

Performance Evaluation of Modern Error Correcting Codes

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Abstract— Modern channel codes help to correct errors that occur due to noise in the channel, improving the effective data throughput without requiring higher transmission power. Modern codes optimize the use of bandwidth, allowing more data to be transmitted efficiently at lower power levels.

With advanced coding, systems can operate effectively at lower E_b/N_0 , reducing the need for high transmit power. This paper introduces various modern channel codes that are near Shannon channel capacity. The need of modern channel codes and how the modern channel code improves the performance of communication systems without increasing the power are explained. The encoder design and BER performance of various modern channel codes such as Turbo code, Polar code, and LDPC code are presented. The comparative performance evaluation of Turbo, Polar, and LDPC code with different block lengths and coding rates is presented.

Index Terms—LDPC-Low Density Parity check code, SNR- Signal to Noise ratio, BER-Bit Error Rate, 5G- Fifth Generation cellular network technology, 4G- Forth Generation cellular network technology.

I. INTRODUCTION

Improve communication system performance by increasing the signal-to-noise ratio (SNR) using the energy per bit to noise power spectral density ratio (E_b/N_0). E_b/N_0 is a key parameter that measures the efficiency of a communication system by comparing the energy used per transmitted bit to the noise level in the channel [1]. Increasing E_b/N_0 directly by boosting transmission power is one way to improve signal quality and minimize error rate [2].

However, this approach is often impractical due to power constraints, battery life in mobile devices, regulatory limits on transmission power, and potential interference with other communication systems.

There are certain challenges to increasing power.

In many practical scenarios, increasing the transmit power isn't feasible because of energy limitations, particularly in mobile or IoT devices that rely on batteries. Higher power levels can cause interference with neighboring channels, degrading the performance of other users or systems.

Also, high-power systems may require more expensive equipment and higher operational costs, especially for large-scale networks. Instead of increasing power, modern channel coding techniques allow more efficient use of the available power and bandwidth, improving the effective E_b/N_0 without increasing the actual transmission power. LDPC codes are widely used in modern systems (e.g., Wi-Fi, 5G, satellite communications) to approach the Shannon limit, which is the theoretical maximum efficiency of a communication system.

To improve communication system performance when increasing power isn't feasible, modern channel coding techniques like LDPC, Turbo codes, and Polar codes can be used to enhance reliability and spectral efficiency, allowing for better performance at lower power levels and reduced interference.

Turbo Codes are used in systems like 3G and 4G LTE [3], known for their near-optimal performance at low E_b/N_0 ratios. Polar Codes are recently adopted in 5G, polar codes are highly efficient and can achieve reliable communication close to theoretical limits, even at low SNR. Reed-Solomon and Convolutional Codes have been used historically and still find application in systems that require error correction and improved reliability.

II. MODERN ERROR-CORRECTING CODES

Modern error-correcting codes have evolved to meet the demands of advanced communication systems, offering greater efficiency, performance, and flexibility compared to classical codes like Hamming, Reed-Solomon, and convolutional codes. These modern codes are designed to approach the theoretical limits of channel capacity and are used in various high-speed data transmission systems, including wireless communication (e.g., 4G, 5G), satellite communications, deep space missions, and storage devices. Modern error-correcting codes like LDPC [4], Turbo [5], and Polar codes [8] have significantly improved the reliability and efficiency of communication systems by approaching the theoretical limits of error correction. Each code type is optimized for different applications, with varying trade-offs in terms of complexity, latency, and error-correction performance. The choice of code depends on the specific requirements of the communication system, such as bandwidth, latency, error rates, and computational resources.

A. LDPC code

A family of linear block codes with a large code word length, often measured in millions of bits, are called Low-Density Parity Check Codes (LDPC) [4]. The LDPC codes belong to a class of capacity-approaching block codes. Robert Gallager was the first to propose LDPC coding. However, until Turbo codes, which are utilized in wireless communication systems, were introduced, these codes were not extensively researched. The channel capacity is nearly reached by the performance of LDPC codes, also known as Gallager codes [4]. LDPC codes were rediscovered in 1996 and continued to accumulate interest. LDPC codes are built on the principle of sparse parity check matrix. A sparse parity check matrix, H , is a characteristic of LDPC codes. If at least half of the elements in a matrix are zero, the matrix is said to be sparse. The low density of 1's in the parity check matrix of LDPC codes is referred to as "low density." The LDPC encode as shown in figure 1

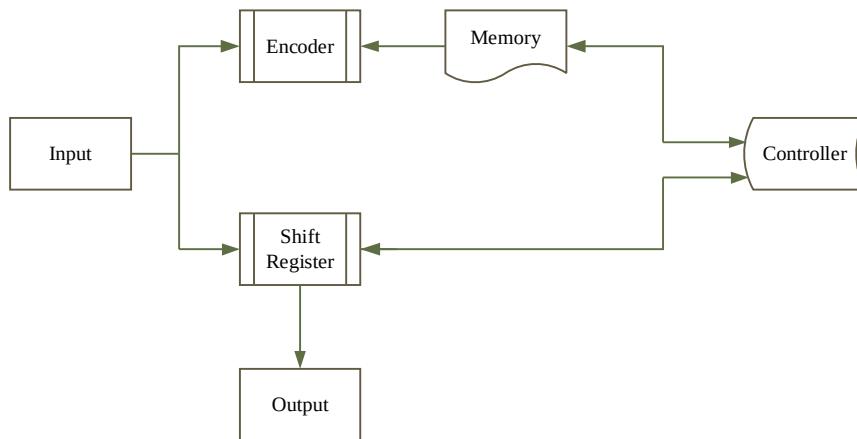


Figure 1. Blocks diagram of typical LDPC encoder

B. Polar code

Arıkan invented polar codes, one of the most modern kinds of popular codes, in 2008[8]. The channel polarization transform is used in their construction. They are the first functional codes that have been designed to

achieve the channel capacity at an indefinite length code, in addition to their excellent performance. Arıkan additionally demonstrated that the complexity of encoding and decoding a polar code of length N is $N \log N$. The Generator matrix, which is derived from the polarization transform, is used for encoding, and the Successive Cancellation (SC) method can be used for decoding.

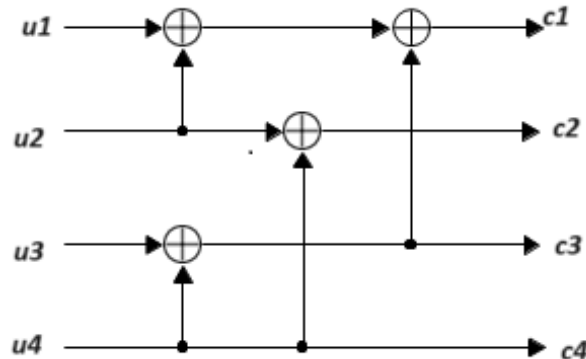


Figure 2. Polar Encoder of length 4

The polar encoder of length 4 as shown in figure 2. The BER performance of polar codes depends on the code rate, block length, decoding algorithm, and channel conditions. Polar codes leverage "channel polarization," splitting the channel into reliable and unreliable bit channels. Information is sent over the reliable channels, while frozen (fixed) bits are assigned to the unreliable channels. Depending on the channel characteristics E_b/N_0 , Frozen, and unfrozen bits are selected based on reliability metrics like Bhattacharyya parameters or mutual information.

C. Turbo code

Turbo codes were implemented in 1993 by C. Berrou [5]. They belong to a group of codes that have near-Shannon channel capacity performance. Two recursive convolutional encoders are used in the standard type of turbo encoding as shown in figure 3.

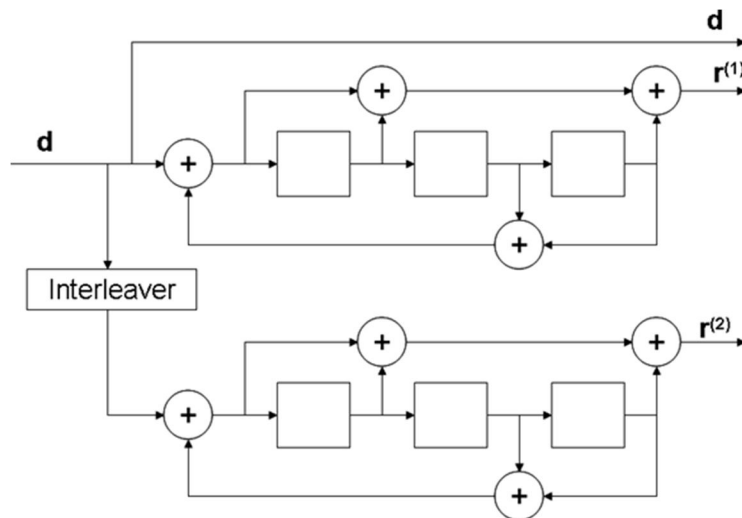


Figure 3. Structure of a Turbo code Encoder

The first encoder receives the input stream, while the second encoder receives a permuted or interleaved version of the input bit stream. Two decoders are employed at the receiving end, each of which decodes the streams of the matching encoder. Like a turbo engine, the two decoders can assist each other iteratively by exchanging probabilistic information of bit values. Turbo codes [6][7] find the application in high-speed data transmission over wireless channels. Popular Turbo codes are used in 4G standards. The Bit Error Rate (BER) performance of Turbo codes as a function of E_b/N_0 is an important metric to evaluate the error-correcting capability of the code under different channel conditions.

Turbo codes are designed to perform close to the Shannon limit, making them highly efficient for noisy communication channels. At low E_b/N_0 , Turbo codes still perform well, though the BER is higher. At higher E_b/N_0 , BER decreases exponentially due to effective error correction. Turbo codes approach Shannon limit theoretical boundary of channel capacity.

III. COMPARISON OF ERROR-CORRECTING CODES

LDPC, Turbo, and Polar codes are the powerful error-correcting codes used in modern communication systems [10]. Each has its strengths and weaknesses depending on the application and performance criteria. The BER performance of LDPC, Turbo, and Polar code are considered for comparison purposes. The simulation parameters for the BER performance evaluation of all three codes are explained in Table 1. For the simulation random binary data bits 1024 are generated and encoded the data using LDPC, Turbo, and Polar codes. Map the encoded bits to symbols using the chosen modulation scheme QPSK. The modulated symbols bit passes through an AWGN channel. At the receiver end, decode the received noisy symbols using the corresponding decoding algorithm. Compare the decoded bits with the original data bits to calculate BER. Perform the simulation for different E_b/N_0 values and compute the BER for each E_b/N_0 .

TABLE I: SIMULATION PARAMETERS FOR BER PERFORMANCE OF LDPC, TURBO & POLAR CODES

Sr. No.	Simulation Parameters	
1.	Modulation Scheme	QPSK
2.	Code Rate	$R=1/2$
3.	Block Length	$N=1024$
4.	Decoder Algorithm	LDPC: Min-Sum decoding. Turbo: Log-MAP or Max-Log-MAP decoding. Polar: Successive Cancellation (SC) decoding.
5.	E_b/N_0 Range	0 to 10 dB
6.	Channel noise	AWGN
6.	Simulation Tool	Python
7.	Simulation Time	15 min

To compare the E_b/N_0 vs. BER (Bit Error Rate) performance of LDPC, Turbo, and Polar codes, you typically simulate the transmission of data over a noisy communication channel (e.g., AWGN) using each coding scheme. The performance metrics are as follows:

- Convergence Rate: How quickly the BER drops with increasing E_b/N_0 .
- Error Floor: The BER level below which further improvement is challenging.
- Complexity: Computational cost of encoding/decoding.

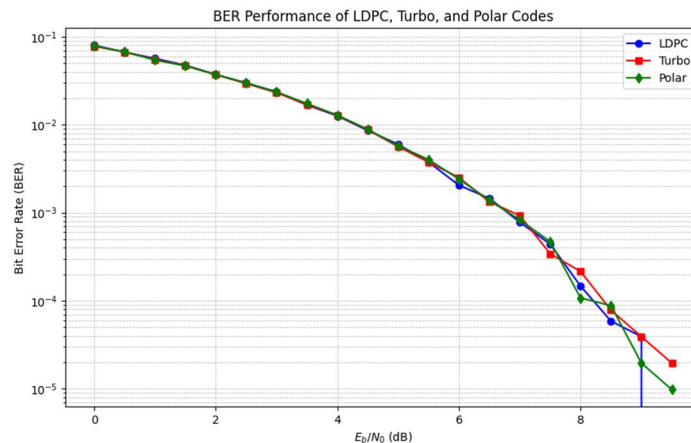


Figure 4. Variation in BER as a function of E_b/N_0 for LDPC, Turbo, and Polar codes with $N=1024$ and QPSK modulation

The graphs shown in Figure 4 are the comparative BER performance for LDPC, Turbo, and Polar code which shows that LDPC codes have good performance near the Shannon limit with moderate complexity and the error floor can occur at high E_b/N_0 . In the case of Turbo code, excellent performance at low E_b/N_0 with high decoding complexity due to iterative decoding and error floor at high E_b/N_0 . While Polar codes, have superior performance with SCL decoding at high block lengths with lower complexity compared to Turbo and LDPC for smaller block

lengths and are sensitive to code construction and decoding algorithms. The detailed comparison of various codes for future-generation technology are shown in Table 2 [9].

LDPC codes are a cornerstone for future-generation mobile communication systems, enabling high-speed, reliable, and efficient data transmission. Their flexibility, scalability, and superior error-correcting capabilities make them indispensable for meeting the diverse requirements of 6G and beyond, including eMBB, URLLC, and mMTC. Continued advancements in LDPC design, such as AI-driven decoding and hybrid error correction, will further strengthen their role in future networks. LDPC codes dominate eMBB in 5G [11], future networks may use a combination of error-correcting codes tailored to specific use cases.

TABLE II: PERFORMANCE OF VARIOUS MODERN CHANNEL CODES FOR FUTURE-GENERATION MOBILE TECHNOLOGY

Feature	LDPC Codes	Polar Codes	Turbo Codes
Performance	Excellent, close to Shannon's limit[12].	Excellent, particularly with long block lengths.	Very good especially at low SNR.
Algorithm	Belief Propagation, Min-Sum.	Successive Cancellation (SC), SCL.	Log-MAP, Max-Log-MAP.
Decoding Complexity	Low to moderate (iterative algorithms).	Low for SC decoding; high for SCL decoding.	High (iterative decoding).
Latency	Very Low	Low	Moderate
Error Floor	Can exhibit an error floor at high SNRs.	Low error floor with successive cancellation list (SCL) decoding.	More prone to error floors than LDPC.
Block Length	Performs well across a wide range.	Superior performance at very long block lengths.	Best at moderate block lengths.
Iterations	Iterative decoding with configurable iterations.	Iterative decoding with high complexity.	SC is non-iterative; SCL has a fixed list size.
Hardware Efficiency	High	Very High	Moderate
Flexibility	Highly flexible and supports variable rates and lengths.	Less flexible and requires a specific design for rates.	Flexible with rate-matching techniques.
Advantages	High performance, widely adopted, scalable.	Capacity-achieving, simple structure, scalable.	Good performance at low SNR, proven technology.
Disadvantages	Requires careful design to avoid error floors.	Sensitive to block length and decoding algorithm.	High decoding complexity, error floors.
Applications	eMBB, mMTC	URLLC	Legacy systems

IV. CONCLUSIONS

Modern channel codes continue to evolve, driven by the increasing demand for reliable, high-speed, and low-latency communication systems. These advancements not only support current technologies but also pave the way for innovations in next-generation communication and computing systems. Modern channel codes are a critical component of communication systems, designed to improve the reliability of data transmission over noisy channels. These codes ensure that information can be transmitted with minimal errors, even in challenging conditions. This paper introduces various modern channel codes which are near Shannon channel capacity. The need of modern channel codes and how the modern channel code improve the performance of communication systems without increasing the power are explained. The encoder design and BER performance of various modern channel codes such as Turbo code, Polar code, and LDPC code are presented. The comparison of Turbo, Polar, and LDPC code with different block lengths and coding rates is presented. Low-density parity-check (LDPC) codes are widely used in error correction due to their near-optimal and fast performance

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