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Underwater Wireless Optical Communication (UWOC)

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DEDICATION

(وَآخِرُ دَعْوَاهُمْ أَنِ الْحَمْدُ لِلَّهِ رَبِّ الْعَالَمِينَ)

To our families, to our friends who have become our families to out supervisor and everyone who was credited with us here, to those who believed in us,adviced us and stood with us we dedicate this success

Alhumdulellah

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I hope this job was able to make its contribution and corresponds to the expectations of all those who have supported me.

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Abstract

Underwater wireless communication refers to transmitting data in unguided water environment through the use of wireless carriers, i.e., radio-frequency wave, acoustic wave, and optical wave. We focus, in this thesis, on the underwater wireless optical communication (UWOC) that employs optical wave as the transmission carriers. In comparison to RF and acoustic counterparts, UWOC has a much higher transmission bandwidth, thus providing much higher data rate. Due to this high-speed transmission advantage, UWOC has attracted considerable attention in recent years. Many potential applications of UWOC systems have been proposed for environmental monitoring, offshore exploration, disaster precaution, and military operations. However, UWOC systems also suffer from severe absorption and scattering introduced by underwater channel. In order to overcome these technical challenges, several new system design approaches, which are different from the conventional terrestrial free-space optical communication, have been explored in recent years.

Chapter 1 : Introduction

Two thirds of the earth’s surface is covered with water. During the past thousands of years, humans have never stopped the exploration of the ocean. In recent years, with an increase of globe climate change and resource depletion of land, there has been a growing interest in the research of ocean exploration system. Underwater wireless communication (UWC) technology enables the realization of ocean exploration systems, and thus attracts more and more attention. UWC refers to transmitting data in an unguided water environment through the use of wireless carriers, i.e. radio-frequency (RF) waves, acoustic waves, and optical waves. Considering the limited bandwidth of RF and acoustic methods and the increasing need for high-speed underwater data transmission, underwater wireless optical communication (UWOC) has become an attractive and viable alternative. In fact, light has been used as a wireless communication method for thousands of years in various forms.
From that time on, a flurry of terrestrial OWC applications appeared. But due to the severe attenuation effects of seawater to visible light and the limited knowledge of aquatic optics, the early development of UWOC was far behind the terrestrial free-space optical (FSO) communications. Based on nearly 20 years experimental and theoretical study of light propagation in the sea, in 1963, Duntley proposed that seawater shows a relatively low attenuation property to light with wavelengths from 450nm to 550nm which corresponds to the blue and green spectrum

In Figure 1.1, sensors located at the bottom of the seabed collect data and transmit via acoustic or optical links to the AUVs and ROVs. Then, AUVs and ROVs relay signals to ships, submarines, communication buoys and other underwater vehicles. Above the sea surface, the onshore data center processes data and communicates with satellite and ships through RF or FSO links. Based on link configurations between the nodes in UWSNs, UWOC can be divided into four categories

(Figure 1.2) a) Point-to-point line-of-sight (LOS) configuration, b) Diffused LOS configuration, c) Retroreflector-based LOS configuration, and d) Non-line-of-sight (NLOS) configuration.

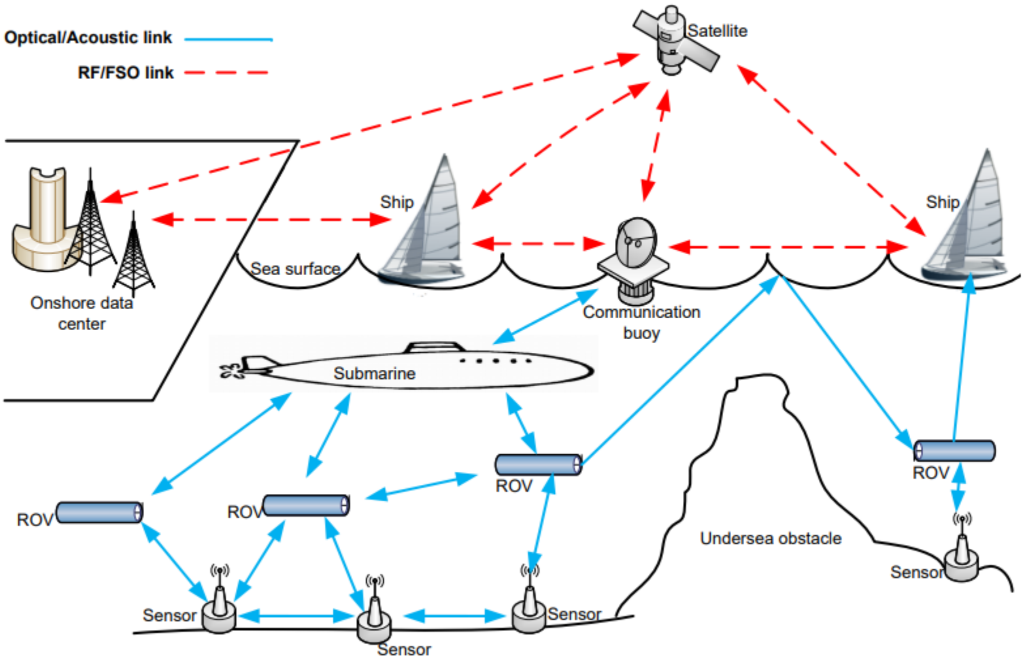
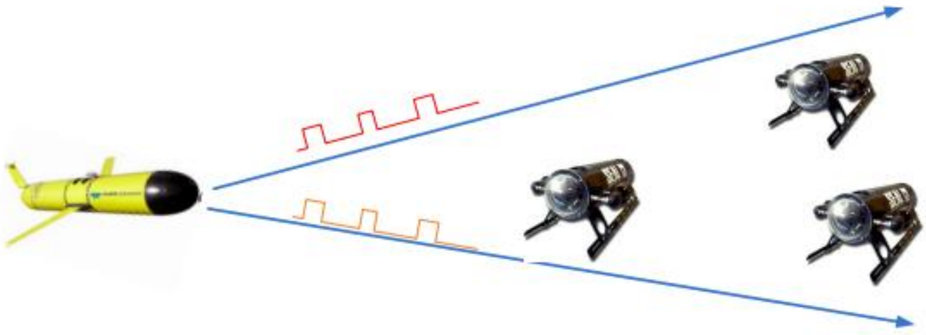
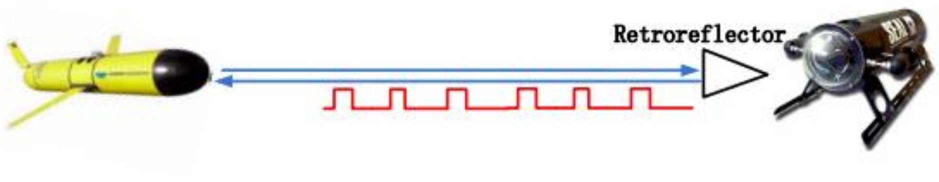

Optical/Acoustic link
RF/FSO link
Satellite
Ship
Ship
Onshore data center
Sea surface
Communication buoy
Submarine
ROV
ROV
ROV
ROV
Undersea obstacle
Sensor
Sensor
Sensor
Sensor

Fig1.1

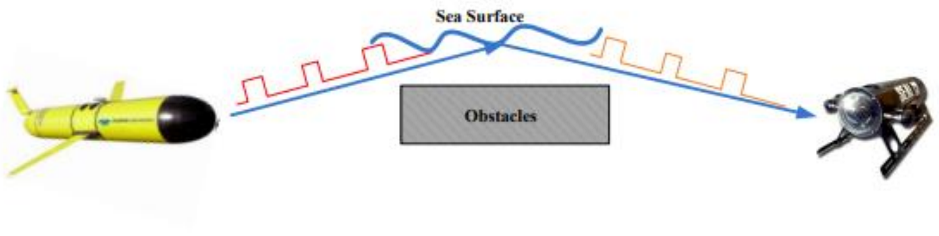
(a) Point-to-point LOS configuration.



(b) Diffused LOS configuration.



(c) Retroreflector-based LOS configuration.



(d) NLOS configuration.

Figure 1.2: Link configurations of UWOC.

1.2 Advantages and challenge

Underwater wireless optical communication (UWOC) systems are an alternative to traditional acoustic and RF methods for underwater communication. UWOC offers several advantages:

- High data rates**:** UWOC can transmit data much faster than acoustic methods, making it suitable for real-time applications.
- Low latency**:** Due to the speed of light in water, UWOC has lower latency than acoustic communication.
- Compact devices**:** UWOC transceivers can be smaller and less expensive than acoustic transceivers.
- However, UWOC also has some challenges:

- Shorter range**:** UWOC has a shorter communication range than acoustic methods due to the absorption of light by water.
- Water conditions**:** UWOC can be affected by water clarity, as factors like turbidity and bubbles can impede signal transmission.

- Highest data rates**:** UWOC can transmit data much faster than acoustic or RF methods, enabling real-time applications like video transmission.
- Lowest latency**:** Due to the speed of light in water, UWOC has minimal delay compared to acoustic methods.
- Lower cost and size**:** UWOC systems can use smaller, cheaper transceivers than acoustic or RF systems.
- Higher security: Because UWOC typically uses line-of-sight (LOS) communication, it's more difficult to intercept signals compared to broadcast methods used by acoustic and RF.

- Signal degradation: Light is absorbed and scattered by water molecules and particles, weakening the signal and causing errors. This is especially problematic in murky water and limits UWOC's range.
- Link instability**:** Movements caused by water currents and waves can misalign the optical transceivers, interrupting communication. This is particularly an issue in vertical links between buoys and the seabed.

- Device robustness**:** UWOC systems require reliable underwater devices that can withstand pressure, temperature variations, and salinity changes. Power consumption and battery life are crucial as solar energy is unavailable underwater.

UWC techniques:

Table 1.1, we summarize the benefits and limitations of the three popular techniques choices to achieve UWC:

UWC technologies	Benefits	Limitations
Acoustic	·Most widely used UWC technology ·Long communication range up to20km	·Low data transmission rate (on the order of kbps) ·Severe communication latency (on the order of second) ·Bulky, costly and energy consuming transceivers ·Harmful to some marine life
RF	.Relatively smooth transition to cross air/water boundaries ·More tolerant to water turbulence and turbidity ·Loose pointing requirements ·Moderated at a transmission rate(upto100Mb/s)at very close distance	·Short link range ·Bulky, costly and energy consuming transceivers
Optical	.Ultra-high data transmission rate(up to Gbps) · Immune to transmission latency ·Low cost and small volume transceivers	·Can't cross water/air boundary easily ·Suffers from severe absorption and scattering ·Moderate link range (up to tens of meters)

Table 1.2, Comparison of parameter underwater wireless communication technologies:

Parameter	Acoustic	RF	Optical
Attenuation	Distance and frequency dependent (0.1–4 dB/km)	Frequency and conductivity dependent (3.5–5 dB/m)	0.39 dB/m (ocean) 11 dB/m (turbid)
Speed	1500 ms^{-1}	2.3×10^8 ms^{-1}	2.3×10^8 ms^{-1}
Data Rate	Kbps	Mbps	Gbps
Latency	High	Moderate	Low
Distance	more than 100 km	≤10 m	10–150 m (500 m potential)
Bandwidth	1 kHz–100 kHz	MHz	150 MHz
Frequency Band	10–15 kHz	30–300 MHz	5×10^{14} Hz
Transmission Power	10 W	mW–W	mW–W

Bounders of the work:

Embarking on a graduation project on underwater wireless optical communication requires awareness of boundaries and constraints:

1. Underwater Environment: Challenges include pressure, temperature, salinity, and turbidity, impacting system performance.

2. Optical Propagation: Underwater light propagation differs due to absorption, scattering, and attenuation, requiring careful system design.

3. Hardware Limitations: Developing robust hardware for transmitters, receivers, and modulators under water poses challenges in size, power, and performance.

4. Data Rate and Range: Achieving high data rates and long ranges is challenging due to signal attenuation and dispersion.

5. Power and Energy Constraints: Powering systems for long deployments is difficult, requiring optimization and alternative energy sources.

6. Regulatory and Legal Constraints: Regulatory requirements such as frequency allocation and licensing must be considered.

7. Cost and Accessibility: Developing technology can be costly, with limited accessibility to resources and testing facilities.

8. Interference and Security: Susceptibility to interference and security concerns require robust solutions such as data encryption.

Understanding and addressing these boundaries is essential for successful project planning and execution in underwater wireless optical communication.

The importance of this project: Creating a graduation project on underwater wireless optical communication holds significant significance for several reasons

1.Advancing Communication Technology: Developing this technology contributes to advancements in communication systems, particularly where traditional methods are ineffective

2.Exploration and Research: Enhances exploration capabilities in unexplored underwater environments, benefiting fields like marine biology and oceanography

3.Environmental Monitoring: Enables real-time monitoring of water quality and marine life behavior, crucial for understanding and protecting marine ecosystems

4.Underwater Infrastructure Maintenance: Facilitates efficient communication for maintenance of structures like oil rigs and pipelines, improving safety and reducing costs

5.Defense and Security: Enhances capabilities for underwater surveillance and defense operations, vital for military and defense applications

6.Commercial Applications: Benefits industries like offshore oil and gas, marine transportation, and aquaculture, enabling tasks such as remote operation and data transmission

7.Global Connectivity: Contributes to achieving global connectivity by connecting remote and underwater regions, fostering global communication networks. Overall, the project plays a vital role in addressing challenges and unlocking opportunities in various underwater domains, including exploration, research, monitoring, infrastructure maintenance, defense, and commercial activities

chapter 2 :UWOC Channel Modeling

In this chapter, we will firstly present background knowledge related to light propagation properties in the underwater environment. Then, UWOC channel modeling techniques, which include link attenuation modeling, geometric misalignment modeling, and turbulence modeling, will be presented.

2.1 Light Propagation in water

Compared with terrestrial FSO communication channels, UWOC channels have several unique characteristics. The existing terrestrial FSO channel models are not suitable for underwater environment; therefore, new reliable channel models must be proposed and studied. In order to derive new channel models for UWOC, we have to firstly understand the basic properties of light propagation in the underwater environment.

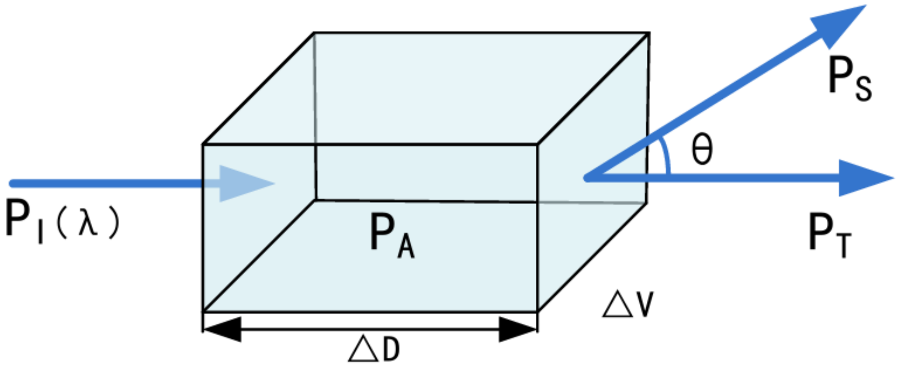


Figure 2.1: Geometry of inherent optical properties for a volume ΔV

Absorption and scattering coefficients are the two major IOPs that determine the underwater light attenuation. Absorption is an energy transfer process in which photons lose their energy and convert it into other forms, such as heat and chemical (photosynthesis). Scattering is caused by variations in the refractive index that changes the propagation direction of photons [35]. Generally, the impacts of absorption and scattering to a UWOC system can cause three undesirable effects. First, in the presence of absorption, the total propagation energy of light is continuously decreasing, which will limit the link distance of the UWOC. Second, in the presence of scattering, since the size of optical aperture is finite, scattering will spread the light beam and result in a reduction of the number of photons collected by the receiver. This will lead to degradation of SNR of the system. Third, due to the light scattering in an underwater environment, each photon may arrive at the receiver panel in different time slots, and multi-path dispersions will occur. The undesirable impacts of multi-path phenomenon include inter symbol interference (ISI) and timing jitter.

In order to derive the absorption and scattering coefficients mathematically, we introduce the simple model in Figure 2.1. We assume that a volume of water ΔV with thickness ΔD is illuminated by a collimated light beam with wavelength λ. We denote the power of incident light as PI. A portion of the incident light power PA is absorbed by water, and another portion of light power PS1 is scattered. PT is the remaining light power that will propagate as desired. According to the law of conservation, we get

*1The reflected light component is included in PS.

PI =PA+PS +PT. (2.1)

Based on (2.1), we define the ratio between absorbed power and incident power PA (2.1) PI as absorbance. Similarly, the fraction between scattered power and incident power PB PI as scatterance. The subsequent absorption coefficient and scattering coefficient are then calculated by taking the limit of absorbance and scatterance as water thickness ΔD becomes infinitesimally small

$$a(\lambda) = \lim_{\Delta D \to 0} \frac{P_A}{P_I \Delta D}, \tag{2.2}$$

$$b(\lambda) = \lim_{\Delta D \to 0} \frac{P_S}{P_I \Delta D}. \tag{2.3}$$

In underwater optics, the overall attenuation effects of absorption and scattering can be described by the attenuation coefficient 2 c(λ) which can be expressed as

c(λ) = a(λ)+b(λ). (2.4)

The unit of attenuation coefficient is m−1. In addition, the author of [2] states that the underwater light absorption coefficient can be further represented as the summation of four absorption factors

a(λ) = aw(λ)+aCDOM(λ)+aphy(λ)+adet(λ) (2.5)

Where aw(λ) is the absorption due to pure seawater, aCDOM(λ) is the absorption due to CDOM, aphy(λ) denotes the absorption due to phytoplankton, and adet (λ) represents the absorption due to detritus. The absorption effect of pure seawater is introduced from two sources: the water molecules and dissolved salt in water such as NaCl, MgCl2, Na2SO4, and KCl . Pure seawater is absorptive except around a 400nm-500nm window, the blue-green region of the visible light spectrum. The corresponding absorption spectrum of pure seawater is shown in Figure 2.2

CDOM 3 refers to colored dissolved organic materials with dimensions smaller than 0.2 mm. In Figure 2.2(b), it shows that the CDOM presents highly absorptive to blue wavelengths (420nm-450nm) and less absorptive to yellow and red light. The absorption effects due to phytoplankton are mainly caused by photosynthesising of chlorophyll. For different phytoplankton species, the characteristics of the absorption effect are also different. Figure 2.2(c) shows a typical absorption coefficient profile shared by all species. We can observe that the aphy(λ) shows a high absorption in the 400-500 nm region and a further peak at about 660 nm.

*2 Also known as extinction coefficient in some optical literatures

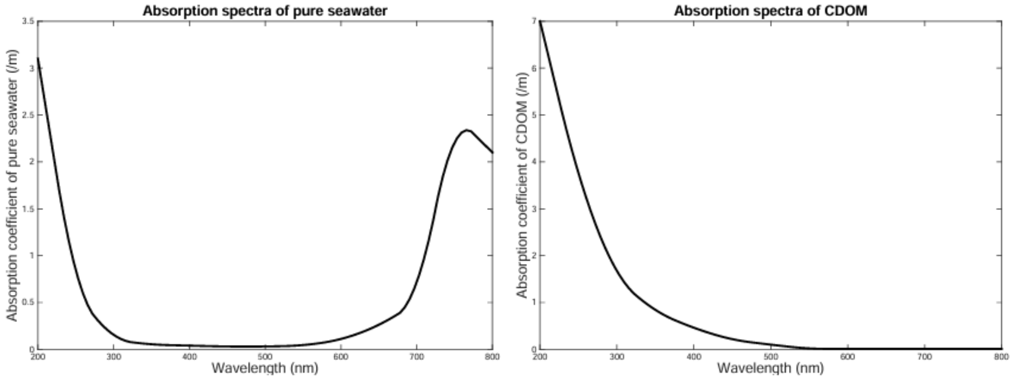
*3 In several optical literatures, it’s also represented as gelbstoff, yellow substances or gilvin.

Detritus includes living organic particles, such as bacteria, zooplankon, detrital organic matter and suspended inorganic particles such as quartz and clay. These substances are grouped together due to their similar absorption behaviour. Figure 2.2(d) shows a absorption curve similar to that if CDOM. The scattering coefficient for underwater light propagation can also be presented as a summation of different scattering factors

$$b(\lambda) = bw(\lambda) + bphy(\lambda) + bdet(\lambda) \qquad (2.6)$$

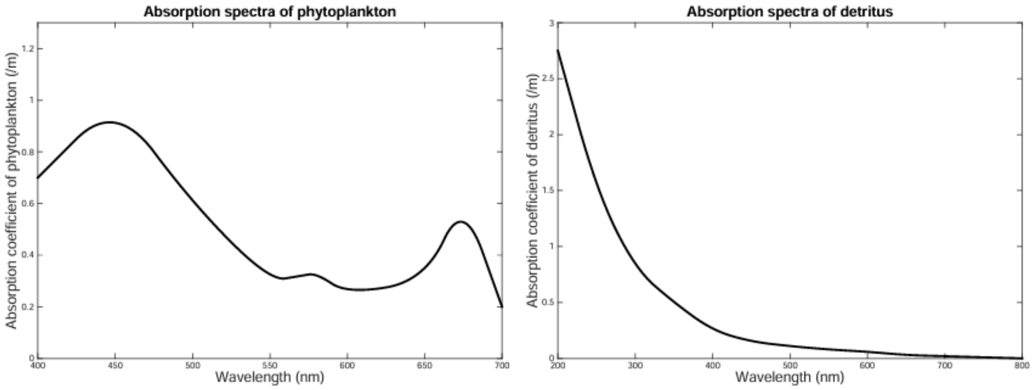
Where bw(λ) is the scattering due to pure seawater, bphy(λ) denotes the scattering due to phytoplankton, and bdet(λ) represents the scattering due to detritus. Compared with absorption, scattering is relatively independent of wavelength. The dominant factor that impacts scattering is the density of particulate matters. In pure seawater, since the refractive index will change with the variations of flow, salinity and temperature, the scattering coefficient will also change. Compared with the size of water molecules, the wavelength of light is relatively large, thus the Rayleigh scattering model can be used to describe the scattering induced by pure seawater. The corresponding scattering spectra is shown in Figure 2.3(a).

Phytoplankton and detritus account for more than 40% of the total scattering effects. Since the scattering light caused by phytoplankton and detritus propagates mainly in the forward direction, Mie scattering model can be used to approximate these two types of scattering. In practice, the exact scattering coefficients highly depends on the density of phytoplankton and detritus. In Figure 2.3(b) and Figure 2.3(c), we present the scattering spectra due to phytoplankton and detritus with different densities. A summary of the above discussion on seawater absorption and scattering characteristics is presented in Table 2.1.



(a) Absorption spectra of pure seawater.

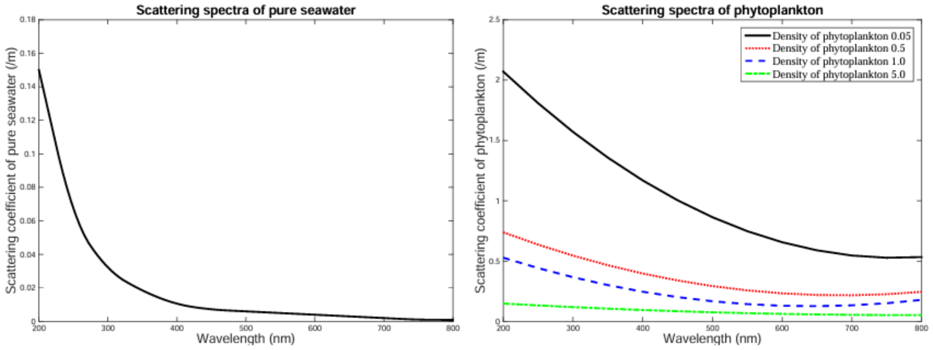
(b) Absorption spectra of CDOM.



(c) Absorption spectra of phytoplankton.

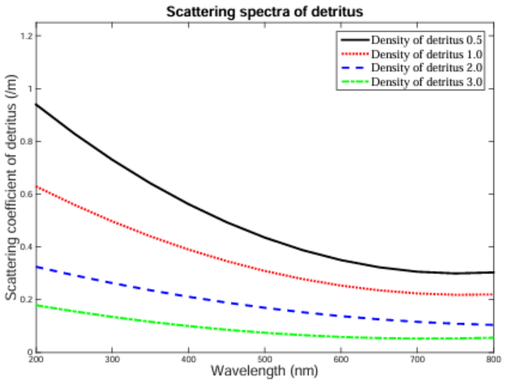
(d) Absorption spectra of detritus.

Figure2.2: Optical absorption spectra for different ocean components.



(a) Scattering spectra of pure seawater.

(b) Scattering spectra of phytoplankton.



(c) Scattering spectra of detritus.

Figure 2.3: Optical scattering spectra for different ocean components.

Table2.1: Summary of absorption and scattering characteristics of seawater

Compositions	Absorption coefficient	Scattering coefficient
Water	Invariant at constant temperature and pressure. Strongly depends on λ	Rayleigh scattering. Small variance compared with absorption. Strongly depends on λ
CDOM	Variable with the density of CDOM. Increase towards short λ	Negligible
Plankton and detritus	Variable with the density of plankton and detritus. Increase towards short λ	Mie scattering. Variable with the density of plankton and detritus. Increase towards short λ
Sea salt	Negligible invisible spectrum. Increase towards short λ	Rayleigh scattering. Doesn't depend on λ

Based on the attenuation coefficient that has been introduced ,Beer-Lambert law provides the simplest and most widely used scenario to describe the light attenuation effects in underwater environment as

$I=I0e^{\wedge}-c(\lambda)z$ (2.7)

$I0$ is the power of transmitted light, z denotes the light transmission distance, I represents the power of light after transmitting z distance, and $c\ (\lambda\ )c(\lambda)$ stands for the attenuation coefficient. The exact value of attenuation coefficient $c(\lambda)$ will change with different water types and water depths. The typical values of $a(\lambda)$, $b(\lambda)$, and $c(\lambda)$ associated with four major water types are given in Table 2.2

In pure seawater, absorption is the main limiting factor; the low scattering coefficient makes the beam free from divergence. In clear ocean waters, there is a higher concentration of dissolved particles that affect scattering. In coastal ocean water, high concentrations of plankton, detritus, and minerals are the dominant sources of absorption and scattering. Turbid harbor water has the highest concentration of dissolved and in-suspension matters, which will severely attenuate..."

The light propagation. More details of water types and variations of attenuation coefficient with other parameters such as depth, pressure, and salinity.

Table 2.2: Typical values of a(λ), b(λ), and c(λ) for different water types

Water Type	***a*(λ) (m^−1)**	***b*(λ) (m^−1)**	***c*(λ) (m^−1)**
Pure Seawater	0.053	0.003	0.056
Clear Ocean Water	0.114	0.037	0.151
Coastal Ocean Water	0.179	0.219	0.298
Turbid Harbor Water	0.295	1.875	2.17

From (2.4) and (2.7), we know that the Beer lambert's law contains two implicit assumptions. First, the transmitter and receiver are perfectly aligned. Second, all the scattered photons are lost even though in reality some of the scattered photons can still arrive at the receiver after multiple scattering events. This assumption severely underestimates the received optical power, especially in the scattering dominant situation. In order to describe the scattering effects more accurately, another important IOP volume scattering function (VSF) is introduced. It is defined as

$$\beta(\theta, \lambda) = \lim_{\Delta D \to 0} \lim_{\Delta \Omega \to 0} \frac{P_S(\theta, \lambda)}{\Delta D \Delta \Omega} \tag{2.8}$$

Where Ps(θ,λ) is the fraction of incident power scattered out of the beam through an angle θ into a solid angle ΔΩ centered on θ (Figure 2.1). VSF is the scattered intensity per unit incident irradiance per unit volume of water. In the view of physics, the VSF can also be interpreted as the differential scattering cross section per unit volume. Integrating β (θ, λ) over all directions (solid angles) gives the scattering coefficient

$$b(\lambda) = \int \beta(\lambda, \theta) d\Omega = 2\pi \int_0^{\pi} \beta(\lambda, \theta) \sin(\theta) d\theta. \tag{2.9}$$

Normalizing (2.8) with the scattering coefficient, we obtain the scattering phase function (SPF), which is defined as

$$\tilde{\beta}(\theta, \lambda) = \frac{\beta(\lambda, \theta)}{b(\lambda)}. \tag{2.10}$$

The scattering phase function is also an important IOP. Considering the difficulty of measuring scattering phase function (SPF), the Henyey-Greenstein (HG) function is commonly introduced to present the SPF

$$\tilde{\beta}(\theta, \lambda) = P_{HG}(\theta, g) = \frac{1 - g^2}{4\pi(1 + g^2 - 2g\cos\theta)^{\frac{3}{2}}} \tag{2.11}$$

In a UWOC link, the optical signal launched from the transmitter will undergo various losses before reaching the receiver. These encompass system loss introduced by transceivers, link loss resulting from water attenuation, geometric misalignment, and water turbulence. As the loss introduced by the transceiver is predominantly characterized by device parameters and design specifications, it presents a challenge to comprehensively and uniformly characterize. Therefore, in Sections 2.2, 2.3, and 2.4, our focus will be on the modeling techniques for these losses in UWOC links.

Here, g represents the average cosine of β in all scattering directions. To elucidate this concept, we have introduced absorption and scattering coefficients, Beer-Lambert's law, as well as VSF. These foundational concepts provide a theoretical basis for constructing more complex UWOC channel models.

2.2 Modeling of Aquatic Optical Attenuation in UWOC

The modeling of aquatic optical attenuation in underwater wireless optical communication (UWOC) systems involves accurately describing the effects of absorption and scattering, which are the two major inherent optical properties (IOPs) affecting light propagation. This modeling task considers specific link configurations, transceiver architectures, and alignment conditions. In the LOS (line-of-sight) configuration, where direct light propagation occurs, and the NLOS (non-line-of-sight) configuration, where indirect or reflected light paths are involved, different attenuation models are introduced to account for absorption and scattering effects

2.2.1 Aquatic Optical Attenuation in LOS Configuration

For simplicity, several researchers utilized the Beer Lambert's law to model LOS UWOC.It sounds like researchers used Beer-Lambert's Law to model LOS UWOC (Underwater Optical Wireless Communication). Beer-Lambert's Law is a fundamental principle in spectroscopy and optics that describes the relationship between the absorption of light and the properties of the material through which it passes. In the context of UWOC, it would likely be used to understand how light propagates through water, considering factors like absorption and scattering. This modeling approach could help in designing efficient underwater communication systems. , the authors evaluated the performance of a UWOC system based on Beer Lambert's law in different water types and different communication ranges. Another general theoretical model of aquatic optical attenuation in UWOC is radiative transfer equation (RTE). As we have presented in Section 2.1, the VSF is an important IOP that describes the scattering characterizations of photons. However, the VSF is difficult to be measured in practice . Furthermore, the VSF can only determine the scattering properties of a single photon at one single refractive index condition. It’s not suitable to model the scattering properties of large number of photons . Considering these two facts, most UWOC researchers employ RTE in their UWOC channel modeling research. Without considering the temporal dispersion of light, the typical twodimensional RTE can be expressed as

$$\vec{n} \cdot \nabla L(\lambda, \vec{r}, \vec{n}) = -cL(\lambda, \vec{r}, \vec{n}) + \int_{2\pi} \beta(\lambda, \vec{n}, \vec{n}')L(\lambda, \vec{r}, \vec{n})d\vec{n}' + E(\lambda, \vec{r}, \vec{n})$$

where ~n is the direction vector, ∇ is the divergence operator, L(λ, ~r, ~n) denotes the optical radiance at position ~r towards direction ~n, β(λ, ~n, ~n0) is the VSF, and E(λ, ~r, ~n) represents the source radiance. RTE is capable RTE is capable of describing the energy conservation of a light wave that is passing through a steady medium The derivations of RTE are complex and lengthy The RTE can be solved both analytically and numerically. Since the RTE is an integro-differential equation involving several independent variables it is difficult to find an exact analytical solution. Thus only few analytical RTE models have been proposed in recent years.

Jaruwat anadilok devised an analytical solution of RTE employing the modified Stokes vector. This model takes both multiple scattering and light polarization effects into account. Based on this model, numerical results show that the ISI and BER are as functions of data rate and link distance. This finding can be further used to predict several performance parameters of UWOC systems such as the maximum communication distance with certain data rate and BER. . proposed a beam-spread function for laser-based UWOC by solving the RTE analytically. The small angle approximation was performed to simplify the derivation. This analytical model reveals the relationship between received optical power versus link range for various transmitter/receiver pointing accuracies. It was also validated through water tank experiments. Besides utilizing analytical solutions, numerical methods are preferred to solve the RTE. In fact, for many practical UWOC applications, finding an exact analytical solution of RTE is even more challenging .
In view of this, most of the researchers focused on developing powerful numerical RTE solvers . The most popular numerical approach to solve RTE is Monte Carlo simulation. It is a probabilistic method to mimic the loss of underwater light propagation by sending and tracking large number of photons . The Monte Carlo method benefits from its easy programming, accurate solution and high flexibility, but it also suffers from random statistical errors and low simulation efficiency.
the authors proposed a channel impulse response of UWOC system by solving the

RTE through Monte Carlo simulation. The authors quantified the channel time dispersion for different water types, link distances, and transmitter/receiver characteristics. A two-dimensional HG phase function was employed to model the VSF as

where PHG(·, ·) is the HG function defined in (2.11); α is the weight of the forward-directed HG function; and gFW D and gBKW D are the asymmetry factors for the forward- and backward-directed HG phase functions, respectively . Based on this numerical channel model, the authors concluded that the channel time dispersion can be neglected when operating at a moderate distance (20m) in a clean water environment. However in highly turbid water, the channel time dispersion can impact the data transmission when operating over a large distance (100m). Based on this conclusion, the system will experience less ISI in the received signal when the transmission distance is short and the water is clear. As a result, complex signal modulation and demodulation can be avoided. In order to validify the Monte Carlo approach for UWOC channel modeling, Frank et al. made a comparison between the results of Monte Carlo simulation and laboratory experiments . The results of the Monte Carlo simulation and the water-tank experiment exhibited reasonable agreement. Up to one Gbps data rate was achieved in a two-meter long water pipe.the authors employed Monte Carlo approach to solve the RTE and calculate the impulse response for a UWOC system over different operation environments.

from Tsinghua University demonstrated a stochastic channel model to represent the

$$P_{TTHG}(\theta) = \alpha P_{HG}(\theta, g_{FWD}) + (1-\alpha)\, P_{HG}(\theta, -g_{BKWD})$$

spatial-temporal probability distribution of propagated photons for non-scattering and single scattering 4 components of UWOC links. The authors adopted the HG function as the probability density function of light scattering angle to simplify the analysis. The proposed stochastic model also exhibited reasonable agreement with the numerical results of Monte Carlo simulation. the

$$h(t) = C_1 \Delta t e^{-C_2 \Delta t} + C_3 \Delta t e^{-C_4 \Delta t}, (t \geq t_0)$$

same research group further proposed a more general stochastic UWOC channel model by taking into account of all three components of propagated photons, which include non-scattering, single scattering and multiple scattering5 components. 4Single scattering components refer to photons that experience only one scattering event during the propagation from source to destination. 5Multiple scattering components refer to photons that experience more than one scattering event during the propagation from source to destination This comprehensive channel model fits well with the Monte Carlo simulations in turbid water environment, such as in coastal or in harbor waters. Following the similar stochastic the Tsinghua researchers also presented a closed-form expression for the angle of arrival (AOA) distribution . This AOA model characterizes how the received intensity of ballistic and single scattering components is distributed over AOA with respect to unit transmission power . Numerical results have validated the proposed AOA distribution by Monte Carlo approach in clear and turbid coastal and harbor water with relatively short link range. Semi-analytical modeling approach has also been employed by several UWOC researchers.

where Δt = t − t0. t is the time scale and t0 = L/v is the propagation time which is the ratio of link range L over light speed v in water . The parameter set (C1, C2, C3, C4) in (2.14) can be computed from Monte Carlo simulation results as

2.2.2 Aquatic Optical Attenuation in NLOS Configuration

transceivers can utilize reflection of the sea surface to overcome link obstacles. Compared with channel modeling of LOS UWOC, investigations of NLOS UWOC channel modeling have received less attention. Light propagation in NLOS configuration experiences the same attenuation effects as in LOS configuration. The major difference between LOS and NLOS channels is the reflection effects introduced by wavy sea surface. Thus accurately describing the reflection effect of sea surface is considered as the most critical part of NLOS channel modeling. Several models that describe the slopes of random sea surface . Similar to channel modeling work of LOS

$$(C_1, C_2, C_3, C_4) = \arg\min \left(\int \left[h(t) - h_{mc}(t) \right]^2 dt \right)$$

configuration, channel models of NLOS link can also be derived both analytically and numerically. To the best of our knowledge, most channel models of NLOS configuration were derived through numerical approaches such as through Monte Carlo simulations. As an example of an analytical approach, Shlomi et al. novel concept of NLOS UWOC network. Each node inside this network can communicate with each other through reflection at the ocean-air interface. Communication from one single node to multiple nodes can also be achieved. The authors derived a mathematical model for the NLOS channel by considering the link attenuation, sea surface slopes and receiver

FOV. Numerical simulation was also performed to test the validity of this NLOS UWOC channel model. Simulation results show that an increase in node separation distance dramatically increases the BER of the NLOS UWOC system. By applying the numerical Monte Carlo method, the authors proposed a path loss model for NLOS UWOC links. The effects of both random sea surface slopes and scattering properties of seawater have been taken into account. Numerical results suggest that the random surface slopes induced by wind or other turbulent sources may strongly corrupt the received signal. However, this effect can be alleviated when the received signal contains multiple dominant scattering light components. Jagadeesh et al. proposed an impulse response for NLOS UWOC based on Monte Carlo simulation. A two-dimensional HG angle scattering function was employed in this simulation process in order to model the multiple scattering effects of light. Based on this impulse response, the authors also evaluated the system performance with different water types and receiver FOV. scattering effects of light. Based on this impulse response, the authors also evaluated the system performance with different water types and receiver FOV.

2.3 Modulaing geometric Misalignment of UWOC:

The term "modulating geometric misalignment" may refer to the process of dynamically adjusting the parameters or characteristics of an underwater wireless optical communication (UWOC) system to mitigate the effects of geometric misalignment. Geometric misalignment occurs when the transmitting and receiving nodes in a UWOC system are not perfectly aligned due to factors such as movement, changes in depth, or environmental conditions.

Here's how the modulation of geometric misalignment in UWOC systems might work:

1. Dynamic Adjustment of Transmission Parameters**:** The UWOC system can dynamically adjust parameters such as the beam direction, beam width, or transmission power to compensate for geometric misalignment. For example, if the receiving node detects that the transmitted optical signal is not properly aligned with its receiver due to movement or environmental factors, it can communicate with the transmitting node to adjust the parameters of the transmitted signal accordingly.
2. Adaptive Modulation Techniques**:** Adaptive modulation techniques can be employed to vary the modulation scheme, symbol rate, or coding rate based on the observed channel conditions, including geometric misalignment. For instance, if the UWOC system detects significant misalignment leading to higher signal attenuation or increased error rates, it can switch to a more robust modulation scheme or reduce the data rate to maintain reliable communication.
3. Feedback Mechanisms: The UWOC system can utilize feedback mechanisms between the transmitting and receiving nodes to exchange information about the quality of the received signal and the degree of misalignment. This feedback can then be used to dynamically adjust the transmission parameters or modulation scheme to optimize performance in real-time.

4. Predictive Algorithms: Advanced algorithms can be developed to predict and anticipate changes in geometric misalignment based on environmental factors or historical data. By proactively adjusting the UWOC system parameters before significant misalignment occurs, it may be possible to maintain more stable and reliable communication links underwater.

Overall, the modulation of geometric misalignment in UWOC involves adapting the transmission parameters, modulation techniques, and feedback mechanisms to optimize communication performance in dynamic underwater environments where misalignment is a common challenge.

Here's how the modeling of geometric misalignment in UWOC can be approached:

1. Geometry and Positioning:
    - Define the geometric parameters of the UWOC system, including the positions and orientations of the transmitter and receiver relative to each other and to surrounding objects.
    - Consider the dynamic nature of underwater environments and how the positions of UWOC nodes may change over time due to factors such as currents, waves, or vehicle movement.
2. Optical Path Calculation:

    1.Use principles of geometric optics to calculate the optical path between the transmitter and receiver under different misalignment scenarios.

    2.Account for factors such as refraction, scattering, and attenuation of light as it propagates through the underwater medium.

3. Beam Propagation Models:
    - Develop models to simulate the propagation of optical beams in underwater environments with geometric misalignment.
    - Consider beam divergence, beam spreading, and beam wander effects caused by misalignment, as well as scattering and absorption of light by water particles and impurities.

4.Misalignment Effects:

- Quantify the effects of geometric misalignment on key parameters of UWOC performance, such as signal strength, signal-to-noise ratio, and bit error rate.
- Investigate how misalignment affects the spatial and angular distribution of optical power at the receiver, leading to variations in received signal quality.

5.Validation and Calibration:

- Validate the accuracy of the geometric misalignment models through experimental measurements in controlled laboratory setups or field tests in real underwater environments.
- Calibrate the models based on empirical data to improve their predictive accuracy and applicability to different UWOC scenarios.

6.Mitigation Strategies:

- Explore strategies to mitigate the effects of geometric misalignment on UWOC performance, such as adaptive optics

techniques, beamforming algorithms, or dynamic reconfiguration of transmitter and receiver positions.
- Evaluate the effectiveness of these mitigation strategies using the developed models and experimental validation.

2.4 Modeling link Turbulence of UWOC:

Modeling the link turbulence of underwater wireless optical communication (UWOC) involves understanding and quantifying the effects of water turbulence on the propagation of optical signals through the underwater medium. Here's how you might approach modeling link turbulence in UWOC:

1. Characterization of Water Turbulence:
    - Begin by understanding the nature of water turbulence in the underwater environment. Turbulence in water can be caused by various factors such as currents, waves, temperature gradients, and underwater topography.
    - Characterize the statistical properties of water turbulence, including turbulence intensity, spatial correlation, and temporal variations. This could involve field measurements, numerical simulations, or empirical models based on experimental data.
2. Effects on Optical Propagation:
    - Investigate how water turbulence affects the propagation of optical signals in underwater communication systems. Turbulence can cause fluctuations in the refractive index of water, leading to phenomena such as beam wander, scintillation, and beam spreading.
    - Quantify the impact of turbulence on key parameters of optical communication, such as signal attenuation, beam divergence, and spatial coherence degradation.
3. Numerical Simulation and Modeling:
    - Develop numerical simulation models to simulate the propagation of optical signals through turbulent underwater environments. This could involve using computational fluid dynamics (CFD) simulations coupled with ray tracing or wave optics simulations to predict the behavior of optical beams in turbulent water.
    - Implement turbulence models that describe the statistical properties of turbulence and its effects on optical propagation, such as the Kolmogorov turbulence model or the Rytov approximation.
4. Experimental Validation:
    - Validate the accuracy of the turbulence models and simulation results through experimental measurements in controlled laboratory environments or field tests in real underwater conditions. This may involve deploying UWOC transceivers in

underwater testbeds or conducting experiments in natural bodies of water.
- Compare the simulated and measured results to assess the validity of the turbulence models and their ability to predict the performance of UWOC systems in practical scenarios.

5. **Mitigation Techniques:**
    - Explore techniques to mitigate the effects of turbulence on UWOC performance. This could include adaptive optics techniques, such as adaptive beamforming or adaptive optics elements, to dynamically compensate for turbulence-induced distortions in the optical signals.
    - Investigate the use of forward error correction (FEC) coding and diversity techniques to improve the robustness of UWOC systems against turbulence-induced fading and signal fluctuations.

By accurately modeling the link turbulence of UWOC, researchers can gain insights into the challenges posed by underwater turbulence and develop strategies to improve the reliability and performance of underwater optical communication systems in turbulent environments.

Chapter 3: UWOC Channel Modulation and Coding Techniques

3.1 Modulation Schemes of UWOC

Underwater Wireless Optical Communication (UWOC) employs modulation techniques similar to Free-Space Optical (FSO) communication. The most popular modulation scheme is On-Off Keying (OOK), which represents binary data using optical pulses. UWOC faces challenges like absorption and scattering, leading to channel fading, which can be mitigated using Dynamic Threshold (DT) techniques. Pulse Position Modulation (PPM) offers higher energy efficiency than OOK but requires tight timing synchronization. Other techniques like Pulse Width Modulation (PWM) and Digital Pulse Interval Modulation (DPIM) are also utilized, each with its advantages and drawbacks. Coherent modulation schemes encode information on optical carriers' characteristics, offering higher sensitivity and spectral efficiency but at higher implementation complexity. Binary Polarization Shift Keying (BPolSK) is ideal for low SNR environments, while Polarized Pulse Position Modulation (P-PPM) combines PPM and PolSK for increased transmission bandwidth and distance in UWOC systems. Subcarrier Intensity Modulation (SIM) offers higher spectral efficiency but requires complex devices. Overall, modulation schemes in UWOC cater to varying trade-offs between energy efficiency, bandwidth utilization, and complexity.

3.2 Channel Coding of UWOC

In underwater wireless optical communication (UWOC), the severe absorption and scattering effects of seawater lead to significant signal attenuation, degrading the system's Bit Error Rate (BER) performance. To address this challenge, Forward Error Correction (FEC) channel coding techniques are employed. FEC adds redundant bits to the transmitted sequence, allowing the receiver to correct a limited number of errors. Researchers have implemented classical block codes like Reed-Solomon (RS), Bose-Chaudhuri-Hocquenghem (BCH), and cyclic redundancy check (CRC) codes in UWOC systems to improve BER performance. Experimental systems utilizing RS codes have shown significant improvement in Signal-to-Noise Ratio (SNR) and BER compared to uncoded systems. Packet-level error correction schemes, combining Manchester codes, Luby Transform (LT) codes, CRC, and RS codes, have been developed to enhance robustness against packet losses in turbid water environments. While simpler block codes are effective, more complex schemes like Low-Density Parity-Check (LDPC) and Turbo codes offer closer performance to the Shannon limit. Despite fewer investigations, LDPC and Turbo codes show promise in improving UWOC system performance, extending link distances, and enhancing power efficiency. Studies comparing RS, LDPC, and Turbo codes provide valuable insights into their efficacy in UWOC systems, paving the way for optimized channel coding techniques in underwater communication.

Table3.1: Summary of literatures on UWOC modulation schemes

UWOC modulations	Commments
OOK	Simple but with low efficiency.
PPM	High energy efficiency.
DPIM	Higher band width efficiency.
PSK	Combined within tensity modulation.
QAM	Combined with intensity modulation.
PolSK	Higher to lerenceto under water turbulence.
SIM	Increasesy stem capacity; low cost.

Table3.2: Summary of literatures on UWOC channel coding

UWOC channel codes	Commments
RS	Simple and robust block codes.
BCH	Simple and robust block codes.

CRC	Simple error-detecting codes.
LT	Practical fountain code.
LDPC	Complex linear block code.
Turbo	Complex convolutional code.

Chapter 4 :Experimental Setups and Prototypes of UWOC

In this chapter, we will study the experimental setups and prototypes of UWOC from different aspects. Firstly, we are going to introduce several typical LOS/NLOS experimental setups and prototypes of UWOC. Secondly, we will review the research of UWOC implementations in several specific topics, which include retroreflector, smart transceiver design, UWOC for underwater vehicles and the hybrid UWOC systems. Finally, we will summarize this chapter and propose the literature classification of experimental UWOC systems.

4.1 Typical LOS/NLOS UWOC systems

As we have mentioned in Chapter 1, although a few commercial UWOC products were proposed in the early 2000s, the large scale commercial applications of UWOC systems have not been realized so far. Most of the UWOC systems are experimental demonstrations and prototypes in laboratory environment. In the remaining of this section, we will provide a comprehensive summary of the recent progress on experimental UWOC research. The purpose of this summary is not to introduce all the UWOC experimental literatures in details, but to provide a general description of the most recent works on UWOC experiments that concern different applications and approaches. According to the link configurations, experimental setups and

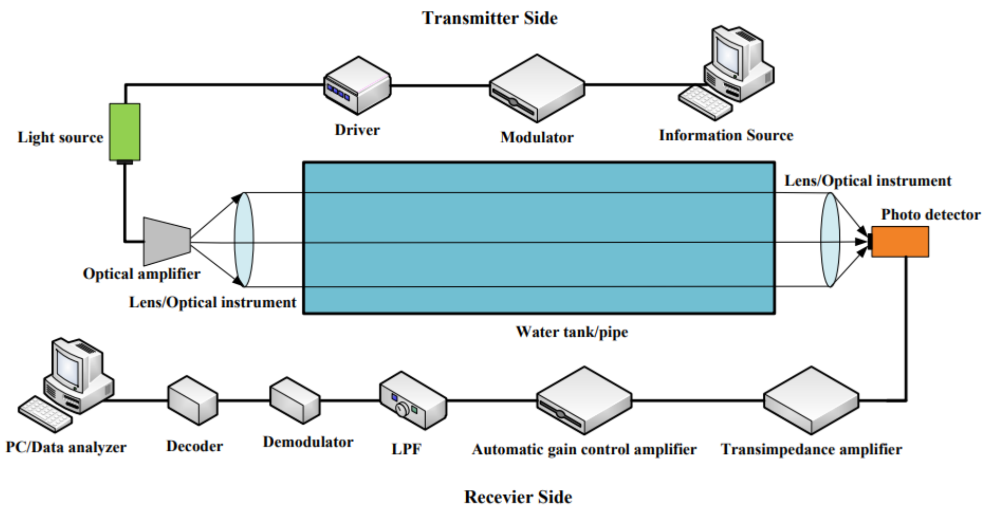


Figure 4.1: A typical laboratory LOS UWOC system based on intensity-modulation direct-detection (IM/DD) technique.

prototypes of UWOC can be divided into two categories: LOS experimental setups and NLOS experimental setups. Due to the simplicity of implementation, most UWOC experimental systems utilize LOS configuration. In Figure 4.1, a typical laboratory LOS UWOC system based on intensity-modulation direct-detection is demonstrated. The configuration of LOS UWOC link is similar to the FSO communication setups . On the transmitter side, the information bits are generated by a personal computer (PC), and then modulated onto optical carriers. In several UWOC experiments, the modulated optical signal will be further amplified by an optical amplifier and then transmitted through lens that are precisely

aligned to focus the light. Water tank or pipe is used to model the underwater transmission link. In order to mimic the different refractive condition and turbidity of underwater environment, Maalox is added in the water to act as a scattering agent for attenuating the light beam . On the receiver side, the optical signal will go through an optical filter and focusing lens. It will then be captured by the photodiode. Since photodiode can only transform the variations of light intensity into corresponding current changes, a trans-impedance amplifier is cascaded as the following stage to convert current into voltage. The transformed voltage signals will then go through a low pass filter to reduce the thermal and ambient noise levels . Further signal processing programs that include demodulation and decoding will be performed at the last two stages of the receiver. The recovered original data will finally be collected and analyzed by a PC or BER tester for evaluating several important performance parameters such as BER. There are two light sources that are commonly used in typical UWOC experimental systems: light-emitting diodes (LEDs) and laser diodes (LDs). As it was stated in Chapter 1, blue or green wavelength has been chosen for the light sources to minimize the aquatic optical attenuation. Compared with LED, LD has higher output power intensity, better collimated properties, narrower spectral spreading, and much faster switching speeds. But at the expense of higher cost, shorter lifetime and dependence on temperature. Thus LDs are more appropriate to be implemented in applications of high-speed UWOC that has strict alignment requirement. In several LD-based UWOC applications, optical diffusers are implemented to reduce the system pointing requirements. Compared with the LD-based UWOC system without diffusers, this diffused LD-based UWOC system can benefit from both high speed and relatively low pointing requirements. On the other hand, since LEDs offer lower output power intensity, wider divergence angles, and lower bandwidths. They can be installed in several diffused UWOC applications with short-range, low-speed link requirement

At the receiver, there are also two types of photodiodes that are widely used in UWOC experiments: P-i-N (PIN) diode and avalanche photodiode (APD). The major difference between these two devices is in the noise performance. For PIN photodiodes, the dominant noise is thermal noise, while for the APDs, the performance is mainly limited by shot noise Since APD can provide higher current gain, it can be implemented in longer UWOC links (tens of meters), but at the expense of more complex auxiliary circuits. Besides PIN diodes and APDs, photomultiplier tubes (PMT) have also been implemented in several UWOC experiments . Compared with photodiodes, PMT benefits from higher sensitivity, higher optical gain and lower noise levels. But it also suffers from high voltage supplies (on the order of hundred volts) and high unit cost. Moreover, PMT is susceptible to shocks and vibration. It can be easily damaged by the overexposure to light. The cost of PMTs are also much higher than photodiodes. Thus PMTs are commonly used in static experimental UWOC systems. Based on the typical LOS UWOC link configuration and the critical devices that we have introduced, lots of experimental UWOC links focusing on channel model verification and system performance analysis have been proposed in recent years.

Since LED benefits from its low cost and stable performance in various environments, several researchers preferred to employ it as the light sources in experimental UWOC systems , Chancey proposed a UWOC system based on high power Gallium Nitride LEDs. This experimental demo is capable of achieving 10 Mbps video transmission over a distance of 12 meters. Simpson from the North Carolina State University demonstrated a UWOC system with signal processing capabilities that utilized high-power LED as the light source. Experimental results show that 1 Mbps data rate is achievable over a distance of 3.66 meter long. Similarly, the author of has also developed a UWOC system that utilized a high-power blue LED as transmitter and a blue enhanced photodiode as receiver. This system successfully accomplished a 3 Mbps data transmission in a 13-meter long water tank. By using the mirrors folding architecture, tested their LED based UWOC system over a distance of 91 meters, a maximum data rate of 5 Mbps was accomplished. Recently, researchers from the Massachusetts Institute of Technology (MIT) presented a bidirectional UWOC system named Aqua Optical . The transmitter of the system consisted of six five watts LEDs with 480 nm wavelength. The researchers tested this demo system in both pool and ocean environment. Experimental results showed in clear pool water, the Aqua Optical can achieve a data rate of 1.2 Mbps at distances up to 30 meters; while in turbid water with only three meters visibility, the system achieved a data rate of 0.6 Mbps over nine meters. As an upgraded version of Aqua Optical, Aqua Optical II can establish a bidirectional underwater communication link between each transceivers . Since Aqua Optical II is designed using a software defined radio, it has more powerful signal processing capabilities than its previous generation and can also achieve a data rate of two Mbps over a distance of 50 meters. Several theoretical channel models have been validated through this testbed . Furthermore, the MIT researchers also performed a real-time video delivery experiment by employing Aqua Optical II . Using the same design approach of software defined radio, Cox et al. from North Carolina State University have also built up a UWOC experiment based on LED . Since software defined radio system is more configurable than conventional hardware implementations, it is convenient to test various modulation formats or digital filtering schemes on UWOC . The authors examined the performance of BPSK and

Gaussian minimum shift keying (GMSK) schemes and accomplished a data rate of one Mbps over a range of 3.66 meters. Most recently, a typical cellular UWOC network prototype based on LEDs was demonstrated in . The authors implemented code division multiplexing access (CDMA) techniques in this prototype and tested the network performance in various water conditions. Besides the experiments that we have already mentioned, other similar recent experimental UWOC systems and prototypes that utilized LEDs as light sources can also be found in

Instead of using LEDs, several experimental setups also utilized lasers as the light sources due to its high bandwidth and lower noise floor . Although laser and laser diodes were invented in the early 1960s, only few early laser-based UWOC experiments have been performed in the 1990s. In recent years, with the cost reduction and popularization of laser devices, there is a surge of laser-based UWOC experimental systems. Cox et al. constructed a laboratory testbed based on a 405 nm blue laser diode and PMT. This setup can provide up to one Mbps underwater data transmission in a distance of 12 meters . Hiskett et al. proposed a laser-based UWOC system by utilizing 450nm laser diode and APD . One 40 Mbps wireless communication link was established over one meter water tank. In , the authors demonstrated a real-time underwater video transmission system by implementing 488 nm blue laser and PMT. Five Mbps high-speed video stream was successfully transmitted through 4.5 meters long underwater channel. Several researchers employed laser to study the spatial and temporal dispersion effects of UWOC links over different modulations, coding schemes and water conditions . Compared with typical LOS UWOC experimental systems, only few UWOC experiments have focused on the diffused and NLOS link configurations. Pontbriand et al. from the Woods Hole Oceanographic Institution (WHOI) demonstrated a broadcasting diffused UWOC system . This system can achieve a data rate up to 10 Mbps over a maximum vertical distance of 200 meters and horizontal radius up to 40 meters , Cochenour et al. employed 532 nm laser and a diffuser to generate diffused light. A diffused UWOC link with up to 1 Gbps data rate meters long water tank was established. On the other hand, the experimental NLOS UWOC links are mainly focused on the applications of underwater ranging and imaging.

Alley et al. proposed a NLOS imaging system that utilized 488 nm blue laser as the illuminator. Experimental results demonstrate that, compared with the conventional

LOS imaging system, this NLOS configuration significantly improves the SNR of imaging. A similar experimental approach that employed modulated pulse laser in NLOS configuration for underwater detection, ranging, imaging, and communications was presented in

4.2 Retroreflectors in UWOC

Retroreflector is an optical device that can reflect arbitrary incident light back to its source (Figure 4.2). Utilizing this beneficial characterization, a modulating retroreflector UWOC system was introduced. In the modulating retroreflector link (Figure 4.3), the active transceiver projects a light beam into the retroreflector. During the reflection process, the modulator will modulate the light beam and add information on it. This information will later be captured and demodulated by the active transceiver. The most significant advantage of modulating retroreflector UWOC system is that most of the power consumption, device weight, volume and pointing requirements are shifted to the active end of the link, thus the passive end will benefit from small dimensions, relatively low power and pointing requirements . There are lots of sensor nodes and underwater vehicles in UWSNs. Each sensor node and underwater vehicle is required to have long enough cruising time due

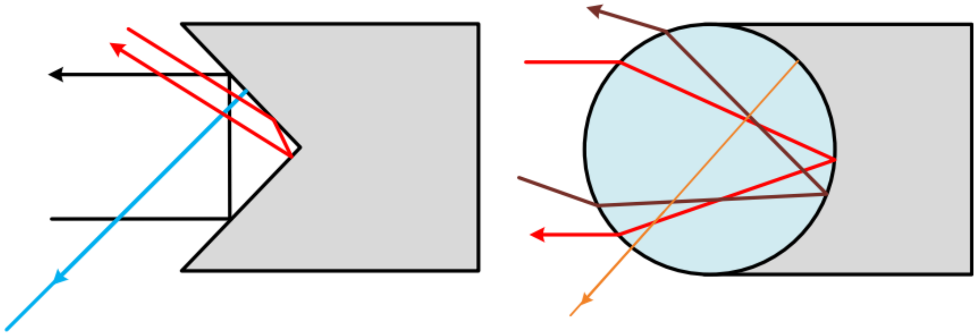


Figure 4.2: Demonstration of corner and spherical retroreflectors.

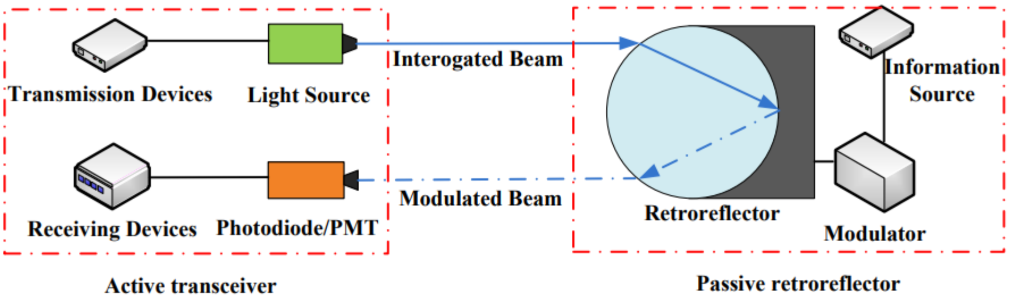


Figure 4.3: Modulating retroreflector link.

to the difficulty of recharging battery. In this sense, modulating retroreflector becomes an attractive choice. In addition to the challenges that involved in a direct UWOC link such as absorption and scattering, retroreflector-based UWOC systems have several additional limitations. Unlike the typical UWOC links, the retroreflector based UWOC links have to transmit through the underwater channel twice, so the link will experience higher attenuation and interference. Furthermore, the backscattered light generated from the interrogating beam can be significant in turbid water where it will eventually surpass the desired retro-reflected signals. Although the concept of implementing retroreflector into FSO communication system has already been proposed for almost 20 years , only few research works on UWOC retro reflector system were demonstrated recently. The first institute that implemented retroreflector FSO communication in marine environment is the U.S. Naval Research Laboratory (NRL). Since late 1990s, the NRL began to launch the research of retroreflector applications in FSO communication and successfully achieved shore-to-shore, boat-to-shore and sky-to-ground retroreflector FSO links . Based on these achievements, NRL researchers then applied the retroreflector link into underwater environment , Mullen et al. employed a polarization discrimination technique to overcome the impact of backscattering on the interrogating light. An experimental test was also performed in laboratory water tank to evaluate the system performance. The authors compared the experimental results of polarized and non-polarized setups with different transceiver FOV and link ranges. Experimental results showed that, by utilizing polarization discrimination technique, the backscatter level can be greatly reduced. This fact will then increase the communication range of retro link. Cox et al. from North Carolina State University proposed a blue/green retro-reflecting modulator for UWOC based on micro-electromechanical system (MEMS). The authors deployed the retroreflector link in a 7.7 meters long water tank and evaluated the system performance with various water turbidities. Experimental results show that 1 Mbps and 500 kbps data rates can be achieved in 2.7 attenuation length 6 and 5 attenuation length respectively.

4.3 Smart Transceivers of UWOC :

As shown Figure 4.1, in a UWOC system, the information waveforms are generated by a source and then transferred by an optical transmitter through the water channel to a specific destination. At the other end of the link, the receiver will collect the optical signal and recover the original information. Although the transmission wavelength is carefully selected in blue/green transparent window to minimize the attenuation effect of sea water, several other factors such as misalignment will still severely degrade the link performance. As we have stated in Chapters 1 and 2 , most UWOC systems utilize point-to-point configuration, and thus precise pointing and tracking requirements are necessary. However, link misalignment is an inevitable phenomena in underwater environment, any variations of refractive index or turbulence of ocean can cause link misalignment and interrupt communication.

Especially in mobile UWOC applications such as AUVs and ROVs, the two ends of a link are all in non static condition, which makes the alignment more difficult to be achieved. Conventionally, there are three common methods to relief the pointing requirements of a UWOC system: using diffused light beam, increasing receiver aperture size, or implementing a dedicated gimbal system. Diffused light beam can effectively increase the illuminated area of a light source, but the communication range also shrinks. Although large aperture can increase the receiver FOV and it has already been implemented in several UWOC systems such as, the extra introduced ambient light and limited transceiver size requirement will still restrict the application of this method. Dedicated gimbal system can be used in several applications that have less size limitation and energy requirements, but for compact UWOC systems that don't have much volume and energy budget, this approach is not practical Considering the limitations of each compensation method that we have introduced, a compact adaptive smart UWOC transceiver that can relax the misalignment requirement with minimized volume and energy cost. Simpson et al. proposed a novel UWOC front-end that introduced the concept of smart transmitter and receiver. The smart quasi-omnidirectional transmitter can estimate the water condition according to the backscattered light captured by the adjacent smart receiver. Based on specific water conditions, the transmitter can take several actions such as changing transmission light wavelength to improve link performance. The transmitter can also electronically switch the beam direction according to the angle of arrival of detected signal. On the receiver side, segmented lens array architecture was implemented to increase the total FOV. By using the information of angle of arrival estimation, the smart receiver can also adjust and steer the FOV towards the direction of desired signals to improve the the SNR of the received signal. Moreover, the CDMA technique has also been implemented in both transmitter and receiver ends to reinforce the system performance in multi-user environment. The authors installed the prototyping smart transceivers in a 3.66-meter long laboratory water tank to evaluate the system performance. Experimental results demonstrate that the smart system can effectively increase the total FOV of the receiver. The preliminary algorithm for angle of arrival estimation and backscatter estimation was also verified to work properly. Other performance aspects such as diversity combining and multi-user CDMA approach were also tested and proved to be effective. This novel trial of smart transceivers provides an adaptive solution to handle the impact of dynamic nature of underwater environment to the UWOC systems. It can be applied to different underwater platforms such as AUVs, ROVs, and other sensor nodes embedded with UWOC system. Several theoretical research works focusing on smart or adaptive UWOC transceivers were also proposed. Tang et al. presented an adaptive gain control scheme for UWOC receivers based on APD. The authors derived a close-form expression that can describe the relationships of optimal gain of APD, link range and receiver offset distance. This result can be further applied to practical design of UWOC transceiver

4.4 UWOC for Underwater Vehicles

The section discusses the use of underwater wireless optical communication (UWOC) for underwater vehicles, including autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs). These vehicles are crucial for various underwater tasks such as resource exploration and maintenance of underwater infrastructure. Three categories of underwater vehicles are identified: tethered, wireless, and hybrid. Tethered vehicles are connected to the surface control platform through cables, providing reliable communication but with limited range. Wireless vehicles operate autonomously using acoustic communication, offering flexibility but with low bandwidth and high latency. Hybrid vehicles combine tethered and wireless systems but are not suitable for large-scale implementations due to cost and complexity. To address the limitations of conventional vehicles, UWOC has been embedded into AUVs and ROVs. The Autonomous Modular Optical Underwater Robot (AMOUR) is introduced as a prototype AUV system developed by MIT's Computer Science and Artificial Intelligence Laboratory (CSAIL). AMOUR utilizes UWOC for tasks such as underwater monitoring and exploration, achieving data rates of one Kbps over short distances. Subsequent upgrades to AMOUR include features like remote control, localization, and time-division multiplexing access (TDMA), enhancing its capabilities for underwater communication and operation To meet the demands of underwater wireless sensor networks (UWSNs) for compact, durable, and high-bandwidth vehicles, researchers have integrated underwater wireless optical communication (UWOC) into autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs). The Computer Science and Artificial Intelligence Laboratory (CSAIL) at MIT introduced the autonomous modular optical underwater robot (AMOUR), designed for tasks such as underwater monitoring, exploration, and surveillance. AMOUR utilizes a modular design approach, allowing it to deploy and recover sensor nodes within sensor networks. The initial version of AMOUR utilizes LEDs as light sources, achieving a data rate of one Kbps over a two-meter distance. CSAIL researchers subsequently upgraded the AMOUR system to incorporate features like remote control, localization, and time-division multiplexing access (TDMA) based on UWOC. These enhancements improve the capabilities of underwater vehicles for communication and operation

Researchers conducted experiments using a cooperative underwater wireless sensor network (UWSN) involving the AMOUR AUV, another AUV called Starbug, and multiple underwater sensor nodes. The experiments involved cooperative tasks such as data transmission, localization, navigation, and physical connection, demonstrating the feasibility of collaboration among different underwater vehicles and sensor nodes. This research also validated a viable approach for achieving long-term operation of UWSNs. Additionally, an upgraded version of the AMOUR vehicle, called AMOUR VI, was demonstrated with a UWOC module for real-time control link. Using blue/green LEDs as light sources, this system achieved high data rates and low latencies in a shallow swimming pool with ambient light. Compared to conventional acoustic ROVs, the UWOC system offered significantly higher data rates and lower latencies. The compact architecture of the vehicle, sealed transmitter and receiver modules, and thruster system for arbitrary movement were also highlighted. Other UWOC research groups have also presented demos and prototypes of optical wireless underwater vehicles, with some implementing hybrid communication systems combining acoustic and optical modules

4.5 Hybrid Acoustic/Optical UWC Systems

and cons of both UWOC and acoustic communication, hybrid acoustic/optical underwater communication (UWC) systems have been proposed to leverage the advantages of both technologies. These hybrid systems integrate acoustic and optical communication modules to enhance reliability and performance in underwater communication networks. While acoustic communication offers mature technology, long link ranges, and lower pointing requirements, optical communication provides high-speed point-to-point data transmission. By combining these technologies, hybrid UWC systems can mitigate the limitations of each approach and provide more robust and flexible communication solutions for underwater applications

Sure, let's dive deeper into the details of the hybrid underwater communication systems discussed in the paragraph

Hybrid Link Configurations: There are two main configurations proposed for hybrid underwater communication systems

First Configuration: In this setup, both acoustic and optical waves are utilized as duplex transmission media. The two ends of the link consist of mobile underwater vehicles equipped with both acoustic and optical transceivers. Depending on the distance between the nodes and water conditions, the system dynamically switches between using optical waves for high-speed data transmission in clear water and employing acoustic methods for connectivity over longer distances or in turbid conditions. While offering high flexibility and reliability, this configuration requires high power consumption and bulky instruments due to the presence of acoustic .transceivers on both ends

Second Configuration: In this setup, the system comprises a static control platform and multiple mobile sensor nodes. Acoustic waves are used to transmit control information from the control platform to the sensor nodes (downlink), while optical waves are employed for communication links between sensor nodes and for transmitting data from sensor nodes to the control platform (uplink). This configuration leverages the diffusion property and long propagation distance of acoustic waves for broadcasting control signals and the high-speed capability of .optical waves for transmitting large volumes of data

Advantages and Disadvantages: Each configuration has its own set of advantages and disadvantages. The first configuration offers high flexibility and reliability but requires more power and bulky instruments due to the presence of acoustic transceivers on both ends. On the other hand, the second configuration utilizes the strengths of both communication methods, allowing for efficient transmission of control signals and high-speed data while minimizing power consumption and equipment size. However, it may be limited by the coverage area of acoustic waves and the range of optical waves

Research Contributions: Several research efforts have been dedicated to exploring and implementing these hybrid underwater communication systems. For example, researchers from the Computer Science and Artificial Intelligence Laboratory (CSAIL) of MIT developed a hybrid underwater sensor network capable of long-term monitoring tasks, including video streaming of the seafloor and real-time data collection. Their system utilized a combination of optical and acoustic communication methods to achieve efficient data transmission and control signaling. Additionally, optimization algorithms and hardware implementations were developed to enhance system performance and reliability

Overall, these hybrid underwater communication systems represent a promising approach to overcoming the limitations of individual communication methods and achieving reliable and efficient communication in underwater environments

In addition to the systems developed by MIT, researchers from various institutions have explored hybrid underwater optical communication (UWOC) systems. For instance, Vasilescu et al. from CSAIL at MIT designed a hybrid system consisting of AquaNodes equipped with RF Bluetooth, acoustic, and optical modules. This system enables communication with each node through different means depending on the application environment, such as using optical signals in clear shallow water and Bluetooth at the water/air interface. The system incorporates TDMA and self-synchronization technologies in each node, achieving a 400-meter long acoustic link with a data rate of 300 bps in ocean environments and establishing an optical link up to eight meters with a data rate of 330 kbps. The collected sensor data, including temperature, pressure, and water chemistry information, can be continuously transmitted to a communication buoy, which relays the information to an onshore .data center for processing and analysis

Furthermore, Farr et al. from WHOI proposed the operation concept of an untethered ROV (UTROV) employing both optical and acoustic communication methods. This UTROV can perform survey and reconnaissance tasks over long distances using a low-bandwidth acoustic modem and communicate optically via ship-based or seafloor-based relays. Additionally, they demonstrated a seafloor borehole observatory system called CORK-OTS, which integrates acoustic modems .with optical systems to achieve high-speed data transmission

Although theoretical research on hybrid UWOC systems is limited, some studies have been conducted. For example, one study proposed a hybrid duplex optical-acoustic communication system, where the downlink from the base station to AUVs is a diffused acoustic link with low bandwidth, and the uplinks are highly directional optical links with high bandwidth. Another theoretical evaluation focused on a communication node equipped with both acoustic and optical transceivers, with a transmission algorithm designed to ensure link alignment and connectivity. Simulation results indicated that the hybrid system has better energy efficiency than a pure acoustic system and is more resilient to environmental factors

4.6 Hardware part

Transmitter Side

1.Modulator

Aim: The modulator's primary function is to encode the data onto the light source. It does this by varying some property of the light (such as intensity, phase, or frequency) in accordance with the input data

Function: In simple terms, the modulator converts electrical signals containing your data into corresponding optical signals. For example, if using On-Off Keying (OOK), the modulator will turn the light source on and off to represent binary data (1s and 0s)

2.Light Source

Aim: To generate the optical signal that will carry the data through the underwater channel

Function: Typically a laser diode or LED that emits light in the blue-green spectrum (450-550 nm), as these wavelengths experience less absorption and scattering in water. The light source produces a coherent and directional beam that can travel longer distances underwater

3.Lens

Aim: To focus and direct the light emitted from the light source

Function: Collimating lenses are used to narrow the light beam, increasing its intensity and reducing divergence. This helps to maintain signal strength over a longer distance and ensures that the light is directed precisely towards the receiver

4.Water Channel

Aim: This is the medium through which the light signal travels

Function: The water channel represents the underwater environment in which your system operates. It includes various factors like absorption, scattering, and possible turbulence that affect the propagation of the optical signal

Receiver Side

5. Optical Band-Pass Filte

Aim: To filter out unwanted light and noise, allowing only the specific wavelength(s) of interest to reach the photodetector

Function: It selectively transmits light within a certain wavelength range and blocks other wavelengths. This helps in reducing noise from ambient light and other sources, improving the signal-to-noise ratio (SNR) of the received signal

6.Lens

Aim: To collect and focus the incoming light onto the photodetector

Function: Similar to the lens on the transmitter side, but here it is used to gather the maximum amount of light from the transmitted beam and focus it onto the small area of the photodetector, thereby increasing the efficiency of the light detection process

7.Photodetector

Aim: To convert the received optical signal back into an electrical signal

Function: Typically a photodiode or avalanche photodiode (APD) that is sensitive to the specific wavelength of light used in the system. It generates a current or voltage proportional to the intensity of the received light, effectively converting the optical signal into an electrical signal

8.Demodulator

Aim: To extract the original data from the received electrical signal

Function: The demodulator processes the electrical signal output from the photodetector and recovers the data that was encoded onto the light at the transmitter side. For instance, in an OOK system, the demodulator would interpret the on-off patterns of the signal as binary data (1s and 0s)

Overall Workflow

1.Data Encoding and Transmission

-The data is first encoded into an electrical signal using the modulator

-This electrical signal controls the light source, modulating its output to represent the data

-The light from the source is focused and directed by the lens, creating a narrow, intense beam

-The beam travels through the underwater channel

2.Signal Reception and Decoding

-At the receiver end, the incoming light signal is first filtered through an optical band-pass filter to remove noise

-The filtered light is focused onto the photodetector by a lens

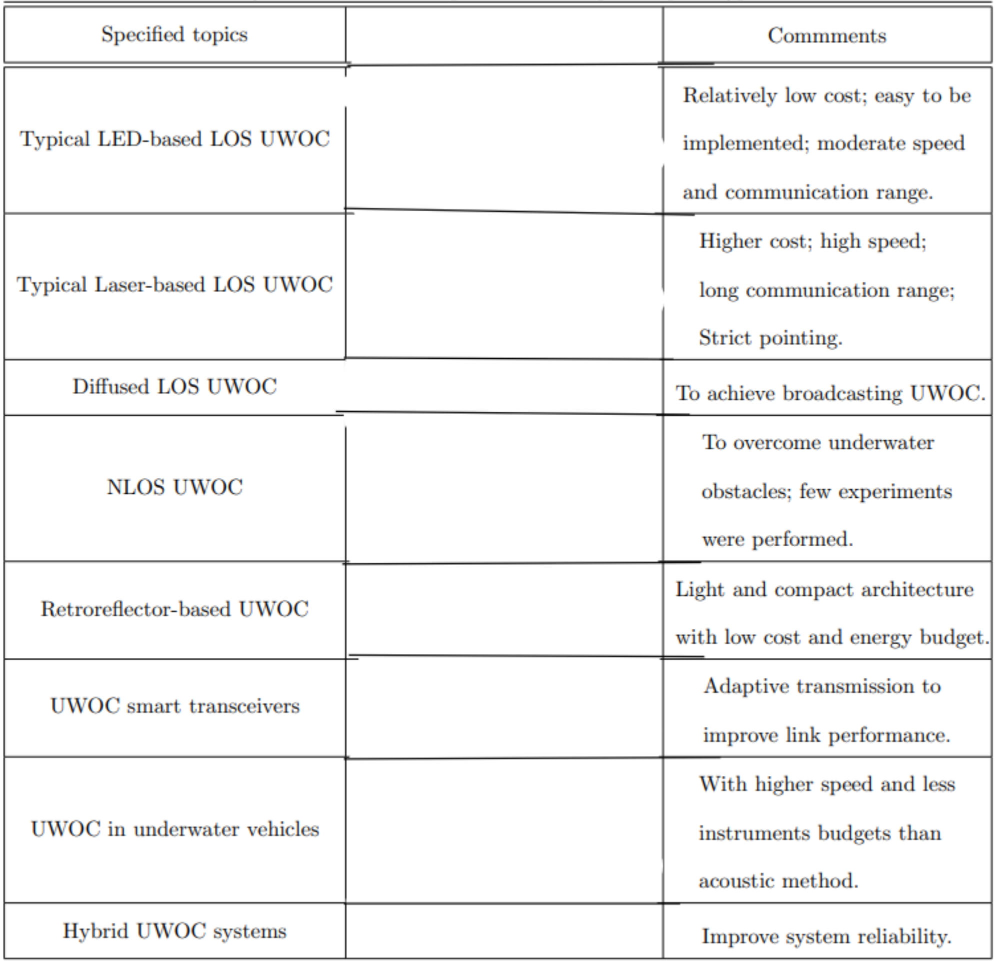
-The photodetector converts the optical signal back into an electrical signal

-The demodulator then processes this electrical signal to extract the original data

By using these tools and components effectively, your underwater optical communication system can achieve reliable data transmission even in challenging underwater environments

4.7 Summary

Table 4.1: Summary of literatures on experimental setups and prototypes of UWOC



Specified topics		Commments
Typical LED-based LOS UWOC		Relatively low cost; easy to be implemented; moderate speed and communication range.
Typical Laser-based LOS UWOC		Higher cost; high speed; long communication range; Strict pointing.
Diffused LOS UWOC		To achieve broadcasting UWOC.
NLOS UWOC		To overcome underwater obstacles; few experiments were performed.
Retroreflector-based UWOC		Light and compact architecture with low cost and energy budget.
UWOC smart transceivers		Adaptive transmission to improve link performance.
UWOC in underwater vehicles		With higher speed and less instruments budgets than acoustic method.
Hybrid UWOC systems		Improve system reliability.

Chapter 5 :Conclusions

In this chapter, we conclude the thesis by summarizing the contributions of this work and suggesting some potential further research topics.

5.1 Summary of Contributions

In this thesis, we have provided a comprehensive technical survey for the research of UWOC. This survey covers three comprehensive aspects of the state-of-the-art of UWOC research in the perspective of communication engineering: UWOC channel modelling, modulation and coding technologies, and experimental UWOC discoveries. The summarization that we've made can provide a comprehensive overview of UWOC as well as potential research directions for the scholars and engineers who are working on this area. In order to conclude the thesis, we will summarize the contributions as follows

− In Chapter 1, we have introduced the history and current development of UWOC. Several significant discoveries of UWOC have been stated. We have also carried out four link configurations that are widely implemented in UWOC systems: point-to-point LOS, diffused LOS, retro reflector-based LOS and NLOS configurations. The corresponding characterizations and application scenarios of each link configurations have also been explained. In the second part of this chapter, we have introduced the advantages and limitations of UWOC by comparing it with other conventional UWC carriers such as acoustic and RF waves.

− Chapter 2 has investigated the channel modeling of UWOC. We have firstly introduced several basic properties of light propagation in water which provide a foundation for UWOC channel modeling. The concept of absorption and scattering coefficients as well as their characterizations in different water types have been stated. Secondly, we have presented the modeling work of aquatic optical attenuation in LOS and NLOS configurations. Several UWOC channel modeling approaches that include analytical and numerical solutions of RTE, stochastic modeling of aquatic optical attenuation have been introduced. Finally, we have demonstrated the modeling of link misalignment and turbulence in UWOC. A summary of each UWOC channel modeling work has been given at the end of this Chapter.

− In Chapter 3, we have studied the channel modulation and coding techniques that applied in UWOC. Several conventional intensity modulation schemes such as OOK, PPM, DPIM and their applications in UWOC systems have been presented. We have also presented the implementations of both simple and complex error correction codes in UWOC. The characterization and performance of each codes in UWOC system have also been presented.

− Chapter 4 has demonstrated the recent progress of UWOC experimental research. Firstly, we have explained the architecture of a typical LOS UWOC experimental system. The recent research works based on this architecture have been introduced. We have also presented the UWOC experimental demonstrations with other link configurations such as diffused LOS and NLOS. Secondly, we have discussed several popular topics of experimental UWOC research which include retro reflector, smart transceivers, UWOC for underwater vehicles and hybrid UWOC systems. The recent progress in each of these topics has been presented in details. Finally, we have summarized the literatures of experimental UWOC in recent years.

Suggested Future

Work Although considerable research work on UWOC have already been proposed during the past few years, large scale commercial applications of UWOC systems have not been realized so far. There are still several challenges in this technology that need to be overcome. According to the previous survey and investigation of UWOC systems, we provide several potential directions for future UWOC research as follows: − On the aspect of UWOC channel modeling, although lots of modeling work focusing on the horizontal LOS configuration have been demonstrated, few channel models have considered the vertical link. Compared with horizontal link configuration, vertical links take into account the variations of refractive index with the depth and temperature, which is a challenging task for future UWOC research. In FSO communications, there are a lot of works considering channel turbulence. However, in UWOC research, turbulence of water has not been fully considered. Another issue is to derive an accurate model for the NLOS UWOC. The modeling of LOS UWO Care relatively mature, several close-to-reality models have already been demonstrated. But for NLOS UWOC, such accurate models have not been proposed so far.

− There are also several potential research directions in the aspect of UWOC transceivers. For most theoretical UWOC research, the impact of transceiver noise to UWOC has not been fully investigated. It’s necessary to study the noise model of UWOC transceivers and use them to evaluate the system performance. As we have presented in the previous chapters, link misalignment is an inevitable phenomena. Although a few research works on smart transceivers for overcoming link misalignment have been proposed, considering the rapid growing of UWSNs, there’s still a need for developing highly intelligent UWOC transceivers. The next generation UWSNs require high bandwidth, energy-efficient, and compact UWOC transceivers to be large-scaly implemented in AUVs, ROVs, and underwater sensor nodes. Thus, there’s huge research potential for developing more advanced and low-cost transmission light sources, receiving devices, as well as energy preservation system for the next-generation UWSNs.

− The design ofappropriate modulation and coding schemes that can adapt the characterizations of underwater environment is another potential research direction. In recent years, researchers have implemented almost all the conventional optical modulation and coding techniques in UWOC. These schemes have been proved useful and improved the system performance. However, few implementations have considered to design a modulation or coding scheme that can dynamically adapt to the link characterization. Since most UWOC systems are embedded on a battery-powered platform, the energy efficiency is thus considered to be important. If there is a mechanism can adaptively switch modulation and coding schemes according to the turbidity of water (applying simple weak error coding scheme in clear water, complex powerful error coding scheme in turbid water), then the system will save considerable energy and have longer cruising time.

− Suitable network protocols are also needed for the UWOC. To this end, most of the research work on UWOC are mainly focusing on the physical layer such as channel modeling, modulation and channel coding. Only few studies on UWOC networks have been demonstrated so far .Considering the unique characterization of wireless optical channel in underwater environment, novel efficient network protocols need to be proposed.

Chapter 6: Experimental Results and Analysis

6.1 Water environments used in the experiment

Lasers in underwater wireless communications are a major challenge due to the effects of the surrounding environment on laser radiation. Effects vary depending on water type, presence of pollutants, and other environmental factors. Let me explain to you the effects that may occur in each of the cases I mentioned:

1.Fresh Water: Underwater lasers in fresh water can work relatively well, especially if the water is clear and uncontaminated. Fresh water reflects a fraction of the radiation, but transmission is still fairly efficient.

The distance reached by the laser is reasonable, but as the distance increases, the scattering increases due to the absorption of light energy by water.

2.Salt water: To make 7 liters of water similar to seawater salinity, which is typically around **3.5% (35 grams of salt per liter of water)**, we need **245 grams of salt** to balance 7 liters of water to match seawater salinity.

Salt water contains salts and minerals that contribute to greater laser scattering compared to fresh water. Salinity causes greater energy absorption and increases dispersion.

as in fresh water, as the data will be affected and its quality will decrease as the distance increases.

3.Water contaminated with impurities and salt

The presence of impurities (such as clay or dirt) with salt water increases dispersion significantly. Impurities act as reflective and scattering elements for light radiation, causing significant energy loss.

In this case, it will be very difficult to transmit data via the laser over long distances, as the signal may stop completely due to light scattering and the inability of the laser to reach the receiver.

4.Water contaminated with impurities, salt and sediments:

Deposits further block the laser beam path, resulting in significant signal loss. Deposits may prevent the laser from transmitting completely or partially.

The distance the data travels may be very small or the signal may not arrive at all if the accumulations are large.

5.Foggy turbid water:

Foggy, turbid water contains a high percentage of suspended particles that scatter the laser significantly. This makes signal transmission through the laser almost impossible over long distances.

Laser data may not arrive in this environment due to the high dispersion of light waves, making communication only possible over very short distances (if they exist at all).

a summary: The more contaminants in the water (salt, impurities, sediments, turbidity), the greater the negative effects on the laser's performance, both in terms of the distance it can reach and the quality of the data.

In pure, fresh water, the laser can work well over medium distances, but the more contamination there is in the water, the more signal quality is greatly affected.

If you are using these types of water in your project, you should consider improvements such as error correction techniques or the use of sensitive and sophisticated devices to improve communication.

distance between transmitter and receiver approximately 1m

Water condition	Effect of laser on distance	Laser effect on data transmission
Fresh Water	The distance the laser can reach is reasonable, but as the distance increases, the scattering increases due to the water absorbing the light energy.	The data is complete
Salt water	Lasers do not travel as effectively over long distances as they do in fresh water.	The data is complete
Water contaminated with impurities and salt	this case, it will be very difficult to transmit data via the laser over long distances	inability of the laser to reach the receiver
Water contaminated with impurities, salt and sediments	The distance the data travels may be very small or the signal may not arrive at all if the accumulations are large.	Data not arrive to the receiver.
Foggy turbid water	signal transmission through the laser almost impossible over long distances	Laser data may not arrive in this environment due to the high dispersion of light waves, making communication only possible over very short distances (if they exist at all).

6.2 Calculate BER:

$$BER = \frac{\text{Number of bit errors}}{\text{Total number of transmitted bits}}$$

A) Pure water:

1) Sent data: HI SUB ONE Data receiver: HI SUB ONE

BER =(0/10)*100= 0 %

2)Sent data: ASDFGJKLQWERTYU Data receiver: ASDFGJKLQWERTY0

BER =(1/16)*100= 6.25 %

B)Water with salt :

Sent data: HI HADEEL LLLOLL Data receiver: HI HADE LLLODR

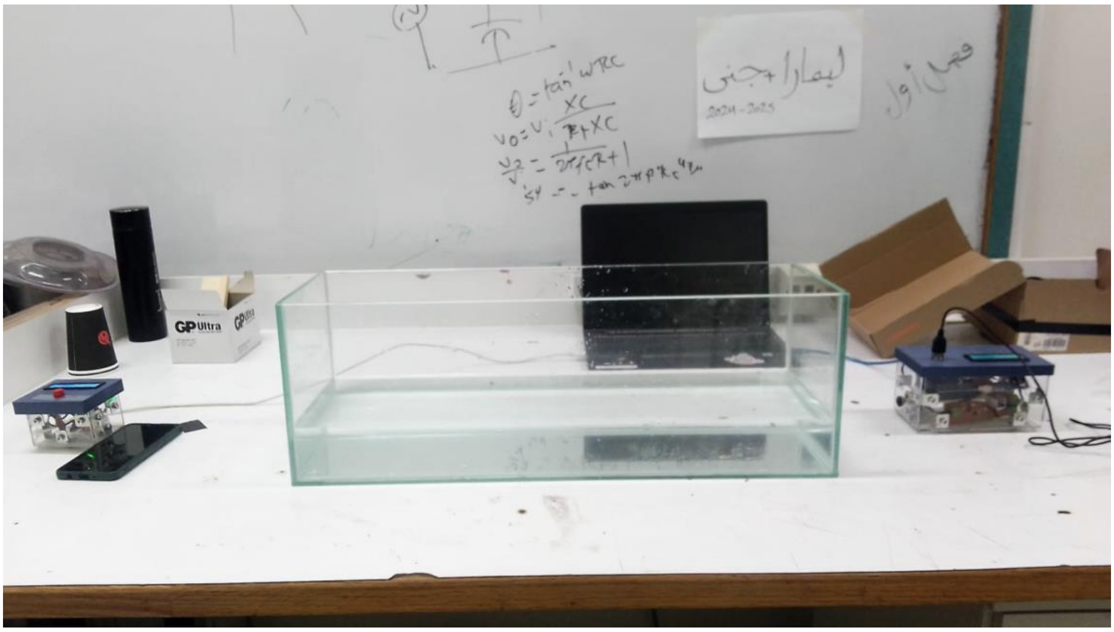
BER =(4/16)*100= 25 %

C)Water ,salt and dirt

Sent data: HI SUBMARINE ONE Data receiver: SUB

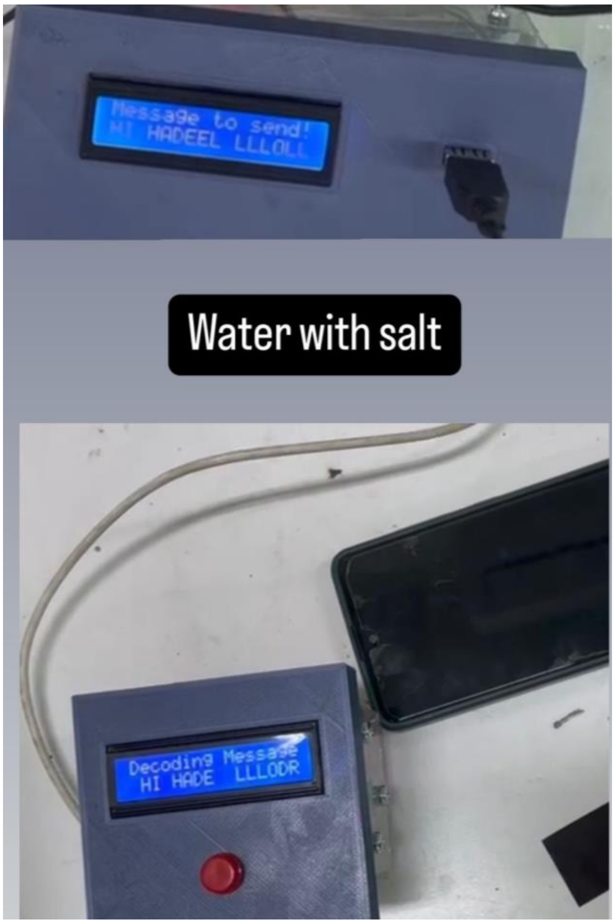
BER =(13/16)*100= 81.25%

Hardware and result:




Message to send!
ASDFGHJKLQWERTYU
Pure water
Decoding Message
ASDFGHJKLQWERTO

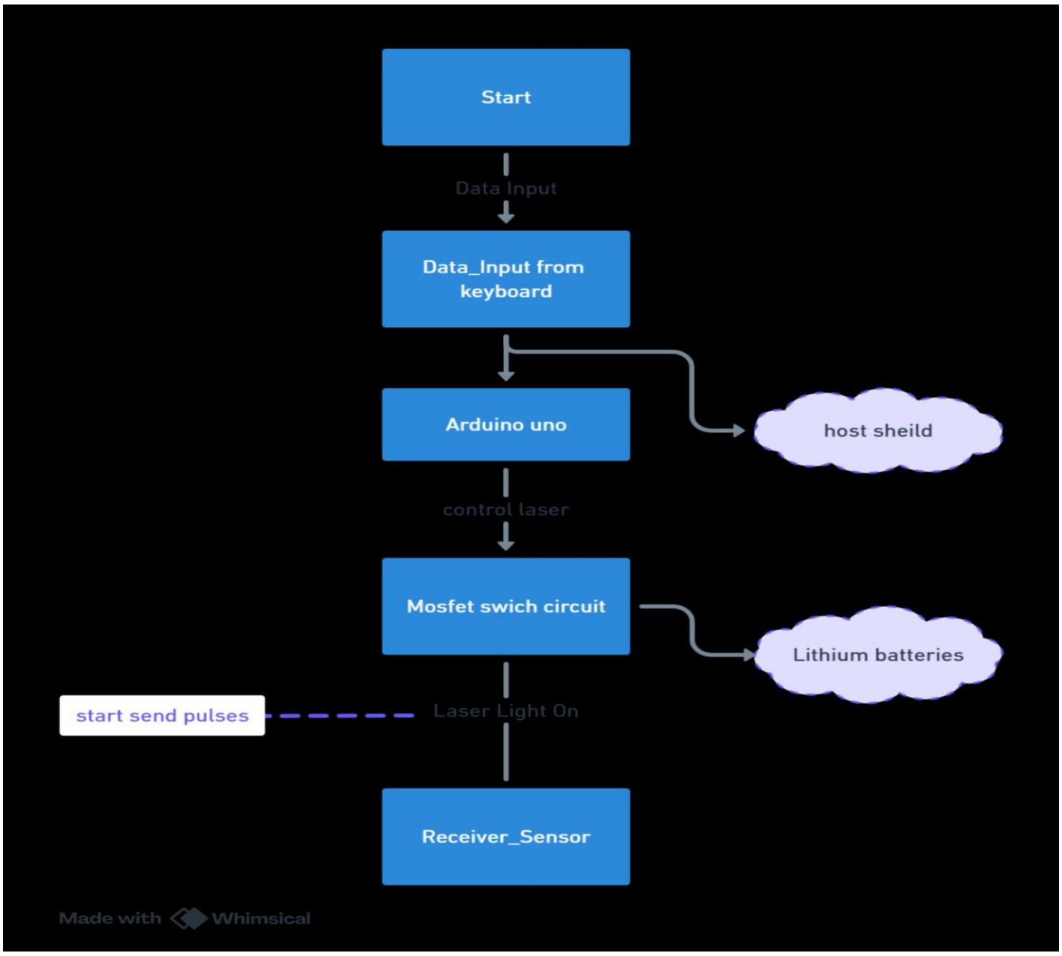

Message to send!
HI SUB ONE
pure water
Decoding Message
HI SUB ONE


Message to send!
HI HADEEL LLLOLL
Water with salt
Decoding Message
HI HADE LLLODR

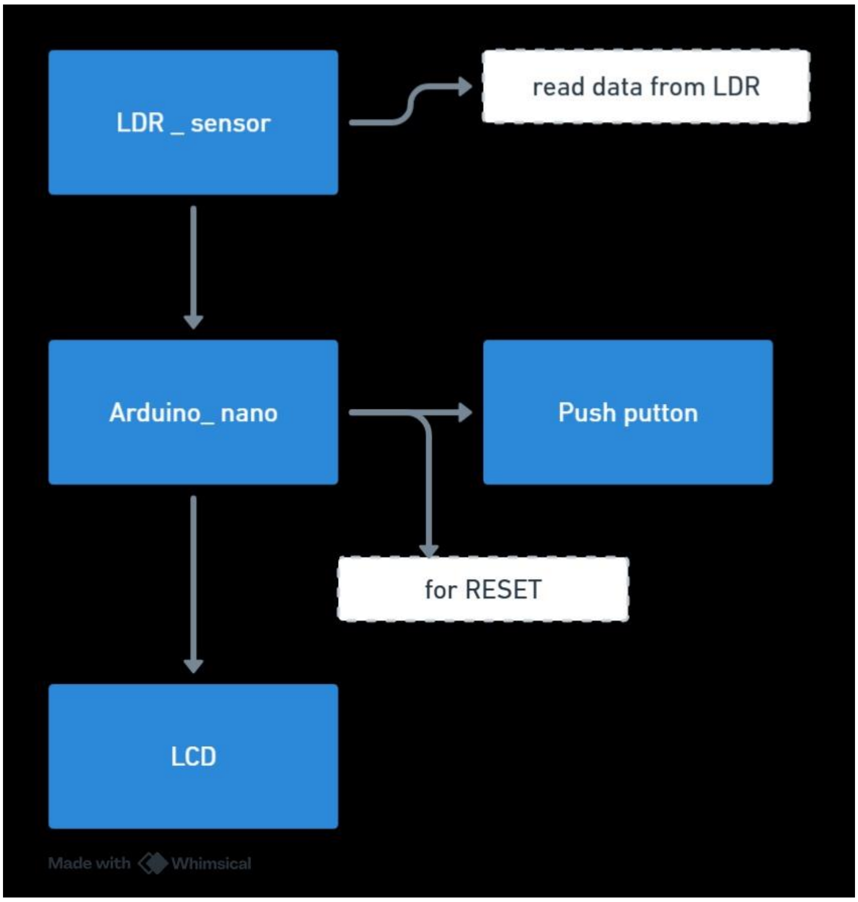

Message to send!
HI SUBMARINE ONE
مع رواسب بعد الترسيب
Water, salt and dirt
Decoding Message
SUB

6.3 Block Diagram

In the transmitter:



In the recriver:



6.4 Hardware Design

6.4.1 Hardware Design TX

Keyboard: To enter data, its type is text (uppercase letters).

2- Mosfet Circuit

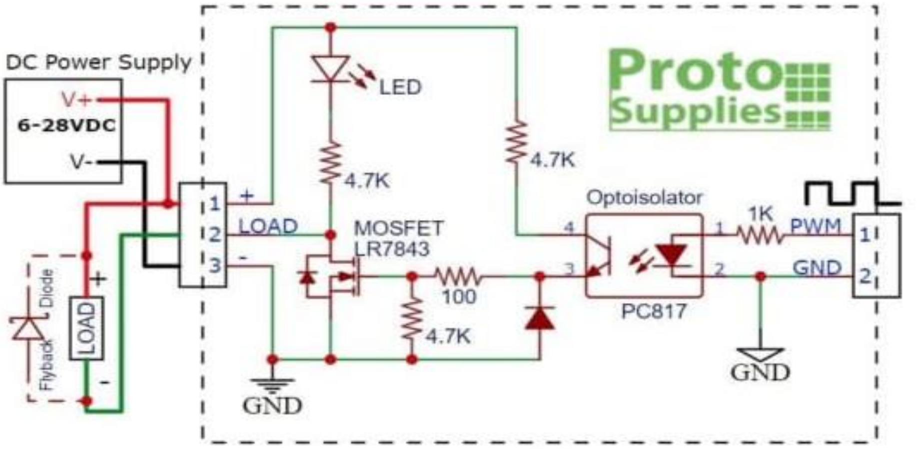
The circuit serves as a **driver circuit** for a laser module, modulating the laser's output intensity based on the input data signal (provided as a PWM signal). This allows the laser to transmit encoded data.

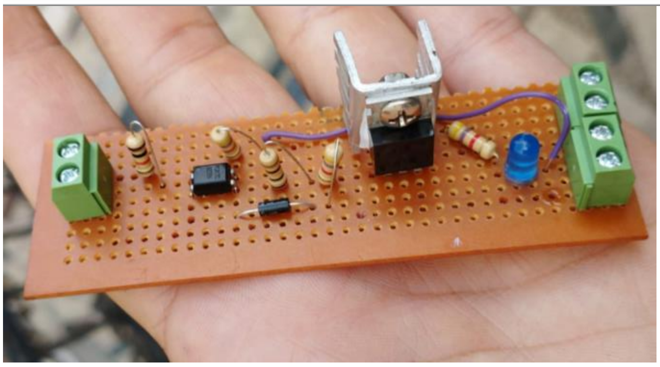
Working Principle:

1. **Data Input as PWM Signal**:
    - The input data is converted into a pulse-width-modulated (PWM) signal. The PWM signal represents the data to be transmitted.
    - This PWM signal is applied at the **PWM input pin** of the circuit.
2. **Optoisolator for Signal Isolation**:
    - The optoisolator (PC817) isolates the PWM input signal (from the controller or microcontroller) from the high-power circuit driving the laser.
    - The LED inside the optoisolator lights up based on the PWM duty cycle, causing the phototransistor inside to conduct.
3. **Laser Control via MOSFET**:
    - The phototransistor in the optoisolator drives the gate of the MOSFET (LR7843), turning it ON or OFF based on the input PWM signal.
    - When the MOSFET is ON, current flows from the DC power supply through the laser module, powering it.

- The PWM signal's duty cycle determines the laser's ON/OFF timing, effectively modulating the laser output to encode data.

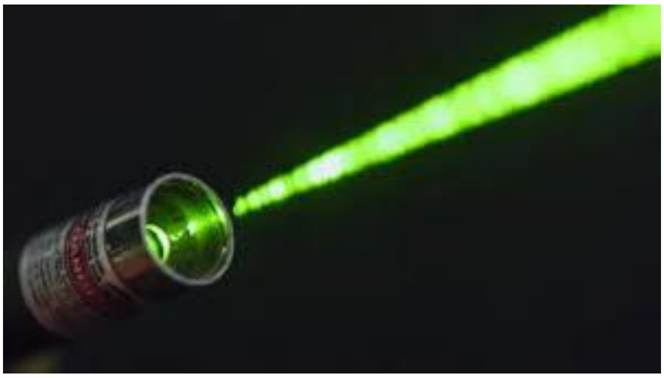
4. **Load as Laser Module**:
    - In this project, the "load" in the circuit is the **laser module**. The laser operates with a controlled current from the DC power supply.
    - The laser's light intensity changes in synchronization with the PWM input signal, allowing data to be transmitted as modulated laser pulses.
5. **Flyback Diode Protection**:
    - If the laser module has inductive components, the flyback diode protects the MOSFET and other components from voltage spikes when the circuit switches OFF.
6. **Indicator LED**:
    - The LED in parallel to the optoisolator input provides a visual indication of the PWM signal activity, confirming the transmission process.





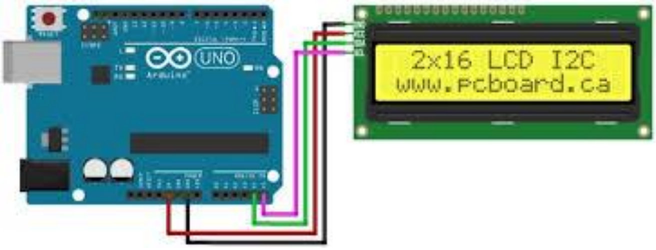
3-USB Host Shield: The function of the USB host shield is to allow communication between the main system (for example, a microcontroller like Arduino) and other devices via USB. It can be used to interface the system with other data storage devices, transmitters, or even a camera to capture data being sent via laser.

4-Laser :Laser is the component that emits a flexible and focused beam of light, and is the basis of underwater optical wireless communication. Laser is used to transmit data from the transmitter to the receiver via light. This type of communication is fast and has a high bandwidth.



5-Battery The battery provides power to all components in the system. Since the system operates in an undersea environment, constant power sources cannot be relied upon, so the battery must be powerful enough to power all components for a sufficient period of time.

6-LCD with I2C LCD with I2C protocol is used to display information needed by the user or system administrator. It can display information such as connection status, distance, or any other relevant data. I2C protocol facilitates communication between microcontroller (such as Arduino) and the LCD using only two wires (data line and ground wire), reducing wiring complexity.



Explaining how these components work together:

1-When data is sent, it is stored or transferred via the USB Host Shield to other components.

2-The MOSFET that controls the laser is turned on to emit light when data is sent.

3-The battery powers all the components.

4-Finally, the LCD displays information related to the status of the connection, such as messages or transmission status.

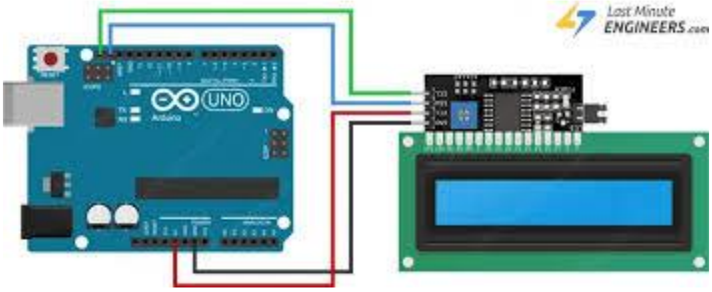
6.4.2 Hardware Design RX:

1-Light Filter: The optical filter is used to filter out the incoming light and ensure that only the desired light (such as laser light) reaches the LDR. It filters out any unwanted light interference (such as ambient light or light reflected from other objects), improving the accuracy and reception of the signal from the laser.

2-LDR Sensor: An LDR sensor is a device used to measure the intensity of light falling on it. When light from a laser reaches the sensor, its resistance changes in response to the intensity of the incoming light. By measuring the change in resistance, the system can detect the presence of a light signal and determine the intensity of the light, allowing it to read the data sent by the laser.

3-Arduino Nano: Arduino Nano is a small microcontroller, which is responsible for processing the signal received from the LDR sensor. It processes the signal and converts it into data that can be displayed or used, such as decoding the data sent via light and converting it into information that can be displayed on an LCD screen or executing commands based on pressing a push button.

4-LCD with I2CThe LCD with I2C is used to display information to the user. It can display received data such as connection status, received messages, or any important details about the system. The I2C protocol makes communication between the Arduino Nano and the LCD simple using just a few wires.



5-Push Button: A push button is used to allow the user to interact with the system. It can be used to reset the system, change the configuration mode, or start/stop a specific operation, such as receiving or sending data. Pressing the button can send certain signals to the Arduino Nano to control various actions.

How the system works together:

1-When the laser transmitter sends light through the water, the light is received at the receiver by the LDR sensor after it passes through the optical filter that removes any unwanted light.

2-The Arduino Nano processes the signal received from the LDR and decodes the data.

3-The received data is displayed on an LCD screen.

4-The user can press a push button to control system functions, such as updating the display or adjusting settings.

6.5 Software Implementation Arduino Code

6.5.1 Arduino Code TX

The software used in this project, Arduino IDE. This is an application written in C and C++ 1-MOSFET as a switch:

TX code :

```
#include <SPI.h>
#include <hidboot.h>
#include <LiquidCrystal_I2C.h>

LiquidCrystal_I2C lcd(0x27,16,4);  // set the LCD address to 0x3F for a 16 chars

int laserPin = 9; // PWM pin for the laser
char output[15];
int n = 0;
int done = 0;
String message = "";


class KeyboardHandler : public KeyboardReportParser
{

  public:
  void OnKeyDown (uint8_t mod, uint8_t key);
  void sendMessage (String message);
  void sendCharacter(char c);
};

void KeyboardHandler::OnKeyDown(uint8_t mod, uint8_t key)
{  lcd.setCursor(0,0);
   lcd.print("Message to send!");

  uint8_t c = OemToAscii(mod, key); //enter is 13
  if(c == 13){
    n=0;
    message = String(output);
    message = "S" + message + "S";
    delay(100);
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print("Sending...");
```

Transmeter.ino

```
    lcd.setCursor(0,0);
    lcd.print("Sending...");
    lcd.setCursor(0,1);
    //`lcd.print(String(message));
    Serial.println(message);
    done = 1;

    Serial.println(message);
    for(int i = 0; i< 17; i++){
      output[i] = ' ';
    }
  }

  if(c >= 65 && c <= 90 || c == 32){
  output[n+1] = '\0';
  output[n] = (char)c;
  lcd.setCursor(n,1);
  lcd.print(output[n]);
  n++;
  Serial.print(message);
  }

  if(c == 0){
    for(int i = 0; i< 17; i++){
      output[i] = ' ';
    }
  }
}

void KeyboardHandler::sendMessage(String message) {
  for (int i = 0; i < message.length(); i++) {
    char c = message.charAt(i);
    sendCharacter(c);
  }
}
```

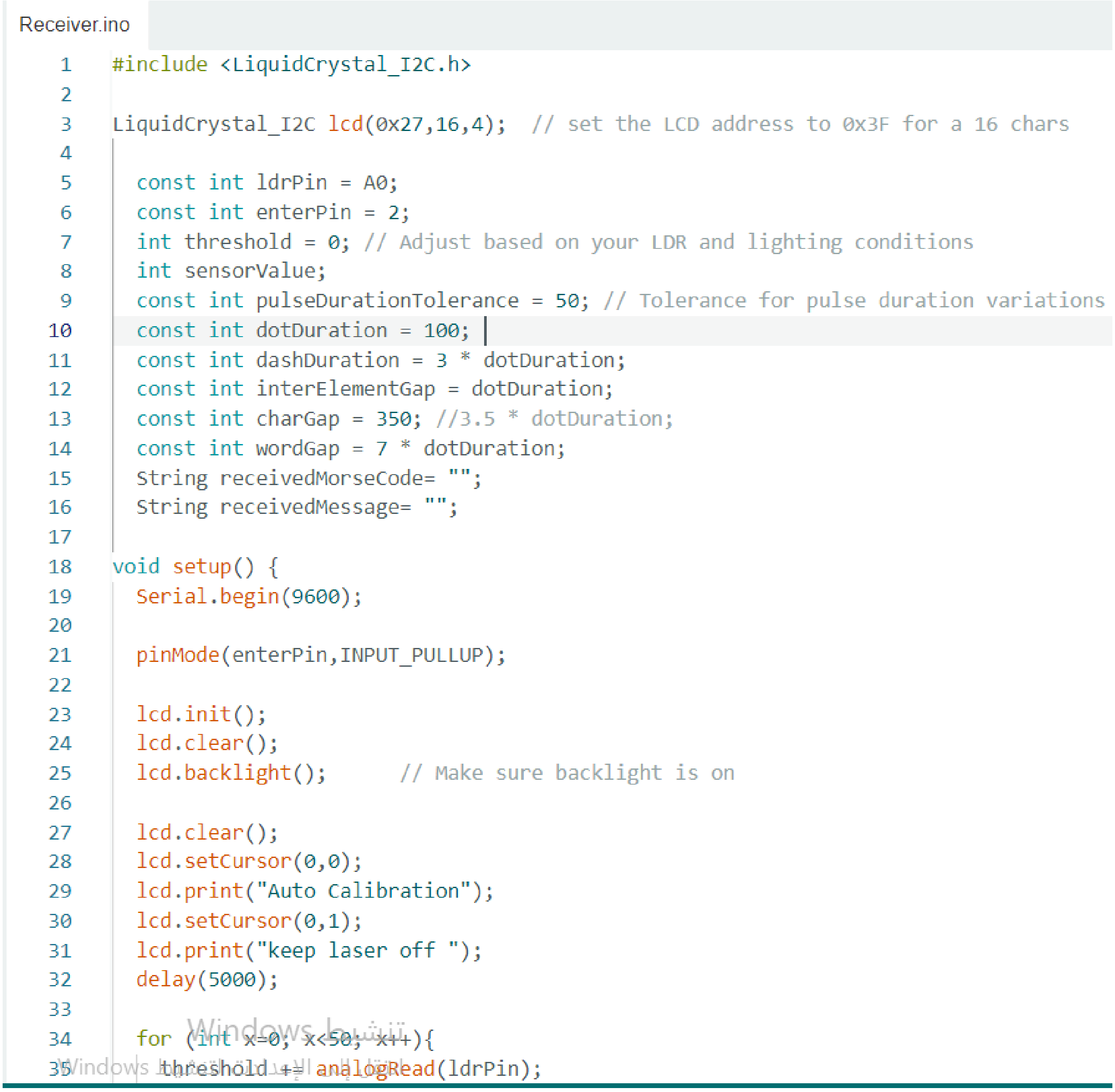
```
void KeyboardHandler::sendCharacter(char c) {
  pinMode(laserPin, OUTPUT);
  // Define durations for dots and dashes (adjust as needed)
  const int dotDuration = 100;
  const int dashDuration = 3 * dotDuration;
  const int interElementGap = dotDuration;
  const int charGap = 3 * dotDuration;
  const int wordGap = 7 * dotDuration;

  // Morse code representation (example)
  String morseCode[26] = {".-", "-...", "-.-.", "-..", ".", "..-.", "--.",
                          "....", "..", ".---", "-.-", ".-..", "--", "-.",
                          "---", ".--.", "--.-", ".-.", "...", "-", "..-",
                          "...-", ".--", "-..-", "-.--", "--.."};

  // Get Morse code for the character
  String charMorse = morseCode[c - 'A'];

  // Send Morse code signals
  for (int i = 0; i < charMorse.length(); i++) {
    if (charMorse[i] == '.') {
      digitalWrite(laserPin, HIGH);
      delay(dotDuration);
      digitalWrite(laserPin, LOW);
      delay(interElementGap);
    } else if (charMorse[i] == '-') {
      digitalWrite(laserPin, HIGH);
      delay(dashDuration);
      digitalWrite(laserPin, LOW);
      delay(interElementGap);
    }
  }
```

6.5.2 Arduino Code RX



```
#include <LiquidCrystal_I2C.h>

LiquidCrystal_I2C lcd(0x27,16,4);  // set the LCD address to 0x3F for a 16 chars

  const int ldrPin = A0;
  const int enterPin = 2;
  int threshold = 0; // Adjust based on your LDR and lighting conditions
  int sensorValue;
  const int pulseDurationTolerance = 50; // Tolerance for pulse duration variations
  const int dotDuration = 100;
  const int dashDuration = 3 * dotDuration;
  const int interElementGap = dotDuration;
  const int charGap = 350; //3.5 * dotDuration;
  const int wordGap = 7 * dotDuration;
  String receivedMorseCode= "";
  String receivedMessage= "";

void setup() {
  Serial.begin(9600);

  pinMode(enterPin,INPUT_PULLUP);

  lcd.init();
  lcd.clear();
  lcd.backlight();      // Make sure backlight is on

  lcd.clear();
  lcd.setCursor(0,0);
  lcd.print("Auto Calibration");
  lcd.setCursor(0,1);
  lcd.print("keep laser off ");
  delay(5000);

  for (int x=0; x<50; x++){
    threshold += analogRead(ldrPin);
```

```
  threshold += analogRead(ldrPin);
  delay(50);
}
threshold = threshold/50;
threshold = abs(threshold-50);

lcd.clear();
lcd.setCursor(0,0);
lcd.print("Threshold: " + String(threshold));
delay(3000);

lcd.clear();
lcd.setCursor(0,0);
lcd.print("Calibrate laser");
lcd.setCursor(0,1);
lcd.print("to hit LDR core");

digitalRead(enterPin);
while(digitalRead(enterPin)){
  delay(100);
}

lcd.clear();
lcd.setCursor(0,0);
lcd.print("Add Light Filter");
delay(1000);

digitalRead(enterPin);
while(digitalRead(enterPin)){
  delay(100);
}
lcd.clear();
delay(3000);
```

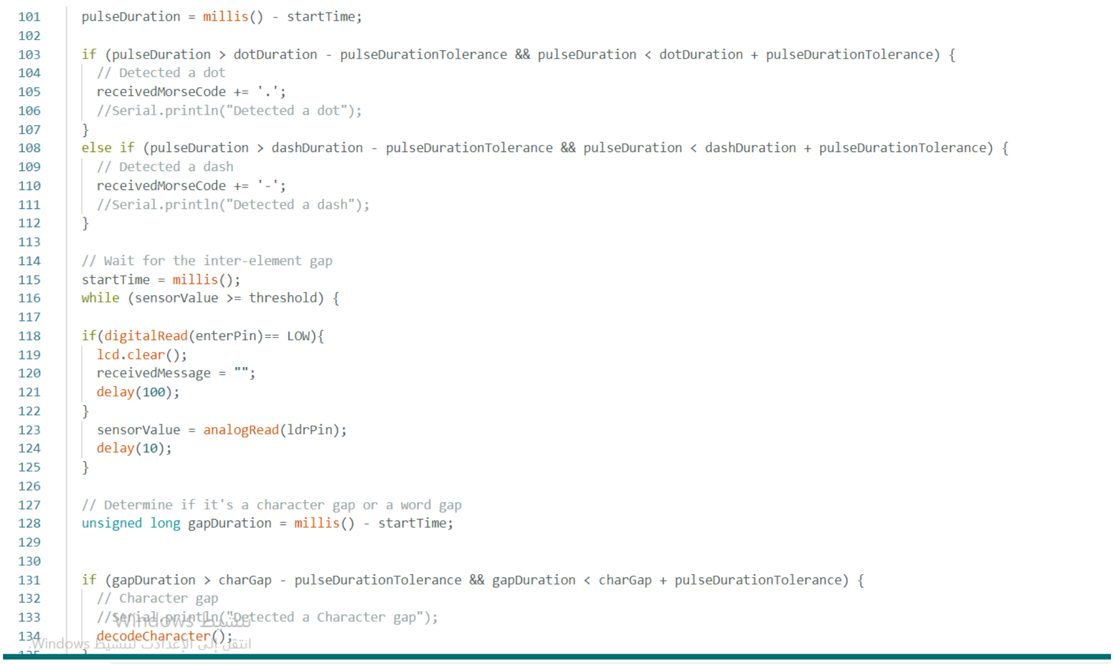
```
void loop() {
  sensorValue = analogRead(ldrPin);
  if (sensorValue < threshold) {
    lcd.setCursor(0,0);
    lcd.print("Decoding Message");
    // Laser detected
    decodeMorseCode();
  }
  lcd.setCursor(0,1);
  lcd.print(receivedMessage);
  Serial.print("Received message: ");
  Serial.println(receivedMessage);
}

void decodeMorseCode() {
  unsigned long startTime = millis();
  bool isPulse = true;
  unsigned long pulseDuration;

  while (sensorValue < threshold) {

  if(digitalRead(enterPin)== LOW){
    lcd.clear();
    receivedMessage = "";
    delay(100);
  }
    sensorValue = analogRead(ldrPin);
    delay(10); // Short delay to avoid rapid readings
  }

  pulseDuration = millis() - startTime;
```



```
pulseDuration = millis() - startTime;

if (pulseDuration > dotDuration - pulseDurationTolerance && pulseDuration < dotDuration + pulseDurationTolerance) {
  // Detected a dot
  receivedMorseCode += '.';
  //Serial.println("Detected a dot");
}
else if (pulseDuration > dashDuration - pulseDurationTolerance && pulseDuration < dashDuration + pulseDurationTolerance) {
  // Detected a dash
  receivedMorseCode += '-';
  //Serial.println("Detected a dash");
}

// Wait for the inter-element gap
startTime = millis();
while (sensorValue >= threshold) {

if(digitalRead(enterPin)== LOW){
  lcd.clear();
  receivedMessage = "";
  delay(100);
}
  sensorValue = analogRead(ldrPin);
  delay(10);
}

// Determine if it's a character gap or a word gap
unsigned long gapDuration = millis() - startTime;


if (gapDuration > charGap - pulseDurationTolerance && gapDuration < charGap + pulseDurationTolerance) {
  // Character gap
  //Serial.println("Detected a Character gap");
  decodeCharacter();
```

```
  }
  else if (gapDuration > wordGap - pulseDurationTolerance && gapDuration < wordGap + pulseDurationTolerance) {
    // Word gap
    //Serial.println("Detected a Word gap");
    decodeCharacter();
    receivedMessage += ' ';
  }
}

void decodeCharacter() {
  // ... (Morse code to character decoding logic here) ...
  String morseCodeTable[26] = {".-", "-...", "-.-.", "-..", ".", "..-.", "--.",
                               "....", "..", ".---", "-.-", ".-..", "--", "-.",
                               "---", ".--.", "--.-", ".-.", "...", "-", "..-",
                               "...-", ".--", "-..-", "-.--", "--.."};
Serial.print("decodeCharacter()");
  char decodedChar = ' ';

  for (int i = 0; i < 26; i++) {
    if (receivedMorseCode == morseCodeTable[i]) {
      decodedChar = 'A' + i;
      break;
    }
  }
  receivedMessage += decodedChar;
  receivedMorseCode = "";

    digitalRead(enterPin);
  if(digitalRead(enterPin)== LOW){
    lcd.clear();
    receivedMessage = "";
    delay(100);
  }
}
```

6.5.3 Morse Code:

We used the **Morse Code** technique for encoding messages, where text is converted into sequences of dots and dashes. For **PWM (Pulse Width Modulation)**, we employed this technique for modulation to control the laser signal, turning it on and off in a pattern that corresponds to the timing of the dots and dashes in the Morse code.

1. Morse Code:

Morse code is one way of encoding text into a series of short signals (dots) and long signals (dashes). Each letter or number has a unique combination of these signals. It finds its applications primarily in communication systems, especially when verbal communication is not possible, such as radio transmissions or light signaling.

Dot (.): A short signal.

Dash (-): A long signal.

Character spacing: Time between dots and dashes of the same character is equal to The gap between the words is seven times the duration :dot duration. Word spacing of a dot normally.

The Morse code in this project is used to encode the message into a series of dots and dashes that can be transmitted using a laser. For example, the letter "A" would be represented as.-, while the letter "B" would be -.

2. How Morse code Works in the Project:

In this project, the text message - such as a word or sentence - is first converted into Morse code. Each character in the message is translated into a series of dots and dashes. These signals are then sent using a laser via PWM - Pulse Width Modulation.

3. Pulse Width Modulation (PWM):

PWM is a technique of getting electrical signals by changing the time of "on" (HIGH) and "off" (LOW) in one cycle of the signal.

How PWM Works:

Duty Cycle: It is the percentage of time the signal is "on" (HIGH) during one cycle. For example, if the signal is HIGH for 50% of the time, then the duty cycle is 50%.

PWM works on the principle that a device - in this instance, a laser - can have its power moderated by pulsing the width - the length of time - the signal is in either a HIGH or LOW state.

:Application of PWM for Laser Control

Dot (.): To send a dot in Morse code, we set the PWM such that it turns the laser on for a very short time-for example, 100 milliseconds-and then off for a short time.

Dash (-): While sending a dash, we set PWM such that it keeps the laser on for a longer time-for example, 300 milliseconds-and then turns it off.

Frequency and Timing: Every element of Morse code requires exact timing, either a dot or a dash. In PWM, the timing is crucial for how long the laser is on or off. For example:

The dot will be a brief period of light (laser on for a short time).

The dash will be a longer period of light (laser on for a longer time).

4. How Morse code and PWM Work Together:

Steps:

Conversion to Morse code The text which needs to be transferred is first of all written as its Morse code form. Example The word "HELLO" can be transfigured like this,

H:.

E:.

L:.-.

L:.-.

O: ---

Send the Data via the Laser:

Every Morse code symbol is converted into light signals (laser on/off).

Dots (.) are converted into short light pulses with PWM.

Dashes (-) are converted into longer light pulses with PWM.

Laser Drive w/ PWM the time-dot or dash-is the basis of a laser pulse, driving this through the PWM module. A simple timing rule can be taken to a Morse code element-dot and dash:

Dot: This is a short opening of the laser.

Dash: The laser is kept open longer than usual.

Laser Off Between Symbols: Between each symbol in Morse code, there is a small gap, or pause, and between words, there is a longer gap to separate the words.

5. Receiving and Decoding the Data:

Sensor: A sensor is placed to receive the laser light.

Decoding: After the light signals are received, the system decodes them using a microcontroller (like Arduino) and converts the signals back into text.

Why PWM is used for Laser Control:

Many different reasons point towards PWM as an ideal controlling method for the laser in this project; most of them relate to:

Accurate Control: PWM allows precise control over the on-time of the laser-a prerequisite in sending accurate Morse code.

Energy Efficiency: By turning the laser on and off rapidly, PWM allows the laser to use power only when it must.

Ease of Use: PWM is quite easy to generate, especially with microcontrollers such as Arduino. It's one of the practical ways through which devices such as lasers can be controlled.

Summary:

Morse code: Used to encode the message into dots and dashes.

PWM: Used to control the laser by turning it on and off for specific durations to match the timing of the dots and dashes.

Laser: Used as a source of light to represent the Morse code.

We can combine Morse code and PWM to transmit messages using light signals-laser-that can be decoded at the receiving end.

6.6 Rules and Limitations

Requirements

Working on the reliance of IEEE standards and international standards concerning optical communications is basically because of the ignorance of the research being carried out on standards and protocols in the field of underwater optic communication using lasers. To transform this conception into an industrial form, we would implement the following process:

The base for developing laser-based optical communication systems will be the IEEE 802.3 Ethernet Standard, modified to account for underwater conditions of light scattering and signal loss.

The ITU-T G.975 Standard lays down error correction methods and optical signal management in order to serve practical data transmission in aquatic environments.

The ISO/IEC 11801 Standard concerns the design of underwater laser systems and stipulates standards for optical communications.

Constraints

Economic Constraints: The limited budget was the major economic constraint. This is because a few specialized suppliers characterize this field of work, hence making the high-quality laser system components, such as underwater lasers and optical sensors very expensive. Furthermore, the current harsh economic situation made it difficult to obtain sufficient funding to acquire the necessary equipment.

Manufacturing constraints: The design was realized in a prototype, but we faced problems with the performance we were targeting because there was a shortage of special optical instruments whose building could stand strong in high underwater pressure. In addition to this, the aquatic medium imposes resistance against corrosion and pressure; thus, the materials were at odds with manufacturing.

Chapter7: Economical Feasibility

In-water optical communication using laser technology has promising economic viability despite there being considerable initial costs regarding equipment, submersible platforms, and deployment. While the high speed and huge bandwidths-carrying capability of the system certainly marks notable merits compared to traditional techniques, operational costs can also mount up - for example, regarding maintenance and energy consumption. Although environmental issues and technical developments carry with them certain risks, potential cost savings via reduced infrastructure and scalability in the long term make it a sweet deal for niche companies in particular, with the advancement and improvement of laser technology.

7.1 Cost analysis:

The fact that underwater optical communication using laser technology is overall more expensive compared to other, more traditional methods of communication, such as acoustic or radio frequency systems, is hindering its market growth.

The benefits it can offer in conditions other than these include higher data transfer rates, low latency in connectivity, and less infrastructure. The initial cost of this technology is well worth it for the potential gain in efficiency in undersea research, exploration, and military operations..

Component	**#OF**	**price (ILS)**	**Total**
LCD	**2**	**60**	**120**
Urduino Nano	1	30	30
Urduino uno	1	40	40
keyboard	1	20	20
UBS host shield	1	50	50
UBS male to female	1	20	20
Fiber glass	1	30	30
Metal connection	1	15	15
Bolts and nuts	1	20	20
Wires	1	25	25
3d parinted covers (70g)	1	50	50
Glass basin	1	200	200
Light filter	1	3	3
Push button	1	10	10
LDR sensor	1	10	10
Mosfet switch circuit:			
Lithium battery	2	30	60
Charging adapter	1	30	30
LED	1	2	2
Resistor 4.7K	2	3	3
Optoisolator (PC817)	1	5	5
MOSFET (LR7843)	1	10	10
Resistor 1K	1	3	3
Resistor 100	1	2	2
Soldering iron	1	10	10
Flyback Diode	1	5	5
Laser pin	1	50	50
Woden base	1	100	100
	1	10	10
Total Cost			750

7.2 Effect on Society:

Lasers-based underwater optical communication can bring a sea change in a number of diversified industries. The main social contribution of improved underwater communication is the improvement in communication networks for military, research, environmental monitoring, and subsea exploration. The clear, quick, and more reliable means of communication this technology will provide could make underwater navigation more secure and efficient, further scientific understanding of marine ecosystems, and develop new technologies in energy sectors such as offshore drilling and renewable ocean energy projects.

The potential contributions to disaster response systems are not negligible either. For example, improved communication during rescue operations using UUVs or submarines would save lives. Equally important, this would enable environmental organizations to increase awareness and sustainability through better monitoring of pollution and protecting marine life that is considered in danger.

7.3 Market Growth

The underwater laser optical communication market will see high growth with expansions in the marine research, oil, and gas exploration, and defense industries. Some of the key industries that may use this technology include:

1. Defense & Security: Overall enhancement in military communication networks, submarine data transmission, and underwater monitoring.
Oil & Gas: Larger capacity for transportation and communication of data between subsea systems and offshore rigs.
2. Marine Research: Oceanographic researchers will be able to transmit data in real time from underwater instruments, hence resulting in more precise environmental monitoring.

3. Telecommunication: Underwater communication lines can be upgraded for quicker and more secure data transfer.
With growing emphasis on marine research and preservation of marine habitats by nations and organizations, the need for effective underwater communication is expected to increase, hence opening up new opportunities in

7.4 Profitability Objectives:

By addressing these major areas, the following profitability objectives of the project can be realized:

1. High-Tech Equipment Design and Sales: The sale of communication systems to industries like oil and gas, marine research, and defense.
2. Communication Services: Subscription-based services to companies that need secure underwater data exchange.
3. Technology Licensing: Licensing of the technology to foreign entities for upgrading their underwater communication infrastructure.
4. Partnerships: In collaboration with private sector enterprises and governments to lay down extensive undersea communication networks that would ensure regular streams of income.

Thus, government contracts and commercial prospects put together will help the project achieve long-term profitability and ensure the advancement of undersea communications technology.

7.5 Cost Comparison between Underwater Laser Communication and Conventional Acoustic Communication:

In general, the initial cost of underwater laser communication systems is higher than that of conventional acoustic communication systems. This is attributed to the high level of development in laser technology, optical components, and equipment. However, benefits such as higher data transfer speeds, energy efficiency, and reduced interference might justify the higher costs for applications needing faster and more secure communication, including marine research, military, and underwater vehicles.

Aspect	Underwater Optical Communication (Laser)	A Traditional Underwater Communication (Acoustic)
Cost	Higher initial cost(laser equipment and setup)	Lower initial cost (well-established technology)
Data Transfer Speed	Higher (high-bandwidth, faster data transmission	Lower (limited bandwidth, slower transmission)
Range	Poor to limited range affected by water clarity and absorption	Longer range affect with less stress based on water clarity
Energy efficiency	More energy-efficient(especially in short distance)	Less efficient(requires more power over long distances)
Technology	Advanced(laser, optical system and electronic)	Basic (uses sound waves, established technology)
Application	Marine research, military, underwater vihecles,AUVs,ROVs	Submarine communication, underwater sensors network
Market growth	Expected to grow (increasing interest in high speed underwater communication)	Stable (well established, but slower growth)
innovation	High(ongoing advancements in laser technology, optics and materials)	Low to moderate(mainly in sensor development, limited innovation in acoustics)

7.6 SWOT analysis for the Underwater Optical Communication using Laser Project:

Strengths:

1- High Data Transfer Rates: It allows for high-speed and high-capacity data transmission.
2- Low Power Consumption: Most energy-efficient than other methods of communication.
3- Low Interference: Not much interference from any external sources.
4- Precision and Security: Accurate and secure forms of communication.
5- Compact Equipment: The system can be fitted into compact equipment suitable for underwater application.

Weakness:

1- Limited Range: Absorption and scattering in water limit its range as the signal gets affected.
2- Line-of-Sight: Requires a line-of-sight between transmitter and receiver.
3- Environmental Sensitivity: Turbidity and water conditions affect signal strength.
4- High Cost: Laser technology and other optical components are very costly.
5- Alignment Sensitivity: Transmitter and receiver alignment must be accurate.

Opportunities:

1-Advancements in Technology: Technological improvements might allow for better performance and longer distances.

2-Marine Research and Exploration: Large scope in oceanographic research.

3-Military and Defense Applications: The system could also be used in secure communications for military underwater vehicles. Commercial Applications: Usage in oil, gas, and other underwater industries.

4- Integration with Autonomous Systems: Improvement in communication with autonomous underwater vehicles.

Threats:

1- Competition from Other Technologies: On longer distances, acoustic communication is still ahead.

2-Environmental Impact: Environmental changes may affect signal quality. Regulatory Issues: The system may face challenges in getting regulatory approval.

3- Technological Barriers: The system still needs improvement to overcome limitations.

4-High Maintenance Costs: The system is sensitive, hence requiring frequent maintenance.

7.7 Conclusions and Recommendations for Underwater Laser Communication

7.7.1 Conclusions

The underwater laser communication project faced challenges such as high initial costs, limited range due to water clarity, and alignment issues. However, it successfully demonstrated the potential for high-speed, secure communication in specific applications like marine research and underwater vehicles. Laser communication offers advantages like faster data transfer and lower power consumption, but environmental factors remain a limitation.

7.7.2 Recommendations

1. **Thorough Research**: Investigate environmental factors and system requirements early to ensure the appropriate technology is selected.
2. **Prototyping**: Conduct small-scale prototypes and real-world testing to identify technical issues early.
3. **Energy Efficiency**: Prioritize low-power systems, especially for underwater vehicles with limited energy.
4. **Alternative Technologies**: Explore combining laser with acoustic or other communication methods for more reliable long-range performance.

5. **Cost Management**: Source components locally where possible to reduce import costs and streamline the procurement process.

By addressing these points, future projects can improve reliability, reduce costs, and expand applications.

Future work:

Advanced technology projects that can be improved and developed in several ways include the underwater optical communication project using lasers. Here are some ideas that can be used to improve and develop the system:

1. Error detection techniques using artificial intelligence:

Error detection and correction: AI algorithms can automatically detect errors in the signal and analyze the resulting data. Deep learning techniques recognize patterns resulting from interference or noise as an error.

Machine learning to improve performance: Models trained on real data analyze and predict errors before they actually occur to reduce downtime and improve communication quality.

2. Transformational modulation techniques:

Multilevel modulation: Advanced modulation techniques, such as phase shift modulation (QAM) or multiple signal key modulation (PSK), can be implemented to enhance data transmission efficiency and thus communication speed.

Orthogonal frequency division modulation (OFDM): OFDM, a type of signal division into different frequency bands, can be applied to reduce interference and enhance stability in communications.

Optical modulation: Developing optical modulation techniques that can reduce signal degradation in the aquatic environment, allowing data to travel longer distances.

3. Leveraging advanced sensing:

Vibration and noise sensing: Sensing mechanisms can be installed to measure vibrations or noise that may affect the system and adjust the data transmission method or enhance the signal in real time.

Aquatic environment sensing: Integrating environmental sensing technologies such as temperature, pressure, and salinity will help improve the system performance and adjust it according to the changing conditions within the aquatic environment.

4. Enhancing system sustainability:

It can be developed using low-power consumption technologies, such as low-power laser systems, supported by energy consumption control technologies such as intelligent power management algorithms. The system status can be continuously monitored to predict failure before it occurs through continuous monitoring and data analysis technologies, thus increasing the reliability of the system. 5. Increasing resistance to environmental effects:

Adaptation to the marine environment: Since the marine environment contains many obstacles such as scattering and absorption resulting from water, the system can be improved using laser technologies with appropriate frequencies that suit the nature of the water.

Using mirrors and cooling equipment: Optimizing the system using special mirrors or cooling technologies to reduce environmental effects that may aggravate the signal.

Project Demo :

https://drive.google.com/drive/folders/1R8_hjL-xUB0xuoT0TzNwh19ASY3S-iiD?usp=sharing

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