

Underwater communication system for shallow water environments using FSK modulation

Nguyen Thi Nga ^{*}, Tran Quang Giang, Vu Hai Lang

Institute of Defense Equipment, Academy of Military Science and Technology, 17 Hoang Sam, Nghia Do, Hanoi, Vietnam.

^{*}Corresponding author: ngadtvt@gmail.com

Received 1 Aug. 2025; Revised 17 Sep. 2025; Accepted 10 Oct. 2025; Published 30 Oct. 2025.

DOI: <https://doi.org/10.54939/1859-1043.j.mst.IITE.2025.107-114>

ABSTRACT

Underwater acoustic communication presents significant challenges due to complex environmental factors such as noise, multipath propagation, and time-varying channel conditions. This paper presents an underwater communication system employing Frequency Shift Keying (FSK) modulation with matched filter-based demodulation to mitigate the impact of noise in shallow water environments, suited to Vietnam's marine area. By leveraging the optimal signal detection capability of the matched filter in noisy and time-varying channels, the system significantly improves communication reliability under harsh underwater conditions. Simulation results demonstrate that the proposed FSK-based system achieves a bit error rate (BER) below 10^{-3} at a signal-to-noise ratio (SNR) exceeding 20 dB. These findings suggest that FSK modulation, combined with matched filter demodulation, is a suitable solution for underwater communication in shallow water scenarios.

Keywords: Underwater acoustic; FSK modulation; Matched filter.

1. INTRODUCTION

Underwater communication is a vital area of research and development, supporting a wide range of marine applications, including submarines, Autonomous Underwater Vehicles (AUV), and Remotely Operated Vehicles (ROV). Due to the high absorption of electromagnetic waves in water, acoustic waves are predominantly used for data transmission in underwater environments. However, underwater acoustic communication (UAC) faces numerous challenges, such as multipath propagation, Doppler shifts, severe signal attenuation, and limited available bandwidth [1]. Consequently, underwater communication systems must incorporate advanced signal processing and modulation techniques to ensure reliable and efficient data transmission [2].

Underwater communication systems can adopt advanced transmission techniques to enhance performance and reliability. A wide range of modulation schemes has been investigated to address the unique and challenging characteristics of the underwater acoustic channel. Numerous research efforts have focused on developing modulation techniques that aim to reduce the bit error rate (BER) and increase system throughput. The amplitude shift keying (ASK) system [3] was developed and experimentally tested in real underwater environments. The study evaluated key performance metrics such as data transmission rate, communication range, and BER under various operating conditions. ASK, being the simplest form of digital modulation, offers ease of implementation and low computational complexity. However, it is highly susceptible to amplitude noise, where voltage fluctuations from external sources can significantly degrade signal quality. Araujo et al. [4] investigated the application of frequency shift keying (FSK) for underwater communication, focusing on performance evaluation across parameters such as communication distance and data rate. FSK is a popular choice due to its implementation simplicity, robustness against amplitude noise, and high reliability, although it still has limitations in terms of data transmission rate.

Due to the severe multipath propagation effects in underwater environments, frequency-

hopping frequency shift keying (FH-FSK) [5] is often employed to maintain long-range communication, mitigate interference, and enhance security. However, this approach is relatively inefficient in terms of bandwidth utilization. To address this limitation, study [6] proposed the use of phase shift keying (PSK) to improve spectral efficiency compared to FSK, while also enhancing noise resilience and reducing the impact of signal distortion. Nevertheless, PSK modulation is highly sensitive to phase noise and requires precise synchronization techniques to ensure reliable system performance.

To further increase data rates and mitigate the effects of noise and multipath propagation, orthogonal frequency division multiplexing (OFDM) techniques [7-9] have been introduced. This technique significantly improves communication efficiency in underwater channels. However, OFDM is inherently sensitive to Doppler-induced frequency shifts, necessitating the implementation of effective Doppler compensation techniques to maintain system stability and accuracy.

Among the modulation schemes, FSK remains particularly attractive for applications in shallow water environments owing to its simplicity, strong noise immunity, and relatively low computational requirements. This paper presents the design and implementation of an underwater communication system employing FSK modulation with environmental parameters suitable for the shallow waters of Vietnam. The proposed system aims to achieve reliable data transmission while maintaining a balanced trade-off between system complexity, energy efficiency, and overall performance.

2. SYSTEM DESCRIPTION

The UAC system using FSK modulation consists of typical components, as shown in figure 1 [4].

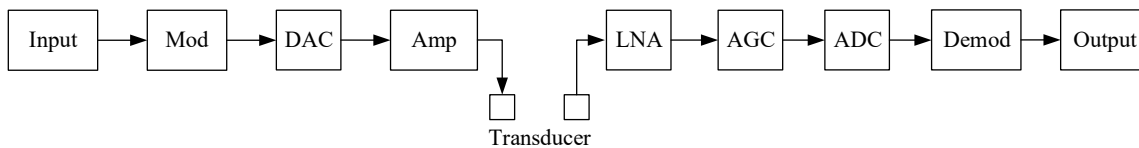


Figure 1. System block diagram.

Binary input data is modulated using the FSK technique, producing a baseband waveform suitable for transmission. FSK modulation is the process of changing the frequency of the input data bits ‘1’ and ‘0’. The FSK signal consists of two frequencies, called BFSK.

The BFSK modulation diagram is shown in figure 2. Two sinusoidal carrier signals with distinct frequencies are employed to represent binary data. Specifically, the two carriers are defined as:

$$\begin{aligned}
 V_1(t) &= A \cos(\omega_c + \Omega)t \\
 V_2(t) &= A \cos(\omega_c - \Omega)t
 \end{aligned}
 \tag{1}$$

where A is the amplitude, ω_c is the center angular frequency, and Ω denotes the frequency deviation.

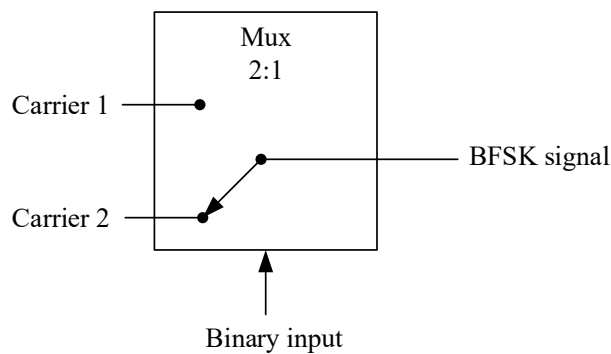


Figure 2. BFSK modulation diagram.

The selection of the carrier signal is governed by the input binary data sequences. When the input bit is logical '1', the multiplexer selects $V_1(t)$, whereas for a logical '0', it selects $V_2(t)$. Consequently, the BFSK signal $V_{BFSK}(t)$ is formed by switching between these two carriers depending on the data bit. Mathematically, the output signal is expressed as:

$$V_{BFSK}(t) = \begin{cases} A\cos(\omega_c + \Omega)t & \text{bit 1} \\ A\cos(\omega_c - \Omega)t & \text{bit 0} \end{cases} \quad (2)$$

This digital waveform is converted to an analog signal by a Digital-to-Analog Converter (DAC) and subsequently amplified to drive the transmitting transducer. The transducer transforms the electrical signal into an acoustic wave, which propagates through the underwater environment and is affected by multipath, attenuation, and Doppler effects.

At the receiver, another transducer captures the incoming acoustic signal and converts it back into an electrical signal. This weak signal is boosted by a Low-Noise Amplifier (LNA), and its amplitude is normalized by an Automatic Gain Control (AGC) circuit to ensure consistent signal levels. The analog signal is then digitized by an Analog-to-Digital Converter (ADC). Finally, the digitized signal is extracted from data by the non-coherent FSK demodulation to operate stably in interference and variable environments. The output is a reconstructed digital bitstream that closely resembles the original input.

3. NON-COHERENT FSK DEMODULATION

Non-coherent demodulation does not require carrier phase or frequency synchronization, making it simpler and more robust in environments with Doppler shifts and multipath fading, such as UAC. It typically uses energy detection or envelope comparison to distinguish symbols, reducing complexity and power consumption. Although it offers higher BER than coherent methods, its reliability in dynamic and noisy channels makes it a practical choice for many UAC systems, in which maintaining accurate synchronization is difficult.

3.1. Non-coherent demodulation using FFT

In non-coherent FSK systems, the Fast Fourier Transform (FFT) [10] is employed as an effective frequency detection technique. This method eliminates the need for carrier phase or frequency synchronization, thereby simplifying the receiver architecture and enhancing robustness in challenging environments characterized by Doppler shifts and multipath fading, such as in UAC. By analyzing the spectral energy across discrete frequencies, the FFT-based detector identifies the dominant frequency component corresponding to each symbol. Its low complexity and resilience to channel fluctuations make it a practical solution for UAC systems where it is difficult to maintain accurate synchronization.

Assume the received discrete-time signal is denoted by $x[n]$, sampled at a rate f_s . The demodulation procedure is as follows:

3.1.1. Frame division

The received signal is segmented into frames, where each frame corresponds to one FSK symbol (i.e., one bit in BFSK). If each symbol spans N samples, the signal is divided into consecutive blocks:

$$x_k[n] = x[n + kN], n = 0, 1, \dots, N - 1 \quad (3)$$

for $k = 0, 1, \dots, K - 1$, where K is the total number of symbols.

3.1.2. Frequency analysis via FFT

An N -point FFT is applied to each symbol frame:

$$X_k[m] = \sum_{n=0}^{N-1} x_k[n] \cdot e^{-j2\pi mn/N}, m = 0, 1, \dots, N-1 \quad (4)$$

The bin m corresponds to a frequency f_m .

3.1.3. Symbol detection

The FFT output magnitude is examined at the frequency bins m_1 and m_2 corresponding to the FSK frequencies f_1 and f_2 . The symbol is detected based on the higher spectral magnitude:

$$bit = \begin{cases} 0, & \text{if } |X_k[m_1]| > |X_k[m_2]| \\ 1, & \text{otherwise} \end{cases} \quad (5)$$

This comparison assumes a BFSK scheme. For M-ary FSK, the decision is made by identifying the frequency bin with the maximum spectral magnitude ($\text{argmax}_m |X_k[m]|$).

The FFT-based non-coherent demodulation technique provides a flexible and low-complexity solution. Although its BER performance is generally inferior to coherent methods, its resilience to synchronization errors and robustness in dynamic channels make it a practical choice for low-SNR and highly dispersive environments. The FFT-based demodulator offers several compelling advantages, such as simplicity, no filter design required, and scalability. Despite these benefits, there are notable limitations: Frequency Resolution Constraint, Doppler Sensitivity. In practice, Doppler-induced frequency shifts may cause the signal's energy to leak outside the expected FFT bin. This effect reduces detection accuracy, particularly in low-SNR or fast-moving channels such as UAC, where even small frequency offsets can cause significant degradation.

3.2. Non-coherent demodulation using matched filter

To address the limitations of the FFT-based approach, particularly in terms of frequency resolution and Doppler sensitivity, matched filter-based non-coherent demodulation presents a more effective alternative [11, 12]. The matched filter maximizes the output SNR for known signal shapes in additive white Gaussian noise (AWGN) and exhibits greater selectivity in distinguishing between FSK frequencies.

In UAC systems, where Doppler effects and multipath propagation significantly degrade performance, the enhanced detection reliability of matched filter-based demodulation becomes advantageous. Although this method incurs higher computational complexity compared to FFT-based techniques, it delivers improved BER performance under challenging channel conditions.

For non-coherent FSK demodulation, the integration of matched filtering with envelope detection provides an effective trade-off between performance and implementation feasibility, offering a practical solution for environments where phase coherence cannot be reliably maintained. The non-coherent demodulation of BFSK signals using a matched filter approach is shown in figure 3, which includes the following steps:

3.2.1. Matched filtering

The received noisy signal is denoted as $x[n]$, which is a sample of the continuous-time signal corrupted by additive noise. The receiver applies two matched filters: $h_1[n]$ and $h_2[n]$, each designed to correlate with the waveform corresponding to frequencies f_1 and f_2 , respectively.

The outputs of the matched filters are computed as:

$$\begin{aligned} y_1[n] &= x[n] * h_1[n], \\ y_2[n] &= x[n] * h_2[n] \end{aligned} \quad (6)$$

where $*$ denotes linear convolution. This step maximizes the output SNR for known signal shapes in AWGN.

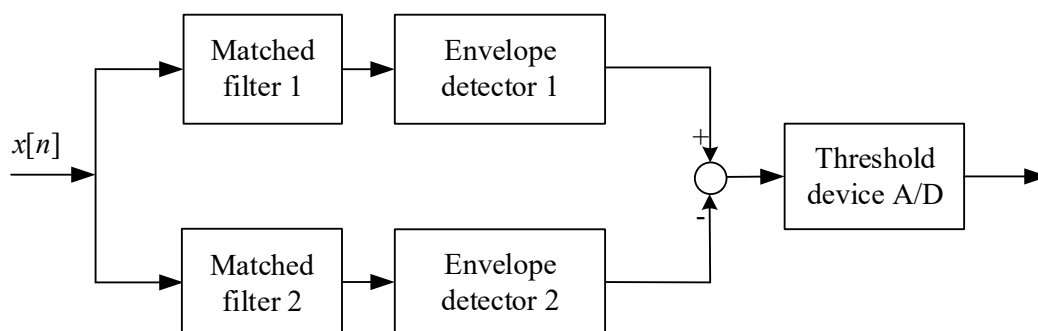


Figure 3. Non-coherent demodulation using matched filter.

3.2.2. Envelope detection

To perform non-coherent detection, the envelope of each matched filter output is extracted:

$$\begin{aligned} e_1[n] &\triangleq |y_1[n]|, \\ e_2[n] &\triangleq |y_2[n]| \end{aligned} \quad (7)$$

These envelope signals reflect the energy corresponding to each BFSK frequency.

3.2.3. Threshold decision

To improve robustness against noise, a noise power threshold γ is introduced. It is estimated based on the average signal energy:

$$\gamma = \alpha \cdot \frac{1}{N} = \sum_{n=0}^{N-1} |x[n]|^2 \quad (8)$$

with a typical value of $\alpha = 0.1$. The final decision is made as follows:

$$bit = \begin{cases} 0, & \text{if } e_1[n] > e_2[n] \ \& \ e_1[n] > \gamma \\ 1, & \text{if } e_1[n] < e_2[n] \ \& \ e_2[n] > \gamma \\ \text{random}\{0,1\}, & \text{otherwise} \end{cases} \quad (9)$$

The proposed non-coherent demodulation approach using matched filtering and envelope detection offers several notable advantages. First, the use of matched filters enables optimal signal detection in AWGN by maximizing the output SNR for known waveform templates. Second, envelope detection eliminates the need for carrier phase synchronization, simplifying the receiver design and reducing computational complexity. Furthermore, the technique demonstrates reliable performance in low-SNR environments and can be readily extended to support multilevel modulation schemes like M-ary FSK (MFSK), making it a flexible and scalable solution for underwater or bandwidth-constrained communication systems.

4. RESULTS AND DISCUSSION

4.1. System setup

To demonstrate the effectiveness of the FSK demodulation models, experiments were conducted to compare the FFT-based demodulator with the matched filter-based demodulator in terms of BER performance over varying SNR levels. The simulator parameters are presented in table 1.

The experiments employed the Bellhop ray-tracing model [13] and the geometric channel model, combined with environmental parameters [14], to predict acoustic wave propagation under different water depths, sea surface and seabed conditions, as well as transmitter–receiver geometry.

For the Bellhop channel model, the water depth was set to 100 m, and the range between transmitter and receiver was approximately 1000 m. The transmitter and receiver depths were 20

m and 50 m, respectively. The sound speed is assumed to be 1500 m/s. The configuration of the model incorporates the transmitter–receiver geometry, the sound speed profile, the sea surface and seafloor, encompassing both reflection and scattering phenomena.

For the geometric channel model, combined with practical environmental parameters of Vietnamese shallow waters, the water depth was set to 100 m and the transmitter–receiver range was 1000 m, with both the transmitter and receiver located at a depth of 50 m. The sound speed was 1500 m/s, salinity 35 ppt, and temperature 30 °C. The number of rays reflecting at the sea surface (N_1) was 80, while the number of rays reflecting at the seabed (N_2) was 70.

Table 1. Parameters of the UAC system using FSK modulation.

Parameters	Value
FFT size N_{FFT}	100
Sampling frequency (kHz)	200
Bandwidth (kHz)	9
Bit duration (ms)	1
Modulation schemes	BFSK, 4FSK
Channel model	Bellhop, Geometric
Noise	AWGN

4.2. Simulation results and discussion

Simulating the BER performance of the MFSK modulation system with $M = 2, 4$ over an underwater acoustic channel, comparing the FFT-based and the matched filter demodulator, is shown in figures 4 and 5.

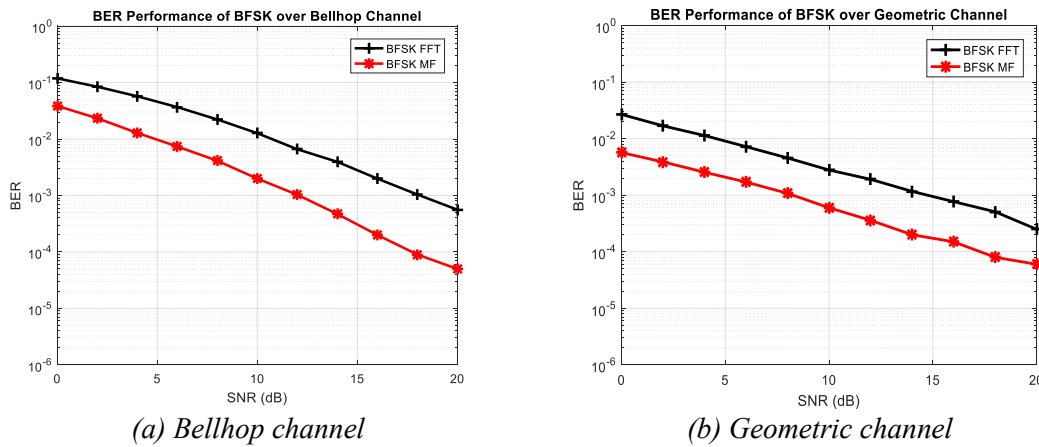


Figure 4. BER performance of the system with BFSK modulation.

Figure 4 illustrates the BER performance of the BFSK system under two channel models: the Bellhop channel and the geometric channel configured with environmental parameters. In both cases, the matched filter (MF)-based non-coherent demodulator consistently outperforms the FFT-based counterpart across the entire SNR range. Specifically, for the Bellhop channel (figure 4a), the MF achieves a BER below 10^{-5} at 20 dB SNR, whereas the FFT method remains at approximately 10^{-3} . A similar trend is observed in the Geometric channel (figure 4b), confirming the robustness and superior detection capability of the MF approach in multipath and noise-affected environments. These results highlight that the matched filter provides a substantial performance advantage over FFT-based demodulation, thereby representing a more reliable option for BFSK detection in shallow-water acoustic communication systems, appropriate for Vietnam’s marine regions.

Figure 5 presents the BER results for 4FSK under the same channels. Similar to BFSK, the 4FSK matched filter consistently provides lower BER than its FFT counterpart. However, both

methods for 4FSK show higher BERs compared to BFSK, indicating increased susceptibility to channel impairments due to the denser symbol constellation. Despite this, the 4FSK matched filter still achieves BERs below 10^{-4} at 20 dB SNR, demonstrating its potential for high data rate applications when combined with the effective demodulator.

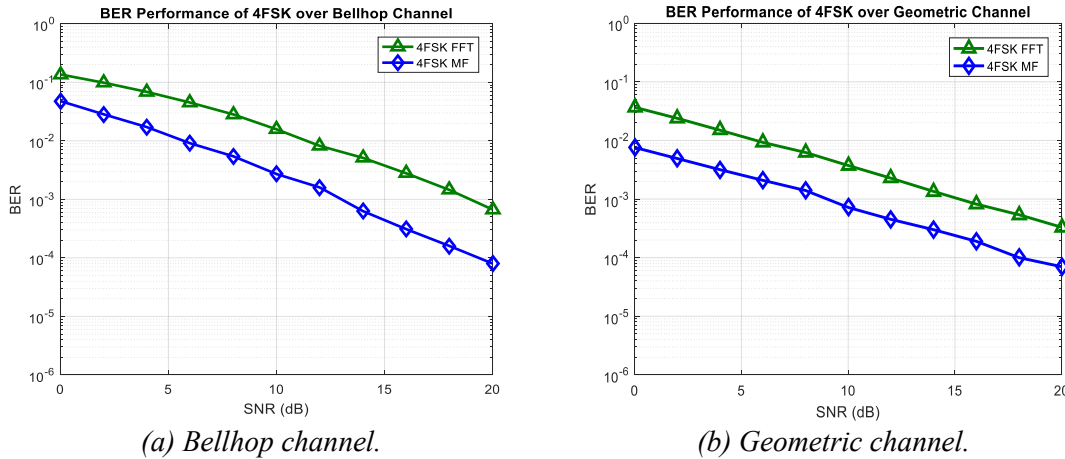


Figure 5. BER performance of the system with 4FSK modulation.

4.2. Complexity assessment

The computational cost, quantified in floating-point operations (flops), of the noncoherent demodulators - matched filter (MF) and FFT - based is given below.

$$C_{FFT} \approx NR(5N_{FFT} \log_2 N_{FFT} + N_{FFT}) \quad (10)$$

$$C_{MF} \approx NM(2L - 1) \quad (11)$$

where N denotes the number of symbols, L the number of samples per symbol, and R the number of analysis windows per symbol (with overlap).

Under fixed parameters, the MF and FFT demodulators exhibit linear $O(N)$ scaling. However, the MF has a substantially smaller constant for BFSK/4FSK, thus offering lower computational cost and better BER in the shallow-water scenarios. FFT becomes comparatively attractive as the M-ary order grows (or when wideband spectral scanning is required), especially with reduced window count.

5. CONCLUSIONS

This study has demonstrated the effectiveness of a non-coherent FSK-based underwater communication system enhanced with matched filter demodulation for shallow water environments. By exploiting the optimal signal detection properties of matched filters, the system achieves reliable performance in the presence of noise, multipath effects, and time-varying channel conditions. Simulation results confirm that the system maintains a bit error rate below 10^{-3} when the signal-to-noise ratio exceeds 20 dB. Importantly, the inclusion of the geometric channel model configured with realistic environmental parameters of Vietnamese marine areas further validates the robustness of the introduced approach under practical sea conditions. These results validate the suitability of FSK modulation combined with matched filter demodulation as a robust and practical approach for underwater acoustic communication in challenging shallow water scenarios.

REFERENCES

[1]. L. M. Brekhovskikh et al., "Fundamentals of ocean acoustics," Springer, Berlin, no. 3rd ed., pp. 140–146, (2003).

- [2]. Z. Li et al., "Underwater acoustic communications," Nature reviews electrical engineering, Vol. 2, pp. 83–95, (2025).
- [3]. M. M. Dawoud et al., "Experimental realization of ASK underwater digital acoustic communications system using error correcting codes," International journal of electronics, Vol. 72, No. 2, pp. 183–196, (1992).
- [4]. L. Araujo et al., "4-FSK high-speed underwater acoustic communication system," OCEANS 2023 - Limerick, Limerick, Ireland, pp. 1–5, (2023).
- [5]. L. M. Wolff et al., "Bitwise ranging through underwater acoustic communication with frequency hopped FSK utilizing the Goertzel algorithm," OCEANS 2017 - Aberdeen, Aberdeen, UK, pp. 1–6, (2017).
- A. Soulias et al., "Coherent phase shift keying (PSK) modulation using low-power micro-controllers for underwater acoustic communications," OCEANS 2022, Hampton Roads, VA, USA, pp. 1–6, (2022).
- [6]. Deshpande et al., "Underwater acoustic OFDM systems using deep neural network," 3rd international conference on intelligent engineering and management (ICIEM), London, United Kingdom, pp. 195–200, (2022).
- [7]. S. Zhou et al., "OFDM for underwater acoustic communications," John Wiley Sons, Ltd, Vol. 9781118458860, pp. 1–386, (2014).
- [8]. Tran Cao Quyen, "Nâng cao tốc độ truyền tin trong một kênh nước biển nông thuộc vịnh Bắc Bộ của Việt Nam dùng điều chế OFDM," National Conference on Electronics, Communications and Information Technology, (2015) (in Vietnamese).
- [9]. Y. T. Chan et al., "Comparison of two FFT-based demodulation schemes for M-ary FSK," MILCOM 92 conference record, San Diego, CA, USA, Vol. 2, pp. 603–607, (1992).
- [10]. W. Xiang et al., "FPGA-based two-dimensional matched filter design for vein imaging systems," IEEE journal of translational engineering in health and medicine, Vol. 9, Art. no. 1800510, (2021).
- [11]. J. Kaur et al., "Performance evaluation of matched filter detection using QAM technique in CR networks in different channel conditions," IEEE 11th Uttar Pradesh section international conference on electrical, electronics and computer engineering (UPCON), Lucknow, India, pp. 1–4, (2024).
- [12]. M. B. Porter, "The BELLHOP manual and user's guide: preliminary draft," Heat, Light, and Sound Research, Inc., La Jolla, CA, USA, Tech. Rep., Vol. 260, (2011).
- [13]. D. V. Ha et al., "Methods of designing shallow underwater acoustic channel simulators," Acoustics Australia, pp. 439–448, (2016).

TÓM TẮT

Hệ thống truyền tin dưới nước cho vùng biển nông sử dụng điều chế FSK

Truyền thông dưới nước vẫn là một thách thức đáng kể do các yếu tố môi trường phức tạp như nhiễu, lan truyền đa đường và điều kiện kênh thay đổi theo thời gian. Bài báo này trình bày một hệ thống truyền thông dưới nước sử dụng điều chế Khóa dịch tần số (FSK) kết hợp với giải điều chế dựa trên bộ lọc phối hợp để giảm thiểu tác động của nhiễu trong môi trường nước nông, phù hợp với vùng biển Việt Nam. Bằng cách tận dụng khả năng phát hiện tín hiệu tối ưu của bộ lọc phối hợp trong các kênh nhiễu và thay đổi theo thời gian, hệ thống cải thiện đáng kể độ tin cậy của truyền thông trong điều kiện khắc nghiệt dưới nước. Kết quả mô phỏng chứng minh rằng hệ thống dựa trên FSK được đề xuất đạt được tỷ lệ lỗi bit (BER) dưới 10^{-3} ở tỷ lệ tín hiệu trên nhiễu (SNR) vượt quá 20 dB. Kết luận cho thấy điều chế FSK, kết hợp với giải điều chế bộ lọc phối hợp, là một giải pháp phối hợp cho truyền thông dưới nước trong các tình huống nước nông.

Từ khóa: Truyền thông dưới nước; Điều chế FSK; Bộ lọc phối hợp.