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Effective Signal Transmission from Underwater to Air Utilizing Hybrid Communication Systems

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Underwater optical communication (UOC) and off-surface areas wireless communications are a rapidly growing field, especially with the emergence of new technologies such as autonomous underwater vehicles and above/water drones. The challenge lies in the absence of a water surface platform to transfer the signal from underwater to off surface. This research investigates the design and implementation of a hybrid communication system that successfully transmits signals from underwater environments to above-water. The study utilizes OFDM as method to generate data on the integration of underwater optical wireless communication (UWOC) at 532nm and LOS optical channel. After adjusting the line of sight through the angle of refraction and overcoming the challenges of water and above water conditions as well as ambient lighting, ambitious results were obtained 100 meters above clear water and 40 meters in haze wither at a depth of 10 meters for transmission. The research has mitigated challenges and enhancing the effectiveness of underwater-to-air communication systems.

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1. Introduction

The research primarily focuses on proposing a means to transmit signals from water to environment air channels. These different environments create a series of challenges in the communication between the two media, which ultimately affects the signal quality. However, the demand for reliable communications in challenging marine environments is increasing, providing a rich opportunity for innovation to address these obstacles. Acoustic communication methods encounter range and bandwidth limitations. Utilize a hybrid approach that employs OFDM as a resource of data transmission [1], over UWOC/LOS optical channel technologies. Characteristics of OFDM, by splitting the frequency band into multiple orthogonal secondary carriers, expand the spectrum usage and thus eliminate the need for additional frequency bands. Furthermore, it is able to withstand multipath fading, which is a common condition in the field of underwater communications due to reflections and refractions, which allows for reliable signal reception. The 532nm frequency used in LED as a transmitting source is suitable for UWOC because it allows better penetration and diffusion of light in water compared to longer wavelengths [2], in addition to high optical efficiency and low power [3]. It has the additional advantage of reducing scattering and absorption, which contributes to clearer signal transmission and thus improved data rates in UWOC systems.

The refraction caused by light passing through the water surface into the air is an additional constraint that the signal faces when it travels through the air, due to the difference in the refractive index between the two media, which leads to the refraction of the beam. [4] This bending of the light causes the signal to deviate, with the possibility of misalignment with the receiver. The refractive index is affected by the angle of incidence as well as the quality and properties of the water. The physical properties of water are also a factor affecting signal propagation, such as turbidity, salinity, etc. [5] in pure seawater; the absorption coefficient is less than in pure ocean water, which contains a higher concentration of dissolved particles, thus causing light to scatter in different directions. [6]. Outside the surface of the water, ambient light noise is encountered by the signal as it exits the water and can interfere with the optical signal.[7] and differences in salinity can change the refractive index of water, further complicating the transmission process.[8] Weather conditions, such as rain, fog, etc., can weaken the light signal. Rain, for example, causes light to be scattered and absorbed more as it travels through the air.[9]

Underwater to Air scenario

The mechanism of transmitting signals from underwater to air channels directly without intermediate platforms is a challenge in itself, in addition to other challenges such as refraction, physical media conditions, attenuation, and ambient light noise. Therefore, a design is required that addresses these challenges as much as possible, such as hybrid communication systems and adaptive modulation techniques that seek to integrate multiple transmission methods to mitigate the challenges to achieve the desired goal.

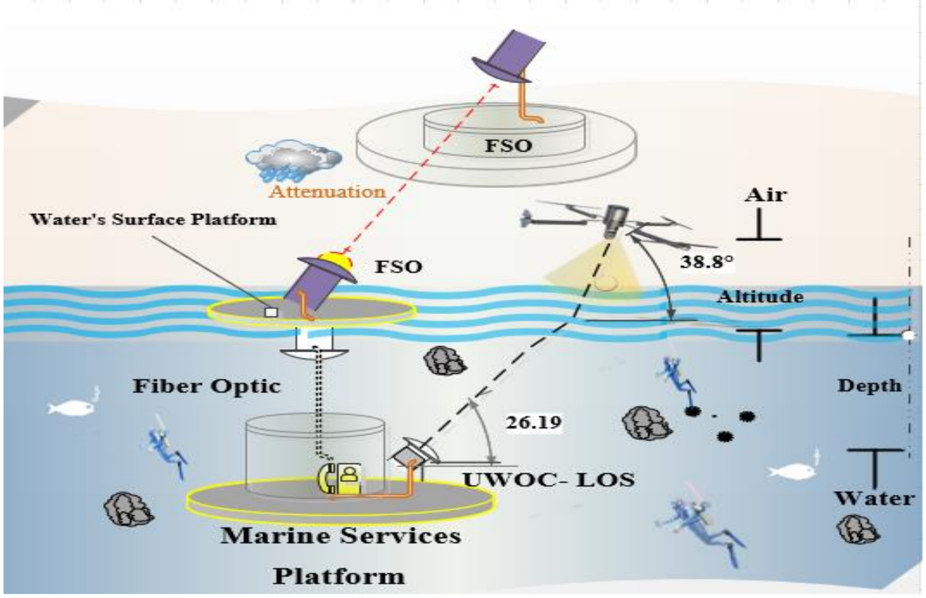


Figure 1. Underwater to Air scenario

The proposed design shown in Figure 1 aims to enhance the effectiveness of underwater-to-air communication systems. Initially, the design assumed that the signal was sent from any platform, whether ground-based, at specific distances determined by the FSO system according to the available vision and weather conditions, where the distance ranges from 23 km in clear weather to tens of meters in complex atmospheres. Alternatively, it is sent from a ship or any floating platform above the water. In general, the signal received from the bidirectional FSO reaches a platform above the water surface to enable the signal to be sent via a 100-meter fiber optic to the underwater marine service platforms. This in turn sends the signal using line-of-sight technology directly into the air, penetrating the water surface to mobile aerial platforms close to the water surface, the height of which is determined depending on some conditions such as the nature of the water and the attenuation resulting from weather conditions.

2. Methodology

The proposed system shown in Figure 2 consists of several main parts and subsystems ,the system has been designed to operate effectively in both the underwater and air channels. Which will be detailed as follows:

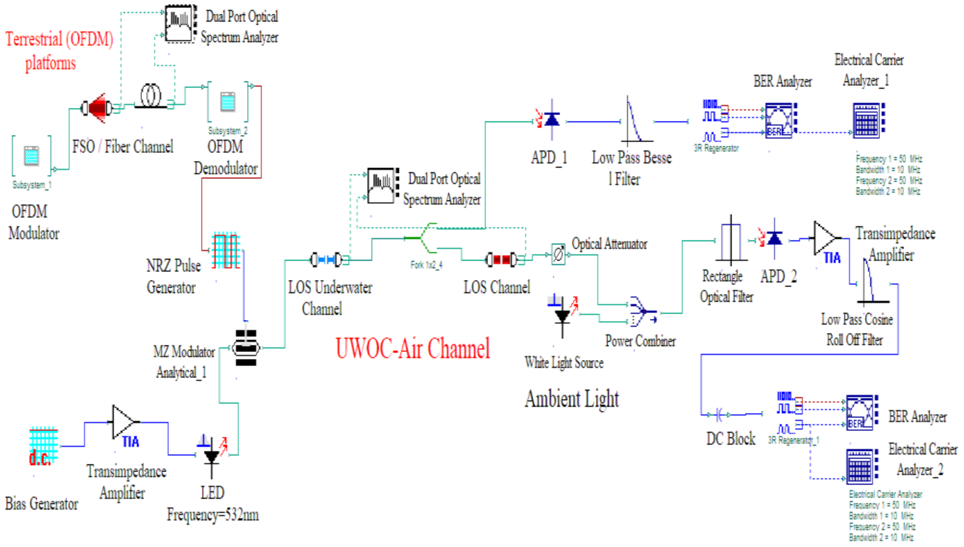


Figure 2. Design for underwater to air system utilizing OptiSystem v.21.

A: Data Generation

- As the first step in the proposed communication system, it is used Pseudo-Random Binary Sequence (PRBS) generator. This part is used to generate a stream of bits that will be the initial input for the next modulation. Bit sequences were used to efficiently encode information and provide a solid basis for data transmission.
- After data generation, the bit sequence is being fed into the QAM subsystem. QAM is a method used to modulate data by changing the amplitude of two orthogonal signals, allowing multiple bits to be encoded in a single symbol. This implementation simply sets the system to encode 8 bits/symbol, thereby increasing data throughput and transmission efficiency.
- The modulated signal is then passed through an Orthogonal Frequency Division Multiplexing mapper. During this phase, there are several major parameters, such as the number of total subcarriers (512), the number of Fast Fourier Transform (FFT: 1024) points, and without using prefix points. OFDM allows effective bandwidth usage, enhancing the systems resistance to interference greatly, which is very valuable in complex environments. The OFDM modulator output is then sent to a low-pass cosine-roll-off filter. For greatly reducing the bandwidth occupied by modulated signals, as well as eliminating interference. This procedure can be considered a step for preparing the signal for transmission, through which the data is converted into a frequency range suitable for propagation over the communication medium.
- The quadrature-modulated signal from the previous stage is sent to a Mach-Zehnder modulator (MZ modulator). Here the electrical signal is converted into an optical signal using a laser source with a wavelength of 1550 nm. The MZ modulator is designed to operate at a frequency of 1 GHz, to transmit the optical signal. Figure 3 show data generation OFDM modulator subsystem.

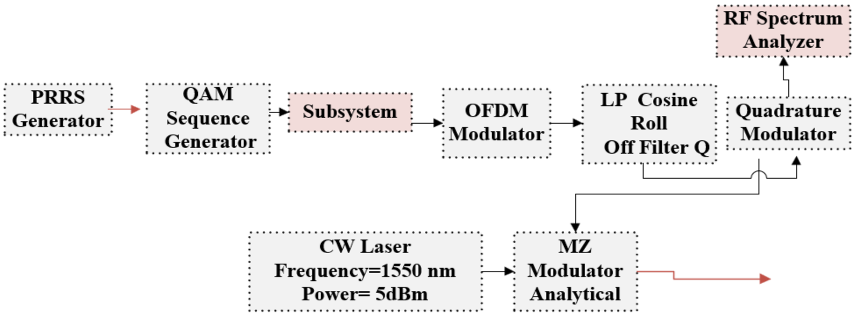


Figure 3. Data Generation OFDM

The previous stages completed the task of generating the signal for transmission over a bidirectional Free Space Optics (FSO) communication channel. The main parameters of this channel were set with a transmission range of 1 km and an attenuation rate of 10 dB/km representing the rainy condition according to Kim Model [10]. Which is connected by optical fibers of 0.1 km length with an attenuation of 0.2 dB/km, the optical fibers were connected for transmitting the signal to an underwater platform.

B: Underwater Communication System

The signal received through fiber optic and arriving via FSO channel from ground platforms or any floating platform above water is transferred to the underwater platform. A comprehensive description is given below according to Figure 4. The system receives the incoming signal via fiber optics and bidirectional FSO, which needs to be routed to an underwater platform. At a stage the signal is quadrature modulated at 7.5 GHz, then OFDM demodulated (512 subcarriers, 1024 FFT points). A subsystem, connected to the system, generates M-ary pulses, and prepares the signal for QAM sequence decoding. Figure 4. illustrates OFDM demodulator operation.

The signal is routed to the Underwater Optical Wireless Communication (UWOC) LOS channel to be prepared for transmission. Where the electrical signal is converted to an optical signal at a frequency of 532 nm via light source (LED), being suitable for the underwater environment. To enhance the strength of the optical signal, optical amplifiers were used to ensure efficient transmission through the underwater and coupled with a photodetector for signal reception.

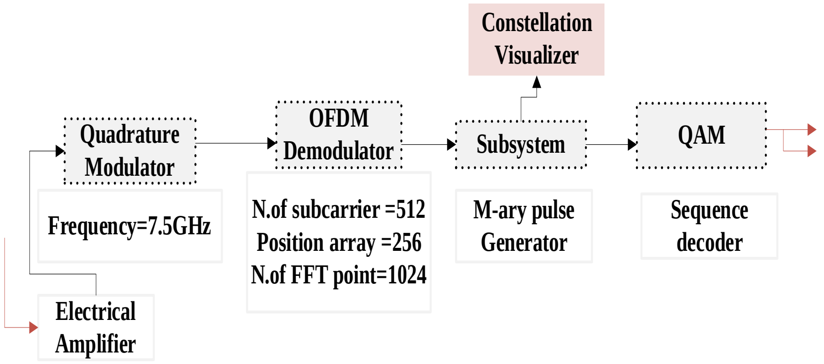


Figure 4. OFDM demodulator operation on underwater platform

C: Underwater-Air Channel

The signal is then transmitted from underwater to the air channel. This step is very important because it involves overcoming some challenges such as refraction, medium effects, ambient light and signal attenuation in the air due to weather conditions. Some of the supporting scientific concepts will be highlighted to enable us to overcome these challenges in the next section.

Table 1: Parameters adopted in LOS Underwater, LOS Channel

Link type	**LOS Underwater**
Frequency	532 nm
Range	Adjustable (m)
Attenuation type	Clear Ocean, Harbor
Absorption coefficient (a)	0.04051/m

Scattering coefficient (b)	0.00251/m
Transmitter aperture diameter	5 cm
Beam divergence	1mrad
Incident half angle	Adjustable (rad)
Receiver aperture diameter	30 cm
Link type	LOS Channel
Distance	Adjustable (m)
Transmitter half-angle (HA)	15 deg
Incidence half-angle (Theta)	Adjustable (deg)
Detection surface area	$5cm^2$
Attenuation	Adjustable dB
Bit rate	1e+009 bit/s

Table 1 shows the most important parameters and specifications for the light and system capabilities in underwater environments that were adopted in this design, with emphasis on the dimensions of the transmission and reception depth and the incidence angles of the light signals, taking into account factors such as absorption and scattering in different water conditions.

The Line-of-Sight (LOS) channel component is added as a supplement to the link channel and receives the signals transmitted from the LOS Underwater Channel component at a frequency of 532 nm at a bit rate up to 1e+009 bit/s. This model calculates the Lambertian order based on the transmitter's half-angle. It relies based on capturing wireless optical signals, in order to ensure the receipt of a reliable signal despite the challenges imposed by the two media during the signal transmission.

In the optical systems domain, this angle (half-incidence angle (ɵ)) is of great importance due to the influence of the interaction of the light with the surfaces (the incident ray and the perpendicular with the surface); therefore, the refractive and reflective coefficients will be affected, which will have a negative impact on the signal transmission mechanism. The detection surface area of 5 cm² is adopted in this design and indicates the area and sensitivity of the detector capable of receiving incoming optical signals from underwater.

Factors Affecting the Air-Water Communication Channel

The main factors affecting the transmission of signals from aquatic environments to air channels are of great importance for the development of communication systems in this field and can be summarized as follows:

- Refraction at the air-water interface.
- The nature of the physical medium.
- Attenuation due to weather conditions.

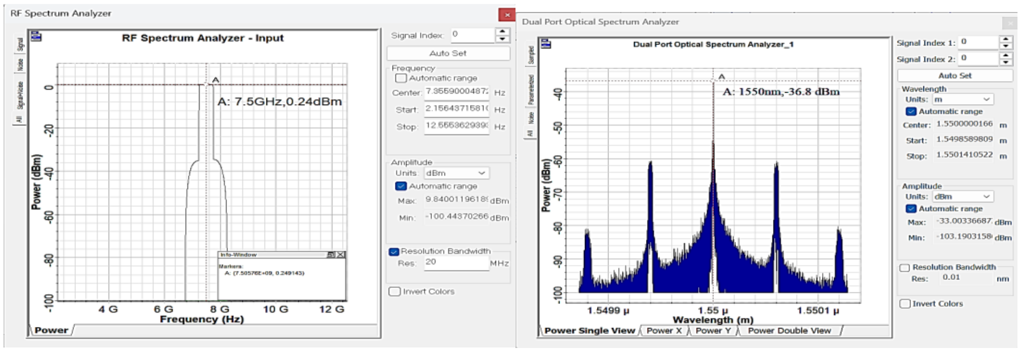
An optical attenuator is added to the line-of-sight transmission channel to simulate environmental conditions that negatively affect the signal as it travels from underwater to above water. The attenuation level is applied in decibels, where the specific decibel is applied to each weather condition such as clear weather and other potential effects on the signal propagation by adjusting the attenuation value for each distance the signal travels. This methodology enhances the reliability of the extracted data and ensures that realistic conditions are accurately reproduced.

Reception and Processing Signal

Subsequently, the interference caused by ambient light and attenuation due to environmental conditions has been added to the signal received from the water, it is received by an avalanche photodiode (APD) which performs the function of converting the optical signal into an electrical signal. An electrical amplifier to ensure sufficient power for further processing amplifies the signal. The optical filter removes unwanted noise to enhance the signal strength. The fundamental phase slope filter limits the bandwidth and in turn reduces interference between symbols. Finally, a bit error rate (BER) analyzer as well as an electronic carrier analyzer, which evaluates the electronic characteristics of the signal to highlight the system performance, evaluate the signal.

3. Results and Discussion

In this section, the most important outputs of the proposed system are presented: the system performance efficiency will be extracted before the signal reaches the underwater platform; via the OFDM transmission system, as well as the effectiveness of the signal received from the FSO bidirectional system, in order to determine the system efficiency before sending the signal to the underwater environments.



Info-Window
Markers:
A: (7.50576E+09, 0.249143)

Signal Index: 0
Frequency
☐ Automatic range
Center: 7.3559000487 Hz
Start: 2.1564371581 Hz
Stop: 12.555362939 Hz
Amplitude
Units: dBm
☑ Automatic range
Max: 9.840011961 dBm
Min: -100.44370266 dBm
☑ Resolution Bandwidth
Res: 20 MHz
☐ Invert Colors

Signal Index 1: 0
Signal Index 2: 0
Wavelength
Units: m
☑ Automatic range
Center: 1.5500000166 m
Start: 1.5498589809 m
Stop: 1.5501410522 m
Amplitude
Units: dBm
☑ Automatic range
Max: -33.00336687 dBm
Min: -103.1903158 dBm
☐ Resolution Bandwidth
Res: 0.01 nm
☐ Invert Colors

(a) (b)

Figure 5. (a) RF Spectrum Analyzer (b) Optical Spectrum Analyzer

Figure 5(a) shows a RF spectrum analyzer for the 7.5 GHz OFDM output signal with a power of 0.24 dBm. Figure 5 (b) displays the spectrum range of wavelengths centered around 1550 nm. This is the typical wavelength for optical communications for an FSO system with a deployment range of 1 km, and the attenuation is set at 10 dB/km, which is representative of the atmospheric disturbances such as rain according to the KM model [11]. Thus, the maximum power value after 1 km is recorded at about -30.83 and the prominent peak in the spectrum indicates a good signal with little noise interference.

Before presenting the results of signal transmission from underwater, it is necessary to understand the effect of the refractive angle of light rays as they are transmitted.

To analyze the behavior of light transmitted from water to air at an angle of 10∘, for example, as an assumption, we take into account the critical angle and the principles of refraction and reflection in the analysis as well.

- Angle of incidence in water, θi=10∘
- Refractive index of water, n1≈1.33
- Refractive index of air, n2≈1.00

The critical angle θc can be calculated using Snell's law:

$$sin(\theta c) \ = n1n2 \qquad (1)$$

Substituting the values:

$$sin(\theta c) = 1.331.00 \approx 0.7519$$

Calculating θc:

$$\theta c = arcsin(0.7519) \approx 48.6 \circ$$

In our current system, the transmission will be from underwater to above water starting at an angle of 3.76 degrees, taking into account the exceedance of the angle of reflection of light in the water due to exceeding the critical angle and the angle of reception of light if it crosses the surface of the water. Since the angle of incidence $\theta i=3.76\circ$ is less than the critical angle $\theta c \approx 48.6\circ$, the light will be refracted in the air instead of being reflected back in the water.

According to the law of reflection, the angle of reflection θr is equal to the angle of incidence when reflection occurs. However, since total internal reflection does not occur in this case, we will focus on refraction.

Using Snell's law to find the angle of refraction θt:

$$n1 sin(\theta i) = n2 sin(\theta t) \qquad (2)$$

Substituting the known values:

$$1.33 sin\ (3.76\ \circ)\ = 1.00 sin(\theta t)$$

Calculating sin (3.76∘):

$$sin\ (3.76\ \circ)\ \approx 0.0872$$

Now substituting this value:

$1.33 \times 0.0872 \approx 1.00 \sin(\theta t)$

$$\theta t\ = arcsin\ (0.0872)$$

$\theta t \approx 5.0\circ$

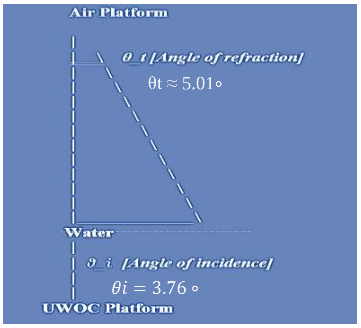


Figure 6. Determine the Angle of Reflection

- θi the angle at which the light enters the water, which is 3.76∘.
- θt the angle at which the light exits into the air, calculated to be approximately 5.01∘.

This diagram in figure 6 illustrates the transition of light from water to air, showing the angles involved in the refraction process.

Table 2 shows the angle values entered in the LOS Underwater Channel system after converting them from degrees to radians, which represent half angles in water. In addition to half of the angles corresponding to each angle in air. The table shows the amount of variation in angle values between water and air.

Table 2. Incident Half Angle in Water and Air

Incident Half Angle in Water (rad)	Incident Half Angle in Water (deg)	Incident Half Angle in Air (deg)
0.0656	3.76	5.00
0.1314	7.53	10.00
0.1925	11.02	14.69

0.2505	14.36	19.10
0.3054	17.49	23.31
0.3578	20.51	27.24
0.4085	23.36	31.14
0.4569	26.19	34.88

Attenuation Coefficients for Different Conditions

To calculate the signal attenuation for a Line-of-Sight (LOS) channel using light at a frequency of 532 nm (which corresponds to green light) over a distance, we can use empirical models that estimate attenuation based on weather conditions. The attenuation can be influenced by various factors, including clear weather, haze and clouds. [12]

After the angles have been determined, it is necessary to add the effect of attenuation on the signal. Typical values of the attenuation coefficient (α) at 532 nm for different weather conditions are as follows:

In Clear Weather: $$\alpha \approx 0.1\, dB/m\alpha \ \approx 0.1 dB/m \tag{3}$$

In Haze: $$\alpha \approx 0.5\, dB/m\alpha \ \approx 0.5\, dB/m \tag{4}$$

In Clouds: $$\alpha \approx 0.5\, dB/m\alpha \ \approx \ 0.5 dB/m \tag{5}$$

(Depends on cloud thickness)

To compensate for the noise caused by sunlight on the transmitted signal in an optical communication system, the Noise Power Spectral Density (PSD) with the visible spectrum and Noise Power represents the cumulative effect of ambient light noise on the signal. An SNR of 10 to 20 dB is generally considered the minimum for reliable communication [13], indicating that the signal must be significantly stronger than the noise.

These values can serve as a baseline for modeling the noise introduced by sunlight on your optical signal as it transitions from underwater to above the surface. Adjust these parameters based on specific environmental conditions and experimental setups for more accurate results.

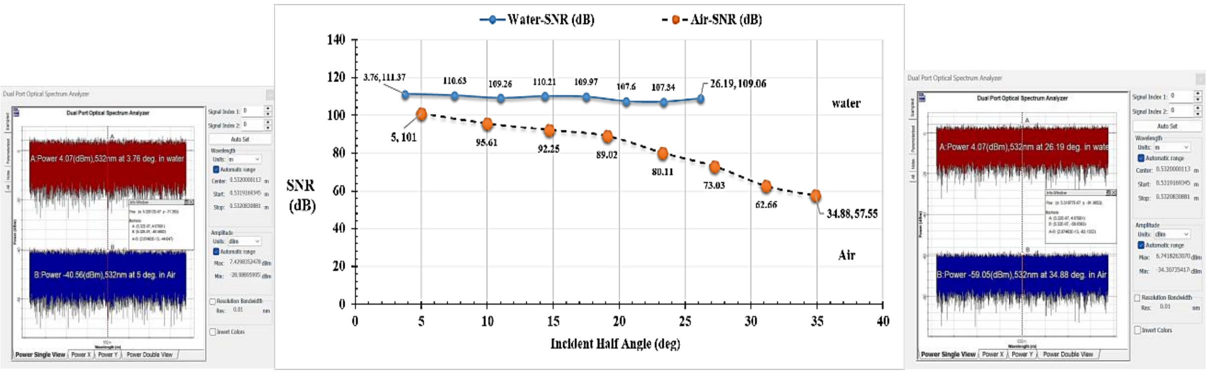


Figure 7. SNR for different Incident Angle in LOS Underwater Channel and LOS Channel at 5.32nm

Figure 7 shows an analysis of the SNR of the two media at a depth of 10 m and the air channel LOS at an altitude of 10 m through half-angle variation, as well as a dual-port optical spectrum analyzer. The signal-to-noise ratio in water is shown in the figure as a blue line to represent the signal ratio that peaks at 111.37 dB at 3.76 degrees and remains relatively stable across the angles. In air, it is shown as orange dots, which indicate a downward trend from 101 dB at 5 degrees to 57.55 dB at 34.88 degrees. The signal-to-noise ratio in water is observed to be high and stable, unlike the behavior of the system in air, which is more affected with each increase in the angle of incidence. The figure on the left side shows the spectrum measurement of the energy readings in water at 3.76 degrees to reach (4.07 dBm) while in air at 5 degrees it reaches (-40.56 dBm). The power spectrum in figure illustrates the differences in signal strength between the two media. In the right panel the power readings for water at an angle of 26.19 degrees are (4.07 dBm) while in air at the corresponding angle due to the refractive index is 34.88 degrees which is (-59.55 dBm). From this clear difference in the ratios of power levels, we can see that water maintains a positive dBm value while in air it drops to negative values. Figures 6 effectively illustrate the variation of the half-incidence angles and signal-to-noise ratios in water and air, highlighting the superiority of water in maintaining high performance.

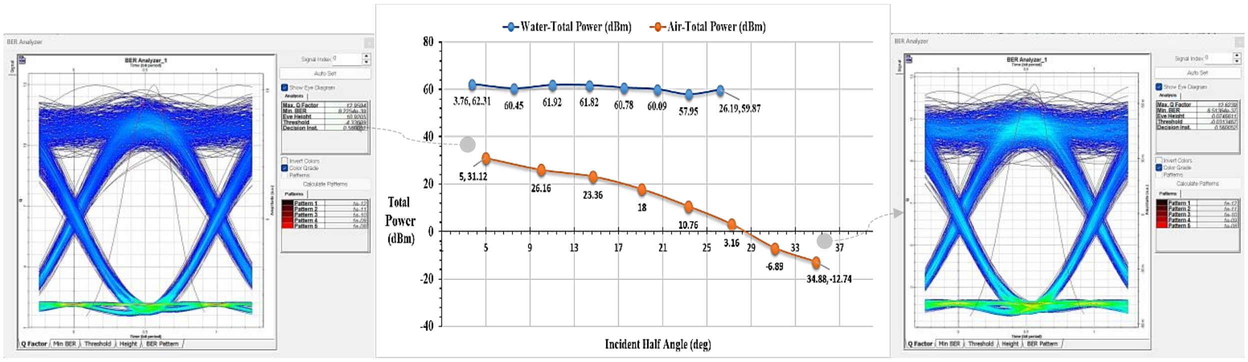
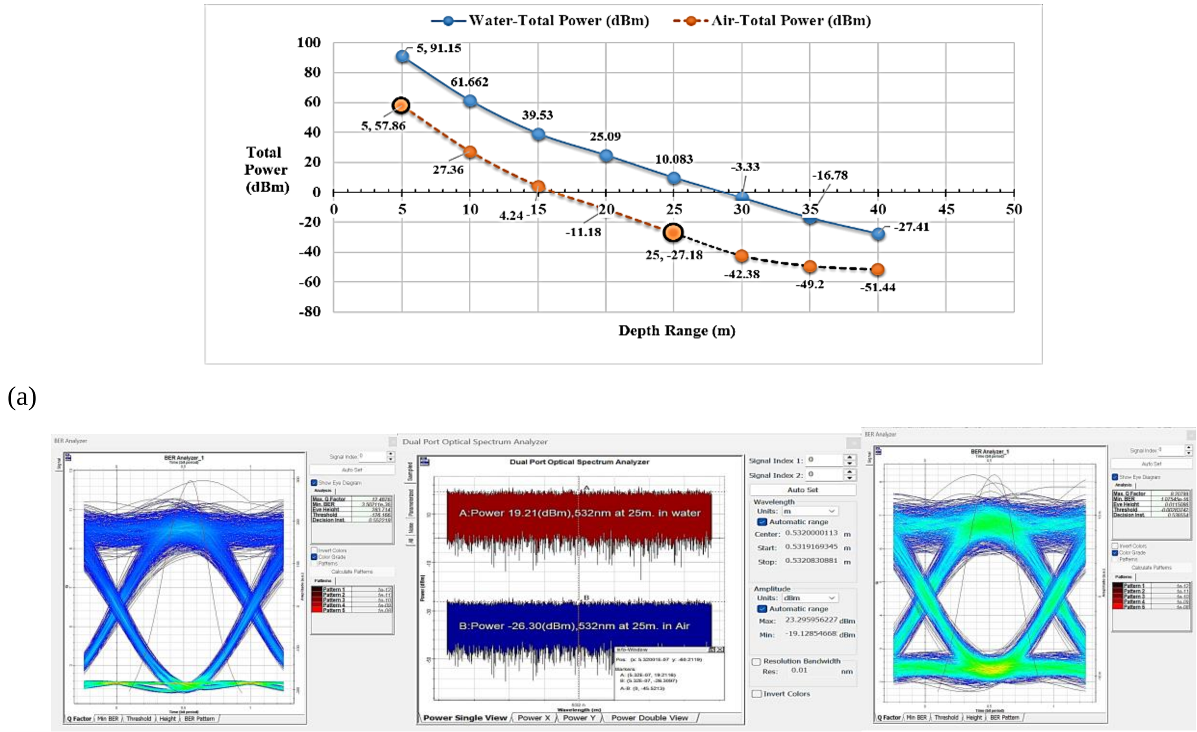


Figure 8. Total power signal for different Incident Angle in LOS Underwater Channel and LOS Channel

Figure 8 displays the total power (in dBm) for two mediums, water and air, across varying half incident angles (in degrees) for the same parameters as the previous figure regarding depth and height above the water. solid blue line showing relatively stable total power values. The values range from 57.95 dBm at 3.76 degrees to around 59.87 dBm at 26.19 degrees, indicating minimal variation. Comparison with total power values for air starts at 31.12 dBm at 5 degrees and decreases steadily to -12.74 dBm at 34.88 degrees, showing a significant decline.

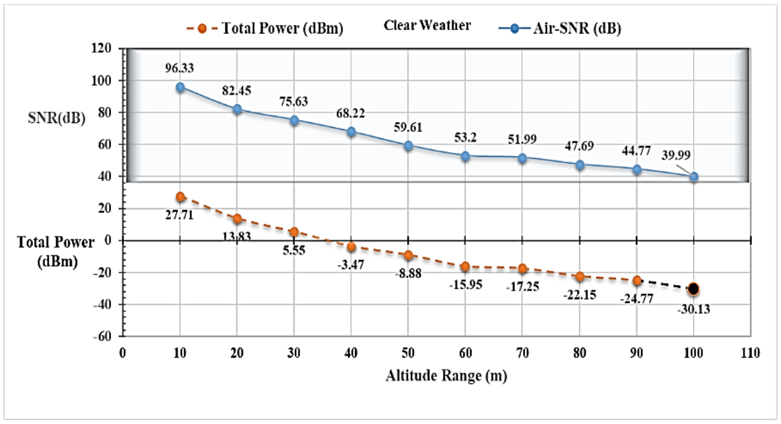


(a)

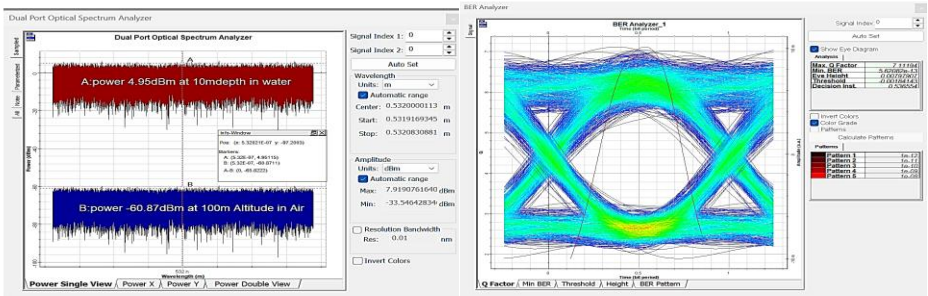
(b)

Figure 9. Total power signal for different depth in LOS Underwater and effective in LOS Channel

Figures 9 include the graph in (a) showing the total power between water and air at different depths and two panels of the spectrum analyzer and the BER analyzer in Figure 9 (b). The blue curve represents the total power starting from 91.15 dBm at 5 m depth and decreasing to about -27.41 dBm which represents the effect of water on the behavior of the system, while the curve (orange dashed dots) represents the behavior of the received signal in air and starts from a total power of 57.86 dBm at a transmission depth of 5 m and gradually decreasing to -51.44 dBm at a depth of 40 m, which shows the loss of power with increasing transmission depth. It is worth noting that the transmission depth of 25 m is the maximum at which the signal can be sensed above water according to the BER readings of 1.07E-16, while at subsequent depths no signal can be sensed that can be received in air. The spectrum analyzer indicates the variation in signal strength at a transmission depth of 25 meters, recording 21.19 dBm in water. In air it recorded -26.30 dBm at symbol (B). The power spectrum highlights the differences in signal strength between the two media.



(a)



Signal Index 1: 0
Signal Index 2: 0

Wavelength
Units: m
☑ Automatic range
Center: 0.5320000113 m
Start: 0.5319169345 m
Stop: 0.5320830881 m

Amplitude
Units: dBm
☑ Automatic range
Max: 7.9190761640 dBm
Min: -33.54642834 dBm

☐ Resolution Bandwidth
Res: 0.01 nm

☐ Invert Colors

Signal Index: 0
☑ Show Eye Diagram

Analysis

Max. Q Factor	7.11194
Min. BER	5.62082e-13
Eye Height	0.00797907
Threshold	0.00184143
Decision Inst.	0.536554

☐ Invert Colors
☑ Color Grade
☐ Patterns

Patterns

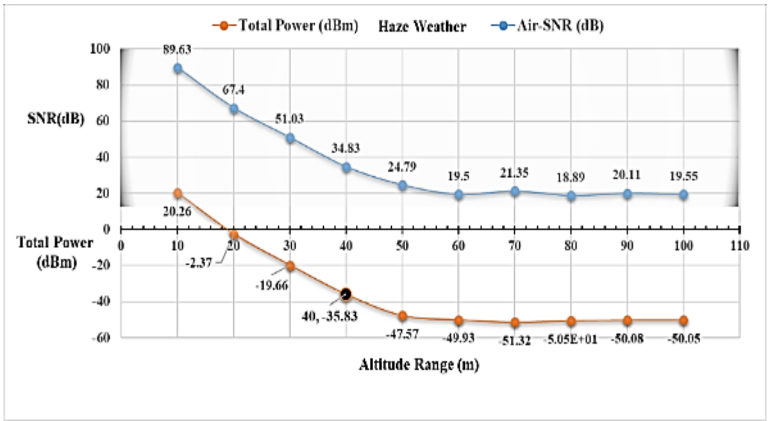
Pattern 1	1e-12
Pattern 2	1e-11
Pattern 3	1e-10
Pattern 4	1e-09
Pattern 5	1e-08

(b)

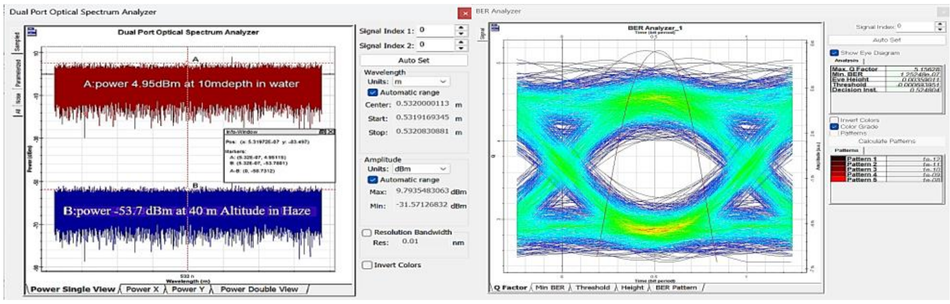
Figure 10. (a) Total power signal for different altitudes, (b) optical spectrum analyzer, and the BER analyzer at a altitude of 100 meters in clear weather.

The figures 10 contain two major sections: (a) graph evaluating total power and SNR at different altitudes, and two panels from a Dual Port Optical Spectrum Analyzer and a BER Analyzer in (b). The chart illustrates a clear inverse relationship between total power and altitude, with total power decreasing significantly, while SNR shows a more gradual decline. It is noted that the power values are high, reaching 27.71 dBm at a height of 10 meters in the air, and begin to gradually decrease to reach -30.13 dBm when reaching a height of 100 meters. This indicates an inverse relationship between increasing height and loss of power.

In section (b), the left panel displays the power readings for two signals: marker (A) in panel water: 4.95 dBm at 10 meters depth, indicating a strong signal, and the (B) indicating to air channel: -60.87 dBm at 100 meters altitude, indicating a significantly weaker signal. Where the right panel, the BER analyzer for the eye chart, shows the error ratio at 100 meters altitude is 5.6E-13, which is still within the permissible limits, and this is evidence of the system's ability to provide 100 meters altitude for direct communication from underwater in clear weather conditions.



(a)



Signal Index 1: 0
Signal Index 2: 0

Wavelength
Units: m
☑ Automatic range
Center: 0.5320000113 m
Start: 0.5319169345 m
Stop: 0.5320830881 m

Amplitude
Units: dBm
☑ Automatic range
Max: 9.7935483063 dBm
Min: -31.57126832 dBm

☐ Resolution Bandwidth
Res: 0.01 nm

☐ Invert Colors

Signal Index: 0
☑ Show Eye Diagram

Analysis

Max. Q Factor	5.15628
Min. BER	1.25248e-07
Eye Height	0.00359011
Threshold	0.000693951
Decision Inst.	0.524804

☐ Invert Colors
☑ Color Grade
☐ Patterns

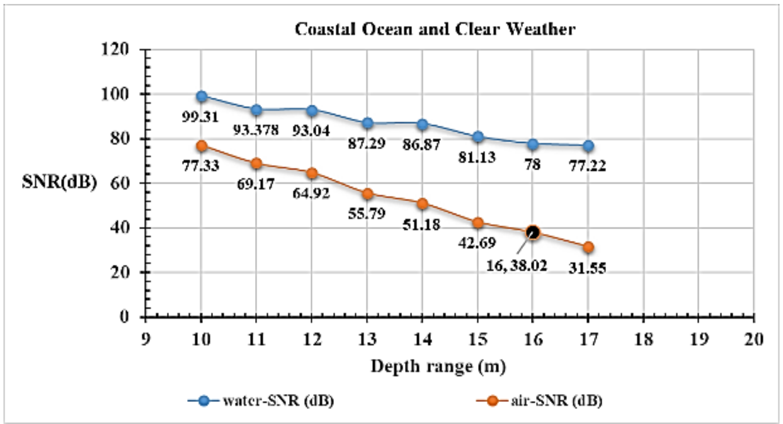
Patterns

Pattern 1	1e-12
Pattern 2	1e-11
Pattern 3	1e-10
Pattern 4	1e-09
Pattern 5	1e-08

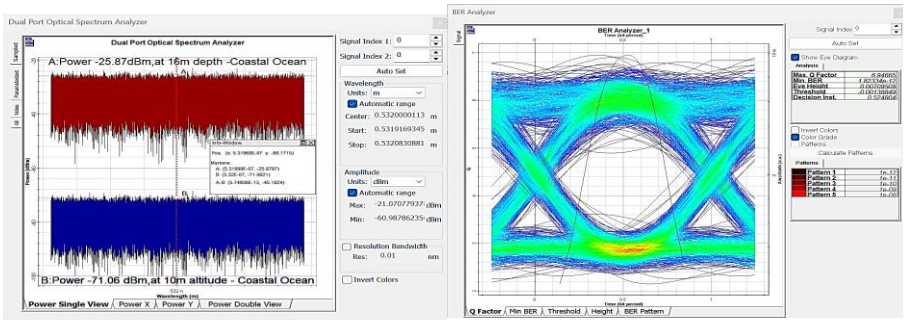
(b)

Figure 11. (a) Total power signal for different altitudes, (b) optical spectrum analyzer, and the BER analyzer at an altitude of 40 meters in Haze condition.

The previous results cannot be achieved for the same distance if the environmental conditions change such as Haze. The effective height decreased between 35-40 meters as shown in Figure 11 (a). In Section (b), the left panel confirmed it, where the power in the air at a height of 40 meters became -53.78 dB with a BER of 1.25E-7. After verifying the efficiency of the system for the permissible depths and effective heights for receiving the signal, in addition to testing the system in clear and turbulent weather, it remains to test the quality of the water through which the transmission is made, and this is what will appear in the following figures.



(a)



A:Power -25.87dBm,at 16m depth -Coastal Ocean

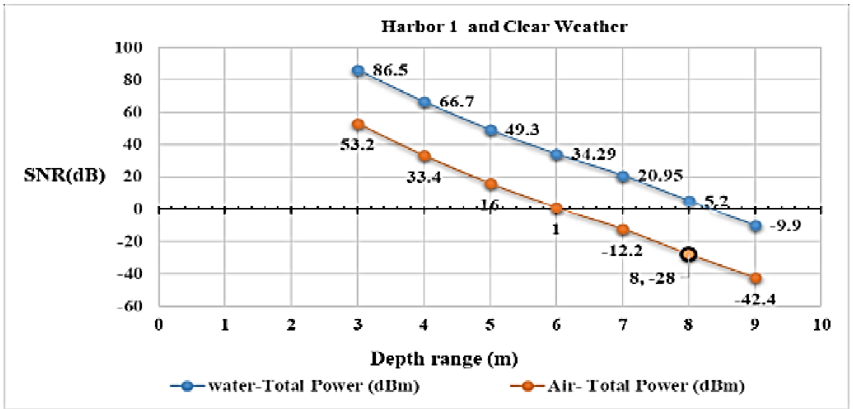
B:Power -71.06 dBm,at 10m altitude - Coastal Ocean

Signal Index 1: 0
Signal Index 2: 0
Wavelength
Units: m
☑ Automatic range
Center: 0.5320000113 m
Start: 0.5319169345 m
Stop: 0.5320830881 m
Amplitude
Units: dBm
☑ Automatic range
Max: -21.07077937 dBm
Min: -60.98786235 dBm
☐ Resolution Bandwidth
Res: 0.01 nm
☐ Invert Colors

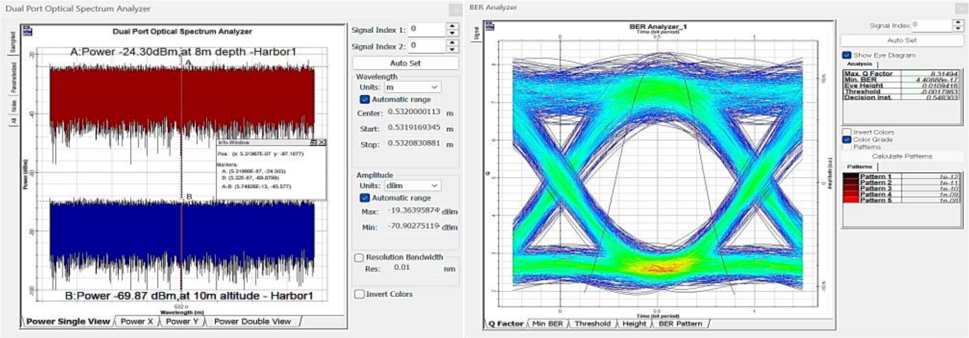
(b)

Figure 12. (a) Total power signal for different depth, (b) optical spectrum analyzer, and the BER analyzer in Coastal Ocean

Figures 12 and 13 with each panel illustrate the distance variation that can be achieved under more severe depth conditions than the previous ones, despite clear air conditions. Signal degradation can be observed with increasing depth, reaching a depth of 16 m in the coastal water quality condition, as shown in Figure 12(a).



(a)



A:Power -24.30dBm,at 8m depth -Harbor1

B:Power -69.87 dBm,at 10m altitude - Harbor1

Signal Index 1: 0
Signal Index 2: 0
Wavelength
Units: m
☑ Automatic range
Center: 0.5320000113 m
Start: 0.5319169345 m
Stop: 0.5320830881 m
Amplitude
Units: dBm
☑ Automatic range
Max: -19.36395874 dBm
Min: -70.90275119 dBm
☐ Resolution Bandwidth
Res: 0.01 nm
☐ Invert Colors

(b)

Figure 13. (a) Total power signal for different depth, (b) optical spectrum analyzer, and the BER analyzer in harbor water

Figures 12(b) show the total signal power at 16 meters, where it achieved -25.87 dBm at a height above the water of 10 meters with a bit error ratio of 1.28e-12, while in Figure 13the system achieved 8 meters with harbor water with a signal power of -24.30 dBm and a BER of 4.4e-17 at a height of 10 meters, as shown in Figure 13(b). Despite the limitations that were previously raised in the focus of our research, necessity dictates that many applications take them into account in the case of applying communications between water and air, and the improvement in signal transmission provides a strong and useful incentive in the case of the impossibility of communication between water and air.

4. Research recommendations

- In order to determine the appropriate angles for proper signal reception between water and air, we need to calculate these angles after refraction. These angles are required to provide an acceptable balance in order to receive the signal despite the factors affecting it in both environments, taking into account the effects of refraction.
- Analysis of additional influencing factors: It requires taking into account other factors that may have a direct effect on the signal strength, such as the depth in the water, the height above the water surface, and the quality of the water through which the signal is transmitted on the one hand, and the ambient lighting conditions and the climatic environment on the other.
- Modifications were made to improve the system design based on experiments to ensure acceptable performance under various signal conditions.
- Scrutinizing these factors would enhance the reliability of the results.

5. Conclusion

This research using a hybrid communication system has made a breakthrough in successfully transmitting signals from underwater to above-water environments. Utilizing OFDM as a data generation method for the integration of underwater wireless optical communications and LOS optical channel. After adjusting the signal transmission parameters, addressing the challenges of line of sight through the refraction angle, and overcoming the challenges of water quality and over-water weather conditions, ambitious results were obtained at 100 meters above clear water and 40 meters in haze at a depth of 10 meters for transmission in Clear Ocean. In water quality, such as harbor conditions, the system achieved a depth of up to 8 meters. The results obtained mitigated the challenges and enhanced the effectiveness of underwater-to-air communication systems.

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