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Research Article

A Power-Efficient Optical Modem for Reliable, Long-Distance Communication Using GFDM Technology in Underwater and Terrestrial Wireless Systems

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Abstract:

This paper presents the design of a GFDM-based optical communication modem using MATLAB SIMULINK to improve the power efficiency, reliability and long distance communication in underwater wireless communication (UWC) systems. Conventional techniques such as orthogonal frequency division multiplexing (OFDM) and single-carrier frequency division multiple access (SC-FDMA) are commonly utilized to enhance data rates, reduce BER, and mitigate the impact of multipath fading. However, these methods come with certain limitations. OFDM, for instance, suffers from a high peak-to-average power ratio (PAPR) and significant out-of-band emissions, whereas SC-FDMA is highly susceptible to inter-symbol interference (ISI) in multipath environments. Generalized frequency division multiplexing (GFDM) provides a better flexibility for reducing the PAPR and improve the robustness against Doppler effects of a critical factor in UWC by using non-orthogonal subcarriers. By using MATLAB SIMULINK, the optical communication modem was developed for long distance signal transmission and reception. This approach enhances channel bandwidth utilization and spatial diversity, making it a more effective solution for underwater wireless communication. As a result, GFDM emerges as a promising alternative to conventional techniques, offering improved modem performance by reducing bit error rate (BER), increasing spectral efficiency, and demonstrating greater resilience to variations in underwater channel conditions.

1. Introduction

Underwater wireless communication (UWC) has become a crucial field for various applications, including environmental monitoring, underwater exploration, marine biology research, oil and gas industry operations, and military and defence activities. It plays a vital role in ensuring reliable data transmission between submerged devices and autonomous underwater vehicles (AUVs) and surface vessels, enabling enhanced control, navigation and monitoring capabilities in underwater communication environment. This UWC faces several challenges due to the limitation of signal propagation in water medium, where electromagnetic waves are highly attenuated and optical signals are significantly scattered, especially for the long distance communication in underwater. A traditional underwater wireless communication (UWC) system, with different underwater assets, such as submarines, autonomous underwater vehicles (AUVs), smaller submersibles, and underwater sensors, communicate with each other and with a surface support ship is as shown in the figure 1. In this figure the surface support ship is used as a central communication hub which is

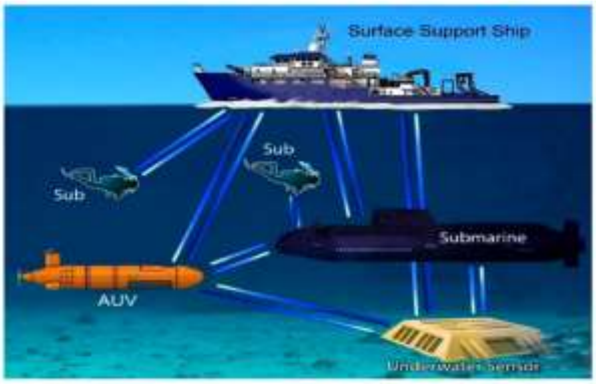

Figure 1. *Underwater Optical wireless communication network*

located on the top of the water surface. It serves as a relay point for transmitting and receiving data to and from in between the underwater assets. The underwater assets are submarines, autonomous underwater vehicles (AUVs), smaller submersibles, and underwater sensors. The blue lines are extended between the ship and the underwater entities represent communication links, that might be either a optical or acoustic or electromagnetic signals, depending on the technology used. The figure 1 highlights a cooperative UWC network where different underwater assets communicate to share data, coordinate the information between them, and relay information to a surface vessel, exemplifying the complexity and need for efficient communication technologies in underwater environments. Traditional UWC techniques mostly depend on acoustic communication due to its range of propagation is long in water. But, acoustic waves are restricted by low bandwidth and high latency, which limits the data rates and is creates a high-speed communication is very difficult. Various modulation techniques, such as orthogonal frequency division multiplexing (OFDM) and single-carrier frequency division multiple access (SC-FDMA), are utilized to improve data rates and mitigate the effects of multipath fading in underwater wireless communication (UWC). Despite their widespread adoption, these methods have certain drawbacks. While OFDM helps achieve a high peak-to-average power ratio (PAPR), it also generates significant out-of-band emissions, affecting transmission efficiency. On the other hand, SC-FDMA is prone to inter-symbol interference (ISI) in multipath underwater environments. To address these challenges, generalized frequency division multiplexing (GFDM) has emerged as a promising alternative. Unlike OFDM and SC-FDMA, GFDM uses non-orthogonal subcarriers, providing greater flexibility and reduced PAPR, which is advantageous for underwater communication where power efficiency is important. GFDM also enhances the spectral efficiency, provides lower latency, and shows improved robustness against Doppler effects, a key consideration given the mobility of underwater equipment and the variability of the environment. These attributes make GFDM highly suitable for UWC, where maintaining reliable, high-speed data communication across complex, dynamic channels is essential.

2. Existing methods on related work

This section provides a literature survey on the topic of optical modems for Underwater wireless communication (UWC) is a critical area of research that explores key concepts, methodologies, and solutions to enhance data transmission efficiency. This study highlights the significance and effectiveness of GFDM in comparison to traditional techniques, demonstrating its advantages in underwater communication systems. It provides the extensive research due to its different applications such as marine exploration, environmental monitoring, and military communications. Traditional acoustic wireless communication system has dominated the field, But, their limitations in bandwidth and low latency have led to the exploration of alternative methods, including optical and radio frequency communication. There a number of works done on this subject [1-27]. A study by reference [19] his study outlines the limitations of underwater acoustic channels, emphasizing the need for efficient communication systems capable of addressing challenges such as multipath fading and Doppler shift. Orthogonal Frequency Division Multiplexing (OFDM) has gained significance in both terrestrial and underwater communication systems due to its robustness against multipath fading. However, one of its major drawbacks is the high peak-to-average power ratio (PAPR), which affects overall transmission efficiency and sensitivity to out-of-band emissions can limit its performance in UWC.

It was demonstrated that while OFDM can improve data rates, its performance deteriorates significantly in underwater environments due to these inherent limitations [15]. Similarly, Single-Carrier Frequency Division Multiple Access (SC-FDMA) has been explored for its efficiency in resource allocation and lower PAPR compared to OFDM. However, it was noted that SC-FDMA is particularly susceptible to inter-symbol interference (ISI) in multipath channels, which is a common occurrence in underwater communications [1]. GFDM has emerged as a promising alternative to OFDM and SC-FDMA, addressing their limitations while enhancing communication performance. In their work, it was highlighted GFDM's use of non-orthogonal subcarriers, which allows for increased flexibility and adaptability in dynamic underwater channels [16]. This flexibility leads to a significant reduction in PAPR, making GFDM more efficient for power-limited underwater systems. Furthermore, the robustness of GFDM against Doppler effects is particularly advantageous for UWC applications.

It was conducted simulations showing that GFDM significantly outperforms traditional methods in terms of spectral efficiency and bit error rate (BER) in underwater scenarios, underscoring its effectiveness for high-data-rate transmission [2]. The integration of MATLAB for modelling and simulating GFDM-based optical modems has facilitated a deeper understanding of their performance in UWC systems. OFDM-Based Underwater Modems: OFDM modems for underwater communication have been designed to exploit frequency diversity and mitigate the impact of multipath propagation. These systems rely on large cyclic prefixes to absorb multipath interference and perform well in shallow-water environments. However, they require complex equalization schemes and are sensitive to Doppler shifts, leading to performance degradation in highly dynamic environments. A hybrid modem is designed for underwater wireless communication which offers high datarate but it produces low SNR and channel power which is presented in [4-8] by using MIMO-OFDM. MIMO-OFDM Modems: Multi-input multi-output (MIMO) systems have been combined with OFDM to enhance spectral efficiency and achieve high data rate. These systems are using multiple antennas to transmit and receive data streams simultaneously, thereby enhancing spatial diversity. Despite these advancements, the computational complexity of MIMO-OFDM systems remains a major challenge, particularly in power-constrained underwater environments. Orthogonal Frequency Division Multiplexing (OFDM) has been extensively studied and applied to underwater communication. It divides the signal into multiple orthogonal subcarriers, allowing for better resistance to multipath interference. However, it is prone to high out-of-band emissions and requires complex synchronization mechanisms to handle Doppler shifts. In summary, each modulation technique has its specific advantages and challenges in underwater communication environments, with different performance metrics such as BER, SNR, data rates, and power efficiency being optimized based on the unique characteristics of each technique. It was utilized MATLAB to design and analyse a GFDM system specifically for underwater communications, revealing improved spectral efficiency and reduced BER compared to OFDM [3]. The simulations demonstrated the potential of GFDM to optimize channel bandwidth, which is critical in the resource-constrained underwater environment. The literature strongly supports the advantages of GFDM over traditional UWC techniques such as OFDM and SC-FDMA. The unique properties of GFDM, including its flexibility, reduced PAPR, and robustness to Doppler effects, position it as a viable solution for enhancing data rates and improving communication reliability in underwater environments. As research continues to evolve, further exploration of GFDM in conjunction with advanced simulation tools like MATLAB will be essential for addressing the ongoing challenges in UWC. This paper presents a GFDM-based optical modem for UWC, implemented using MATLAB. The proposed modem configuration optimizes the spectral efficiency, bandwidth, and spatial diversity in underwater channels, ultimately improving performance in terms of bit error rate (BER) reduction and data capacity. The results demonstrate that GFDM not only addresses the limitations of current modulation techniques but also provides a more resilient approach to UWC, showing promise for enhancing underwater communication systems.

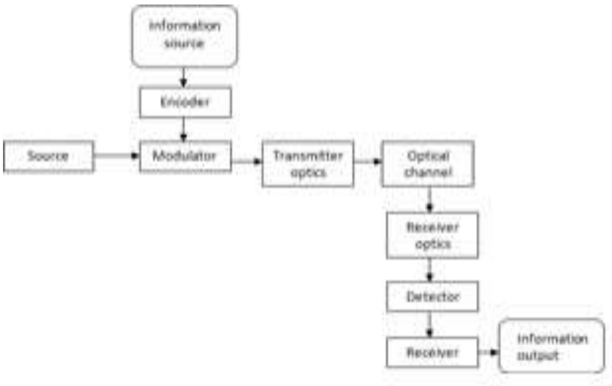

Figure 2. *Schematic representation of optical communication system*

3. Comparison of acoustic and optical communication

A modem facilitates the conversion of digital signals into analog signals for transmission over a communication medium. On the transmitting end, these signals undergo modulation using various techniques such as FSK, PSK, BPSK, and QPSK. At the receiving end, the modem demodulates the incoming analog signals and reconstructs them back into their corresponding digital form. One of the primary challenges in underwater communication is designing a modem that is both cost-effective and energy-efficient. This section explores the fundamentals of underwater optical communication and the design aspects of its modem.

3.1 Optical communication

Underwater communication primarily utilizes optical and acoustic waves for information transmission, with each method offering distinct advantages and limitations. Optical waves, a subset of electromagnetic waves, operate within a wavelength range of 400nm to 700nm [13]. Their high frequency, short wavelength, and rapid transmission speed enable high-speed communication of up to 1 Gbps [11,14]. One of the key inherent properties used in this process is the attenuation coefficient (c), which helps determine the loss of optical power and is measured in m^{-1} [9,10]. Both scattering and absorption contribute to attenuation in underwater optical communication. According to Beer's law, the optical power (I_0) over a distance (d) with a transmitted power (I_t) is determined using Equation 1. Figure 2 illustrates the schematic representation of an optical communication system.

$$I_0 = I_t e^{-cd} \qquad (1)$$

The refractive index (n) is defined as the ratio of the speed of light in a vacuum to its speed in a given medium. It can be linked to the attenuation coefficient using Equation 2 [12,20].
The complex refractive index is expressed as:

Complex refractive index, $m = n + i_k$ (2)

Where i_k represents the imaginary electrodynamic absorption coefficient. This coefficient is associated with absorption through the factor $4\pi/\lambda$, where λ denotes the wavelength of the transmitted signal.

3.2 Acoustic Communication

In an underwater environment, sound waves travel at a relatively slow speed of approximately 1500 m/s. These waves propagate through multiple paths, resulting in signal dispersion. In addition to path loss, spreading loss also occurs, which increases proportionally with the transmission distance. As a result, the total path loss can be determined using Equation 3.

$$a(l,f) = (l/l_r)^k \, a(f)^{l-l_r} \qquad (3)$$

where f- frequency of signal, l – transmission distance (considered with reference to a distance l_r) k- path loss exponent, $a(f)$ – absorption coefficient

3.3 Design of Underwater Acoustic Modem

The key components of an underwater communication system include a power unit, a processing unit, and signal adaptation circuitry. The power unit comprises a battery and DC/AC converters, ensuring a stable power supply. The processing unit consists of a processor and a small memory, with the option to incorporate external memory if needed. A loudspeaker or hydrophone serves as the signal source. The circuitry is responsible for adapting signals for processing by the processor. In commercial modems, RS-232 or a USB port is commonly used for programming or retrieving stored data. Figure 3 presents the block diagram of the underwater acoustic communication modem. A performance comparison of acoustic and optical underwater communication using the telemetry method has been conducted. Optical communication offers a range of 100 meters with a data rate of 1 Mbps, achieving a performance efficiency of 30,000 bits per joule. In contrast, acoustic communication covers several kilometres, but with a lower data rate of 1 Kbps and a performance efficiency of 100 bits per joule. Table 1 presents a comparative analysis of underwater communication systems [17,18].

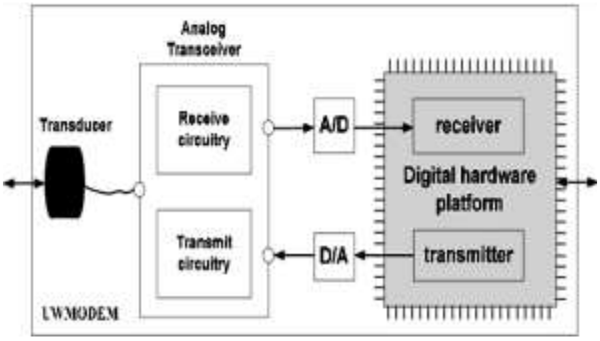

Figure 3. *Block diagram of underwater acoustic communication modem*

Table 1. *Comparison of underwater communication systems*

Parameter	Acoustic	Optical
Transmission distance	Upto 20Km	10-30 m
Attenuation	Distance and frequency Dependent	Distance
Speed	1500 m/s	2.255 x 10^8m/s
Transmission power	Few tens of watts	Few watts
Cost	High	Low
Data rate	In Kbps	Upto Gbps
Antenna size	0.1m	0.1m
Latency	High	Low

4. Proposed method

In this paper, a power-efficient optical modem has been proposed, which can take the optical signals as the input. Optical signals are transmitted in the optical channel using high-intensity laser or LED sources, which convert electrical signals into optical form. These optical signals propagate through optical Fibers or free-space optical communication links, ensuring minimal signal loss and high data rates. The signals are modulated using GFDM techniques to achieve efficient spectral utilization and robustness against channel impairments. Advanced photodetectors at the receiver end convert the optical signals back into electrical form for further processing.

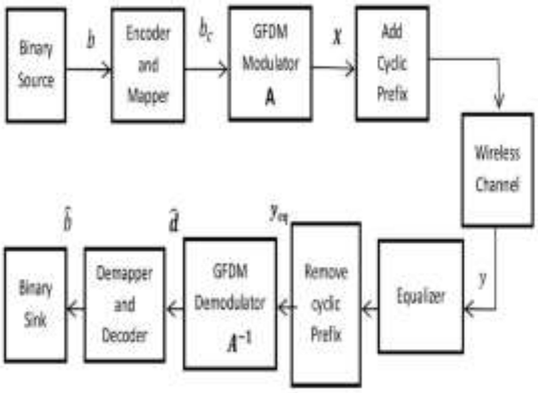

Figure 4. *Block diagram of GFDM Communication system*

The figure 4 shows a block diagram of a Generalized Frequency Division Multiplexing (GFDM) communication system. The diagram can be split into two main sections: the Transmitter and the Receiver. The transmitter section of this block diagram consists of a Input Binary source which generates digital binary data stream that is to be transmitted to encoder and mapper. Encoder adds error-correction coding to the input bit stream to improve robustness against noise and channel impairments. Mapper converts the encoded bits into complex symbols using modulation techniques (like QAM or PSK). GFDM Modulator applies GFDM modulation to the symbols, which involves subcarrier mapping and circular filtering to create a multi-carrier signal after that Add Cyclic Prefix a cyclic prefix is added to the modulated signal to handle multipath fading and to prevent inter-symbol interference (ISI). Now the transmitted signal, is then sent over the channel. Here the channel is modelled as a Additive white Gaussian Noise. The receiver section of a GFDM block diagram consists of a remove cyclic prefix, at this stage the cyclic prefix is removed to restore the original signal format. GFDM demodulator Performs the inverse operation of the GFDM modulator, extracting the original data symbols by applying filtering and subcarrier demapping. Demapper converts the received symbols back into the corresponding bit stream. Decoder applies error correction decoding to recover the original input bit stream from the encoded bits. The final output is the recovered data stream, which is ideally identical to the input bit stream.The figure 5 shows the simulation circuit of the proposed GFDM based optical modem for underwater communication. This figure shows a Generalized Frequency Division Multiplexing (GFDM) based Simulink model for an underwater wireless communication modem. The model uses blocks for transmitting, processing, and receiving signals in an underwater environment, which is typically challenging due to high attenuation, noise, and multi-path effects. The transmitter section consists of a different signal processing blocks such as it generates a stream of random symbols that represents digital data to be transmitted. The sampled data is modulated using 16-QAM (Quadrature Amplitude Modulation) and this converts the digital symbols into complex-valued signals that can be transmitted over a channel. D1_matrix & D2_matrix are used to process the QAM-modulated signals for different transmission paths. They prepare the signals for transmission by applying transformations. FFT (Fast Fourier Transform) is applied to convert the signals from the time domain to the frequency domain. The signals are normalized to ensure consistent power levels. It is applied to modify the signal phase for transmission**.** Sum_x1_x2 is used to combined signals from different paths before transmission. The combined signal is packed into a structured format for transmission. This LED3 & LED4 are used to transmit the packed signals. The LEDs convert the electrical signals into optical signals that can be received by photodiodes. Then receiver section converts the optical signals into digital data. PhotoDiode3 & PhotoDiode4 detect the optical signal from the LEDs. The detected light intensity is converted back into an electrical signal.

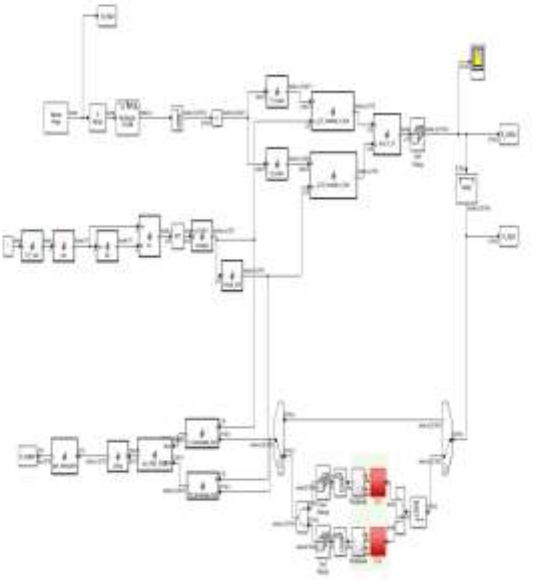

Figure 5. *Proposed simulation circuit of a underwater optical communication modem using GFDM*

Input Packing 1 & 3 blocks are used to unpack the received signals and prepared for demodulation. D1_demodulate_freq & D2_demodulate_frequency Blocks are used to demodulate the received signals using the same matrices which is used at the transmitter. This helps to reconstruct the transmitted data. AWGN (Additive White Gaussian Noise) Simulates real-world noise that might be present in a communication channel. The received signals are

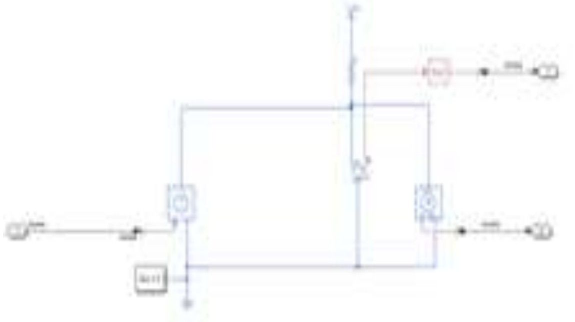

Figure 6. *Illustrates the diagram of the LED block.*

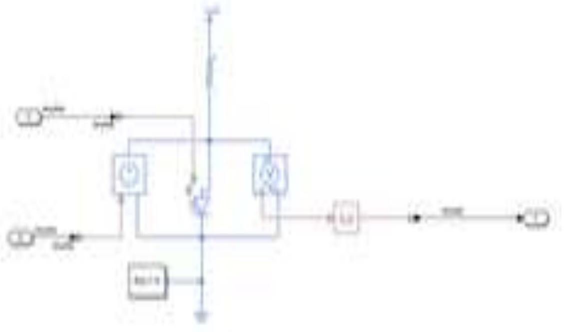

Figure 7. *Conversion of light into electrical signals*

demodulated to recover the original digital data. The complex-valued QAM signals are mapped back to symbols. Unmap block Converts demodulated signals back into their original digital form.

Sum_Dhat1_Dhat2 block is the reconstructed signals from different demodulation paths are summed to obtain the final output. Rx_output block Display the final received data after demodulation and reconstruction. Therefore, the integration of GFDM in our optical modem offers improved spectral efficiency, flexibility, and reduced interference, making it a promising solution for next-generation optical and acoustic communication systems. GFDM uses non-orthogonal subcarriers, which are more resistant to Doppler shifts and multipath effects than OFDM. A tailored pulse shaping filter is applied to each subcarrier to reduce out-of-band emissions and minimize inter-symbol interference (ISI). A novel channel estimation technique is employed to compensate for time-varying multipath effects. The system adaptively adjusts the modulation parameters based on channel conditions to maintain optimal performance. The modem includes a power allocation mechanism that dynamically adjusts transmission power based on channel conditions, ensuring efficient use of energy without sacrificing performance. Low-density parity-check (LDPC) codes are applied to enhance error correction, thereby improving reliability at lower power levels. Figure 6 shows illustrates the diagram of the LED block and the conversion of light into electrical signals is displayed in figure 7.

6. Simulation results

MATLAB-Simulink is used for the simulation of a OPTICAL Modem using GFDM transmitter and receiver for Underwater Wireless Communication. MATLAB R2020 version is used for the simulation. Figure 8 shows the input to the transmitter in this the bit values at different bit positions being sent to the transmitter, these bit values range from 0 to approximately 15. Here the shown bit positions varies from 2000 to 2200 and the signal appears to fluctuate randomly within this range. Figure 9 shows the output to the transmitter in this values are ranges from 0 to about 15, but there is significant degradation or alteration in comparison to the transmitter input. Figure 10 shows the power spectral density of transmitter output using Welch's method which is used to reduce the spectral leakage in this the range of frequencies over which the signal is present i.e., the bandwidth approximately 50 MHz and the average power level within the main bandwidth (in dB/Hz) fluctuates between

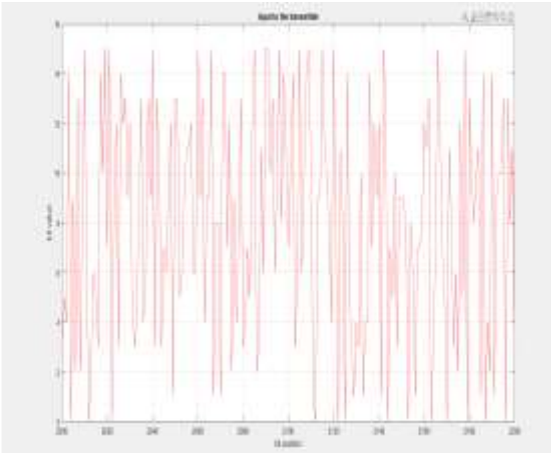

Figure 8. *Input to the transmitter*

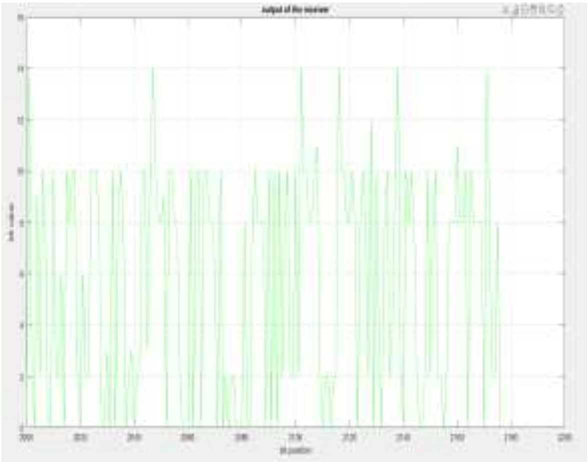

Figure 9. *Output of the transmitter*

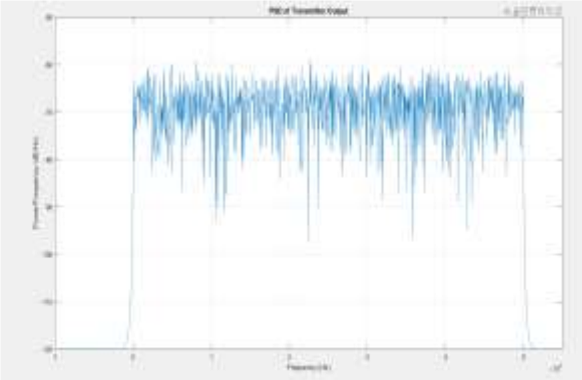

Figure 10. *Power spectral density*

approximately -70 dB/Hz and -60 dB/Hz. The figure 11 shows a real-time spectrum analyzer or FFT-based analysis with adjustable windowing (Chebyshev window) and overlap settings. The spectrum is displayed in a frequency range of approximately -25 MHz to 25 MHz, with channel power 39.572 dBm, representing the total power within the selected frequency range.

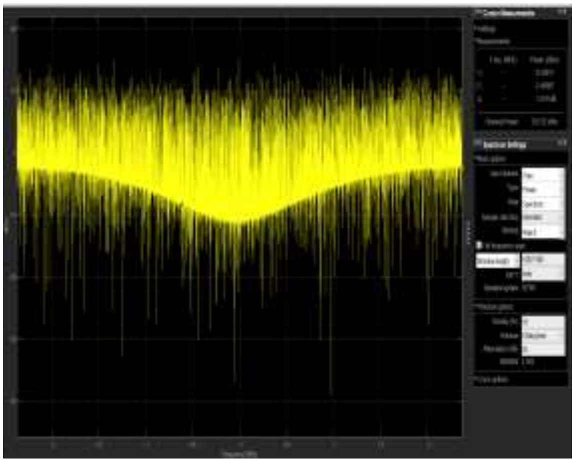

Figure 11. *Power spectrum analysis with power distribution*

7. Conclusion

This paper presents the design of a power-efficient optical modem capable of receiving optical signals as input. Optical signals are transmitted through the optical channel using high-intensity laser or LED sources that convert electrical signals into optical form. These optical signals travel through optical fibers or free-space optical communication links, ensuring minimal signal loss and supporting high data rates. The functionality of the proposed modem design is validated through simulations, which demonstrate strong signal transmission capabilities, efficient bandwidth utilization, and stable power distribution. These features enable the system to manage dynamic inputs while providing reliable and efficient data communication. The primary objective of this design is to enable long-distance communication with reduced power consumption and optimized data transmission. By concentrating more energy in a smaller frequency range, the system improves spectral efficiency. For long-distance transmission, focusing on a narrow bandwidth ensures greater efficiency. Simulation results confirm the successful transmission and reception of optical signals, validating the efficiency of the proposed optical modem. Furthermore, the system is designed to achieve a high signal-to-noise ratio (SNR), low out-of-band emissions, and resilience to inter-symbol interference (ISI) and multipath fading. The future work involves implementing the proposed optical modem for both terrestrial and underwater applications to realize effective underwater communication, paving the way for its practical deployment in real-world environments.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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- **Funding information:** The authors declare that there is no funding to be acknowledged.
- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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