC-A-SCL polar coding scheme and I-CRC-A-I-SCL polar coding scheme at different CRC lengths. As we have shown in figure 4.12 the performance of both polar coding schemes increases with increasing CRC length. The FER value of the I-CRC-A-I-SCL polar coding scheme at CRC length 16 has a better performance compared to I-CRC-A-SCL polar coding scheme at CRC lengths 8 and 16. When we see the performance of the I-CRC-A-SCL polar coding scheme at CRC lengths 8 and 16; the performance of the I-CRC-A-SCL polar coding scheme at list size 16 has a better performance compared to I-CRC-A-SCL polar coding scheme at list size 8.

4.8 BER and FER Analysis and Comparison of CRC-A-I-SCL and I-CRC-A-I-SCL Polar Codes by Varying Code Rate

In this simulation, we have compared the performance of the CRC-A-I-SCL polar coding scheme and the I-CRC-A-I-SCL polar coding scheme by plotting BER versus Eb/No and FER versus Eb/No at different code rate. The performance of both coding schemes is compared under AWGN channel and BPSK modulation. The main target of this part of our simulation is to study the effect of code rate on both coding schemes. We have used the parameters listed in table 4.11. From these parameters, we have used list size 8, code rate 1/4 and 1/2, and CRC length 4.

Table 4.11 Simulation parameters for comparing CRC-A-I-SCL and I-CRC-A-I-SCL polar coding schemes at different code rate

Polar block size	(32,128), (64,128)
Code rate	1/4, 1/2
Block Size/Frame size	1000
Eb/No	0.4-3.6dB
List size	8
CRC-length	4

In figure 4.13 BER versus Eb/No for CRC-A-I-SCL and I-CRC-A-I-SCL polar coding schemes is plotted. The analysis and comparison of CRC-A-I-SCL and I-CRC-A-I-SCL polar coding schemes are simulated at code rates of 1/4 and 1/2 with a frame size of 1000 which we have listed in table 4.11. We also considered the list size and CRC length 8 and 4 respectively. As we have shown in figure 4.13 and table 4.12 the performance of CRC-A-I-SCL and I-CRC-A-I-SCL degrades with increasing the code rate. Generally, the performance of polar coding schemes degrades with increasing the code rate. From this simulation, we have understood that code rate has a greater effect on the performance of polar coding schemes. When we compare both CRC-A-I-SCL and I-CRC-A-I-SCL the performance of I-CRC-A-I-SCL has better than CRC-A-I-SCL polar coding scheme. By considering the Eb/No value 1.6dB at a code rate of 1/4 the bit error rate of CRC-A-I-SCL is 0.0018 (0.18%) means 0.18% bits are in error and the bit error rate of I-CRC-A-I-SCL is 0.0005 (0.05%) this also means 0.05% bits are in error as we have understood from those results I-CRC-A-I-SCL polar coding scheme has better performance. When we increase the code rate from ¼ to ½ this means at a code rate of ½ the bit error rate of CRC-A-I-SCL at 1.6dB is 0.0102 (1.02%) this shows there are 1.02% bits in error and the bit error rate of I-CRC-A-I-SCL is increased to 0.0071 (0.71%). As we have understood from figure 4.13 and Table 4.12 by taking sample Eb/No value of 1.6dB; the performance of the I-CRC-A-I-SCL polar coding scheme is reduced by increasing the code rate from 1/4 to 1/2. The effect of code rate on I-CRC-A-I-SCL polar coding scheme at Eb/No value of 1.6dB there are 0.05% of bits are in error at a code rate of ¼ and by increasing the code rate to ½ there are 0.71% of bits in error. When we see the effect of code rate in polar coding schemes as the code rate linearly increases there is a loss or degradation in the performance of polar coding schemes.

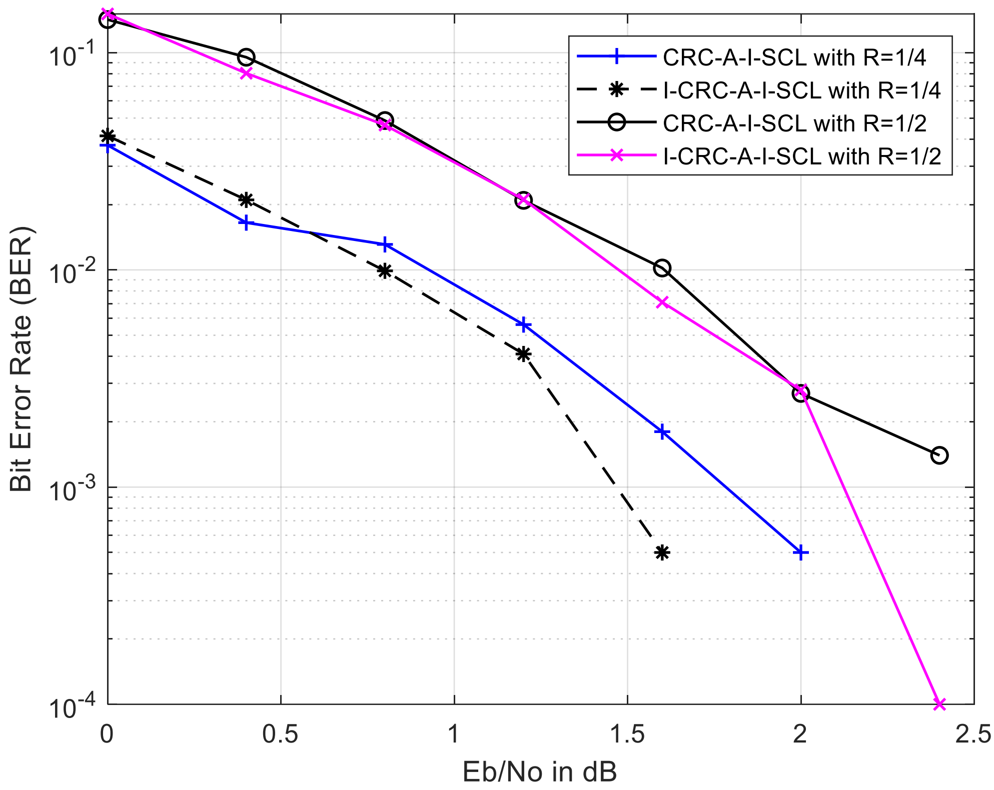

Figure 4.13 BER versus Eb/No for CRC-A-I-SCL and I-CRC-A-I-SCL polar coding schemes with different code rates and fixed list size

At lower Eb/No value the performance of both polar coding schemes is almost the same. When Eb/No increases the performance of the I-CRC-A-I-SCL polar coding scheme increases grammatically as shown in figure 4.13. The performance of the I-CRC-A-I-SCL polar coding scheme is better than the performance of the CRC-A-I-SCL polar coding scheme at a higher Eb/No value and lower code rate.

Table 4.12 BER for the comparison and analysis of CRC-A-I-SCL and I-CRC-A-I-SCL polar coding schemes at different code rate

Eb/No in dB	BER			
	CRC-A-I-SCL polar		I-CRC-A-I-SCL polar	
	Rate		Rate	
	1/4	1/2	1/4	1/2
0.4	0.0165	0.0953	0.021	0.0804
0.8	0.0131	0.0487	0.0099	0.0464
1.2	0.0056	0.0211	0.0041	0.0211
1.6	0.0018	0.0102	0.0005	0.0071
2	0.0005	0.0027	0	0.0028
2.4	0	0.0014	0	0.0001
2.8	0	0	0	0
3.2	0	0	0	0
3.6	0	0	0	0

In figure 4.14 the FER versus Eb/No for CRC-A-I-SCL polar coding scheme and I-CRC-A-I-SCL polar coding scheme is plotted at different code rates. In this simulation, we consider different code rates like 1/4 and 1/2. From this simulation, we have understood that the values of BER and FER increase with increasing code rate. Due to this, the performance of both polar coding schemes decreases with increasing code rates. When we compare the performance of both polar codes according to their FER value the performance of the I-CRC-A-I-SCL polar coding scheme has better performance than CRC-A-I-SCL polar coding scheme. From table 4.13 when we take the Eb/No value of 2.4dB 0 frames are in error for CRC-A-I-SCL polar coding scheme at a code rate of 1/4 and 3 frames are in error at a code rate of 1/2. When we see the performance of I-CRC-A-I-SCL at the same Eb/No value 0 frames are in error at a code rate of 1/4 and 1 frame is in error at a code rate of 1/2 out of 1000 frames. In this case, as we have understood from this simulation result the performance of the I-CRC-A-I-SCL polar coding scheme at different code rates has better performance than CRC-A-I-SCL polar coding schemes.

Due to its high-performance I-CRC-A-I-SCL polar coding scheme is used in 5G wireless communication networks that need lower BER value and FER value.

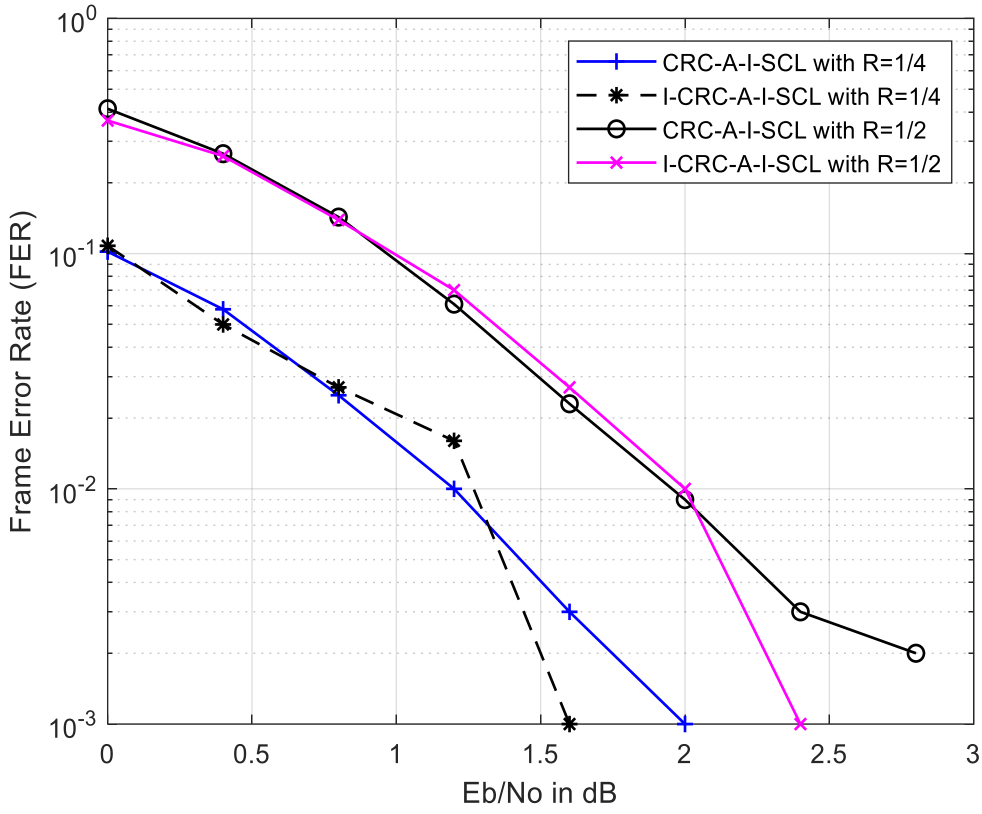

Figure 4.14 FER versus Eb/No for CRC-A-I-SCL and I-CRC-A-I-SCL polar coding schemes at different code rates and list size 8

I-CRC-A-I-SCL polar coding scheme combines the advantages of both Interleaved-CRC-A-SCL (I-CRC-A-SCL) polar coding scheme and the CRC-A-Interleaved-SCL (CRC-A-I-SCL) polar coding scheme. As we have tried to define in Chapter 3 I-CRC-A-SCL polar coding scheme is used to early detect errors and CRC-A-I-SCL polar coding scheme is used to mitigation of burst errors. In this case, I-CRC-A-I-SCL polar coding scheme combines both early error detection and mitigation of burst errors in 5G wireless communication networks. By combining those two improvements of the polar coding scheme I-CRC-A-I-SCL polar coding scheme has better performance in terms of both FER and BER.

Table 4.13 FER for the comparison and analysis of CRC-A-SCL and I-CRC-A-SCL polar coding schemes

Eb/No in dB	FER			
	CRC-A-I-SCL polar		I-CRC-A-I-SCL polar	
	Rate		Rate	
	1/4	1/2	1/4	1/2
0.4	0.058	0.266	0.05	0.26
0.8	0.025	0.143	0.027	0.139
1.2	0.01	0.061	0.016	0.07
1.6	0.003	0.023	0.001	0.027
2	0.001	0.009	0	0.01
2.4	0	0.003	0	0.001
2.8	0	0.002	0	0
3.2	0	0	0	0
3.6	0	0	0	0

4.9 BER and FER Analysis and Comparison of CRC-A-I-SCL Polar and I-CRC-A-I-SCL Polar by varying List Size

In this part of our simulation, we have compared both CRC-A-I-SCL polar coding scheme and I-CRC-A-I-SCL polar coding scheme at different list sizes. We have used the parameters listed in table 4.12 to compare these polar coding schemes at different list sizes, code rate 1/2, and CRC length 16 for 1000 frames.

Table 4.14 Simulation Parameters to compare CRC-A-I-SCL and I-CRC-A-I-SCL by varying list size at code rate 1/2

Polar block size	(64,128)
Code rate	1/2
Frame size/No of frames	1000
List size	8,16
CRC length	16
Eb/No	0.4-3.6dB

In this simulation, the bit error rate versus Eb/No and frame error rate versus Eb/No are plotted for different bit energy-to-noise spectral ratios (Eb/No). The encoder has 48 information bits and 128 codeword length which means the code rate is 1/2 with 80 bits for redundancy.

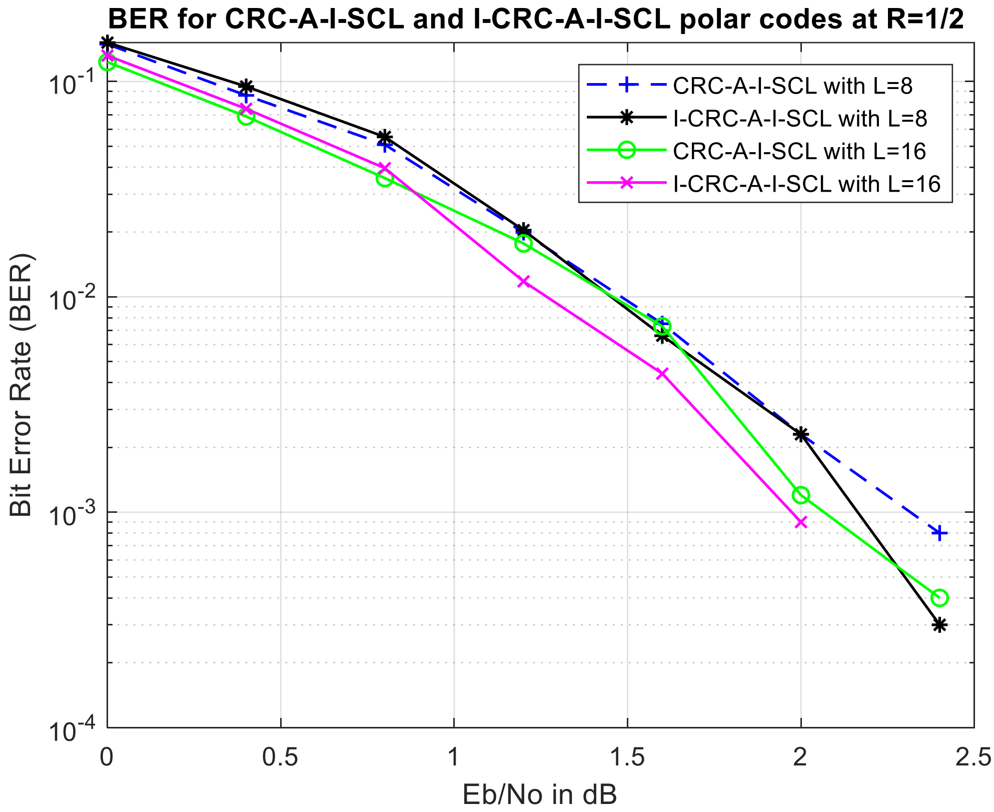

Figure 4.15 BER versus Eb/No for CRC-A-I-SCL and I-CRC-A-I-SCL polar coding schemes by varying list size at code rate 1/2 and CRC length 16

But we have 16 CRC bits there will be 64 redundant bits with zero assigned in their position according to the reliability sequence. The SCL decoder produces 8 different decoded messages and from these 8 decoded messages the CRC detector selects the best message from the list. As shown in the figure 4.15 the list size is changed from 8 to 16 for both polar coding schemes. When the list size increases from 8 to 16 the decoder produces 16 different decoded messages so there will be more options for the CRC detector. As we try to say in the above the encoder has 48 information bits and 128 codeword length bits which means the code rate is 1/2 with 80 bits for redundancy. In this simulation with Eb/No of 2.4dB, we obtain 0.08% BER for CRC-A-I-SCL at a list size 8 and by increasing the list size to 16 the BER will be 0.04%. When we see the BER of the I-CRC-A-I-SCL polar coding scheme at both list sizes; at the list size of 8 the BER is 0.03% and at the list size of 16 it is reduced to 0%. As we have understood from this simulation as list size increases the performance of both coding schemes increases up to the limit. Increasing the list size further is not necessary.

Table 4. 15 BER for the comparison and analysis of CRC-A-I-SCL and I-CRC-A-I-SCL polar coding schemes at code rate 1/2

Eb/No in dB	BER			
	CRC-A-I-SCL polar		I-CRC-A-I-SCL polar	
	List size		List size	
	8	16	8	16
0.4	0.0862	0.0688	0.0948	0.0747
0.8	0.0509	0.0356	0.0553	0.0396
1.2	0.0204	0.0177	0.0204	0.0118
1.6	0.0075	0.0073	0.0066	0.0044
2	0.0023	0.0012	0.0023	0.0009
2.4	0.0008	0.0004	0.0003	0
2.8	0	0	0	0
3.2	0	0	0	0
3.6	0	0	0	0

In figure 4.16 the FER versus Eb/No is simulated at different list sizes for both CRC-A-I-SCL polar coding scheme and I-CRC-A-I-SCL polar coding scheme. At Eb/No of 2.4dB, the FER value for CRC-A-I-SCL polar coding scheme at list size 8 is 0.2% and when we increase the list size to 16 the FER value is reduced to 0.1%. In the case of the I-CRC-A-I-SCL polar coding scheme, the FER value is given as 0.2% at a list size of 8 and 0% at a list size of 16. In this case, also the performance of both coding schemes increases in a good manner.

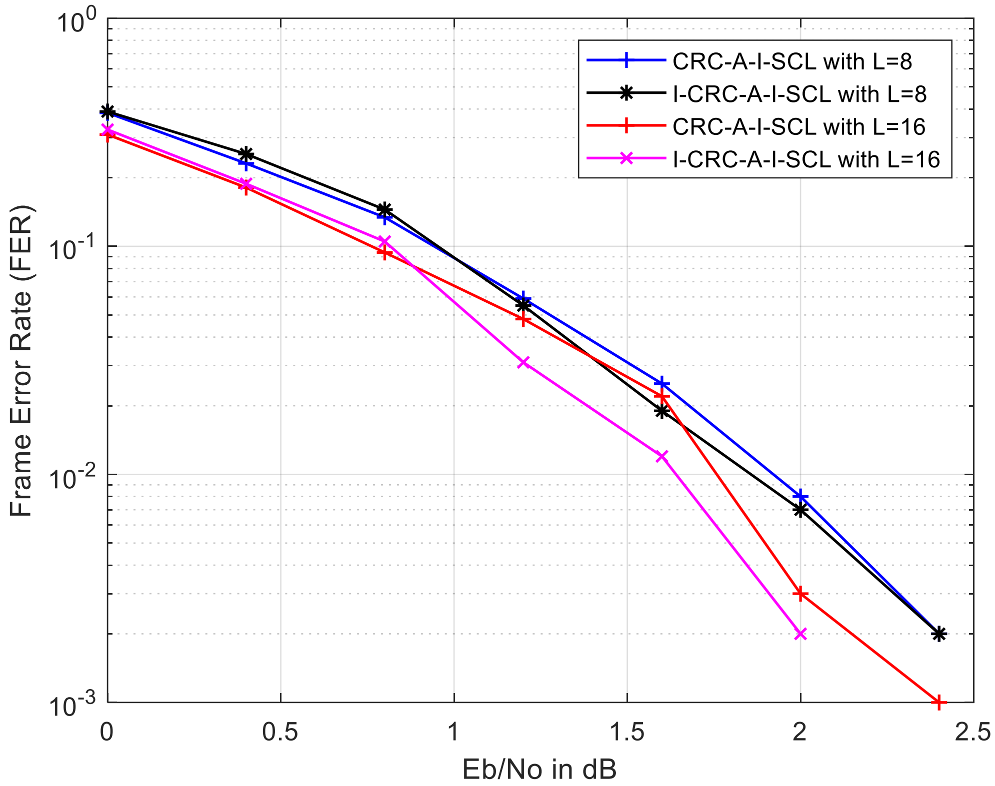

Figure 4.16 FER versus Eb/No for CRC-A-I-SCL and I-CRC-A-I-SCL polar coding schemes by varying list size at code rate1/2 and CRC length 16

When the list size is increased the receiver has much more candidates to the decoder this helps the receiver to get error-free information because if there are more candidates in the polar decoder this increases the chances of finding the correct codeword and thereby improving the error correction performance. As we have shown from both figures the performance is affected by the list size. But increasing the list size further is not recommended. Generally, when we compare the performance of both polar coding schemes I-CRC-A-I-SCL has higher performance than CRC-A-I-SCL polar coding scheme because it can mitigate burst errors and detects the error early. Therefore I-CRC-A-I-SCL polar coding scheme is better relative to CRC-A-I-SCL polar coding schemes.

Table 4.16 FER for the comparison and analysis of CRC-A-I-SCL and I-CRC-A-I-SCL polar coding schemes at code rate 1/2

Eb/No in dB	FER			
	CRC-A-I-SCL		I-CRC-A-I-SCL	
	List size		List size	
	8	16	8	16
0.4	0.231	0.181	0.254	0.188
0.8	0.134	0.094	0.145	0.105
1.2	0.059	0.048	0.055	0.031
1.6	0.025	0.022	0.019	0.012
2	0.008	0.003	0.007	0.002
2.4	0.002	0.001	0.002	0
2.8	0	0	0	0
3.2	0	0	0	0
3.6	0	0	0	0

4.10 BER and FER Analysis and Comparison of CRC-A-I-SCL Polar Coding Scheme and I-CRC-A-I-SCL Polar Coding Scheme by varying CRC Length

In this simulation, we have compared CRC-A-I-SCL polar coding scheme and I-CRC-A-I-SCL polar coding scheme by plotting both BER versus Eb/No and FER versus Eb/No at different CRC lengths. In this part of our simulation, we have understood the effect of changing CRC length on the CRC-A-I-SCL polar coding scheme and the I-CRC-A-I-SCL polar coding scheme. For the full completion of this simulation, we have used the parameters listed in table 4.17.

Table 4.17 Simulation Parameters for comparison and analysis of CRC-A-I-SCL and I-CRC-A-I-SCL polar coding schemes by varying CRC length at code rate 1/2

Polar block size	(64,128)
Code rate	1/2
Block size/Frame size	1000
List size	16
CRC length	8,16
Eb/No	0.4-3.6dB

Both BER versus Eb/No and FER versus Eb/No are plotted in Figure 4.17 and Figure 4.18 for different CRC lengths with code rate of 1/2 and list size of 16 under BPSK modulation and AWGN channel respectively to know the effect of changing CRC length on both CRC-A-I-SCL polar coding scheme and I-CRC-A-I-SCL polar coding scheme.

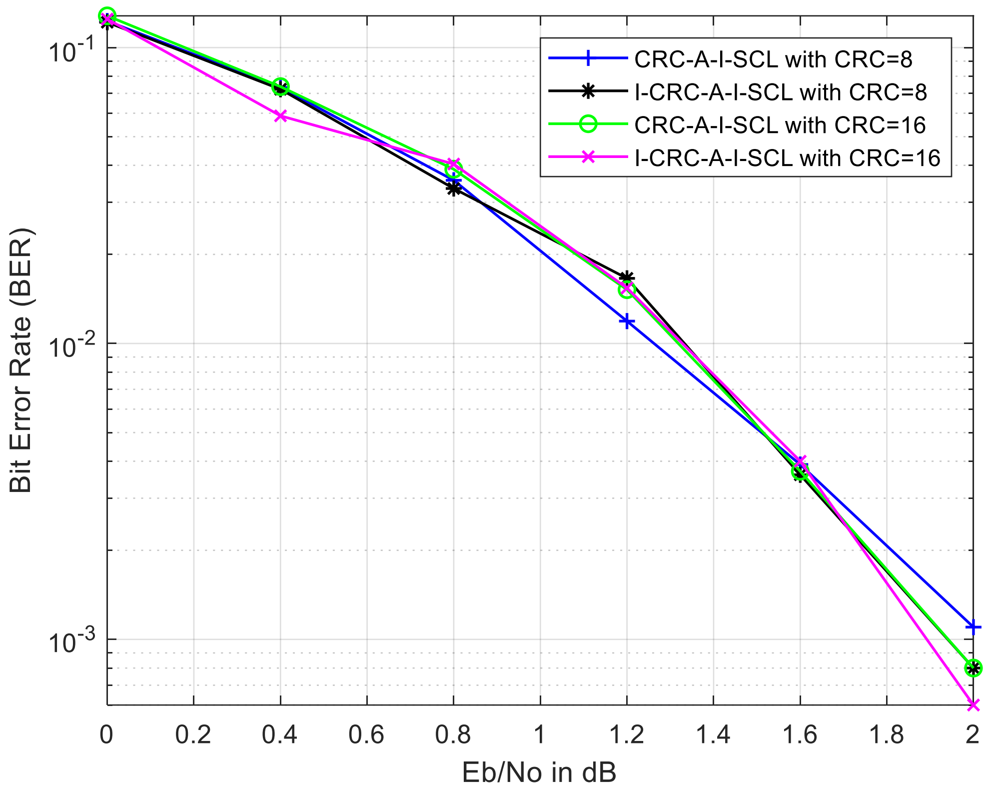

Figure 4.17 BER versus Eb/No for CRC-A-I-SCL and I-CRC-A-I-SCL polar coding schemes by varying CRC length at list size16

As we have shown in figure 4.17 as the CRC length increases the performance of both polar coding schemes increases. The performance of the I-CRC-A-I-SCL polar coding scheme at CRC length 16 has a better performance compared to I-CRC-A-I-SCL at CRC length 8 and CRC-A-I-SCL at CRC lengths 8 and 16. I-CRC-A-I-SCL polar coding scheme at CRC length 8 has almost the same performance as CRC-A-I-SCL polar coding schemes. When we compare the performance of the CRC-A-I-SCL polar coding scheme at a CRC length of 16 and 8; CRC-A-I-SCL at a CRC length of 16 has better performance than the CRC-A-I-SCL polar coding scheme at a CRC length of 8. We have also plotted the FER versus Eb/No for both polar coding schemes at different CRC lengths in figure 4.18 as we have said above.

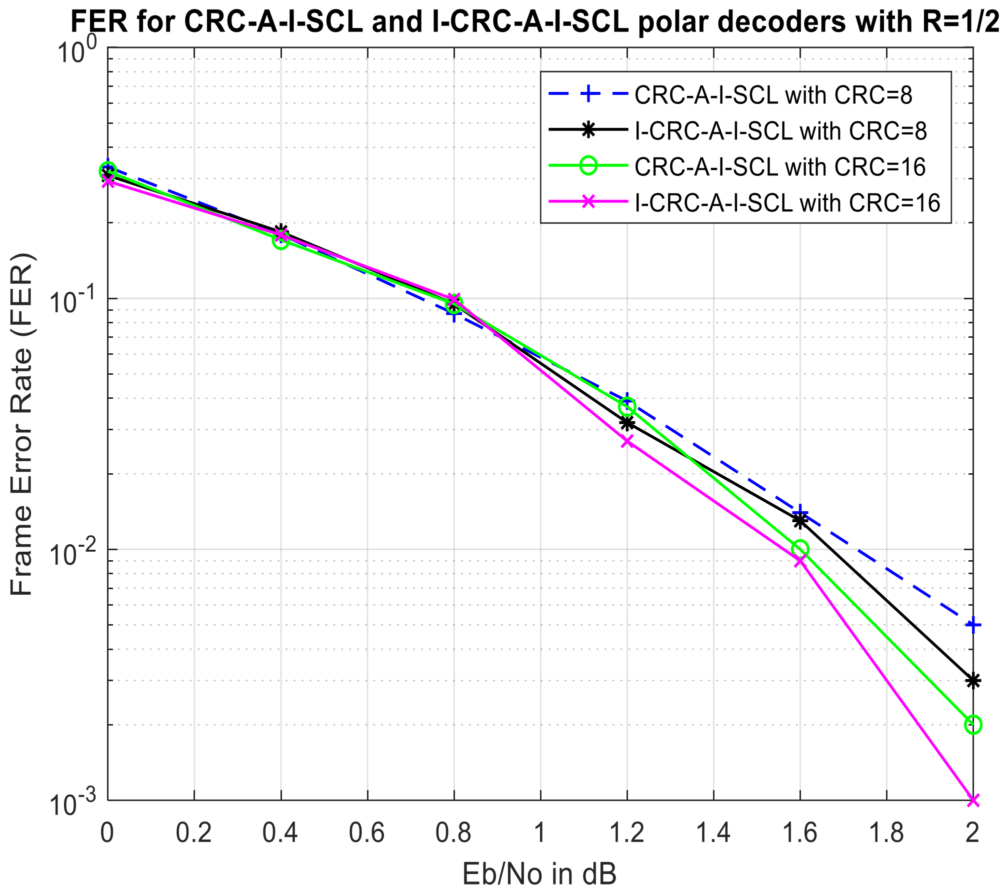

Figure 4.18 FER versus Eb/No for CRC-A-I-SCL and I-CRC-A-I-SCL polar coding schemes by varying CRC length at list size16

In this simulation, we have understood that the value of the FER decreases as the CRC length increases. As shown in figure 4.18 the performance of both coding schemes increases as the CRC length increases. From this part of our simulation, we have tried to understand the effect of CRC length on both the CRC-A-I-SCL polar coding scheme and the I-CRC-A-I-SCL polar coding scheme. Increasing the CRC length reduces the BER and FER values by increasing the error detection ability of polar coding schemes but increasing the CRC length further is not good in polar coding schemes.

4.11 BER and FER Analysis and Comparison of Polar Coding Schemes at Code Rate 1/4

To compare the performance of all polar coding schemes which are included in our work, we have used the following simulation parameters which are listed in table 4.18. These polar coding schemes are compared under the AWGN channel and BPSK modulation scheme. In this simulation, we have used a code rate of 1/4, a frame size of 1000, a CRC length of 8, and a list size of 8. The list size and CRC length are not considered for both SC and I-SC polar coding schemes because SC and I-SC polar coding schemes are undependable in list size and CRC length

Table 4.18 Simulation parameters for comparison of polar coding schemes at code rate 1/4

Parameter	SC polar	I-SC polar	CRC-A-SCL polar	I-CRC-A-SCL polar	CRC-A-I-SCL polar	I-CRC-A-I-SCL polar
Code rate	1/4	1/4	1/4	1/4	1/4	1/4
No of Frames	1000	1000	1000	1000	1000	1000
CRC length	-	-	8	8	8	8
Polar block size	(32,128)	(32,128)	(32,128)	(32,128)	(32,128)	(32,128)
List size	-	-	8	8	8	8

The performance comparison and analysis of all polar coding schemes such as SC polar coding scheme, I-SC polar coding scheme, CRC-A-SCL polar coding scheme, I-CRC-A-SCL polar coding scheme, CRC-A-I-SCL polar coding scheme, and I-CRC-A-I-SCL polar coding scheme are compared by plotting the BER versus Eb/No and FER versus Eb/No in dB at a code rate of 1/4, list size 8 and CRC length 8 for different Eb/No value. We have tabulated the result of the BER value in table 4.19 and the FER value in table 4.20 for the SC polar coding scheme and I-SC polar coding scheme with a polar block size of (32,128) and code rate 1/4 and for CRC-A-SCL, I-CRC-A-SCL, CRC-A-I-SCL and I-CRC-A-I-SCL polar coding schemes with list size 8 and CRC length 8.

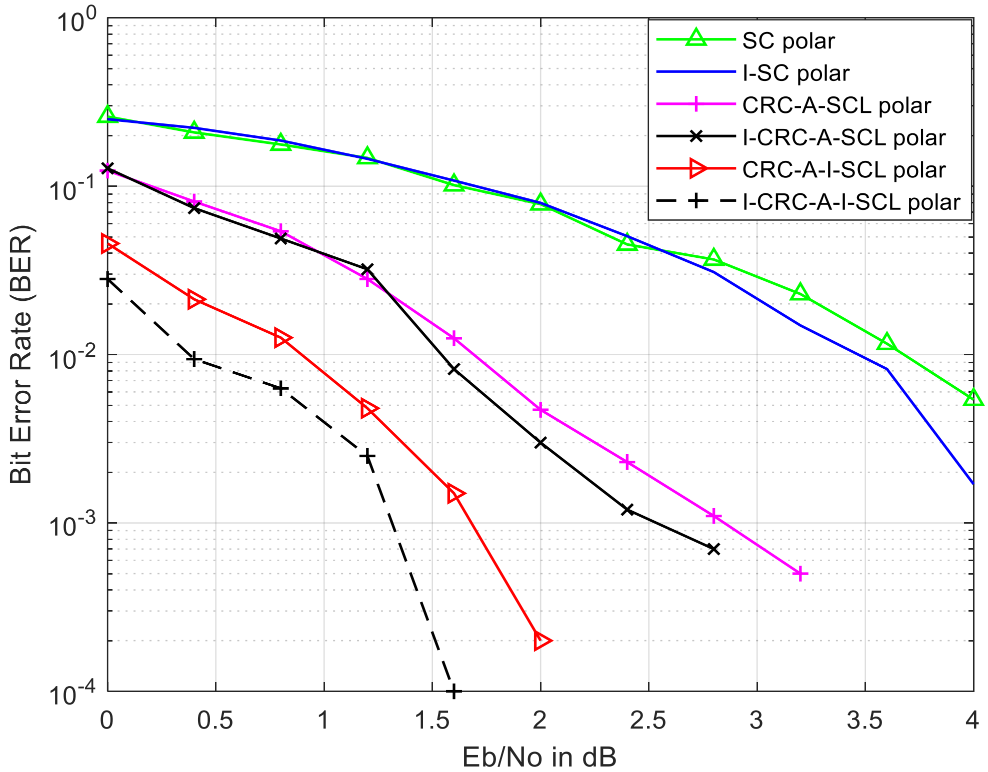

Figure 4.19 BER versus Eb/No for all polar coding schemes at code rate 1/4

Table 4.19 BER for comparison of polar coding schemes at R 1/4

Eb/No in dB	BER					
	SC polar	I-SC polar	CRC-A-SCL polar	I-CRC-A-SCL polar	CRC-A-I-SCL polar	I-CRC-A-I-SCL polar
0.4	0.2087	0.2221	0.0811	0.0741	0.0213	0.0094
0.8	0.1769	0.1867	0.054	0.0489	0.0126	0.0063
1.2	0.1454	0.1454	0.0281	0.0321	0.0048	0.0025
1.6	0.1015	0.108	0.0125	0.0082	0.0015	0.0001
2	0.0782	0.0796	0.0047	0.003	0.0002	0
2.4	0.0451	0.0505	0.0023	0.0012	0	0
2.8	0.0367	0.0309	0.0011	0.0007	0	0
3.2	0.0229	0.0149	0.0005	0	0	0
3.6	0.0116	0.0082	0	0	0	0

When we see in table 4.19 the values of the BER are tabulated from figure 4.19. If we take the Eb/No value of 2dB for the SC polar coding scheme 7.82% bits are in error; we also see that there are 0.47% bits in error at the same Eb/No value for CRC-A-SCL polar coding scheme. In the transition of polar coding schemes from SC polar coding scheme to CRC-A-SCL polar coding scheme, there is a gain of 12.8dB Eb/No approximately. When we see the gap between CRC-A-SCL and I-CRC-A-SCL polar coding schemes by taking the Eb/No value 2.4dB; the BER value of CRC-A-SCL polar is 0.23% and the BER value of I-CRC-A-SCL polar coding scheme is 0.12%. The gain in Eb/No between these coding schemes is 4.45dB. When we see I-CRC-A-I-SCL and CRC-A-I-SCL polar coding schemes; the BER value of CRC-A-I-SCL polar coding scheme at Eb/No of 1.6dB is 0.15% and also the BER value of I-CRC-A-I-SCL polar coding scheme at the same Eb/No is 0.01%. Compared to CRC-A-I-SCL polar coding schemes I-CRC-A-I-SCL polar coding scheme has a gain of 11.76dB. Therefore, this shows that I-CRC-A-I-SCL polar coding schemes have a significant improvement in error correction performance and it shows that it is an effective polar coding scheme in improving the reliability of 5G wireless communication networks relative to other polar coding schemes because of better error correction performance.

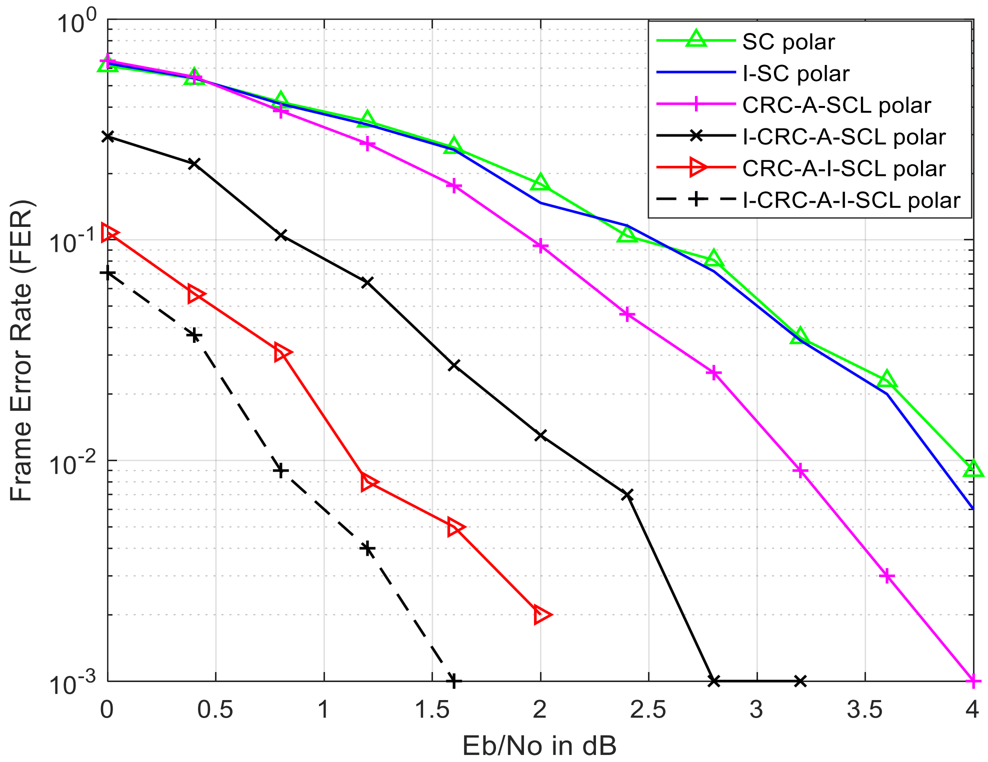

Figure 4.20 FER versus Eb/No for all polar coding schemes at code rate 1/4

Table 4.20 FER for comparison of all polar coding schemes at code rate 1/4

Eb/No in dB	FER					
	SC-polar	I-SC polar	CRC-A-SCL polar	I-CRC-A-SCL polar	CRC-A-I-SCL polar	I-CRC-A-I-SCL polar
0.4	0.548	0.548	0.548	0.221	0.057	0.037
0.8	0.413	0.412	0.384	0.105	0.031	0.009
1.2	0.345	0.333	0.273	0.064	0.008	0.004
1.6	0.262	0.256	0.176	0.027	0.005	0.001
2	0.179	0.147	0.094	0.013	0.002	0
2.4	0.104	0.116	0.046	0.007	0	0
2.8	0.081	0.072	0.025	0.001	0	0
3.2	0.036	0.035	0.009	0.001	0	0
3.6	0.023	0.02	0.003	0	0	0

From figure 4.20 the FER value of polar coding schemes is evaluated in table 4.20. From this table when we take Eb/No value 1.6dB there are 262 frames in error out of 1000 frames in SC polar coding scheme and also when we see the FER value of I-SC polar coding scheme, CRC-A-SCL polar coding scheme, I-CRC-A-SCL polar coding scheme, CRC-A-I-SCL polar coding scheme and I-CRC-A-I-SCL polar coding scheme are 256, 176, 27, 5 and 1 frames are in error out of 1000 frames respectively. From this result, we have understood that more frames are in error for SC and I-SC polar coding schemes. When we compare the number of frames present in error for CRC-A-SCL, I-CRC-A-SCL, CRC-A-I-SCL, and I-CRC-A-I-SCL polar coding schemes fewer frames are in error in I-CRC-A-I-SCL polar coding scheme. From this understanding, I-CRC-A-I-SCL polar coding scheme is better for 5G wireless communication networks due to its greater improvement in error correction performance.

4.12 BER and FER Analysis and Comparison of Polar Coding Schemes at Code Rate 1/2 and List Size 8

In this part of our simulation, the performance of polar coding schemes is compared and analyzed at a code rate of 1/2, list size 8, and CRC length 8 as we have listed in table 4.21. In this case, only the code rate is changed from 1/4 to 1/2 from the previous part of our simulation which focuses on code rate 1/4 but other parameters are the same like list size and CRC length. We need to understand the effect of increasing code rate on polar coding schemes by keeping another parameter constant. In our previous simulations, we have done the performance evaluation of polar coding schemes at a code rate of 1/4. In this case, also we have used BPSK modulation and the AWGN channel model.

Table 4.21 Simulation Parameters for Comparison of Polar Coding Schemes at code rate 1/2 and List size 8

Parameters	SC polar	I-SC polar	CRC-A-SCL polar	I-CRC-A-SCL polar	CRC-A-I-SCL polar	I-CRC-A-I-SCL polar
Code rate	1/2	1/2	1/2	1/2	1/2	1/2
Frame size	1000	1000	1000	1000	1000	1000
CRC length	-	-	8	8	8	8
Polar block size	(64,128)	(64,128)	(64,128)	(64,128)	(64,128)	(64,128)
List size	-	-	8	8	8	8

In this part of our work, we have understood the effect of code rate by plotting BER versus Eb/No and FER versus Eb/No for all polar coding schemes that we have included in our context. We have used the parameters such as polar block size (64,128), frame size 1000, CRC length 8, and list size 8. In this simulation, we have tried to study the effect of changing the code rate from the previous simulation by keeping another parameter constant.

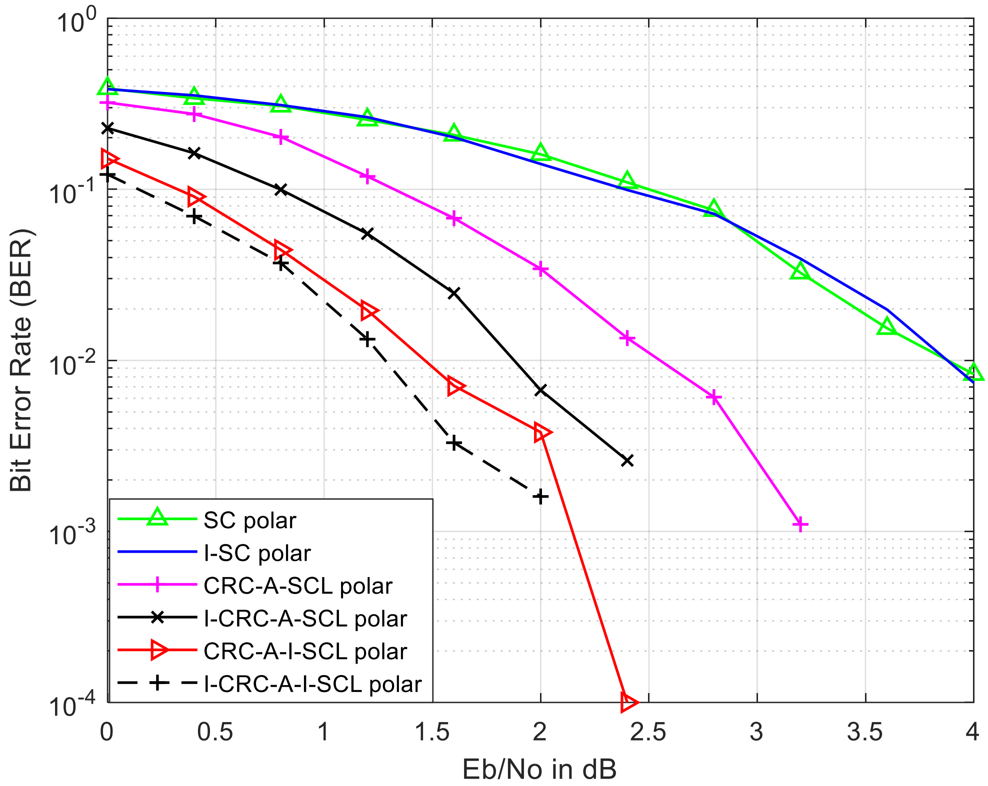

Figure 4.21 BER versus Eb/No for all polar coding schemes at code rate 1/2

As shown in figure 4.21 which shows the plot of BER versus Eb/No for polar coding schemes. From this simulation part, CRC-A-I-SCL and I-CRC-A-I-SCL polar coding schemes have better performance relative to other polar coding schemes as we have shown from the result in table 4.22. When we evaluate the performance analysis of polar coding schemes for a code rate of 1/2 at list size 8 and CRC length 8 the value of the BER for I-CRC-A-I-SCL polar coding schemes at Eb/No value of 2dB is 0.0016 means there are 0.16% bits in error and also the BER value of CRC-A-I-SCL polar coding scheme is 0.0038 this also indicates 0.38% bits are in error. When we compare both these coding schemes there is a gain of 4.62dB in the I-CRC-A-I-SCL polar coding scheme relative to the CRC-A-I-SCL polar coding scheme. When we see polar coding schemes at a code rate of 1/4 at Eb/No of 2dB the BER value of CRC-A-I-SCL polar coding scheme is 0.0002 means there are 0.02% bits in error and for I-CRC-A-I-SCL polar coding scheme the BER value is 0 means there are 0% bits in error. From this result, the performance of a polar coding scheme at a low code rate is higher than the performance at a greater code rate. As we have shown in our result the value of BER for I-CRC-A-I-SCL is 0 because we have used less number of transmitted bits which is why BER becomes 0.

Table 4.22 BER for comparison of polar coding schemes at code rate 1/2 and list size 8

Eb/No in dB	BER					
	SC polar	I-SC polar	CRC-A-SCL polar	I-CRC-A-SCL polar	CRC-A-I-SCL polar	I-CRC-A-I-SCL polar
0.4	0.3407	0.3541	0.2755	0.1627	0.0907	0.0697
0.8	0.311	0.311	0.2026	0.0996	0.0443	0.0371
1.2	0.2549	0.264	0.119	0.055	0.0196	0.0133
1.6	0.2078	0.2014	0.0678	0.0247	0.0071	0.0033
2	0.1602	0.1407	0.0343	0.0067	0.0038	0.0016
2.4	0.1098	0.0991	0.0135	0.0026	0.0001	0
2.8	0.0754	0.0719	0.0061	0	0	0
3.2	0.0325	0.0393	0.0011	0	0	0
3.6	0.0154	0.0198	0	0	0	0

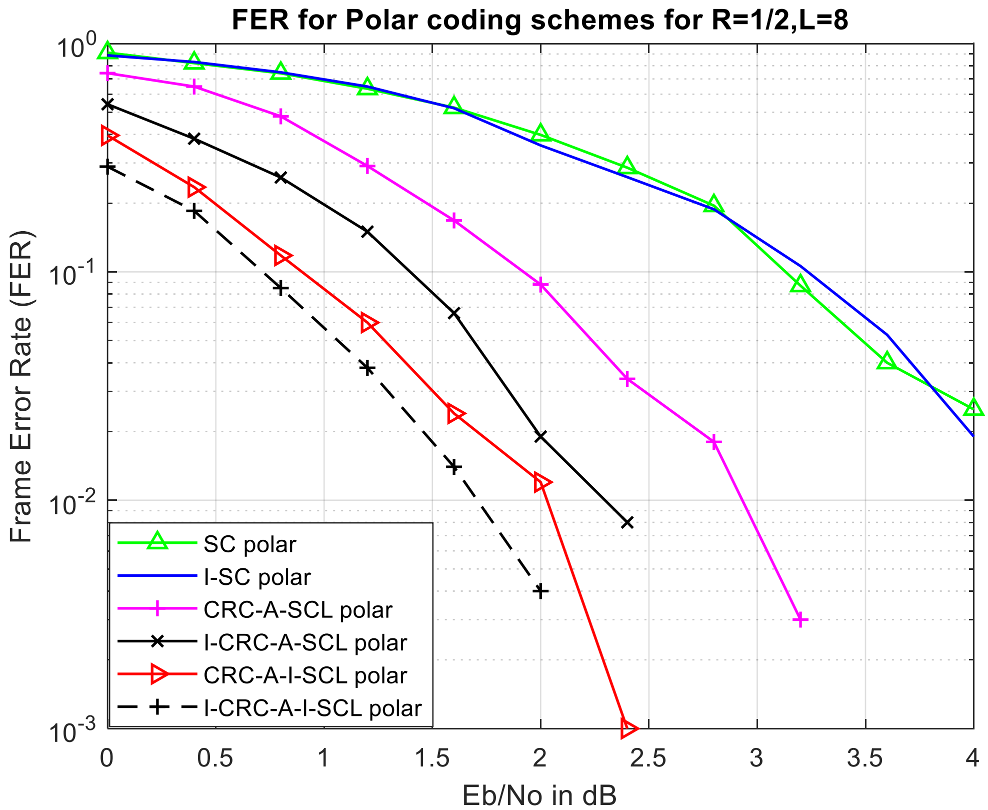

Figure 4.22 FER versus Eb/No for all polar coding schemes at code rate 1/2, list size 8, and CRC length 8

As shown in figure 4.22 FER versus Eb/No is plotted and its result is tabulated in table 4.23. In this case, the CRC-A-I-SCL and I-CRC-A-I-SCL polar coding schemes have better performance than other polar coding schemes. By taking the Eb/No value 2dB there are 19 frames in error out of 1000 frames for I-CRC-A-SCL polar coding scheme, 12 frames are in error out of 1000 frames for CRC-A-I-SCL polar coding scheme and also 4 frames are in error out of 1000 for I-CRC-A-I-SCL polar coding scheme this simulation result is at a code rate of 1/2. As we have shown in the simulation of polar coding schemes at code rate 1/4 at Eb/No 2dB the FER value of the CRC-A-I-SCL polar coding scheme is 2 out of 1000 and I-CRC-A-I-SCL polar coding scheme has FER value 0 out of 1000. In comparison to the code rate of 1/2, the FER value of CRC-A-I-SCL is 12 and I-CRC-A-I-SCL has a FER value of 4 out of 1000 frames. Therefore, the FER value at code rate 1/4 is less than the FER value at code rate 1/2. From this understanding, the BER and FER values have a direct proportion to the code rate and we conclude that the performance of polar coding schemes at code rate 1/4 has better performance than at code rate 1/2.

Table 4.23 FER for comparison of all polar coding schemes at code rate 1/2 and list size 8

Eb/No in dB	FER					
	SC polar	I-SC polar	CRC-A-SCL polar	I-CRC-A-SCL polar	CRC-A-I-SCL polar	I-CRC-A-I-SCL polar
0.4	0.83	0.83	0.648	0.383	0.235	0.185
0.8	0.748	0.748	0.48	0.259	0.118	0.085
1.2	0.634	0.648	0.291	0.15	0.06	0.038
1.6	0.521	0.521	0.168	0.066	0.024	0.014
2	0.398	0.358	0.088	0.019	0.012	0.004
2.4	0.286	0.26	0.034	0.008	0.001	0
2.8	0.195	0.188	0.018	0	0	0
3.2	0.087	0.106	0.003	0	0	0
3.6	0.04	0.053	0	0	0	0

4.13 BER and FER Analysis and Comparison of Polar Coding Schemes at Code Rate 1/2 & List Size 16

In title 4.13 the performance of polar coding schemes is simulated by changing the code rate from 1/4 to 1/2 by holding the list size 8 and CRC length 8 from the previous simulation. In this part of our simulation, the performance of polar coding schemes is evaluated by increasing the list size from 8 to 16 by holding the code rate 1/2 and CRC length 8. For SC polar and I-SC polar coding schemes, the list size is not considered because list size is only considered in SCL polar coding schemes. Parameters are listed in table 4.24.

Table 4.24 Simulation parameters for Comparison of Polar Coding Schemes at code Rate 1/2 & List size 16

Parameters	SC polar	I-SC polar	CRC-A-SCL polar	I-CRC-A-SCL polar	CRC-A-I-SCL polar	I-CRC-A-I-SCL polar
Code rate	1/2	1/2	1/2	1/2	1/2	1/2
Frame size	1000	1000	1000	1000	1000	1000
CRC length	-	-	8	8	8	8
Polar block size	(64,128)	(64,128)	(64,128)	(64,128)	(64,128)	(64,128)
List size	-	-	16	16	16	16

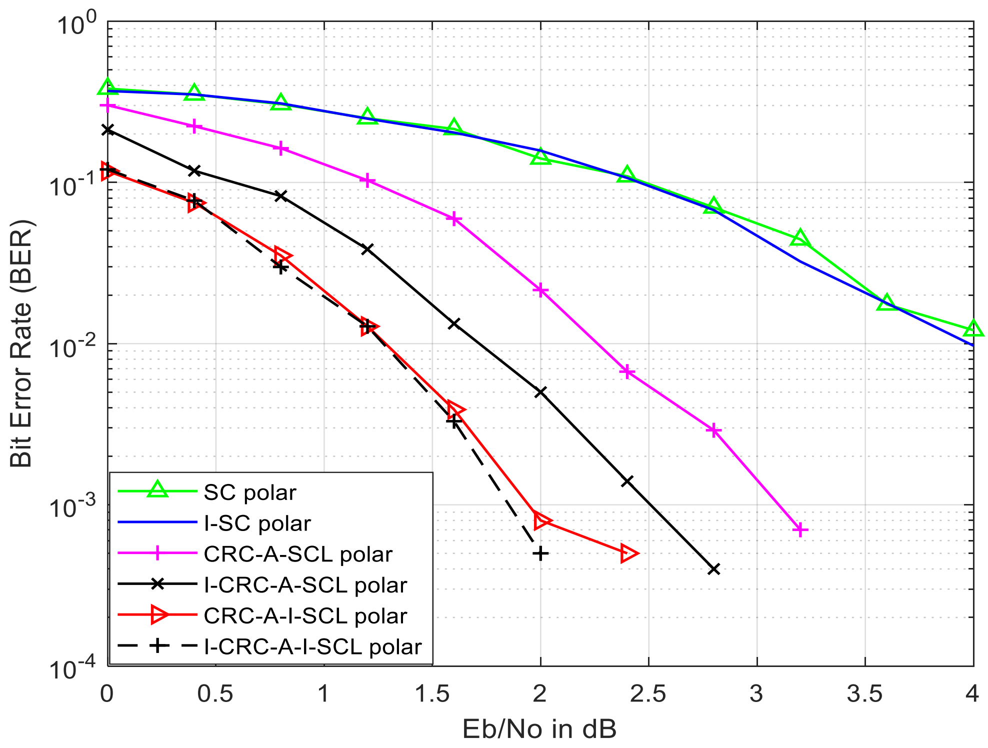

Figure 4.23 BER versus Eb/No for all polar coding schemes at code rate 1/2 & List size 16

Table 4.25 BER for comparison of polar coding schemes at code rate 1/2 & list size 16

Eb/No in dB	BER					
	SC polar	I-SC polar	CRC-A-SCL polar	I-CRC-A-SCL polar	CRC-A-I-SCL polar	I-CRC-A-I-SCL polar
0.4	0.3513	0.3513	0.2234	0.1181	0.0747	0.0771
0.8	0.3093	0.3093	0.163	0.0823	0.0352	0.0299
1.2	0.2485	0.2485	0.103	0.0385	0.0128	0.0128
1.6	0.2145	0.2039	0.0596	0.0133	0.0039	0.0033
2	0.1407	0.1575	0.0215	0.0050	0.0008	0.0005
2.4	0.1092	0.1066	0.0067	0.0014	0.0005	0
2.8	0.0699	0.0674	0.0029	0.0004	0	0
3.2	0.0443	0.0323	0.0007	0	0	0
3.6	0.0178	0.0178	0	0	0	0

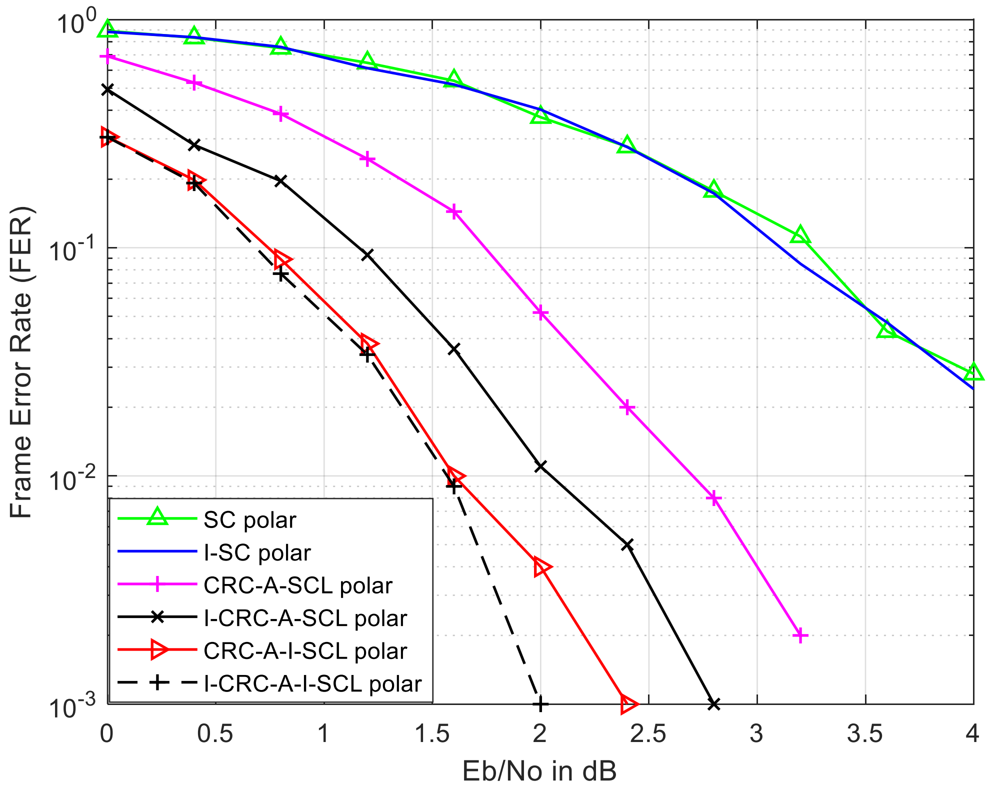

Figure 4.24 FER versus Eb/No for all polar coding schemes at code rate 1/2 & L 16

Table 4.26 FER for comparison of polar coding schemes at code rate 1/2 & list size 16

Eb/No in dB	FER					
	SC polar	I-SC polar	CRC-A-SCL polar	I-CRC-A-SCL polar	CRC-A-I-SCL polar	I-CRC-A-I-SCL polar
0.4	0.836	0.836	0.529	0.282	0.192	0.192
0.8	0.758	0.758	0.386	0.196	0.089	0.077
1.2	0.646	0.612	0.245	0.093	0.038	0.034
1.6	0.539	0.519	0.144	0.036	0.01	0.009
2	0.373	0.403	0.052	0.011	0.004	0.001
2.4	0.276	0.276	0.02	0.005	0.001	0
2.8	0.177	0.173	0.008	0.001	0	0
3.2	0.112	0.085	0.002	0	0	0
3.6	0.043	0.047	0	0	0	0

As we have plotted in figure 4.23 code rate is the most affecting parameter in the performance of polar coding schemes. When the list size increases from 8 to 16 the performance also increased. For a code rate of 1/2 at list size 8 at Eb/No of 2dB for CRC-A-SCL polar coding scheme the BER is 3.43% at list size 8 and when the list size is 16 the BER becomes 2.15%. For I-CRC-A-SCL polar coding scheme the BER value at list size 8 is 0.67% and at list size 16 it is improved to 0.5%. When we see the remaining polar coding schemes CRC-A-I-SCL polar coding scheme has a BER value of 0.38% at list size 8 and 0.08% at list size 16 and also the BER for I-CRC-A-I-SCL is 0.16% at list size 8 and 0.05% at list size 16. In this simulation, we have understood that when the list size increases the performance also increases because as the list size increases the number of candidate solutions also increases that is why the performance of the polar coding scheme increases with increasing of list size.

4.14 BER and FER Analysis and Comparison of Polar Coding Schemes at Code Rate 1/2 & CRC Length 16

In this simulation, we have also compared the performance of polar coding schemes by changing the CRC length from 8 to 16 and keeping the code rate 1/2 and list size 16. In this simulation, we have observed that increasing the CRC length improves the performance of polar coding schemes but further increasing the CRC length is not good. The parameters we have used in this simulation are listed in table 4.27.

Table 4.27 Simulation Parameters for Comparison of Polar Coding Schemes at Rate 1/2 & CRC Length 16

Parameters	SC polar	I-SC polar	CRC-A-SCL polar	I-CRC-A-SCL polar	CRC-A-I-SCL polar	I-CRC-A-I-SCL polar
Code rate	1/2	1/2	1/2	1/2	1/2	1/2
Frame size	1000	1000	1000	1000	1000	1000
CRC length	-	-	16	16	16	16
Polar block size	(64,128)	(64,128)	(64,128)	(64,128)	(64,128)	(64,128)
List size	-	-	16	16	16	16

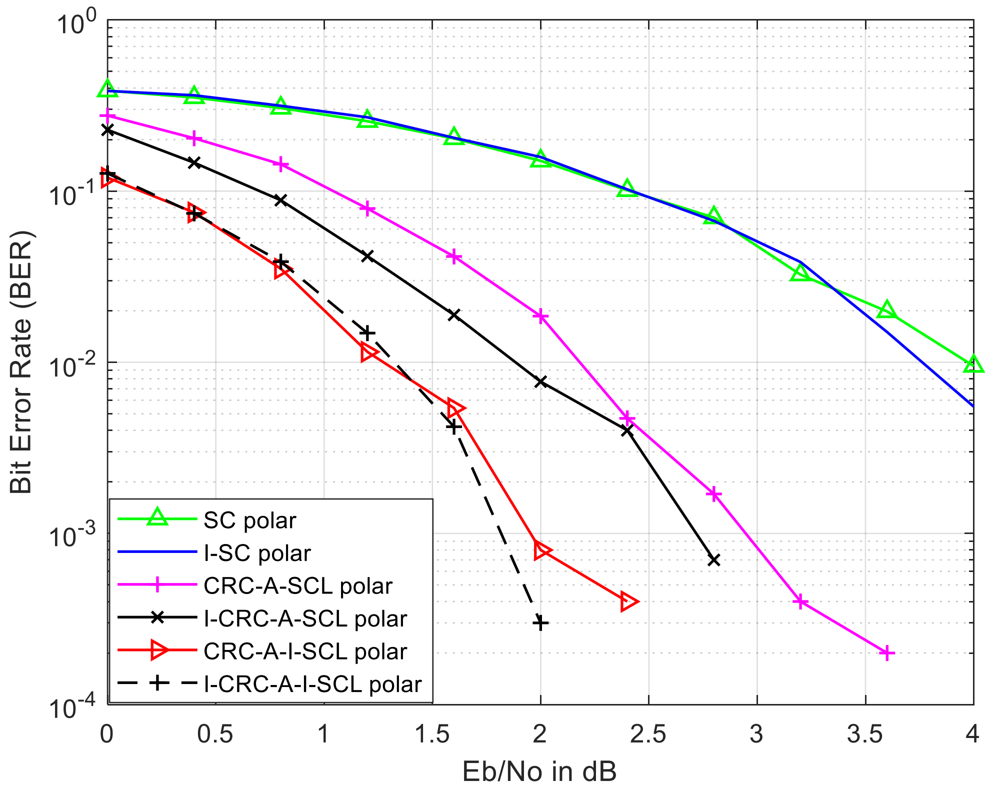

Figure 4.25 BER versus Eb/No for all polar coding schemes at code rate 1/2, CRC length 16, and list size 16

Table 4.28 BER for comparison of all polar coding schemes at code rate 1/2 and CRC length 16

Eb/No in dB	BER					
	SC polar	I-SC polar	CRC-A-SCL polar	I-CRC-A-SCL polar	CRC-A-I-SCL polar	I-CRC-A-I-SCL polar
0.4	0.3525	0.3629	0.2035	0.1465	0.0741	0.0741
0.8	0.3058	0.3152	0.1435	0.0884	0.0352	0.0387
1.2	0.2559	0.2698	0.0791	0.0417	0.0115	0.0148
1.6	0.2047	0.2047	0.0415	0.0189	0.0054	0.0042
2	0.1502	0.1581	0.0186	0.0077	0.0008	0.0003
2.4	0.1023	0.1023	0.0047	0.0040	0.0004	0
2.8	0.07	0.067	0.0017	0.0007	0	0
3.2	0.0325	0.0385	0.0004	0	0	0
3.6	0.0198	0.015	0.0002	0	0	0

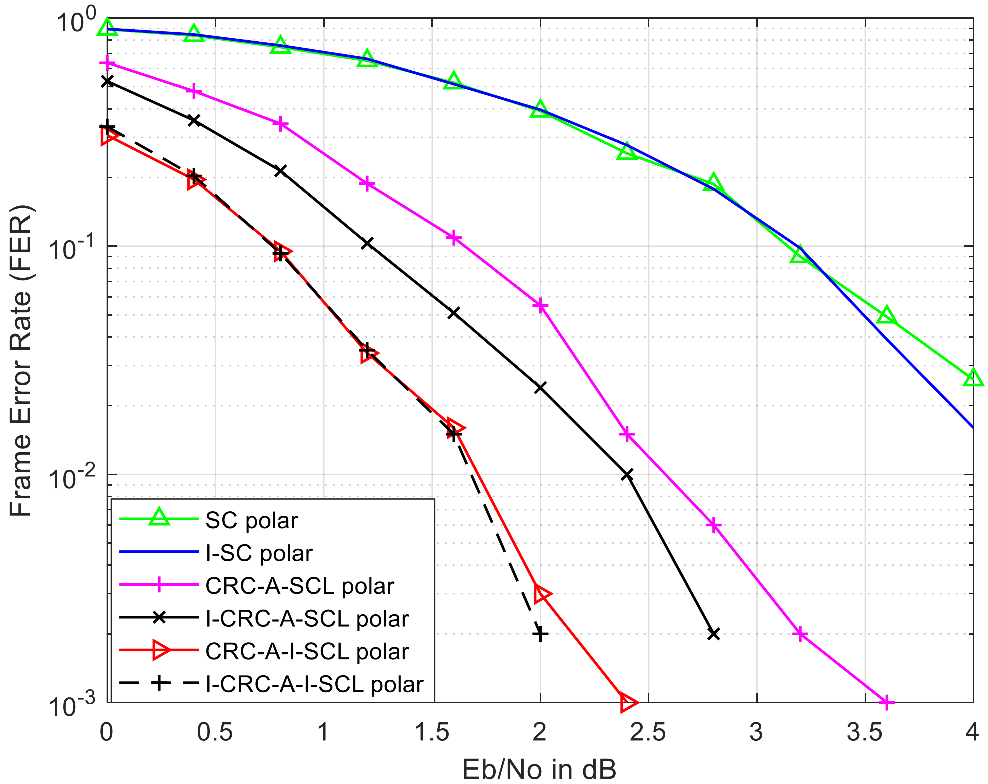

Figure 4.26 FER versus Eb/No for all polar coding schemes at code rate 1/2, CRC Length 16, and list size 16

Table 4.29 FER for comparison of all polar coding schemes at code rate 1/2 and CRC length16

Eb/No in dB	FER					
	SC polar	I-SC polar	CRC-A-SCL polar	I-CRC-A-SCL polar	CRC-A-I-SCL polar	I-CRC-A-I-SCL polar
0.4	0.846	0.846	0.478	0.356	0.196	0.203
0.8	0.745	0.757	0.344	0.214	0.093	0.093
1.2	0.662	0.662	0.188	0.103	0.034	0.035
1.6	0.513	0.513	0.109	0.051	0.016	0.015
2	0.396	0.396	0.055	0.024	0.003	0.002
2.4	0.255	0.277	0.015	0.010	0.001	0
2.8	0.187	0.178	0.006	0.002	0	0
3.2	0.09	0.098	0.002	0	0	0
3.6	0.049	0.039	0.001	0	0	0

4.15 BER and FER Analysis and Comparison of Polar Coding Schemes at Rate 1/2, CRC Length 16, and List Size 8

In the above simulation, the performance evaluation and comparison of polar coding schemes are simulated at code rate 1/2, CRC length 16, and list size 16. In this part of our simulation, the performance is evaluated and compared by decreasing the list size from 16 to 8. The list size is not considered for SC polar coding scheme and I-SC polar coding scheme. The parameters which are used in this part of our simulation are listed in table 4.30. In the above simulation, we have used the parameters like code rate 1/2, list size 16, and CRC length 16. In this case, we have reduced the list size from 16 to 8 to see the effect of reducing list size in polar coding schemes when we compare it with the previous simulation results. When the list size is reduced, the polar decoder considers fewer candidate codewords during the decoding process, which can lead to a decrease in the error correction performance of the scheme. Specifically, as the list size decreases, the probability of selecting the correct codeword decreases, which can increase the decoding error rate. Therefore, this simulation gives us full information about the effect of reducing list size on polar coding schemes.

Table 4.30 Simulation Parameters for Comparison of Polar Coding Schemes at Rate 1/2, CRC Length 16, and List Size 8

Parameters	SC polar	I-SC polar	CRC-A-SCL polar	I-CRC-A-SCL polar	CRC-A-I-SCL polar	I-CRC-A-I-SCL polar
Code rate	1/2	1/2	1/2	1/2	1/2	1/2
Frame size	1000	1000	1000	1000	1000	1000
CRC length	-	-	16	16	16	16
Polar block size	(64,128)	(64,128)	(64,128)	(64,128)	(64,128)	(64,128)
List size	-	-	8	8	8	8

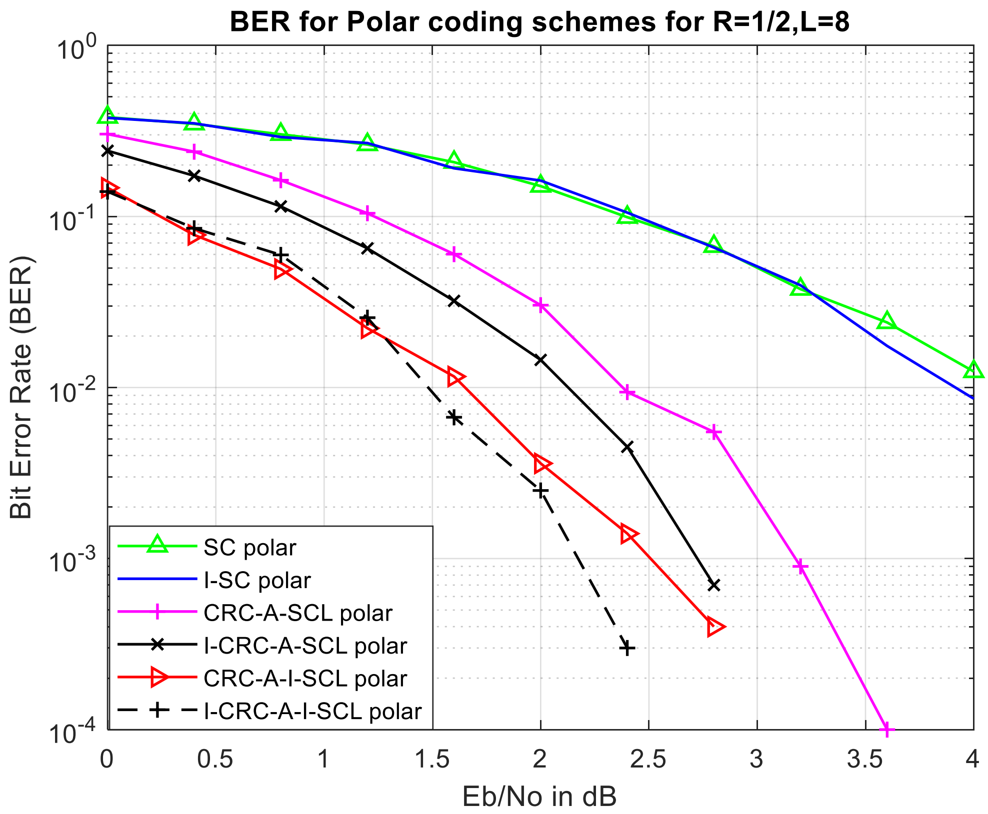

Figure 4.27 BER versus Eb/No for all polar coding schemes at code rate1/2, List size 8 and CRC length 16

As we have plotted in figure 4.27 when the list size is reduced from 16 to 8 and keeping the code rate and CRC length constant the performance of polar coding schemes is also reduced. For code rate 1/2 and list 16 at Eb/No of 2dB, the BER value of the polar coding schemes is 2.15%, 0.5%, 0.08%, and 0.05% for CRC-A-SCL, I-CRC-A-SCL, CRC-A-I-SCL, I-CRC-A-I-SCL polar coding schemes respectively. When we see the simulation at list size 8 the BER value is found as follows 3.03%, 1.45%, 0.36%, and 0.25% for CRC-A-SCL, I-CRC-A-SCL, CRC-A-I-SCL, and I-CRC-A-I-SCL polar coding schemes respectively. As we have understood from this result increasing or decreasing in list size affects the performance of polar coding schemes.

Table 4.31 BER for comparison of polar coding schemes at code rate 1/2, list size 8, and CRC length 16

Eb/No in dB	BER					
	SC polar	I-SC polar	CRC-A-SCL polar	I-CRC-A-SCL polar	CRC-A-I-SCL polar	I-CRC-A-I-SCL polar
0.4	0.3503	0.3503	0.2391	0.1729	0.078	0.0853
0.8	0.3022	0.2913	0.1629	0.1145	0.0493	0.0596
1.2	0.2686	0.2686	0.1044	0.0651	0.0222	0.0256
1.6	0.2076	0.1913	0.0602	0.0321	0.0116	0.0067
2	0.1505	0.1621	0.0303	0.0145	0.0036	0.0025
2.4	0.099	0.1053	0.0094	0.0045	0.0014	0.0003
2.8	0.0658	0.0658	0.0055	0.0007	0.0004	0
3.2	0.0376	0.0396	0.0009	0	0	0
3.6	0.024	0.0175	0.0001	0	0	0

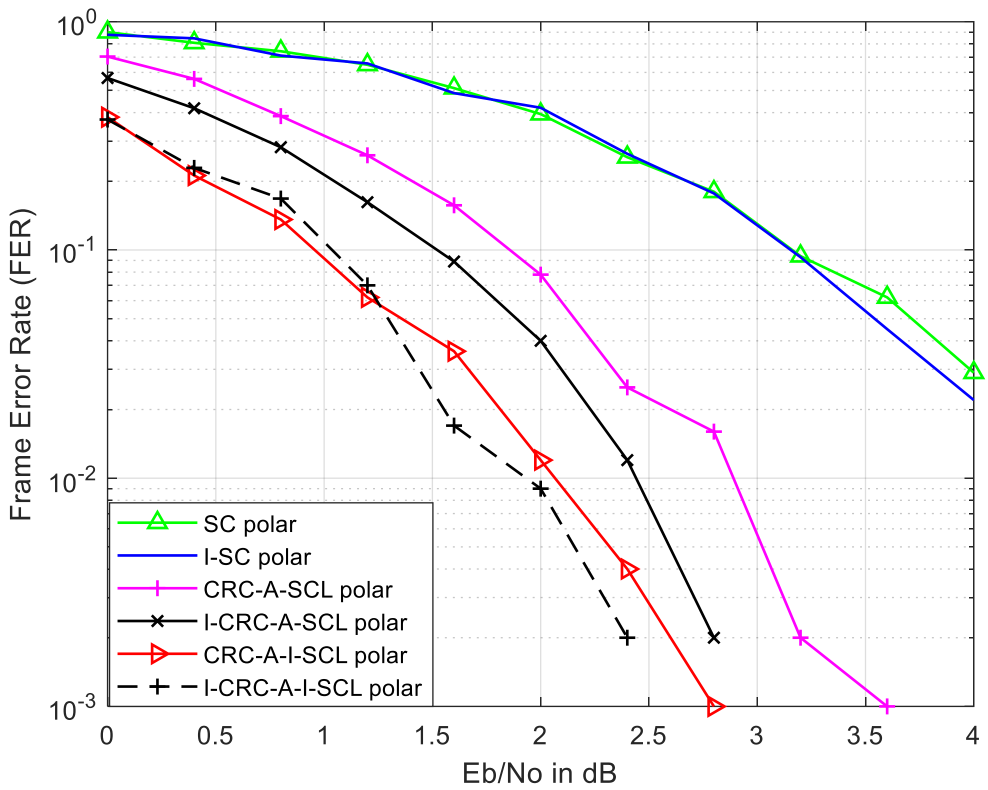

Figure 4.28 FER versus Eb/No for all polar coding schemes at code rate 1/2, CRC length 16, and List size 8

We have also tried to evaluate the performance of polar coding schemes in terms of FER versus Eb/No for 1000 frames. As we have plotted in figure 4.28, we compare the performance in terms of FER by reducing the list size from 16 to 8 by keeping the code rate and CRC length constant from the previous simulation. For code rate 1/2 and list size 16 at Eb/No 2dB, the FER value is given as 5.5%, 2.4%, 0.3%, and 0.2% for CRC-A-SCL, I-CRC-A-SCL, CRC-A-I-SCL, and I-CRC-A-I-SCL polar coding schemes respectively. When we reduce the list size from 16 to 8 the performance of the polar coding schemes is reduced. The FER value of the coding schemes, in this case, is also found as 7.8%, 4%, 1.2%, and 0.9% for CRC-A-SCL, I-CRC-A-SCL, CRC-A-I-SCL, and I-CRC-A-I-SCL polar coding schemes. When we compare the value at list size 16 and list size 8; the FER value at list size 8 is greater than the FER value at list size 16. This means the performance of polar coding schemes degrades when the list size decreases because of fewer candidates.

Table 4.32 FER for comparison of all polar coding schemes at list size 8, CRC length 16 and code rate 1/2

Eb/No in dB	FER					
	SC polar	I-SC polar	CRC-A-SCL polar	I-CRC-A-SCL polar	CRC-A-I-SCL polar	I-CRC-A-I-SCL polar
0.4	0.809	0.846	0.562	0.418	0.212	0.229
0.8	0.743	0.711	0.386	0.282	0.136	0.168
1.2	0.648	0.657	0.26	0.162	0.062	0.07
1.6	0.512	0.487	0.157	0.089	0.036	0.017
2	0.394	0.42	0.078	0.04	0.012	0.009
2.4	0.255	0.264	0.025	0.012	0.004	0.002
2.8	0.18	0.177	0.016	0.002	0.001	0
3.2	0.093	0.093	0.002	0	0	0
3.6	0.062	0.045	0.001	0	0	0

4.16 Comparison of our Work with Existing Results

We have reviewed many papers related to our title but we have used one paper to compare with our work. BER Comparison Between Convolutional, Turbo, LDPC, and Polar Codes is one paper from what we have reviewed. In this paper, they plotted BER versus Eb/No over AWGN channel and BPSK modulation. They have seen their result by varying list size and code rate. At Eb/No of 4.26dB and code rate of 1/2, they found their BER value 0.01 and we found an approximate result with their work at 2.4dB which is 0.0094 BER value for CRC-A-SCL polar coding scheme, 0.0045 BER value for I-CRC-A-SCL polar coding scheme, 0.0014 BER value for CRC-A-I-SCL polar coding scheme and 0.0003 BER value for I-CRC-A-I-SCL polar coding scheme. When we compare our result with the performance comparison of polar and turbo codes at a code rate of 1/2 and Eb/No of 2.6Db they found the BER value 0.01 means 1% over AWGN channel and BPSK modulation. When we see our result at a code rate of 1/2 and Eb/No of 2.8Db we found a BER value of 0.0055 (0.55%) for CRC-A-SCL polar coding scheme, 0.0007 (0.07%) for I-CRC-A-SCL polar coding scheme, 0.0004 (0.04%) for CRC-A-I-SCL polar coding scheme and 0% for I-CRC-A-I-SCL polar coding scheme. In our case we have compared six polar coding schemes from these we found that I-CRC-A-SCL, CRC-A-I-SCL, and I-CRC-A-I-SCL have better performance.

CHAPTER 5

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In our thesis work the performance of polar coding schemes such as SC polar, I-SC polar, CRC-A-SCL polar, I-CRC-A-SCL polar, CRC-A-I-SCL polar, and I-CRC-A-I-SCL polar coding schemes are compared by considering the parameters such as bit error rate and frame error rate for different value of bit energy to noise spectral ratio, CRC length, code rate, and list size by using BPSK modulation over AWGN channel. For SC polar code and I-SC polar code, the performance is mostly reduced by increasing the code rate. Therefore, the performance of SC polar and I-SC polar are affected by the code rate but list size does not affect the performance of SC and I-SC polar coding schemes. In the performance evaluation of polar coding schemes which depend on CRC bits as its outer code together with list decoding and CRC code detection; list-CRC decoding depends on the length of the CRC code and its divisor. From the simulation of CRC-A-SCL polar coding schemes increasing the list size further is not necessary. As we have understood from the simulation graphs and tabulated results the performance is highly affected by code rate. This means that by increasing the code rate there will be less place for redundancy bits because of this the transmitted message cannot be correctly decoded by the decoder which leads to more errors.

Generally, we are focused on the performance evaluation and comparison of six polar coding schemes such as SC, I-SC, CRC-A-SCL, I-CRC-A-SCL, CRC-A-I-SCL, and I-CRC-A-I-SCL. As we have understood from the result I-CRC-A-SCL, CRC-A-I-SCL, and I-CRC-A-I-SCL polar coding schemes have better performance relative to other polar coding schemes. When we see the overall performance I-CRC-A-I-SCL polar coding scheme has the best performance of the remaining five polar coding schemes from which we have to include it in our context. Finally, from the performance evaluation and comparison of polar coding schemes polar codes with lower code rate performs better than polar codes with higher code rate. I-CRC-A-I-SCL polar coding scheme is better for 5G wireless communication networks due to its high error correction performance.

5.2 Recommendations

In our thesis work, we have considered the performance evaluation of polar coding schemes for 5G wireless communication networks. In this thesis work, we have considered BER and FER for the performance evaluation of polar coding schemes. Further study should be included other parameters such as latency, computational complexity, spectral efficiency, and flexibility for further evaluation and comparison of the performance of polar coding schemes. Polar coding with deep learning is also our recommendation for future work.

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