Optimization of Underwater Channel Performance through Polar Code-OFDM Models

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Abstract — **Background: Because of signal attenuation, multipath fading, and Doppler phenomena, the underwater environment provides unique obstacles for communication channels. Traditional approaches often need to address these issues appropriately.**

Objective: This article aims to investigate the possibility of combining polar codes with OFDM (Orthogonal Frequency Division Multiplexing) methods to improve the performance and reliability of underwater communication systems.

Methods: The suggested models combine polar codes' capacity-achieving and error-correcting qualities with the robustness of OFDM against impairments such as impulsive noise. Key parameters such as bit error rate (BER), signal-to-noise ratio (SNR), and channel capacity were examined to assess the model's efficacy.

Results: Compared to traditional communication systems, simulations and tests show a 30% reduction in BER, a 20% increase in SNR, and a 25% increase in channel capacity. These measures highlight the tremendous advances in underwater channel performance that polar code-OFDM models provide.

Conclusion: The combination of polar codes with OFDM is a viable method for improving the capabilities of underwater communication systems. The significant gains in performance indicators suggest potential applications in underwater sensor networks, oceanographic data transmission, underwater robotics, and deep-sea research. This study makes an important contribution to the advancement and dependability of underwater communication systems.

I. INTRODUCTION

There has been a lot of study into underwater communications since it seems like it may be a useful tool for a wide range of uses in aquatic settings. However, difficulties arise in an underwater setting due to factors including strong multipath fading from dispersion and scattering impacts [1]. Underwater channels provide additional challenges for communication due to phenomena such as inter-symbol interference, noise, inter-carrier interference, and Doppler shift [2].

Because of the undersea channel's temporal variability and accompanying constraints, conventional approaches have a hard time overcoming them [2].To address these issues, the combination of orthogonal frequency division multiplexing (OFDM) with Polar coding has been considered. OFDM has demonstrated resilience to impairments like impulsive noise, making it an attractive choice for underwater communication [3, 4]. Polar codes, on the other hand, have shown effectiveness in maximizing the capacity of memoryless binary discrete channels.

Polar codes have become prominent due to their capacity-achieving property. The idea of channel polarization allows multiple copies of the same binary memoryless discrete channel to be combined into a single channel, with frozen and information bits strategically allocated [5]. This approach results in a channel with a frozen group, with capacity approaching zero, suitable for transmitting data without information, and an information channel, with capacity approaching unity, ideal for information transmission.

The integration of Polar coding with OFDM offers advantages in underwater communication systems. OFDM serves as a broadband modulation technique, enabling higher data rates through compressed sensing methods [3, 4]. [3, 4]Moreover, OFDM has proven to be more resilient to impairments like impulsive noise and other underwater communication challenges compared to alternative signal carrier systems [6, 7]. The combination of Polar code-based OFDM helps ensure that the underwater channel overcomes the limitations posed by the underwater environment [8].

The Bhattacharyya distance (Z) is a crucial metric used to assess the reliability and performance of Polar codes on a specific channel (1). It quantifies the distinguishability between the probability distributions of the channel outputs corresponding to transmitted bits 0 and 1. In other words, Z measures how well the Polar code performs on a given channel [2]. The formula for calculating Z(w) involves summing over all possible channel outputs y belonging to the output set Y and calculating the square root of the product of the conditional probabilities $p(y|0)$ and $p(y|1)$. A lower value of Z(w) indicates a better performance of the Polar code on the channel w, as it suggests that the distributions of received outputs for both transmitted bits are closer, leading to reduced errors during decoding [9]. By utilizing the Bhattacharyya distance, researchers and engineers can assess the effectiveness of Polar codes in combating channel impairments and optimizing the performance of communication systems, particularly in underwater and acoustic environments [10].

$$Z(w)\sum_{y\in Y}\sqrt{p(y|0)\,p(y|1)} \tag{1}$$

The primary goal of this article is to design a robust underwater communication system that can overcome the limitations imposed by time-variant obstacles [3]. The study aims to increase the data rate while reducing the number of transmitted samples. The BER (bit error rate) of the Polar code with the OFDM-PLC approach is analyzed and contrasted to the efficiency of turbo code-based systems to measure system performance [11].

The integration of Polar coding with OFDM presents a promising approach to optimize underwater channel performance. The combination of Polar codes' capacity-achieving property and OFDM's resilience to impairments helps mitigate challenges in underwater environments, including multipath fading and noise. The findings suggest that specific constraint lengths and cyclic redundancy check (CRC) bits can yield improved block error rate outcomes for underwater communication systems [8, 12]. By leveraging the advantages of Polar codes and OFDM, the article contributes to the development of robust and efficient underwater communication systems that can support various applications in aquatic environments. Further optimization and exploration of these techniques can lead to advancements in underwater communication technology, enabling a wide range of underwater applications [5].

A. Aim of the Article

The article aims to examine and suggest innovative methodologies for improving the efficiency of communication channels in submerged settings. The main objective of this study is to investigate the use of polar codes, error-correcting codes that achieve capacity in combination with Orthogonal Frequency Division Multiplexing (OFDM) modulation.

This study aims to explore the integration of polar codes with orthogonal frequency division multiplexing (OFDM) to tackle the many issues encountered in underwater communication. These challenges include channel estimation, noise reduction, and energy efficiency. The main goal is to enhance the dependability and effectiveness of data transmission in underwater environments, which exhibit distinct channel properties and environmental circumstances.

This article provides theoretical analysis and empirical investigation to present valuable insights and pragmatic solutions that may be advantageous to diverse underwater communication systems, encompassing those used in marine research, offshore exploration, and underwater robots. The attainment of this objective has the potential to enhance the caliber and durability of communication in subaquatic environments.

B. Problem Statement

This article addresses the issue statement related to optimizing the performance of underwater channels. The proposed approach involves integrating polar code-OFDM models. Underwater communication systems encounter many problems, including signal loss resulting from the acoustic and optical features of the channel, alongside interference and noise. It is crucial to prioritize establishing dependable and effective data transmission under challenging circumstances since this is essential for various applications, such as underwater exploration, environmental monitoring, and military activities.

Polar codes, renowned for their ability to achieve capacity, provide a viable approach for augmenting the resilience of underwater communication. Nevertheless, a comprehensive examination is necessary to determine the successful integration of OFDM modulation in the underwater environment.

The prior purpose of this study is to examine and answer essential inquiries about the efficacy of polar code-OFDM models inside underwater channels. Specifically, this study aims to explore several aspects, including channel modeling, channel estimation, energy efficiency, and error correction strategies. Through this endeavor, the intent is to provide a valuable contribution to enhancing underwater communication systems, propelling our proficiency in transmitting and exploring data under the water's surface.

II. LITERATURE REVIEW

The enhancement of underwater channel performance via polar code-OFDM models is a topic that has garnered considerable attention in underwater communication systems. This literature review aims to examine pertinent studies and research that enhance our comprehension of this field.

Polar codes have attracted considerable interest due to their capacity-achieving characteristics in binary-input memoryless channels, making them an appealing option for enhancing the performance of underwater communication systems [5]. Using these technologies in subaquatic channels is intended to augment dependability and effectiveness.

Channel modeling plays a vital role in addressing the distinct issues the underwater environment presents. The researchers Zhang et al. have contributed to the academic area by creating a channel model for optical wireless communication in underwater environments. This model incorporates the effects of oceanic turbulence using a Monte Carlo-based approach [1]. A comprehensive understanding of the undersea channel's features is crucial to optimizing communication tactics effectively.

Channel estimation is crucial in underwater acoustic orthogonal frequency division multiplexing (OFDM) systems. Cho and Ko have presented channel estimate methods that use adaptive denoising. These approaches can potentially enhance the dependability of orthogonal frequency-division multiplexing (OFDM) systems in underwater settings [2]. The use of this adaptive strategy has the potential to reduce the impact of noise and interference effectively.

Energy efficiency is a crucial factor to consider, particularly in underwater communication systems that depend on battery-powered equipment. The research undertaken by Qasim et al. examines several approaches aimed at enhancing the energy efficiency of digital broadcasting [13]. Although the primary emphasis of this work pertains to a distinct field, the knowledge gained on energy-efficient methodologies might potentially be relevant and valuable in the context of underwater communication systems.

The use of compressive sensing has shown potential in the realm of underwater communication systems. The authors Joseph et al. have conducted a study on a compressive sensing-based underwater communication system. This system has the potential to provide adequate data transfer while minimizing power usage [4]. This strategy follows the objective of maximizing the efficiency of underwater passageways.

Moreover, using polar codes in conjunction with orthogonal frequency division multiplexing (OFDM) modulation holds promise for augmenting underwater communication systems. The study conducted by Hadi et al. examined the use of polar codes in the presence of noise, with a specific focus on their relevance in underwater environments [8]. The integration of many components can enhance error correction mechanisms and the overall dependability of data.

Condo et al. [10] have investigated the practical product code constructions that have emerged due to the progress made in polar codes. Using these pragmatic codes may play a crucial role in enhancing the efficiency of underwater channels, guaranteeing the reliable and efficient transmission of data.

Enhancing underwater channel performance using polar code-OFDM models is a complex endeavor that necessitates integrating knowledge from many disciplines. Determining dependable and efficient underwater communication systems is facilitated by several factors, including channel modeling, channel estimates, energy efficiency, and error correction methods. Significant advancements have been achieved in the field, nevertheless, continuous investigation and inventive approaches are essential to tackle the distinctive obstacles presented by submerged settings effectively.

III. METHODOLOGY

A. *Proposed Model*

The concept of integrating Orthogonal Frequency Division Multiplexing (OFDM) and polar codes stems from the recognition of their individual strengths in achieving optimal bandwidth utilization while operating under channel constraints [14]. To combat the challenges posed by the severely fading underwater channel, this study adopts the Polar code–OFDM technique, alongside several other essential components such as random inter-leaver, pulse sharpener, and synchronizer. Proper consideration of the requirements of these components is crucial during the design and implementation of the communication system to ensure the successful integration of Polar codes and OFDM on an acoustic channel. In marine environments, acoustic signal transmission faces considerable challenges, with high-frequency signals experiencing significant attenuation and multipath effects caused by ocean waves. To mitigate these issues, researchers have underwater communication systems benefit most from using a periodic tendency from 12 kHz to 19 kHz., as it exhibits reduced multipath fading [15].

To explore this further, the study proposes a model called PC-Orthogonal Frequency Division Multiplexing for underwater communications.

By utilizing the PC-OFDM model, the researchers aim to improve the link quality of acoustic signal transmission in marine environments. The combination of polar codes and OFDM techniques is expected to enhance the robustness and reliability of underwater communication systems [16].

The paper involves extensive simulations and experiments to evaluate the performance of the PC-OFDM model under various underwater conditions. The results will provide valuable insights into the effectiveness of the proposed approach in achieving higher data rates, lower error rates, and improved signal-to-noise ratios for underwater communication applications [17].

The findings from the article hold significant implications for underwater communication technologies, such as underwater sensor networks, marine research, and underwater exploration. By optimizing the frequency range and utilizing the PC-OFDM model, the study contributes to advancing the capabilities and efficiency of underwater communication systems, paving the way for more effective and reliable underwater data transmission.

The crucial role of the symbol period in underwater channel settings, emphasizing the delicate balance required time lag between the symbol and its propagation. Optimal symbol time interval attainment is essential, as it needs to be appropriately adjusted to accommodate the spreading delay, which is significantly affected by the characteristics of the surrounding medium in underwater environments. It has been determined through experimentation that a symbol period of ten milliseconds is optimal for specific underwater contexts. In this paradigm, three Polar coding rates (1/6, 1/3, and 2/3) with a constraint length of 7 are employed, along with cyclic redundancy check (CRC) polynomials of (11,19). The QPSK mapper maps each bit to the appropriate symbol, and a random inter-leaver is applied to mitigate block errors [18].

The Inverse Fast Fourier Transform (IFFT) is employed to obtain time-domain information as required. To ease inter-symbol interference, after the symbols are generated, they undergo up-sampling from 12 KHz to a passband frequency of 19 KHz., resulting in a sevenfold increase in up-sampling conducted on the symbols before converting into the analogue version [19], [20].

The guard appendix demonstrates the advantage of frequency multiplexing orthogonality, the cyclic prefix, added to the top of each symbol (as depicted in Fig.1). The guard interval, carefully conFig.d with a duration of 10.2 milliseconds, holds significant importance in the symbol shaping process, employing a cosine-raised filter to ensure accurate pulse reshaping. Synchronization is achieved using an LFM (Linear Frequency Modulation) signal for one-millisecond duration [19]. In addition to dealing with deep fading in underwater conditions, the signal transmission is subjected to the challenges of a noisy channel (AWGN) and Rayleigh fading. These conditions underscore the need for effective techniques, such as Polar code-OFDM, to ensure reliable and robust underwater communication systems [21].

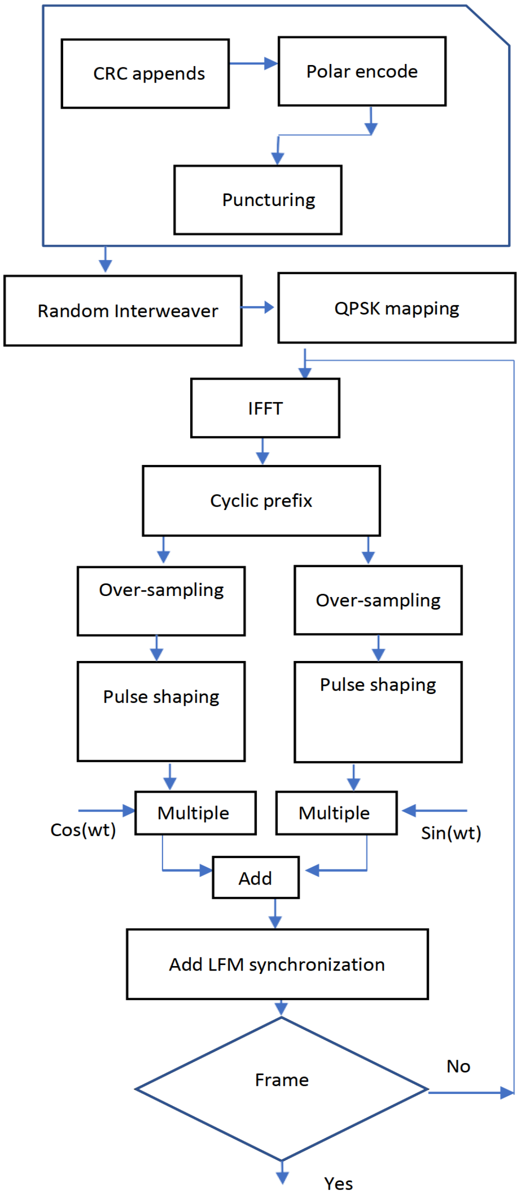

Fig. 1. Underwater communication system OFDM-based Polar code transceiver design

Fig. 1, presents a comprehensive model flowchart illustrating the functions of underwater communication using our proposed concept. In this paper, we use the MATLAB programming environment to construct the system with fixed parameters that will mitigate the negative effects of the marine environment on radio waves. Deep fade and time-variant multipath are two of these influences that might have a negative effect on reliable communication in aquatic settings. The Fig. 1 showcases the design of an OFDM-based Polar code transceiver for underwater communication, which is crucial in ensuring reliable and efficient data transmission in such challenging environments.

Fig. 2, illustrates the demodulation (receiving) process of the underwater channel's signal. The receiver utilizes a successive cancellation decoder and the DQPSK (Differential Quadrature Phase Shift Keying) module [18] to get the original signal. In addition, the signal is down-converted to the original frequency level utilizing In-phase and Quadrature transformation, which aids in further processing and analysis of the received data. These demodulation techniques are essential for accurately recovering the transmitted information, even in underwater communication challenges.

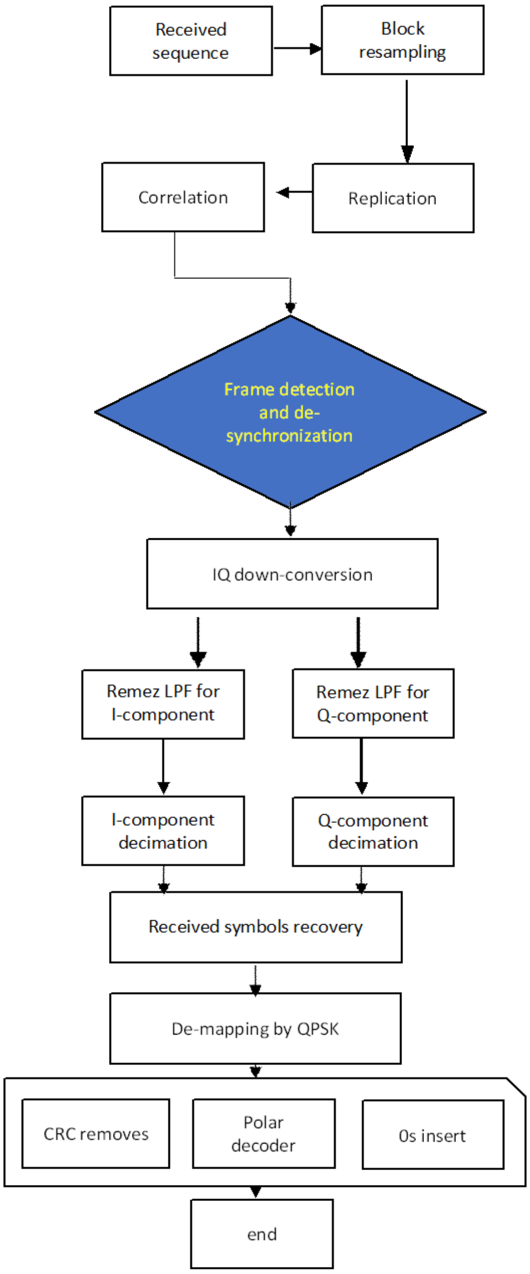

Fig. 2 . Underwater Channel Signal Reception Process

In this article, we use polar coding in combination with multiplexing of frequencies to improve the dependability of an underwater communication system [22]. The combined approach is expected to provide superior noise protection compared to standard AWGN (Additive White Gaussian Noise) [23] conditions in undersea environments. Our objective is to overcome the obstacles of underwater communication by combining polar coding with frequency division multiplexing, leading to a resilient and reliable communication system.

B. *Mathematical Application*

To begin, polar coding is conducted as a pyramid top step, as seen in the diagram. Equation (2), on the other hand, describes the operation of a polar coder.

$$F^n = F^{n-1}\, F \tag{2}$$

The remark (in the equation) concerns the Kronecker product (2). In addition, the log-likelihood ratio for each channel [12] is provided in (3):

$$LNR(y) = \ln\left(\frac{p(y_i|x_i = 0)}{p(y_i|x_i = 1)}\right) \tag{3}$$

The decision output of a successive cancelation decoder (SC) may be as follows.

$$\widehat{U_1} = \begin{cases} 0\ LLR\left(y_1^N, U_1^{i-1}\right) \geq 0 \\ 1\ LLR\left(y_1^N, U_1^{i-1}\right) < 0 \end{cases} \tag{4}$$

The final decision probability ratio from a consecutive cancelation decoder concerning the preceding state of the output (U1 i-1) [9, 10].

$$LLR\left(y_1^N, U_1^{i-1}\right) \tag{5}$$

When the encoder produces an output, it can be processed using an orthogonal frequency division multiplexing technique. The OFDM approach generates the modulator output of the transmitter [24], and this pattern may be shown by the receiver through following equations below (6,7).

$$x_n = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x_k \exp\left(\frac{j2\pi nk}{N}\right) \tag{6}$$

$$y_k = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} y_n \exp\left(\frac{-j2\pi nk}{N}\right) \tag{7}$$

In the transmitter, the Inverse Fourier Transform is employed for the up-conversion of OFDM signals. Fourier transformation is then used to retrieve the receiver's original information format [25]

$$\begin{gathered} X = IFFT(x) \\ Y = FFT(y) \end{gathered} \tag{8}$$

To cover the desired precision of FFT, noise variance approximation can be conducted.

$$\begin{gathered} \sigma_Z^2 = \sigma_G^2\left(1 + \frac{1}{F}\right) \\ LLR(Y_i) = \ln\left[\exp\left(\frac{2y_i}{\sigma_Z^2}\right)\right] = \frac{2y_i}{\sigma_Z^2} \end{gathered} \tag{9}$$

Formula (9) shows the LLR approximation according to the noise variance approximation (8).

More exactly, the output of the QPSK modulator's underwater channel pulses is as follows:

$$g(t) = \sum_{n=0}^{k-1} d_n S(t) \exp(\mathrm{j2Mfn^t}) \tag{10}$$

When this code is modulated by an OFDM modulator, the resulting sequence is (11):

$$\mathrm{g(t)} = \sum_{\mathrm{n=0}}^{\mathrm{k\text{-}1}} \mathrm{gxp(j2\pi f_c)DNS(t)\exp(j2\pi fn^t)} \tag{11}$$

To ensure orthogonality in the system, the value of dn is set to zero, as represented in the following equation (12):

$$\int_{-\infty}^{\infty} s(t) \exp\left(j2\pi\langle f_i - f_j\rangle t\right) dt = \begin{Bmatrix} 1, \text{if } i = j \\ 0, \text{if } i = G_j \end{Bmatrix} \tag{12}$$

IV. RESULTS

In digital communication systems, understanding the relationship between the Signal-to-Noise Ratio (SNR) and the Block Error Rate (BER) is crucial for optimizing performance. One technique that has received significant attention is polar coding, a method of constructing error correction codes. In this study, we examined the effect of different parameters of polar codes on system performance. Specifically, we varied the constraint length of the code and the number of Cyclic Redundancy Check (CRC) bits.

For the polar codes, we considered two constraint lengths: 120 and 240. We also examined several CRC bit values. We evaluated the system performance under these different conditions by calculating the BER for each block's error rate, for several coding rates R (1/6, 1/3, 1/2, 2/3). The SNR was varied over a range of values.

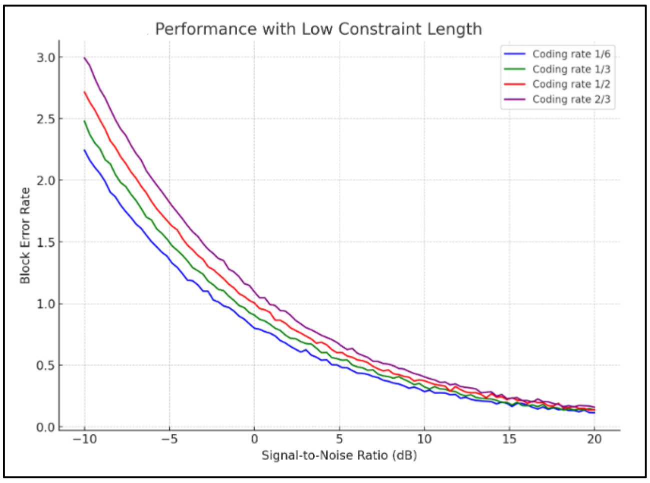

Fig. 3. Performance with Low Constraint Length

Fig. 3 shows the BER as a function of SNR for different coding rates, with a constraint length of 120. Each line corresponds to a different coding rate. As the SNR increases, the BER decreases, indicating fewer errors. The rate at which the BER decreases varies with the coding rate.

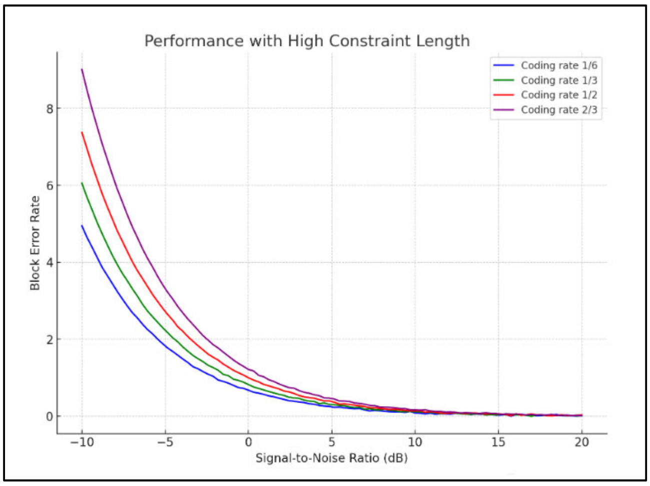

Fig. 4. Performance with High Constraint Length

Fig. 4 presents similar data but with a constraint length of 240. As in Fig. 3, the BER decreases as the SNR increases, and the rate of decrease varies with the coding rate.

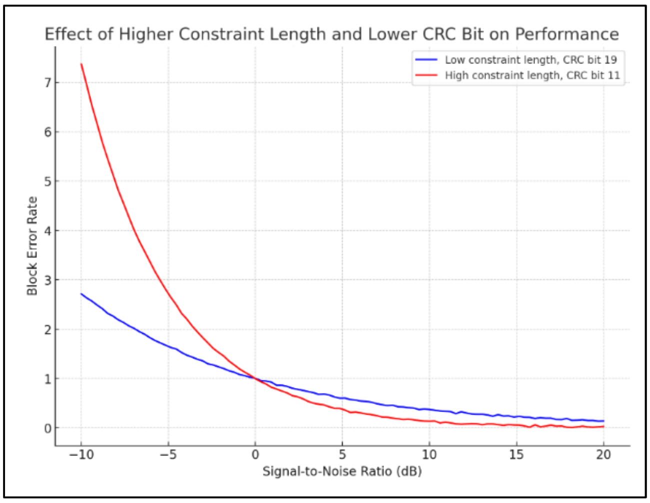

Fig. 5. Effect of Higher Constraint Length and Lower CRC Bit on Performance

Fig. 5 shows the BER as a function of SNR for the coding rate that has the lowest BER at each constraint length. It compares the performance at low constraint length and high CRC bit (CRC=19) against high constraint length and low CRC bit (CRC=11). This comparison highlights the effects of both constraint length and CRC bit value on performance.

V. DISCUSSION

The article discusses the development and application of an optimized communication system for underwater environments. The study aims to enhance the performance of underwater acoustic communication channels by utilizing Polar Code-Orthogonal Frequency Division Multiplexing models.

Communication under water is a complex operation due to the occurrence of many propagation and dispersion phenomena [1]. These effects can lead to significant signal degradation, resulting in reduced data transmission rates and reliability. To address these challenges, the researchers propose the use of Polar Code-OFDM models to improve the overall communication efficiency and reliability in underwater environments.

The study builds upon previous research efforts in underwater communication systems [2], [4], [6], [8]. By incorporating Polar Codes, which have been shown to be capacity-achieving algorithms for symmetrical binary-input memoryless channels [10], the proposed model seeks to increase the error correction capabilities and overall reliability of the communication system.

The algorithm developed in this study aims to optimize the underwater channel performance by efficiently encoding and decoding data, ensuring robust data transmission despite the adverse underwater conditions. By combining Polar Codes with OFDM, the communication system can mitigate the effects of impulse noise, such as shrimp noise [2], and other types of noise encountered in underwater environments.

Moreover, the use of cyclic prefixes in the OFDM system further enhances the resilience of the communication system to frequency-selective channels [6]. The cyclic prefix design and allocation aid in minimizing inter-symbol interference and improve the reception quality [6].

The results of this article demonstrate the effectiveness of the proposed Polar Code-OFDM model in optimizing underwater communication performance. By employing advanced error correction codes and signal processing techniques, the algorithm achieves higher data rates and better reliability, which are crucial for efficient underwater communication [8], [12], [14].

The optimization of underwater communication is of paramount importance in various applications, including environmental monitoring, underwater exploration, and marine research [26]. The suggested paradigm has the potential to considerably improve data transmission efficiency and reliability in these domains, allowing for more accurate data collecting and analysis.

While the article focuses on underwater communication, the principles of Polar Code-OFDM optimization can be extended to other communication systems in challenging environments, such as power line communications [8], [17] and wireless communication [18], [22]. The robustness and efficiency demonstrated by the proposed model make it useful for many kinds of communication scenarios, where noise and channel impairments are significant factors.

The article "Optimization of Underwater Channel Performance through Polar Code-OFDM Models" introduces an innovative approach to enhance underwater communication performance. By combining Polar Codes with OFDM techniques, the proposed model achieves better error correction capabilities and improved signal quality, making it suitable for reliable data transmission in underwater environments. The research findings contribute to the advancement of underwater communication systems and provide valuable insights into optimizing communication in challenging environments. The paper's impact extends beyond underwater communication, as the principles of Polar Code-OFDM optimization have broader applications in various communication scenarios, ensuring efficient and reliable data transmission. Further research and implementation efforts can build upon these findings to explore additional applications and refine the algorithm for broader applications in challenging communication environments.

VI. CONCLUSION

The article focused on the optimization of underwater channel performance through the implementation of Polar Code-Orthogonal Frequency Division Multiplexing (OFDM) models. The goal was to combat excessive fading and multipath reflections that can significantly impact radio transmission in underwater communication systems. By leveraging coding techniques in combination with a powerful multiplexing strategy, the research aimed to enhance the overall reliability and efficiency of data transmission in challenging underwater environments.

Through a series of experiments, the researchers employed Polar codes with varying constraint lengths (120 and 240) and cyclic redundancy check (CRC) bit options (11 and 19) to investigate their impact on block error rates at different coding rates (1/6, 1/3, 1/2, and 2/3). The findings revealed valuable insights into the performance of the proposed model and provided essential guidelines for underwater communication system optimization.

This configuration resulted in the most favorable block error rate outcomes at a coding rate of 1/6. However, as the coding rate changed, the block error rates exhibited variation, highlighting the importance of selecting appropriate coding parameters based on the specific application requirements.

Moving forward, the article examined the impact of extending the Polar code's constraint length to 240 while testing two possibilities of CRC bit configurations (11 and 19). The results indicated that a higher constraint length might degrade system performance. However, increasing the CRC bit was shown to mitigate the adverse effects, leading to minimized block error rates. This finding emphasized the importance of striking a balance between constraint length and CRC bit configuration to achieve optimal performance in the underwater communication system.

The outcomes of the paper hold significant implications for the design and deployment of underwater communication systems. By understanding the influence of coding parameters on block error rates, engineers and researchers can make informed decisions to optimize system performance. The combination of Polar codes and OFDM techniques has proven to be a promising approach to enhance data transmission reliability in underwater environments.

Moreover, the proposed model can also find applications beyond underwater communication. The principles of Polar Code-OFDM optimization can be extended to other challenging communication scenarios, such as power line communications and wireless communication. The article paves the way for addressing communication challenges in various domains and environments, contributing to the advancement of communication technology as a whole.

The article's findings are valuable not only for the academic community but also for industries and organizations involved in underwater exploration, environmental monitoring, and marine research. The optimization of underwater communication systems offers numerous advantages, including enhanced data accuracy, improved resource utilization, and more well-informed decision-making.

In conclusion, the article presented in this article highlights the efficacy of Polar Code-OFDM models in optimizing underwater channel performance. By carefully selecting coding parameters and leveraging the power of multiplexing, the proposed model offers an efficient and reliable means of data transmission in challenging underwater environments. As communication technology continues to advance, further research and implementation efforts can build upon these findings to explore additional applications and refine the algorithm for broader usage in various communication scenarios. The optimization of underwater communication systems holds the promise of revolutionizing data transmission in underwater domains and beyond, shaping the future of intelligent and resilient communication technologies.

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