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A Testbed for Investigating the Effect of Salinity and Turbidity in the Red Sea on White-LED-Based Underwater Wireless Communication

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Abstract: Several industrial and scientific underwater applications require high-speed wireless connectivity. Acoustic communications have low data rates and high latency, whereas attenuation in seawater severely limits radio frequency communications. Optical wireless communication is a promising solution, with high transmission rates (up to Gb/s) and little attenuation in water at visible wavelengths. This study explores the feasibility of white-LED-based underwater optical wireless communication (UWOC) by considering Red Sea parameters. High salinity is the most prominent attribute of the Red Sea that can affect underwater communication and requires investigation. Considering this, the received signal intensity fluctuation under increasing water salinity was experimentally investigated. In the same experiment, the impact of growing turbidity was tested, as it is the most influential parameter and tends to block the entire LED-based communication system with little increase. The experimental results show that the signals are affected less by salinity and more by turbidity but are found to be sufficiently strong to be used for communication in the Red Sea. Finally, it was concluded that a white LED is capable of sending data at the maximum possible salinity values of 40 g/L. However, the turbidity can significantly limit the transmission distance to less than 60 cm.

Keywords: underwater optical wireless communication (UWOC); light emitting diodes (LEDs); Red Sea; salinity; turbidity; short-range communication

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1. Introduction

The Red Sea is one of the world's busiest shipping waterways, connecting the Mediterranean, Africa, and Asia through the Suez Canal, and providing an alternative route via the Cape of Good Hope. It is a vital link in the political and economic stability of many countries in that region [1]. The Red Sea coast of the Kingdom of Saudi Arabia is approximately 2000 km in length. Saudi Arabia is working to develop its Red Sea coastline, most notably through megaprojects such as NEOM, LINE, and the Red Sea Project, all of which are part of Saudi Vision 2030 efforts [2–4]. These projects will incorporate smart city technologies such as the Internet of Things (IoT), augmented reality (AR), virtual reality (VR), autonomous vehicles, hyperloops, and many other applications. The key to enabling and implementing these technologies is wireless communication infrastructure [5,6].

The use of wireless communications in terrestrial devices should be explained, whereas underwater wireless communication has become an area of interest. It is receiving more attention as research on marine-related challenges progresses rapidly and has become a critical concern for all countries worldwide. This technology has vast potential for various applications, such as oceanography studies, oil and gas exploration, and military applications. The Red Sea is the world's most intriguing area for hydrocarbon exploration and mineral discovery, but it has been underexplored. Saudi Arabia is the world's most significant producer and exporter of oil, with a quarter of the world's proven oil reserves [7]. Aramco, a Saudi oil company, aims to employ various cutting-edge technologies, ranging from artificial intelligence (AI) to unmanned vehicles (UVs), to boost efficiency, productivity, and sustainability. Underwater wireless communication (UWC) technology plays a vital role in enabling these technologies. In addition, the strategic and economic importance of the Red Sea requires advanced security technology. The UWC plays a vital role in military applications to conduct underwater surveillance, detect intrusion, and plan attacks, if needed. Another military application is to prevent any rival state from sabotaging the waters by laying a communication system in the water.

Furthermore, autonomous submarines capable of sending real-time messages through a UWC are being used to control drug traffickers. Moreover, unmanned underwater vehicles (UUVs) and autonomous underwater vehicles (AUVs) are increasing rapidly. Therefore, the amount of data to be transferred and the associated data rates continue to increase to fulfil the demands of the aforementioned applications [8]. Employing underwater cables or tethers to provide data links is expensive, requires additional maintenance, and its installation is restricted or difficult in many areas. In the current situation, underwater wireless connection is inevitable.

Acoustic waves are the most commonly used underwater communication system, with a range of several kilometers. Acoustic communication is characterized by extremely low bandwidth (only 100 bps), with high latency owing to the reflections, and relatively low throughput, owing to the speed of sound. Consequently, real-time communication for dynamically managing underwater vehicles and operations is impractical. Radio communication can provide a higher data rate; however, its high conductivity in seawater restricts it to a shorter distance. Considering the abovementioned factors, underwater optical wireless communication (UWOC) is a possible alternative or complementary solution. UWOC offers many technical advantages, including high data rates and secure connectivity. It also provides economic benefits such as reduced installation and operating expenses. UWOC systems can be classified into two types based on the transmitter light source: laser-based (LDs) and light-emitting-diode-based (LEDs). Although LDs have a larger modulation bandwidth than LEDs, LEDs are more suitable for medium-bit-rate applications due to their lower cost, higher power efficiency, and longer lifetime.

LEDs were first employed for underwater illumination in the 2000s and are currently the industry standard. They are now found in a wide range of applications, from indicator lights to solid-state illumination, and are available in various shapes and sizes. Owing to their high optical power density, they have been used in underwater white light illumination to extend the underwater lighting distance. LEDs have gained considerable attention in recent years for data transmission applications, where LED luminaires are used to provide both general-purpose lighting and Mb/s or Gb/s optical wireless connectivity. If this technology is successfully implemented, every light bulb can be used to transmit wireless data, similar to a Wi-Fi hotspot, and significantly contribute to a greener, more cost-effective, and brighter future.

In this work, the feasibility of LED-based UWOC, considering the Red Sea environment, was investigated. The Red Sea's most obvious characteristic that should be investigated is its high salinity, which can affect underwater communication. In light of this, an experimental investigation was conducted to determine how received signal intensity changed as water salinity increased. Moreover, as turbidity is the most important parameter and likely to completely block an LED-based communication system with a minor increase, its effect was also examined. The results presented here can serve as the starting point for further investigation into the use of UOWC in the Red Sea environment.

The rest of the paper is organized as follows: Section 2 presents a literature review; Section 3 provides the characteristics of the Red Sea; and Sections 4 and 5 discuss the experimental setup and the obtained results, respectively. The study is concluded in Section 6, which also highlights future research directions.

2. Literature Review

Many recent studies have explored higher data rates and extended transmission ranges using LED-based systems. Using five primary-colored LEDs, Zhou et al. [9] showed a transmission of 15.17 Gb/s over 1.2 m of clear tap water. Wang et al. [10] demonstrated a transmission of 2.175 Gb/s over 1.2 m of clean tap water using a single green LED, operating at 521 nm. Tian et al. [11] experimentally verified a 200 Mb/s data rate with a BER of 3.0×10^6, through a tap water tank of 5.4 m. Kumar et al. [12] investigated the performance of white, blue, and green LED arrays in transmitting voice in real time, through a 50 cm tap water tank. The findings show that blue light has the lowest attenuation and exhibited the best performance.

Significant progress has been made in research on underwater LED-based systems, both theoretically and experimentally. However, most of these studies were performed using tap water and did not consider the effect of real water channel parameters, such as salinity, turbidity, and temperature, on system performance. The fundamental characteristics of various water bodies, from shallow to deep oceans, vary widely, making the propagation of underwater optical beams very challenging. Therefore, a complete understanding of the effect of water parameters on the light beam propagation for UWOC is required.

Over the past few years, great and valuable studies have been conducted to investigate the effect of different real water channel parameters on both LED and LD UWOC systems. Swathis et al. [13] calculated the received power for various wavelengths such as 470 nm, 525 nm, and 660 nm based on the attenuation coefficients for pure sea, clear ocean, coastal water, and harbor water types. They concluded that the blue spectrum has a better communication window than the red and green spectrums for pure sea, clear ocean, and coastal water types. However, the green spectrum performs better in harbor water than the blue and red spectrums. Therefore, the type of water and chlorophyll content affects the wavelength choice.

Hassan et al. [14] used three types of water channels including clear, sea, and cloud water to test the received light intensity from LED and laser diodes at different transmitting distances up to 50 cm. Seawater was collected from Mengabang Telipot beach in Kuala Terengganu. In the seawater, they found that the received power from red laser light is approximately 35% higher than the power from green LED light.

Experimental studies were performed by Kumar et al. [15,16] using a 450 nm LD transmitter to investigate the effect of salinity on a transmission distance of up to 2 m. The results showed that at less than 40 cm, salinity of 35 g/L can block more than 90% of the laser's power [15]. The authors also determined that the transmission depth of the saline water channel is only about 60 cm [16].

Another water channel parameter that may affect the UWOC system performance is air bubbles. Hagem et al. [17] demonstrated a UWOC system for swimming applications using a 520 nm LED transmitter and an integrated detector–preamplifier. The system achieved a communications range of more than 1 m in all three scenarios under consideration: still pool water, still spa water, and bubbles spa water. The effect of bubbles produced by a spa jet is quite noticeable and significantly exceeds the effect of the bubble density and size expected by a swimmer. Oubei et al. [18] experimentally investigated the performance of green-LD-based UWOC links in the presence of different air bubble sizes. The received signal intensity was measured at five different beam sizes and under four bubble sizes. Large bubbles with a size comparable to the beamwidth can result in a deep fade or complete communication loss.

To the best of the authors' knowledge, no prior study considers the Red Sea salinity and turbidity effect on a white-LED-based UWOC link. Therefore, this study aims to explore the feasibility of such a system, considering the Red Sea environment. An experimental investigation of the effect of varying salinities and turbidities of water on the performance of the LED-based UWOC system, in terms of the received power at different link distances, was performed.

3. Characteristics of Red Sea

The Red Sea has a total length of approximately 2100 km and is enclosed by deserts. It is connected to the Indian Ocean through the Bab-el-Mandeb and Gulf of Aden.

3.1. Red Sea Salinity

Salinity is defined as a measure of salt concentration in water. Chloride and sodium account for over 85% of the ions in seawater, which is the same as table salt. The salinity in seawater is expressed in parts per thousand (ppt). Parts per thousand is the number of parts, or grams, of salt present in a kilogram (1000 g) of seawater. In normal seawater, an average of 35 parts of dissolved salt are typically present per thousand parts of water (35 ppt). This is equivalent to 35 g of dissolved salt per kilogram of seawater.

Owing to high rates of evaporation (up to ~2 m/yr), low mean annual rainfall from 3 mm/yr (N) to 150 mm/yr (S), and a lack of river intake, the Red Sea has a high salt concentration. The saltiness increases towards the north, as shown in Figure 1 [19]. It increases along its axes, reaching 3.8% by about 17° N, 3.9% by about 22° N, and 4.0% by about 26° N.

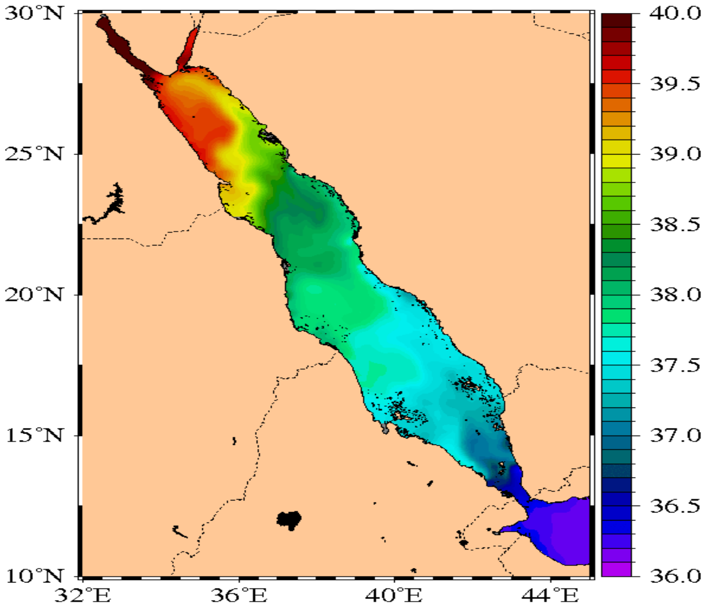

Figure 1. Salinity map.

3.2. Red Sea Turbidity

Another significant parameter that affects the LED-based UWOC link is water turbidity, which can block wave propagation between the transmitter and receiver. Turbidity is a measure of the cloudiness of water. Several materials can cause turbidity, including clay, silt, mud, plankton, and chemicals in the water.

The name of the unit of turbidity is referred to as the Formazin nephelometric unit (FNU). Turbidity in the high sea ranges from 1 to 3 FNU. The outermost parts of the coastal waters are usually 2–6 FNU. Turbidity in some estuaries can peak at up to 80 FNU [20]. To the best of my knowledge, the only reported data for Red Sea turbidity is found in [21], where the turbidity of water from the Thuwal, coastal area, is 2.34 ± 0.12 NTU. However, turbidity varies according to location, season, and weather. In open sea areas, algal abundance mainly affects the water turbidity.

4. Materials and Methods

An experimental testbed was set up to examine the behavior of optical signals in terms of received power at different salt concentrations and turbidity levels. Typically, a testbed includes a transmitter, a receiver, and a water tank. Figure 2a represents the block diagram of an experimental testbed, with the actual experimental setup shown in Figure 2b. Table 1 summarizes the specifications of the equipment used to create the experimental testbed.

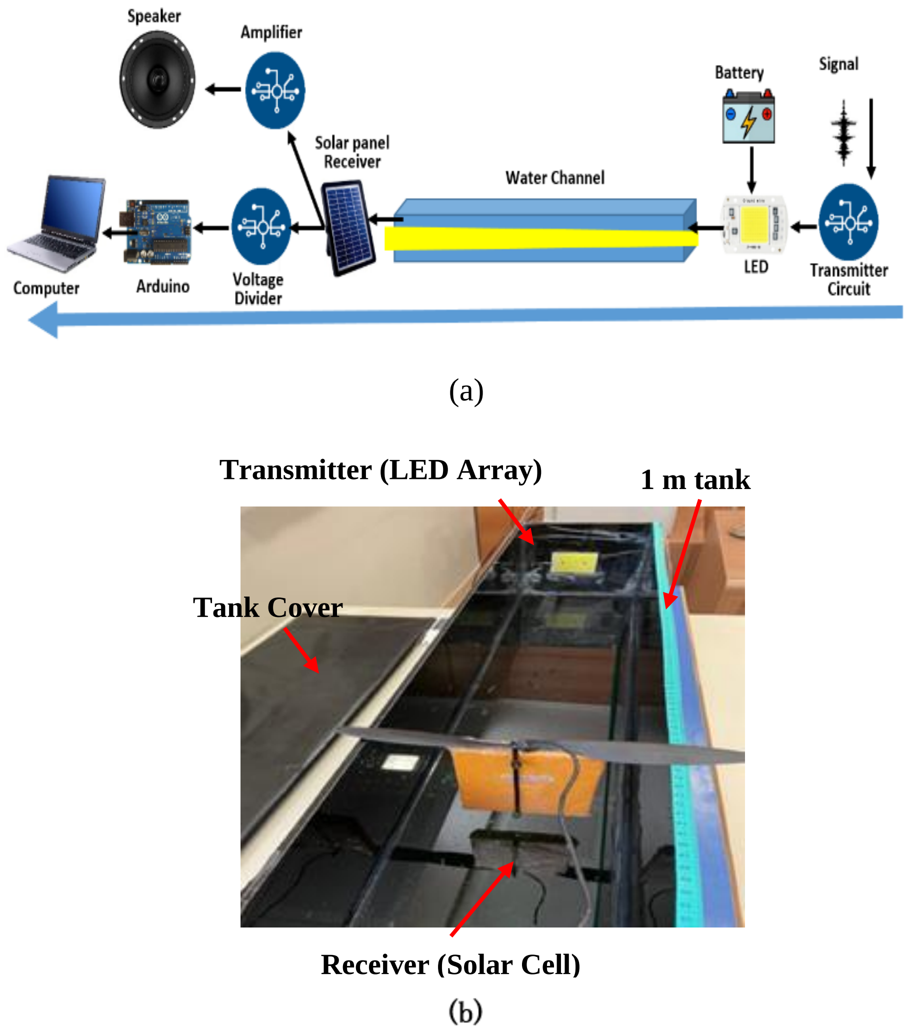

Figure 2. LED-based UWOC system, (**a**) block diagram, and (**b**) experimental testbed.

Table 1. The LED-based UWOC system specification.

Components	Parameters	Value
Transmitter	Dimension	60 mm × 50 mm
	Light color	White
	Output power	48 W
Receiver	Dimension	120 mm × 65 mm
	Maximum Power (Wp)	1.5
	Maximum Power Voltage	6 V

The system starts working with a sound wave that transmits through water using a light source. This sound wave is fed to the transmitter circuit that converts this digital signal to an analog light wave. The transmitter circuit is connected to an LED light array source to physically transmit the signal through a water medium, and an extra power source is used to enhance the signal so that it can cover more distance and provide better results. Once light passes through the water tank, the intensity of received signals is measured using a photocell panel. The output of the photocell is passed to two separate circuits. One of them is an amplifier to enhance the signal to audible levels, and the other is a voltage divider to measure the power of the received signal.

4.1. Light Transmitter Unit

A white-LED array was deployed to transmit optical data through a water channel. It consists of 96 LEDs. The maximum power delivered by the LED source is 48 W. The LED array was attached to one side of the water tank to transmit light signals through the water, as shown in Figure 2b. The signal is transmitted using a circuit shown in Figure 3. This circuit is composed of an NPN transistor, a power source of 9 V, and an array of LEDs. This power source is used to enhance the signal to achieve better coverage.

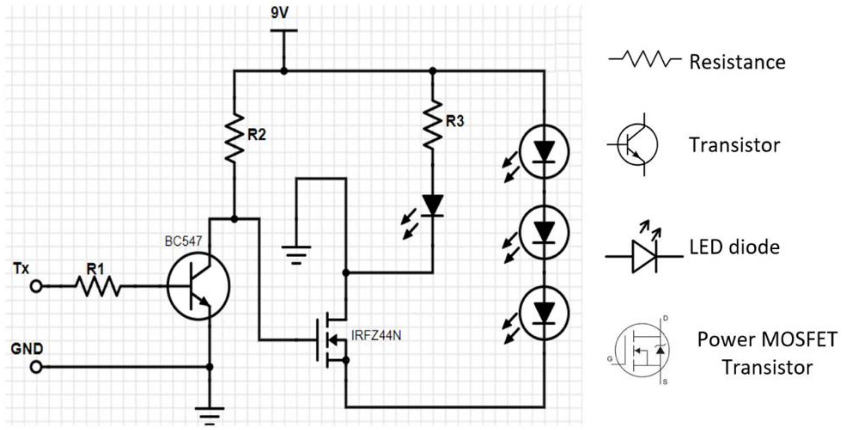

Figure 3. Light communication transmitter circuit diagram.

4.2. Underwater Channel

As shown in Figure 2b, a glass tank with dimensions of 20 × 20 × 100 cm was used as the water channel. The tank was placed on a table and marked with centimeter grid divisions to monitor light characteristics at different points by moving the receiver inside the water. All tank sides were covered with a black color to reduce the reflection effect during the experiment. A top cover with the same black coat was placed on top of the tank to reduce ambient noise.

4.3. Light Receiver Unit

On the receiver side, an off-the-shelf solar panel was used to capture and measure the intensity of light signals. The received signal passes through two paths, a signal amplifier and a voltmeter, as shown in Figure 2a. The amplifier is used to enhance the signal by using an external power source to make it audible. While IC LM385, as illustrated in Figure 4, was used as a voltage meter to measure the received voltage to estimate the signal power dissipated during the transmission as follows:

$$p(t) = \frac{R_1}{\left(R_f + R_1\right)^2} V_{out}^2$$

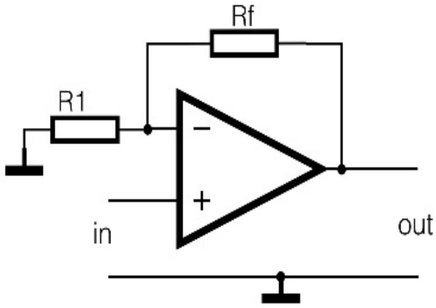

Figure 4. LM385 voltage measurement.

5. Results and Discussion

Several scenarios were designed to perform a set of experiments to evaluate the performance of LED-based underwater wireless communication considering the Red Sea parameters. A comparison with other reported works in the literature was discussed whenever possible. The results and discussion of optical transmission and resulting power at the receiver include: (i) baseline measurements, (ii) salinity effect, and (iii) turbidity effect.

1. Baseline: First, the light transmission was tested in an empty tank (without water), and the operation of all components was verified. The tank was filled with pure water (distilled water) as the baseline. Several measurements of light power were taken at different transmission distances (100, 80, 60, 40, and 20 cm). Fifty readings were taken at each point, and an average of all readings was considered as the output for better accuracy. Figure 5 shows that the received power through pure water is higher than that through air (empty tank). This result was expected due to the total internal reflection from the water–air surface occurring, increasing the amount of light collected by the receiver. This result is consistent with Ref [22].

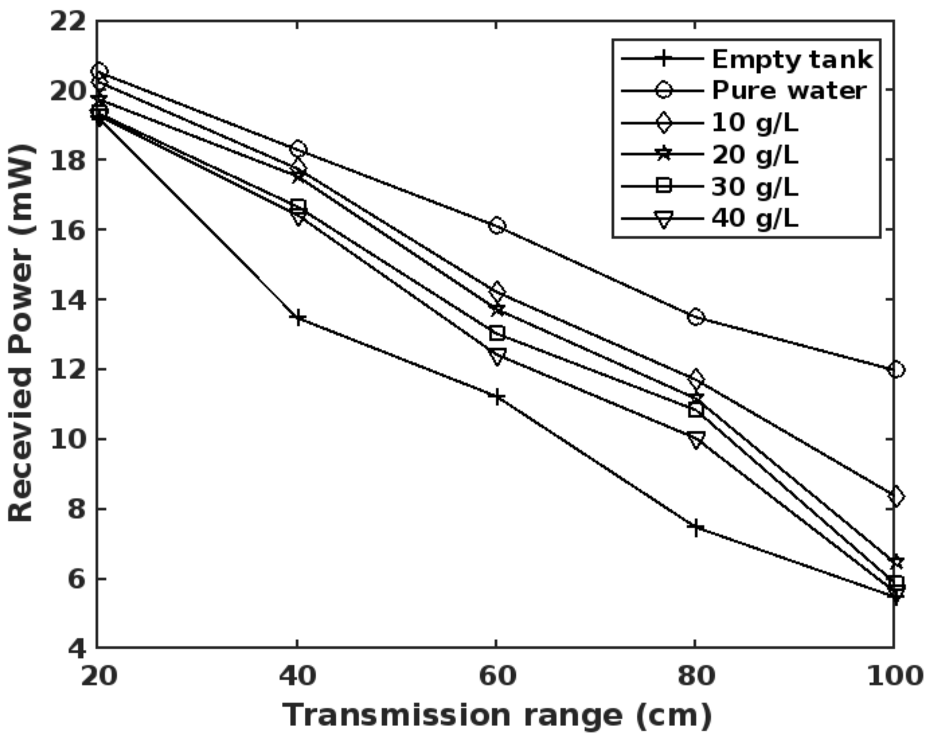

Figure 5. Comparison of received power with different salinity at different transmission distances.

Hassan et al. reported using four different types of light sources, including white, green, and yellow LEDs, and a red laser LD [14]. The underwater link distance is plotted against the normalized received power from 0 cm to 50 cm with a 10 cm gap scale. It is seen that as the underwater link distance increased, the received power of the optical signal from all the light sources decreased. When compared to LED, laser diodes produced light with a normalized intensity that was at least 41% higher. Because the light beam produced by a laser diode is focused and highly collimated, it can produce more power than an LED [23,24]. For the same transmission distance of 50 cm, the received power of the white LED signal declines by 85%, whereas in the present work, only 10% was lost. This is due to the high-power white LED used in our experiment which translates into a high intensity of transmitted light. A much higher light intensity of at least 41% is produced by the red laser diode as compared to the used LEDs. A decline of approximately 35% is observed for the red LD, compared to an approximately 30% decline when using our white LED.

2. Effect of salinity: The second scenario was to investigate the effect of salinity on the system; salt with different concentrations was added to pure water, as the minimum salinity of the Red Sea was 36 g/L, and the maximum salinity was 40 g/L. Salt concentrations of 10, 20, 30, and 40 g/L were used in this experiment. The relationship between the received power and various salt concentrations at different transmission distances is shown in Figure 5. This shows that salinity affects the performance of the LED-based UWOC link as the received power decreases with an increase in salinity. For example, at a transmission distance of 1 m, the power loss increased from 3% to 53% for 10 and 40 g/L, respectively. Moreover, the received power decreased with link length. It is also observed in Figure 5 that the received power at maximum salinity at a transmission distance of 1 m is 50% less compared to the pure water channel. These results suggest that the transmission for 1 m was of high quality and successful even at the highest salinity.

In another reported work [15,16], a 450 nm blue LD is used; the present findings are consistent with the UOWC investigation for transmission distances of 2 m and 200 m. The authors demonstrated that the received power gradually decreased as the salinity of the water channel increased. The results showed that at less than 40 cm distance, salinity of 35 g/L can block more than 90% of the laser's power [18]. It is concluded that the transmission depth for saline water channels is limited to approximately 60 cm [19]. Therefore, considering the simplicity and cost-effectiveness of these systems, an LED-based system would be suitable for short-range applications in saline water. Nevertheless, both LEDs and LDs may be used as light source transmitters in a hybrid UWOC system, as proposed by Xuan Huang et al. [25]. To make optical alignment less challenging, LDs are used for high-precision positioning, while LEDs are used for coarse alignment.

3. Effect of turbidity: The third scenario studied the impact of turbidity. When an optical wave passes through turbid water, it is attenuated significantly. Scattering is a type of accumulation that implies that the greater the turbidity, the greater the impact on signal quality. With a maximum water salinity of 40 g/L, the water's turbidity is increased as dirt is gradually added. Turbidity level was measured using the EXO 2 turbidity sensor. After that, power readings were collected at various turbidity levels, including 6.8, 15.84, 24.75, and 39 NTU. As shown in Figure 6, turbidity significantly affects the LED-based UWOC link. Even a small amount can block most of the channels. It is observed that 6.8 NTU of turbidity (maximum salinity) can block more than 80% of the channel at transmission distance of more than 60 cm. The results of the turbidity analysis are consistent with those reported in Refs. [22,23], which showed that the received power gradually decreased as the turbidity of the water increased. However, turbidity is a relative value because it varies with the type of additive contained in the water.

Considering the maximum Red Sea salinity of 40 g/L and reported turbidity of 2.4 FTU in [21], the ~1 m white-LED-based UWOC is feasible in the Red Sea environment. An example of an application for short-range LED-based communication is a real-time swimmer's feedback. Short-range communication for this system requires approximately 1 m between sensors mounted on the swimmer's wrist and a receiver on his/her goggles [26]. This feedback can provide crucial information such as lab rate and stroke rate. Another important example is communication between divers [27]. Normally, communication between divers is via hand signals or by using underwater writing slates. However, using hand signals enables basic communication yet needs extensive memorization. Slates, on the other hand, do not permit real-time communication as it takes time to write and draw the partner's attention underwater. Therefore, it can be concluded that white-LED-based UWOC is a promising technology for short-range application in the Red Sea environment.

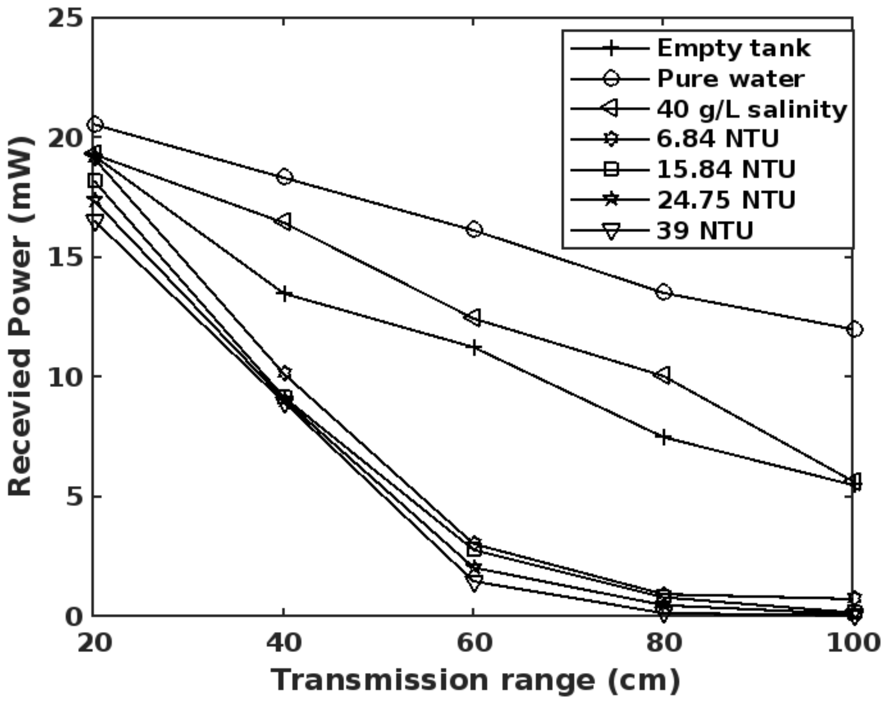

Figure 6. Comparison of the received power with different turbidity at different transmission distances.

6. Conclusions

In this study, an experimental evaluation of the effects of salinity and turbidity on the performance of an LED-based UWOC system in terms of the received optical power was carried out. The results confirmed that the quality of the received optical signal was affected by salinity, turbidity, and transmission distance. The effect of turbidity was pronounced and far exceeded the effect of salinity. Considering the parameters of the Red Sea, which are a maximum salinity of 40 g/L and turbidity of 2.34 NTU, LED-based UWOC can be considered to be a promising technology for carrying a large amount of data over a short-range transmission. This technology will allow the user to utilize the light source to observe marine life and transmit information remotely.

In the future, an additional experiment will be conducted under various environments by changing water temperature, water flow velocity, and so on. In addition, LEDs of different colors will be tested considering the Red Sea environment. Further studies and tests in a real marine environment are needed.

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