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Performance Analysis of Underwater Optical Communication System in Turbulent Link

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HIGHLIGHTS

- Implementing PWM-PPM was better than PWM for 650 nm and 60mw laser diode.
- The attenuation in turbulent water due to bubbles has been higher than that in clear water.
- The attenuation decreases as the bubbles move away from the transmitter.
- The letter "e" was the highest SNR, while letter "a" was the lowest SNR.

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ABSTRACT

Underwater wireless optical communication (UWOC) systems have been identified as a suitable replacement technology with high data rates over relatively medium transmission ranges for underwater communication. In the research, we propose a new optical hybrid modulation format for carrying the letters over underwater wireless optical communication (UWOC) system. This hybrid modulation format combines pulse position modulation (PPM) with digital pulse interval modulation (DPIM) to increase the transporting speed. The proposed UWOC system is experimentally investigated in the laboratory over a clean and turbulent water channel. The message was electrically modulated in the transmitter with PPM-DPIM format and then applied to a laser diode. The laser diode emitted light at a wavelength of 650 nm with a power of 60 mW. At the receiver, the photodiode, with its amplifier circuits, sends the received signal to the microprocessor to restore the origin message. The results showed that the received power and signal-to-noise ratio (SNR) decreased with elongating the transmission distance. In addition, the attenuation is raised with increasing distance. The bubbles source is also situated at distances of 25 cm, 50 cm, and 75 cm from the transmitter in turbulent waters. The results showed that locating the bubble source decreases the system's performance. The best results were obtained when the bubble source was 75 cm away from the transmitter. Finally, the hybrid modulation formats (PPM-DPIM) can increase the speed of letter transmission, reduce the bit error rate (BER), and minimize the effect of scattering and attenuation in water channels.

1. Introduction

Underwater wireless communication (UWC) systems have been considered alternatives to wired communications [1]. Because water constitutes 71% of the globe, transmitting information and communication to every point in the seas has become very necessary. The UWCs indicate the data transition through an undirected water environment using wireless carriers like waves, radio-frequency (RF), optical, and acoustic waves [2,3].

Underwater research and exploitation have expanded dramatically in the previous decade, from oceanographic studies to offshore oil extraction [4]. As a result, there is a rising demand for underwater wireless communication (UWC) systems that are both dependable and high-data-rate. Acoustic waves have traditionally been utilized to establish underwater communication. However, due to the substantial frequency-dependent attenuation of sound in salt water, the bandwidth of an underwater acoustic channel is restricted to hundreds of kHz [5].

Temperature, salinity, pressure, and turbulence all affect attenuation. The nominal acoustic attenuation as a function of frequency is shown in Figure1(a). Acoustic communication methods suffer from a considerable time delay due to the slow transmission of sound waves. Furthermore, due to the conductivity of saltwater at radio frequencies, radio frequency (RF) transmission is severely constrained [6]. The electrical conductivity of seawater is approximately 4.3 Siemens/m, which is 2 to 3 orders of magnitude greater than that of natural freshwater. The RF attenuation in seawater as a function of frequency is shown

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in Figure 1(b) [6].This technology can contribute to many uses in underwater environmental monitoring, gas and oil exploration, and the military [7, 8].

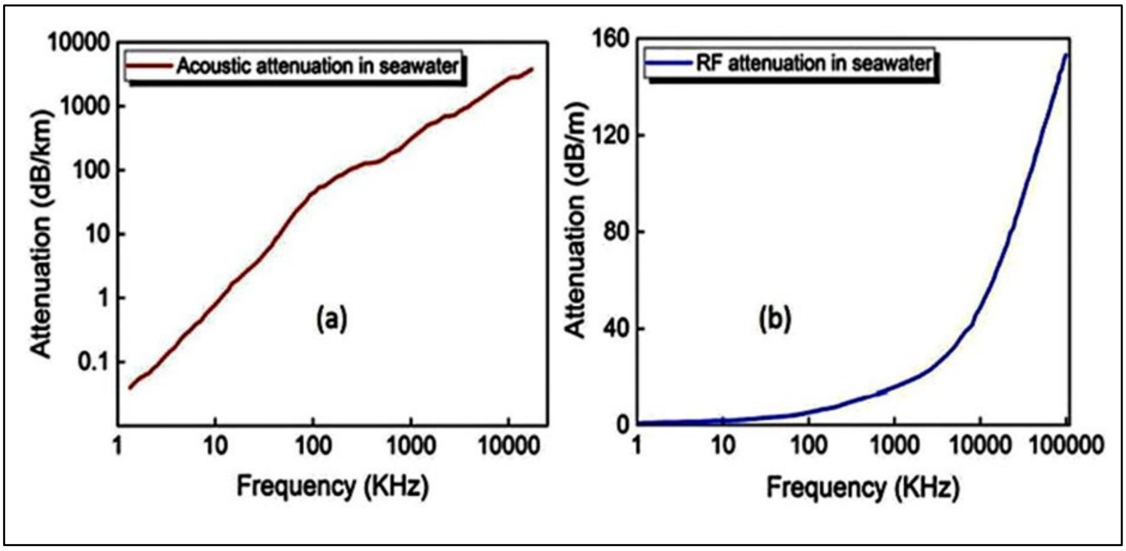

Figure 1: (A) Acoustic attenuation in representative seawater, (B) RF attenuation in seawater [6]

UWOC systems have been used early for military objectives, particularly underwater communications UWOC systems [9]. Schirripa [10] examined the possibility of wireless optical communications between underwater terminals and above-ground (satellite). Researchers from the University of California's Lawrence Livermore Laboratory demonstrated a one-way optical communication system from land to a submarine. A blue-green laser source was used to create light pulses in the transmitter of the UWOC system [11]. Because of its small construction, it could be transported by plane or land vehicle. The transmitter focuses the transmitter's output light beam on a relay satellite that reflects the beam to a submarine [12]. Both US and Russian navies have established other UWOC tests of the satellite-to-submarine and plane-to-submarine topologies[13]. Mixed optical communication lines of tens of kilometers in Free-space optical communication (FSO) and a few tens of meters UWOC have been established. Military applications have dominated UWOC's attention throughout the years [1]. The huge commercial marketing of UWOC has so far been unsuccessful. Only a few UWOC systems were marketed, such as the BlueComm UWOC system, which can transfer 20 Mbps of data underwater over a 200-meter distance [14]. Researchers proposed the notion of underwater wireless sensor networks (UWSNs) to meet the high needs for ocean exploration to deliver high bandwidth data transfer, which aided the development of UWOC [3]. The UWOC market has begun to show signs of a bright future. UWSNs comprise many dispersed nodes, including autonomous underwater vehicles (AUVs)[15], seabed sensors, relay buoys, and remotely operated underwater vehicles. These nodes can detect, process, and communicate, allowing for collaborative underwater environmental monitoring [16]. The following are some examples of underwater wireless communication applications: It is also utilized for pollution control and climate monitoring. It includes an application for identifying things on the ocean floor as well [17]. Environmental monitoring and oceanographic data gathering are also carried out via underwater radio communications. Archaeology, search and rescue, and defensive devices are all included in these undersea applications. It also includes applications for identifying things on the ocean floor. Equipment monitoring and control, as well as autonomous underwater vehicles, employ AUVs [18]. It can also be used in underwater autonomous vehicles' voice guidance technology [19]. It is also utilized in environmental monitoring applications, including climate logging, pollution management, and natural catastrophe predictions for port security.

UWOC due to its scalability, versatility, and reliability, has recently been implemented to meet a range of requirements in various underwater applications. Optical transmission has higher bandwidth, better security, and lower time latency, as compared to its conventional equivalent, namely acoustic communication. This helps UWOC to be a strong alternative to high-speed and large-data underwater communications requirements such as imaging, real-time video processing, and high-throughput sensor networks [20-25]. In 2013, Asmahan Assad et al developed an underwater optical communication system with a 532nm LD. Different sorts of water were utilized in different places (distilled, Euphrates, Tigris, and Shat Al Arab). Finally, she discovered that the Tigris River provides the greatest underwater transmission for long-distance links. In 2016, Jing Xu et al used a Monte Carlo model to explore the property of red laser transmission in water about channel bandwidth and extinction coefficient [26]. In highly murky water, he found, red light favored the blue-green laser. In addition, a broadband underwater optical wireless communication system based on cost-effectiveness was suggested and proven experimentally. Salah et al. investigated the BER and losses in an underwater optical wireless communication system (UWOC) with various water types in 2017 [27]. Salt and Maalox content were found to enhance BER and power losses. In 2017, Hassan Makine Oubei et al. investigated the performance of underwater wireless optical communication networks while varied air bubble populations were available [28]. The UWOC link performance was decreased as a result of the deteriorated quality of the received signal caused by the air bubbles.

In this paper, a new combination of modulation formats is proposed to enhance the transmission performance of the UWOC system. PPM is combined with DPIM to modulate the letters of the transmitted massage. First, the transmitter sends the optical PPM-DPIM signal over the water tank. Consequentially, the receiver restores the original message from the detected signal and displays it on the screen of the personal computer. In order to show the effect of the water channel on the performance of the proposed system, the signal launched into clear, and turbulent water channels. The results reveal that the attenuation coefficients are increased with enlarging channel length for clear and turbulent water channels. Further, the attenuation coefficient is raised when the turbulent source become near to the transmitter. In addition, the value of SNR depends on the type of letter, in which the letter "e" has the highest SNR. To our knowledge, this is the first time use of hybrid PPM-DPIM modulation formats in UWOC systems.

2. Theoretical and Background

Optical transmissions in an underwater medium such as clear, ocean, turbid and harbor, or other forms displayed considerable variation compared to the wavelength. The large information bandwidth available at visible wavelengths has also opened the possibility for high-speed, wireless communications in the underwater environment. Unfortunately, the propagation of light underwater is affected by both absorption and scattering [29]. The extinction coefficient C(λ) of the aqueous medium consists of the absorption coefficient and the scattering α(λ), and β(λ) respectively [30].

$$C(\lambda) = \beta(\lambda) + \alpha(\lambda) \quad (1)$$

The propagation loss factor is a function of wavelength, the channel length according to Berr-lambert law[30].

$$L_{Pr}(\lambda, z) = exp(-C(\lambda)d) = \frac{P_R(\lambda)}{P_T(\lambda)} \quad (2)$$

So,

$$C(\lambda) = \frac{1}{d}\ln\frac{P_T(\lambda)}{P_R(\lambda)} \quad (3)$$

where: $P_T(\lambda)$: optical transmitting power, $P_R(\lambda)$: optical receiver power, *d*: The length of the water channel.

Due to the no homogeneity that seawater exhibits, α (λ) changes with temperature and depth of water [31]. Then will be the corresponding phrase.

$$\mathrm{L\ (m)} = \frac{1}{\alpha(\frac{dB}{m})} 10\log_{10}\frac{P_T}{P_R} \quad (4)$$

The signal-to-noise ratio (SNR) is the proportion of signal power to noise power in dB [32,33]. Equation 5 has been used to calculate it.

$$\mathrm{SNR} = 10\log\frac{\mathrm{P_s}}{\mathrm{P_n}} \quad (5)$$

P_n Is the average noise power, and P_s is the average signal power.

Characters were sent using the UWOC system using a new combination of pulse position modulation (PPM) with - digital pulse interval modulation (DPIM) format.

In UWOC systems, the pulse position modulation (PPM) scheme is a common modulation approach. PPM offers significantly greater energy efficiency than OOK modulation and does not require dynamic thresholding. However, it requires the cost of a lower bandwidth utilization rate and transceivers that are more complicated. In pulse position modulation, each of the M bits broadcast was modulated as a single pulse in one of the 2^Mtime slots, with the pulse position representing the transmitted data. The major disadvantage of PPM modulation is the necessity for precise time synchronization. Any timing jitters or synchronization will significantly reduce the system's BER. Several scholars have examined the performance of the PPM scheme over UWOC channel models in recent years.

In UWOC, digital pulse interval modulation (DPIM) is also frequently used. An "On" optical pulse slot is transmitted first, followed by a series of "Off" slots in this modulation. The number of "Off" slots is determined by the transmitted symbol's decimal value, and a guard slot is frequently included to avoid transmitting consecutive "On" pulses [34]. DPIM also outperforms PPM and PWM in terms of spectrum efficiency. The fault propagation in demodulation is the most serious issue with DPIM. DPIM is used in a variety of UWOC applications for ROVs and AUVs.

3. Experimental setup of the UWOC system

The UWOC system consists of the transmitter, the water channel, and the receiver as shown in Figure 2. The message, which comprises letters, was applied to the transmitter. The letters were modulated by pulse position modulation and digital pulse interval modulation (PPM-DPIM) hybrid format. The results were obtained for pure water and pure water in the presence of turbulence. The UWOC transmitter uses a 650 nm wavelength directly modulated laser diode. PC (personal computer) sends a digital signal to an Arduino, which controls the transmitter via pulse position modulation and digital pulse interval modulation based on the data sent bit. The signal was modulated using pulse position modulation and digital pulse interval modulation. The laser's applied voltage was 4 V, and it uses 60 mW optical power to produce electrical optical power.

The water tank has length, width, and height measurements of 1 m, 30 cm, and 40 cm, respectively. In addition, was filled with 60 liters of pure water. The glass thickness of the transmission window was 3 mm. To create air bubbles in the water tank, an electric motor (air pump type) was utilized; the motor has two degrees of air bubbles speed: low and high, and the motor was practically operated at low speed. To achieve regular turbulence of air bubbles, the electric motor was attached to a plastic pipe, with the other end of the plastic pipe connected to a jet. The jet was set at three different distances from the transmitter: 25 cm, 50 cm, and 75 cm. The received signal was detected by a PIN photodiode that converts an optical signal into an electrical signal. Then, the massage was demodulated by an Arduino microcontroller that connected to the personal computer. The massage was displayed on the screen and saved into a file.

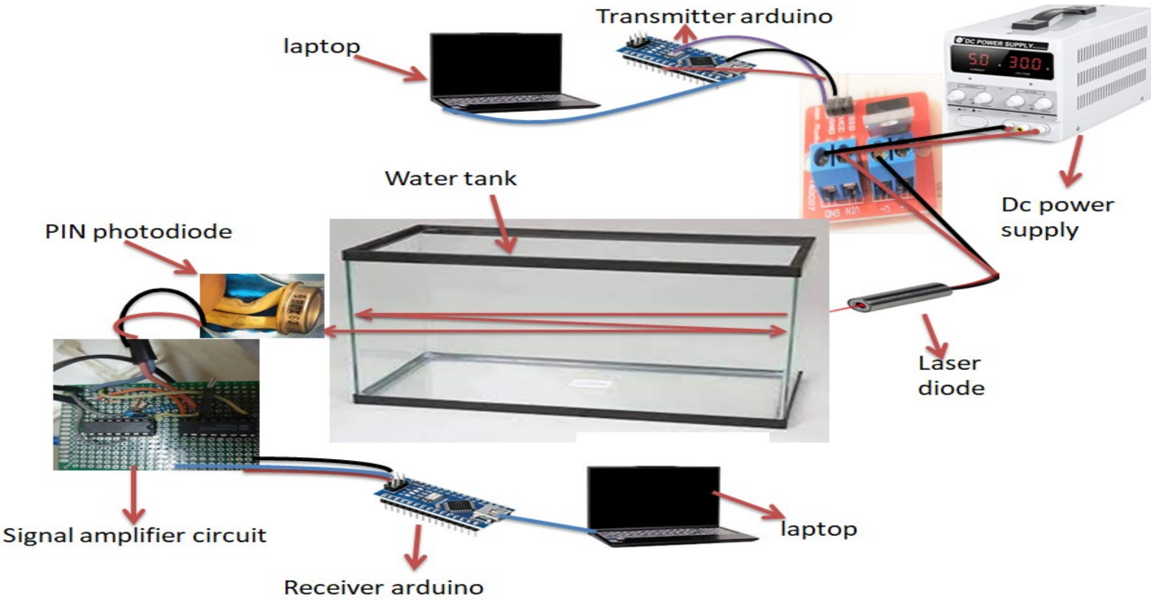

Figure 2: Shows an experimental setup for a UWOC system using a 650 nm laser diode source

4. Results and discussion

The examination and measurements of the results were carried out in two cases, the first case without the presence of turbulence (static water), and the second case with the presence of turbulence using a bubbler device placed at different distances from the transmitter (dynamic water). The attenuation and SNR were measured at distances of 1 m, 2 m, and 3 m using reflective mirrors (planar mirrors). Figure 3 depicted the attenuation as a function of transmission distance. The attenuation is measured for clear water with the absence and presence of turbulence due to bubbles. The power of the laser is adjusted at 60 mW. The attenuation is calculated using Equation (4)[31]. The attenuation is measured for a distance of (1 m, 2 m, and 3 m) respectively. It can be observed that the attenuation increased with extending the distance. The value of the attenuation increased from 0.372 dB to 5.032 dB when the distance increased from 1 m to 3 m. As expected, the losses due to attenuation are increased by extending the transmission long. The reason for this, the light is subjected to more absorption in addition to scattering and reflection.

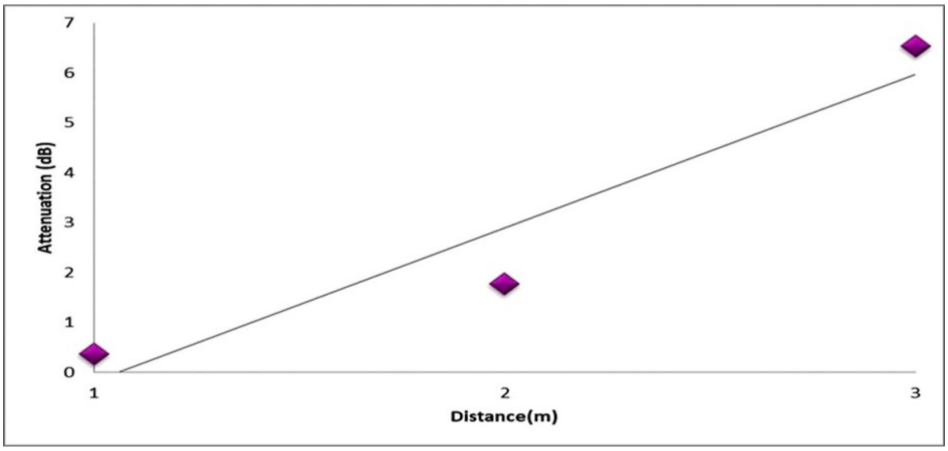

Figure 3: The attenuation against distance in clear water

The signal-to-noise ratio (SNR) is measured as a function of distances to explore the quality of propagated signal through the water channel. Here, SNR is registered according to a group of transmitted letters (a, b, e, h, and z) that propagated over the aforementioned water channels. The SNR is calculated using Equation (5) [32] from the measurements of transmitted and received powers. Figure 4 shows the obtained results for clear water. In general, the SNR is reduced with increasing the transmission distance. The highest SNR is recorded for clear water without turbulence. The SNR of a turbulence water channel with a bubble source at 25 cm is the lowest. In other words, the SNR is limited by the location of the bubble source, where it is raised by reducing the distance between the bubble source and the transmitter. In addition, the measured SNR across the clear water channel 1 m long was 34.49 dB and it was higher than that achieved in [34].

In clear water, the SNR of transmitting the "e" letter is higher than other letters. This is due to the average power of the "e" letter being higher than the other tested letters. In contrast to other letters, the "e" letter has the highest ratio of turn-on time (Ton) to signal period, which is called a duty cycle. The "e" letter has the largest duty cycle equal to 0.78571 and therefore has the highest values of SNR. For example, the recorded SNR for the "e" letter in a clear water channel at a distance of 1 m is 34.5 dB while it is equal to 31.3 dB for the "h" letter. Also, the recorded SNR for the "e" letter in a clear water channel at a distance of 3 m is 11.96 dB while it is equal to 8.75 dB for the "h" letter.

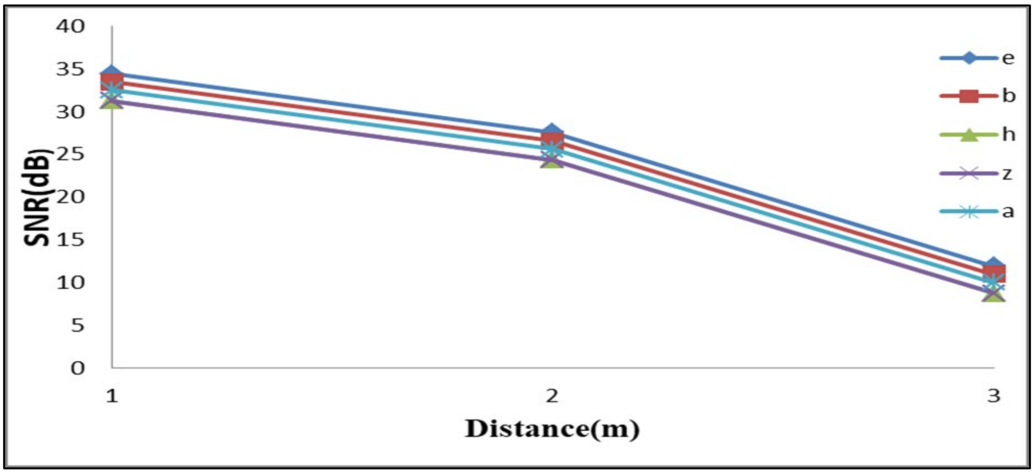

Figure 4: Signal-to-noise ratio versus distance in clear water

To demonstrate the effect of bubbles on the transmitted signal inside the water medium, the source of the bubble is located at distances of 25 cm, 50 cm, and 75 cm apart from the transmitter. Figure 5 displays the attenuation versus the transmission distance when the source of the bubble is allocated 25 cm apart from the transmitter. It can be noticed that the attenuation is raised with increasing distance. The attenuation is changed from 2.39 dB to 9.54 dB as the distance increases from 1 m to 3 m. In contrast, to clear water, the attenuation was raised by about 2 dB at 1 m and 3 dB at 3 m. Moreover, the attenuation was measured for bubbles source positioned at 50 cm and 75 cm apart from the transmitter as shown in Figure 6 and Figure 7. Fortunately, the recorded attenuation is lower than that bubble source at 25 cm. In other words, the magnitude of attenuation depends on the position of the bubble source, where it is raised by reducing the distance between the bubble source and the transmitter.

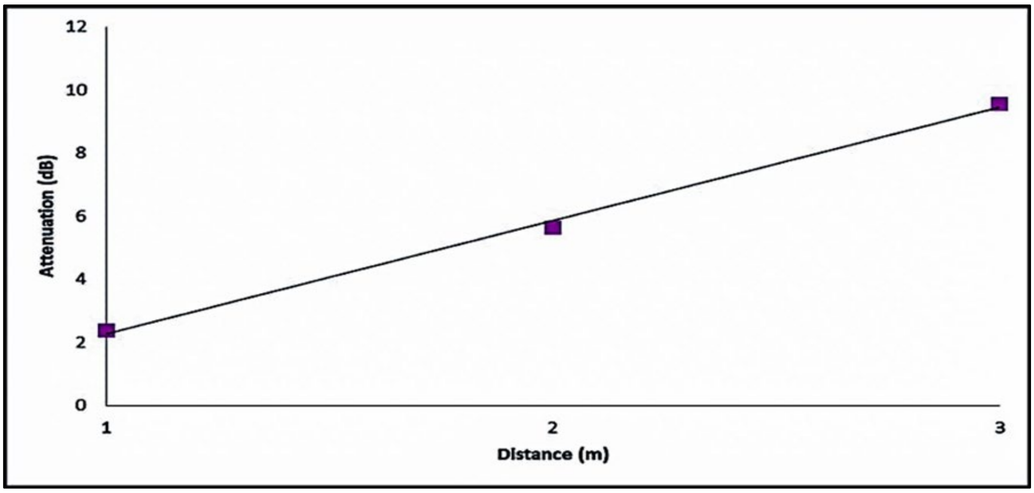

Figure 5: Attenuation versus distance in a clear water channel with bubbles at 25 cm from the transmitter

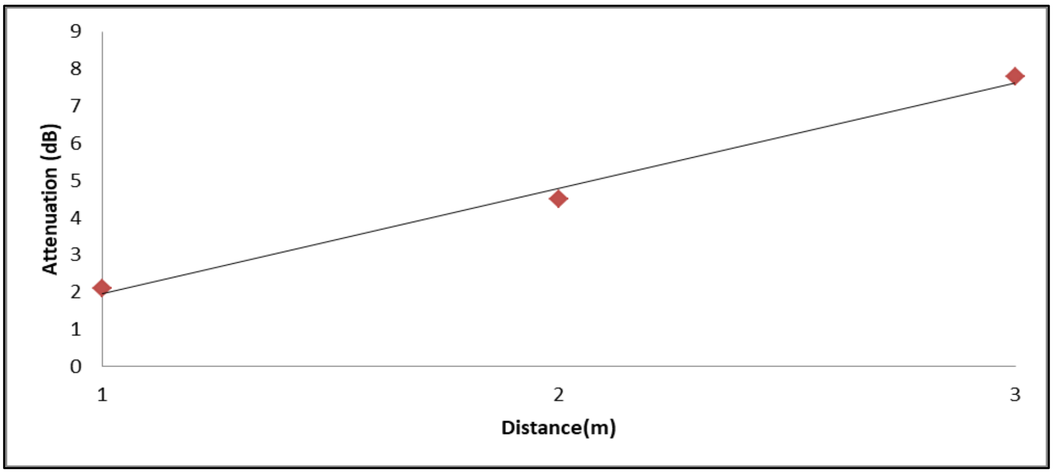

Figure 6: The attenuation against distance in clear water with bubbles after 50 cm

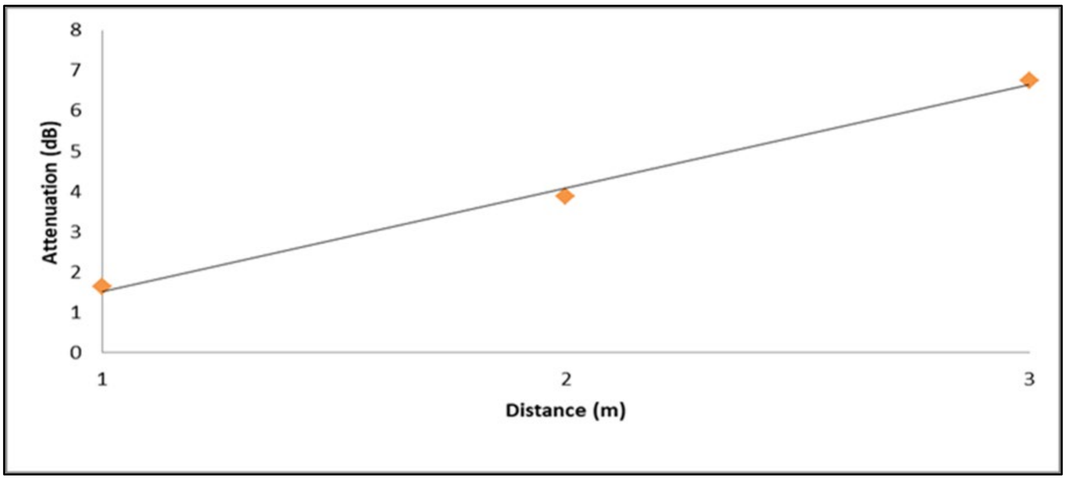

Figure 7: The attenuation versus distance in clear water with bubbles after 75 cm

The SNR was measured at three distances 1 m, 2 m, and 3 m., For example, SNR was measured at a distance of 3 m. The measured SNRs for the "e" and "h" letters in a clear water channel with a bubble source at 25 cm are 9.1 and 5.74 dB as illustrated in Figure 8. At the same distance, the SNRs for "e" and "h" letters in a clear water channel with a bubble source at 50 cm are 10.71 dB and 9.71 dB as illustrated in Figure 9. At the same distance, the SNRs for "e" and "h" letters in a clear water channel with a bubble source at 75 cm are 10.74 dB and 11.74 dB as illustrated in Figure 10.

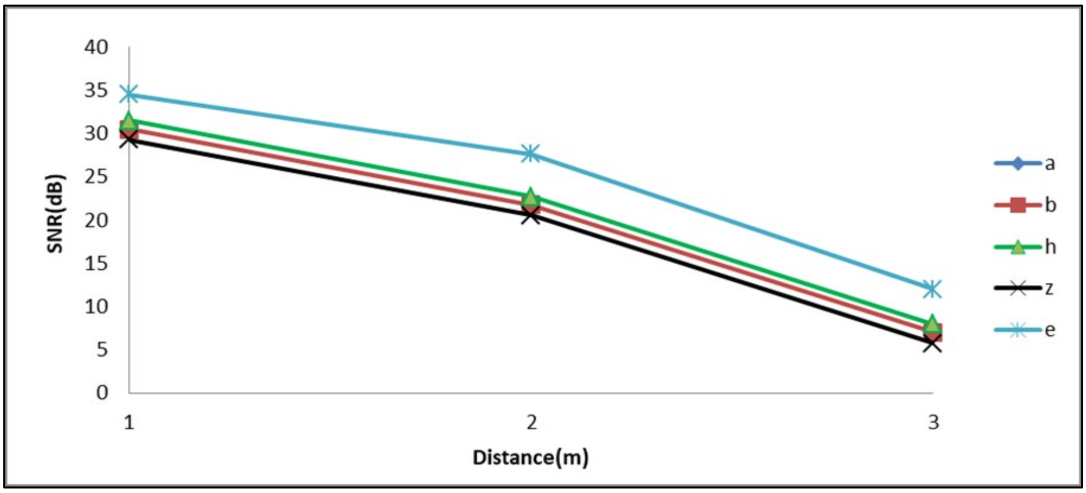

Figure 8: Signal-to-noise ratio against distance in clear water with bubbles after 25 cm

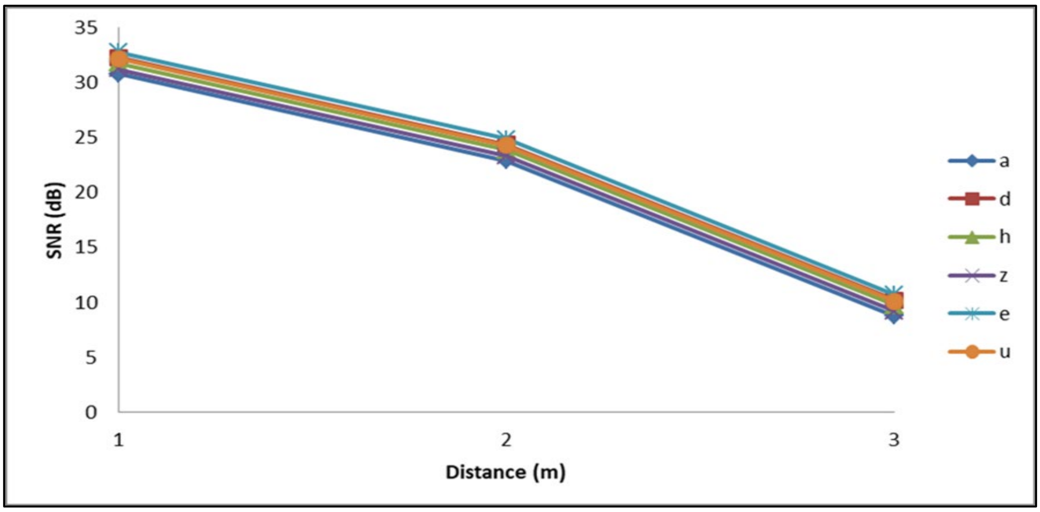

Figure 9: Signal-to-noise ratio and distance in clear water with bubbles after 50 cm

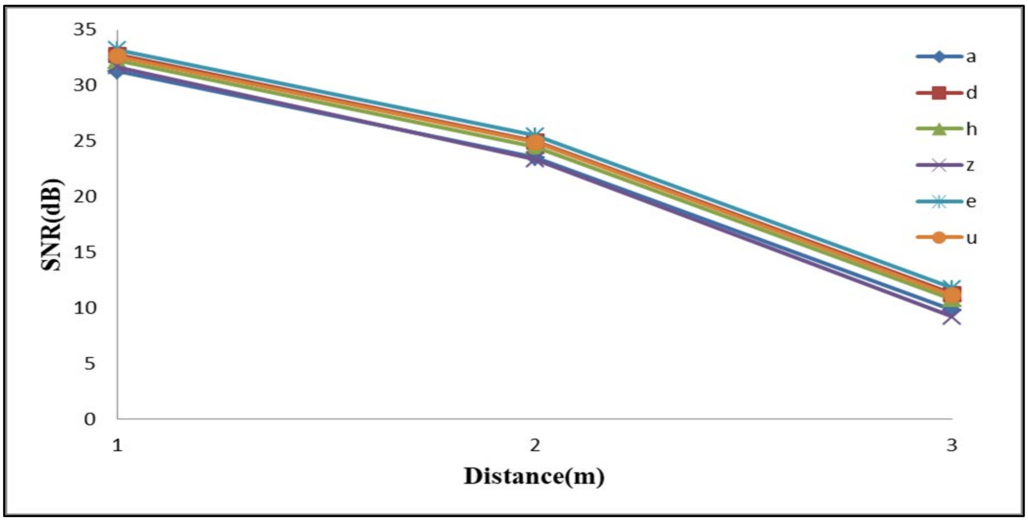

Figure 10: Signal-to-noise ratio and distance in clear water with bubbles after 75 cm

In previous research, a wavelength of 640 nm was used using PWM at a distance of 1 meter to obtain good results [34] table. Another different wavelength was used using PWM for a distance of 7 meters to obtain better results than the previous research [35].The above results are presented in Table (1) and compared with the current work.

Table 1: Comparison of the proposed study to existing literature using various modulation techniques in clean water

Modulation formats	Transmitting distance	Transmittd power	Received power in 1m	Attenuation coefficient α in 1m	SNR In 1m	Ref.
PWM	1 m	80 mw	32 mw	9.79 dB/m	24.6 dB	[34]
PWM	7 m	50 mw	23 mw	3.37 dB/m	33.6 dB	[35]
PWM -PPM	1 m,2 m,3 m	60 mw	35.8 mw	2.33 dB/m	34.4 dB	This work

5. Conclusion

In the system, the transmitter and receiver have been designed to transport character by the proposed UWOC system. 60 mW laser sources with a wavelength of 650 nm are used to carry the massage. In addition, three types of water channels, namely; clear water, salty water, and turbulence channels, have been examined. The results were found in the laboratory for these channels. The turbulence has been induced using a bubble source placed on three positions 25, 50, and 75 cm apart from the transmitter.

The values of attenuation and SNR for the PPM-DPIM UWOC system have been measured in all cases of two types of channels. The results showed that the attenuation increase with increasing distance, while the SNR decreases with increasing distance from 1 to 3 m. Also, the attenuation becomes high for the water channel with bubbles, specifically, when the position bubble source is near to the transmitter. This is due to occurring higher scattering with bubbles. In a clear water channel, the transmission performance of the PPM-DPIM UWOC system is better than in the presence of turbulence.

Author contributions

software, Murtadha M. Joudha; validation, Salah A. Adnan, and Jassim K. Hmood; formal analysis, Salah A. Adnan; investigation, Jassim K. Hmood; resources, Murtadha M. Joudha; data curation, Salah A. Adnan; writing—original draft preparation, Murtadha M. Joudha; writing—review and editing, Salah A. Adnan; visualization, Jassim K. Hmood; supervision, Salah A. Adnan, and Jassim K. Hmood; project administration, Salah A. Adnan. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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