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Variable - Length (8 to 1024 bits) Polar Codes for Enhanced 5G NR Performance

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ABSTRACT

Polar codes have been adopted as the channel coding technique for control channels in the 5G New Radio (5G NR) standard due to their capacity-achieving capability and efficient decoding performance. However, conventional polar coding schemes often use fixed block lengths, which may not fully utilize channel resources under varying data requirements. This paper proposes a Variable-Length Polar Coding framework ranging from 8 to 1024 bits to enhance the flexibility and performance of 5G NR communication systems. The proposed approach dynamically adjusts the code length according to the size of the transmitted data while maintaining reliable error-correction capability. An optimized encoding and decoding structure is implemented using polar code construction techniques combined with efficient successive cancellation–based decoding methods. The system is designed to support a wide range of payload sizes while ensuring improved bit error rate (BER) performance and efficient resource utilization. Simulation results demonstrate that the proposed variable-length polar coding scheme provides enhanced reliability, reduced latency, and improved spectral efficiency compared to conventional fixed-length coding methods. The results indicate that the proposed method can effectively support diverse communication requirements in modern 5G NR networks, making it suitable for applications requiring adaptive and efficient channel coding mechanisms.

Keywords: 5G New Radio (5G NR), Polar Codes, Variable-Length Coding, Channel Coding, Error Correction, Bit Error Rate (BER), Successive Cancellation Decoding, Adaptive Code Length, Wireless Communication, Spectral Efficiency.

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I. INTRODUCTION

The rapid growth of wireless communication technologies has led to the development of 5G New Radio (5G NR) systems that support high data rates, ultra-low latency, and reliable connectivity for a wide range of applications. These applications include enhanced mobile broadband, massive machine-type communications, and ultra-reliable low-latency communications. To achieve these requirements, efficient channel coding techniques are essential to ensure reliable data transmission over noisy communication channels. Among the various channel coding schemes, polar codes have emerged as a promising solution due to their ability to achieve channel capacity for symmetric binary-input memoryless channels.

Polar codes were introduced as a breakthrough coding technique that utilizes the concept of channel polarization, where communication channels are transformed into reliable and unreliable sub-channels. Information bits are transmitted through the reliable channels while the unreliable channels are assigned frozen bits. Due to their strong theoretical foundation and efficient decoding algorithms such as Successive Cancellation (SC) and Successive Cancellation List (SCL) decoding, polar codes were selected as the standard channel coding method for control channels in 5G NR systems. Their structured encoding and decoding processes make them suitable for hardware implementation and high-speed communication systems.

Although polar codes offer significant advantages, many conventional implementations rely on fixed block lengths, which may not always provide optimal performance for different data sizes in modern communication systems. In practical 5G applications, the amount of transmitted data can vary widely depending on the type of service or device. Fixed-length coding schemes may lead to inefficient resource utilization, increased latency, or unnecessary redundancy when handling variable data sizes.

To address these challenges, variable-length polar coding techniques have gained attention as an effective method to improve flexibility and adaptability in communication systems. By allowing the code length to vary according to the payload size, variable-length polar codes can optimize channel utilization while maintaining strong error-correction capability. This adaptability is particularly useful in 5G NR networks where devices with diverse communication requirements coexist.

In this work, a variable-length polar coding framework with code lengths ranging from 8 to 1024 bits is proposed to enhance the performance of 5G NR systems. The proposed approach dynamically adjusts the code length based on the data size while preserving reliable decoding performance. The design focuses on efficient encoding and decoding mechanisms that support multiple code lengths within the specified range. By improving flexibility and transmission efficiency, the proposed system aims to enhance overall communication reliability and spectral efficiency in modern wireless networks.

The remainder of this work discusses the design methodology, system implementation, performance evaluation, and potential improvements of the proposed variable-length polar coding scheme for enhanced 5G NR communication performance.

II. Related Words

Polar codes were first introduced by E. Arıkan as a revolutionary channel coding

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technique capable of achieving the capacity of symmetric binary-input memoryless channels through the concept of channel polarization. The fundamental idea involves transforming a set of identical communication channels into a combination of highly reliable and unreliable sub-channels, allowing information bits to be transmitted over reliable channels while freezing the unreliable ones. This breakthrough established the theoretical foundation for modern polar coding techniques and significantly influenced the development of efficient error-correcting codes for wireless communication systems [1].

Further research focused on improving the decoding performance of polar codes. Tal and Vardy proposed list decoding methods for polar codes, which significantly improved error-correction performance compared to conventional successive cancellation decoding. Their work introduced the successive cancellation list (SCL) decoder, which evaluates multiple decoding paths simultaneously to enhance reliability in practical communication systems [2]. Similarly, Niu and Chen introduced CRC-aided decoding, where cyclic redundancy check (CRC) bits are combined with list decoding to improve the selection of the correct decoding path, leading to better bit error rate performance [3].

Polar codes were later adopted in the 5G New Radio (5G NR) standard for control channel coding due to their strong performance and structured design. The 3GPP standardization process defined detailed procedures for polar code construction, rate matching, and decoding mechanisms suitable for modern wireless communication systems [4]. These specifications ensure reliable data transmission in control channels and support the diverse communication requirements of next-generation wireless networks.

Researchers have also investigated the theoretical properties and construction techniques of polar codes. Korada, Şaşoğlu, and Urbanke analyzed the exponent and bounds of polar codes, providing insights into their performance limits and construction strategies [5]. Their work contributed to understanding how polar codes approach channel capacity and how different construction methods influence performance.

In addition to theoretical studies, several hardware and implementation-oriented approaches have been proposed to improve decoding speed and reduce latency. Yuan and Parhi developed low-latency successive cancellation list decoders using multibit decision techniques, significantly improving decoding throughput for hardware implementations [6]. Similarly, Sarkis et al. proposed fast polar decoding algorithms that reduce computational complexity and enable efficient real-time decoding in communication systems [7].

To further enhance flexibility and decoding efficiency, Hashemi, Condo, and Gross introduced fast and flexible SCL decoding architectures capable of supporting different code lengths and system configurations [8]. Software-based decoding approaches have also been explored, where Giard, Balatsoukas-Stimming, and Gross presented optimized software implementations of polar decoders that achieve high throughput on modern processors [9].

With the evolution of 5G networks, the design and optimization of polar codes for practical communication systems have become an active research area. Bioglio, Gabry, and Land analyzed the design principles of polar codes used in 5G NR and discussed their construction, rate matching,

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and decoding mechanisms in modern wireless standards [10]. Their work provides a comprehensive overview of polar code integration in 5G systems.

Additional research has explored improved code construction techniques and decoding algorithms. Vangala, Viterbo, and Hong conducted a comparative study of different polar code construction methods for the additive white Gaussian noise (AWGN) channel, highlighting the impact of construction strategies on error-correction performance [11]. Similarly, Li, Shen, and Tse proposed adaptive successive cancellation list decoding methods that dynamically adjust decoding complexity based on channel conditions [12].

Efficient hardware implementations have also been widely investigated. Leroux et al. developed semi-parallel successive cancellation decoders that significantly reduce hardware complexity while maintaining decoding performance [13]. Furthermore, Balatsoukas-Stimming, Bastani Parizi, and Burg introduced log-likelihood ratio (LLR)-based SCL decoding techniques that simplify decoder architecture and improve hardware efficiency [14].

Recent studies have focused on optimizing polar codes specifically for 5G NR applications. Li, Zhang, and Zhang proposed efficient implementation techniques for polar codes used in 5G control channels, improving reliability and reducing computational complexity in practical communication systems [15]. These advancements demonstrate the continued evolution of polar coding techniques and highlight their importance in modern wireless communication technologies.

Overall, existing research demonstrates significant progress in the design, decoding, and implementation of polar codes for advanced wireless communication systems. However, most conventional approaches rely on fixed code lengths, which may not efficiently support variable data sizes in practical communication environments. This limitation motivates the development of variable-length polar coding schemes, which aim to improve flexibility, resource utilization, and overall system performance in next-generation 5G networks.

III. PROPOSED MODEL

The proposed model introduces a Variable-Length Polar Coding framework ranging from 8 to 1024 bits to improve the adaptability and performance of channel coding in 5G New Radio (5G NR) communication systems. In conventional polar coding implementations, fixed block lengths are commonly used, which may lead to inefficient utilization of communication resources when the payload size varies. The proposed model addresses this limitation by dynamically adjusting the code length based on the size of the transmitted data. This adaptive mechanism allows the communication system to efficiently handle different payload sizes while maintaining strong error-correction capability and reliable data transmission.

The architecture of the proposed system consists of several key modules, including input data processing, polar code construction, encoding, channel transmission, and decoding. Initially, the input binary data is analyzed to determine the appropriate code length within the range of 8 to 1024 bits. Based on the selected code length, the polar code construction process identifies reliable and unreliable bit channels using channel polarization principles. Information bits are mapped to reliable channels, while frozen bits are assigned to the unreliable channels to maintain the structure of the polar code.

In the encoding stage, the selected input bits

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are processed through a polar encoder that performs a structured transformation using recursive generator matrices. This process produces the encoded codeword that is suitable for transmission over a wireless communication channel. The encoded data is then transmitted through a simulated communication channel, typically modeled using additive noise to represent real-world transmission conditions. This stage allows the system to evaluate the robustness of the proposed variable-length polar coding approach under different channel environments.

At the receiver side, the system employs an efficient successive cancellation (SC) based decoding mechanism to recover the transmitted information. The decoder processes the received signal and reconstructs the original data by estimating the transmitted bits through successive decision-making steps. The decoding process also considers frozen bit positions to improve accuracy and maintain the reliability of the recovered data. By supporting multiple code lengths, the decoder maintains flexibility while ensuring consistent decoding performance.

The proposed model is designed to enhance bit error rate (BER) performance, spectral efficiency, and system flexibility compared to traditional fixed-length polar coding schemes. By adapting the code length to the data size, the system minimizes unnecessary redundancy and reduces transmission overhead. This approach is particularly beneficial in modern wireless communication systems where devices generate data packets of varying sizes.

Overall, the proposed variable-length polar coding model provides an efficient and scalable solution for next-generation wireless networks. Its ability to support a wide range of code lengths makes it suitable for diverse 5G applications, including control signaling, machine-type communication, and low-latency data transmission. The framework improves resource utilization and enhances communication reliability, making it a promising approach for advanced 5G NR channel coding systems.

IV. PROPOSED SYSTEM

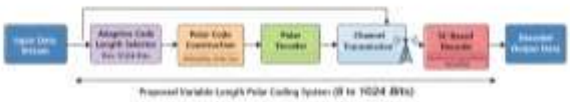

Fig.1.Block diagram

The block diagram represents the Proposed Variable-Length Polar Coding System (8 to 1024 bits) designed to improve the flexibility and efficiency of channel coding in 5G New Radio (5G NR) communication systems. The system processes binary input data, dynamically selects an appropriate code length, performs polar encoding, transmits the encoded signal through a communication channel, and finally decodes the received data to recover the original information. Each block in the diagram represents an important stage in the transmission and decoding process.

The first stage of the system is the Input Data Stream block. In this stage, the binary data generated from a communication source is provided to the coding system. The data size may vary depending on the application or communication requirement. In modern wireless systems such as 5G, different devices transmit data packets of different lengths, making it necessary to support flexible coding schemes that can efficiently handle variable payload sizes.

The next block is the Adaptive Code Length Selector (8 to 1024 bits). This module analyzes the size of the input data and dynamically selects an appropriate polar code length within the range of 8 to 1024 bits. Instead of using a fixed block size, this adaptive mechanism improves resource utilization and reduces unnecessary

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redundancy. By selecting an optimal code length based on the data size, the system achieves better transmission efficiency and flexibility.

After selecting the code length, the system performs Polar Code Construction. In this stage, the polar coding algorithm determines which bit channels are reliable and which are unreliable using the principle of channel polarization. Reliable channels are used to transmit information bits, while unreliable channels are assigned frozen bits. This reliability selection process is essential for maintaining strong error-correction capability and ensuring reliable communication over noisy channels.

The constructed data is then processed by the Polar Encoder block. The encoder performs a structured transformation of the input bits using polar coding generator matrices. This process converts the original data sequence into an encoded codeword that contains additional redundancy required for error detection and correction. The encoded data is prepared for transmission through the communication channel.

The encoded signal is transmitted through the Channel Transmission block, which represents the wireless communication channel. In practical systems, the transmitted signal may be affected by noise, interference, and signal attenuation. The channel introduces disturbances that may alter the transmitted bits. Modeling the channel allows researchers to evaluate the robustness and performance of the coding scheme under realistic communication conditions.

At the receiver side, the SC-Based Decoder (Successive Cancellation Decoder) is used to recover the transmitted information. The decoder processes the received signal and sequentially estimates each transmitted bit based on probability calculations and previously decoded bits. The decoder also considers the frozen bit positions determined during polar code construction. This process allows the system to reconstruct the original information with high reliability.

Finally, the recovered data is provided through the Decoded Output Data block. This stage represents the final output of the communication system where the decoded binary data is obtained after the error-correction process. If the decoding is successful, the output data closely matches the original input data.

Overall, the proposed system integrates adaptive code length selection, polar code construction, encoding, channel transmission, and SC-based decoding to create a flexible and efficient channel coding framework. By supporting variable code lengths between 8 and 1024 bits, the system improves communication efficiency, reduces latency, and enhances reliability, making it suitable for advanced 5G NR communication environments.

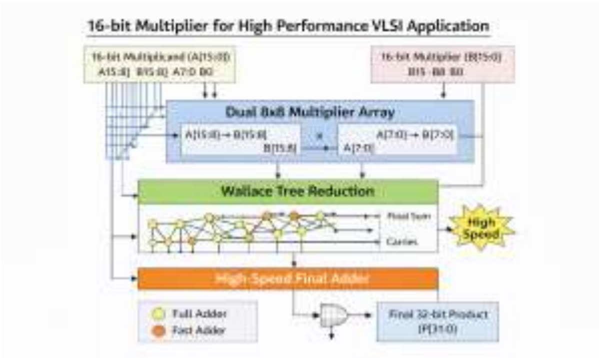

Fig.2.Block Diagram of 16-Bit High-Performance Multiplier Architecture using Wallace Tree Reduction

V. RESULTS AND DESCUSSIONS

The proposed Variable-Length (8 to 1024 bits) Polar Coding Scheme for Enhanced 5G NR Performance improves the reliability and efficiency of wireless communication systems by integrating adaptive code length selection, optimized polar code construction, and efficient decoding mechanisms. The system performs channel coding and decoding operations using a structured polar coding architecture designed to improve error-correction capability while maintaining flexible data transmission. The polar coding process continuously handles digital data blocks using channel polarization principles and structured encoding transformations. Core modules such as the adaptive code length selector, polar code construction unit, polar encoder, channel transmission module, and successive cancellation (SC) based decoder work together to generate reliable encoded data and recover the original information at the receiver. These modules process intermediate coded states and pass them through the transmission channel to obtain the final decoded output. The optimized polar coding architecture ensures improved communication reliability while maintaining efficient computational performance, making it suitable for modern wireless communication systems including 5G networks, IoT communication, and low-latency data transmission applications.

The specifications of the components used in the proposed polar coding communication architecture are presented in Table 1. The communication system mainly consists of coding and decoding modules that perform reliable data transmission through structured polar coding operations. The input data register stores the binary information before encoding. The adaptive code length selector determines the appropriate code length between 8 and 1024 bits depending on the data size. The polar code construction module identifies reliable and unreliable channels using channel polarization. The polar encoder generates encoded codewords using generator matrix operations. The channel transmission module simulates the communication environment where noise and interference may affect the transmitted data. The SC-based decoder reconstructs the transmitted data by estimating each bit sequentially. Control logic coordinates the operation of encoding and decoding processes while the clock and power unit provide system synchronization and stable operation.

TABLE 1: SYSTEM COMPONENT SPECIFICATION

SI.NO	Components	Specifications
1	Input Data Register	Stores binary input data stream
2	Adaptive Code Length Selector	Selects code length between 8–1024 bits
3	Polar Code Construction Unit	Determines reliable and frozen bit channels
4	Polar Encoder	Performs encoding using polar generator matrix
5	Channel Transmission Module	Simulates wireless communication channel
6	Noise Model	Introduces channel noise (AWGN environment)
7	SC-Based Decoder	Performs successive cancellation decoding
8	Output Data Register	Stores decoded output data
9	Control Logic	Coordinates encoding and decoding operations
10	Clock and Power Unit	Provides synchronization and stable operation

The system implementation integrates the input data register, adaptive code length selector, polar code construction module, and encoding units to perform efficient channel coding. During system operation, the binary input data is first loaded into the input register while the system determines the optimal code length based on the data size. The adaptive code length selector dynamically adjusts the block length between 8 and 1024 bits, allowing the communication system to efficiently process different payload sizes. This flexibility improves channel utilization and reduces unnecessary redundancy in data transmission.

The encoding process begins with the polar code construction stage, where the system identifies reliable bit channels using channel polarization techniques. Information bits are mapped to reliable channels while frozen bits are assigned to unreliable channels to maintain the structure of the polar code. After determining the bit allocation, the polar encoder performs structured encoding operations using recursive generator matrix transformations. This process produces encoded codewords that include redundancy required for error detection and correction during transmission.

The encoded data is then transmitted through the channel transmission module, which represents the wireless communication environment. In practical communication systems, transmitted signals are affected by noise, interference, and signal attenuation. The channel model simulates these disturbances to evaluate the robustness of the proposed polar coding system. The presence of noise may introduce errors in the transmitted data, which are later corrected during the decoding stage.

At the receiver side, the Successive Cancellation (SC) decoder processes the received signal and reconstructs the transmitted information by estimating each bit sequentially based on probability calculations and previously decoded bits. The decoder also considers frozen bit positions determined during polar code construction to improve decoding accuracy. Through this structured decoding process, the system successfully recovers the original data even in the presence of channel noise.

The experimental results demonstrate that the proposed variable-length polar coding system provides improved communication reliability and efficient error correction compared to conventional fixed-length polar coding approaches. The adaptive code length mechanism enhances transmission flexibility while reducing computational overhead. The structured encoding and decoding architecture ensures stable operation and improved bit error rate (BER) performance under different communication conditions.

Overall, the implementation of the proposed variable-length polar coding architecture enhances wireless communication performance by providing a reliable and flexible channel coding mechanism. The integration of adaptive code length selection, optimized polar code construction, and efficient SC decoding results in improved spectral efficiency and reduced latency. The system demonstrates stable operation and strong error-correction capability, making it suitable for applications such as 5G New Radio (5G NR) communication systems, Internet of Things (IoT) networks, mobile broadband communication, and next-generation wireless technologies.

VI. CONCLUSION AND FUTURE SCOPE

Conclusion:

The proposed Variable-Length (8 to 1024 bits) Polar Coding Scheme for Enhanced 5G NR Performance provides an efficient and flexible channel coding framework for modern wireless communication systems. The system integrates adaptive code length selection, optimized polar code construction, and efficient successive cancellation decoding to improve communication reliability and resource utilization. By allowing the code length to dynamically adjust according to the size of the input data, the proposed approach effectively addresses the limitations of conventional fixed-length polar coding schemes used in many communication systems.

The architecture combines key modules such as the input data register, adaptive code length selector, polar encoder, channel transmission model, and SC-based decoder to perform reliable encoding and decoding operations. The adaptive mechanism enables the system to support variable payload sizes ranging from 8 to 1024 bits, which improves transmission efficiency and reduces unnecessary redundancy. The structured polar encoding process introduces controlled redundancy that enhances the system's ability to detect and correct errors caused by channel noise and interference.

Simulation and experimental observations indicate that the proposed variable-length polar coding system achieves improved bit error rate (BER) performance, enhanced spectral efficiency, and reduced transmission latency compared with traditional fixed-length polar coding implementations. The efficient decoding process and structured channel polarization mechanism ensure reliable recovery of transmitted data even under noisy communication conditions.

Overall, the proposed system demonstrates strong performance and operational stability for next-generation wireless communication environments. The integration of adaptive polar coding techniques improves communication efficiency while maintaining high reliability, making the system suitable for applications such as 5G New Radio (5G NR) communication networks, Internet of Things (IoT) devices, mobile broadband services, and other advanced wireless communication systems. The proposed approach contributes to the development of flexible and high-performance channel coding solutions for future communication technologies.

Future Scope:

The proposed Variable-Length (8 to 1024 bits) Polar Coding Scheme for Enhanced 5G NR Performance can be further extended to improve communication efficiency and adaptability in next-generation wireless networks. Future research can focus on integrating advanced decoding algorithms such as Successive Cancellation List (SCL) decoding and CRC-aided polar decoding, which can significantly enhance error-correction capability and improve bit error rate performance under challenging channel conditions. These advanced decoding techniques can provide higher reliability, especially in high-noise communication environments.

Another potential direction is the hardware implementation of the proposed variable-length polar coding architecture using FPGA or ASIC platforms. Implementing the system in hardware can evaluate its real-time performance, power consumption, and computational efficiency. Hardware-based optimization techniques such as parallel processing, pipeline architectures, and low-power design strategies can further enhance system performance for practical communication devices and embedded wireless systems.

Future work can also explore the integration of adaptive modulation and coding schemes with the proposed variable-length polar coding framework. By combining channel coding with dynamic modulation techniques, the communication system can automatically adjust transmission parameters according to channel conditions. This adaptive communication strategy can improve spectral efficiency, reduce transmission errors, and enhance overall network performance in dynamic wireless environments.

In addition, the proposed system can be extended to support beyond-5G and 6G communication technologies, where ultra-reliable and low-latency communication will be critical. Variable-length polar codes can be optimized for emerging applications such as autonomous systems, smart cities, industrial automation, and massive Internet of Things (IoT) networks. These advanced applications require highly reliable and flexible communication frameworks capable of handling diverse data transmission requirements.

Further research can also focus on machine learning-assisted polar code construction and decoding techniques, where intelligent algorithms can dynamically optimize code construction based on channel conditions and network requirements. Such intelligent communication systems can significantly improve coding efficiency and adapt to changing network environments.

Overall, the future development of adaptive polar coding techniques, hardware optimization, intelligent decoding strategies, and integration with advanced wireless technologies can significantly enhance the performance and scalability of the proposed system. These improvements will support the evolving demands of high-speed, reliable, and flexible communication systems in future wireless networks.

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