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EFFECTIVE DESIGN AND IMPLEMENTATION OF POLAR CODE DECODING AND ENCODING WITH SUCCESSIVE CANCELLATION

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ABSTRACT: - Polar codes represent a pivotal advancement in coding theory, being the first class of codes to achieve the capacity of symmetric binary-input memoryless channels (BIMCs). This literature review explores the evolution and enhancement of polar codes, focusing on key aspects such as channel polarization, finite-length performance, successive-cancellation (SC) decoding, successive-cancellation list (SCL) decoding, CRC-aided decoding, and their integration into the 5G standard. The review highlights significant contributions from various researchers who have addressed practical challenges, proposed novel decoding techniques, and demonstrated the practical relevance of polar codes in modern communication systems. The discussion underscores the potential of polar codes in achieving high reliability and efficiency in data transmission, paving the way for their application in next-generation wireless networks and beyond. Future research directions are also identified, emphasizing the need for further optimization and exploration of polar codes in emerging communication technologies.

Keywords :- Polar Codes; Channel Polarization; CRC-Aided Decoding; Finite-Length Performance; Error Correction Coding; 5G Standard; Communication Systems; Capacity-Achieving Codes.

I. INTRODUCTION:

Over the past ten years, polar codes—a class of capacity-achieving codes—have attracted more attention and research attention from the academic and industry sectors. Polar codes were first introduced by Arikan [1]. Polar codes have been chosen as the channel coding method for uplink and downlink control information in the enhanced mobile broadband (eMBB) communication service, specifically within the ongoing standardisation process of 5th generation wireless systems (5G) by the 3rd Generation Partnership Project (3GPP).

.In addition to eMBB, polar codes are also being considered for other critical frameworks within the 5G ecosystem, such as ultra-reliable low-latency communications (URLLC) and massive machine-type communications (mMTC). Constructing polar codes involves determining the reliability values associated with each bit to be encoded, a task that can be efficiently executed with given parameters like code length and signal-to-noise ratio (SNR).

But the wide range of code lengths, speeds, and channel conditions that the 5G architecture envisions makes it unfeasible to have a different reliability vector for every combination of parameters. Therefore, a great deal of work has gone into creating polar codes that are modest in complexity but have excellent error-correction capabilities in a range of code and channel configurations.

Even though polar codes will soon be widely used in 5G, most of the literature that has already been written on them ignores the unique codes created for this standard and the encoding procedures that go along with them. The research community must include these codes in assessments of error-correction performance and encoder/decoder designs, given their impending significance.

The speed and complexity overheads associated with the encoding and decoding operations can be significant, and the decoder's performance is closely related to the polar code's properties. Ensuring 5G standard compliance can greatly increase the relevance of works that concentrate on hardware and software implementations.

An industry standard, such as those developed by 3GPP, represents a consensus among competing companies to deliver interoperable products. These standards reflect the current state of the field rather than its ultimate pinnacle, as they are often a compromise among different agendas.

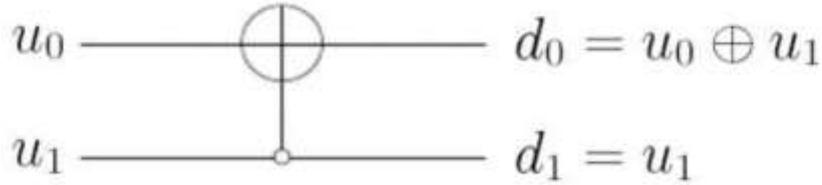

Fig. 1: Basic polarization kernel $\mathbf{G_2}$.

Fig:1-Basic polarization

We provide an overview of the polar code encoding procedure described in 5G [2] in this work, including topics such as code concatenation, interleaving functions, subchannel allocation unique to polar codes, and rate-matching techniques. Our goal is to provide readers with an easy-to-read, comprehensive reference to comprehending and applying 5G-compliant polar code encoding. Our work is to help readers understand the standard by improving its presentation and making its contents easier to read, without trying to replace the standard itself.

EXISTING PARITY-CHECK POLAR CODING FOR 5G:

The existing polar encoder architecture is based on a recursive construction that involves splitting the code into two smaller sub-codes and applying the same operation recursively. This architecture has been used in many applications and is well established. By altering the current architecture or fusing it with other coding strategies, the suggested architectures seek to enhance the polar code's performance.

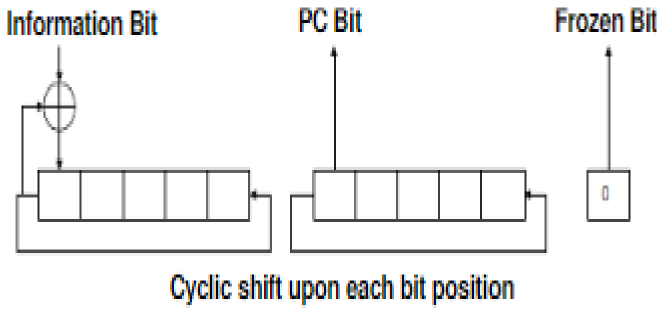

fig:2- Cyclic shift register implementation of PC functions

The existing parity-check coding performs better and costs a fraction of the implementation. Its readily reproducible code creation also permits the reporting of "1-bit" fine-granularity simulation findings over thousands of examples, allowing for code rates and lengths. The results that have been made public offer a fundamental standard for upcoming optimisation projects involving polar codes.

II. LITERATURE REVIEW ON POLAR CODES

Polar codes, introduced by Erdal Arikan in 2009, represent a breakthrough in coding theory as they are the first to achieve the capacity of symmetric binary-input memoryless channels (BIMCs). The following literature review explores the development and enhancement of polar codes, focusing on their construction, performance, and practical applications.

1. Channel Polarization and Capacity-Achieving Codes

Arikan's seminal work in 2009 laid the foundation for polar codes by introducing the concept of channel polarization, a method that transforms a set of identical channels into a new set of channels that are either nearly perfect or nearly useless for transmitting information. This polarization process enables the construction of capacity-achieving codes for symmetric BIMCs (Arikan, 2009).

2. Finite-Length Performance and Concatenated Design

Eslami and Pishro-Nik (2013) investigated the finite-length performance of polar codes, addressing practical limitations such as stopping sets and error floors. They proposed a concatenated design to improve the error performance, thereby enhancing the practical applicability of polar codes in real-world communication systems (Eslami & Pishro-Nik, 2013).

3. Successive-Cancellation Decoding and Node Identification

Hanif and Ardakani (2017) focused on improving the speed of successive-cancellation (SC) decoding, which is essential for the practical implementation of polar codes. They introduced methods for the identification and decoding of new nodes within the SC decoding process, significantly reducing the decoding time (Hanif & Ardakani, 2017).

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4. Successive-Cancellation List Decoders

Hashemi, Condo, and Gross (2016) further advanced the decoding techniques for polar codes by developing fast and flexible successive-cancellation list (SCL) decoders. These decoders enhance the error-correction performance by considering multiple decoding paths simultaneously, thereby approaching the maximum-likelihood decoding performance (Hashemi, Condo, & Gross, 2016).

5. CRC-Aided Decoding

Niu and Chen (2012) introduced a CRC-aided decoding scheme for polar codes, which incorporates a cyclic redundancy check (CRC) into the decoding process. This technique improves the error detection and correction capability of polar codes, making them more robust for practical communication applications (Niu & Chen, 2012).

6. Polar Codes in 5G Standard

Thangaraj (2018) discussed the integration of polar codes and low-density parity-check (LDPC) codes in the 5G standard. This lecture highlights the relevance of polar codes in modern communication systems, emphasizing their role in achieving high reliability and efficiency in next-generation wireless networks (Thangaraj, 2018).

7. Mathematical Methods and Algorithms

Moon's comprehensive textbook on error correction coding provides an in-depth analysis of the mathematical foundations and algorithms underlying polar codes. This resource is essential for understanding the theoretical aspects and practical implementation challenges of polar codes (Moon, 2018).

8. Practical Decoding Algorithms

Zhang et al. (n.d.) present a detailed overview of the primary concepts and practical decoding algorithms for polar codes. Their work serves as a practical guide for engineers and researchers, offering insights into the efficient implementation of polar codes in various communication systems (Zhang, Niu, Chen, & Lin, n.d.).

III. PROPOSED POLAR ENCODER AND DECODER FOR 5G COMMUNICATION:

CHANNEL POLARIZATION:

When channel polarisation was initially described in the literature, it explained how N independent copies of a binary-input discrete memoryless channel (B-DMC) are used to create N "synthetic" bit-channels. These artificial channels go through a "polarisation" process that gives them variable probability of correctly decoding by altering their dependability in sending a single bit. Extreme capacities can be achieved when the mutual information of these synthetic channels approaches either perfect noiselessness (near 1) or total noise (near 0) with a large enough N.

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Such polarised channels, where the fraction of noiseless channels approaches the capacity of the original B-DMC, can be efficiently constructed with the use of polar codes. The discovery of the basic polarisation kernel, or matrix G2 = [1 0 1 1], which represents the polarisation phenomenon, provides the basis for polar codes. With d0 = u0? u1 and d1 = u1, this matrix makes it easier to encode a two-bit input vector u = [u0, u1] into a code word d = [d0, d1], where d = u · G2.
In binary erasure channels (BECs), where a transmitted bit is either correctly received or lost with probability d, the effect of polarisation introduced by G2 is more noticeable. A larger erasure probability, d0 = (2-d)d > d, results from the sequential decoding of input bits, which shows that u0 cannot be recovered as u0 = d0? d1 if any of the code bits have not been received. A reduced erasure probability, d1 = d^2 < d, results from the decoding of u1 if at least one of the two code bits has been received. As such, u0 is sent over a synthetic BEC that is degraded and has an erasure probability of d0 > d, whereas u1 is sent over a synthetic BEC that is enhanced and has an erasure probability of d1 < d.

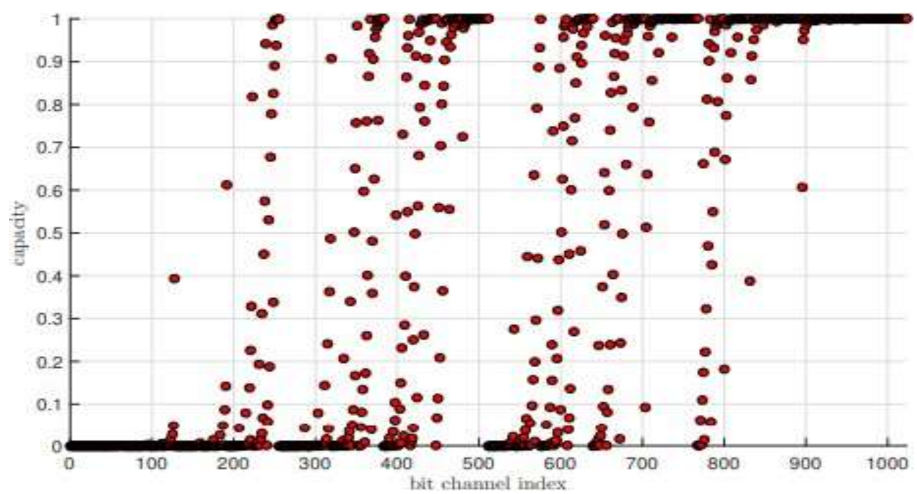

Fig:3- Bit-channel capacity virtualized across a BEC 1/2.

POLAR CODE ENCODING IN 5G:

Following the notation specified in the 3GPP technical specification, polar code encoding is essential to 5G communication systems. Different kinds of control and payload information are encoded using these codes over various physical channels. In particular, uplink control information (UCI) is carried across the physical uplink shared channel (PUSCH) and the physical uplink control channel (PUCCH) and is encoded using polar codes. On the other hand, in the downlink, they encode the payload in the physical broadcast channel (PBCH) and the downlink control information (DCI) over the physical downlink control channel (PDCCH).

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In order to meet the needs of 5G applications, where the quantity of information bits, A, is fixed, a codeword of length E is created in order to achieve the required rate, R = A/E, as required by higher communication layers. To meet these needs, polar codes are first constructed as a mother code of length N = 2n. Then, using methods like puncturing, shortening, or repeating, the mother code is matched to the desired code length E.

The mother code's maximum bound, Nmax, is dependent on the channel that is being used, while the minimum length, Nmin, is bounded to be 32. Nmax is configured as 1024 for uplink channels and 512 for downlink channels. The 5G polar codes framework's proposed order of encoding processes is shown in Figure 6. Using a payload of G code bits, vector "a" encapsulates the A information bits meant for transmission.

The message may be split and segmented into two parts, each of which would be encoded independently and then sent simultaneously, depending on the particular code settings. A0 is the length of each segmented vector "a0," and each is encoded into an E-bit polar codeword. Every A0-bit vector also has an L-bit CRC added to it. This creates a vector called "c" that has K = A0 + L bits and is interleaved.

A mother polar code of length N, together with the related bit channel reliability sequence and frozen set, are created after the desired code rate R and codeword length E are established. While the remaining bits in the N-bit "u" vector are locked, the interleaved vector "c0" and potential parity-check bits are assigned to the information set.

Vector "u" is then encoded as d = u · GN, where the generator matrix for the chosen mother code is represented by GN = G2?n. After encoding, "d" is divided into 32 equal-length blocks by a sub-block interleaver, which then jumbles the blocks to create "y," which is fed into a circular buffer. Applying rate matching techniques like puncturing, shortening, or repetition makes the N-bit vector "y" into the E-bit vector "e."

Vector "f," which is now prepared for modulation and transmission as "g" after concatenation, if required, is computed using a channel interleaver in the final step. The design and execution of polar codes in 5G systems are made easier by the availability of dependability sequences linked to various N values.

RELIABILITY SEQUENCES:

N = 8: 1 2 3 5 4 6 7 8

N = 16: 1 2 3 5 9 4 6 10 7 11 13 8 12 14 15 16

N = 32: 1 2 3 5 9 17 4 6 10 7 18 11 19 13 21 25 8 12 20 14 15 22 27 26 23 29 16 24 28 30 31 32

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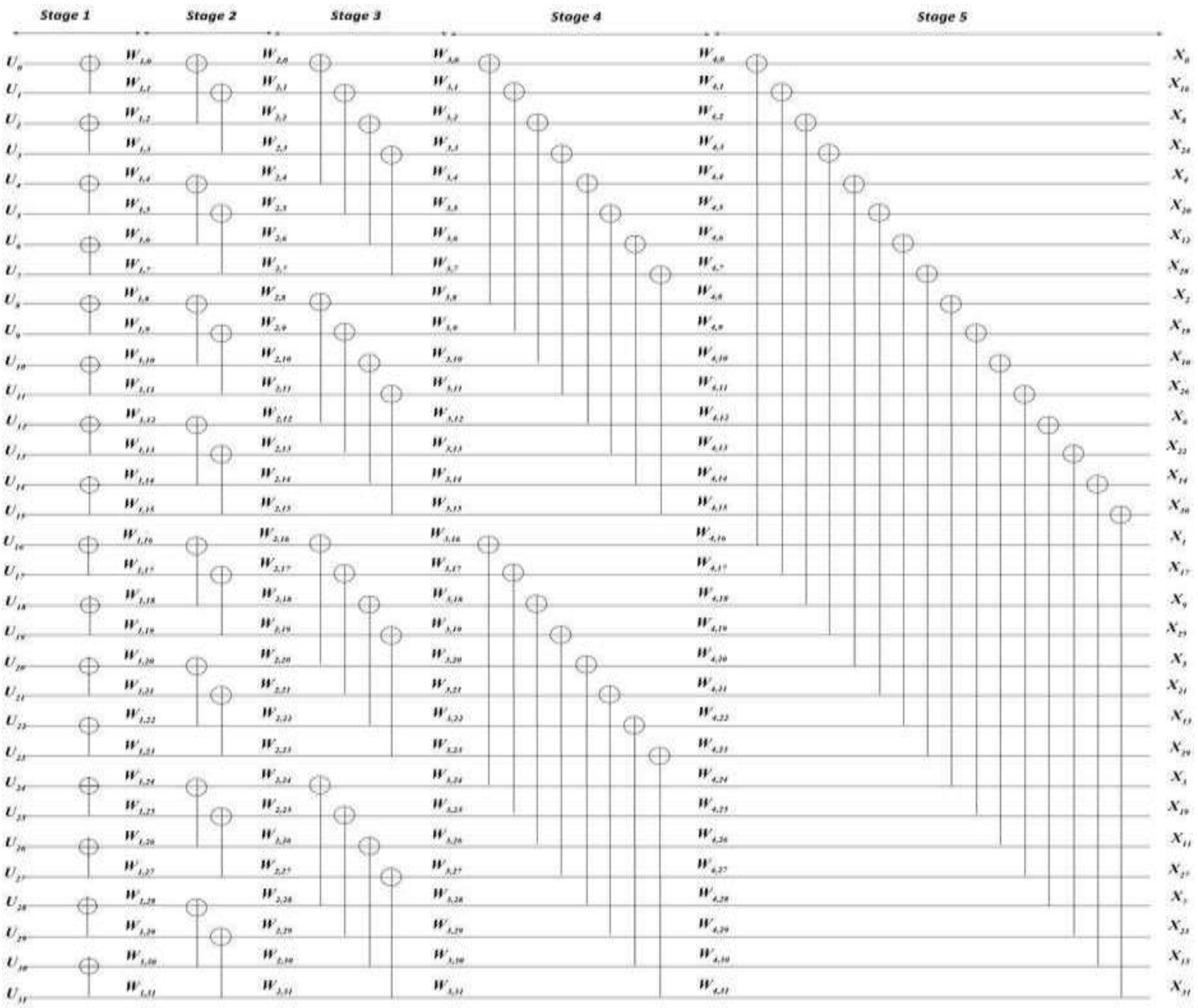

Fig:4- Encoder of an (32, 17) polar code.

FROZEN SET DESIGN:

In polar coding, "freezing" occurs when the remaining N - K bits are set to zero in order to reach a transmission rate R = K/N, where K channels are used to send information. The generator matrix is created by joining the kernel's Kronecker product. Because of its effectiveness in both encoding and decoding, a binary tree structure is frequently used to depict this process. This structure is especially useful for larger changes.

The leaf nodes in this form receive inputs and are connected to the main node to produce the output. The XOR or mod-2 addition is performed after the node summation. Nevertheless, the bit-channels' reliability order is not universal because it depends on the code length and channel conditions.

Although it comes at a significant processing expense, the density evolution (DE) method, which was first suggested and then improved, provides theoretical assurances on estimation accuracy. The polarisation effect on bit-channels imposes a partial reliability order that has been studied recently, opening the door to the creation of a universal reliability sequence that is independent of channel circumstances.

The design of the frozen set for any polar code with a length equal to or less than 1024 is made easier by this sequence, which consists of 1024 bit-channel indices arranged by reliability order. Interestingly, this universal dependability sequence may be used to directly extract sub-sequences for shorter codes, which saves sequence storage space.

This nested dependability structure is a long-lasting residue of the standardisation process and represents a major breakthrough in the design of polar codes. This innovation was made possible by using list decoders, adding assistant bits to the code, and taking distance properties into account when designing short polar codes.

POLAR CODE DECODING IN 5G:

Additionally, successive cancellation (SC), a decoding technique inherent to polar codes, has been developed. With a decoding complexity of O(Nlog2(N)), it can be modelled as a depth-first binary tree search with priority to the left branch, where the leaf nodes are the N bits to be approximated and soft information on the received code bits is entered at the root node.

In SC every node in the binary tree are supposed to do some operations. a) It receives some beliefs from the parent node and send some information to the left child b) once it receives the decision from the left child then it sends some beliefs to the right child c) Once it receives the decision from the right child it combines them and send it to the parent node. These are the three different operation these nodes will do. Lets start with the operation from the interior node(all the nodes other than leaf nodes in the binary node). All the three different operation these interior nodes could perform are (L, R,U operations)

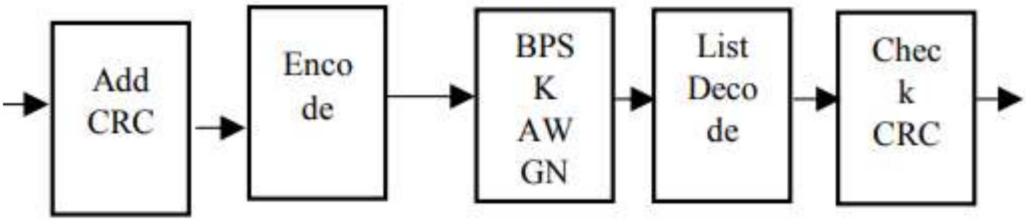

Fig:5-List decoding block diagram.

The first step in list decoding to add CRC (K= A+L) where A is a message bit and L is the length of the CRC bit .K bit is the actual message to be encrypted. The N bit codewords will be obtained in the encoder. Then the list decoding will be performed after the BPSK and AWGN. The codeword or the message word which actually passes the CRC is putout as a message estimate. Each of the codeword which passes through the CRC there is a metric associated with that. This is called path metric. Path metric is an importantnotion in List decoding it serves multiple purposes. It keeps the complexity in control and also it gives the indication of how good the code word is all about. Path metric is a belief on each code word.

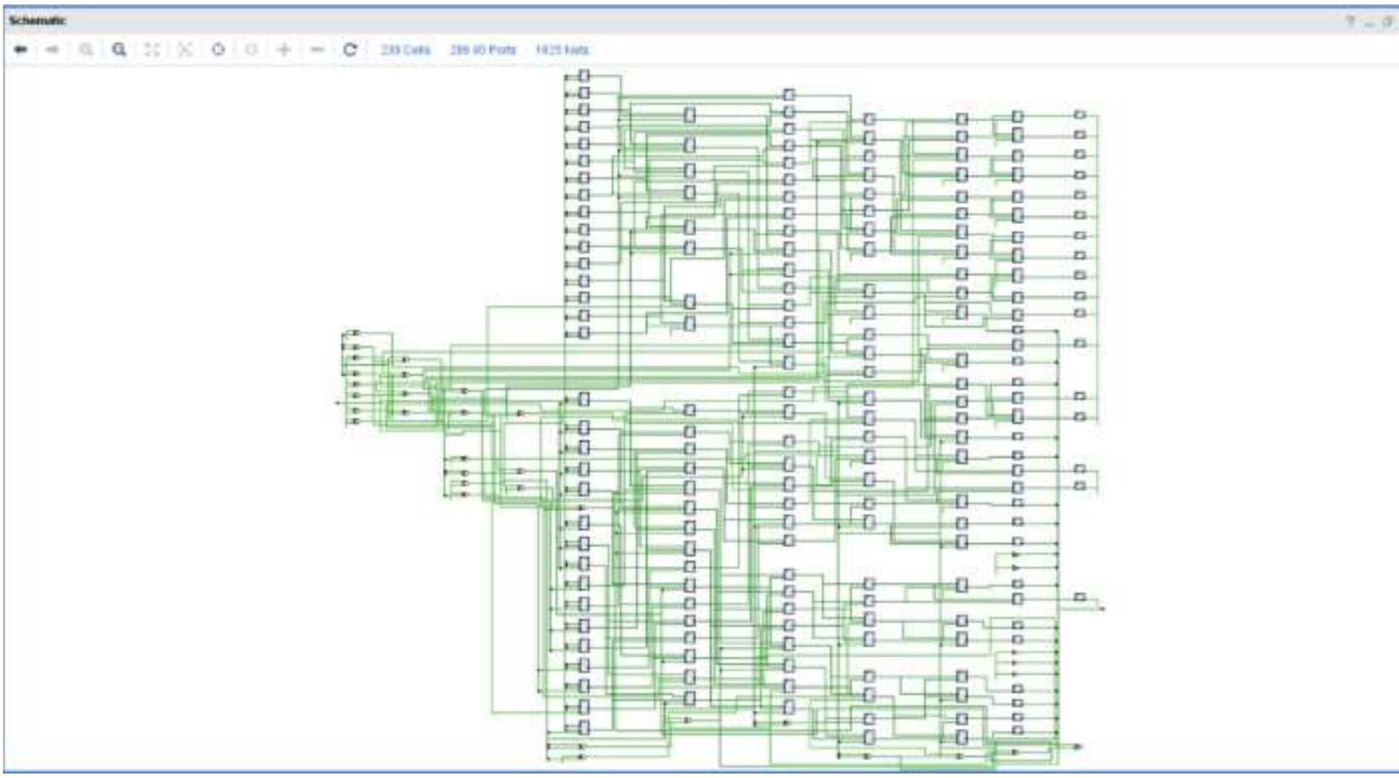

Fig :6- 32 bit Polar decoder

- Successive cancellation is a technique used in various fields, including information theory, error correction coding, and signal processing. In information theory, the term "successive cancellation" typically refers to a method employed in polar code decoding, which is a type of error-correction code.
- In polar code decoding, successive cancellation is a key algorithm used to decode received information. The basic idea is to systematically cancel out unreliable information bit by bit, gradually refining the estimates of the transmitted bits until the correct message is obtained.
- $L = f(r_1, r_2) = sgn(r_{1}) * sgn(r_{2}) * min(|r_{1}|, |r_{2}|)$
- $G = f(r_{1}, r_{2}, b) = r_{2} + (1 - 2b) * r_{1}$

Here we should make Hard decision i.e. if the child node output is less than zero then the output will be 1 or if it is greater than or equal to zero .

Generally speaking, the code length and channel condition determine the bit-channel reliability order, which makes it non-universal. When a wide variety of code lengths and rates are anticipated, this non-universality creates enormous practical challenges for the creation of polar codes. Numerous techniques have been put forth to quickly and with minimal complexity create frozen sets. Arıkan first suggested using Monte-Carlo simulations in addition to Bhattacharyya parameter tracking to evaluate bit-channel reliabilities. Although it comes at a significant computing cost, the density evolution (DE) method, which was first presented in and refined upon, can offer theoretical guarantees on the estimation accuracy.The DE/GA approach, which is based on the Gaussian approximation (GA) of density evolution, has been developed for bit-channel reliability estimate for AWGN channels. It yields reliable results with minimal complexity.

However, the on-the-fly design approach greatly increases coding latency, making it difficult to meet 5G networks' strict criteria. New approaches to developing a universal reliability sequence that works with different channel conditions have been made possible by recent studies into the partial reliability order caused by the polarisation effect on bit-channels. These research and large-scale simulations have impacted 5G standardisation by suggesting a single, global bit-channel reliability sequence.

. This sequence, which consists of 1024 bit-channel indices sorted by reliability order, provides a basic framework for determining unique reliability sequences for every polar code that is being considered for 5G applications. Surprisingly, it can be used to build the frozen set of any polar code with a length of at most 1024, regardless of the channel conditions. Reducing the amount of storage space needed to store sequences is made easier by the ability to create sub-sequences for shorter codes directly from the universal reliability sequence. An important development in polar code design, this hierarchical reliability structure is a lasting legacy of the standardisation process.

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This astounding outcome has been attained by using list decoders, assistant bits in the code, and distance properties in the design of short polar codes. SC-driven decoding Originally designed for Successive Cancellation (SC) decoding, polar codes allow channel capacity to be reached at limitless code lengths. Even though other decoding algorithms like 4 BP and SCAN were released, 3GPP decided to give the development of a SC-based decoder at the receiver end priority due to their insufficient error correction capabilities. Soft information was expressed in likelihood terms in the original SC formulation, which turned out to be numerically unstable and inappropriate for hardware implementations. Initially, log-likelihoods were used to reduce this instability; eventually, log-likelihood ratios (LLRs) took their place.

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Despite its low-complexity implementation in hardware and software, the Successive Cancellation (SC) algorithm's error-correction performance is often subpar at reasonable code lengths. As such, a great deal of work has gone into minimising this restriction. Eventually, Successive Cancellation List (SCL), a list-based decoding method for polar codes, was introduced. The idea is to use multiple SC decoders in parallel, each of which keeps track of distinct code word candidates, or pathways, at the same time. The bit is approximated as both 1 and 0 upon reaching a leaf node, hence doubling the amount of potential code words.

The number of paths is then limited by calculating a path measure for each option to weed out less likely candidates. Even at moderate code lengths, SCL significantly improves SC's error-correction performance—especially when the code is concatenated with an outer code acting as a "genie," like a cyclic redundancy check (CRC), though at the cost of more complexity. CRC-assisted (CA) SCL has become a standard for assessing error-correction performance for 5G. Larger list sizes increase SCL's effectiveness but also increase the complexity of its implementation.

A significant advancement in digital communication is polar communication, which is made possible by the use of polar codes. Polar codes have become an essential component of modern communication systems due to their capacity-achieving abilities, low-complexity encoding and decoding processes, and flexibility in a variety of communication circumstances. Their inclusion as a fundamental component of 5G wireless communication standards, where flexibility, efficiency, and dependability are critical factors, emphasises their importance even more.

As the need for fast, low-latency, and wide-ranging connectivity increases in the 5G and beyond era, polar communication is well-positioned to meet these changing needs. Polar communication provides the potential to open up new avenues for wireless communication research and development, spurring innovation across multiple industries and accelerating the realisation of a technologically advanced and more interconnected world.

IV. RESULTS & DISCUSSION

The advancements in polar codes have been remarkable, from the theoretical underpinnings established by Arikan to the practical enhancements and implementations. The integration of polar codes into the 5G standard signifies their maturity and readiness for widespread adoption. The improvements in decoding techniques, such as SCL and CRC-aided decoding, have addressed many of the practical challenges, making polar codes highly competitive with other advanced error-correcting codes.

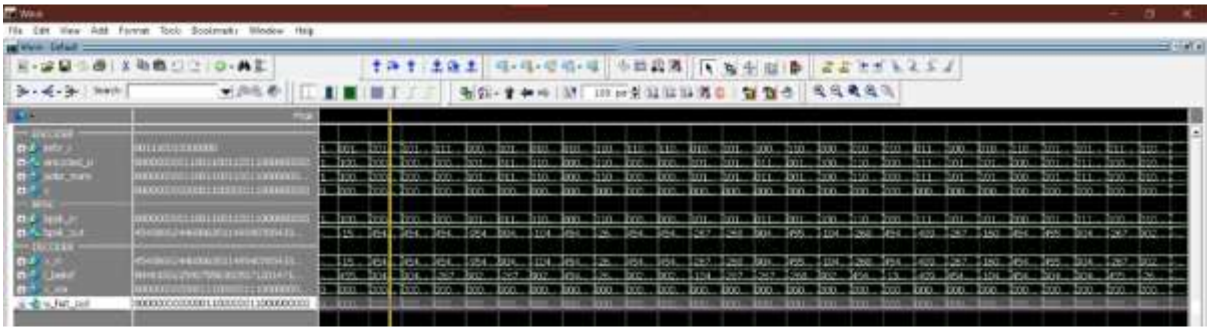

Fig:7-Simulation result for polar encoder and decoder 32 bit

Future research is likely to focus on further optimizing the performance of polar codes, particularly at finite lengths, and exploring their application in emerging communication technologies such as the Internet of Things (IoT) and beyond 5G networks. Additionally, the development of more efficient hardware implementations and decoding algorithms will be critical to maximizing the potential of polar codes in practical scenarios.

V. CONCLUSION:

This paper describes how to encode and decode 32 bit polar codes in the context of the 5G wireless systems standard. It provides readers with an understandable illustration that they can use to understand, carry out, and practice 5G-compliant polar code operations. The presented encoding chain is an example of how various needs for the improved Mobile Broadband (eMBB) control channel have been successfully met, with minimal description and encoding/decoding complexity being balanced over a wide range of code lengths and rates.

Future Scope:

Polar Code Design in 5G New Radio presents promising avenues for advancement in modern communication systems. Here are some potential areas where further research and development may yield significant enhancements:

1. Low-Latency Communication: The already demonstrated potential of Polar Codes in 5G NR for low-latency communication can be further optimized. Research avenues could explore methods to

refine Polar Code designs for even lower latency in critical applications like autonomous vehicles and remote surgery.

2. High-Speed Communication: Addressing the escalating demand for high-speed data transfer, Polar Code design optimization can support higher data rates. This entails investigating new code rates, lengths, and construction techniques to facilitate even faster data transmission.

3. Resource-Constrained Communication: Polar codes can be configured to function well in communication systems with limited resources, such as machine-to-machine (M2M) and Internet of Things (IoT) systems.. This involves developing codes capable of managing increased noise and interference while conserving computational resources.

4. Beyond 5G Communication: Polar Code design holds potential for future communication systems beyond 5G, such as 6G and beyond. Research in this domain can explore leveraging Polar Codes as a channel coding scheme for emerging wireless communication technologies.

In essence, the future scope of Polar Code design in 5G NR is expansive, offering opportunities for significant advancements in modern communication systems.

REFERENCES

1.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.

2.Eslami, A., & Pishro-Nik, H. (2013). "On finite-length performance of polar codes: stopping sets, error floor, and concatenated design." IEEE Transactions on Communications, 61(3), 919-929.

3.Hanif, M., & Ardakani, M. (2017). "Fast successive-cancellation decoding of polar codes: identification and decoding of new nodes." IEEE Communications Letters, 21(11), 2360-2363.

4.Hashemi, S. A., Condo, C., & Gross, W. J. (2016). "Fast and flexible successive-cancellation list decoders for polar codes." IEEE Transactions on Signal Processing, 65(21), 5756-5769.

5.Niu, K., & Chen, K. (2012). "CRC-Aided Decoding of Polar Codes." IEEE Communications Letters, 16(10), 1668-1671.

6.Thangaraj, A. (2018). "LDPC and Polar Codes in 5G Standard." NPTEL Lecture, Electrical Engineering Department, Indian Institute of Technology Madras.

7.Moon, T. K. (Second edition). Error Correction Coding: Mathematical Methods and Algorithms.

8.Zhang, Q. T., Niu, K., Chen, K., & Lin, J. (n.d.). Polar Codes: Primary Concepts and Practical Decoding Algorithms.