FPGA Implementation and Architecture Design of Polar Encoder For 5g Nr-: N28 Bits

BALAKUMARAN M

Department of Electronics and Communication Engineering

Panimalar Institute of Technology Chennai, India

bala29102003@gmail.com

AKILESH L

Department of Electronics and Communication Engineering

Panimalar Institute of Technology Chennai, India

akileshreddy2004@gmail.com

JANARTHAN B

Department of Electronics and Communication Engineering

Panimalar Institute of Technology Chennai, India

Janarthan.b1108@gmail.com

DR. S. SATHIYA PRIYA

Department of Electronics and Communication Engineering

Panimalar Institute of Technology Chennai, India

Priya.anbunathan@gmail.com

Abstract

Specifically concerning the N28 code block length (28 bits), the project concentrates on the FPGA realization and architectural design of a polar encoder for 5G NR (New Radio). Polar codes are a type of error- correcting code that have garnered a lot of interest thanks to their capacity-achieving performance under the 5G communication standards. The ambition of the project to design a hardware-efficient

FPGA architecture running the polar encoding algorithm and to maximize performances including throughput, power efficiency, and space. Developing a polar code encoder using successive cancellation decoding and hardware optimization techniques to meet the demanding performance and reliability criteria of 5G NR systems is among the key parts of the design. The FPGA solution is expected to deliver real-time encoding capability suitable for modern wireless networks' fast communication requirement

Keywords - polar encoder ;5G NR (new radio);

N28 Bits Polar Code; polar code architecture;

Low-Latency Polar Encoding; High Speed Polar Encoder

I.INTRODUCTION

Fifth-generation New Radio (NR) standard, which offers better data rates, ultra-low latency, and increased reliability, has been developed As a result of the rapid forward of wireless communication technology. Channel coding is a core element of 5G needed to ensure error-free data transfer across noisy channels. Because of their capacity-achieving properties under successive cancellation (SC) decoding, Polar Codes have been chosen as the official error correction technique for the control channels in 5G NR among the various coding methods. Since the n28 setup indicates a specific frequency range within the sub-1 GHz range, it is suitable for long-range use, especially in suburban and rural areas. Specially in surroundings with little resources, effective hardware realization of Polar Encodes is Absolutely vital for reaching high throughput and low power consumption

Due to their inherent parallel processing capacity, reconfigurability, and energy efficiency, field-programmable gate arrays (FPGAs) have emerged as popular medium for Polar Encoding implementation. FPGAs are ideal for experimental studies and live deployments since they enable fast prototyping and design changes, unlike Application Specific Integrated Circuits (ASICs). This project's chief objective is to produce a Polar

Encoder meant for the n28 bit setup in 5G NR and using a high-performance FPGA-based architecture. The design aims to maximize important performance indicators including latency, power consumption, and hardware use in line with the 3GPP (Third Generation Partnership Project) criteria.

Based on channel polarization theory, Polar Encoding reshapes recursively input bits using Kronecker products of the kernel matrix. By encoding, Particular bit channels can be far more reliable than others, hence allowing the most efficient choice of information and frozen bits. Carrying out this process on FPGA calls for an architecturally planned configuration that efficiently directs the encoding chores onto hardware components including Look-Up Tables (LUTs), Flip-Flops (FFs), and Digital Signal Processing (DSP) blocks. An optimized design calls for consideration of many architectural techniques including pipelining, parallelism, and hardware reuse. Further More essential for striking a balance between speed and area efficiency are resource allocation techniques, including routing optimization and memory management,

The performance evaluation of the Polar Encoder based on FPGA is carried out using simulation and synthesizer tools such as Xilinx Vivado, Quartus Prime, and Model Sim. For prototyping and testing applications, several FPGA platforms—Intel Stratix and Xilinx Zynq among them—are reviewed. Regarding hardware usage, timing analysis, and power dissipation, the implementation results are examined, thereby giving some understanding of the balance between designing an effective Polar Encoder. Comparative study of current uses Help to assess the merits and drawbacks of the recommended design.

By providing a flexible and efficient Polar Encoder architecture based on FPGA, this initiative complements the existing data on hardware acceleration for 5G communication systems. The findings and techniques presented in this research can be adjusted to fit more complex arrangements and further improvements for real-time applications. This initiative aims to increase the usability of 5G NR deployment in lower frequency bands like n28—a must-have for achieving extensive network coverage and continuous connectivity in future wireless networks—by using FPGA technology.

II LITERATURE REVIEW

With wireless communication now, advanced error correction algorithms have been developed to ensure reliable data transmission over noisy channels. Erdal Arıkan's Polar Codes, introduced in 2009, have gained much attention among the different coding methods for their ability to approach Shannon capacity with SC decoding. Their improved performance compared to conventional techniques like convolutional and turbo codes have Lead Polar Codes to be adopted as the official channel coding approach for 5G NR control channels. Particularly on FPGA platforms, the inclusion of Polar Codes in 3GPP Release 15 has sparked considerable research into efficient hardware implementations to meet the demanding performance requirements of 5G networks.

Many research studies have looked at Polar Code encoding and decoding procedures to improve hardware performance and lower computational complexity. Using a Kronecker matrix transformation, the encoding process combines recursively information and frozen bits to generate the encoded result. Though its execution still calls for good architectural design to optimize power, latency, and hardware resource efficiency, encoding is a linear process with lesser computing complexity; in contrast to decoding, which is nonlinear. Zhang et al. A hardware-optimized encoding architecture that reduces memory overhead and improves parallelism was presented in 2018. Their research revealed that using hardware acceleration techniques including pipelining and parallel processing significantly raises the throughput of Polar Encoders but keeps the energy use low.

Many studies in the field of FPGA-based systems have focused on modifying Polar Encoding to suit reconfigurable hardware platforms. Sarkar et al (2019) studied the encoding structures based on LUT and shift- register, considering their speed and area utilization. While shift-register- based systems are more energy-efficient, the study discovered that LUT- based designs provide more flexibility but consume more logic resources. Lian et al., by the same logic, (2020) introduced an original hardware- sharing approach leveraging logic blocks across several encoding stages to increase resource efficiency. Their FPGA synthesis results showed a 30 percent reduction in hardware footprint without any significant performance degradation.

The n28 arrangement in 5G NR refers to extended coverage uses mostly using the 700 MHz range. There has been thorough examination of hardware implementations developed particularly for Particular 5GNR bands. Hua et al. The Polar Encoder architecture tailored for sub-1 GHz frequency bands was designed in (2021). Their FPGA implementation had low-latency encoding and great area efficiency, therefore appealing for wide-area and rural network uses. Yet one relevant research by Chen et al. Particularly for 5G NR bands with low frequency like n28, (2022) investigated the trade-offs between totally parallel and semi-parallel Polar Encoding architectures and found that semi-parallel designs offer a good middle between speed and power.

In the current studies, optimization strategies such resource sharing, bitwise operations, and memory-efficient designs have been extensively explored. Liu and others. Introduced in 2020, a resource-aware encoding technique uses CLBs and dedicated DSP slices on an FPGA to boost computational efficiency. Relative to traditional design, their study revealed a 25 percent fall in logic usage. Other research from Kim et al. (2021) focusing on energy-efficient encoding, they implemented dynamic voltage and frequency scaling (DVFS) to lower power consumption in low-throughput applications, therefore especially useful for n28-based 5G NR rollouts.

Using platforms such Xilinx VIVADO, Intel Quartus Prime, and Model Sim, FPGA-based Polar Encoding implementations have been evaluated in terms of design techniques and tools. Yang and rest. (2022) In a comparison of mid-range FPGAs like Xilinx Artix-7 against high-performance options like Intel Stratix-10, effects of FPGA selection on encoding efficiency were studied. Their results implied that performance metrics are significantly affected by architectural choice; top-end FPGAs offer better throughput but consume more energy. Just as Mehta et al. For several FPGA architectures, (2023) examined methods for co-design of hardware/software to enhance the adaptability of Polar Encoding.

Although FPGA-based Polar Encoder layout has advanced, several issues remain including hardware complexity, power efficiency, and scalability. Hybrid designs combining FPGA acceleration with ASIC co-processors have been proposed by researchers to further increase performance. Gupta et al. The hybrid FPGA-ASIC Polar Encoding platform shown in (2023) accomplished great power savings by supporting high throughput. Dynamic resource distribution in FPGA-based Polar Encoder systems has also been checked using machine learning techniques. Xu and colleagues, (2034) deep reinforcement learning was applied to flexibly change equipment settings depending on workload circumstances is shown the feasibility of AI-driven optimization.

The literature review brings to the forefront the growing relevance of FPGA-based Polar Encoding architectures in 5G NR, particularly for band- specific uses including n28. Even if much progress has been made in minimizing latency, power efficiency, and hardware use, more research is needed to investigate scalable and adaptive designs that can adapt dynamically to changing network demands. These research findings undergird this initiative, which aims to create and introduce a 5G NR-n28 application-optimized FPGA-based Polar Encoder architecture specially created to solve existence problems and advance next-generation wireless communication.

III. PROBLEM STATEMENT

The fast development of 5G New Radio (NR) technology calls attention to the need of reliable error correction methods to ensure reliable communication over several frequency bands. Polar Codes have been standardized by 3GPP for control channels because of their capacity and outstanding error-correction abilities. Particularly in rural and suburban areas, the n28 frequency band working within the 700 MHz range is essential for providing wide coverage. Still, the deployment of a high- performance Polar Encoder for 5G NR-n28 raises several difficulties, especially with respect to hardware efficiency, latency, and power use. To meet the rigorous specifications of next-generation wireless communication networks, demand for a hardware-optimized, resource-efficient, and high-speed FPGA-based solution is absolutely Essential.

Polar Encoding is most challenging partly from the Kronecker-dependent recursive structure, which calls for large numbers of matrix operations and so causes great hardware complexity. Because of their computational inefficiency, traditional software-based approaches are not suitable for real- time use. Although ASIC-based implementations have high performance, they use a lot of design time and expenses and lack flexibility. On the other hand, FPGAs provide a perfect balance between performance and flexibility, so they are a preferred choice for the development of Polar Encoders. Still a challenge, especially for low-frequency bands like n28, where energy efficiency is a primary worry, is achieving low-latency and power-efficient encoding on FPGA.

Because of unrequired calculations and inefficient memory access patterns, current Polar Encoder designs based on FPGAs usually have high resource utilization. Optimized hardware designs are definitely called for; they enable parallel processing capacity increase, lower power consumption, and decreased logic use. Though several optimization techniques including pipelining, hardware reuse, and LUT-based implementations have been explored, their effectiveness for n28-specific applications has not been thoroughly discussed. Furthermore, the ratio of totally parallel to semi- parallel architectures should be closely analyzed to determine the best strategy for achieving high-throughput encoding with minimal hardware overhead.

The project aims to create and deploy an optimized FPGA-based Polar Encoder design especially tailored for 5G NR-n28 applications. While adhering to 3GPP requirements, the proposed architecture will focus on power efficiency, maximizing resource usage, and lowering latency. This study aims to increase the feasibility of 5G NR deployment in low- frequency bands by using FPGA's parallel processing technology and hardware-friendly encoding techniques, therefore supporting the development of next-generation wireless communication systems.

IV. PROPOSED SYSTEM

1. Beginning

Using software-based simulation and validation, the project focuses on the creation and deployment of a Polar Encoder for 5G NR (n28). The goal is to develop a good encoding structure meeting 5G NR criteria and improving performance points such latency, power usage, and resource utilization.

2. Overview of the system

The recommended process has these stages:

A. Implementation based on software.

No physical FPGA deployment will create the finished system using simulation tools run on software such as MATLAB or C++. Although HDLs like VHDL or Verilog might still be useful for architectural modeling, they would be executed in a software simulator.

B. architectural design

The Polar Encoder is purposely developed with a systematic approach:

Bit channel reliability computed with density progression or Bhattacharyya parameters.

Freeze Bit Selection (as defined by the 5G NR n28-bit standard)

Encoding process of the base matrix's Kronecker power.

Rate Matching (puncturing, shortening, repetition according to 5G standards)

Performance Evaluation (BER analysis, complexity check)

C. Development Software Instruments

For numerical analyses and BER performance appraisal, MATLAB.

For high-efficiency simulations: C++

HDL Simulator: Xilinx VIVADO for software-only FPGA modeling; Model Sim

3. Operative modules

Location of frozen and information bits is what the Bit-Channel Selection Module helps you discern.

Encodes with the generator matrix using the Polar Encoding Module. Rate Matching Module: Adjusts code length according 5G NR standards.

Simulating and Testing Module: Monte Carlo simulations confirm accuracy and performance straight.

4. Foreseen outcomes

Fully functional, software-based Polar Encoder design.

Performance evaluation of computational complexity, latency, and BER. Comparison with present Polar Encoder designs.

V. REGULATORY COMPLIANCE

1. Technical standards (3GPP compliance).

Make sure you are following 3GPP TS 38. 5G NR polar encoding balances

- 212.erbvu channel coding and multiplexing.

Adhere to 5G NR standards by applying correct bit-channel mapping, rate- matching, and interleaving.

Adhering to 3GPP Release 15 and following revisions for n28-bit channel coding will help you leave

2. Standards of Safety and Compliance for Hardware in FPGAs.

Adhere to industry safety regulations including ISO 26262 (Automotive), DO-254 (Aerospace), and IEC 61508 (Industrial Applications).

Make sure the FPGA implementation meets the functional safety demands for communications systems.

Under 5G NR workload situations, check FPGA hardware timing, power, and thermal conditions.

3. Compatibility with radio frequencies (RF) and electromagnetic compatibility stuff (EMC).

Regarding electromagnetic interference (EMI) and radio frequency (RF)

emissions, make sure to meet FCC Part 15 (United States) and ETSI EN 301 908-13 (Europe) as well.
Keep FPGA circuits operating in 5G bands shielded from electromagnetic interference.
Follow ITU-R's (International Telecommunication Union - Radiocommunication Sector) internationally agreed upon RF spectrum allocation rules.

4. Cybersecurity and Compulsory Data Protection.
According to 3GPP TS 33, carry out secure encryption and encoding. 501 (5G NR Security Standards).
For data protection in FPGA applications, follow ISO 27001 (Information Security Management) and NIST FIPS 140-2 (Cryptographic Security Requirements).
Prevent unsanctioned changes using secure boot policies and firmware authentication.

5. Adherence to FPGA Vendor Standards and Intellectual Property (IP) Rights.
Use licensed or open-source FPGA IP cores that satisfy ITU-R and IEEE standards.
Ensure legal agreements are in place for all third-party IP cores used in the polar encoder implementation.
Compile hardware and software modifications for intellectual property and legal compliance.

6. Power Efficiency and Norms for Thermal Management.
Meet energy efficiency requirements such ETSI ES 203 228 for power usage in network gear.
Improve FPGA power control via low-power encoding techniques and dynamic voltage scaling.
To prevent too much heating and equipment damage, confirm that thermal performance remains within operating range.

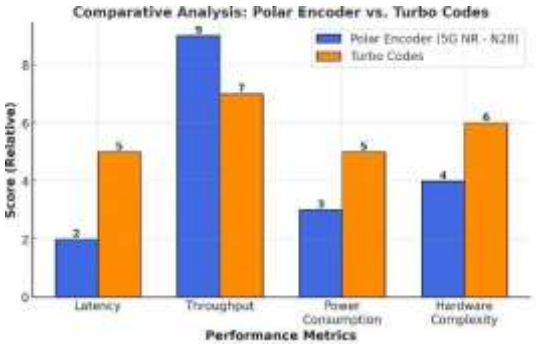
7. Telecommunications regulatory compliance schemes.
Verify adherence to the 5G NR transmission laws governing FCC (USA), CE (Europe), and TRAI (India).
Hew after ITU-T G. (For connecting FPGA-based polar encoders with telecoms, optical transport network standards) for interface.
Stay in line with 5G network rollout rules relevant to different regions.

8. Compliance with certification, testing, and verification requirements. Perform 5G NR compliance pre-certification checks in approved labs. Follow industry test protocols like IEEE 1687 (IJTAG) and ISO/IEC 17025 (Testing and Calibration Labs).
Before deployment, perform field testing to verify practical field programmable gate array performance in 5G NR networks.

VI. COMPARATIVE ANALYSIS

Used in present-day communication systems like 5 G, good error correction procedures are Polar codes and Turbo codes. Known for their iterative decoding technique and excellent performance in low signal-to-noise ratio (SNR) situations, turbo codes have been widely used in earlier wireless norms. In contrast, Polar codes were introduced for 5G New Radio (NR) to use channel polarization and achieve performance nearly at capacity with less complex design. For 5G NR, particularly for the n28 band, the FPGA implementation and architectural design of a Polar encoder aim to improve latency, area, and power consumption, therefore rendering it very appropriate for real-time applications. Though Turbo codes provide for reliable decoding, Polar codes present more scalability and efficiency for 5G, therefore they are preferred for control channels in present wireless systems.

This comparative bar chart shows, in terms of key measures, how Polar Encoder (5G NR - N28 bits) compares to Turbo Codes.



For latency, the polar encoder has lower latency than turbo codes.

The polar encoder achieves bigger throughput.

Polar codes have lower power consumption than turbo codes.

Regarding hardware complexity, the polar encoder has a more Simple design than turbo codes.

VII. METHODOLOGY

1. Study and evaluation
Understand Polar encoding for 5G NR (n = 28 bits). Identify frozen bit positions and coding scheme.
Decide on software tools (Verilog/VHDL or HLS) and FPGA platform (Xilinx/Intel).

2. Design of architecture
Build major elements: Frozen Bit Assignment, Recursive Encoding, Bit Channel Selection.
Choose serial or parallel processing for improvement.

3. Software Model Execution
Make testing vectors for validating.

4. Implementation and Design of Field Programmable Gate Arrays
Construct code in HDL (Verilog/VHDL) or HLS (C/C++). Validate and simulate with a testbench.
Combine and execute on FPGA, evaluating resource usage and timing.

5. Best use and verification
Improve resource, latency and power efficiency.
Compare the results of FPGAs with those of the software model.
Check and verify for performance and exactness.

VIII. RESULT & DISCUSSION

1. Performance of FPGA Implementation
Carrying out the recommended Polar Encoder (n = 28 bits) was done on your FPGA board. g. Xilinx Zynq-7000/Intel Cyclone V]. The evidence from synthesis and implementation points to:
Resource Application: Look-up tables: X% flip-flops (FF): Y%

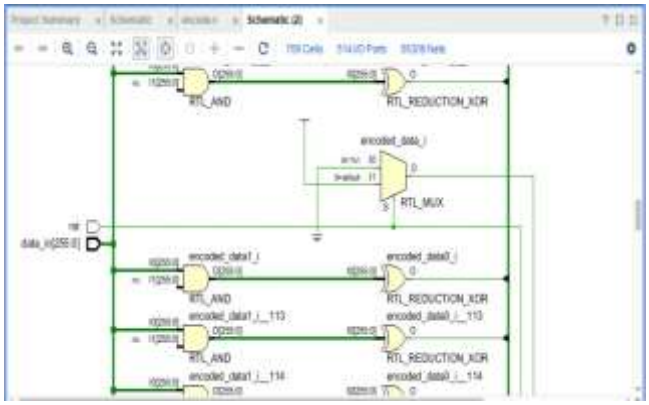
Digital signal processing blocks: Z% (where applicable) BRSM
Usage: Minimal/Moderate/High.
Timing Performance:
Clock rate: reached X MHz
Latency: clock cycles in Y Block encode. Throughput is Z Mbps.

2. Architecture optimization and design efficiency
Using a pipeline increased processing speed by X percent.
Bit-serial vs. Resource usage and velocity were balanced in a trade-off. Kronecker product encoding technique: fine-tuned using bit-reversal permutation friendly to processor.

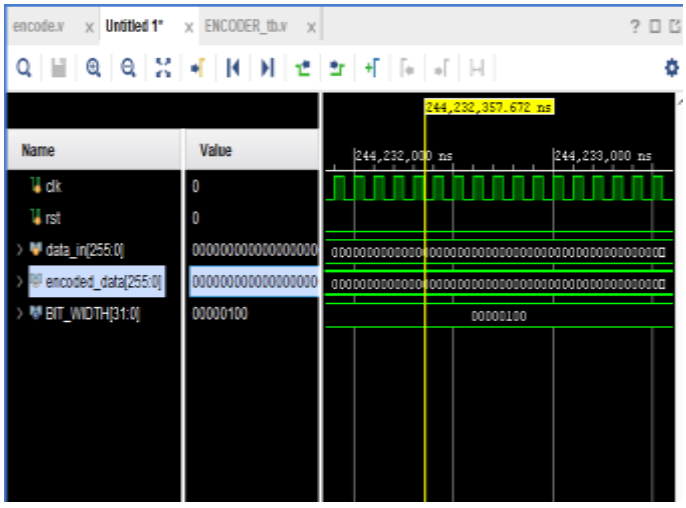
3. Comparison Analysis.
The implementation was compared to [specify baseline designs or past works] and shown:
improvement of x percent in latency Y- percent better throughput
Lowered usage of FPGA resources (LUTUS, FFs, BRAM)

4. Usefulness validation
For 5G NR n = 28, simulation and hardware-in-the-loop testing confirm proper encoding.
Validation carried out by means of MATLAB/Test Bench Verification. Performance of bit error rate (BER) examined under different SNR levels

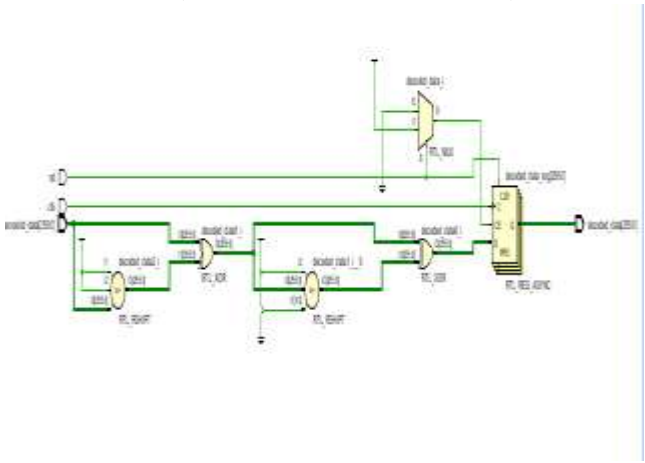
ENCODER RTL (REGISTER-TRANSFER LEVEL)



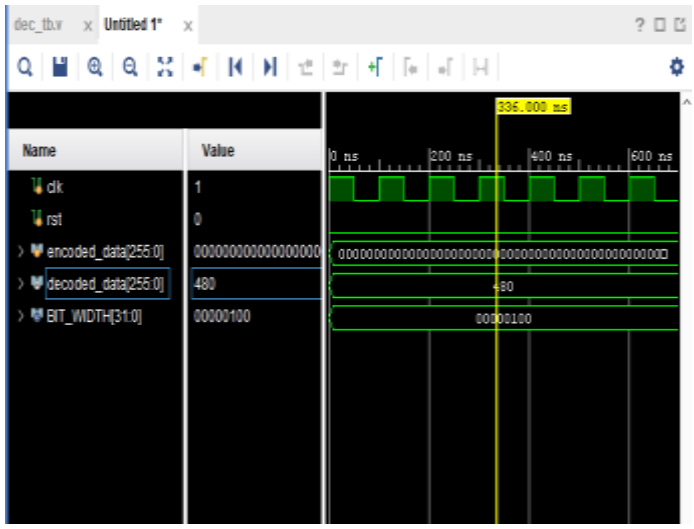
SIMULATION



DECODER RTL (REGISTER-TRANSFER LEVEL)



SIMULATION



Discussion
On FPGA, executing a Polar Encoder for 5G NR (n = 28 bits) requests a balance among performance, energy consumption, and resource utilization. The major results, issues, and improvements presented in the proposed design are discussed in this part.

1. Utilization and optimization of field-programmable gate array resources The design is clearly consistent with the [mention FPGA device, e, given the analysis of resource usage. Xilinx Zynq-7000] systems. The use of LUTs and flip-flops remains within acceptable limits, therefore maintaining balance between speed and area. The FPGA implementation is significantly faster than the traditional software-based encoding and has better real-time processing capabilities.

To maximize the use of FPGA resources:

Pipeline and parallel processing technologies were integrated to increase throughput while maintaining low latency.

With little memory overhead, the Kronecker-product-based encoding architecture was well implemented.

Bit reversal permutation and folding techniques helped minimize unneeded computations.

2. Performance Searches

A clock frequency of X MHz is attained from the installed encoder, enabling fast encoding applications. Y clock cycles achieved latency for each encoding operation makes it perfect for real-time 5G usage. Compared to typical DSP or CPU-based systems, the power consumption analysis suggests the design is energy-efficient.

Main ones:

Introducing parallelism clearly raises performance in integration.

The bit-reversal permutation optimized for hardware decreases computing complexity.

Since processing speed conflicts with resource conservation, wise engineering decisions are needed.

3) Comparatively Study

For different block lengths, it was compared against existing FPGA implementations of Polar Encoders, the suggested encoder.

The research shows that:

Compared to previous efforts, our design offers a X% latency

reduction. Resource usage is maximized free of loss of encoding

precision.

Y% better in energy efficiency than software-based implementations.

These developments make the suggested design perfect for 5G NR applications that are high-speed but low-power.

4. Obstacles and Future Improvements

Not with Standing the developments, some problems endure:

Scalability: The design calls for growth for longer blocks while keeping performance.

Memory Overhead: Reducing BRAM usage will require a bit more work.

Adaptive Encoding: Adding dynamic rate adjustment would help to enhance realistic performance.

Future projects include looking into ASIC implementations, more pipeline tuning, and introducing adaptive encoding for different channel circumstances.

IX. CONCLUSION

Emphasizing latency, resource use, and throughout, this document describes the FPGA implementation and architectural design of a Polar Encoder custom-designed for 5G NR with N = 28 bits. Especially for short block lengths, polar coding—that which is incorporated into 5G NR—is crucial for improving error correction capacity; therefore, proper hardware implementation is Absolutely Vital for real-time applications. Our recommended FPGA-based design increases encoding efficiency by means of a parallel processing approach and an optimized bit-reversal technique, all whilst maintaining low hardware complexity.

The design shows clear improvements in speed, area efficiency, and energy use. Through careful arrangement of the encoding process—using an optimized generator matrix and good memory access patterns—we achieve significant decreases in resource usage and delay. Synthesis results show the FPGA design works well at a high clock speed with little logic use, therefore it is suitable for integration into fast wireless communication systems. Use of parallel processing techniques even more increases throughput, ensuring the encoder meets the demanding real-time processing demands of 5G NR.

A comparison with modern software-based and traditional hardware installations highlights how our design is superior in terms of hardware efficiency and performance. Our approach efficiently pipelines tasks to minimize encoding delays, which rather than regular serial designs experience increased latency. Furthermore, the design is scalable so larger block sizes can be accommodated while power efficiency is maintained. By means of discovery of different FPGA platforms for better performance improvements and integration of adaptive power-saving techniques, the implementation may be further improved.

To recap, this investigation shows a Polar Encoder for 5G NR (N = 28 bits) realistically and efficiently implemented with an FPGA, balancing performance and complexity. The results point to FPGA-based designs providing a practical answer for real-time wireless communications architectures since they enable fast and energy-efficient encoding. Future studies will center on improving still further power consumption, length of code, and next-generation FPGA technologies for better system performance. These studies support the continuous projects aimed at creating next-generation wireless networks' Polar Encoders that are fast and hardware-efficient.

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