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Designing and Analysis of Underwater Optical Wireless communication system

1st Ali F.Kaeib
Department of Electric and Electronic Engineering
Sabratha University Faculty of engineering
Sabratha,Libya
Ali.kaeib@sabu.edu.ly

2nd Omar .A. Alshawish
Department of Electric and Electronic Engineering
Sabratha University Faculty of engineering
Sabratha ,Libya
omar.alsadiq.alshawish@gmail.com

3rd Suhayl Ali Altayf
Department of Electric and Electronic Engineering
Sabratha University Faculty of engineering
Sabratha ,Libya
suhayl.altayf@gmail.com

4th MOHAMED.A.GAMOUDI
Department of Electric and Electronic Engineering
Sabratha University Faculty of engineering
Sabratha ,Libya
mohammedalialgamoudi@gmail.com

***Abstract*—Underwater wireless communications, have more attention day after day, due to their wide applications in the military, and in the scientific community. It is also useful in vehicles and devices that are deployed underwater which are difficult to connect with wires. Acoustic communications mostly used underwater technology nowadays, this technology suffers from limited bandwidth and capacity, and for this reason, a complementary technology like underwater wireless optical communication (UOWC) is to be in the field. In this paper, we simulated the UOWC system with Optisystem software to measure the maximum distances in different underwater mediums. In this simulation, three types of seawater are used: pure seawater, Coastal Ocean, and turbid harbor. The intensity modulation for the message signal was performed using a Mach-Zehnder Modulator and Laser Diode as the light source. Results were compared between the wavelength at the beginning of the visual light spectrum and the wavelengths that have the minimum attenuation in the same visual spectrum, in terms of the transmitting distance and the transmitting power. A signal was sent for more than 100 m in clear ocean water with 1 mW, while the same type of water signal was sent for the same distance with 0.35 mW (65% saving) using different operating wavelengths.**

Keywords—Underwater, Communication, Optisystem, simulation, Laser, wavelength

I. . INTRODUCTION

In the previous years, underwater wireless communications (UWC) draw additional and more attention with the progress in exploring oceans. UWC plays its role within the study of global climate change by perciptive the oceans through sensing element networks [1]. UWC may be established by using radio frequency (RF), acoustic waves, or optical waves. But acoustic waves give long distances, however the data rate and bandwidth are limited, whereas RF waves attenuate quickly and that makes the communication link shorter than acoustic waves, on the other hand underwater optical wireless communications (UOWC) are thought-about as honest different because it capable of providing high data rates for moderate distances and, with low power consumption and fewer mass requirements. UOWC is more difficult to due to the massive scattering and absorption of the optical beam underwater, but its advantages make it worth it.

II. UNDERWATER WIRELESS COMMUNICATION METHODS

There are many ways to transfer data underwater some of them are wired and the others are wireless. The use of optical fiber cable is wide due to its significant advantages, but when the application that we want to communicate with is not large or stationary like AUVs, submarines, and other moving machines, the optical fiber or any other wired methods are not sufficient enough, the focus is on the wireless communications, and the researchers are focusing on it on the meanwhile.
There are three common ways to communicate wirelessly underwater [2], and these methods are:

- Radiofrequency (RF) waves.
- Acoustic waves.
- Optical waves.

And each one of the methods mentioned before has its advantages over the other two.

A. Radiofrequency (RF) waves:

RF waves are one portion of the electromagnetic (EM) spectrum, and it consists of frequencies from 3 kHz to 300 GHz. RF waves provide high speeds but they can't go far from the source due to the huge attenuation applied to it. Many types of research had used RF waves underwater, but they suffered from a huge loss, and the main reason for that is the conductivity of sea-water, where it is equal to 4 mhos/m, which is approximately double the conductivity in the freshwater. The absorption coefficient of freshwater ($\alpha_{fresh\ water}$) is frequency independent, unlike the seawater absorption coefficient ($\alpha_{sea\ water}$) which increases with the increase of frequency [2]. The absorption coefficient of sea-water and freshwater are determined by:

$$\alpha_{sea\ water} \approx \sqrt{\pi f \mu \sigma} \qquad (1)$$

$$\alpha_{fresh\ water} \approx \frac{\sigma}{2}\sqrt{\frac{\mu}{\varepsilon}} \qquad (2)$$

Where: f is The operating frequency, μ is The permeability, σ is The conductivity, ε is The permittivity.

RF waves have variable latency due to the medium and can be used in applications that do not require line of sight (Non-Line of Sight) (NLOS), between the transmitter and receiver, and in turbid water that requires high power consumption.

B. *Acoustic waves:*

Examples of mechanical waves are sound waves and waves in water. Mechanical waves are a result of disturbance or vibration withinside the matter. These mechanical waves travel via medium by inflicting the molecules to collide with every different moving power from one to the next. Electrical signals are converted to acoustic waves by a sound generator in the transmitter whereas the opposite happens in the receiver side by the water stethoscope. The speed of sound propagation in the air is equal to 334 m/s at 20° C if the air is dry while in sea-water it is approximate to 1500 m/s and, we say approximately because some factors affect the speed of acoustic waves [2], and these factors are:

- The temperature.
- Pressure (Depth).
- Salinity.

For underwater wireless communications, acoustic waves are the most used technology for the last few years. Underwater acoustics are typically linked with frequencies between 10 Hz and 1 MHz. sound propagation in the ocean at frequencies less than 10 Hz is normally impossible without going down to the bottom, whereas frequencies more than 1 MHz are rarely employed since they are quickly absorbed by seawater. Acoustic waves have relatively low absorption in underwater environments, but like any other technology acoustic waves also have their disadvantages:

- Multi-path propagation.
- High bit error rate.
- Low propagation speed in comparison to electromagnetic waves.
- High background noise.
- Limited bandwidth.
- High latency.
- Doppler spread.

C. *Optical waves:*

some underwater applications including the new generation of autonomous underwater vehicles (AUVs) have recently necessitated the development of complementary technology, capable of large bandwidths at short to mid-range distances. The use of optical wireless communications is being studied as a viable solution. RF waves attenuate quickly and drastically reduce the link length, whereas acoustic waves have enjoyed great success underwater due to their greater link lengths, but the data rates are limited, therefore UOWC is considered as a viable alternative, even if its transmission distances are limited (only about 100 m) but comparing to the acoustic waves; optical waves provide high bandwidths underwater, high propagation speeds that reach to 2.255 x 10^8 m/s, and low power consumption.

III. CLASSIFICATION OF WATER AND JERLOV WATER TYPES

The physical nature of water does not only vary geographically but also according to the vertical depth, the waters of the seas and oceans can be divided into three layers in general according to their depth which are:

- The euphotic zone:
  This layer is the topmost layer. This layer receives the largest amount of sunlight compared to the other two layers, this zone contains a lot of photosynthetic life in the form of chlorophyll, which is the major component of phytoplankton. In clear ocean water this zone can be up to 200 m deep, 40 m deep in continental shelves, and 15 m deep in coastal water [2].
- Dysphotic zone:
  This layer is the layer below the euphotic zone, and in this layer, the sunlight is not sufficient as the first layer but it still exists in small amounts and this amount is not enough for the growth of the photosynthetic life.
- The aphotic zone:
  This layer has the lowest order of the three layers, where it locates further below the dysphotic layer, where no sunlight ever reaches. Which makes the aphotic layer freed from photosynthetic life.

Each layer of the layers mentioned above has its unique physical properties and requires special instruments to link between them.

Jerlov water types are another classification of water that depends on the geographic location and turbidity, which are I, IA, IB, II, III, 1C, 3C, 5C, 7C, and 9C [3][4], the types I, IA, IB, II, and III represents open ocean waters, Type I is the clearest and type III is the most turbid, while those suffixed with 'C' represent coastal waters with increasing turbidity from 1 to 9, (type 1 is clearest and type 9 is most turbid).

the most famous classifications used for this type of researches are derived from jerlov water types and these types are:

A. *Pure seawater.*

The total absorption in pure water (lack of suspended particle matter) and absorption by salts in pure saltwater is considered as the absorption in pure water. In the visible spectrum The second one is thought to be insignificant (400 - 700 nm). The key limiting element here is absorption, which increases as the wavelength increase.

In pure seawater, the water absorption coefficient is given by:

$$\alpha_{sea\ water}(\lambda) < \mathrm{K}\,(\lambda) - \frac{\mathrm{b}\,(\lambda)}{2} \qquad (3)$$

Where: λ is the operating wavelength, K (λ) is the diffuse coefficient, and b (λ) is the scattering coefficient.

B. *Clear ocean water:*

The concentration of dissolved particles in ocean water is higher, including dissolved salts, mineral components, colorful dissolved organic stuff, and so on. They are further classified into Type 1 - III (based on Jerlov water type) depending on the concentration of suspended particles and their geographic location.

C. Coastal ocean water:

When compared to clear ocean water, this type contains a much larger concentration of dissolved particles, which raises the turbidity level. This water type has a greater absorption and dispersion effect than clear ocean water.

D. Turbid harbor water:

It has the highest concentration of dissolved salts and suspended particles and therefore, limits the propagation of optical beam due to absorption and scattering.

IV. THE OPTICAL PROPERTIES OF WATER AND THE MAIN FACTORS THAT AFFECT UOWC

There are two types of optical characteristics in water:

- Inherent optical properties (IOPs): These are features that are solely dependent on the medium and thus unaffected by ambient light. The absorption coefficient, scattering coefficient, attenuation coefficient, and volume scattering function are all inherent optical parameters that are used to calculate the link budget in UOWC[5].
- Apparent optical properties (AOPs): these are the properties of the ambient light field that are affected by both the medium (IOPs) and the directional structure. The ambient light levels for communication near the water surface are evaluated using AOPs. Radiance, irradiance, and reflectance are three often utilized AOPs. [5].

Many factors have to be considered when designing a UOWC system, due to its great influence on the propagation of the optical beam, and these factors are:

A. Absorption and scattering.

Absorption and scattering are the two major factors that influence underwater optical transmission. The absorption of an optical beam signifies a reduction in its intensity, whereas the scattering of an optical beam represents a change in its direction [1][6]. When the power is irradiated with a light beam of incidence power Pi, a small part of the incident light is absorbed by the water, denoted by Pa, and another fraction is dispersed, denoted by Ps. Pt will continue to pass through water undamaged for the remainder of the light power, and fig 1 shows a simple model that represents that.

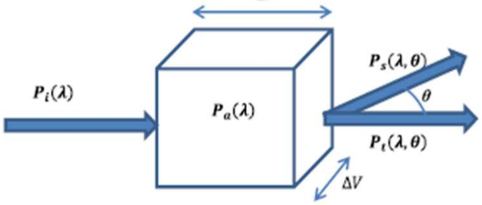

Fig. 1. Geometry of inherent optical property [7].

According to the conservation of energy:

$$P_i(\lambda) = P_a(\lambda) + P_s(\lambda) + P_t(\lambda) \qquad (4)$$

The absorbance (A) is defined as the ratio of absorbed power to the incident power. Similarly, the ratio of scattered power to the incident power is defined as scatterance (B):

$$A(\lambda) = \frac{P_a(\lambda)}{P_i(\lambda)} \qquad (5)$$

$$B(\lambda) = \frac{P_s(\lambda)}{P_i(\lambda)} \qquad (6)$$

The absorption and scattering coefficients $(\alpha(\lambda), b(\lambda))$ can be obtained by the next equations when Δr are approaches to zero:

$$\alpha(\lambda) = \lim_{\Delta r \to 0} \frac{\Delta A(\lambda)}{\Delta r} = \frac{dA(\lambda)}{dr} \qquad (7)$$

$$b(\lambda) = \lim_{\Delta r \to 0} \frac{\Delta B(\lambda)}{\Delta r} = \frac{dB(\lambda)}{dr} \qquad (8)$$

The overall attenuation underwater is denoted by the letter *c* which is calculated by the next formula:

$$c(\lambda) = \alpha(\lambda) + b(\lambda) \qquad (9)$$

TABLE. I. Shows the Typical values of chlorophyll concentration (C), absorption, and scattering coefficients $(\alpha(\lambda), b(\lambda))$ and the overall attenuation coefficient $c(\lambda)$ for different water types, work out with $\lambda = 532\ nm$.

TABLE. I. Absorption and scattering coefficients for different water types [8].

Water type	C (mg/m^3)	$\alpha(\lambda)$ (m^{-1})	$b(\lambda)$ (m^{-1})	$C(\lambda)$ (m^{-1})
Pure seawater	0.005	0.053	0.003	0.056
Clear ocean	0.31	0.069	0.08	0.151
Coastal ocean	0.83	0.088	0.216	0.305
Turbid harbor	5.9	0.295	1.875	2.170

Light is scattered when it falls on various types of suspended particles in its path. The scattering of light by suspended particles. Depending on the size of particles. There are two types of scattering:

- Rayleigh scattering: Occurs if the particle's size is smaller than the wavelength of light. It is used to describe the scattering in pure seawater as it is more pronounced at shorter wavelengths due to the salts and ions in it. The probabilities of forward and backward scattering, in this case, are equal. And Rayleigh scattering coefficient in pure seawater, (b_w) can be obtained by:

$$b_w(\lambda) = 0.005826\left(\frac{400}{\lambda}\right)^{4.322} \qquad (10)$$

- Mie scattering: Occurs due to the interaction of the particles larger than the wavelength of light. In case, the probability of forward scattering is higher than backward scattering it is better to describe the scattering by Mie scattering, where scattering coefficients for large and small particles of ocean water are given by the following formulas:

$$b_l(\lambda) = 1.151302\left(\frac{400}{\lambda}\right)^{1.17} \qquad (11)$$

$$b_s(\lambda) = 0.341074\left(\frac{400}{\lambda}\right)^{0.3} \qquad (12)$$

Finally, we can conclude that both absorption and scattering affect the light propagation underwater, where the overall attenuation in pure seawater is largely affected by absorption, whereas in regions closer to land, where the excess of particulate and organic matter, attenuation is dominated by scattering. And fig. 2 shows the attenuation (absorption + scattering) in dB/m for different ocean waters.

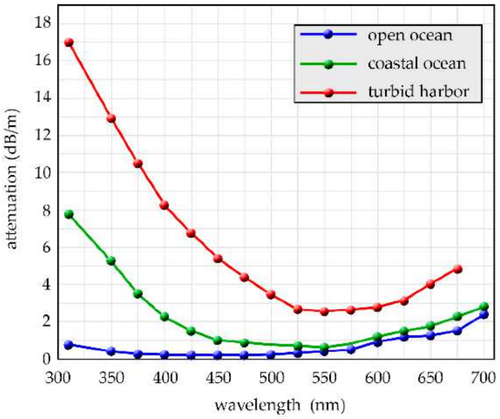

Fig. 2. Attenuation for different ocean water types [8].

B. *Turbulence.*

This turbulence is caused by many reasons such as the variation in the refractive index due to fluctuation in the temperature, salinity level, density, and pressure of water, all these factors make fluctuations in the received signal intensity and this phenomenon is called the scintillation and degrades the performance of the UOWC system. However, the effect of pressure on the refractive index is negligible, while the salinity level in the deep seawater is usually stable and the fluctuation in the water temperature is small therefore the channel fading caused by the water turbulence is negligible for the most practical cases.

C. *Pointing and alignment.*

In the UOWC systems, we have to keep on the line of sight (LOS) between the transmitter and receiver, even if the optical beam that is used is narrow but the movement of the underwater vehicle (UV) and ocean currents and other sources of turbulent can affect the LOS, and due to that the pointing and alignment between the transmitter and receiver is very important to maintain a reliable link.

D. *Multipath interference.*

When a transmitted optical signal reaches the receiver after encountering many scattering objects or multiple reflections from other submerged bodies, multipath interference occurs. As a result of the inter-symbol interference (ISI), a phenomenon known as waveform time dispersion (time spreading) occurs, lowering the data rate (a form of distortion of a signal in which one symbol interferes with subsequent symbols). This is an unwelcome phenomenon in which past symbols have the same impact as noise, reducing the reliability of transmission. However, unlike acoustic waves, which propagate at considerably slower speeds than optical waves, multipath interference is not as prominent.
in UOWC systems due to the high propagation speeds of light. In shallow water, optical waves reflect from the surface and the bottom, generating several signals at the receiver, whereas in deep water, these reflections can be ignored.

E. *Physical obstruction.*

Underwater settings are teeming with marine life, such as a school of fish or other living organisms. The presence of these orgasms in the optical link may cause a brief signal loss at the receiver, necessitating the use of error correction techniques, signal processing techniques, and redundancy measures such as Automatic Repeat Request (ARR) and Forward Error Correction to ensure data retransmission when lost (FEC).

F. *Background noise.*

Background noise is the noise that comes from the background. This Noise is strongly dependent on two things which are the operating wavelength and geographical location. In general, harbors are noisier than deep oceans due to man-made noise that is present in the harbor side. The majority of noise sources in aquatic environments have a continuous spectrum and a Gaussian distribution. Diffused extended background noise, background noise from the Sun or other stellar (point) objects, and scattered light captured by the receiver are the main sources of background noise. [2].

V. OPTICAL MODULATION

Choosing the best modulation technique is considered a big challenge for any communication system. Modulating can be accomplished in one of two ways: changing the signal input (driving current) or alternating the continuous wave output after the light has been generated.. In optical communication systems, all modulations fall under two basic types: direct modulation and external modulation.

- Direct modulation: This is the simplest to do, and it occurs when the current is changing by the modulation signal (message signal) before it reaches the laser diode. Direct modulation is simple to execute and can be done with just a laser driver and no complicated circuitry.
- External modulation: When modulation is applied to a laser signal after it has been generated, it is known as external modulation. External modulation applies modulation to the continuous wave (CW) laser output via an external device. And it’s this kind that we’ll employ in our simulation. External modulation has the advantage of quicker speeds (larger bandwidths), but it also increases the cost and complexity of the laser systems.

VI. SYSTEM DESIGN & SIMULATION

The underwater optical communication system is made up of three components: a transmitter, a water channel, and a receiver. A block schematic for a rudimentary UOWC system is shown in fig. 3.

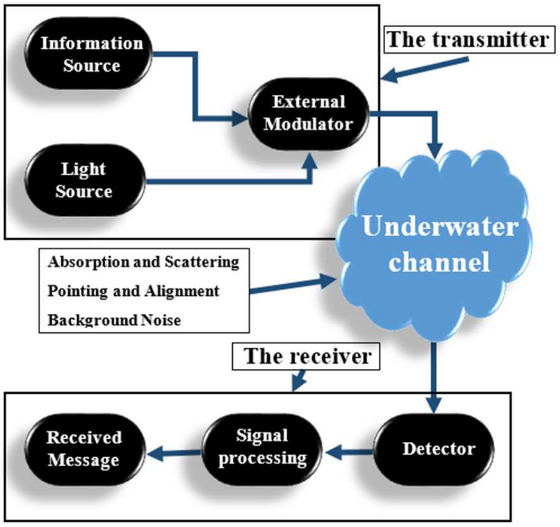

Fig. 3. A block diagram for a simple UOWC system.

A. *The transmitter:*

The optical transmitter transforms the electrical data signal into an optical signal, which then projects into the transmission channel. [9]. From fig. 3 we can see that the transmitter has three components which is the information source which represents the device that gives us the message signal, the light source which represents the photon source that we use to transmit the information such as Light Emitting Diodes (LEDs) or Laser Diodes (LDs) which is the one we used due to its higher optical power output and its ability to switch faster than LEDs, and the modulator to modulate the information signal into an optical signal and for this part, we used the Mach - Zehnder Modulator due to its high data rate and low driving voltage. which is considered as an external intensity modulator.

B. *The communication channel:*

Communicating an information signal over space requires a path or medium. These paths are called communication channels. In this work, paper the carrier is an optical signal which travels through an underwater medium, whose properties differ from one type of water to another as we explained before.

C. *The receiver:*

The optical receiver detects the optical signal and converts it to an electrical signal. [9]. The optical detector, converts the received optical signal into an electrical signal and must quickly respond to all incident photons sent by the transmitter without introducing additional noise, and for this research, we used the Positive-Intrinsic–Negative (PIN) photodiode as a detector, and the signal processing components, which represent the amplification, filtering, and any other signal processing components transmission, storage efficiency, and subjective quality, and to also emphasize or detect components of interest in a measured signal. Fig. 4. Shows the simulation circuit designed using the Optisystem software.

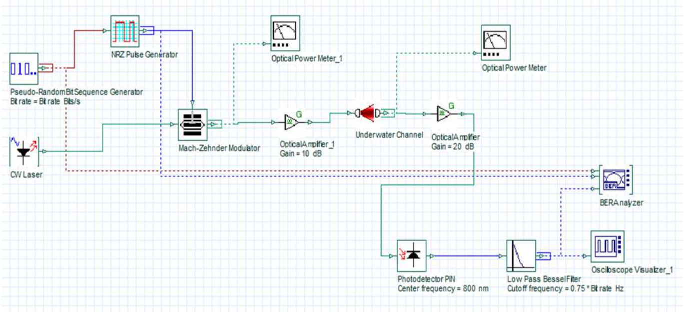

Fig. 4. The simulation circuit we designed using the Optisystem

For the circuit shown above we used different parameters some of them change depending on every case but also few of them will remain constant in all cases. The variable parameters will be included in the results table, while the constant parameters are: 10 dB gain and noise figure of 4 dB for the amplifier before the channel and the same for the other amplifier except the gain which will be 20 dB. The PIN photodetector will have a responsitivity of 1 A/W and a dark current of 100 nA. The low pass filter will have a depth of 100 dB and a cutoff frequency equal to 0.75 of the bitrate.

VII. RESULTS AND DISCUSSION

In this paper two cases were simulated and compare:

Case 1: when the optical carrier has an operating wavelength at the beginning of the visual spectrum (350 - 370 nm).
Case 2: when the optical carrier has the optimum operating wavelength where the attenuation at its minimum value on the visual spectrum.
Both cases are working on the same bitrate which is 10Gb/s. The main purpose of making two cases is to compare them with each other and see how the variation of the operating wavelength of the optical carrier can affect the transmission underwater.
NOTE: case 1 and case 2 are similar in the simulation circuit which is shown in fig. 4, but with a slight difference that on case 2 we decreased the attenuation to its minimum value, and according to the results, the amplifier has been removed at the transmitter.

In case 1 the power was fixed-parameter at 1, 5, 50, and 1000 mW, and increase the distance until we reached the maximum distance that has no Bit Error Rate (0 BER), while in case 2 we removed the transmitting amplifier and do the opposite of case 1 which that set the distance as fixed-parameter at the same maximum distance in case 1 and change the transmitting power. The purpose of that is to calculate the power that needs to send the same signal for the same distance but using another operating wavelength that has less attenuation value. TABLE II shows the results for both cases.

TABLE II. Simulation results for both cases (case 1 and case 2).

Water type	Attenuation (dB/km)	Pt (mW)	L (m)	Pr (dBm)	Q factor	λ (nm)
Case 1						
Clear ocean water	390	1	103	-33.28	40.89	~ 350
		5	121	-33.34	40.62	
		50	147	-33.48	39.38	
		1000	180	-33.35	40.62	
Coastal ocean water	5400	1	7.4	-33.07	48.22	~ 350
		5	8.5	-32.05	53.91	
		50	10.5	-32.86	45.25	
		1000	13	-33.35	40.62	
Turbid harbor	11000	1	3.6	-32.71	46.36	~ 370
		5	4.3	-33.45	39.65	
		50	5	-31.16	65.55	
		1000	6.4	-33.55	38.87	
Case 2						
Clear ocean water	250	0.35	103	-23.36	39.65	~ 475
		1	121	-23.36	40.18	
		4.3	147	-23.56	38.74	
		29	180	-23.52	39.07	
Coastal ocean water	700	3×10^{-3}	7.4	-17.8	38.79	~ 532
		3.6×10^{-3}	8.5	-18.35	38.98	
		5×10^{-3}	10.5	-19.26	39.21	
		7.5×10^{-3}	13	-20.26	39.31	
Turbid harbor	2500	7.5×10^{-3}	3.6	-20.16	40.18	~ 532
		11×10^{-3}	4.3	-21.05	39.42	
		17×10^{-3}	5	-21.62	40.66	
		36×10^{-3}	6.4	-22.69	38.55	

Where: Pt is the transmitting power in the CW laser diode, Pr is the received power before the amplification, L is the maximum distance that the signal could reach with 0 BER, Q is the quality factor, and λ is the operating wavelength

From TABLE. II the difference we can see in power between cases 1 and 2, for instance in clear ocean water the signal was sent for more than 100 m with 1 mW in case 1 (λ= 350 nm) and 0.35 mW in case2 (λ = 475 nm) which saves about 65% of power, this saving varies from one water type to the other and from one power value to the other, but in all cases, there are saving in power due to the decrement of the attenuation value that happens when we choose the optimum wavelength for the medium we deal with.

VIII. CONCLUSION

In this paper, the results obtained from the simulation show that the attenuation of the underwater medium is largely affected by the operating wavelength used in transmission. Also that this type of communication can be affected by the type of water that the signal travels in. In case 2 the power required was calculated to transmit the signal for the same distance in case 1 but with different attenuation by using another optical wavelength to reach minimum power consumption at 83% of saving transmitting power in the clear ocean and more than 99% in coastal water and turbid harbor. In general UOWC technology is affected by a lot of factors but on the other hand, it provides high data rates for moderate and short distances, also it has high bandwidth and it is a free band but it still needs more study and improvements before it can be used as solo technology but it can be used to enhance other technologies by building hybrid systems between UOWC systems and other systems like acoustic systems.

REFERENCES

[1] F. Jasman and R. J. Green, "Monte Carlo simulation for underwater optical wireless communications," *Proc. 2013 2nd Int. Work. Opt. Wirel. Commun. IWOW 2013*, pp. 113–117, 2013, doi: 10.1109/IWOW.2013.6777789.

[2] H. Kaushal and G. Kaddoum, "Underwater Optical Wireless Communication," IEEE Access, vol. 4, pp. 1518–1547, 2016, DOI: 10.1109/ACCESS.2016.2552538.

[3] M. G. Solonenko and C. D. Mobley, "Inherent optical properties of Jerlov water types,"

[4] A. Kumar, S. Prince, N. Vedachalam, and V. D. Prakash, "Ocean water channel modeling and estimation of power link budget for underwater wireless link," *Proc. 2017 Int. Conf. Wirel. Commun. Signal Process. Networking, WiSPNET 2017*, vol. 2018-Janua, pp. 1269–1272, 2018, DOI: 10.1109/WiSPNET.8299987.

[5] L. J. Johnson, F. Jasman, R. J. Green, and M. S. Leeson, "Recent advances in underwater optical wireless communications," *Underw. Technol.*, vol. 32, no. 3, pp. 167–175, 2014, DOI: 10.3723/ut.32.167.

[6] L. J. Johnson, R. J. Green, and M. S. Leeson, "Underwater optical wireless communications:Depth dependent variations in attenuation," *Appl. Opt.*, vol. 52, no. 33, pp. 7867–7873, 2013, doi: 10.1364/AO.52.007867.

[7] C. D. Mobley, Light and Water: Radiative Transfer in Natural Waters. San Diego, CA, USA: Academic, 1994.

[8] G. S. Spagnolo, L. Cozzella, and F. Leccese, "Underwater optical wireless communications: Overview," *Sensors (Switzerland)*, vol. 20, no. 8, 2020, doi: 10.3390/s20082261.

[9] H. Brundage, "Designing a Wireless Underwater Optical Communication System," p. 69, 2010