Comparative Performance Analysis of Polar Coding Schemes for 5G and Beyond Enhanced Mobile Broadband Communication

Solomon Tagesse Hibiso

A Thesis Submitted to

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, 2022

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APPROVAL PAGE OF MSc. THESIS

I/we hereby confirm that the thesis review committee's recommendations and suggestions have been successfully incorporated into the final thesis entitled "**Comparative Performance Analysis of Polar Coding Schemes for 5G and Beyond Enhanced Mobile Broadband Communication**" by Solomon Tagesse Hibiso.

Major Advisor	Signature	Date
Co-advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by **Solomon Tagesse Hibiso** have read and evaluated the thesis entitled "**Comparative Performance Analysis of Polar Coding Schemes for 5G and Beyond Enhanced Mobile Broadband Communication**" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Electronics and Communication Engineering.

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DECLARATION

I declare that this thesis entitled "**Comparative Performance Analysis of Polar Coding Schemes for 5G and Beyond Enhanced Mobile Broadband Communication**" is my work and has not been submitted yet to any university for similar purpose. The references used in this thesis are recognized by proper citations.

Name of student	Signature	Date

RECOMMENDATION OF ADVISORS

I, the advisor/supervisor of this thesis, hereby certify that I have closely advised/supervised the student while developing this thesis and read the thesis entitled "**Comparative Performance Analysis of Polar Coding Schemes for 5G and Beyond Enhanced Mobile Broadband Communication**" prepared under my guidance by Solomon Tagesse Hibiso. Therefore, I recommend submitting of the thesis to the department by following an applicable procedures.

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Major Advisor	Signature	Date
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Co-advisor	Signature	Date

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LIST OF ABBREVIATIONS

3GPP	3rd Generation partnership project
ARQ	Automatic Repeat Request
BCCH	Broadcast Control Channel
BCH	Broadcast Channel
BDMC	Binary Discrete Memoryless channel
BER	Bit Error Rate
BLER	Block Error Rate
CRC-A-I-PC	CRC Aided Interleaved Polar Code
CCCH	Common Control Channel
CRC	Cyclic Redundancy Check
D2D	Device to Device
DCCH	Dedicated Control Channel
DCI	Downlink Control Information
DL-SCH	Downlink Shared Channel
DTCH	Dedicated Traffic Channel
E_b/N_o	Bit Energy to Noise Ratio
EMBB	Enhanced Mobile Broadband
FECC	Forward Error Control Coding
HD	High Definition
IoT	Internet of things
ITU	International Telecommunication Unit

LPDC	Low Density Parity Check Code
LLR	Log-Likelihood Ratio
MMTC	Massive Machine-Type Communications
NR	New Radio
PBCH	Physical Broadcast Channel
PCCH	Paging Control Channel
PCH	Paging Channel
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PRACH	Physical Random Access Channel
PUSCH	Physical Uplink Shared Channel
PUCCH	Physical Uplink Control Channel
RACH	Random Access Channel
QoS	Quality of Service
SC	Successive Cancelation
SCD	Successive Cancelation Decoding
SCLD	Successive Cancelation List Decoding
SISO	Soft Input Soft Output

ABSTRACT

Since we are in the era of ever fast growing communication technology, there are so many areas that are struggling to improve the quality of service in the customer satisfaction at anywhere and anytime. The emerging of the 5G and beyond enhanced communication system is focused on improving the quality of services in the way of communication, reliability of data transmission, and the security of the systems. The need for ultra-reliable error free communications is emerging in many application area like mobile broadband communication, where good connectivity is essential to the transmission of reliable information in real scenario. Channel coding techniques such as convolutional and Turbo codes that were used in 4G LTE are replaced by polar codes and LDPC codes for 5G and beyond system. Since PC are recent than low density parity check codes and for polar coding schemes different improvements can be made under different parameters variation to increase the performance. In this thesis the performance metric parameters such as bit error rate, block error rate and computational complexity for different value of bit energy to noise spectral ratio, block length, code rate and list size for polar code with successive cancellation decoding, interleaving polar code with successive cancellation decoding, cyclic redundancy check aided polar code with successive cancellation list decoding and cyclic redundancy check aided interleaving polar code with successive cancellation list decoding are analyzed for noisy binary erasure channels. And also the most performance affecting parameters such as code rate, CRC size, and list size by comparing the BER, BLER and computational complexity are identified. For the simulation purpose Matlab R2020a is used. For better comparison of the polar coding schemes speech signal and text is used in the encoding and decoding process. Finally, the results are interpreted, discussions are made and conclusion and future work is drawn based on the results obtained. Based on the results obtained CRC aided interleaving polar code with SCLD has BER of 0.02% and CRC aided polar with SCLD has 0.19% at Eb/No of 2.2dB, list size 8 and CRC size 16 over BPSK AWGN channel for a code rate of 1/2. The uncoded case has BER of 3.75% at the same Eb/No and PC without CRC and interleaving has BER of 3.09%.

Key words: 5G and beyond 5G, BER, BLER, computational complexity, Polar coding, eMBB

CHAPTER ONE

1. INTRODUCTION

1.1. Background of the Study

In digital communication in need of reliable quality of services channel coding is an art state process in detecting and correcting bit errors. It is also known as forward error control coding. FECC is performed both at the transmitter and at the receiver. At the transmit side, channel coding is referred to as encoder, where extra bits that are called parity bits or redundant bits are added with the defined way. At the receive side the channel coding is referred to as the decoder. Channel coding enables the receiver to detect and correct errors, if they occur during transmission due to noise, interference and fading (Faruque, 2017). Polar coding is a channel coding technique that uses the channel polarization technique which is splitting the channels and ordering them as bad and good. In a sense of polar coding the channels are virtual which the bit positions of the code word are. In the splitting of the channels there is creating the capacity inequality of the bit channels. The bit channels having lower capacity are used to transmit the redundant bits which are all zero in polar coding.

The performance of a radio link is determined by the bit error rate, block error rate and the computational complexity at a given signal to noise ratio. A channel coding solution is primarily measured by its ability to correct errors at a given E_b/N_o.

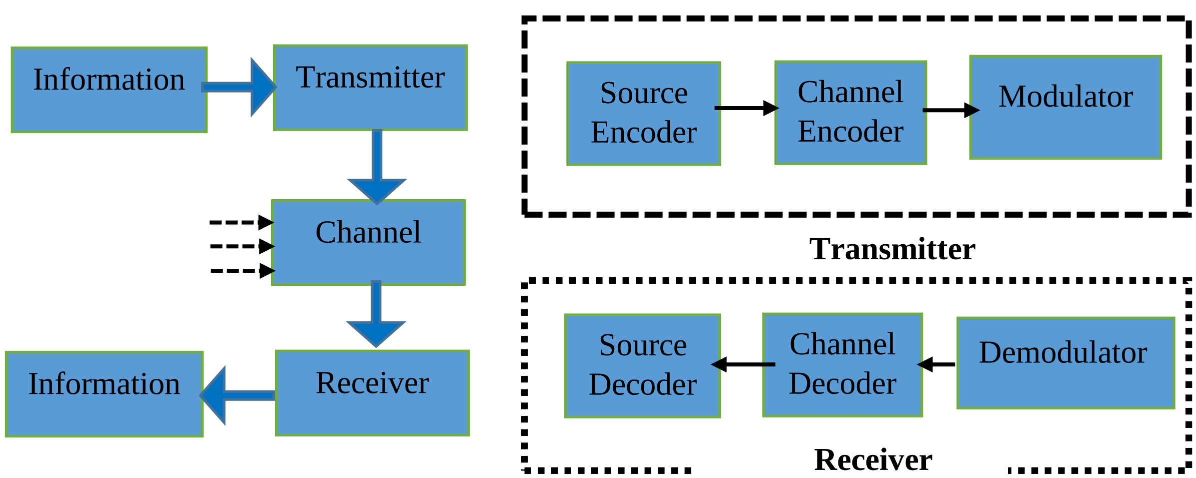


Figure 1.1 Basic structure of communication system (Faruque, 2017)

In improving quality of service for communication the main concern is the cost of the implementation. If increasing the bandwidth is considered to increase the capacity of the communication channels it is difficult because bandwidth is the scarcest. As the size and speed of digital data networks continues to increase, bandwidth efficiency becomes increasingly important. This is the main concern 5G and beyond enhanced mobile broadband communication, where the digital signal processing is evaluated by considering the bandwidth resources. Polar coding forms a very valuable preprocessing step in the transmission of digital bit-stream. Since bandwidth is scarce and therefore expensive, a coding technique that requires fewer redundant bits with better error detection and correction performance is highly acceptable.

Channel coding seeks to eliminate channel errors caused by impairments, such as noise and fading, and therefore increase the performance of the communication system. There are two basic ways of implementing redundancy addition to control errors. Automatic repeat request and Forward error control coding.

The ARQ approach adds parity, or redundant bits, to the sent data stream, which the decoder uses to detect a data error. When the receiver identifies an error, the receiver requests that the data be resent to recover it. Because the data must be re-transmitted, this strategy uses a lot of bandwidth.

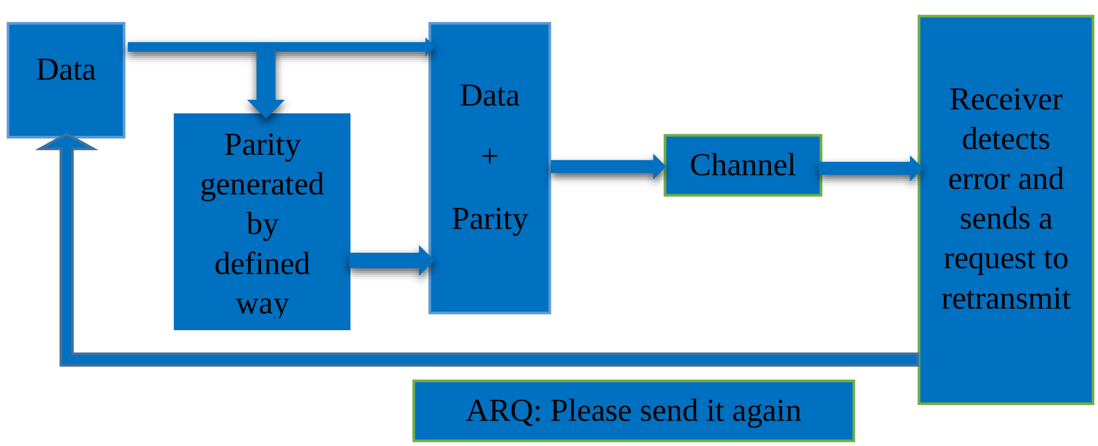


Figure 1.2 ARQ Technique (Faruque, 2017)

In a system which utilizes FECC coding, the data are encoded with the redundant bits to allow the receiver to not only detect errors, but to correct them as well. In this system, a sequence of data signals is transformed into a longer sequence that contains enough redundancy to protect the data. In polar coding the redundant bits are zero bits. But the main concern is the position of these bits. The bit positions are known for both the transmitter and the receiver.

1.2 Statement of the Problem

Wireless transmission in a radio channel is used to convey bits of information between transmitter and receivers in communication systems. Due to some channel impairments when the received bits are compared to the transmitted bits they typically differ subject to communication errors on the receiver. The prime objectives of 5G and beyond wireless communications are very low error for a reliable communication. To increase the reliability of the wireless communications system channel coding is responsible to this activity by adding extra bits in a controlled fashion and is considered to be most important and researchable element of communication system. The coming new generation network is expanding to enhance 5G and beyond use cases. The new scenarios of the coming generation are a combination of one or more usage element. So polar coding plays a massive role in the improvement of performance to the emerging communication technology. So there should be comparative performance analysis of the polar coding schemes for the enhanced mobile broadband communication and using the advantage of one to another to increase the bit error rate and block error rate performance.

1.3 Objectives

1.3.1 General Objective

The main objective of this thesis work is comparative performance analysis of polar coding schemes for 5G and beyond enhanced mobile broadband communication

1.3.2 Specific Objectives

The specific objectives of the thesis work are:

- To analyze and simulate polar coding with SC decoding for 5G and beyond eMBB
- To analyze and simulate Interleaving polar coding with SC decoding for 5G and beyond eMBB

- To analyze and simulate CRC aided polar coding with SCL decoding technique for 5G and beyond eMBB
- To analyze and simulate CRC aided interleaving polar coding by SCL decoding for 5G and beyond eMBB
- To compare the BLER, BER and computational complexity performance by changing parameters such as code rate, CRC size and list size for polar coding schemes for 5G and beyond eMBB

1.4 Significance of the thesis work

There are several technical issues in communication system design including channel coding that need to be addressed for the successful existing network scenario and next generation network deployment that focus on the customer satisfaction. Channel coding is an essential part in baseband processing and enables reliable transmission. 5G and beyond system should have higher capacity, higher data rates, lower latency, higher security and better QoS. For the reliable communication the performance should be analyzed. This thesis is simulation-based investigation which relies on theoretical data. We will be constrained in the promising of advanced version of existing coding for the next generation wireless network.

1.5 Scope of the thesis

The main aim of near-future wireless communications include very low error, better data rates, more spectral efficiency, higher energy efficiency, and lower latency. Channel coding tends to enhance the reliability and spectral efficiency of the enhanced mobile broadband system by adding extra bits in a defined way and is considered to be the most crucial element of the communication system. So channel coding can be applied to many communication scenario like satellite communication, radar communication.

1.6 Main Contributions of the Thesis Work

This thesis focused on the comparative performance analysis of polar coding schemes for 5G and beyond enhanced mobile broadband communication. The performance metric parameters such as bit error rate, block error rate for different value of Eb/N_o, Block length, code rate and list size for 5G and beyond is analyzed and compared. The performance comparison parameters for polar coding with SC decoding, I-polar SC decoding CRC aided polar coding with SCL decoding, CRC aided interleaving polar coding with SCL decoding are compared.

1.7 Limitations of the Thesis Work

In this thesis work the performance of polar coding schemes are comparatively analyzed. The research work is limited to simulation-based study and the performance measuring parameters are limited to BER, BLER and computational complexity for error correcting capability and error detection is not considered.

1.8 Thesis Organization

The rest part of the thesis organized as follows. Chapter 2 presents the literature review and the related papers of the subject matter. It provides a whole overview of the problem's background. It refers to what research has already 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 the results and discussions are briefly presented. Finally Conclusions and future research work directions are offered at the end.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Channel Coding

Channel coding is an art of reducing errors being employed by the communication system in order to counteract the effects of the environment through which the message is being distorted. This technique involves redundancy addition to the message block being transmitted so that the transmission errors can be easily recognized by the receiver, and then possibly correct to by decoding techniques that is suitable to the encoding technique. Such error-control codes are being used in all kinds of radio communications where high reliability is needed, such as mobile networks, satellite communications, and industrial networks and so on (Abdulwhab & Kadhim, 2018).

2.2 Channel Coding Overview for 4G and 5G Use Cases Aspect

The NR physical layer is in charge of power control, multiplexing and channel coding, link adaptation, beam management, uplink synchronization and timing control, random access procedures and multi-antenna mapping and processing. EMBB technologies are used to enable wireless internet access to mobile devices.

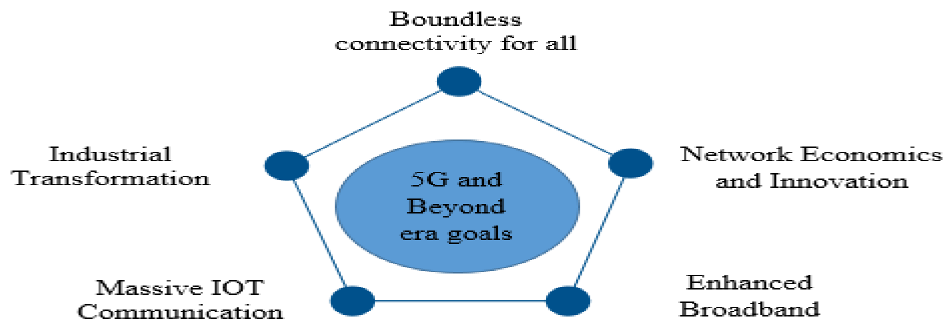


Figure 2.1 5G and Beyond era goals (Popovski et al., 2021).

2.3 Enhanced Mobile Broadband (eMBB)

EMBB service is the main target for 5G and beyond communications to fulfill the requirement of high-throughput while being used for some services of high priority. To reach to the latest applications, the system bandwidth needs to be widely increased (Abdullah & Ameen, 2021).

5G NR support a wide array of services and applications and therefore, data blocks that will be used for each of these services and applications will vary in length. Hence it is fundamental that the channel code supports multiple coding rates to minimize the use of wasteful encoded bits which degrade spectrum efficiency, throughput and latency (Maunder, 2016).

Requirement of the eMBB scenario is to support a much wider range of code rates, code lengths and modulation orders than the 4G Long Term Evolution (LTE). In order to satisfy the requirements of eMBB, 5G needs to achieve significant enhancements in spectral efficiency, signaling efficiency, bandwidth and coverage compared to 4G. In order to achieve high spectral efficiency, channel coding. Channel coding plays an important role in order to have a fast and error free communication since data transmission occurs in an imperfect channel environment. The selected channel code must have an excellent BLER performance in a specific range of block lengths and code rates. Convolutional codes (CC), turbo codes, LDPC codes and polar codes are the competing coding schemes considered as the candidates for 4G LTE and 5G. However, CC is not considered for the eMBB scenario of 5G since it has a poor performance in large block lengths and low code rates. Turbo codes are also not selected for eMBB use case for 5G since it has highest complexity than the others (H. Gamage et al., 2017).

2.4 Channel Coding Techniques

2.4.1 Turbo Codes

Turbo codes which are based on convolutional codes were developed in 1990. But were not published until 1993 (Gazi, 2018). Data channels were using turbo codes in LTE network they are used for are generated by using the parallel concatenation of two recursive systematic convolutional encoders (Rao, 2015). Turbo codes are applicable in several types of communication systems like deep space communications, 3G/4G mobile communication in Universal Mobile Telecommunications System (UMTS) and LTE standards and Digital Video Broadcasting (DVB) (H. N. Gamage, 2016).

2.4.2 Convolutional Codes

Convolutional codes were used for 2G, 3G network and 4G network they are used for control channels. And belong to the channel coding techniques groups of linear error-correction codes (Jihwan & Lee, 2020).

Convolutional codes can be either systematic or non-systematic. Parameters that characterize convolutional code are (n, k, and m) number of output bits, input bits and the third one is memory registers. The ratio of number of output bits (k) to the number of input bits (n) is the code rate (k/n) in a given encoder cycle (Chandrasekhar et al., 2020). These codes are mainly used for error correction in communication system. Similarly, the encoded bits mainly depend on the present input bits and past input bits. The responsible decoding algorithm is Viterbi algorithm for the function of convolutional code. Several approaches are being used performance improvements and easiness of implementations for this method of coding patterns. (Benson Mansingh et al., 2020).

2.4.3 Low Density Parity Check Codes

LDPC codes were proposed in Robert Gallagher's doctoral dissertation in 1962. Practically they were not used until 1997 when their good performance was showed by Mackay. In 5G LDPC codes belongs to quasi-cyclic (QS) LDPC codes (Bae et al., 2019). The main advantage of QS-LDPC codes is reflected in the possibility of parallel encoding and decoding, which further contributes to the high-throughput of LDPC encoders and decoders. As their name says, LDPC codes are described with sparse parity check matrix H that defines a set of linear equations (Maunder, 2016).

2.4.4 Polar Codes

Polar codes which are capacity-achieving codes presented by Arikan Erdal at Bilkent University in Ankara This means by using polar coding schemes full capacity of a channel can be achieved. Having this feature they found application in 5G and beyond enhanced mobile broadband communication. The root idea in polar coding is to divide the channels of having capacity I(W) into N channels with some of them having capacity approaching one and the rest approaching to zero. In the positions of zero capacity nothing is transmitted but made frozen at the transmitter and this is known also at the receiver so the receiver has no duty of decoding these frozen bits. So I(W) number of channels will be channels with no noise and the rest, 1-I(W) will become completely noisy. This combining and splitting is done by channel polarization. Then, these perfect channels are used for data transmission and the rest are frozen to zero (Bioglio et al., 2021).

Polar coding schemes are those constructed as a result of the channel polarization technique using kernel transform. It is done by channel combining and splitting, and at infinite length, the channels (bits' positions) will polarize in the sense that some of channels will be highly reliable, and the rest will be unreliable. If the information bits are put only into the reliable channels, and foreknown bits (usually zeros) are put into the unreliable channels, then the channel capacity can be achieved. The main and leading task of polar code construction is to find this set of the most reliable and unreliable channels. The unreliable sets are usually called the frozen set (Koike et al., 2021).

2.5 Basic Building Block of Polar Decoding

In the last stage of binary tree representation left child bit is decoded then after calculating the min-sum approximation of 2 beliefs and then decoding the second bit applies both the first bit and 2 beliefs (Stefan *Miclea*, 2020).

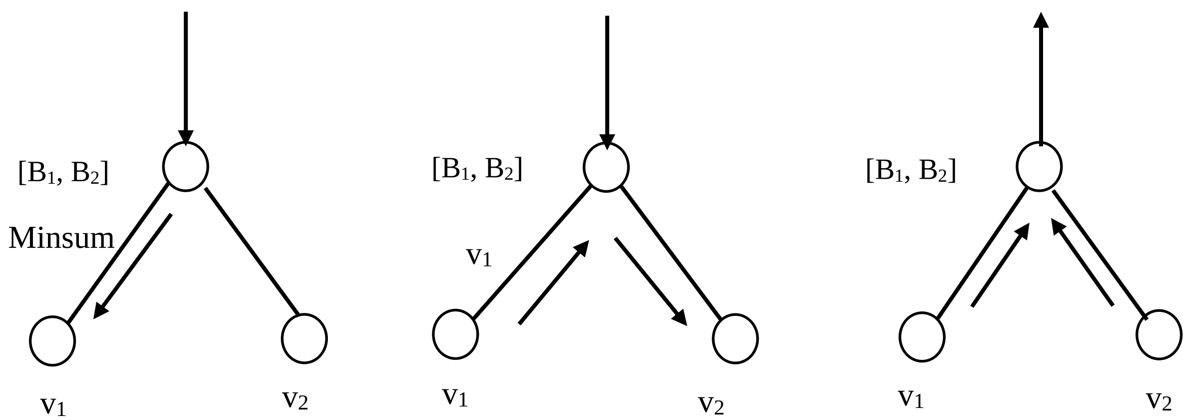


Figure 2.2 Basic building block of polar decoding (Stefan *Miclea*, 2020).

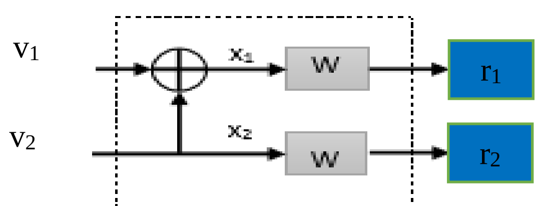


Figure 2.3 Building block of Arikan polar encoding (Sharma & Salim, 2020)

2.6 Polar Coding Schemes and Their Decoding Techniques

The design of a good polar code depends on the mapping of the information bits to the input bits to the polar encoder kernel. The information bits should be put on the K best (or most reliable) bit channels. The remaining N-K input bits which are not drawn from the information bits are called frozen bits. Typically, the frozen bits are set to 0. The set of positions for frozen bits is called the frozen set and the set of positions for information bits is called the information bits set. There are different techniques in polar coding schemes (Bae et al., 2019). In information theory, a polar code is a linear block error-correcting code. The code construction is based on a multiple recursive concatenation of a short kernel code which transforms the physical channel into virtual outer channels (Xi et al., 2018).

2.7.1 Polar Codes with SC Decoding

Polar codes are those constructed as a result of the channel polarization transform (Bae et al., 2019). The idea is that by channel combining and splitting, and at infinite length, the channels (bits' positions) will polarized in to good and bad bit channels. In the sense that some of channels will be highly reliable, and the rest will be unreliable. And it uses Arikan's standard successive cancelation decoding structure (Kim et al., 2021).

2.7.2 Interleaving Polar Codes with SC Decoding

An interleaver is a hardware device commonly used in conjunction with error correcting codes to counteract the effect of burst errors. Interleavers are in widespread use and much is known about them from an engineering standpoint (Andrews et al., 2007).

2.7.3 CRC-A Polar codes with SCL Decoding

They apply the advantages of cyclic redundancy check in the polar codes to improve the bit errors rate and in the decoder list of decoded message will be produced from these decoded message (Kim et al., 2021).

2.7.4 Interleaving CRC-A- Polar codes SCL Decoding

Interleaving is a tool that is used to reduce burst error that may occur in a random way. To improve the existing error control codes so that they can recover the original message bits. It is performed before transmission to distribute the data bits and if a part of the information is changed during transmission in the channel it can be recovered by rearranging the data after recovering

2.8 Polar Kernel Encode

From initially polar codes are categorized in to linear block codes that uses matrix kernel product to encode the message block. For a (N, K) polar code where K is the information block length and N is the coded block length or mother codeword length. Here the value N is set as power of 2. $N=2^n$ for some positive integer n (Sarajevo, 2021).

$$G_2=\begin{bmatrix}1 & 0\\1 & 1\end{bmatrix} \tag{2.2}$$

The encoded codeword x for input bits v is given by

$$x=vG_N \tag{2.3}$$

Where v includes both the information payloads and the frozen bits.

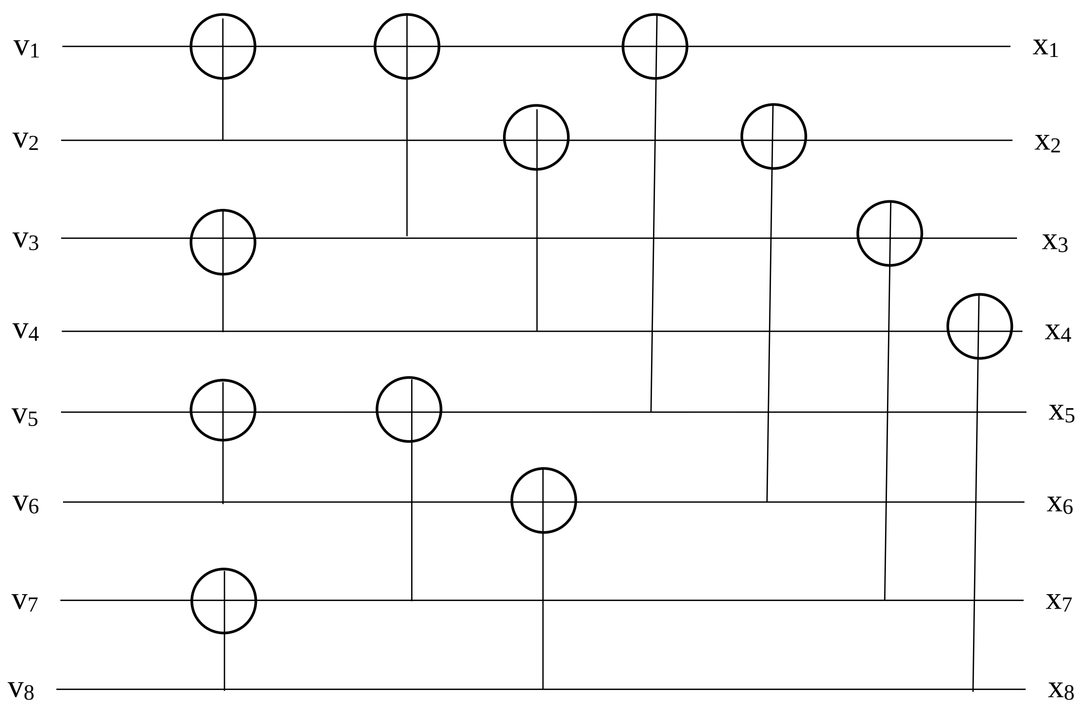


Figure 2.4 Polar encoder kernel with N=8 (Xi et al., 2018)

Polar codes are well constructed because the transmitter and the receiver has common information called reliability sequence. In terms of encoding and decoding operations redundant bit channels will be the frozen set. The ordered bit positions or bit channels are termed a polar sequence. Different polar sequence or reliabilities of polar codes for bit channels may be calculated by selecting different values of the design parameter. In other words, multiple polar sequences could be derived by selecting different values of the design parameter.

2.9 Soft Input Soft Output (SISO) Decoder Min-sum Approximation

In SISO decoder the receiver considers the channel log likelihood ratio and also the extrinsic log likelihood ratio of incoming beliefs. In the decoding process by using binary tree representation the received N beliefs are reduced to 2 beliefs. Then after the Minsum approximation at the leaf node is applied then by hard decision the first bit is decoded. If this bit is frozen it is set to 0. At the next step in tree representation the second bit will be decoded by considering the first decoded bit and the value of log likelihood ratio. That means there is a sequential decoding procedure.

2.10 BPSK in AWGN Channel Transmission and Reception

After channel coding and interleaving data are then entered serially to the digital modulation mapper (Siksha, 2016).

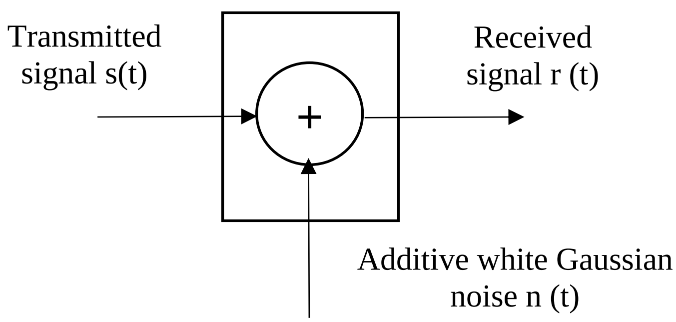


Figure 2.5 Additive white Gaussian noise addition on transmitted signal

$$\text{BER}=\frac{1}{2}erfc(\sqrt{\frac{E_b}{N_0}}) \tag{2.7}$$

The signal from the transmitter needs to be added with random noise of specific strength. The strength of the generated noise signal depends on the desired SNR level which usually is an input in such simulations (Goldsmith, 2005). In wireless communications, signal modulation is critical. Signals can travel longer distances with the help of modulation. There are different modulation schemes available for wireless communications. Binary Phase Shift Keying where binary refers to two phase offsets (Goldsmith, 2005)

2.11 Related Works

A research paper on "***Performance Comparison between Turbo and Polar Codes***" focused on the Bit Error Rate evaluation and analysis of the codes for varying block lengths and code rates. In 4G LTE system Turbo codes are used and polar codes are selected to a coding scheme for 5G. The BER performance of the proposed codes are compared for various values of block lengths and code rates. The channel considered for the data transmission is the Additive White Gaussian Noise (AWGN). The information bits are modulated using Binary Phase Shift Keying (BPSK). In Turbo codes in 4G LTE system the performance is increasing by increasing the block length and decrease as the code rate increases (Vaz et al., 2019).

Research paper on "***BER Comparison between Convolutional, Turbo, LDPC, and Polar Codes***" are analyzed BER performance for channel coding techniques chosen for 4G such as Convolutional and Turbo and channel coding techniques chosen for 5G such as LDPC and Polar Codes. According to the paper in convolutional codes the input information bits are encoded in a bit-by-bit stream fashion, in such way that the input bits are convolved with predefined polynomials, hence the name "convolutional" indicates. The common algorithm used in decoding for convolutional codes, are the Viterbi algorithm. In 4G channel coding convolutional codes performed the lowest performance. For Turbo coding the performance is mainly dependent on the number of iteration. For going more than 8 iterations does not provide that much performance. And according to the paper Turbo code are the most complex code in decoding structure. For this purpose polar codes and LDPC codes are chosen for 5G system (Ellinas et al., 2017).

Research Paper on "***Polar Codes Analysis of 5G Systems***" by M. Dhuheir and s. Öztürk on 2018. They studied polar coding schemes in 5th generation communications systems and introduced the rate-matching polar code approach. Traditional polar coding schemes, according to the study, have a problem in coding rate in which they attain a predefined code rate R. Using either shortening or puncturing approaches, the rate-matching approach solved this problem by assuming a codeword M that is less than the mother codeword N. Polar code was compared with two competitor codes that could be used in 5G-NR, turbo codes and LDPC codes, in this study. The comparison focused on the advantages and disadvantages of each code scheme in order to assess its performance accomplishments and shortcomings (Dhuheir & Ozturk, 2018).

A research paper on "***The Development, Operation and Performance of the 5G Polar Codes***" by Z. B. Kaykac Egilmez, L. Xiang, R. G. Maunder and L. Hanzo on 2020

They provided a survey of the operation and performance of the polar codes used in the channels of 3GPP NR. They began by giving an outline and the motivation for history of mobile communication and NR's implementation. An end-to-end example of PUCCH polar encoding was shown to explain the step-by-step behavior of these components. Finally, BLER analysis was used to quantify the NR polar codes error correction and error checking capabilities (Kaykac Egilmez et al., 2020).

A research paper on "***Application of Bit Interleaving to Convolutional Codes for Short Packet Transmission***" by Wang, M., Zhan, M., Yu, K., Deng, Y., Shi, Y., & Zeng, J. on 2019

Bit interleaving technique is applied to the convolutional codes coding scheme, then compared the packet error rate with and without interleaving module. The impact of interleaving technology on the packet error rate of convolutional codes was studied using numerical simulations. When the interleaving technique is applied to the convolutional coding scheme for short packet transmission, the packet error rate of convolutional codes increases, and the data transmission reliability decreases, according to this paper. Although interleaving technology is a commonly used strategy for improving the efficiency of error correcting codes in channel coding, it is not necessarily suited for short packet delivery, as seen in the above explanation. Short packets, on the other hand, experience less delay than long packets. (Wang et al., 2019).

On a research paper entitled "***Survey of Polar Codes***" explained the key components in polar codes based on binary discrete memoryless channel. They discussed about a method to construct polar codes coding and decoding. The simulation results were carried out by using a particular BEC channel and the SC decoding algorithm. They obtained and presented simulation results for bit error rate versus erasure probability of BEC for different code rates. For higher erasure probability the performance is decreased at certain code rate (Kaime et al., 2019).

A research paper on "***Reliability Based Candidate Selection of List Decoding for Polar Code***" presented an adaptive candidate selection method for polar code list decoding. If a parent PM's reliability is strong, so are the children candidates', and their prospects of survival are also strong. If a parent PM's reliability is low, the likelihood of its children candidates surviving is also low. The trustworthiness of their parent candidates determines the quantity of children candidates. Furthermore, if a parent PM's reliability is low, the number of children candidates is reduced to on. For a code rate 0.1851 BLER versus Eb/No was plotted (Kim et al., 2021).

On a research paper "***5G New Radio channel coding for messaging in Smart Grid***" determined which of the 5G channel coding techniques perform better for smart grid application. In this work LDPC code are compared with polar code. According to the paper LDPC code has better performance than polar coding. They also compared the performance of CRC-A-polar SCL decoding with the LDPC coding and for list size 8 and above polar coding outperforms LDPC for lower Eb/No ranges (Maksimović & Forcan, 2021).

A research paper ***"on error correction performance of LDPC and polar code for the 5G type communication***" The error correction performance evaluation of LDPC code and polar code for short to medium information block lengths (K ≤ 1024) at a coding rate of 1/3 was evaluated. The communication channel and modulation technique are AWGN and BPSK, respectively. According to the findings, LDPC codes perform worse than Polar codes with CRC-SCL decoders for short information block lengths. (Belhadj & Abdelmounaim, 2021).

Table 2.1 Comparative study of the literature reviews

Author(s), year	Title	Methodology used	Contributions	Gap
Vaz, A. C., Gurudas Nayak, C., & Nayak, D. (2019).	Performance Comparison between Turbo and Polar Codes	Iterative decoding for Turbo and SC for polar	Estimated BER for polar with Turbo codes	Only code rate and block length is considered
Marwan Dhuheir, Sıtkı Öztürk (2018)	Polar Codes Analysis of 5G Systems	Successive Cancelation for Polar decoding for Low density parity check code Log likelihood ratio soft decision	Summarized the comparison between polar, Low density parity check, and turbo codes	Limited on the code rate parameter to compare the performance

Zeynep B. Kaykac Egilmez, Luping Xiang , et al (2020)	The Development, Operation and Performance of the 5G Polar Codes	Log likelihood ratio estimation in decoding	Characterized the error correction and error detection performance of the 3GPP new radio polar codes	Rate matching considered but different decoding techniques in polar codes are the gap
(Maksimović & Forcan, 2021)	5G New Radio channel coding for messaging in Smart Grid	Polar coding by polar transform and	Determined which of the 5G channel coding techniques perform better for smart grid application	Limited parameters
Wang, M., Zhan, M, et al (2020)	Application of Bit Interleaving to Convolutional Codes	Interleaving channel coding	BLER performance improvement for short packet length	Interleaving technique only is applied to Convolutional Codes
(Ellinas et al., 2017)	BER Comparison between Convolutional, Turbo, LDPC, and Polar Codes	Viterbi algorithms for codes iterative decoding for Turbo codes message passing on tanner graph and SC for polar codes	Compared the coding schemes of 4G LTE and 5G in terms of the BER for different information block lengths, and code rates	Compared the BER for only code rate 1/2 of the coding schemes
Aarti Sharma, Mohammad Salim (2017)	Polar Code: The Channel Code Contender for 5G Scenarios	Successive cancelation Min sum iteration	Code construction by Channel polarization	Focused only on the Channel polarization gaps on different decoding techniques
(Belhadj & Abdelmounaim, 2021)	On error correction performance of LDPC and polar code for the 5G type communication	Channel polar transform And layered min-sum	Compared LDPC and polar code for different block length and Showed LDPC code are good at high block length	Considered block length parameter for comparison

To successfully accomplish this thesis work the related works listed above are reviewed. On the reviewed papers the parameters they used the methods applied their contributions and the gaps are stated. Most of the papers focused on 4G LTE and 5G NR channel coding performance analysis. According to the reviewed papers Turbo and Convolutional codes are used in 4G LTE system but in 5G system LDPC and polar codes are used. For LDPC codes the base matrices are used to encode the information bits. But under polar codes different parameters can be considered to analyses the performance in a different way. For this case we selected polar codes for 5G and beyond for enhanced mobile broadband under different parameters.

CHAPTER THREE

3. MATERIALS AND METHODS

3.1 Introduction

In this thesis work for successful accomplishment relevant related secondary sources of data such as different books in polar coding researcher's, previous studies, different Institute of Electrical and Electronics Engineers (IEEE) journals, articles, development in 5G and beyond technology in general, and basics of polar coding in particular, were revised.

3.2 Materials

In this research work, software such as MATLAB/R2020a is used. MATLAB is the computing software that run in computer and consists of technical toolboxes and Simulink.

3.3 Methodology

- Generating input data
- Prepare a mathematical modelling to the channel encoding and decoding process
- Preparing the mathematical modelling to calculate the bit error rate

3.4 Data Generation

To analyze the performance under the parameters BER, BLER and computational complexities random data is generated in Matlab. In data generation is based on the required block length and the code rate to avoid the bias in comparison of the performance.

3.5 Mathematical Model of Channel Polarization

In binary input communication channels ideally there are perfect and imperfect channels. In perfect channels the capacity is one that means if zero is sent some output y_0 will be received and if one is sent some output y_1 will be received. In second case for a channel transition probability W

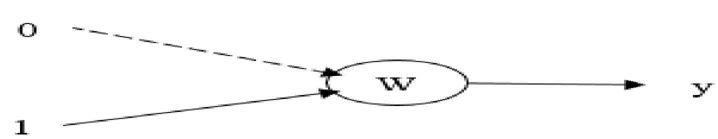


Figure 3.1 simple binary channel (Kaime et al., 2019)

$$W(y/0)=W(y/1) \quad (3.1)$$

If the channel transition probability W is given by the equation 3.1. In this the capacity is zero and no coding is necessary and this channel is useless. If we create two copies of original channel W that the capacity occurs in middle between the perfect and zero capacity channel and the channel W is binary input channel by using this channel multiple times

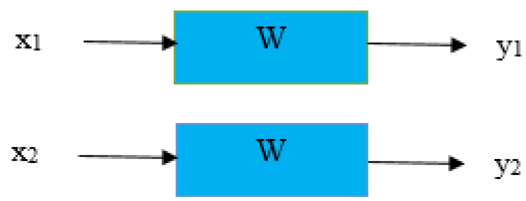


Figure 3.2 Two identical channels having equal capacity

In figure 3.2 same channel W is used two times with inputs x_1 and x_2 to give outputs y_0 and y_1 respectively. If we do the dependence between the inputs x_1 and x_2 in a systematic way we gate:

In figure 3.3 we can relate the inputs x_1 and x_2 of both channels by using the new binary inputs v_1 and v_2.

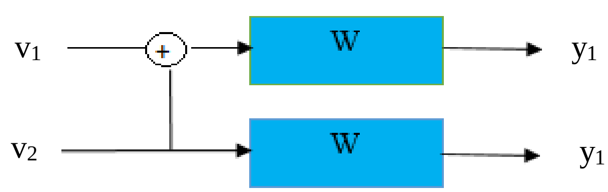


Figure 3.3 arranging the inputs in systematic fashion (Mude & Bhukya, 2019)

$$x_1=v_1+v_2 \quad (3.2)$$

$$x_2=v_2 \quad (3.3)$$

Let’s define two channels W^- and W+

$$W^-: v_1 \rightarrow y_1, y_2$$

$$W^+: v_2 \rightarrow y_1, y_2, v_1$$

Suppose v_1, v_2 …v_n influence an observation z

$$\tilde{v}_1=\phi_1(z) \quad (3.4)$$

$$\tilde{v}_2= \phi_2(z, \tilde{v}_1) \quad (3.5)$$

$$\tilde{v}_3= \phi_3(z, \tilde{v}_1, \tilde{v}_2) \quad (3.6)$$

$$\tilde{v}_n= \phi n(z, \tilde{v}_{1,} \tilde{v}_2 \ldots\ldots \tilde{v}_{n-1}) \quad (3.7)$$

To do the analysis of what W^- and W^+ channels will be obtained considering BEC with erasure probability p (Kaime et al., 2019).

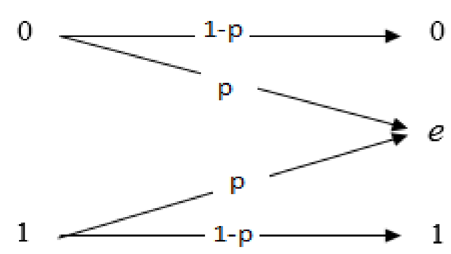


Figure 3.4 binary erasure channel

For W^- channel with input v_1

Possible values of the outputs y_1 and y_2 and their equivalent value is tabulated in table 3.1

Table 3.1 equivalent value estimation for input v_1 of BEC

	y_1	y_2	equivalent
	e	*e*	*e*
v_1	*e*	v_2	*e*
	v_1+v_2	*e*	*e*
	v_1+v_2	v_2	v_1

So the channel W^- has an erasure probability (1-((1-p)(1-p))]

$$W^-\equiv BEC\ (2p-p^2) \quad (3.8)$$

For W^+ channel with input v_2

Possible values of the outputs y_1 and y_2 and their equivalent value is tabulated in table 3.2

$W^+\equiv BEC\ (1-(p\ (1-p)\ +p\ (1-p) + (1-p)\ (1-p)))$

$W^+ \equiv BEC(p^2)$

Table 3.2 equivalent value estimation for input v_2 of BEC

	y_1	y_2	v_1	equivalent
	e	*e*	v_1	*e*
v_2	*e*	v_2	v_1	v_2
	v_1+v_2	*e*	v_1	v_2
	v_1+v_2	v_2	v_1	v_2

When we compare the erasure probability of W+ and W- channels the erasure probability of W+ channel is less than the erasure probability of W- since p is in between 0 and 1 so the inequality $p^2<2p-p^2$ holds true

The capacity is splitten by sequential way of duplicating in to p2 and 2p-p2. The average capacity of the two channels is same as the capacity of the original channel but inequality is created in between two identical channel.

In the above procedure of channel polarization we duplicated one channel in to identical channels and created inequality between them. What we have to do now is repeating the above procedure for more channels.

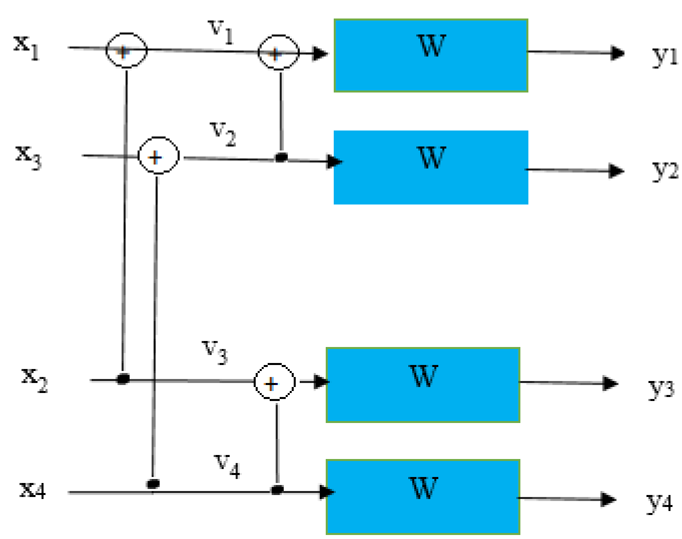


Figure 3.5 Cascaded building block

The cascade results in the following channels are

$$W^{--}: x_1 \longrightarrow y_1y_2y_3y_4 \quad (3.9)$$

$$W^{-+}: x_2 \longrightarrow y_1y_2y_3y_4x_1 \quad (3.10)$$

$$W^{+-}: x_3 \longrightarrow y_1y_2v_1y_3y_4v_3 \quad (3.11)$$

$$W^{++}: x_4 \longrightarrow y_1y_2v_1y_3y_4v_3x_3 \quad (3.12)$$

Virtual channels when the number of recursions becomes large, the virtual channels tend to either have high reliability or low reliability (in other words, they polarize), and the data bits are allocated to the most reliable channels.

$$I(W)=1-p \quad (3.13)$$

$$I(W-)+I(W+) = 2I(W) \quad (3.14)$$

$$I(W^{+})= 2I(W)-I(W)^2 \quad (3.15)$$

$$(W^{-})= I(W)^2 \quad (3.16)$$

The polarization effect brought by polar codes allows dividing the N-bit input vector v between reliable and unreliable bit-channels.

For n inputs by duplicating each channels obtained

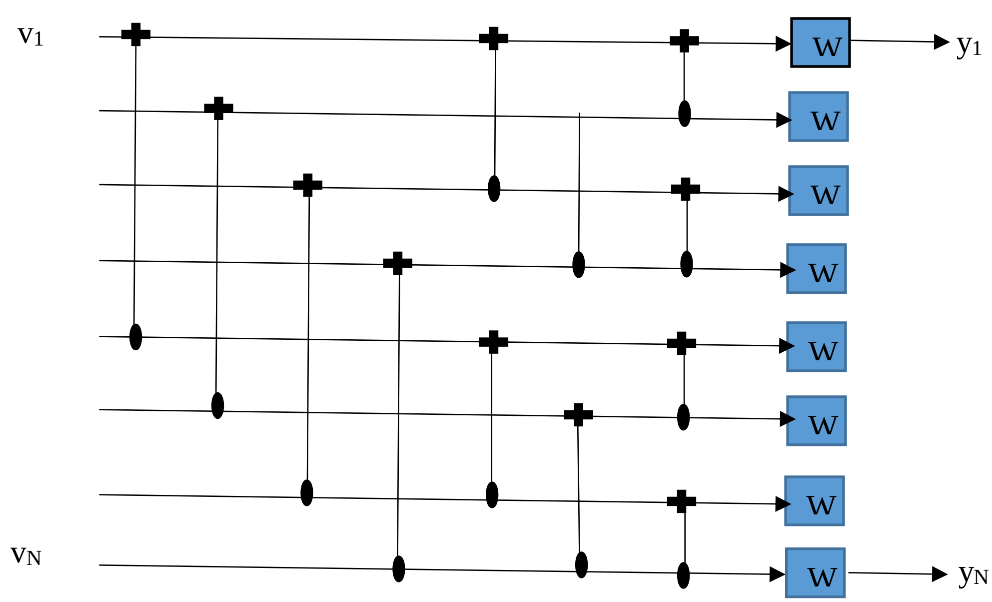


Figure 3.6 Stepwise polarization of the original channels

The coding procedure of the polar code is composed by two blocks: the first one compute and choose the k most reliable positions in which the information bits are placed and the second one is the coding module. The k positions of information bits are corresponding to k small values of error-prone. In polar coding the redundant bits are added in non-systematic fashion. To identify the redundant bits and information bit position channel polarization plays the great role. To plot the capacity percentage versus the channel indices. Polarized bit channel having capacity splitten into higher and lower capacity and in the second graph the capacity is in increasing order. In figure 3.7 the capacity percentage is plotted in increasing order so the channel indices having lower capacity will be used to hold redundant bits.

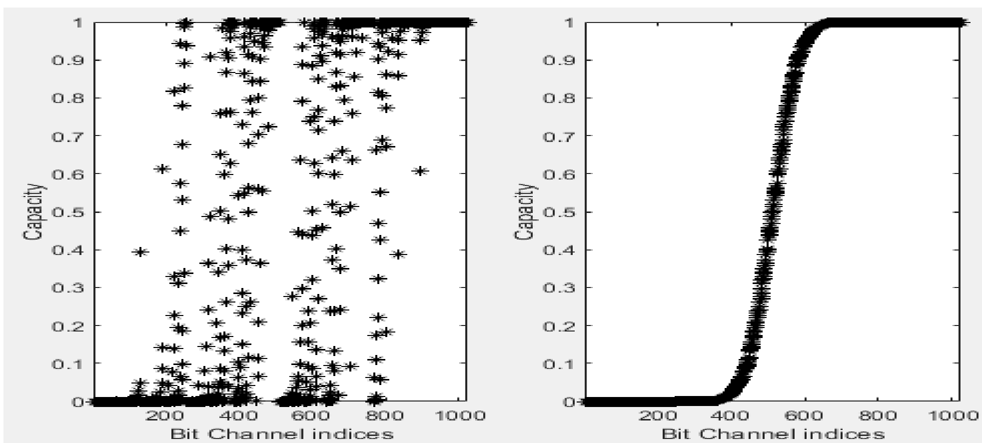


Figure 3.7 Polarized bit channel having capacity splitten into higher and lower capacity

3.6 Polar Coding Schemes

5G and beyond data and control streams from/to MAC layer are encoded /decoded to by choosing the k most reliable positions offer transport and control services over the radio transmission link

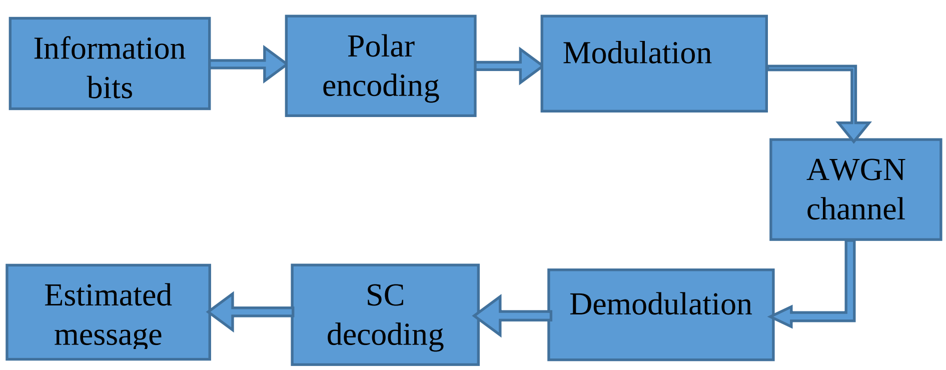


Figure 3.8 Polar coding with SC decoding block diagram

The k positions of information bits are corresponding to k small values of error-prone computed by the parameter. (p^2, $2p-p^2$) p is the erasure probability of binary erasure channel.

3.6.1 Polar coding with SC and Polar Transform

A polar codes (N, K) are a linear block code of length $N=2^n$ and rate K/N. They can be expressed mathematically by the multiplication between the vector information and matrix generator as G_N where G_N is NxN matrix Kronecker product of 2x2 kernel

K is the size of DCI and UCI

N is the code word size of the layers that are mapped to PUCCH, PDCCH and BCH

The encoding is performed by kernel matrix

$$G_2=\begin{bmatrix}1 & 0\\ 1 & 1\end{bmatrix} \tag{3.17}$$

The encoded codeword x for input bits v is given by (Mude & Bhukya, 2019)

$$c=vG_N \tag{3.18}$$

Where v= (v_1, v_2… v_{N-1}) denotes the input vector, and G_N is the matrix generator.

Where v includes both the information payloads and the frozen bits.

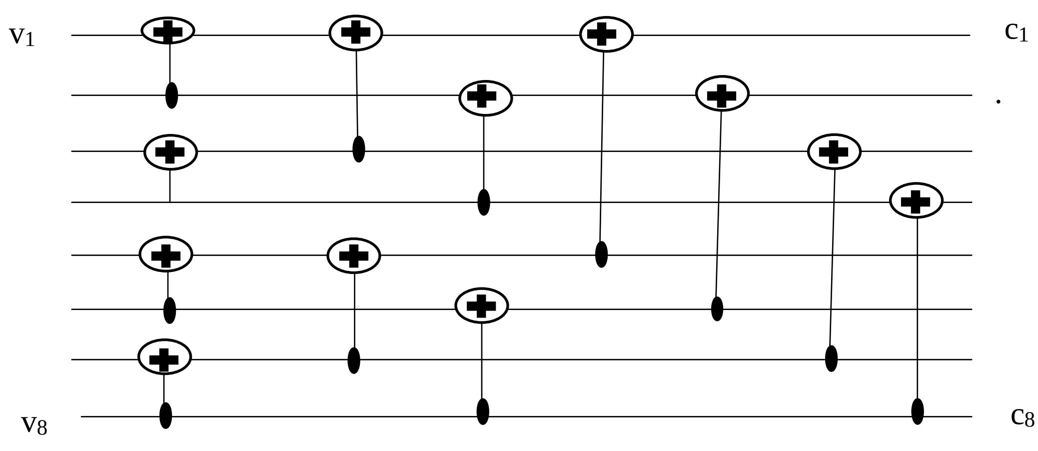


Figure 3.9 Polar encoder factor graph with N=8

For higher polar block size the Kronecker matrix is grown as shown below in equation 3.19, equation 3.20 and the general trend of expanding the matrix is in equation 3.21.

$$G_4=\begin{bmatrix} G_2 & 0 \\ G_2 & G_2 \end{bmatrix} \tag{3.19}$$

$$G_4=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 \end{bmatrix} \tag{3.20}$$

$$G_N=\begin{bmatrix} G_{N/2} & 0 \\ G_{N/2} & G_{N/2} \end{bmatrix} \tag{3.21}$$

Binary tree representation of the polar coding schemes is shown in figure 3.10 for N=2 and figure 3.11 for N=4 (Bioglio et al., 2021)

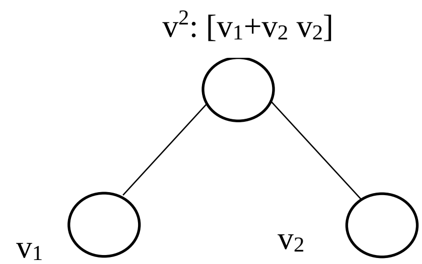


Figure 3.10 Binary tree representation for polar transform of N=2

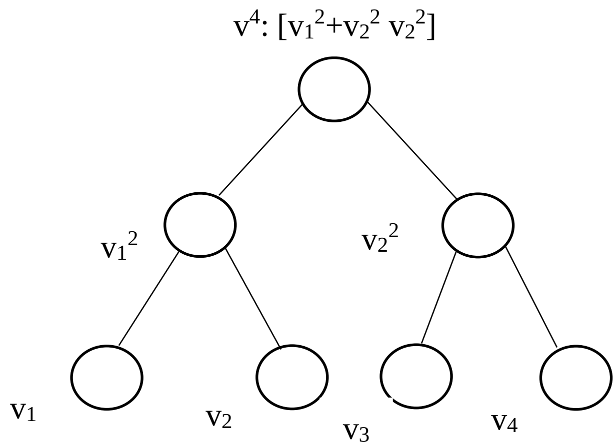


Figure 3.11 Binary tree representation for polar transform of N=4

For (N, K) polar we will have N bits of codeword for K bits of message. To encode the message bits the procedure steps are:

- A vector v of length N have to be formed
- From the polarized channels obtaining the least capacity N-K channels
- Setting v_i frozen for those N-K positions of v and rest K bits of v are called message bits

3.6.2 Interleaving Polar Coding with SC decoding

In wireless communication Interleaving functions are the most key component in channel coding techniques. Thus, channel coding and interleaving techniques represent fundamental elements in wireless communication systems. To interleave the coded information bits $c_1, c_2, \ldots\ldots\ldots c_N$ to $c'_1, c_2', \ldots\ldots\ldots c_N'$. The pseudocode or the steps to interleave the coded bits

For n=0 up to N-1

i=floor (32n/N)

g(n)=d(i)(N/32)+mod(n,N/32)

c'(n)=x(g(n))

end

d(i) is the pattern found on (TSGR, 2020).

The code rate for the coding schemes is given by equation (3.22)

$$\text{Code rate} = K/N \tag{3.22}$$

3.6.3 CRC-A-Polar Coding with SCL Decoding

We can attach cyclic codes to correct errors due to impairments in the communication channel. A better way to apply cyclic codes and how they can be analyzed is to represent them as polynomials. The power of each term shows the position of the bit and the coefficients show the value of the bit in that position.

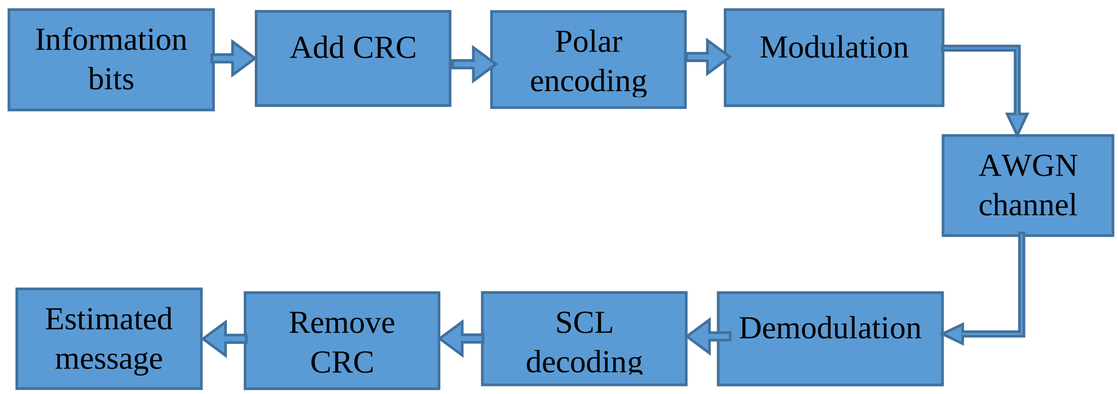


Figure 3.12 Cyclic redundancy check added polar coding

In a (N,K) polar encoding we will have K message block that is given by $m_0, m_1, m_2, m_3 .. m_K$ and the parity bits by $p_0, p_1, p_2 \ldots\ldots\ldots p_{L-1}$ where K is the size of the input sequence and L is the number of parity bits. The parity bits are generated CRC generator polynomials: Here divisor is the generator polynomial and to obtain the dividend we have left-shifted the data word L bits (multiplying by x^L).

$$\text{Dividend} = x^L(m_0 x^{k-1} + m_1 x^{k-2} + \ldots\ldots\ldots\ldots\ldots + m_{k-1} x^0) \quad (3.23)$$

$$= m_0 x^{k+L-1} + m_1 x^{k+L-2} + \ldots\ldots\ldots\ldots\ldots + m_{k-1} x^L \quad (3.24)$$

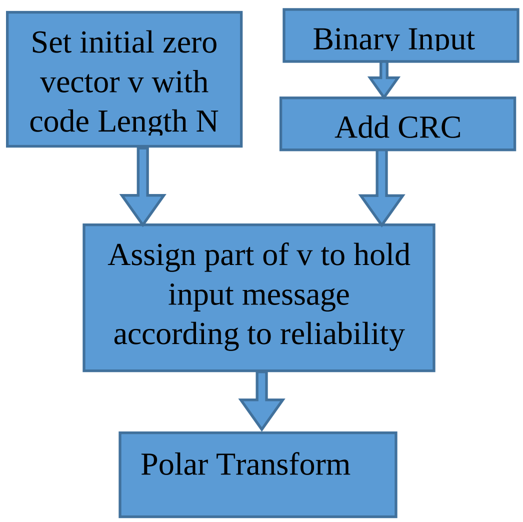


Figure 3.13 Flow chart for cyclic redundancy check added polar coding

Then the data with CRC becomes

$$d(x) = m_0 x^{k+L-1} + m_1 x^{k+L-2} \ldots\ldots\ldots\ldots\ldots + m_{k-1} x^L + p_0 x^{L-1} + p_1 x^{L-2} + \ldots\ldots\ldots p_{L-2} x + p_{L-1} \quad (3.25)$$

$$d = [d_1\ d_2\ d_3 \ldots\ldots\ldots\ldots\ldots\ldots d_{L+k}] \quad (3.26)$$

To polar encode the message with CRC it will be followed as the procedure stated in

When we calculate the information rate it will not be N/(K+L) but it is N/K because the CRC don't contain any information

3.6.4 CRC-A- Interleaving Polar Coding with SCL Decoding

The bits input to the sub-block interleaver are the coded bits $x_0, x_1, x_2 \ldots\ldots x_{N-1}$.

The coded bits $x_0, x_1, x_2 \ldots\ldots x_{N-1}$ are divided into 32 sub-blocks. The bits output from the sub-block interleaver are denoted as $c_0, c_1, c_2 \ldots c_{N-1}$ generated as follows

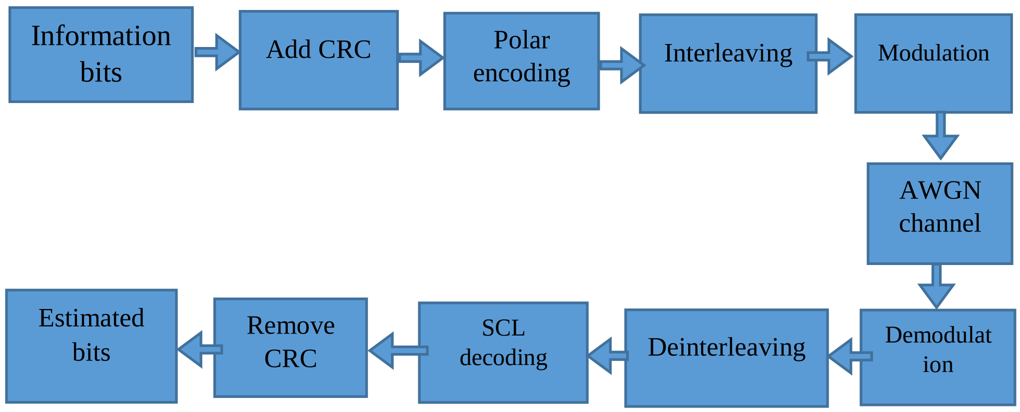


Figure 3.14 CRC-A interleaving polar coding block diagram

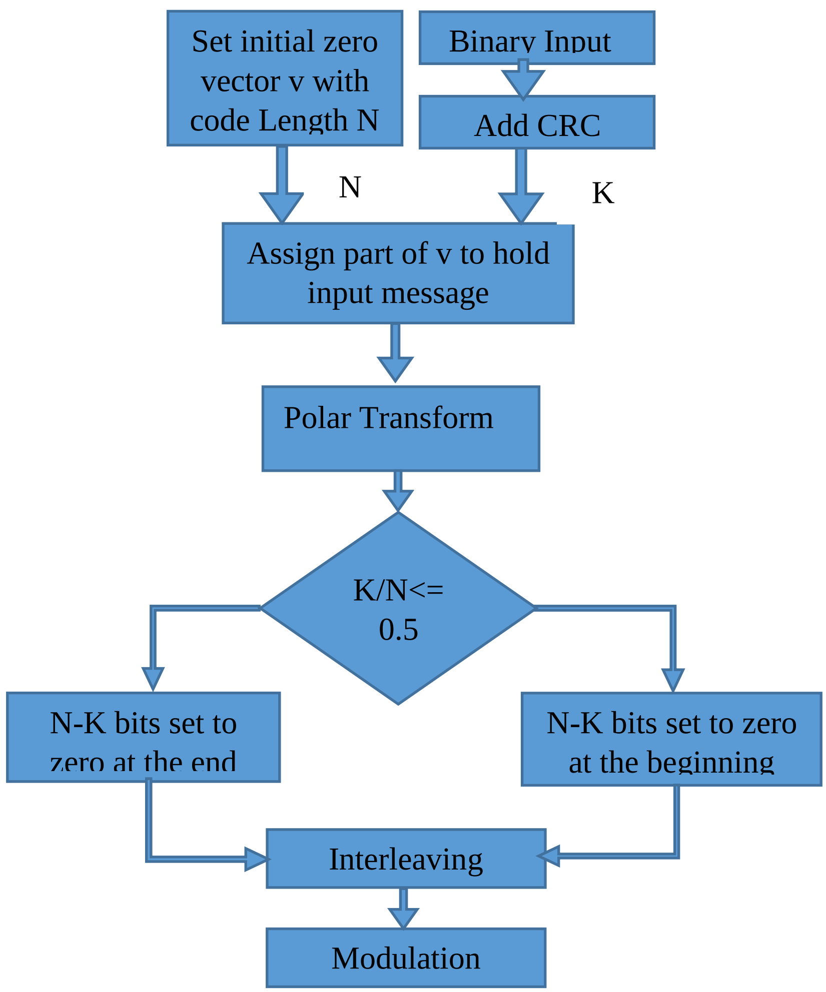


Figure 3.15 Flow chart of CRC added interleaved encoding part

Polar codes based on the 2 × 2 polarization kernel have a power of two as their length. Thus, rate matching is applied to modify the length and adjust the rate.

3.7 Modulation Mapper

In modulation process adding message signal to a carrier signal in order to transmit data is processed.

In 5G different modulation techniques are used like BPSK, QPSK and higher order QAM. Modulation scheme adopted for 5G is able to provide a high level of spectral efficiency. For simplicity BPSK modulation technique is selected for performance comparison purpose.

BPSK modulation, that uses two-phase levels for the carrier phase, is the most basic form of phase modulation. BPSK is the most efficient of all digital modulation schemes. As a result, BPSK is used to produce high bit rates with low energy use. The phase of the sinusoidal carrier is altered based on the data bit to be transmitted in binary phase-shift keying. Bits are encoded into a single symbol via BPSK modulation, and the symbol transmission rate sets the bandwidth of the sent signal.

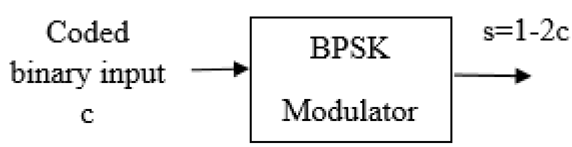


Figure 3.16 BPSK modulation of coded binary data

3.8 Channel Modelling

The channel serves as a path between the UE and the BS. There are various channel models that have been researched. It is necessary to have some awareness of several types of channel models and their properties in order to design and create a wireless communication system. When modeling networks, channel models are used to see how the system design functions in different states and under different conditions. A white Gaussian noise is added to the signal traveling over the AWGN Channel. In AWGN, the channel's amplitude frequency response is flat (resulting in boundless or infinite bandwidth) and the phase frequency response is flat for all frequencies, resulting in modulated signals with no amplitude loss or phase distortion. In this thesis work AWGN channel model is considered to compare the performance of the polar coding schemes. The received signal r(t) is given by equation (3.27) for transmitted signal s(t) and n(t).

$$r(t)=s(t)+n(t) \tag{3.27}$$

3.9 Deinterleaving

An interleaver is defined as a device that reads the symbols from an input vector deinterleaving is done by rearranging the bits back to how they were arranged before interleaving process. Rearranging is performed according to the reversed interleaver pattern in index. The steps are:

```
For n=0 up to N-1
        i = floor ((32*n)/N);
        J (n+1) = P (i+1)*(N/32) + mod (n,
        N/32);
        r (J(n+1)+1) = r(n+1)
end
```

3.10 SC Decoding

As its name indicates, the SC decoding takes successive decisions on the information bits. In this case the receiver observes the channel output vector and estimates the elements of the input vector in a successive manner. The main task of this decoding algorithm is to generate an estimate vector but not the actual vector corresponding to the input vector

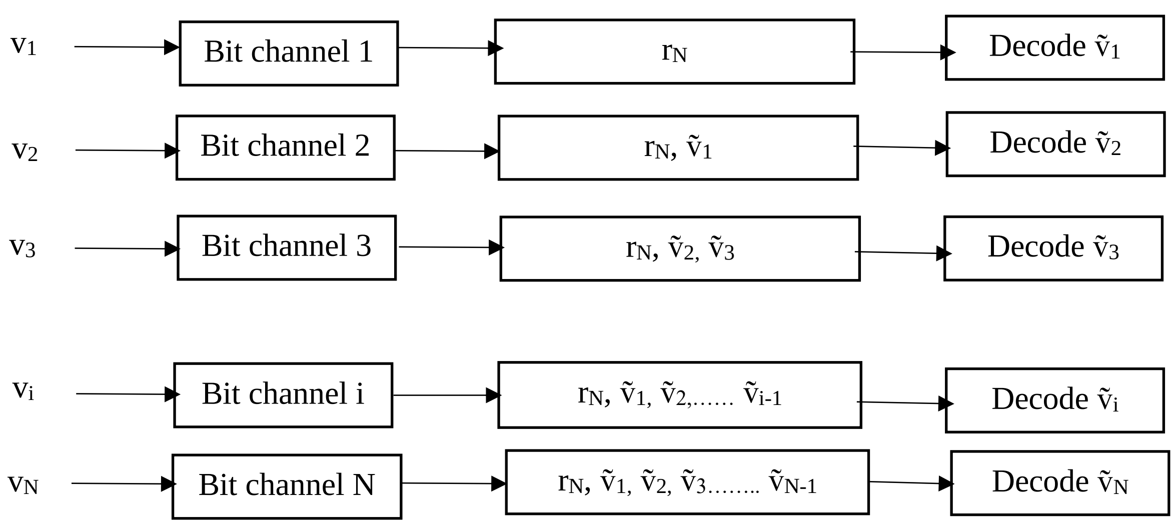


Figure 3.17 Step by step Successive cancelation decoding structure

In the receiver part the decoder has the information by the help of reliability sequence about the frozen bits and can decode this bits as 0 with error zero.

If the bit position is containing the message bits these will be decoded by soft in soft out decoder

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 polar codes successively we can calculate the probability as following (Albert Raj et al., 2021).

$$P_r(c_i = 0/r_i) = \frac{f(r_i/c_i=0)p_r(c_i=0)}{f(r_i)} \quad (3.28)$$

$$P_r(c_i = 1/r_i) = \frac{f(r_i/c_i=1)p_r(c_i=1)}{f(r_i)} \quad (3.29)$$

It is known that $p_r(c_i = 0)= p_r(c_i = 1) = 1/2$

The likelihood ratio is given by

$$\frac{P_r(c_i=0/r_i)}{P_r(c_i=1/r_i)} = \frac{f(r_i/c_i=0)}{f(r_i/c_i=1)} \quad (3.30)$$

$$= \frac{\frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(r_i-1)^2}{2\sigma^2}}}{\frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(r_i+1)^2}{2\sigma^2}}} \quad (3.31)$$

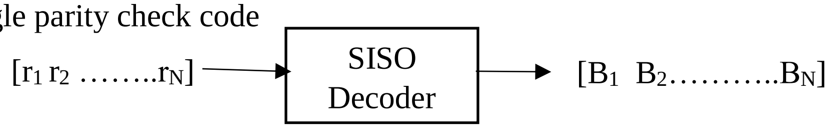
Then when we estimate the log-likelihood ratio(Albert Raj et al., 2021)

$$\log\frac{P_r(c_i=0/r_i)}{P_r(c_i=1/r_i)} = \frac{2}{\sigma^2} r_i \quad (3.32)$$

In a general way

$$\log\left(\frac{P_r(c_i=0/r_1,r_2,..r_N)}{P_r(c_i=1/r_1,r_2,..r_N)}\right) = (r_1 + r_2 + \cdots r_N)\frac{2}{\sigma^2} \quad (3.33)$$

For a Single parity check code



The beliefs B are the sum of intrinsic beliefs and extrinsic beliefs

$$B_i = b_{in} + b_{extr} \quad (3.34)$$

$$b_{intr,i} = \frac{2}{\sigma^2} r_i \quad (3.35)$$

$$b_{ext,\,1} = \mathrm{sgn}(b_{in,2})\ \mathrm{sgn}(b_{in,3})\ldots\ldots\ \mathrm{sgn}(b_{in,N})(\min(\ |b_{in,2}|,|b_{in,3}|,\ldots\ldots|b_{in,N}|)) \quad (3.36)$$

$$b_{ext,\,2} = \mathrm{sgn}(b_{in,1})\ \mathrm{sgn}(b_{in,3})\ldots\ldots\ \mathrm{sgn}(b_{in,N})(\min(\ |b_{in,2}|,|b_{in,3}|,\ldots\ldots|b_{in,N}|)) \quad (3.37)$$

$$b_{ext,\,N} = \mathrm{sgn}(b_{in,1})\ \mathrm{sgn}(b_{in,2})\ldots\ldots\ \mathrm{sgn}(b_{in,N})(\min(\ |b_{in,2}|,|b_{in,3}|,\ldots\ldots|b_{in,N-1}|)) \quad (3.38)$$

In Single parity check codes single bit is appended to the end of each frame, the bit is 1 if the data portion of the frame has odd number of 1's. Otherwise, it is 0. This way, the total number of 1's in each data frame is always even

3.10.1 SC Decoding for N=2

For received value of two values r_1 and r_2 by message passing on tree

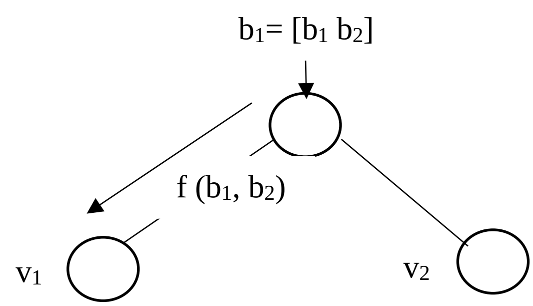


Figure 3.18 SC decoding binary tree for first bit estimation

The belief for $\tilde{v}_1$ is given

$$B(\tilde{v}_1) = f(b_1, b_2) = \mathrm{sgn}(b_1)\ \mathrm{sgn}(b_2)\ \min(|b_1|,|b_2|) \quad (3.39)$$

As shown in the binary tree below for two received value which is the building block for decoding polar codes the decoder estimates the first bit by minsum approximation of function $f(r_1,r_2)$ which is given by (Albert Raj et al., 2021).

$$f(b_1,b_2) = \mathrm{sgn}(b_1)\mathrm{sgn}(b_2)\min(|b_1|,|b_2|) \quad (3.40)$$

After estimating the first bit by minsum approximation successively the second bit will be estimated. If the bit is frozen according to the reliability sequence since the decoder has prior information about the reliability sequence it will automatically decoded as zero.

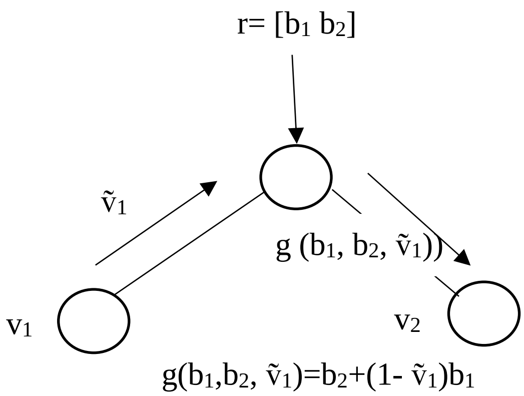


Figure 3.19 SC decoding binary tree for second bit estimation (Bioglio et al., 2021)

3.10.2 SC Decoding for N=4

As its name indicates the successive cancelation decoding technique uses the successive estimating of the received beliefs that means after estimating the in the bit in the first position it will estimate the bit in second position. Then again uses these two bits to estimate the bits in third position. Here the way to decode four received values is the extension from the decoding process for N=2. From the original received four values there is a reduction of beliefs to two values.

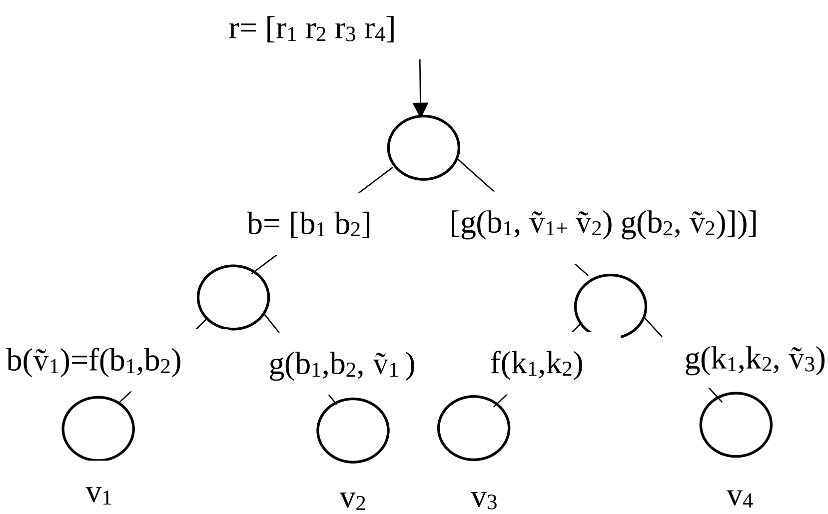


Figure 3.20 Successive cancelation decoding (Bioglio et al., 2021)

$$b_1=f\ (r_1,\ r_3) \tag{3.41}$$

$$b_2=f\ (r_2,\ r_4) \tag{3.42}$$

$$b\ (\tilde{v}_1)=f\ (b_1,\ b_2) \tag{3.43}$$

$$[k_1\ k_2]=g(r_2, r_4, \tilde{v}_2) \quad g(r_1, r_3, \tilde{v}_{1+} \tilde{v}_2) \tag{3.44}$$

$$[k_1\ k_2] = [g\ (b_1, \tilde{v}_{1+} \tilde{v}_1)\ g(b_2, \tilde{v}_2)] \tag{3.45}$$

The decoding order in binary tree in

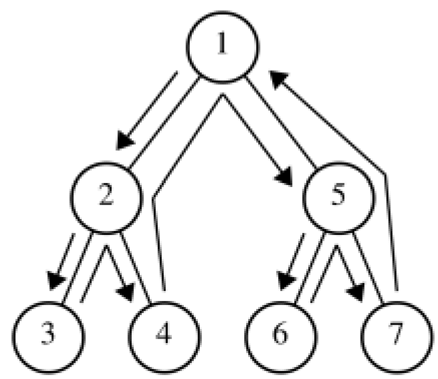


Figure 3.21 belief flow order in decoding structure for SC decoder

3.10.3 SC Decoding for General N Codewords

In the decoding process of N received beliefs as discussed above the first thing that the decoder do is reducing the number of belies by half again and until it reaches to two values. Then the successive decoding takes place.

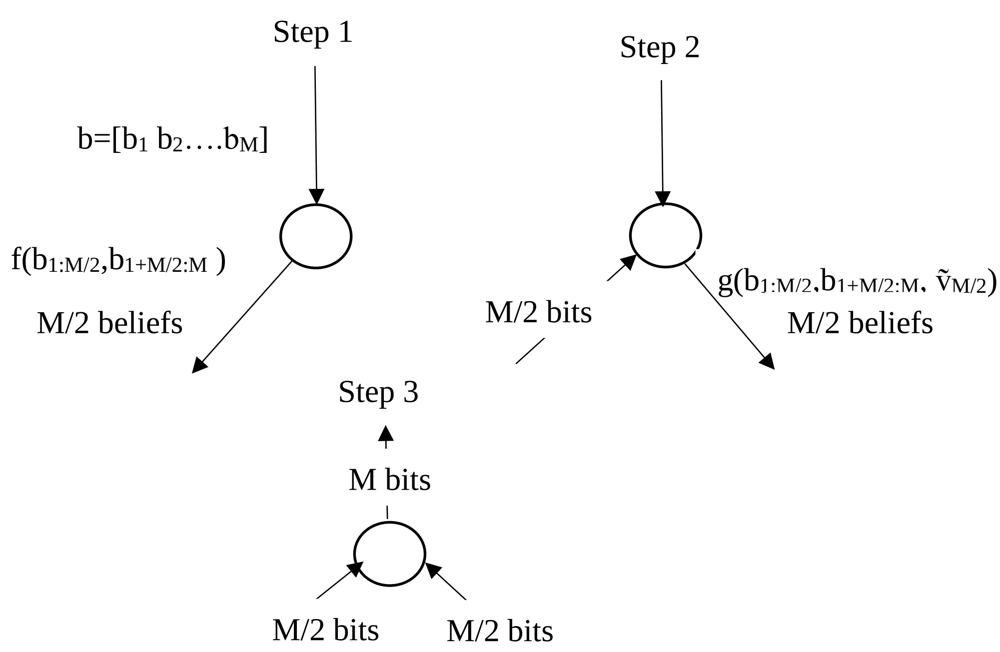


Figure 3.22 Belief flow order in decoding structure for SC for N codewords

Where the functions in the binary tree diagrams are expressed as

$$f(x_{1:p},y_{1:p})=[f(x_1,y_1)\ f(x_2,y_2)\ldots\ldots\ldots\ f(x_p,y_p)] \quad (3.46)$$

$$g(x_{1:p},y_{1:p},\tilde{v}_p)=\ )=[g(x_1,y_1,\tilde{v}_1)\ g(x_2,y_2,\tilde{v}_2)\ldots\ldots\ldots\ g(x_p,y_p,\tilde{v}_p)] \quad (3.47)$$

$$g(x,y,v)=y+x(1-2v) \quad (3.48)$$

And by minsum approximation the function is given by (Albert Raj et al., 2021)

$$f(r_1,r_2,\ldots\ldots r_N)=(sgn(r_1)\ sgn(r_2)\ldots\ldots\ldots\ sgn(r_N))\min(|r_1|,|r_2|\ldots\ldots\ldots|r_N|) \quad (3.49)$$

3.11 SCL Decoding

In SCL decoding a specified number of estimated bits will be there. These estimated values are the candidates to pass to the next stage if the decoder has more decoded series than the specified list value. We have to use the cyclic redundancy check to choose from the list.

How to produces specified number of codewords at the decoder is by decoding as per the belief and against belief. Against belief is used to compromise the error in as per belief decoding.

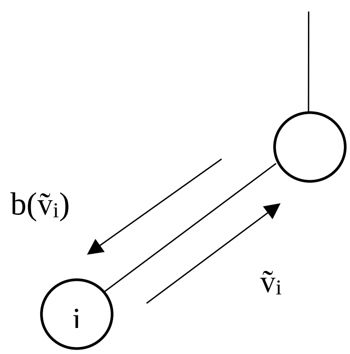


Figure 3.23 belief flow structure for SCL decoding for N codewords

$$\text{For } b(\tilde{v}_i)\geq 0: \hat{u}_i=0 \text{ has } dm_i=0 \text{ and } \tilde{v}_i=1 \text{ has } dm_i=|b(\tilde{v}_i)| \quad (3.50)$$

$$\text{For } b(\tilde{v}_i)\leq 0: \tilde{v}_i=1 \text{ has } dm_i=0 \text{ and } \tilde{v}_i=0 \text{ has } dm_i=|b(\tilde{v}_i)| \quad (3.51)$$

In the decoding process the path metric is assigned for each path in the binary tree diagram. Path metric is the sum of decision metric in each path. In the diagram shown below what happens at $\tilde{v}_3$ is sorting the decoders based on their path metric values and continuing with the surviving L decoders where L is the list size SCLD is a tree-based decoding algorithm that attempts to find the most likely path between the root and leaf nodes. Unlike the SC, which only keeps track of one path at each decoding stage, the SCLD keeps track of L alternative

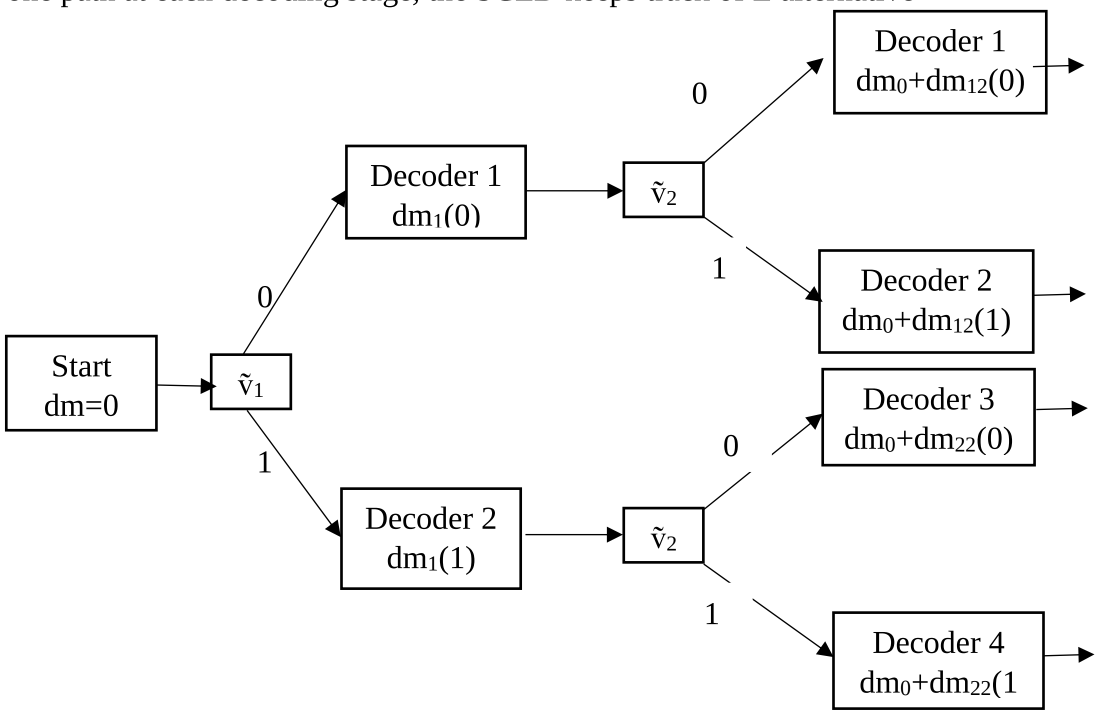


Figure 3.24 SCL decoded bits flow

3.11.1 CRC of the List Decoders

The cyclic redundancy check is based on division of polynomials over the integers modulo 2, that is, the set of polynomials where each coefficient is either zero or one and multiplied with power of position of the bits. In list decoding of polar coding we have a number of decoded bits series.}

$$\left.\begin{aligned} d_1(x) &= \tilde{v}_{11}x^{N-1} + \tilde{v}_{12}x^{N-2} + \tilde{v}_{13}x^{N-3} \ldots\ldots\ldots\ldots + \tilde{v}_{1N-1}x + \tilde{v}_{1N} \\ d_2(x) &= \tilde{v}_{21}x^{N-1} + \tilde{v}_{22}x^{N-2} + \tilde{v}_{23}x^{N-3} \ldots\ldots\ldots\ldots + \tilde{v}_{2N-1}x + \tilde{v}_{2N} \\ &\qquad\qquad\qquad\cdot \\ &\qquad\qquad\qquad\cdot \\ d_1(x) &= \tilde{v}_{L1}x^{N-1} + \tilde{v}_{L2}x^{N-2} + \tilde{v}_{L3}x^{N-3} \ldots\ldots\ldots\ldots + \tilde{v}_{LN-1}x + \tilde{v}_{LN} \end{aligned}\right\} \quad (3.52)$$

If the CRC polynomial is given by $g_d(x)$ we can evaluate the quotient and remainder

$$\frac{d_L(x)}{g_d(x)} = q(x) + r(x) \quad (3.53)$$

In the decoding process with multiple codewords the paths are compared as the number of decoded codeword are higher than the specified value L. But at the last stage the decoder is left with L number of decoded codewords for same message block sent. Since only one decoded codeword is accepted at the end CRC division takes place to choose the best.

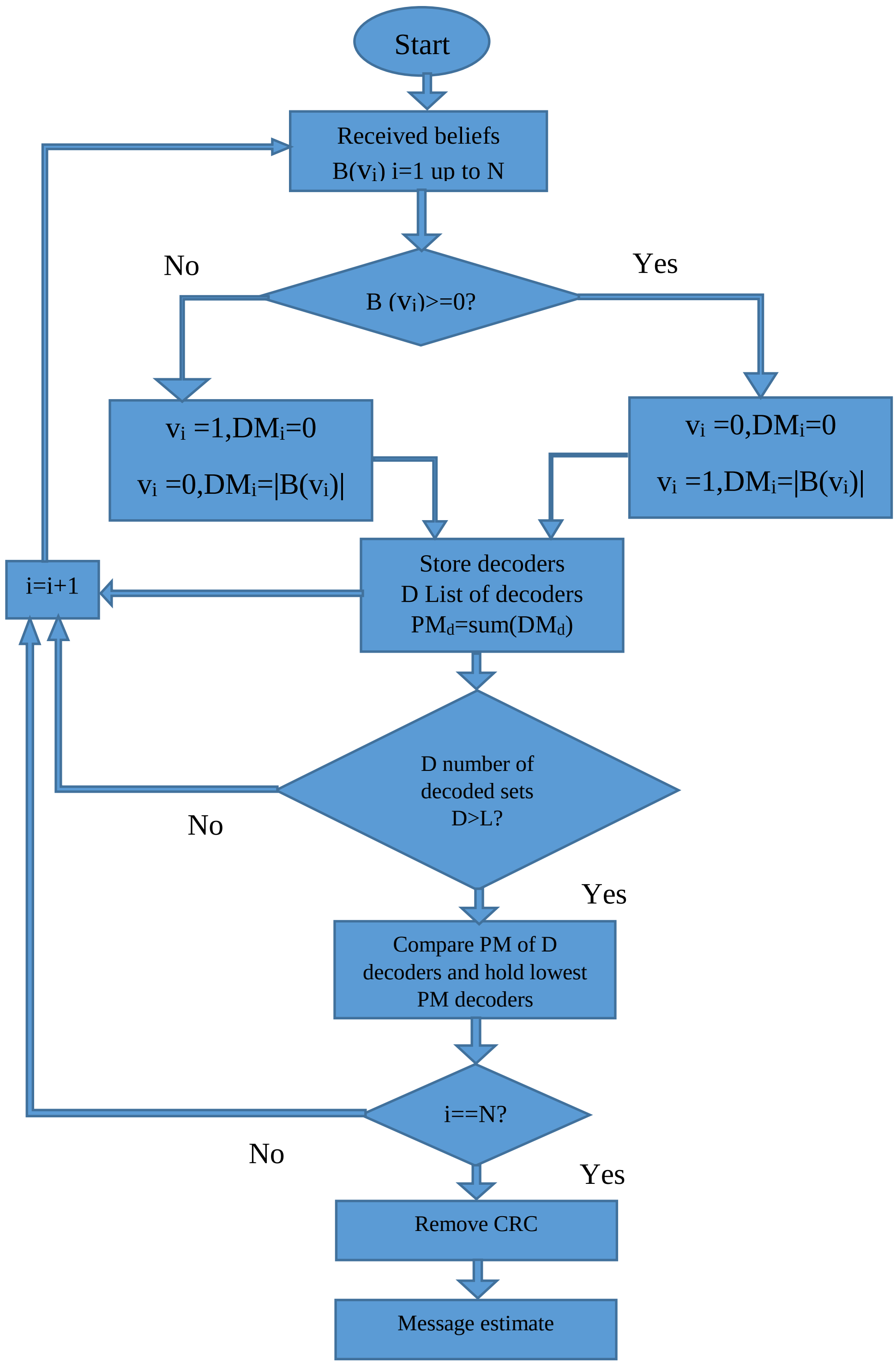


Figure 3.25 Flow chart for CRC added polar coding SCL decoding

3.12 Throughput Analysis of eMBB

For NR, the approximate data rate for a given number of aggregated carriers in a band is computed as follows.(Kabalci & Ali, 2020).

$$\text{Data rate}=\sum_{j=1}^{J}(v_L^{(j)} . f^{(j)}. R.\frac{N^{BW(j),\mu}.12}{T_s^{\mu}}(1-OH^{(j)})) \quad (3.54)$$

J is the number of aggregated component carriers in a band

v_L is the maximum number of supported layers

f is the scaling factor taking the values 1, 0.8, 0.75, and 0.4 and it relates the number of layers and the component carriers

R: is the code rate

μ : is the numerology which is the configuration of waveform parameters

T_s^{μ} "Is the average symbol period

$T_s^{\mu}=\frac{10^{-3}}{14.2^{\mu}}$

$N^{BW(j),\mu}$ Is the maximum resource block allocation in bandwidth $BW^{(j)}$ with numerology μ

$OH^{(j)}$ is the overhead and takes the following values 0.14, for frequency range FR1 for DL 0.18, for frequency range FR2 for DL 0.08, for frequency range FR1 for UL 0.10, for frequency range FR2 for UL. The frequency range FR1 is 0.45GHz -6GHz and FR2 is 24.25GHz – 52.6GHz

3.13 Computational Complexity Analysis

There are a number of activities in encoding and decoding polar coding schemes that use a method called channel polarization to achieve the symmetric capacity of any binary-input discrete memoryless channel. In error correcting procedure there are different decoding structures. For a polar code with successive cancelation decoding of codeword length of N which is 2^n where n=1,2 …in encoding there are n encoding stages each stages with XOR operations of n/2 (Koike et al., 2021)

$$C=N\log_2 N \quad (3.55)$$

Also for the decoding procedure the decoding complexity is calculated by equation above. For a CRC aided polar code with SCL decoding technique the calculation of the number of additions of the CRC algorithm is carried out and also encoding operation(Turdiev et al., 2020).

$$A=k.g \tag{3.56}$$

Where k is the length of message block and g is the length of the polynomial. Then the total complexity is

$$C=2k.g+N\log N+ LN\log N \tag{3.57}$$

For CRC aided interleaved polar code with SCDL decoding technique the computational complexity will be 2N added in equation (3.57) interleaver and deinterleaver structure.

CHAPTER FOUR

4. RESULTS AND DISCUSSIONS

4.1 Introduction

In this section simulation results are shown. The simulations are based on the previous chapters' concept. To combatively study the performance based on the block error rate and bit error rate in each section the simulation parameters are specified. Based on the result obtained interpretations are made. The simulations are done using MATLAB R2020a software package. The parameters of interest for this thesis are

- Polar codeword size
- Message block size
- Eb/N_0
- Noise
- BER
- BLER
- Computational complexity
- CRC length
- List size
- Code rate

In consideration of polar codeword size different block sizes are tested and evaluated against each other in the same conditions. This allows analysis on performance variations depending on the size of the blocks being encoded and decoded. Possible polar codeword sizes for polar codes are 2^n. Message block size is the amount of message bits and CRC bits combined.

Eb/N0 (dB) - A range of values representing the signal strength. Performance results with different Eb/N_0 (dB) are interesting to measure and compare to see the performance differences, in decibel between simulations.

Noise - AWGN is the type of noise used for all the simulations in this thesis work.

Code rate: Is the ratio of information bits to codeword bits

BER- Is defined as the total number of bits in errors in transmission that is divided by the total number of transmitted bits during a study time interval. Bit error ratio is a unit less performance measure also expressed as a percentage.

To calculate the bit error rate

- Total number of bits will be obtained
- Number of bits in error at the receiver should be obtained
- Finally, calculating the bit error rate which is Number of bits in error divided by total number of bits transmitted.

Block error rate (BLER) - is the ratio of errored blocks to total transmitted blocks. A block is in error at least one bit in the block is in error.

4.2 Theoretical BER for BPSK Modulation over AWGN

In figure 4.1 the theoretical BER in BPSK Modulation over AWGN for uncoded case is plotted. This will be the base line to compare the performance of the polar coding schemes. That means the coding schemes will have the capacity to overcome the problem in uncoded case.

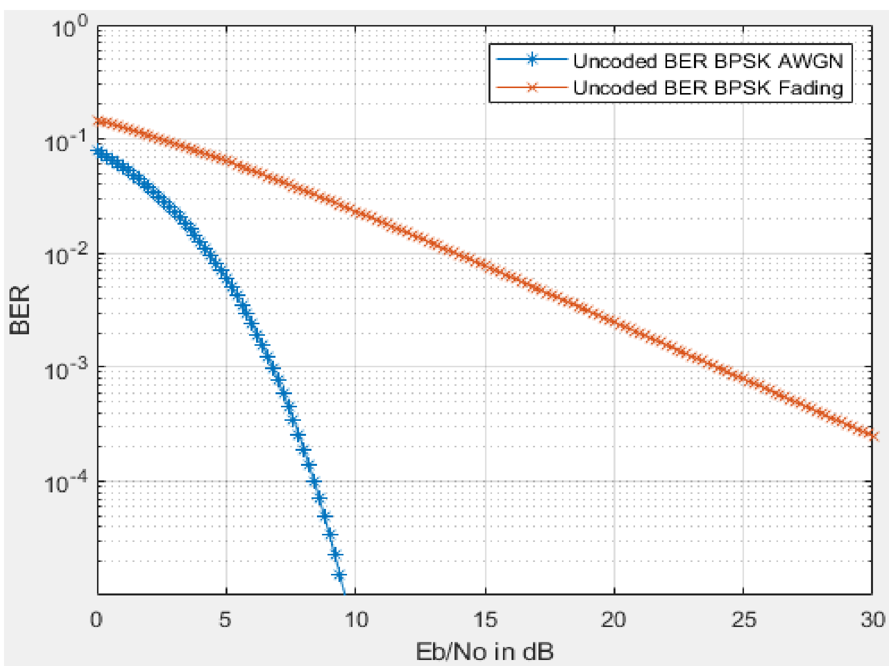


Figure 4.1 Theoretical BER for BPSK Modulation over AWGN

In figure 4.1 the BER is plotted for different value of Eb/No in AWGN.

Table 4.1 Theoretical BER for BPSK Modulation over AWGN and Fading Channel

E_b/N_0(dB)	BER	
	AWGN	Fading
0.2	0.0786	0.1464
0.6	0.0693	0.1384
1	0.0605	0.1306
1.4	0.0522	0.1230
1.8	0.0445	0.1156
2.2	0.0375	0.1085
2.6	0.0311	0.1016
3	0.0255	0.0951
3.4	0.0205	0.0888
3.8	0.0162	0.0828

For an uncoded transmission of the information high amount of Eb/No is needed to reduce the error in reception. In table 4.1 at Eb/No of 3dB 2.55% BER for AWGN channel and 9.51% for fading channel is obtained. But coding overcomes this issue by improving the error rate in small Eb/No.

4.3 BLER and BER Evaluation for Polar Code by SC Decoding by Varying Code Rate

To evaluate the performance of polar coding by SC decoding technique under AWGN channels for the parameters listed in table 4.2. In this simulation effect of code rate on the performance is studied under AWGN channel and BPSK modulation. As it can be seen from the table and also the graph as the code rate increases there is degradation of the performance.

Table 4.2 Simulation parameters for polar code by SC decoding

Polar size and codeword size	(54,128),(64,128),(76,128),(102,128)
Code rate	0.4219,0.5, 0.5940, 0.7968
Block size	1000
Eb/No	0.2-3.8dB

For code rate 0.4219 with information bits size 54, code rate 0.5, code rate 0.5940 with information bits size 76 and code rate 0.7968 with information bits size 102 with Polar block size of 128 the BER and BLER with 1000 blocks are tabulated in table 4.3 as shown below.

As we can the table result as well as the graph if we take 3dB Eb/No for code rate of 0.7968 from 1000 blocks 192 blocks or blocks are in error but if the code rate is reduced to 0.5938 from the total 1000 blocks 58 will be in error. Again if the code rate is reduced to 0.4219 the number of blocks in error is 17.

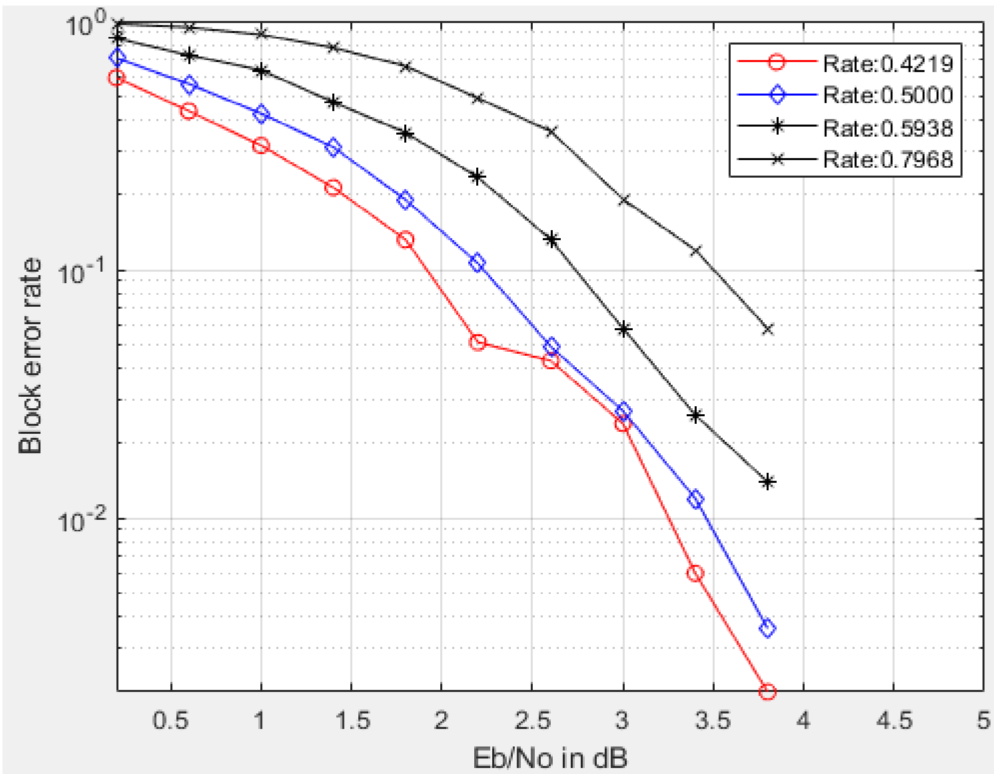


Figure 4.2 BLER versus Eb/No for polar code by SC decoding by varying code rate

Table 4.3 BLER for polar code with SC varies code rate

E_b/N_0(dB)	BLER			
	Code rate			
	0.4219	0.5	0.5938	0.7968
0.2	0.5800	0.7100	0.8520	0.9740
0.6	0.4340	0.5590	0.7300	0.9440
1	0.3320	0.4250	0.6350	0.8820

1.4	0.2260	0.3110	0.4720	0.7820
1.8	0.1110	0.1910	0.3560	0.6590
2.2	0.0740	0.1060	0.2350	0.4900
2.6	0.0260	0.0490	0.1320	0.3600
3	0.0170	0.0270	0.0580	0.1920
3.4	0.0030	0.0120	0.0260	0.1200
3.8	0.0010	0.0020	0.0140	0.0580

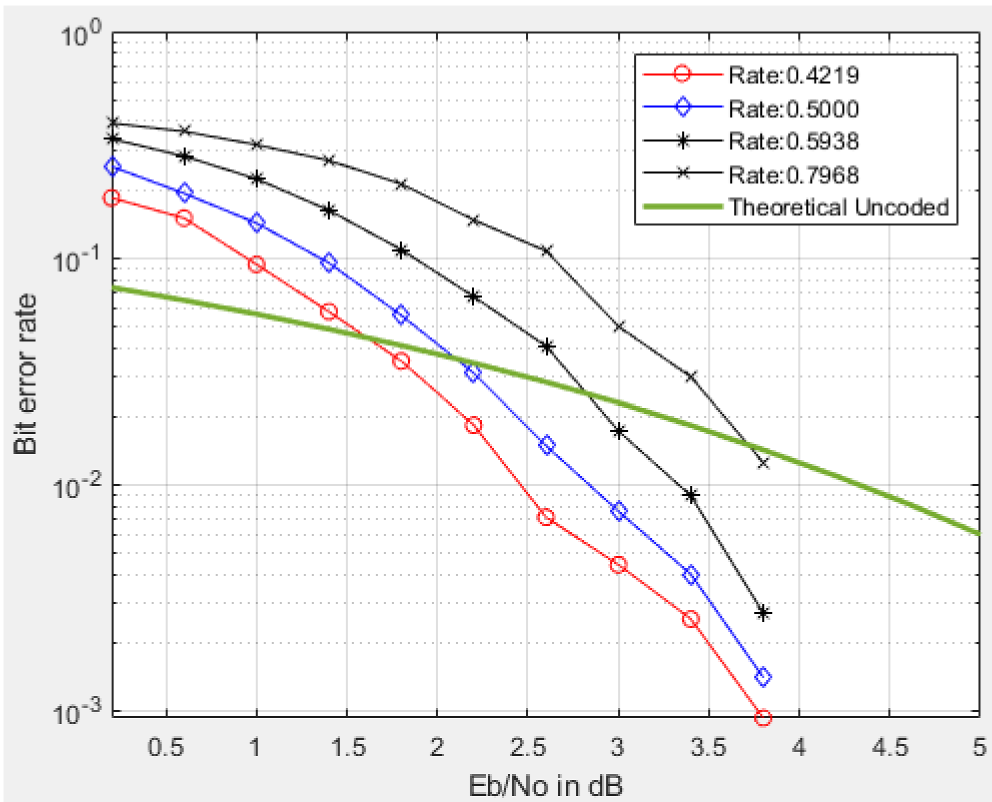


Figure 4.3 BER versus Eb/No of polar code SC decoding by varying code rate

Table 4.4 BER for polar code with SC varies code rate

E_b/N_0(dB)	BER			
	Code rate			
	0.4219	0.5	0.5938	0.7968
0.2	0.1838	0.2530	0.3371	0.3933
0.6	0.1495	0.1924	0.2655	0.3615
1	0.0933	0.1422	0.2337	0.3156

1.4	0.0577	0.0948	0.1705	0.2689
1.8	0.0349	0.0556	0.1197	0.2118
2.2	0.0182	0.0309	0.0780	0.1468
2.6	0.0071	0.0148	0.0423	0.1070
3	0.0044	0.0076	0.0172	0.0497
3.4	0.0025	0.0040	0.0080	0.0297
3.8	0.0009	0.0014	0.0041	0.0125

From table 4.4 and 4.3 for the comparative study of the block error rate and bit error rate for example if we take 0.558 block error rate and 0.1838 bit error rate at 0.2dB Eb/No for BPSK modulation under AWGN channel in table 4.3 and 4.4 for a code rate of 0.4219 and if the code rate is increased to 0.5938 the block error rate becomes 0.8520.

From the whole performance if we want to increase the code rate from 0.4219 to 0.5938 there is loss of 0.8dB. 5G and beyond eMBB in chapter 3 the data rate is linearly affected by the code rate. For a code rate increase from 0.4219 to 0.5938 there is a data rate change of 1.4074 times the original by holding the MIMO layer, component carriers, and number of resource block, frequency range and numerology constant. For 5G UCI and DCI by polar- SC the codeword layers are mapped to the physical channels PUCCH and PDCCH. For having UCI or DCI 54 containing the codeword length 128 that means with code rate 0.4219 at Eb/No of 3.8dB we get BLER of 0.0010. If the code rate is increasing the performance is decreasing.

4.4 BLER and BER for I-Polar Code by SC Decoding by Varying Code Rate

To evaluate the performance of interleaving polar coding by successive cancelation decoding technique under AWGN channels in BPSK modulation for the parameters listed in table 4.5. As it can be seen from the table and also the graph as the code rate increases there is degradation of the performance. In this simulation effect of code rate on the performance is studied.

Table 4.5 Simulation parameters for I-polar code SC decoding by varying code rate

Polar Block size	(54,128),(64,128),(76,128),(102,128)
Code rate	0.4219, 0.5,0.5940, 0.7968
Block size	1000
Eb/No	0.2-3.8dB

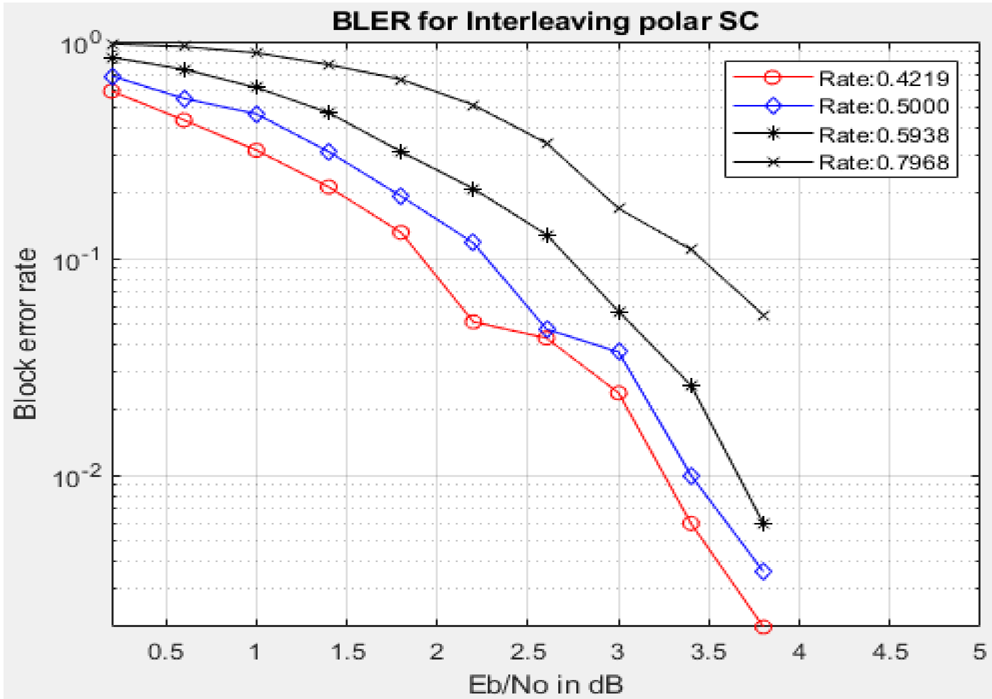


Figure 4.4 BLER versus Eb/No for I-polar code SC decoding by varying code rate

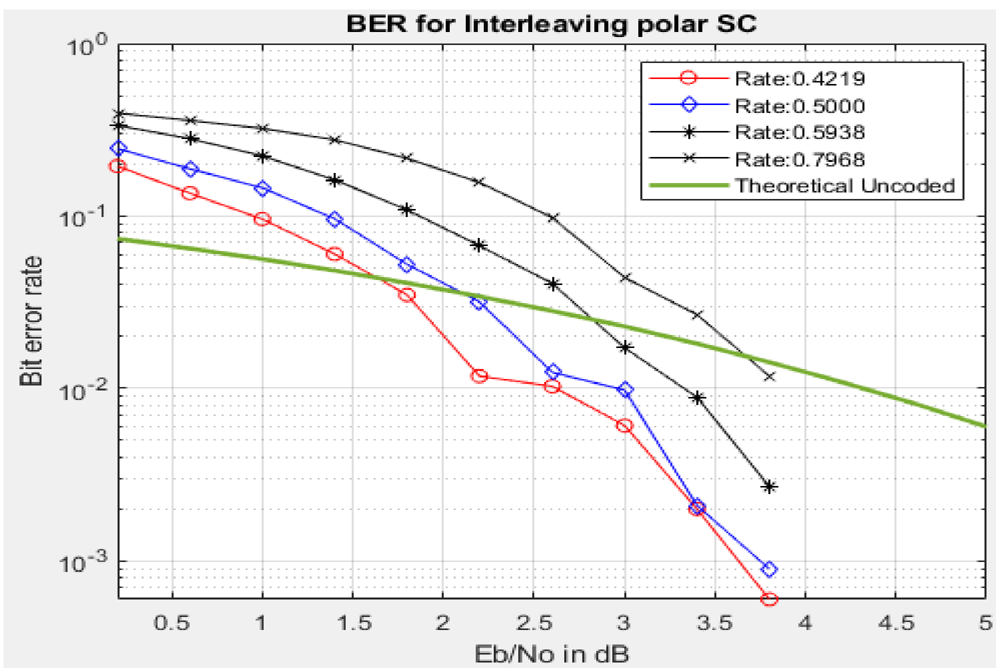


Figure 4.5 BER versus Eb/No for I-polar code with SC decoding varying code rate

Table 4.6 BLER and BER for I-polar code SC decoding by varying code rate

	BLER	BER

E_b/N_0(dB)	Code rate				Code rate			
	0.4219	0.5	0.5938	0.7968	0.4219	0.5	0.5938	0.7968
0.2	0.5920	0.6960	0.8470	0.9770	0.1945	0.2458	0.3350	0.3944
0.6	0.4350	0.5470	0.7460	0.9500	0.1354	0.1877	0.2808	0.3581
1	0.3160	0.4650	0.6140	0.8890	0.0960	0.1456	0.2229	0.3220
1.4	0.2140	0.3110	0.4710	0.7840	0.0602	0.0964	0.1620	0.2766
1.8	0.1320	0.1940	0.3110	0.6700	0.0349	0.0525	0.1085	0.2157
2.2	0.0510	0.1180	0.2100	0.5110	0.0118	0.0318	0.0673	0.1567
2.6	0.0430	0.0473	0.1290	0.3410	0.0103	0.0124	0.0406	0.0978
3	0.0240	0.0370	0.0570	0.1700	0.0061	0.0098	0.0172	0.0440
3.4	0.0060	0.0100	0.0260	0.1100	0.0020	0.0021	0.0089	0.0268
3.8	0.0020	0.0016	0.0060	0.0550	0.0006	0.0009	0.0027	0.0118

As shown in figure 4.5 and 4.4 and table 4.6 for BLER and BER of interleaving polar code with successive cancelation decoding the code rate significantly affects the performance as same manner as polar code with successive cancelation decoding. For a code rate of 0.7965 at Eb/No of 3.8dB we get BLER of 5.5% and for a code rate of 0.5938 at Eb/No of 3dB we get BLER of 5.7% but for a code rate of 0.4219 at Eb/No of 2.2dB we get BLER of 5.1% in three case the gain is 0.8dB.

4.5 BLER and BER Evaluation for CRC-A-Polar Code with SCL Decoding by Varying CRC for List Size 8

In the simulation of CRC aided polar codes by SCL decoding technique the performance is studied by varying the CRC length for the parameters listed in table 4.7.

Table 4.7 Simulation parameters for CRC-A-polar code SCL decoding by varying CRC size

Polar message size and codeword size	(54,128)
Code rate	0.4218
No of Blocks	1000
CRC length	4, 8, 16
CRC polynomial	p^4+p+1, $p^8+p^4+p^3+p^2+1$, $p^{16}+p^{12}+p^3+p+1$

Block error rate and bit error rate is plotted in figure 4.6 and figure 4.7 for different size of the CRC with code rate = (54/128) = 0.4218 with for BPSK modulation and AWGN channel model by CRC length=4, 8 and 16 and list size =8. For CRC length 4 the polynomial used is p^4+p+1, for CRC length 8 the polynomial used is $p^8+p^4+p^3+ p^2+1$ and for CRC length 16 the polynomial used is $p^{16}+p^{12}+p^3+ p+1$.

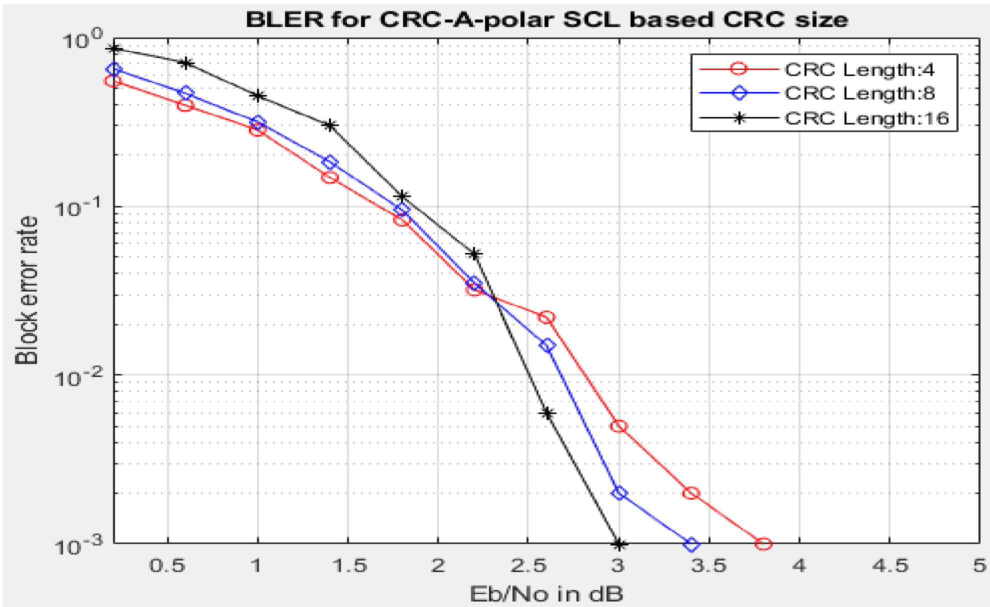


Figure 4.6 BLER versus Eb/No of CRC-A-polar code by SCLD based on CRC size

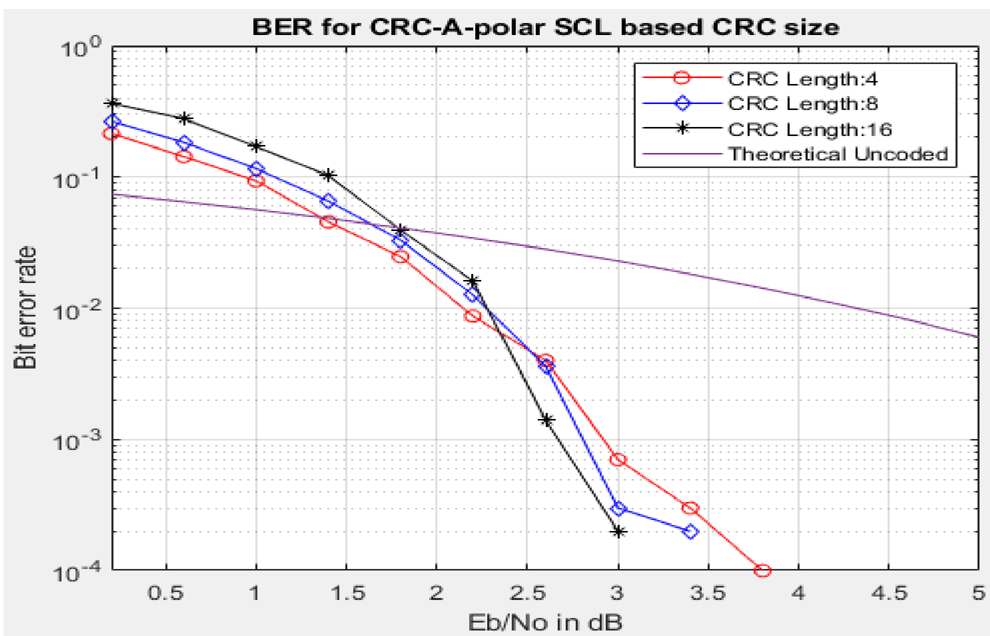


Figure 4.7 BER versus Eb/No of CRC-A-polar code by SCLD based on CRC size

Table 4.8 BLER and BER for CRC-A-polar code by SCL decoding by varying CRC size

E_b/N_0(dB)	BLER	BER

	CRC length=4	CRC length=8	CRC length=16	CRC length=4	CRC length=8	CRC length=16
0.2	0.5530	0.6550	0.8620	0.2143	0.2661	0.3641
0.6	0.3970	0.4660	0.7090	0.1429	0.1833	0.2778
1	0.2830	0.3160	0.4510	0.0935	0.1159	0.1703
1.4	0.1480	0.1830	0.3000	0.0455	0.0655	0.1023
1.8	0.0830	0.0950	0.1140	0.0247	0.0330	0.0394
2.2	0.0320	0.0350	0.0520	0.0087	0.0126	0.0161
2.6	0.0220	0.0150	0.0060	0.0040	0.0036	0.0014
3	0.0050	0.0020	0.0010	0.0007	0.0003	0.0002
3.4	0.0020	0.0010	0	0.0003	0.0002	0
3.8	0.0010	0	0	0.0001	0	0

As shown in figure 4.6 and 4.7 in the performance analysis of polar codes along with CRC code as its outer code together with the list decoding and CRC code detection list-CRC decoding depends on the length of the CRC code and its divisor or the generator polynomial. In CRC aided polar code by SCL decoding by varying CRC size the decoder produces decoded series of bits from these decoded message the CRC detector selects the best.

By observing the graph of block error rate and bit error rate and the table values there is the increase of performance when CRC length is increasing from 4 to 8 and also to 16 for higher Eb/No and also up to 16. BLER and BER vs Eb/No improvement is achieved by increasing the length of the CRC.

4.6 BLER and BER for CRC-A-Polar Code by SCL Decoding for Different List Sizes

In the following table and the graph for CRC aided polar code by SCL decoding is computed for different list size by the parameters listed below in table 4.9.

Table 4.9 Simulation parameters for CRC-A-polar code by SCL decoding for different list sizes at code rate 0.6719

Polar message size and codeword size	(86,128)
Code rate	0.6719
Blocks	1000

CRC polynomial	$p^{16}+p^{12}+p^{3}+ p+1$
CRC length	16
List size	4, 8, 16

Table 4.10 Simulation parameters for CRC-A-polar code by SCL decoding for different list sizes at code rate 0.7968

Polar Block size	(102,128)
Code rate	0.7968
No of Blocks	1000
CRC polynomial	$p^{16}+p^{12}+p^{3}+ p+1$
CRC length	16
List size	16, 32

In table 4.11 the simulated block error rate and bit error rate is tabulated for different bit energy to noise spectral ratio. In this simulation the encoder has 86 information bits and 128 codeword bits that means the code rate is 0.6719 with 42 bits for redundancy.

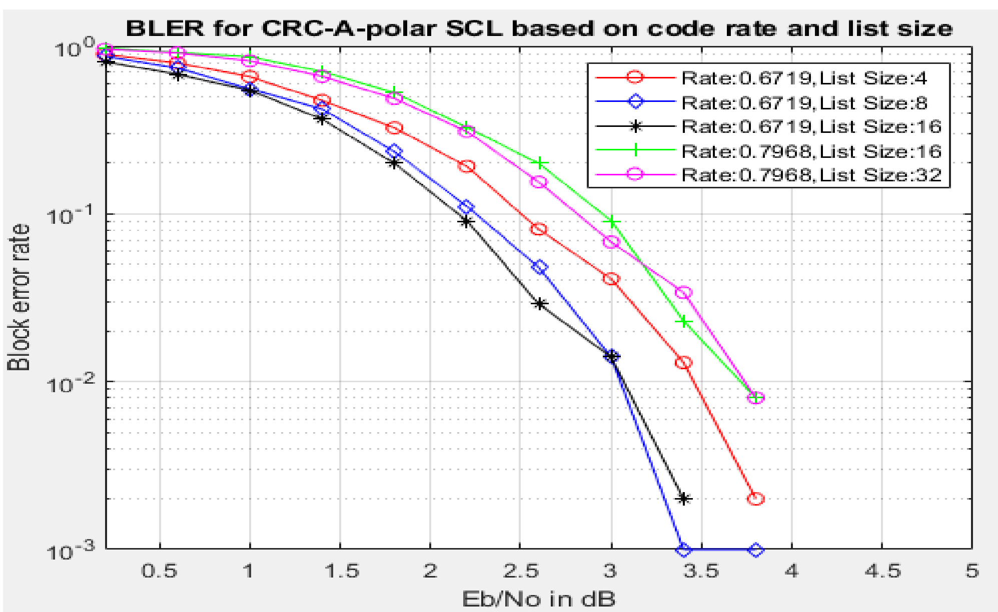


Figure 4.8 BLER versus Eb/No for CRC-A-polar code by SCL decoding for varies code rate and list size

Table 4.11 BLER and BER CRC-A-polar code by SCL decoding for different list sizes

E_b/N_0(dB)	BLER			BER		
	L=4	L=8	L=16	L=4	L=8	L=16
0.2	0.8930	0.8710	0.8090	0.3656	0.3518	0.3392
0.6	0.7950	0.7410	0.6790	0.3075	0.2952	0.2753
1	0.6580	0.5570	0.5460	0.2473	0.2164	0.2121
1.4	0.4750	0.4220	0.3670	0.1707	0.1572	0.1427
1.8	0.3260	0.2350	0.2000	0.1113	0.0855	0.0746
2.2	0.1920	0.1110	0.0910	0.0633	0.0381	0.0317
2.6	0.0810	0.0480	0.0290	0.0257	0.0141	0.0086
3	0.0410	0.0140	0.0140	0.0125	0.0047	0.0059
3.4	0.0130	0.0010	0.0020	0.0039	0.0002	0.0006
3.8	0.0020	0.0010	0	0.0007	0.0001	0

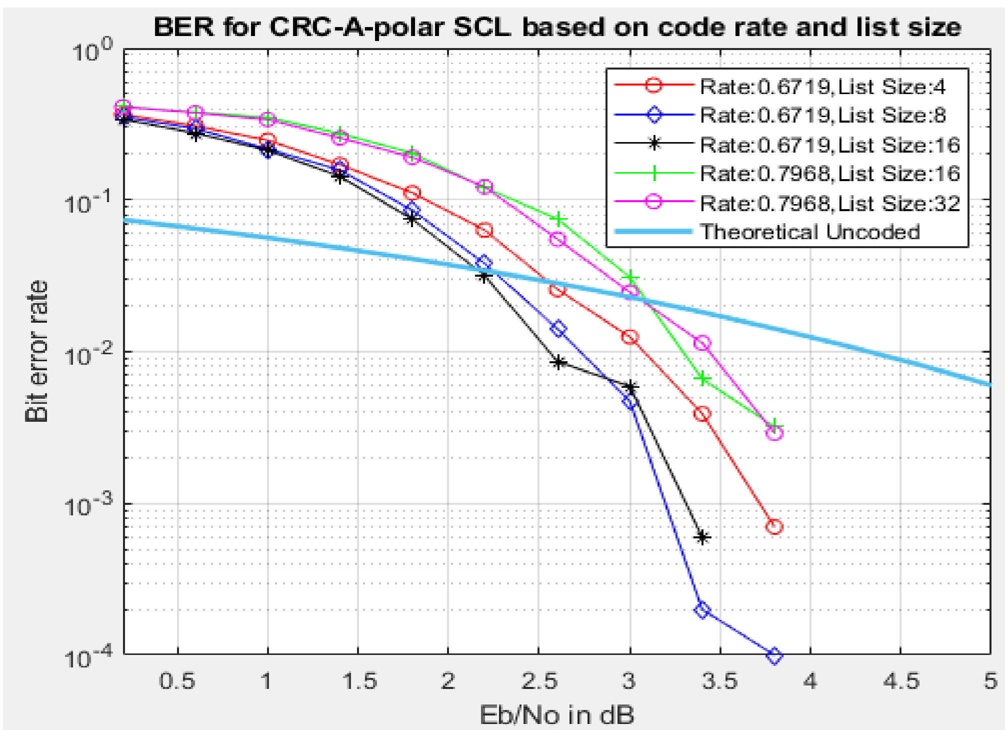


Figure 4.9 BER versus Eb/No for CRC-A-polar code by SCL decoding for varies code rate and list size

But we have 16 CRC bits there will be 26 redundant bits with zero assigned in their position according to the reliability sequence. The SCL decoder produces 4 different decoded messages and from this 4 decoded messages the CRC detector selects the best message from the list. In this simulation with Eb/No of 3.8dB we can obtain 2 blocks in error from 1000 total blocks and BER of 0.07%.

As shown in figure 4.9 and 4.8 the list size is increased from 4 to 8. In this case the decoder produces 8 different decoded messages so there will be more options for the CRC detector. As indicated above the encoder has 86 information bits and 128 codeword bits that means the code rate is 0.6719 with 42 bits for redundancy. Again we have 16 CRC bits there will be 26 redundant bits with zero assigned in their position according to the reliability sequence. CRC aided polar code by SCL decoding with list size 8 for Eb/No 3.8 dB we obtain BLER of 0.1% and BER of 0.01%.

Again by increasing the list size to 16 at the receiver the decoder produces 16 messages from which one message is selected by the CRC detection. Here we obtain BLER of 0% and BER of 0%. In this case the performance is increased in a good manner but the complexity is also increasing.

In the next performance comparison the block error rate and bit error rate is simulated for different bit energy to noise spectral ratio. In this simulation the code rate is increased to 0.7968 but the list size is kept as 16 and the encoder has 102 information bits and 128 codeword bits that means the code rate is 0.7968 with 26 bits for redundancy. But we have 16 CRC bits there will be 10 redundant bits with zero assigned in their position according to the reliability sequence. The SCL decoder produces 16 different decoded messages and from this 16 decoded messages the CRC detector selects the best message from the list. In this simulation with Eb/No of 3.8dB we can obtain 0.8% BLER and BER of 0.32%.

To analyze the effect of list size on performance here the by keeping the code rate as 0.7968 but increasing the list size as 32 BLER of 0.8% and BER of 0.29% is obtained at Eb/No of 3.8dB.

Table 4.12 BLER and BER for CRC aided polar code by SCL decoding by varying list size and code rate increased

E_b/N_0(dB)	BLER		BER	
	L=16	L=32	L=16	L=32
0.2	0.9720	0.9590	0.4126	0.4099
0.6	0.9160	0.9110	0.3779	0.3756
1	0.8660	0.8180	0.3495	0.3383
1.4	0.7060	0.6610	0.2737	0.2564
1.8	0.5290	0.4870	0.2032	0.1912
2.2	0.3280	0.3100	0.1205	0.1221
2.6	0.2000	0.1550	0.0747	0.0550

3	0.0910	0.0680	0.0309	0.0246
3.4	0.0230	0.0340	0.0066	0.0114
3.8	0.0080	0.0080	0.0032	0.0029

For CRC-A-SCL decoding four different cases are taken and the BLER and BER is plotted and tabulated. In the first three cases code rate of 0.6719 is constant but varying the list size from 4 to 8 and from 8 to 16. For Eb/No of 3.4dB 1.3% BLER and 0.39% BER obtained with list of 4. If the list size is increased to 8 we obtained 1.4% BLER and BER of 0.47% for Eb/No 3dB so gain of 0.4dB but by increasing list size from 8 to 16 the performance increase is very low as seen in the graph and also in the table 4.11 . By taking the advantage of list size increase in performance but increasing the code rate from 0.6719 to 0.7968 the performance is degraded. It can be suggested that there is no need to increase the list size above 8.

For 5G NR UCI acknowledgment (ACK), scheduling request (SR), channel state information (CSI) mapped to PUCCH and for DCI grant information will be mapped to PDCCH. When the list size is increased the receiver has much more complexity that needs more hardware in the PDCCH and PUCCH. From the graph the performance is more affected by the code rate. It is known that by increasing the code rate there will very low room for redundancy this indicates the decoder will have low potential to correctly decode the transmitted message.

4.7 BLER and BER for CRC-A-I-Polar Code by SCL Decoding for Different List Size and Code Rate

For CRC aided interleaved polar coding the simulation is tested under the following parameters. As it is known that we can use any number of bits of code word for CRC aided interleaved polar coding which is not the power of 2.

Table 4.13 Simulation parameters for CRCA-I-polar code by SCL with code rate 0.7968

Polar Block size	(102,128)
Code rate	0.7968
No of blocks	1000
CRC polynomial	$p^{16}+p^{12}+p^{3}+p+1$
CRC length	16

List size	4,8

As we see by increasing the list size the performance is also increasing but when the code rate is increasing the performance is decreasing. To compromise this effect from the above simulation the code rate is increased from 0.7968 to 0.8437and compared for list size of 8 and 16.

Table 4.14 Simulation parameters for CRC-A-I-polar code by SCL decoding with code rate 0.8437

Polar message size and codeword size	(108,128)
Code rate	0.8437
No of blocks	1000
CRC polynomial	$p^{16}+p^{12}+p^{3}+ p+1$
CRC length	16
List size	8, 16

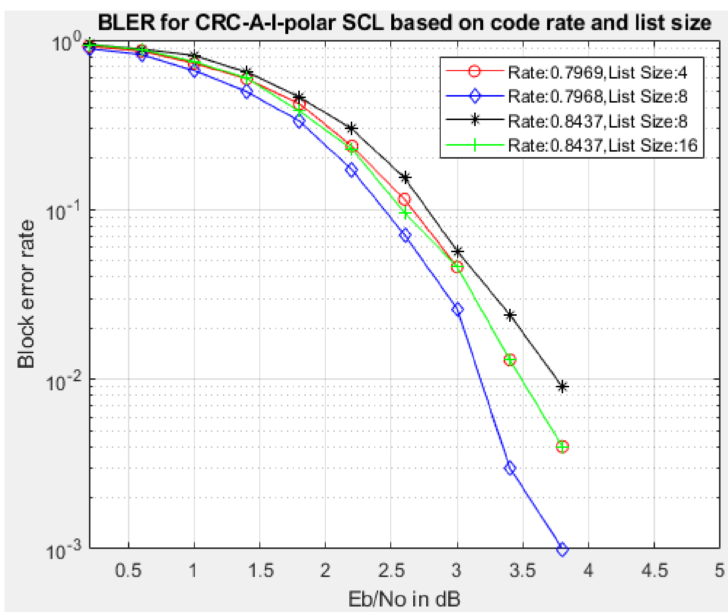


Figure 4.10 BLER versus Eb/No for CRC-A-I-polar by SCLD by code rate and list size

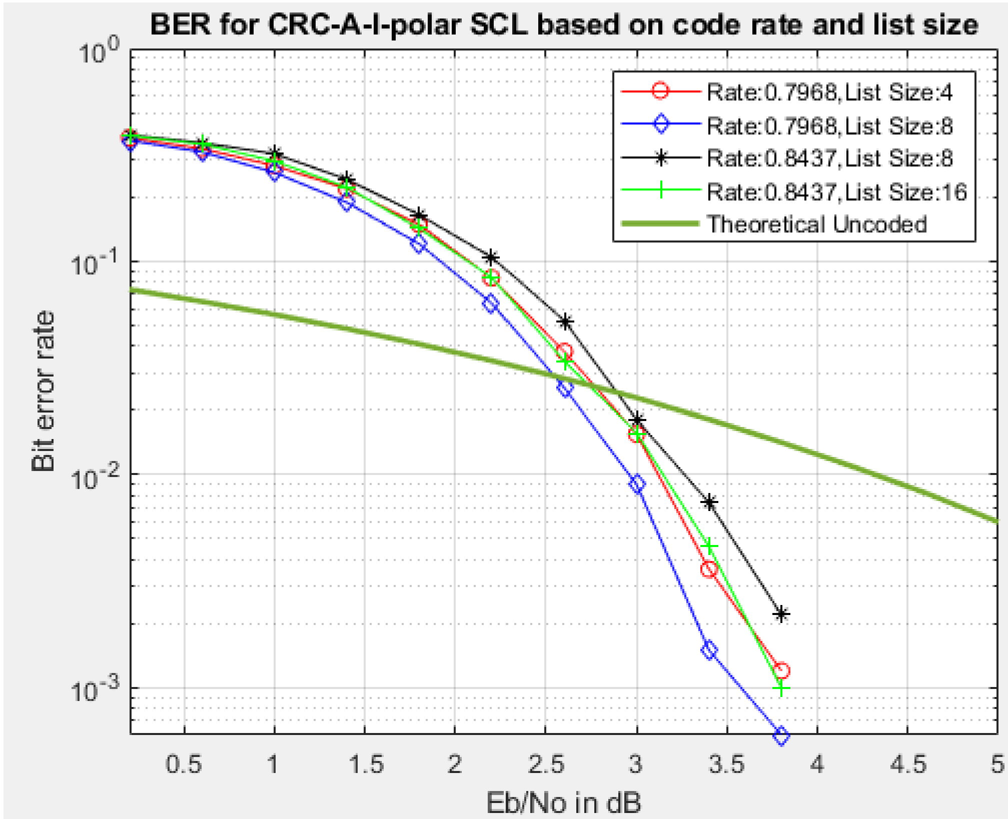


Figure 4.11 BER versus Eb/No for CRC-A-I-polar code by SCLD by varying code rate and list size

In table below 4.15 the BLER and BER is tabulated for code rate of 0.7968 and CRC size of 16 with list size of 4 and 8 for 1000 blocks. In this case for Eb/No of 3.4 dB we can obtain the BLER of 0.3% and BER of 0.15% at list size of 8 but for list size 4 we can obtain 0.4% BLER and BER of 0.12% at 3.8dB with 0.4dB gain.

Table 4.15 BLER and BER for CRC-A-I-polar code by SCL decoding with code rate 0.7968

E_b/N_0(dB)	BLER		BER	
	L=4	L=8	L=4	L=8
0.2	0.9200	0.8910	0.3805	0.3695
0.6	0.8630	0.8230	0.3384	0.3267
1	0.7320	0.6610	0.2818	0.2617
1.4	0.5900	0.4970	0.2192	0.1894
1.8	0.4220	0.3330	0.1492	0.1209
2.2	0.2370	0.1720	0.0837	0.0638
2.6	0.1150	0.0710	0.0377	0.0255

3	0.0460	0.0260	0.0155	0.0090
3.4	0.0130	0.0030	0.0036	0.0015
3.8	0.0040	0.0010	0.0012	0.0006

Table 4.16 BLER and BER for CRC-A-I-polar code by SCL decoding with code rate 0.8437

E_b/N_0(dB)	BLER		BER	
	L=8	L=16	L=8	L=16
0.2	0.9440	0.9410	0.3930	0.3895
0.6	0.8860	0.8780	0.3607	0.3556
1	0.8130	0.7480	0.3204	0.2961
1.4	0.6480	0.5960	0.2429	0.2229
1.8	0.4620	0.3810	0.1656	0.1431
2.2	0.2990	0.2280	0.1048	0.0842
2.6	0.1540	0.0960	0.0527	0.0340
3	0.0570	0.0460	0.0181	0.0157
3.4	0.0240	0.0130	0.0074	0.0046
3.8	0.0090	0.0040	0.0022	0.0010

As shown in the graph figure 4.10 and figure 4.11 of BLER and BER rate of 0.7968 with list 4 and rate 0.8437 with list size 16 have slightly close performance. By increasing the list size to 16 computational complexity increases with less increasing of the performance so rate 0.7968 with list size 8 outperforms the others.

In the performance study of the polar code the most dominant parameter is the code rate. In data rate analysis the code rate is one multiplier factor. To study the effect of code rate on eMBB by keeping J the number of aggregated component carriers, number of supported layers, scaling factor, numerology, average symbol period, maximum resource block allocation in bandwidth, overhead and frequency range constant for code rate increase from 0.6771 to 0.8913 the data rate is multiplied by 1.3163.

4.8 BLER and BER for Polar Coding Schemes by Varying Polar Block Size for Rate 1/2

In this simulation scenario the effect of polar block size is studied by keeping the code rate 1/2 for all the schemes such as polar coding with SC decoding, CRC aided polar coding with SCL decoding and CRC aided interleaving polar code by SCL decoding.

The performance evaluation for block size helps for 5G and beyond eMBB in encoding the multimedia information to choose the better performance coding schemes. High data contents media such as video, audio contains huge block size.

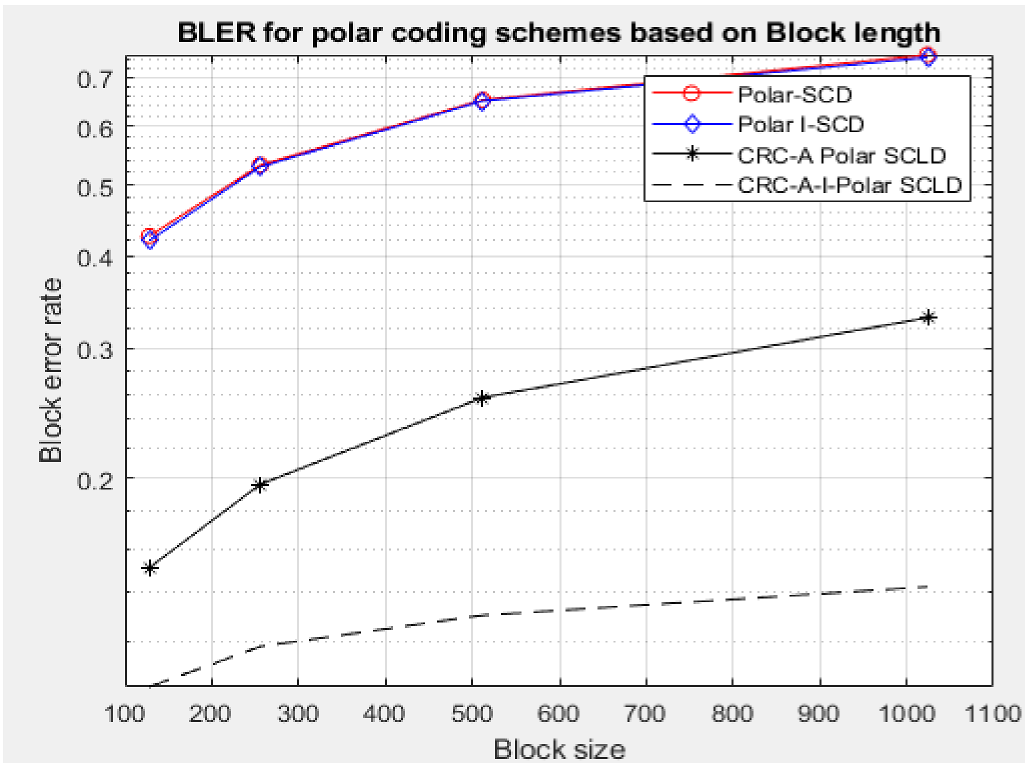


Figure 4.12 BLER versus polar codeword length plot at code rate 1/2

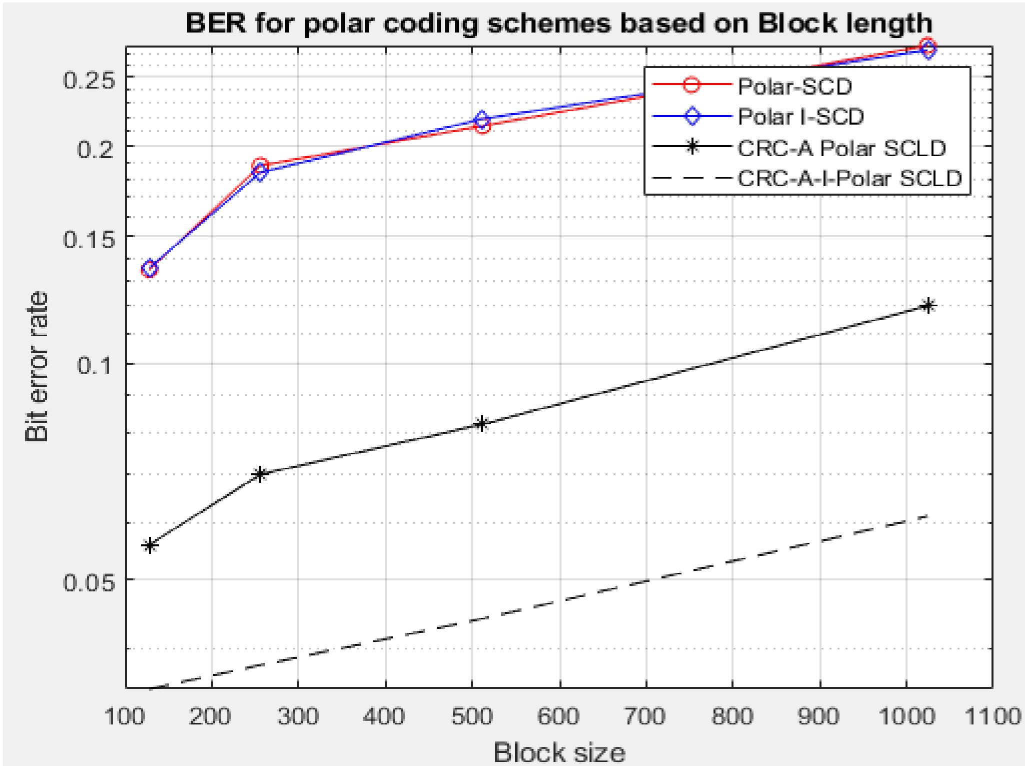


Figure 4.13 BER versus polar codeword length plot at code rate 1/2

Table 4.17 BLER and BER for polar coding schemes by varying Polar block size

	Polar block size N	Polar-SCD		Polar I-SCD		CRC-A Polar SCLD		CRC-A-I Polar SCLD	
		BLER	BER	BLER	BER	BLER	BER	BLER	BER
1dB Eb/ No	128	0.4260	0.1348	0.4200	0.1357	0.1510	0.0559	0.1040	0.0352
	256	0.5320	0.1883	0.5290	0.1842	0.1960	0.0700	0.1180	0.0380
	512	0.6520	0.2138	0.6500	0.2187	0.2570	0.0822	0.1301	0.0441
	1024	0.7510	0.2766	0.7450	0.2726	0.3300	0.1201	0.1422	0.0612

As it can realized from the plotted simulation result in Figure 4.12 and figure 4.13 for polar coding with SC decoding, interleaving polar coding with SC decoding, CRC aided polar coding with SCL decoding and CRC aided interleaving polar code by SCL decoding when increasing the polar block size the BLER and BER is increasing. So there is a tradeoff relation between the polar block size and the polar code BLER and BER performance. If we take a CRC aided polar code with SC decoding of (64,128) and (128,256) at Eb/No of 1dB the polar code (64,128) has BLER performance of 15.1% and (128,256) has 19.6%.

4.9 BLER and BER Performance Evaluation for Polar Coding schemes at CRC size 16

Table 4.18 Simulation BLER and BER performance evaluation for Polar coding schemes at CRC size 16

Parameters	Polar SCD	Polar I SCD	CRC-A Polar SCLD	CRC-A- I Polar SCLD
Code rate	0.7968	0.7968	0.7968	0.7968
No of blocks	1000	1000	1000	1000
CRC polynomial	-	-	$p^{16}+p^{12}+p^{3}+p+1$	$p^{16}+p^{12}+p^{3}+p+1$
CRC length	-	-	16	16
Polar block	(102,128)	(102,128)	(102,128)	(102,128)
List size	-		8	8

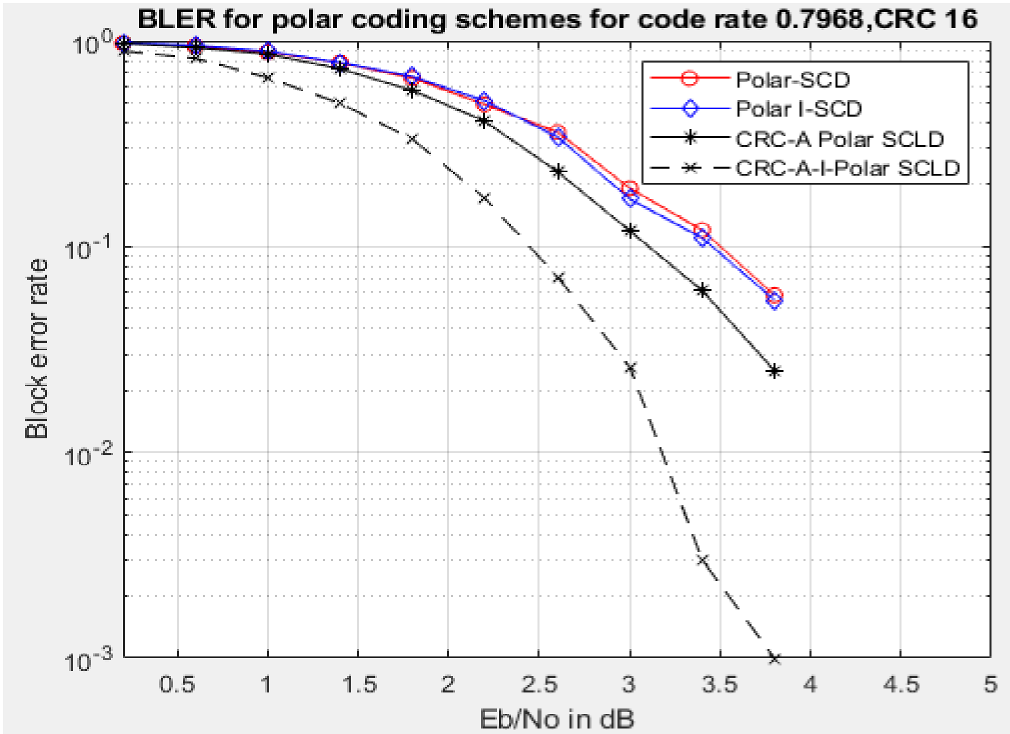


Figure 4.14 BLER Versus Eb/No for Polar coding schemes for CRC Length 16

Table 4.19 BLER for polar coding schemes at CRC Length 16

BLER				
E_b/N_0(dB	Polar SCD	Polar-I- SCD	CRC-A Polar SCLD	CRC-A- I Polar SCLD
0.2	0.9740	0.9770	0.9720	0.8910
0.6	0.9440	0.9500	0.9270	0.8230
1	0.8820	0.8890	0.8620	0.6610
1.4	0.7820	0.7840	0.7310	0.4970
1.8	0.6590	0.6700	0.5740	0.3330
2.2	0.4900	0.5110	0.4070	0.1720
2.6	0.3600	0.3410	0.2310	0.0710
3	0.1920	0.1700	0.1190	0.0260
3.4	0.1200	0.1100	0.0610	0.0030
3.8	0.0580	0.0550	0.0250	0.0010

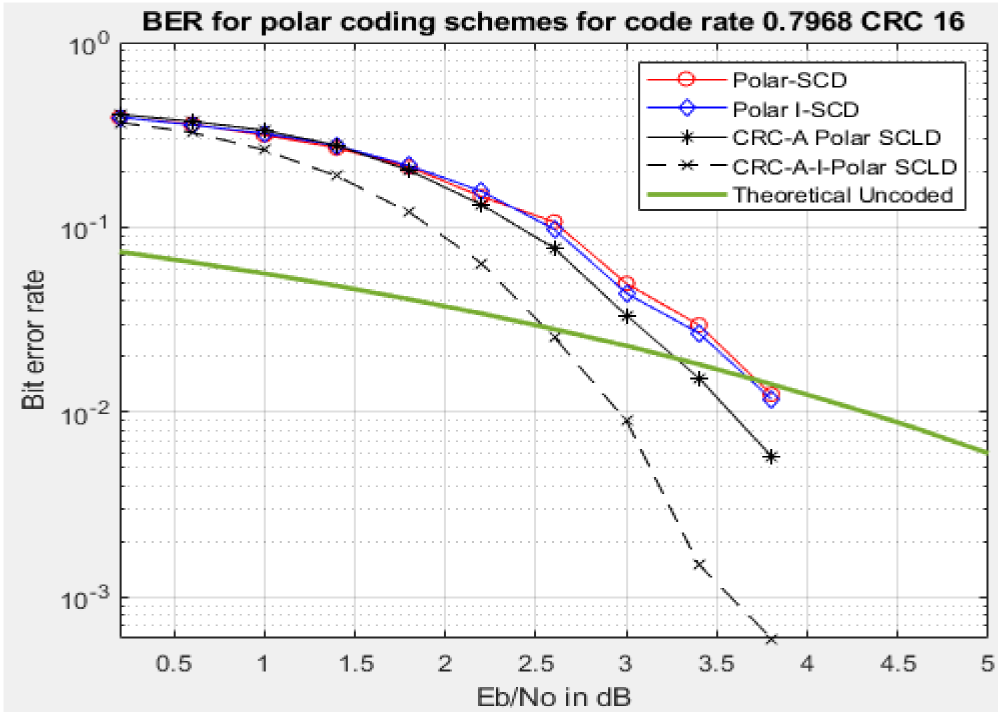


Figure 4.15 BER Versus Eb/No for Polar coding schemes for CRC Length 16

Table 4.20 BER for polar coding schemes at CRC Length 16

BER				
E_b/N_0(dB	Polar SCD	Polar-I- SCD	CRC-A Polar SCLD	CRC-A- I Polar SCLD
0.2	0.3933	0.3944	0.4079	0.3695
0.6	0.3615	0.3581	0.3746	0.3267
1	0.3156	0.3220	0.3350	0.2617
1.4	0.2689	0.2766	0.2772	0.1894
1.8	0.2118	0.2157	0.2032	0.1209
2.2	0.1468	0.1567	0.1326	0.0638
2.6	0.1070	0.0978	0.0772	0.0255
3	0.0497	0.0440	0.0334	0.0090
3.4	0.0297	0.0268	0.0153	0.0015
3.8	0.0125	0.0118	0.0058	0.0006

The length of the CRC code and its divisor or generating polynomial are important factors in the performance study of polar codes with CRC code as their outer code, as well as list decoding and CRC code detection. The decoder creates decoded series of bits from these decoded messages, and the CRC detector picks the best in CRC aided polar code via SCL.

4.10 BLER and BER Performance Evaluation for Polar Coding Schemes at Code Rate 1/2

To compare the overall performance for the four coding scheme with their respective decoding techniques the following simulation parameters in table 4.21.

Table 4.21 Performance measuring parameters for polar coding schemes with code rate of 1/2

Parameters	Polar SCD	Polar I SCD	CRC-A Polar SCLD	CRC-A- I Polar SCLD
Code rate	1/2	1/2	1/2	1/2
No of blocks	1000	1000	1000	1000
CRC polynomial	-	-	$p^{16}+p^{12}+p^{3}+p+1$	$p^{16}+p^{12}+p^{3}+p+1$
CRC length	-	-	16	16
Polar block	(128,64)	(128,64)	(128,64)	(128,64)
List size	-		8	8

For a comparative study of polar coding schemes such as for polar coding with SC decoding, interleaving polar coding with SC decoding, CRC aided polar coding with SCL decoding and CRC aided interleaved polar code by SCL decoding the BLER and BER is simulated. First polar coding with SC decoding with polar block of (128,64) with rate 1/2 and for CRC aided polar coding with SCL decoding and CRC aided interleaved polar coding with SCL decoding with list size 8 and CRC size 16 is compared for blocks of 1000.

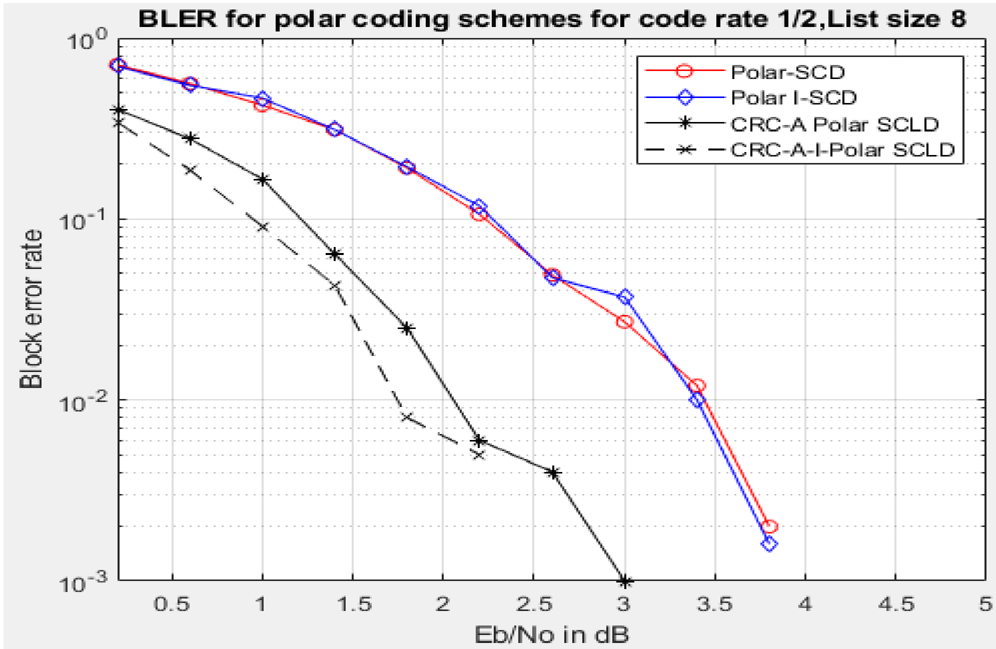


Figure 4.16 BLER versus Eb/No for different polar coding schemes with code rate 1/2

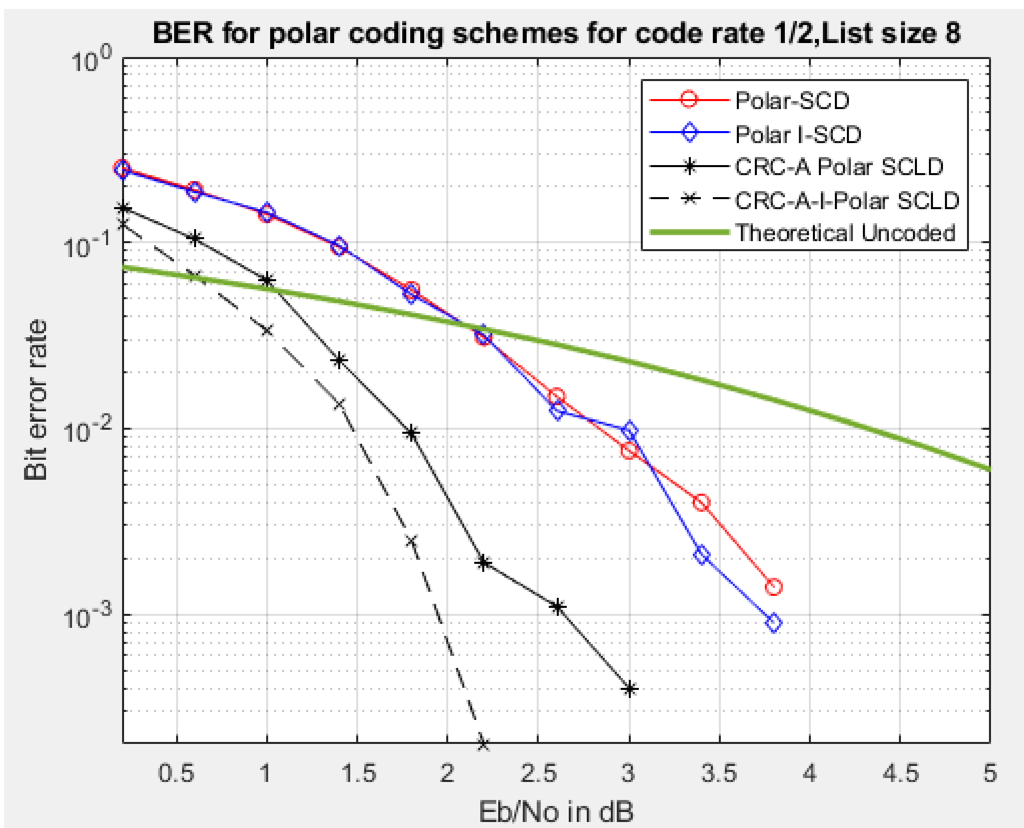


Figure 4.17 BER versus Eb/No for different polar coding schemes with code rate 1/2

Table 4.22 BLER versus Eb/No for polar coding schemes with code rate 1/2

E_b/N_0(dB)	BLER			
	Polar SCD	Polar I-SCD	CRC-A Polar SCLD	CRC-A- I-Polar SCLD
0.2	0.7100	0.6960	0.4030	0.3410
0.6	0.5590	0.5470	0.2770	0.1860
1	0.4250	0.4650	0.1660	0.0910
1.4	0.3110	0.3110	0.0640	0.0430
1.8	0.1910	0.1940	0.0250	0.0080
2.2	0.1060	0.1180	0.0060	0.0050
2.6	0.0490	0.0473	0.0040	0
3	0.0270	0.0370	0.0010	0
3.4	0.0120	0.0100	0	0
3.8	0.0020	0.0016	0	0

Table 4.18 BER versus Eb/No for polar coding schemes with code rate 1/2

BER				
E_b/N_0(dB	Polar SCD	Polar-I- SCD	CRC-A Polar SCLD	CRC-A- I Polar SCLD
0.2	0.2530	0.2458	0.1545	0.1258
0.6	0.1924	0.1877	0.1046	0.0666
1	0.1422	0.1456	0.0627	0.0336
1.4	0.0948	0.0964	0.0232	0.0136
1.8	0.0556	0.0525	0.0094	0.0025
2.2	0.0309	0.0318	0.0019	0.0002
2.6	0.0148	0.0124	0.0011	0
3	0.0076	0.0098	0.0004	0
3.4	0.0040	0.0021	0	0
3.8	0.0014	0.0009	0	0

From table 4.17 and 4.18 if we take Eb/No of 3.8dB polar coding with SC decoding has the performance of 2 blocks error of 1000 with BER of 0.14% then next CRC-A-polar coding with SCL decoding with list size 8 has 4 blocks in error of 1000 and 0.11% of BER so in the transition of polar coding scheme with SC decoding to next CRC-A-polar coding with SCL decoding there is approximately gain 1dB Eb/No.

Again using CRC aided interleaving polar coding with SCL decoding at Eb/No of 2.2dB 5 of 1000 blocks are in error and 0.02% of BER with gain of 0.4dB relative to CRC aided polar coding with SCL decoding.

5G NR UCI acknowledgment (ACK), scheduling request (SR), channel state information (CSI) mapped to PUCCH and for DCI grant information will be mapped to PDCCH when the DCI/ICI is coded by CRC-A-SCL or CRC-A-I-SCL polar coding schemes at code rate of 1/2. In 4G LTE the performance of convolutional code is low but for Turbo code the decoder uses iteration to increase the performance. For more number of iterations the performance could be improved with very high complicated decoding structure. Due to this Turbo code has no longer use in 5G and above eMBB.

4.11 BLER and BER performance evaluation for Polar coding schemes at code rate 0.7968 List size 8

In this category the performance evaluation parameters are simulated for polar coding schemes at code rate 0.7968 and list size 8.

Table 4.23 Simulation parameters for Polar coding schemes at code rate 0.7968

Parameters	Polar SCD	Polar I SCD	CRC-A Polar SCLD	CRC-A- I Polar SCLD
Code rate	0.7968	0.7968	0.7968	0.7968
No of blocks	1000	1000	1000	1000
CRC polynomial	-	-	$p^{16}+p^{12}+p^3+p+1$	$p^{16}+p^{12}+p^3+p+1$
CRC length	-	-	16	16
Polar block	(102,128)	(102,128)	(102,128)	(102,128)
List size	-	-	8	8

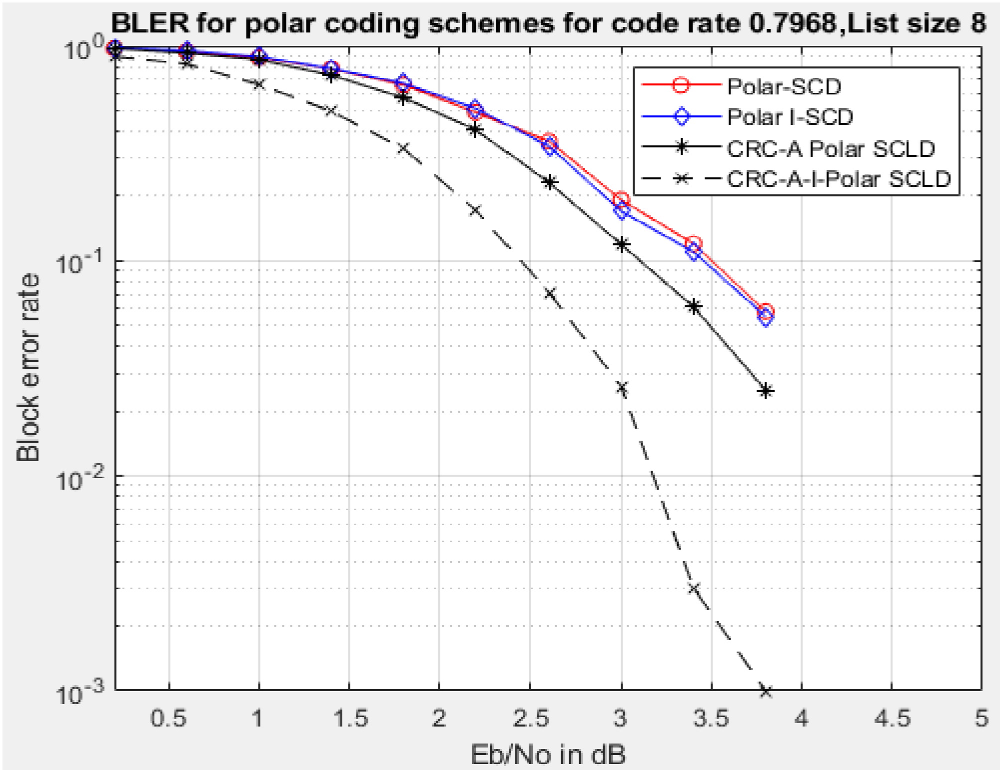


Figure 4.18 BLER Versus Eb/No for Polar coding schemes at code rate 0.7968

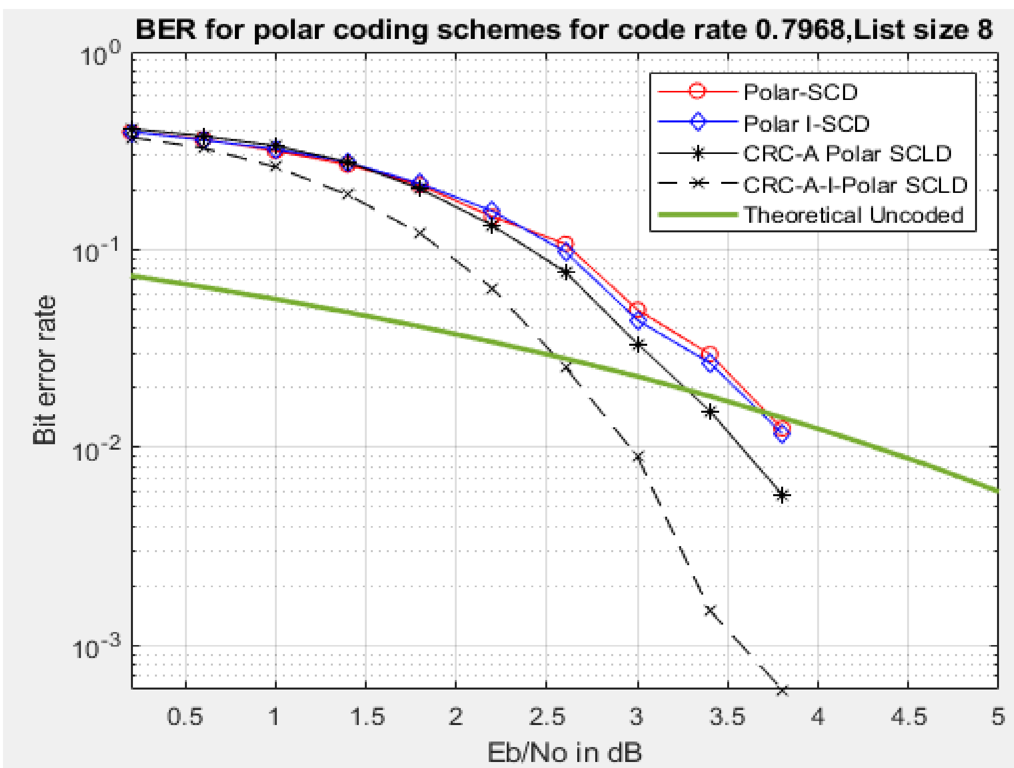


Figure 4.19 BER Versus Eb/No for Polar coding schemes at code rate 0.7968

As shown in figure 4.18 and 4.19 plot of BLER and BER versus Eb/No for polar coding schemes CRC-A-I-SCLD scheme and CRC-A-SCLD scheme performs better than the others. For performance evaluation of polar coding schemes for rate 1/2 at list size 8 CRC aided interleaving polar coding with SCL decoding at Eb/No of 2.2dB 5 of 1000 blocks are in error and 0.02% of BER with gain of 0.4dB relative to CRC aided polar coding with SCL decoding. When the code rate is increasing the performance is decreasing.

Table 4.24 BLER simulation for Polar coding schemes at code rate 0.7968 and list size 8

BLER				
E_b/N_0(dB	Polar SCD	Polar-I- SCD	CRC-A Polar SCLD	CRC-A- I Polar SCLD
0.2	0.9740	0.9770	0.9720	0.8910
0.6	0.9440	0.9500	0.9270	0.8230
1	0.8820	0.8890	0.8620	0.6610
1.4	0.7820	0.7840	0.7310	0.4970
1.8	0.6590	0.6700	0.5740	0.3330
2.2	0.4900	0.5110	0.4070	0.1720
2.6	0.3600	0.3410	0.2310	0.0710
3	0.1920	0.1700	0.1190	0.0260
3.4	0.1200	0.1100	0.0610	0.0030
3.8	0.0580	0.0550	0.0250	0.0010

Table 4.25 BER simulated value for Polar coding schemes at code rate 0.7968 and list size 8

BER				
E_b/N_0(dB	Polar SCD	Polar-I- SCD	CRC-A Polar SCLD	CRC-A- I Polar SCLD
0.2	0.3933	0.3944	0.4079	0.3695
0.6	0.3615	0.3581	0.3746	0.3267
1	0.3156	0.3220	0.3350	0.2617
1.4	0.2689	0.2766	0.2772	0.1894
1.8	0.2118	0.2157	0.2032	0.1209
2.2	0.1468	0.1567	0.1326	0.0638
2.6	0.1070	0.0978	0.0772	0.0255
3	0.0497	0.0440	0.0334	0.0090
3.4	0.0297	0.0268	0.0153	0.0015
3.8	0.0125	0.0118	0.0058	0.0006

4.12 BLER and BER Performance Evaluation for Polar Coding Schemes at List Size 4

In the above section the performance for polar coding schemes is mentioned by varying the code rate form 1/2 to 0.7968 by holding the list size 8. In this section the performance is evaluated by decreasing the list size to 4. For polar coding schemes polar SCD and polar I-SCD the list size is not considered.

Table 4.26 Table Simulation parameters for Polar coding schemes at list size 4

Parameters	Polar SCD	Polar I SCD	CRC-A Polar SCLD	CRC-A- I Polar SCLD
Code rate	0.7968	0.7968	0.7968	0.7968
No of blocks	1000	1000	1000	1000
CRC polynomial	-	-	$p^{16}+p^{12}+p^{3}+p+1$	$p^{16}+p^{12}+p^{3}+p+1$
CRC length	-	-	16	16
Polar block	(102,128)	(102,128)	(102,128)	(102,128)
List size	-	-	4	4

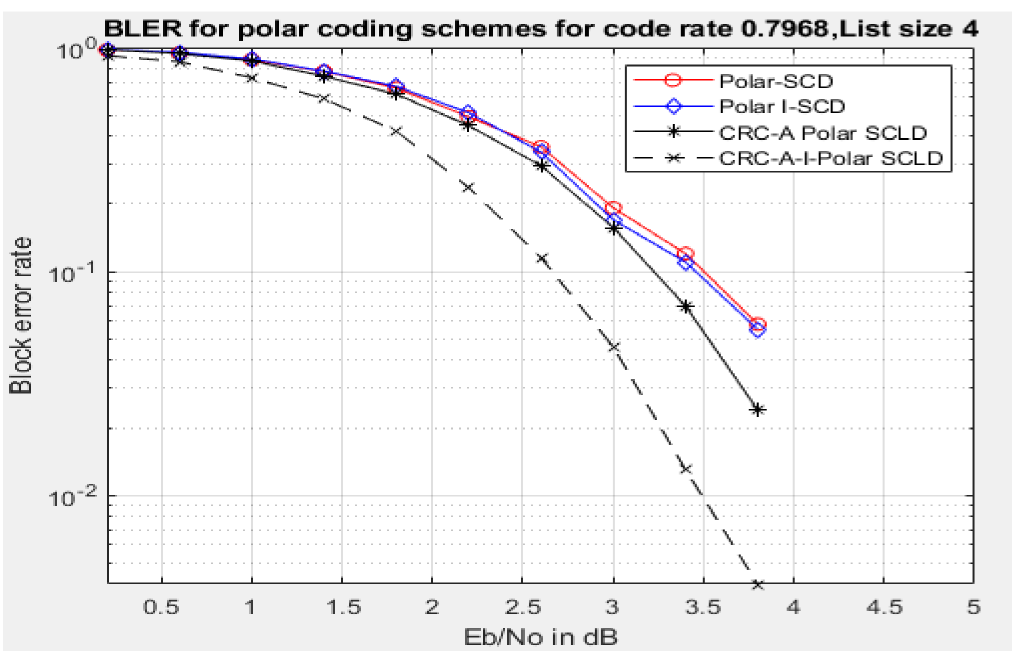


Figure 4.20 BLER Versus Eb/No for Polar coding schemes at list 4

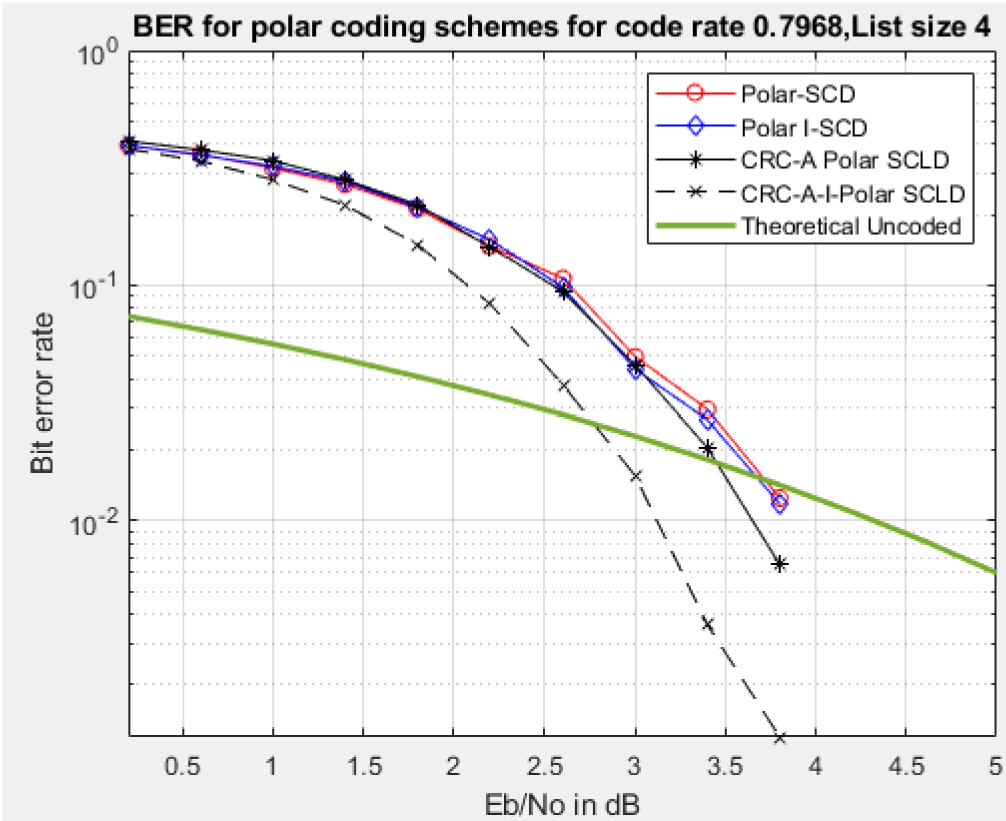


Figure 4.21 BER Versus Eb/No for Polar coding schemes at list 4

Table 4.27 BLER simulated value for polar coding schemes at list size 4

BLER				
E_b/N_0(dB	Polar SCD	Polar-I- SCD	CRC-A Polar SCLD	CRC-A- I Polar SCLD
0.2	0.9740	0.9770	0.9760	0.9200
0.6	0.9440	0.9500	0.9400	0.8630
1	0.8820	0.8890	0.8720	0.7320
1.4	0.7820	0.7840	0.7440	0.5900
1.8	0.6590	0.6700	0.6180	0.4220
2.2	0.4900	0.5110	0.4480	0.2370
2.6	0.3600	0.3410	0.2960	0.1150
3	0.1920	0.1700	0.1570	0.0460
3.4	0.1200	0.1100	0.0700	0.0130
3.8	0.0580	0.0550	0.0270	0.0040

Table 4.28 BER simulated value for Polar coding schemes at list size 4

BER				
E_b/N_0(dB	Polar SCD	Polar-I- SCD	CRC-A Polar SCLD	CRC-A- I Polar SCLD
0.2	0.3933	0.3944	0.4118	0.3805
0.6	0.3615	0.3581	0.3770	0.3384
1	0.3156	0.3220	0.3397	0.2818
1.4	0.2689	0.2766	0.2812	0.2192
1.8	0.2118	0.2157	0.2209	0.1492
2.2	0.1468	0.1567	0.1456	0.0837
2.6	0.1070	0.0978	0.0940	0.0377
3	0.0497	0.0440	0.0458	0.0155
3.4	0.0297	0.0268	0.0204	0.0036
3.8	0.0125	0.0118	0.0065	0.0012

As plotted and shown in figure 4.20 and 4.21 the code rate is the most affecting parameters. When the list size is decreased to 4 the performance is decreased also. For code rate 0.7968 list size 8 at Eb/No of 3.8dB for CRC-A-SCLD BLER of 2.5% obtained and for CRC-A-I-SCLD BLER of 0.1% when the list size is decreased to 4 by holding the code rate constant the BLER at Eb/No of 3.8dB for CRC-A-SCLD BLER of 2.7% obtained and for CRC-A-I-SCLD BLER of 0.4%.

4.13 Result Comparison with Existing Work

From the papers on literature result for polar coding the paper BER Comparison between Convolutional, Turbo, LDPC, and Polar Codes reported BER value over AWGN channel and BPSK modulation for Eb/No 4.26dB at code rate 1/2 was 0.01 in our work we get 0.0094 at Eb/No of 1.8dB for CRC-A Polar SCLD and 0.0025 for CRC-A-I Polar SCLD. Next at Eb/No of 4.5dB BER of 0.001 is obtained in our result 0.0011 BER is obtained at Eb/No CRC-A Polar SCLD and 0 BER for CRC-A-I Polar SCLD.

From the result obtained from the paper reliability based candidate selection of list decoding for polar code the performance is computed for the code rate of 0.1851 for Eb/No of 1.75dB 0.01 BLER is obtained in our work BLER of 0.0094 is obtained for CRC-A Polar SCLD and 0.0025 is obtained for CRC-A-I Polar SCLD at Eb/No of 1.8dB for a code rate 1/2. And form the result obtained Performance Comparison between Turbo and Polar Codes for a code rate 1/2 BER of 6% is obtained for Eb/No of 1.8dB over AWGN channel model in BPSK modulation. In our work BER of 0.94% for CRC-A-SCLD schemes is obtained and BER of 0.25% is obtained for code rate 1/2 in AWGN channel in BPSK modulation.

In our work in comparative study CRC-A-SCLD and CRC-A-I-SCLD schemes have comparable performance with CRC-A-I-SCLD having better performance.

4.14 Performance Comparison of Polar Coding Schemes by Speech Signal Encoding and Decoding

Polar coding speech signal by successive cancelation decoding techniques, CRC aided polar coding by SCL decoding and CRC aided interleaved polar coding by SCL decoding for a polar block size of (750,1024) of the total 18,000 samples the total bits is 144,000.

Table 4.29 Simulation parameters for polar coding schemes of speech signal

Parameters	Polar SCD	Polar I SCD	CRC-A Polar SCLD	CRC-A- I Polar SCLD
Code rate	0.7324	0.7324	0.7324	0.7324
CRC polynomial	-		$p^{16}+p^{12}+p^{3}+p+1$	$p^{16}+p^{12}+p^{3}+p+1$
CRC length	-		16	16
List size	-		8	8
Eb/No in dB	3dB	3dB	3dB	3dB
Sampling rate	22050	22050	22050	22050
No of blocks	192	192	192	192
Polar block	(750,1024)	(750,1024)	(750,1024)	(750,1024)
Samples	18,000	18,000	18,000	18,000
BLER	0.1302	0.1197	0.0260	0.0156
BER	0.0401	0.0384	0.0070	0.0003

As plotted in figure 4.22 the simulation of the speech it is sampled at the sampling rate of 22050 that means there is sampled value of 22050 per second. This sampled value is converted into 8 bit binary. The binary information is then polar encoded and decoded. For Polar coding with SC decoding the decoded speech with 3dB Eb/No is very corrupted with much more error. Also For interleaving polar coding with SC decoding the plotted speech data is slightly same as polar coding with SC decoding.

But for CRC aided polar coding with SCL decoding the speech is slightly close to the original transmitted speech finally the CRC aided interleaved polar coding with SCL decoding the speech signal has almost no error.

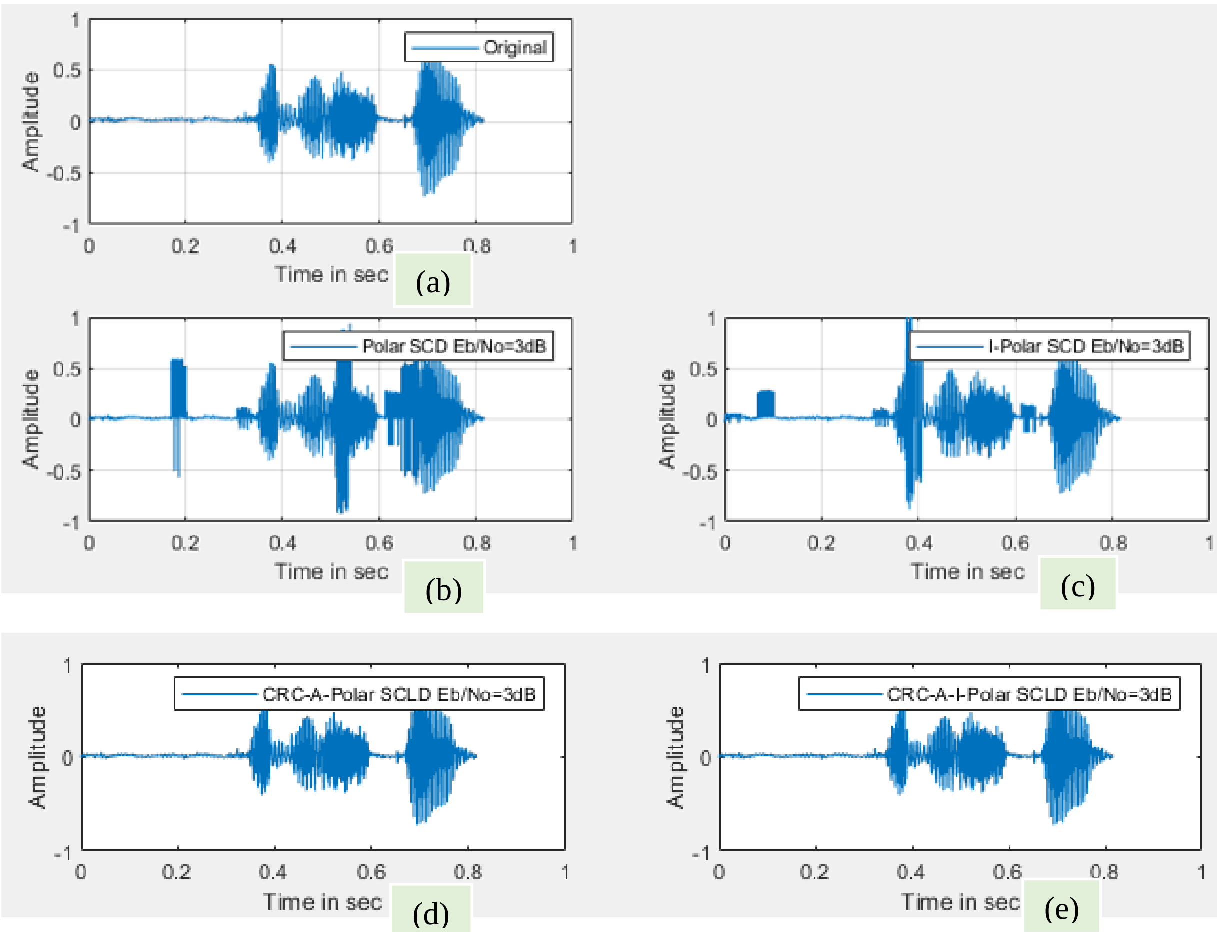


Figure 4.22 Performance comparison plot of speech signal for polar coding schemes

When the transmitted speech signal in figure 4.22 (a) encoded and decoded is under the polar coding schemes for CRC-A-polar SCLD and CRC-A-I-SCLD the received speech signal is better than the other coding schemes as shown in figure 4.22 (d) and (e).

4.15 Performance Comparison of Polar Coding Schemes by Text Signal Encoding and Decoding

In previous simulations the data is generated in Matlab to compare the performance in this section text message is used to compare the performance. The alphabets are converted to series of bits and the bits are encoded. Codes 32-127 are common for all the different variations of the ASCII table, they are called printable characters, represent letters, digits, punctuation marks, and a few miscellaneous symbols. We will find almost every character on our keyboard.

Polar coding text signal by successive cancelation decoding techniques, CRC aided polar coding by SCL decoding and CRC aided interleaved polar coding by SCL decoding for a polar block size of (184,256) is tabulated in table below.

Table 4.30 Text message encoding and decoding demonstration simulation parameters

Parameters	Polar SCD	Polar I SCD	CRC-A Polar SCLD	CRC-A- I Polar SCLD
Code rate	0.7187	0.7187	0.7187	0.7187
CRC polynomial	-	-	$p^{16}+p^{12}+p^3+p+1$	$p^{16}+p^{12}+p^3+p+1$
CRC length	-	-	16	16
List size	-	-	8	8
Eb/No in dB	3dB	3dB	3dB	3dB
BER	0.0491	0.0428	0.0061	0.0020
Transmitted text message	'Adama Science and Technology University Department of Electronics and Communication Engineering School of Electrical Engineering and Computing Office of Graduate Studies Adama Ethiopia'			

For the simulation parameters listed above to encode, the text message is converted into binary bits in Matlab by the extended ASCII codes with each bits having 8 bits.

Table 4.31 Transmitted and received text message evaluation for polar coding schemes

Polar coding schemes	Received text message

<table>
<tr><td>Polar SCD</td><td>'AdámA SãIeÎCe and ôeÃHnoLogY UNiVårsIty ÄEĐarTmeNÔ of eÌEãTronICÓ ÁND CoíMUNÉÃatioN eÎgiNEårING SCÈOïl oF eÌEÃtRiCAl ENgiNEeÒiNG Ánd ãOmPUTiNg€ oFFiCE€ OF gRáÄUATE óTUDIES adAMA€ eTHIOPIA'</td></tr>
<tr><td>Polar-I- SCD</td><td>'Adamé sCIencE aNd€ tecÈnOäOgy UNiVÅRsIty DepaR|ment Çf åLektroNiC{ aÎä€ CoMEUnIcA|IÏN engineERIfÇ sc@ogl Ïf EÄeÃüzicAÌ(ÅngInMerInG IND KÏmX]TÉnÏffikm Of GRal}aTE {|UdAes adaea(mThiopaa'</td></tr>
<tr><td>CRC-A-Polar SCD</td><td>‘Adama Scaence !nd Techn/logy Universit9 Departee.t of`El%ctro.ik3 and Communica4iof Eng)nmering Schoo,(of Electrical Enginemring ifd Coeputing Office of Graduate Studies Adama Ethiopia'</td></tr>
<tr><td>CRC-A-I-Polar SCD</td><td>'Adama Scaence and Technglogy Ufiversitq Department of Electronic and Communication Engineering School of Electrical Engineering and Computing(Office of Graduate Studies Adama Ethiopia'</td></tr>
</table>

For Eb/No of 3dB the decoded received text message is tabulated for the polar coding schemes as we see for polar coding with SC decoding the decoded text is highly erroneous but CRC aided polar coding with SCL decoding the decoded text is slightly close to the transmitted text. Finally the decoded text message is very close to the transmitted text for CRC aided interleaved polar coding with SCL decoding.

4.16 Comparative Study of Computational Complexity

There are a number of activities in encoding and decoding of polar coding schemes that use a method called channel polarization to achieve the symmetric capacity of any binary-input discrete memoryless channel. Different decoding structures are used in mistake correction procedures. For a polar code with successive cancelation decoding of codeword length of N which is 2^n where n=1,2 …in encoding there are n encoding stages having each stages with XOR operations of n/2.

Table 4.32 Simulation parameters for Comparative study of computational complexity

Parameters	Polar SCD	Polar I SCD	CRC-A Polar SCLD	CRC-A- I Polar SCLD
CRC length	-	-	16	16
List size	-	-	8	8
Message block length	128	128	128	128

For the above simulation the computational complexity versus polar block size is plotted in figure 4.23 below.

For Polar coding with SC decoding the encoding and decoding computational complexity increases with increasing the size of the codeword. For a CRC-A- polar coding with SCL decoding the computational complexity depends on the CRC length and also the message block in addition to the polar block size. For CRC A-I-polar coding with SCL decoding the computational complexity increases with interleaving but it has slightly close computational complexity with For a CRC-A-polar coding with SCL decoding.

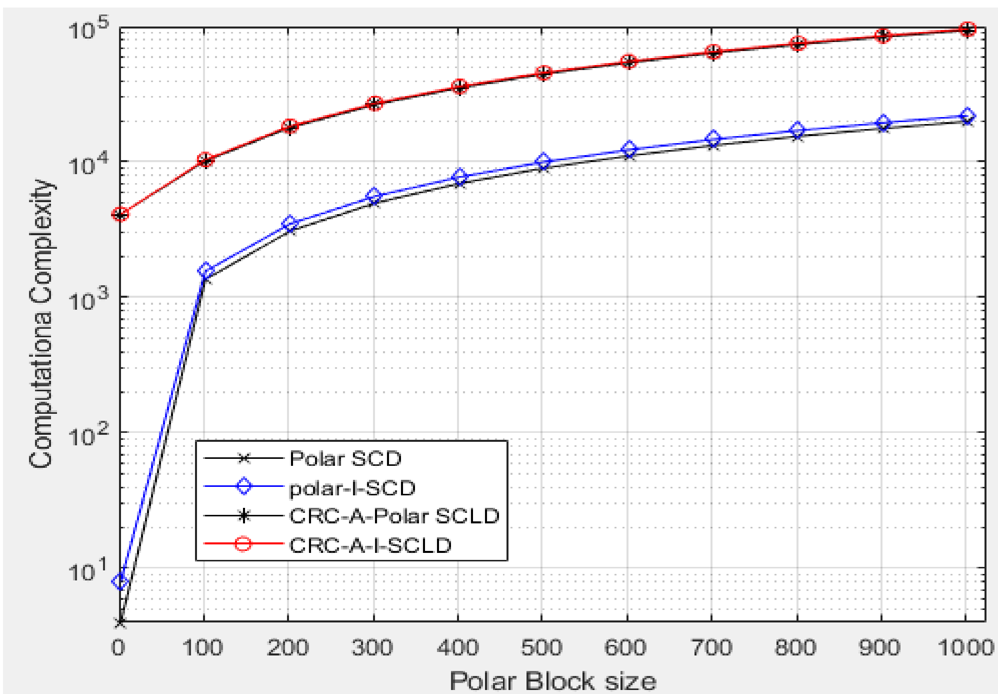


Figure 4.23 computational complexity versus polar block size for polar coding schemes

For a real time signal of 5G and beyond eMBB for services like Scheduling request on PUCCH with low block size that require a lower jitter the polar coding scheme with lower code rate and lower complexity is required. To transmit high block size signal like speech signal scheme with high code rate is required.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

To make sure the reliability of an enhanced mobile broadband for 5G and beyond enhanced mobile broadband becomes difficult, as it needs the high code rate to the transportation of information. The need for ultra-reliable error free communications is emerging in many application area like mobile broadband communication, where good connectivity is essential to the transmission of reliable information in real scenario.

In 4G LTE Turbo codes and convolutional codes are used for mobile broadband communication system for data and control channels. Convolutional codes are poor in performance as compared in the literature and Turbo codes are good in performance for higher iteration. But for higher iterations the efficiency is low for higher complexity.

In this thesis the performance metric parameters such as bit error rate, block error rate and computational complexity for different value of bit energy to noise spectral ratio, block length, code rate and list size for polar code with SC decoding, interleaving polar code with SC decoding, CRC aided polar code with SCL decoding and cyclic redundancy check aided interleaved polar code with SCL decoding are analyzed for noisy binary erasure channel.

For polar code by SC decoding the performance is mostly degraded by increasing the code rate. For 5G and beyond enhanced mobile broadband in equation throughput the data rate is linearly affected by the code rate. For a code rate increase from 0.4219 to 0.5938 there is a data rate change of 1.4074 times the original by holding the MIMO layer, component carriers, and number of resource block, frequency range and numerology constant. BLER and BER of I-polar code with SC decoding the code rate significantly affects the performance as same manner as polar code with SC decoding. In the performance analysis of polar codes along with CRC code as its outer code together with the list decoding and CRC code detection list-CRC decoding depends on the length of the CRC code and its divisor or the generator polynomial

From the simulation of CRC A-polar codes-SCL decoding that there is no need to increase the list size above 8. This is because when the list size is increased the receiver has much more complexity that needs more hardware. From the graph the performance is more affected by the code rate. It is known that by increasing the code rate there will very low room for redundancy this indicates the decoder will have low potential to correctly decode the transmitted message.

Generally of the four polar coding schemes considered in thesis work such as polar code SCD, I-polar SCD, CRC-A-polar SCL decoding and CRC-A-I- polar SCLD from the performance analysis by generating random message block, text message and speech signal. CRC-A-polar SCL and CRC-A-I- polar SCL decoding outperforms the other schemes two schemes and CRC-A-I- polar SCL decoding is the best.

Finally from the performance analysis of polar coding for polar block size with same code rate lower polar block sizes performs well than higher block sizes. For 5G and beyond enhanced mobile broadband the logical channels are defined by what information type is transferred by them. Control channels are used to transfer control related information and traffic channel are used to transfer user related information. Control channels are shorter in block length than data channel so polar codes are very applicable for control channels.

5.2 Recommendations

In this thesis work the comparative performance analysis of polar coding schemes for 5G and beyond enhanced mobile broadband is considered. In this thesis performance improving function such as CRC and interleaving are included. For further study another function like scrambler should be included to increase the security of the system. Also for the performance analysis capacity and spectral efficiency should be included. The future recommendation could be channel coding and deep learning, as well as the justification for using machine learning in channel coding.

REFERENCES

Abdullah, D. M., & Ameen, S. Y. (2021). Enhanced Mobile Broadband (Embb): a Review. *Journal of Information Technology and Informatics (JITI)*, *01*(01), 13–19.

Abdulwhab, W., & Kadhim, A. (2018). Comparative Study of Channel Coding Schemes for 5G. *Journal of Electronic Systems*, *8*(3), 95. https://doi.org/10.6025/jes/2018/8/3/95-102

Albert Raj, A., Judson, D., & Beno, A. (2021). Efficient Construction of Successive Cancellation Decoding of Polar Codes using Logistic regression Algorithm. *Journal of Physics: Conference Series*, *1998*(1). https://doi.org/10.1088/1742-6596/1998/1/012010

Andrews, K., Heegard, C., & Kozen, D. (1997). *A Theory of Interleavers*, School of Electrical Engineering, Cornell University, Ithaca

Arikan, E. (2009). Channel polarization: A method for constructing capacity-achieving codes for symmetric binary-input memoryless channels. *IEEE Transactions on Information Theory*, *55*(7), 3051–3073. https://doi.org/10.1109/TIT.2009.2021379

Bae, J. H., Abotabl, A., Lin, H. P., Song, K. B., & Lee, J. (2019). An overview of channel coding for 5G NR cellular communications. *APSIPA Transactions on Signal and Information Processing*, 1–33. https://doi.org/10.1017/ATSIP.2019.10

Belhadj, S., & Abdelmounaim, M. L. (2021). On error correction performance of LDPC and Polar codes for the 5G Machine Type Communications. *2021 IEEE International IOT, Electronics and Mechatronics Conference, IEMTRONICS 2021 - Proceedings*, 7–10. https://doi.org/10.1109/IEMTRONICS52119.2021.9422665

Benson Mansingh, P. M., Titus, T. J., & Yuvaraju, M. (2020). BER ANALYSIS of CHANNEL CODING TECHNIQUES for 5G NETWORKS. *IOP Conference Series: Materials Science and Engineering*, *932*(1). https://doi.org/10.1088/1757-899X/932/1/012091

Bioglio, V., Condo, C., & Land, I. (2021). Design of Polar Codes in 5G New Radio. *IEEE Communications Surveys and Tutorials*, 29–40. https://doi.org/10.1109/COMST.2020.2967127

Chandrasekhar, R., Monika, G., Preeti, V. S., Sindhuja, K., & Reddy, S. P. S. (2020). BER Analysis of NR-LDPC Decoding Algorithms for Next Generation Wireless Communications. *Journal of Critical Reviews*, *7*(05), 1368–1378. https://doi.org/10.31838/jcr.07.05.249

Chiu, M. C. (2020). Interleaved polar (I-Polar) codes. *IEEE Transactions on Information Theory*, *66*(4), 2430–2442. https://doi.org/10.1109/TIT.2020.2969155

Dhuheir, M., & Ozturk, S. (2018). Polar codes analysis of 5G systems. *2018 6th International Conference on Control Engineering and Information Technology, CEIT 2018*, *October*, 25–27. https://doi.org/10.1109/CEIT.2018.8751838

Ellinas, G., IEEE Communications Society, Institute of Electrical and Electronics Engineers. Region 8, Panepistēmio Kyprou, & Institute of Electrical and Electronics Engineers. (2017). Proceedings of the 24th International Conference on Telecommunications : ICT 2017 : Theme: Intelligence in Every Form : 3-5 May 2017, Limassol, Cyprus. *IEEE Access*.

Faruque, S. (2012). Radio Frequency Channel Coding Made Easy. In *Springer*. http://www.nature.com/nature/journal/v414/n6859/abs/414118a0.html%5Cnhttp://link.springer.com/content/pdf/10.1007/978-1-4614-1320-2.pdf

Gamage, H. N. (2016). *Waveforms and Channel Coding for 5G*, 63.

Gamage, H., Rajatheva, N., & Latva-Aho, M. (2017). Channel coding for enhanced mobile broadband communication in 5G systems. *EuCNC 2017 - European Conference on Networks and Communications*, 6–11. https://doi.org/10.1109/EuCNC.2017.7980697

Gazi, O. (2018). Channel Coding Theorem. *Signals and Communication Technology*, 235–271. https://doi.org/10.1007/978-981-10-8432-4_4

Goldsmith, A. (2005), *Teaching WIRELESS COMMUNICATIONS*, Faculty of Information Technology and Electrical Engineering

Jihwan, S., & Lee, H. K. (2020). Burst Error Correction for Convolutional Code Concatenated with Hamming code with a block interleaver. *2020 International Conference on Artificial*

Intelligence in Information and Communication, ICAIIC 2020, 531–533. https://doi.org/10.1109/ICAIIC48513.2020.9065198

Kabalci, Y., & Ali, M. (2020). Throughput Analysis over 5G NR Physical Uplink Shared Channels. *Proceedings - 2020 IEEE 2nd Global Power, Energy and Communication Conference, GPECOM 2020*, 345–349. https://doi.org/10.1109/GPECOM49333.2020.9247906

Kaime, I. El, Madi, A. A., & Erguig, H. (2019). A Survey of Polar Codes. *7th Mediterranean Congress of Telecommunications 2019, CMT 2019*, 1–7. https://doi.org/10.1109/CMT.2019.8931392

Kaykac Egilmez, Z. B., Xiang, L., Maunder, R. G., & Hanzo, L. (2020). The Development, Operation and Performance of the 5G Polar Codes. *IEEE Communications Surveys and Tutorials*, *22*(1), 96–122. https://doi.org/10.1109/COMST.2019.2960746

Kim, D., Kim, S., Kim, I., & Kim, M. G. (2021). Reliability Based Candidate Selection of List Decoding for Polar Code. *IEEE Vehicular Technology Conference*, *2021-April*. https://doi.org/10.1109/VTC2021-Spring51267.2021.9448742

Maksimović, M., & Forcan, M. (2021). 5G New Radio channel coding for messaging in Smart Grid. *Sustainable Energy, Grids and Networks*, *27*, 100495. https://doi.org/10.1016/j.segan.2021.100495

Maunder, R. G. (2016). A Vision for 5G Channel Coding. *Accelercomm White Paper*, *September*, 1–14.

Mude, S., & Bhukya, R. N. (2019). Polar Code and Polarization using Bhattacharya Parameter. *2018 IEEE 9th Annual Information Technology, Electronics and Mobile Communication Conference, IEMCON 2018*, 151–154. https://doi.org/10.1109/IEMCON.2018.8615026

Murata, T., & Ochiai, H. (2018). Performance Analysis of CRC Codes for Systematic and Nonsystematic Polar Codes with List Decoding. *Wireless Communications and Mobile Computing*, *2018*. https://doi.org/10.1155/2018/7286909

Patil, M. V., Pawar, S., & Saquib, Z. (2020). Coding Techniques for 5G Networks: A Review. *2020 3rd International Conference on Communication Systems, Computing and IT Applications, CSCITA 2020 - Proceedings*, 208–213. https://doi.org/10.1109/CSCITA47329.2020.9137797

Prayogo, G. K., Putra, R., Prasetyo, A. H., & Suryanegara, M. (2018). Evaluation of LDPC code and polar code coding scheme in 5g technology-massive machine type communication. *Proceedings of 2018 10th International Conference on Information Technology and Electrical Engineering: Smart Technology for Better Society, ICITEE 2018*, 170–174. https://doi.org/10.1109/ICITEED.2018.8534937

Rao, K. D. (2015). Channel coding techniques for wireless communications. In *Channel Coding Techniques for Wireless Communications*. https://doi.org/10.1007/978-81-322-2292-7

Rao, K. D., & Babu, T. A. (2019). Performance Analysis of QC-LDPC and Polar Codes for eMBB in 5G Systems. *Proceedings - 2019 International Conference on Electrical, Electronics and Computer Engineering, UPCON 2019*, 1–6. https://doi.org/10.1109/UPCON47278.2019.8980142

Rinaldi, F., Raschellà, A., & Pizzi, S. (2021). 5G NR system design: a concise survey of key features and capabilities. *Wireless Networks*, *27*(8), 5173–5188. https://doi.org/10.1007/s11276-021-02811-y

Sarajevo, E. (2021). *4G vs 5G Channel Coding Techniques*. *March*, 17–19.

Sharma, A., & Salim, M. (2020). Performance evaluation of polar code for ultrareliable low latency applications of 5G new radio. In *Lecture Notes in Electrical Engineering* (Vol. 546). Springer Singapore. https://doi.org/10.1007/978-981-13-6159-3_28

Siksha, A. A. (2016). *BER Performance of OFDM based WiMAX (IEEE Effect OFDM based WiMAX (IEEE 802 . 16d) System*. *JUNE 2013*, 3–12. https://doi.org/10.12691/ajeee-3-1-2

TSGR. (2020). *TS 138 212 - V16.2.0 - 5G; NR; Multiplexing and channel coding (3GPP TS 38.212 version 16.2.0 Release 16)*. *0*.

https://portal.etsi.org/TB/ETSIDeliverableStatus.aspx

Turdiev, O. A., Smagin, V. A., & Kustov, V. N. (2020). Investigation of the computational complexity of the formation of checksums for the Cyclic Redundancy Code algorithm depending on the width of the generating polynomial. *CEUR Workshop Proceedings*, *2803*, 129–135.

Vaz, A. C., Gurudas Nayak, C., & Nayak, D. (2019). Performance Comparison between Turbo and Polar Codes. *Proceedings of the 3rd International Conference on Electronics and Communication and Aerospace Technology, ICECA 2019*, 1072–1075. https://doi.org/10.1109/ICECA.2019.8822077

Wang, M., Zhan, M., Yu, K., Deng, Y., Shi, Y., & Zeng, J. (2019). Application of bit interleaving to convolutional codes for short packet transmission. *Proceedings - 2019 IEEE International Conference on Industrial Cyber Physical Systems, ICPS 2019*, 425–429. https://doi.org/10.1109/ICPHYS.2019.8780371

Wu, H., & Wang, H. (2019). Decoding Latency of LDPC Codes in 5G NR. *2019 29th International Telecommunication Networks and Applications Conference, ITNAC 2019*, 0–4. https://doi.org/10.1109/ITNAC46935.2019.9077972

Xi, F., Ye, C., & Olesen, R. L. (2018). A Polar Code Hybrid Rate Matching Scheme. *2018 European Conference on Networks and Communications, EuCNC 2018*, 6–10. https://doi.org/10.1109/EuCNC.2018.8442685

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