BER Performance based on Orthogonal Frequency Division Multiplexing in Underwater Acoustic Communication System on non-Gaussian Distribution

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ABSTRACT

The field of underwater communication has attracted significant attention from researchers interested in investigating activities below the water's surface. The underwater environment presents unique challenges such as limited bandwidth, low data rates, propagation delays, and a high Bit Error Rate (BER). This study focuses on Underwater Acoustic (UWA) communication and analyzes error performance in Amiriyat Fallujah, Al Anbar, Iraq. Orthogonal Frequency Division Multiplexing (OFDM) is a multiplexing technique that has been adopted in UWA along with turbo and convolutional codes. The research revealed that the noise in UWA does not follow a Gaussian distribution, whereas the t-distribution noise is fitted to the collected data. Furthermore, the turbo code exhibited superior performance compared to the convolutional code, achieving a 4.5 dB advantage at a BER of 10^{-3}.

Keywords-channel coding; OFDM; underwater communication

I. INTRODUCTION

The exploration of underwater environments has attracted increasing scientific interest due to the vast, undiscovered potential beneath the ocean's surface. Fortunately, the development of communication systems in the last decade, especially wireless communication systems, has enabled new applications that have helped marine scientists uncover new, previously unknown secrets [1]. Several communication applications based on electromagnetic, acoustic, and optical wireless carriers have been adopted in the underwater communication environment. Although terrestrial wireless communication applications are based on known rules, these rules do not apply in the water medium. Therefore, communication in the underwater environment is more challenging [2]. Sound waves are often preferred for certain applications due to their lower attenuation compared to electromagnetic signals. Electromagnetic signals, on the other hand, are highly absorbed in the oceanic environment, making them ineffective for underwater communication patterns [3]. Moreover, optical communication faces challenges underwater due to particle suspension in seawater and light scattering in the upper water column, leading to inefficient signal transmission [4, 5]. Therefore, acoustic communication systems have become essential for underwater wireless signal propagation. However, Underwater Acoustic (UWA) channels face challenges such as high Bit Error Rates (BER), which can result in poor communication quality and significant propagation delays [6-8]. Other challenges include limited available bandwidth, the complex and dynamic nature of the underwater channel, and other formidable obstacles [2, 9]. Nonetheless, due to their propagation characteristics, UWA channels are considered to be one of the most challenging communication channels. The acoustic wave from the ocean surface and seabed is known for its reflection and low-speed propagation problems. In addition, the nonuniformity of the sound speed causes the reflection of the acoustic wave in the water, resulting in a significant multipath delay spread, which leads to severe Inter-Symbol-Interference (ISI), especially in high symbol rate single-carrier systems. Besides, due to the low speed of sound, coupled with the motion of the transceiver platforms as well as the fluctuation of the propagation medium, the Doppler effect is almost inevitable in UWA communications, resulting in a time-varying channel [10]. The underwater ambient noise has a significant impact on communication systems, particularly in UWA environments where impulsive noise sources are prevalent. These sources, including human industrial activities, marine life noise, heavy rain, and strong winds, contribute to the challenge of maintaining reliable communications [11, 12]. Impulse noise in underwater environments is often modeled using various statistical distributions, including t-distribution, symmetric alpha-stable distribution, Gaussian Mixture Model (GMM), sparse vector, and Bernoulli-Gaussian Hidden Markov Model (BGHMM) [10]. A probability density function (pdf) with a wide tail and impulsive behavior is commonly used to evaluate noise characteristics in terms of type and performance. The t-distribution is a preferred model due to its wider tails compared to the Gaussian distribution [13]. In signal processing, the Gaussian distribution is used and appreciated because of its significant characteristics along with minimal computational requirements, whereas the white Gaussian noise acts as the baseline noise. The UWA channel experiences several noise types such as radiation noise, environmental noise, and target self-noise. Real-world communication systems experience higher error rates due to the non-Gaussian complex acoustic noise that occurs in real-world scenarios. Several research studies demonstrate that the UWA channel operates outside the white Gaussian distribution parameters [7, 14]. Channel coding is the most important factor in UWA communication systems, and the four most well-known channel coding techniques used are Convolutional Codes (CC), Turbo Codes (TC), Polar Codes (PC), and Low-Density Parity-Check (LDPC). Lars M. Wolff in [15] introduced the CC with M-ray Frequency Shift Keying (MFSK) to improve the BER performance in UWA communication, where the convolutional coding is characterized by simplicity and error correction effectiveness. Authors in [14] compared various channel coding schemes, and he concluded that the TC scheme has superior performance in error correction. Meanwhile, TC requires a trade-off between computational complexity and BER degradation capability. PC is another promising channel coding scheme in UWA communication systems. Yushuang Authors in [16] compared the performance of the PC and CC schemes in terms of BER reduction capability, and he concluded that the PC outperforms the CC in improving the channel coding. Authors in [17] introduced single-carrier LDPC (SC-LDPC) coding in shallow water environments, and he showed that the SC-LDPC code leads to a significant improvement compared to traditional LDPC codes. In conclusion, channel coding schemes have a direct impact on the BER performance and improve the reliability of UWA communication systems. The type of modulation scheme also plays an important role in reducing channel noise and improving the reliability of UWA communication systems. One of the modern multiplexing techniques is Orthogonal Frequency Division Multiplexing (OFDM), which exhibits promising performance [18]. The OFDM system has several advantages due to its inherent characteristics such as resilience to ISI, combating multipath fading, parallel transmission of symbols, low complexity of tab equalization in the receiver, robustness to frequency selective fading and Doppler shift [5]. Therefore, the OFDM system is an attractive modulation technique to achieve reliable communication with a high data rate in UWA communication systems. Several researchers have adopted the OFDM system to improve the error correction and BER performance. Authors in [19] worked to improve the signal detection accuracy by developing a trans-detector based on the OFDM technique to mitigate ISI and inter-carrier interference. Authors in [20] improved the BER performance and signal accuracy of a UWA communication system by using OFDM to combat multipath fading and the channel effect by assigning an appropriate pilot of subcarriers. Mustafa Sami introduced a shallow water UWA communication system based on OFDM, where the BER performance and the effect of channel coding schemes with and without the OFDM system were investigated [13, 21-23].

In this paper, the noise of the UWA communication system has been examined and analyzed by obtaining a sample from the underwater environment of Amiriyat Fallujah, Al Anbar, Iraq. The results show that the noise follows a t-distribution noise and not a Gaussian distribution noise. In addition, this paper evaluates the effect of TC and CC channel coding schemes on the error correction. The BER performance of the system has been evaluated with and without the OFDM system. The results indicate that the TC is superior to the CC for improving the BER reduction capability and the OFDM system improves the UWA communication system performance in terms of error correction in the selected area.

II. CHANNEL NOISE ANALYSIS

In this section, an analysis of the channel characteristics is performed using a fitting tool in MATLAB to determine the noise statistic distribution based on the selected area. This analysis is used to derive the Binary Phase Shift Keying (BPSK) error probability expressions.

A. Data Collection

This section presents the noise collection method for the Underwater Acoustic Noise (UWAN) of the selected area. The UWA noise samples were collected directly from the underwater environment at Amiriyat Fallujah, Al Anbar, Iraq (33°12'15.0"N 43°54'24.4" E) on August 24, 2023. Figure 1 shows the experimental site where the data were received by a Dolphin Ear 200 series broadband hydrophone (7 Hz ~ 22 kHz). The experimental site is located approximately 100 m from the shore, at depths of 1 m and 4 m, with the bottom of the Euphrates River at a depth of 9 m. During the day, the wind speed was approximately 18 knots and the river surface temperature was approximately 24 °C as measured by the TDS-3. A 7 s sample was taken at each depth with a salinity of 10 ppt and a pH of 7.5. Additionally, the speed of sound was 1558.2 m/s and 1558.25 m/s at depths of 1m and 4 m, respectively, obtained using the Medwin equation [23].

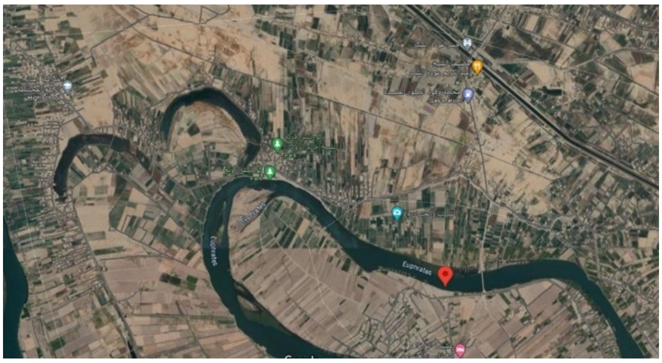
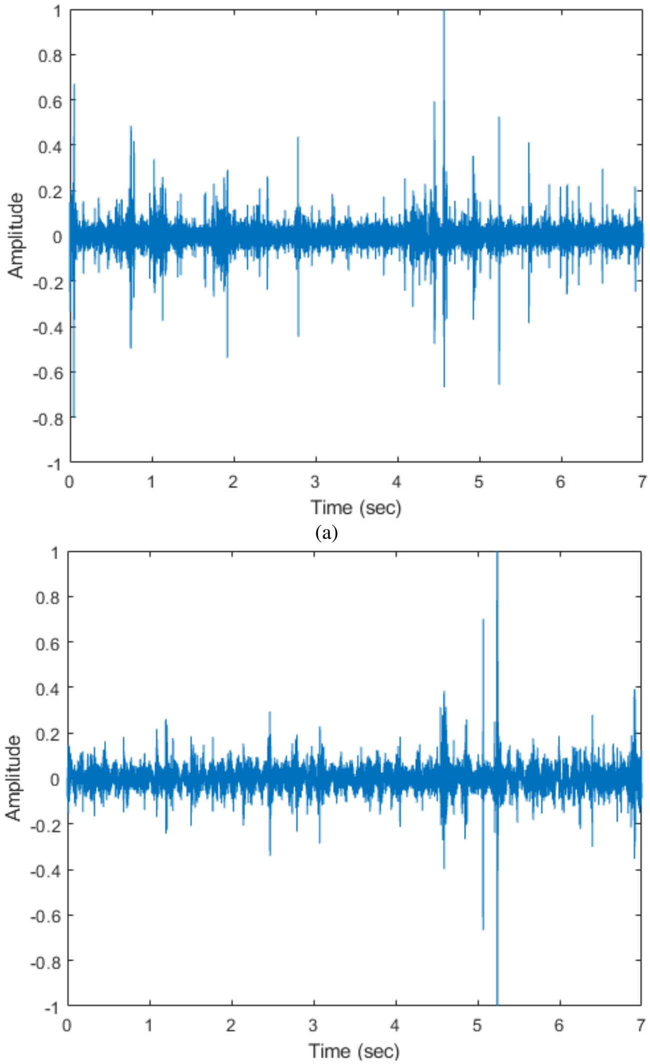


Fig. 1. Experimental test site.

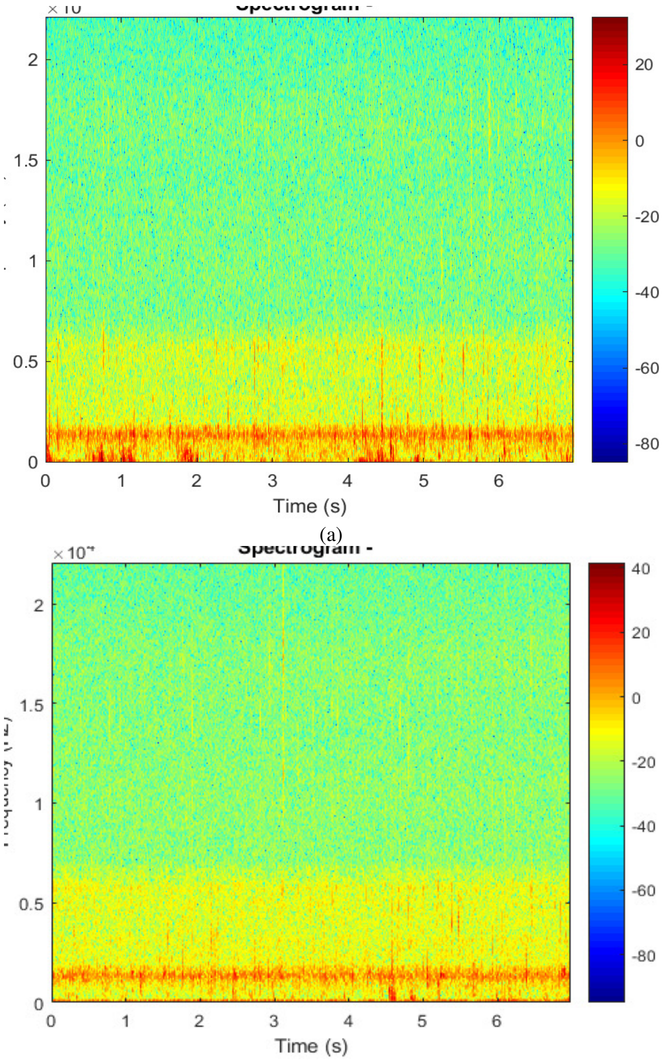
Figure 2 shows the time representation waveform of the UWAN data collected at depths of 1 m and 4 m. In addition, Figure 3 illustrates the Time and Frequency Representation (TFR) of the collected data, detailing both the time and frequency aspects of the noise signal.



(a)

(b)

Fig. 2. Time plot of the UWAN at depths of (a) 1 m and (b) 4 m.



(a)

(b)

Fig. 3. Time and frequency plot of the UWAN at depths of (a) 1 m and (b) 4 m.

B. Data Analysis

The collected data are analyzed using Gaussian and t-distribution in MATLAB's fitting tool. A comparison of the two methods indicates that the *pdf* of UWAN clearly fits the t-distribution, as depicted in Figure 4. Therefore, the assumption of a Gaussian distribution is unsuitable for UWAN at the experimental test site.

The equation below shows the t-distribution *pdf*, which is expressed as [24]:

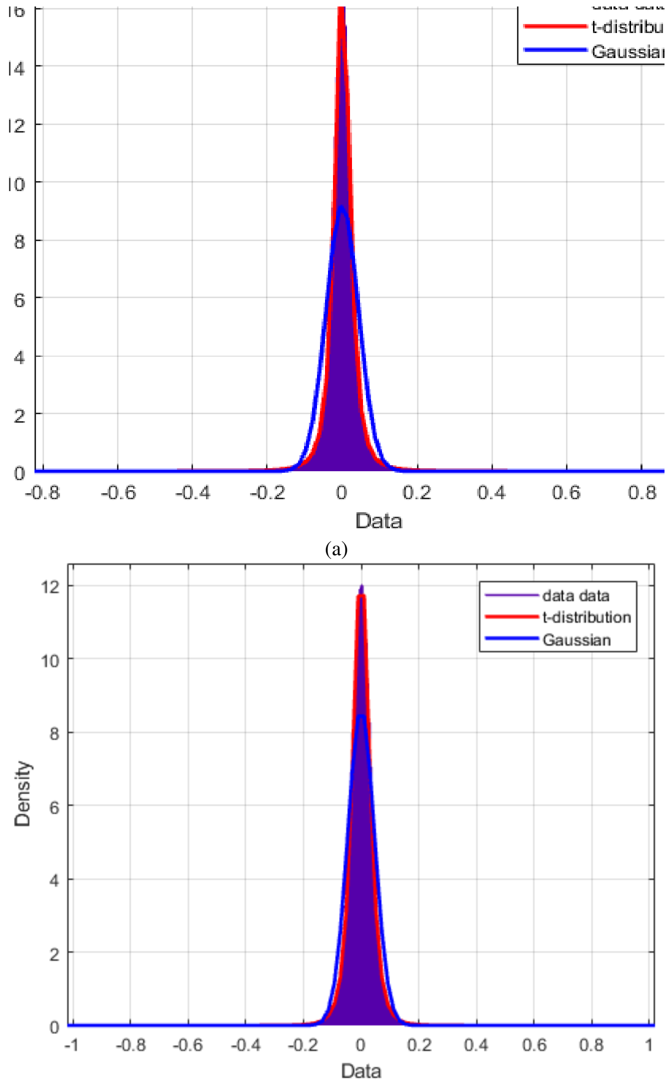
$$\rho_{(l,nu)} = \frac{\Gamma\left[(nu+1)/2\right]}{\sqrt{\pi nu}\;\Gamma(nu/2)}\left(1+\frac{l^2}{nu}\right)^{\frac{-(nu+1)}{2}} \qquad (1)$$

where $\Gamma[\cdot]$ is the gamma function and nu is the degree of freedom that regulates the distribution dispersion. When the value of nu is low the tails of the *pdf* are wider. However, to model a random variable y with variance $\sigma > 2$, the following changes of variables can be made:

$$l = \sqrt{\frac{nu}{\sigma^2 (nu-2)}}\, y \tag{2}$$

and accordingly, a new scaled *pdf* function can be written as:

$$f_T(x, nu) = \frac{\Gamma\left[\frac{(nu+1)}{2}\right]}{\sigma\sqrt{\pi(nu-2)}\,\Gamma\left(\frac{nu}{2}\right)} \times \left(1 + \frac{x^2}{\sigma^2 (nu-2)}\right)^{\frac{-(nu+1)}{2}} \tag{3}$$



(a)

(b)

Fig. 4. Comparison of the UWAN distribution with t-distribution and Gaussian distribution: (a) 1 m, (b) 4 m.

For $nu = 4$, the *pdf* is:

$$f_T(x, 4) = \frac{0.534}{\sigma}\left(1 + \frac{x^2}{2\sigma^2}\right)^{-2.5} \tag{4}$$

Finally, for $nu = 4$, the symbol error probability of the binary UWAN channel can be written as [25]:

$$P_{BPSK} = 0.534\sqrt{\frac{2E_b}{N_o}}\int_0^{\infty}\left[1 + \frac{2E_b}{N_o}\frac{(x+1)^2}{2}\right]^{-2.5} dx \tag{5}$$

III. CHANNEL CODING

Channel coding adds redundancy to a subset of valuable bits in communication systems to secure symbols in noisy channels and to mitigate transmission errors. The key step in channel coding is to divide the coding into multiple subsets. The four common types of channel coding schemes are CC, TC, PC, and LDPC codes [14].

A. *Convolutional Code*

The CC encoder is shown in Figure 5, where the encoder operates with an input bit k and three registers D_1, D_2, and D_3. This encoder corresponds to a rate $R = 1/2$ and produces two output bits n_1 and n_2 for each input bit k. The encoding process begins with the initialization of the shift register. The encoder generates output bits n_1 and n_2 after receiving the input bit k, and this operation is done based on the current state of the shift register and predefined polynomials. The shift register inserts the input bit k and operates with feedback paths that have been defined by the generator polynomials. This results in the generation of output bits n_1 and n_2. After generating the output bits, all bits are shifted to the right and then the current input bit k is inserted into the leftmost register D_1. This operation is repeated for each subsequence input bit k, resulting in the output coding sequence based on the CC structure. In brief, convolutional coding works to encode the input bits k into two output bits n_1 and n_2 with a bit rate of $R = 1/2$. Through systematic processing guided by the generator polynomials, this encoder facilitates the creation of reliable encoded sequences for transmission in the communication systems.

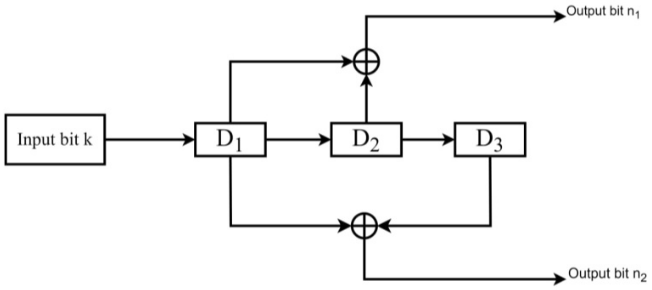


Fig. 5. Convolutional code encoder.

B. Turbo Code

In the early 1993s, Berrou, Glavieux, and Thitimajshima presented a seminal paper introducing a new class of error-correcting code known as "turbo code". This code demonstrated error rates closer to the Shannon limit than previously achieved, while maintaining significantly lower complexity compared to existing codes of the time. The encoder structure of TC is characterized by the parallel concatenation of two CCs with an interleaved positioned between them. This interleaved plays a crucial role in reordering the data before it enters the second convolutional encoder [26].

Despite the computational complexity compared to CC, the adaptability and robustness of TC make it vital for ensuring reliable communication in various challenging scenarios, cementing its role as a key technology in modern communication systems [27]. Although TC is known for its robust error correction capabilities, it has inherent obstacles [28]. The computational complexity of TC requires high processing power and memory, making it resource-intensive for encoding and decoding operations. In addition, the iterative decoding process increases latency, making it unsuitable for real-time applications. At low SNR, TC can exhibit an error floor phenomenon, where error rates no longer decrease. Furthermore, its non-linear structure makes it difficult to analyze and implement compared to simpler coding schemes [26].

IV. SYSTEM DESIGN

This section presents a detailed overview of the OFDM system in UWA. Figure 6 depicts the block diagram of the OFDM system [29]. First, the baseband symbols are generated after the binary data input is formed by a certain constellation mapping scheme. Next, the constellated sequences are converted from serial to parallel form, and the parallel symbols are inserted into the N-IFFT to modulate the symbols by N-independent subcarriers. After the IFFT operation, the symbols are transformed from the frequency domain to the time domain. Then, the cyclic prefix (CP) is applied to the symbols by appending part of the symbol end to the symbol beginning to prevent the data from ISI [13]. Finally, the OFDM signal obtained is transmitted to the receiver side by the channel pattern. At the receiver side, all the operations in the transmitter are reversed to obtain the original signal at the end of the receiver side.

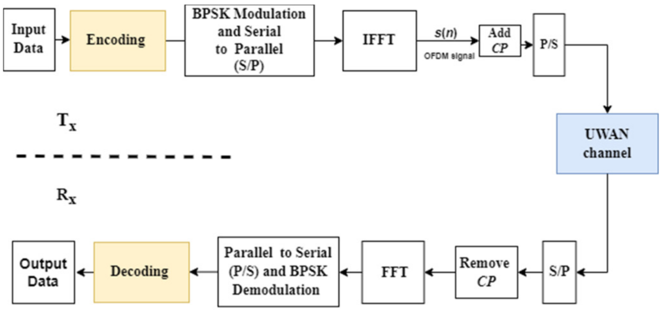


Fig. 6. Turbo code block diagram.

V. RESULTS AND DISCUSSION

In this section, the evaluation of the UWA communication system is presented based on two main phases. First, the error performance is investigated and analyzed in terms of the SNR. Second, the computational complexity of the system is analyzed based on different channel encodings. The results presented are obtained using MATLAB simulation in the presence of additive t-distribution noise with a *nm* value of 4, as obtained from the fitting tool. Table I illustrates the simulation parameters of the communication scheme.

TABLE I. COMMUNICATION PARAMETERS

Parameter	Value
Modulation constellation (M)	BPSK
Subcarriers (N)	256
Number of symbols	2000
Degree of freedom (nu)	4
Cyclic prefix (CP)	36
Channel coding	TC; CC
Rate code (R)	1/2
Decoding algorithms	max-log-MAP; Viterbi

A. Bit Error Rate Performance

The simulation results shown in Figure 7 demonstrate the BER performance for BPSK modulation with a *nu* parameter set to 4. In the figure, the BER performance of the UWA system is depicted by a blue line representing the simulation data and a red line representing the mathematical calculations. Additionally, the black line corresponds to the Additive White Gaussian Noise (AWGN) channel. Data points on the y-axis exhibit a BER of less than or equal to 10^{-6}. Clearly, the comparison between the mathematical BER and the simulated data for the UWA system reveals no discrepancies, indicating consistency between the two. This suggests that the t-distribution channel utilized in the simulation aligns closely with the mathematical model. Moreover, the BER performance of the signal in the t-distributed UWAN channel surpasses that of the Gaussian distribution in the AWGN channel.

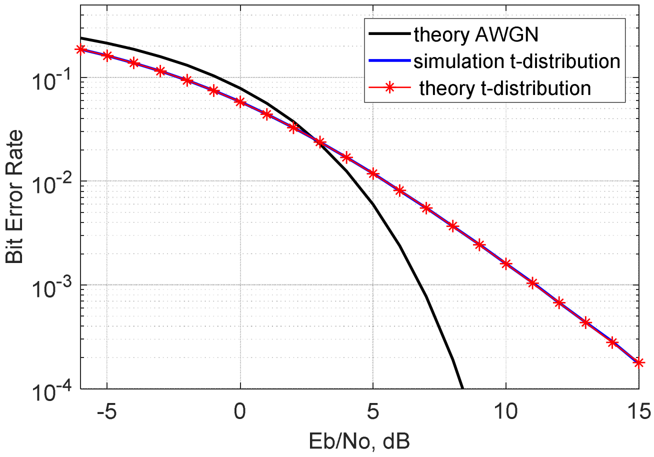


Fig. 7. Comparison of single carrier BER for AWGN and UWAN channels.

The simulation results of BER with E_b / N_o are shown in Figure 8. The TC data are shown in pink color for OFDM, the CC data are shown in green color for OFDM, and the uncoded data are shown in blue color for OFDM. The decoding algorithms used are max-log-MAP and Viterbi with an approximation for TC and CC schemes, respectively. The results are given for a rate R of ½. Figure 8 clearly shows that the TC outperforms the CC in OFDM by 4.5 dB at BER 10^{-3}. However, when comparing uncoded systems with TC and CC, there is a significant difference of about 9 dB and 5 dB, respectively. Because of the random interleaving in TC, the message length is short, so the random position in the medium is not truly random. In addition, punctured TC restricts the decoding ability to correct errors because some of the parity bits are removed.

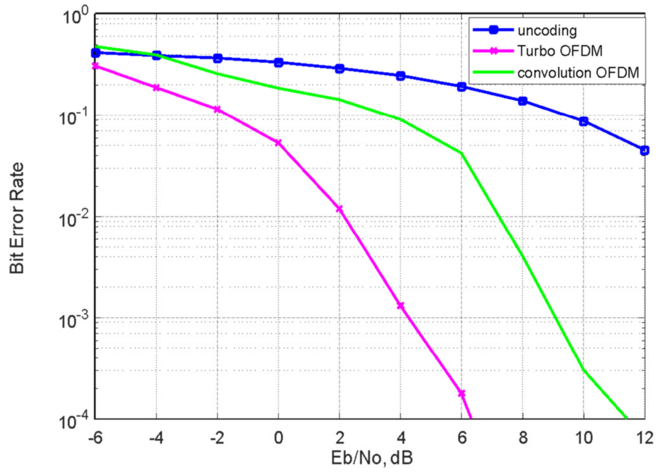


Fig. 8. BER comparison of OFDM with different channel codes.

B. Computational Complexity

Computational complexity is a crucial performance metric to be evaluated in code development and application, particularly in UWA. Hence, this study analyzes and discusses the complexity pattern, which is essential for examining the computational complexity in the encoding and decoding processes. Understanding the complexity of the decoding algorithm and determining the number of iterations is essential for a fair comparison between different schemes. Decoding complexity can be assessed using mathematical operations such as addition, subtraction, multiplication, division, and comparison. Different conclusions can be drawn based on the development of the code.

The computational complexity parameters of the TC scheme are obtained and compared with the CC scheme. Table II shows the equations for determining the number of operations for each scheme. K, R, m and N represent the information block length, code rate, memory length, and encoded block length, respectively [30].

Figure 9 depicts the change in computational complexity based on the information block length K. Comparing the two methods, it can be seen that the TC scheme has the lowest computational complexity. On the other hand, the TC scheme has a higher computational complexity compared to the CC scheme in terms of iterations because it is constructed by an iterative algorithm with a high number of iterations. This leads to an increase in computational complexity. Therefore, while TC may offer improved performance in terms of error correction, it comes at the cost of requiring more computational resources. The trade-off between these two features must be carefully considered when choosing between TC and CC coding schemes for a particular application. The comparison is illustrated in Figure 10.

TABLE II. COMPUTATIONAL COMPLEXITY OF TC AND CC

Method	**Computational complexity**
TC [31]	$I_{\max} \times 16 \times K \times 2^m + I_{\max} \times 8 \times K \times 2^m$
CC [32]	$4 \times R \times N \times 2^m$

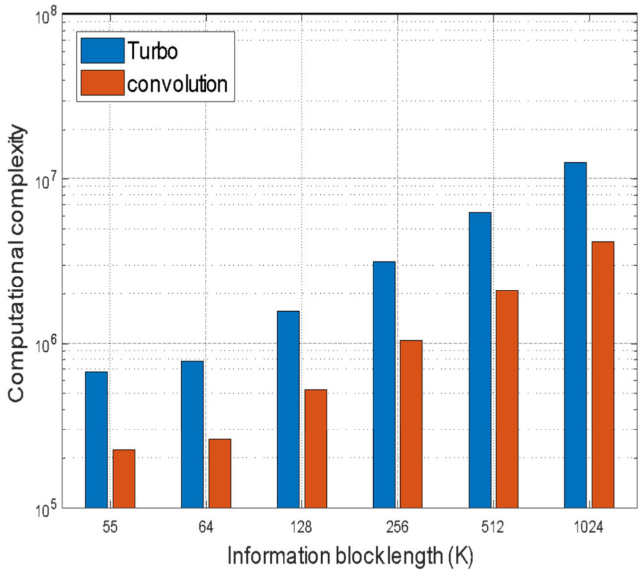


Fig. 9. Computational complexity versus information block lengths for Turbo and convolution coding rate.

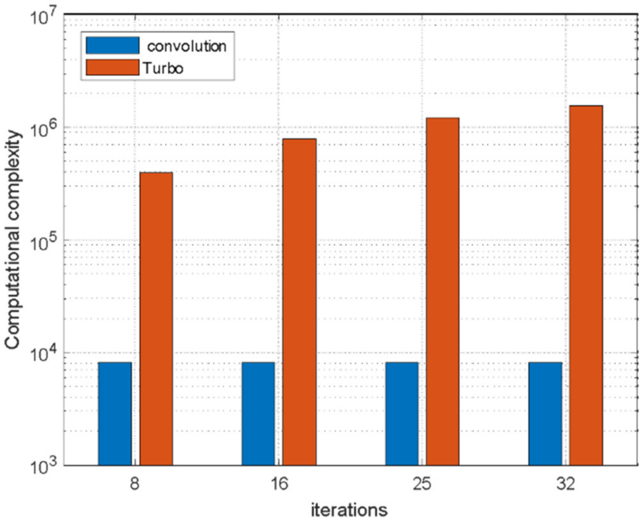


Fig. 10. Computational complexity versus iterations for turbo and convolution coding rate.

VI. CONCLUSION

In this study, a coexisting Orthogonal Frequency Division Multiplexing (OFDM) system and Underwater Acoustic (UWA) communication system were introduced to evaluate the performance of UWA communication in Amiriyat Fallujah, Al Anbar, Iraq. By comparing the performance of turbo coding and convolutional coding, MATLAB simulations revealed that UWA channel coding with turbo coding is viable. It effectively reduces the Bit Error Rate (BER) and increases the communication data rate. Turbo code (TC) exhibits lower error rates than Convolution Code (CC), which suffers from drawbacks such as the need of an interleaved, time delay, and complex decoding algorithms. Therefore, convolutional coding outperforms turbo coding in underwater communications. Despite its tolerance to delay and complexity, TC is a competitive error correction option. The balance between BER reduction and computational complexity in channel coding schemes is a critical factor when selecting a channel coding scheme for BER reduction.

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