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Performance Analysis of Underwater Wireless Optical Communication with Varying Salinity: Experimental Study

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Abstract: This paper exhibits the performance of visual light communication in the underwater environment at different salt concentrations. The output is measured in terms of the signal received power at different link budgets. A series of experiments were conducted to verify the results and concluded that light attenuation increases with an increase in water salinity. Furthermore, we analyzed that salinity also affects data rate and link budget. It is found that water salinity cannot block the communication completely as the maximum possible saturation is 40% which can degrade the system by upto 20% only. Along salinity, we also tested the system performance against turbidity and found that it has a much more significant effect. A slight increase in turbidity may block a more considerable portion of the communication channel. The study can help researchers when developing an underwater communication system using visible light for freshwater or salty water (seawater). As per our observation, visual light communication is feasible for both of these environments as even in the saltiest water, it will work because the maximum concentration of salt and percentage of turbidity will not degrade the system beyond a specific limit.

Keywords: *Optical Communication, Visual Communication, LiFi, Underwater Wireless Communication*

1. Introduction

The study of the ocean is always a great interest of human beings for the prospective of military, industry, transportation, mineral exploration, and scientific research. Communication is the primary concern and key to success for any of these activities. Wireless communication under and over the water is more challenging and different from conventional terrestrial communication methods. Radio waves are the most used wireless technology in terrestrial applications but are not very effective in underwater conditions due to rapid absorption in water. Radio waves like electromagnetic (EM) waves offer a high data rate but for short distances. They can undergo a smooth transition through air/freshwater medium but are highly attenuated in salt water. To make it successful for this medium, it needs bulky and costly transceivers along large transmission antenna [1]. In the last few decades, acoustics waves have become an excellent alternative to radio technology for underwater environment however, their low band, high latency, high transmission losses, multipath propagation etc., (see Table 1) restrict their use and let the researchers to think about other choices.

Optical communication emerges as a better option as it can provide higher bandwidth and data rate and other advantages like superior security, less power consumption and lower implementation cost [2]. Optical communication can also be used for terrestrial and space communication as it provides better results and more environment and human-friendly [3-6]. Under present circumstances, it has great potential in the underwater environment as observed in Table 2, which shows it can provide a better data rate over a reasonable distance compared to other available technologies.

Table 1. Acoustic wave characteristics (Distance covered VS bandwidth)

Distance (Km)	*Data Rate (Kbps)*
Very Long 1000	0.5
Long 10-100	5
Medium 1-10	10
Short 0.1-1	30
Very short <0.1	500

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Table 2. A brief comparison of different underwater communication technologies

Parameters	***Acoustic***	***RF***	***Optical***
Data rate	Kbps	Mbps	Gbps
Distance	Upto 100s Km	Upto 10 meter	10-100 meter
Transmission power	10s of watts	mW to 100s of Watts	10s of Watt
Attenuation	0.1 to 4dB/Km	3.5 to 5 dB/Km	0.39 -11 dB/m Turbidity dependent
Latency	High	Moderate	Low
Bandwidth	1-00 KHz (depending on distance)	MHz	10-150 MHz

Underwater optical communication (UWOC), we name underwater visual light (UWVL) communication because, in this research, we studied visible light as a communication medium in the underwater environment. It can get Gbps of throughput at a few hundred meters. This distance limitation exists due to the high frequency of the optical carrier, optical absorption and scattering in water, suspended particles, and strong disturbance caused by the sun. The major problem to establish wireless optical link in underwater is that optical signal is greatly affected due to optical characteristics of the medium. However, the benefits of using underwater optical links outweigh its drawbacks and work well for moderate communication ranges. Various research studies like [7-9] are conducted to observe the behavior and performance of UWOC communication theoretically and experimentally and agree that it offers high-capacity underwater wireless transmission over moderate ranges. The author of [10] experimentally proved that argon-ion laser light operating at 514 nm could carry 50 Mbps over a distance of 9 m. In 1995, LED-based communication was established theoretically to achieve 10 Mbps and 1 Mbps of throughput for a distance of 20 m and 30 m, respectively. However, later this work was extended in 2013 in another research [7]. In the study [11], data is communicated up to 2.2 m experimentally at the speed of 320 kbps using a unidirectional optical wireless link. Further, this work was evaluated by repeatedly replacing different parameters, including omnidirectional communication with uni-direction, an LED source with laser, and a seafloor environment with a lab testbed [12]. Later on, different articles were written to show the performance of underwater optical communication and got different results. Some of them are shown in Table 3.

Table 3. Underwater optical communications studies

Study	Light source	Power	Rata Rate	Distance covered
[13]	Laser diode	10 mW	1 Gbps	2 m
[14]	LED	5W	0.6	3 m
[15]	Laser	40 mW	1.45 Bbps	4.8 m
[16]	Laser	15 mW	4.8 Gbps	5.4 m
[17]	Laser	12 mW	2.3 Gbps	7 m
[18]	Laser	3 W	1 Gbps	8 m
[19]	LED	0.1 W	1 Gbps	18 m
[20]	LED	30 mW	10 Mbps	20-30 m
[21]	Laser	1 W	1 Gbps	30-50 m
[22]	LED	5 W	1.2 Mbps	200 m

When we talk about optical communication, we usually have two choices: an optical transmitter, either LED, a diffuse light source, or laser, a concentrated beam. Although it depends on the application and can vary, choosing an LED system over a laser is considered better due to operating as diffuse light. When an optic is inserted in the transmitter, the light beam has more possibility to become more diffuse or tighter. On the other hand, when dealing with laser, alignment is complex and becomes difficult to handle [23]. After the transmitter, optical modulation is the next critical component of the underwater optical communication system. An ideal modulation can help to improve the data rate and system range and has an important role in energy efficiency. The receiver is the third essential component of any optical system, along with the transmitter and modulation. It is a photoreceptor that captures the signal and sends it to the demodulated.

Regarding the challenges of optical communication, optical beam propagation is one of the significant issues in the underwater environment. Its characteristics vary in different water bodies due to the presence of various elements including salt, turbidity, chemical dissolved substances and debris. In general, the total absorption in seawater is same as in pure water, however the difference is caused by absorption of salts in water and lack of other suspended particles.

Recently, various research studies have been published to improve the effectiveness of UWOC, especially its communication range, where multiple-input multiple-output (MIMO) is one of the most common options to enhance the range of UWOC systems. For example, the mathematical expression proposed in [24] shows that MIMO can help to improve the communication range of UWOC systems even under the strong turbulent channel. Along MIMO, relay-stressed is another technique that has been employed to improve the communication range under UWOC based systems. To increase the communication distance, intermediate relay nodes can be introduced along with various relaying techniques, making it more effective. When we talk about the recent efforts for this purpose then [25] has shown an improvement of 32 dB in BER when employed a dual-hop transmission under the range of 90m in an ocean channel. Moreover, to make the UWOC communication more effective, researchers are also studying the factors that limit the performance of UWOC channel e.g., turbulence due to salinity, turbidity and temperature fluctuations.

Most of the research studies mentioned above use the laser as a communication source and tap water as a medium. Only a few employed visible light and underwater sea environments. The most prominent factors affecting the optical wireless link are the salinity and turbidity of the water. The distinction of our work is that we studied these factors and their effects on visible light communication experimentally.

1.1. Ocean Salinity

When we think about the sea, the first thing that comes to mind is salty water. The unit of seawater salinity is gram per-kg or parts per thousand (ppt) while also expressed psu (practical salinity unit) where both terms are almost equivalent to each other. Mostly 35 grams or 35% of salt is dissolved in one liter of seawater, but it can vary from area to area and mostly ranges between 32-37 grams per litter (32% – 37%). Different levels of saltiness in all five oceans are shown in Fig. 1, where salinity is increasing from green to red. Around the globe, there are many ocean parts where hardly any rainfall is witnessed while warm dry winds cause lots of evaporation which leads to increased saltiness. The Dead Sea is the saltiest in the world, where salinity can reach up to 40 %, which is the maximum salt solubility in water. As a result of this impairment, we can conclude that small variations in salinity and temperature can produce an optical signal fading, sometimes called oceanic turbulence, which can lead to degrading the overall performance of such a system. Usually, there are two methods to measure seawater salinity: electrical conductivity (EC), which measures in micro-centimeter, and the number of salt particles in the solution. In our experiments, we tested the performance of visual light communication under varying salinity from 0 to 40 gram/little of water channel, and the results are presented in the next section.

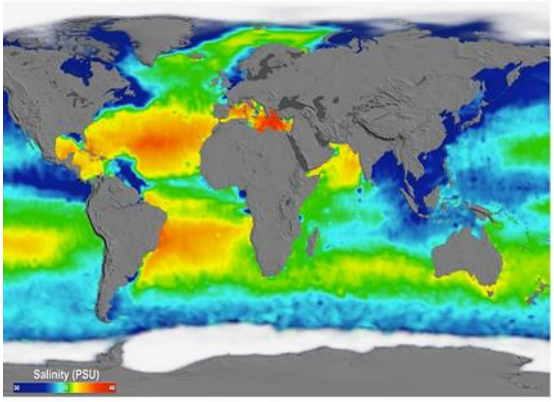

Fig. 1. Salinity of seas [26]

1.2. Ocean turbidity

Ocean turbidity is the amount of cloudiness/haziness due to suspended particles in seawater, mostly that are too small to see with the naked eye. Due to such suspended particles in seawater, turbidity considerably affects optical communication.

As described in a previous study, a slight change in turbidity value may block a larger portion of communication bandwidth [27]. This study concludes that turbidity mainly increases from the center of the sea to the sides, ranging from 5.8 to 2%, while its measuring unit is Formazin Nephelometric Unit (FNU). The optical wireless communication channels are scattered mainly due to such impurities and turbidity in the open water and create a significant inter-symbol interference (ISI) which seriously reduces both channel capacity and the maximum practical information rate. Along with salinity, we also tested the turbidity of the red sea near Sharma city, as shown in Fig. 2, and found that it ranges from 3.75 to 5.8 depending upon its distance from the shore.

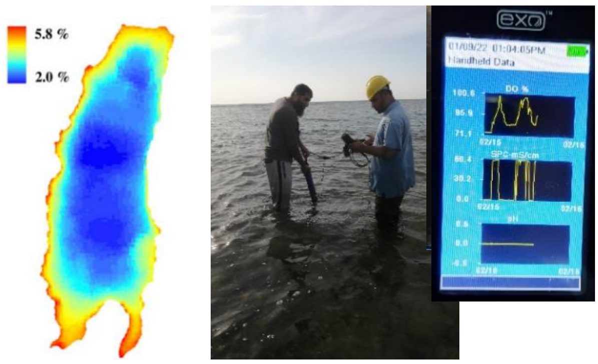

Fig. 2. Testing the salinity and turbidity of the Red Sea

2. Experimental Setup

We conducted a sequence of experiments to test the performance of underwater visual light (UWVL) communication. For that, a cubical box of metal was made to build a testbed of size 150 x 30 x 30 cm. A transparent glass window of size 10 x 10 x10 cm was made on both sides of the box to attach the light transmitter and receiver. The light transmitter was fixed at one end while we kept the receiver moveable to move inside or outside the water box to measure the received voltage at different locations. A music source of signals was encoded and transmitted using ordinary white light LED panel through the water channel. On the other side, we had two types of circuits, an amplifier, and a voltage divider. An amplifier was used to hear the quality of the received signal physically. At the same time, the output of the voltage divider was given to an Arduino board and then attached to a computer for analyzing the received signal quality. The experimental setup with all the details discussed above is shown in Fig. 3, while the block diagram is given in Fig. 4.

Once the experimental setup is completed, we test the developed system initially without water in the channel to calibrate the system in air and note the results at different distances from the transmitter. We tried to keep the transmitter and receiver perfectly aligned before taking any readings. While different underwater link lengths are tested against various data rates to check the bandwidth suitability. Then we repeated the same experiments by filling the channel with distilled water to check the performance of visual light communication with pure water, and the results were noted. The next sequence of the same experiments was conducted with varying water salinity from 5 % to 40% at different locations of 20cm to 100cm. Another set of experiments was conducted by changing water turbidity with keeping all other facts constant. During the experiments, uniform turbulence was also created by injecting water streams to get the received optical channel's probability density function (pdf).

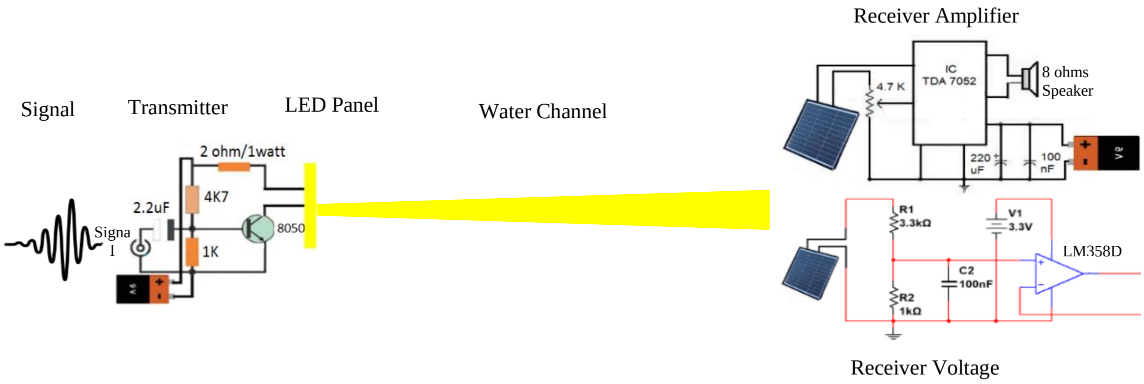

Fig. 3. Underwater visual light experimental setup

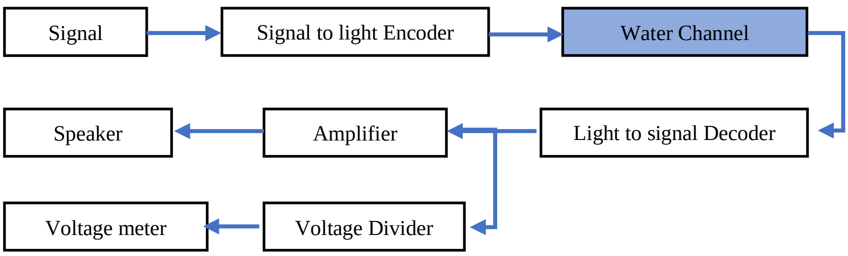

Fig. 4. Underwater visual light communication system block diagram

Each investigation was conducted multiple times, and each time an average of 50 readings of the received signal was taken by the attached computer to get an averaging result at each point with different channel parameters, and the results were logged in a file for further analysis.

3. Result Analysis

Fig. 5 expresses the performance of visible light in air and pure water. Received signal power (mW) is plotted against distance traveled (cm) in the underwater environment. As expected, the transmission in pure water is higher than in the air. The reason behind is the small and closed structure (closed from above as well) is used during the experiments hence the back-and-forth illumination resulted the higher received signal power.

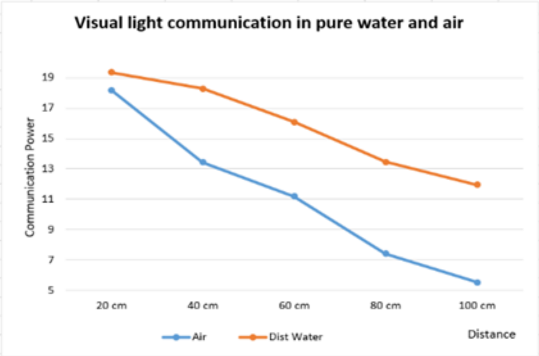

Fig. 5. Visual light communication performance in pure water VS air.

Fig. 6 exhibits the performance of UWVL communication while increasing water salinity against increasing travel distance. Here received signal power is plotted against the traveled distance. We analyzed that increasing salinity affects the communication power, and this effect becomes wider with signal travel distance.

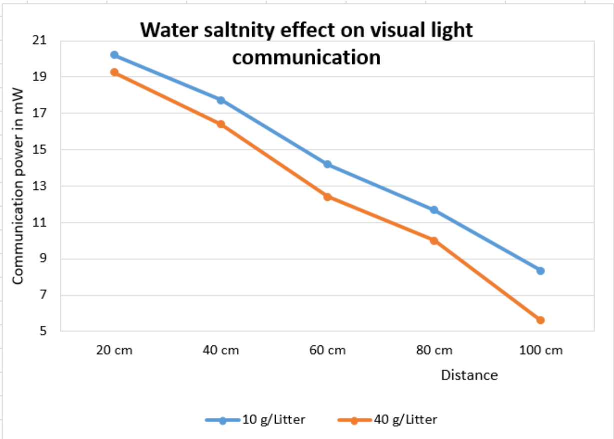

Fig. 6. Effect of water salinity on underwater visual light communication.

The overall picture of UWVL communication performance is shown in a graph Fig. 7 under different medium and channel conditions. Another interesting view is observed when we plotted received signal power against different channel conditions while curve trends show travel distances, as shown in Fig. 8. Here, it can be observed that as the length of the communication link is increased, the quality of the received signal started to decrease against a given data rate. While, the results in this graph reflect that the overall performance of UWVL degrades as the length of the communication channel and data rate is increased. Based on this fact, it can be concluded that depending on the requirement and considering current optical wireless communication practices, either an increased data rate with a small communication range or a lower data rate with a higher communication range can be achieved.

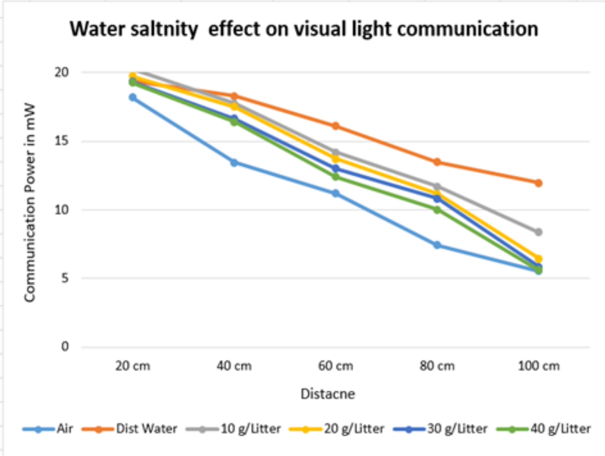

Fig. 7. Overall effect of increasing water salinity on UWVL communication under different mediums.

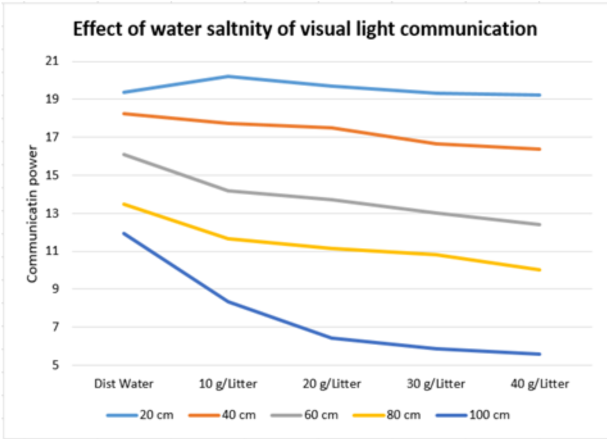

Fig. 8. Overall effect of increasing water salinity on UWVL communication under varying distances.

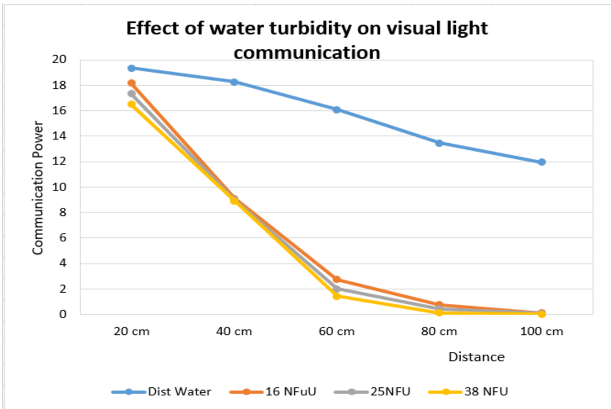

Fig. 9. Effect of changing turbidity on UWVL communication.

The effect of water turbidity is also analyzed during this experiment, and it found that it has much higher impact on communication. A little increase in value can block the whole communication channel, as shown in Fig. 9. To improve the UWVL system performance, we must consider the effects of turbidity when designing underwater communication links. While various techniques that have been commonly used in free-space optics can also be utilized for this purpose. While implementing the UWVL system, adaptive optics can be handy to enhance the beam front when propagating through turbid water.

4. Conclusion

This research aimed to prove experimentally that visual light communication is feasible in the underwater environment. The most prominent utility of underwater communication is under the sea, while recent sea explorations have become critical for many purposes. Wireless communication is the key to success for many underwater applications in this modern era. The salinity level of seawater varies in different areas of the world. In this regard, we tested the effect of water salinity on underwater visual light communication in the laboratory where the samples were taken from the Red Sea. We found that up to 40% of signals are not much-deviated. Hence, communication is possible without any significant loss. The second factor is turbidity. Turbidity in the sea also varies at different locations and is found high in shallow water near the beach areas but very low in the center of the sea. It differs from 5.8 % to 2% from the beach to the center of the sea. However, we found that, unlike salinity, turbidity significantly impacts visible light communication. Still, the good thing is the maximum measured value is 5.8%, which allows the communication to maintain acceptable quality. UWVL is an emerging communication system with great potential to offer high-speed communication channels within the blue-green length band. However, systems based on this technology are subject to severe performance degradation when applied in seawater environments, especially due to undissolved particles that make the water turbid. Based on found results, we can say that visual light communication is quite feasible in the underwater environment, but more research is required to increase its efficiency, especially to estimate the pdf of the received optical channel.

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Conflicts of interest

The authors declare no conflicts of interest.

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