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Underwater Optical Wireless Communication

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ABSTRACT Underwater wireless information transfer is of great interest to the military, industry, and the scientific community, as it plays an important role in tactical surveillance, pollution monitoring, oil control and maintenance, offshore explorations, climate change monitoring, and oceanography research. In order to facilitate all these activities, there is an increase in the number of unmanned vehicles or devices deployed underwater, which require high bandwidth and high capacity for information transfer underwater. Although tremendous progress has been made in the field of acoustic communication underwater, however, it is limited by bandwidth. All this has led to the proliferation of underwater optical wireless communication (UOWC), as it provides higher data rates than the traditional acoustic communication systems with significantly lower power consumption and simpler computational complexities for short-range wireless links. UOWC has many potential applications ranging from deep oceans to coastal waters. However, the biggest challenge for underwater wireless communication originates from the fundamental characteristics of ocean or sea water; addressing these challenges requires a thorough understanding of complex physio-chemical biological systems. In this paper, the main focus is to understand the feasibility and the reliability of high data rate underwater optical links due to various propagation phenomena that impact the performance of the system. This paper provides an exhaustive overview of recent advances in UOWC. Channel characterization, modulation schemes, coding techniques, and various sources of noise which are specific to UOWC are discussed. This paper not only provides exhaustive research in underwater optical communication but also aims to provide the development of new ideas that would help in the growth of future underwater communication. A hybrid approach to an acousto-optic communication system is presented that complements the existing acoustic system, resulting in high data rates, low latency, and an energy-efficient system.

INDEX TERMS Underwater optical wireless, optical beam propagation, visible light, radio frequency, acoustic communication, hybrid optical-acoustic system, modulation and coding.

I. INTRODUCTION

In the last few years, the interest towards optical wireless communication has increased for terrestrial, space and underwater links as it is capable of providing high data rates with low power and mass requirement. Many of researchers have carried out work for terrestrial and space links [1]–[6], however underwater optical wireless links are relatively less explored as it is more challenging than atmospheric links. The significant hurdle for reliable underwater communication is due to wide range of physical processes in various types of underwater environments ranging from shallow coastal water to deep sea or oceans. The present technology uses acoustic waves for underwater communication whose performance is limited by low bandwidth, high transmission losses, time varying multipath propagation, high latency and Doppler spread. All these factors lead to temporal and spatial variation of acoustic channel which ultimately limits the available bandwidth of the system. The current available underwater acoustic communication can support data rate up to tens of kbps for long distances (ranging in kms) and up to hundreds of kbps for short distances (few meters). Depending upon the transmission distance, acoustic link is classified as very long, long, medium, short and very short links. Table 1 provides a typical bandwidth for various underwater acoustic communication links with different ranges.

However, various underwater vehicles, sensors and observatories require a communication link with data rates ranging from few to tens of Mbps. In case of large and stationary devices, fiber optic or copper cables are used to achieve high data rates but they require significant engineering and maintenance issues. In case of moving platforms, a good alternative is a wireless link with high

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TABLE 1. Typical bandwidth for different ranges in underwater acoustic links [7]–[10] ("*" implies dependence on water type, range, horizontal/slant transmission).

Distance	Range (km)	Bandwidth (kHz)	Data Rate*
Very long	1000	< 1	~ 600 bps
Long	10 - 100	2 - 5	~ 5 kbps
Medium	1 - 10	≈ 10	~ 10 kbps
Short	0.1 - 1	20 - 50	~ 30 kbps
Very short	< 0.1	> 100	~ 500 kbps

data rates. Electromagnetic (EM) waves, in the radio frequency (RF) range, is a good option for underwater wireless communication when used for high data rate transfer in short distances. The speed of EM waves mainly depends upon permeability (μ), permittivity (ϵ), conductivity (σ) and volume charge density (ρ) which varies according to the type of underwater conditions and frequency being used. It has been observed that attenuation of RF waves increases with the increase in frequency and are heavily attenuated by sea water. Optical waves on the other hand have high bandwidth but they are affected by other propagation effects due to temperature fluctuations, scattering, dispersion and beam steering. Wireless underwater communication is limited to short distances due to severe water absorption at optical frequency band and strong back scatter from suspended particles. However, there is a relatively low attenuation optical window of blue-green wavelengths of EM spectrum underwater. For this reason, UOWC has observed a surge in interest from development of blue-green sources and detectors. The blue-green wavelengths are capable of proving high bandwidth communication over moderate ranges (up to 100s of meters). A comparison between different wireless underwater technologies is presented in Table 2. A more extensive discussion and comparison of underwater communication systems with their pros and cons is found in [11].

A. AIM AND SCOPE OF THE SURVEY

This survey aims to provide an overview of various challenges and current technologies used in UOWC system. Various experiments, future perspectives, and applications are presented in this paper. Through this paper, the author is highlighting the relatively less explored technology of UOWC which is a potential alternative solution for low cost and less powered devices. The scope of this survey is to determine the performance of UOWC system for variety of underwater environments and develop a realistic system design model for underwater optical channel. This paper focuses on various interesting features in rapidly varying underwater channel that affects the reliability and feasibility of underwater optical communication link. Various technologies that improve the efficiency of UOWC system such as hybrid acousto-optic system and cooperative diversity are also discussed in this paper. These technologies not only provide an energy efficient system but also improves the capacity and range for the applications that demands real time video streaming via underwater network.

B. RELATED SURVEYS AND PAPER CONTRIBUTION

Lot of literature is available for the advancement of underwater acoustic communication but very less work is available for UOWC. The literatures that are available for UOWC does not provide a holistic coverage of the topic. In [15], the author focused on communication link models by providing the link performance based on these models. A report by D. Anguita et al. [16] highlights the prospects and problems of optical wireless communication for applications in the field of sensor networks. In [17], the author highlighted the measuring techniques in oceanic optical properties but it lacks to provides the readers with basic background in UOWC. In [18], the author focused on the underwater

TABLE 2. Comparison of different wireless underwater technologies.

Parameters	Acoustic	RF	Optical
Attenuation	Distance and frequency dependent (0.1 - 4 dB/km) [12]	Frequency and conductivity dependent (3.5 - 5 dB/m) [13]	0.39 dB/m (ocean) - 11 dB/m (turbid) [14]
Speed (m/s)	1500 m/s	$\approx 2.255 \times 10^8$	$\approx 2.255 \times 10^8$
Data rate	~ kbps	~ Mbps	~ Gbps
Latency	High	Moderate	Low
Distance	up to kms	up to ≈ 10 meters	≈ 10 - 100 meters
Bandwidth	Distance dependent [8]: 1000 km < 1kHz 1 - 10 km ≈10 kHz < 100 m ≈ 100 kHz	≈ MHz	10 - 150 MHz
Frequency band	10 - 15 kHz	30 - 300 Hz (ELF) (for direct underwater communication system) or MHz (for buoyant communication system)	10^{12} - 10^{15} Hz
Transmission power	tens of Watts (typical value)	few mW to hundreds of Watts (distance dependent)	Few Watts
Antenna size	0.1 m	0.5 m	0.1 m
Efficiency	≈ 100 bits/Joules		≈ 30, 000 bits/Joules
Performance parameters	Temperature, salinity and pressure	Conductivity and permittivity	Absorption, scattering/turbidity, organic matter

optical channel model for use by wireless communication systems. They defined the inherent and apparent optical properties to differential between various water types. With this survey, we hope to provide the readers with the complete resource and the current achievements in the area of UOWC. In this survey, our contributions are follows:

(I) Providing the readers with strong and coherent understanding of underwater optical channel and its research challenges
(II) Summarizing various UOWC systems demonstrated till 2015 by presenting their system parameter description
(III) Giving through and exhaustive literature on various challenges for underwater optical communication
(IV) Developing a unique literature taxonomy of various lasers operating in blue-green spectrum
(V) Providing sufficient graphical representations to enhance the understanding of concept

C. PAPER ORGANIZATION

The rest of the paper is organized as follows: Section II discusses the physical aspects of underwater wireless communication. Section III provides the description of various challenges imposed by channel for optical beam propagation underwater. Section IV discusses various underwater link configurations like line-of-sight (LOS), retro-reflector, diffused, non-LOS (NLOS). These are the alternative methods to prevent the LOS for establishing optical link in random underwater environment. Modeling of aquatic optical attenuation in underwater optical communication is discussed in Section V. Section VI presents system design requirements for underwater communication which describes the choice of transmitter, receivers or modulators. Section VII discusses cooperative diversity in UOWC to address the concern of large link coverage due to adverse underwater environment. Section VIII presents hybrid acousto-optic system which complements the existing acoustic system by providing high data rate and low latency when operating within optical range and with long range as well as robustness when operating outside optical range. Section IX gives future research scope and finally, the last section concludes the survey.

II. PHYSICAL ASPECTS OF UNDERWATER WIRELESS COMMUNICATION

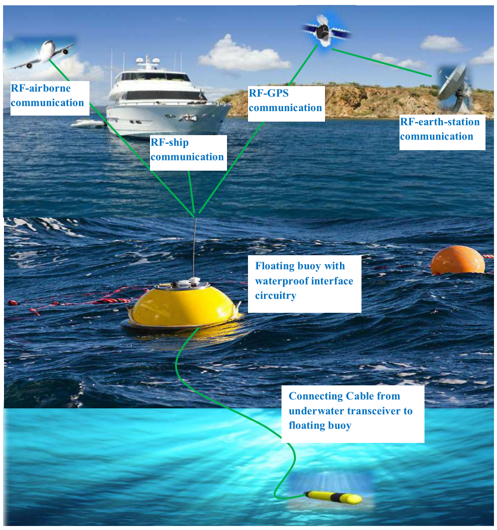
In this Section, various physical carriers for underwater wireless communication are discussed for their state of art. We aim to provide a brief overview of all the primary carriers i.e., acoustic, RF and optical that are used for underwater wireless communication system.

A. HISTORICAL BACKGROUND

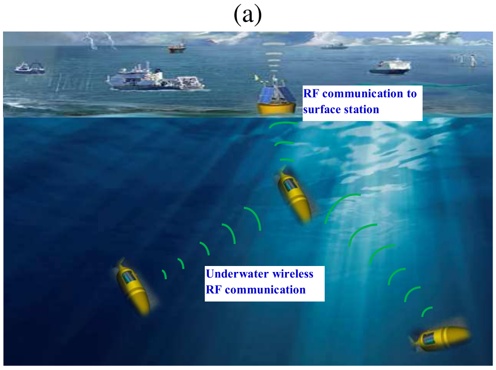
Underwater wireless information transfer from a various underwater networks (that may include autonomous underwater vehicle (AUV) or unmanned underwater vehicle (UUV) or sensor networks) has been under active research over many decades. This section will present the historical background of various physical waves (acoustic, RF and optical) and compare their pros and cons based on efficient underwater wireless communication.

(I) **Acoustic waves**: Among the three types of waves mentioned above, acoustic waves are used as primary carrier for underwater wireless communication due to their relatively less absorption and long coverage distance. The first underwater audio communication was developed in United States using single sideband (SSB) suppressed carrier amplitude modulation at carrier frequencies between 8 and 15 kHz using simple voice band and pulse shaping filters [19]. The received signal has poor quality and requires the ability of human ear and brain to detect and process the distorted speech. With the advancement in digital communication in 1960, a relative improvement in data rate and operational range has been observed. In [20], an improved throughput has been observed using multipath compensation techniques. Over a period of time, many researchers have developed sophisticated methods for channel estimation and designed various algorithms to provide more effective underwater acoustic communication [21]–[25]. Orthogonal frequency division multiplexing (OFDM) has also been extensively used in underwater acoustic communication to achieve high data rates without the need of complex equalizers [26]–[30]. But despite of incredible technological advancements, the underwater acoustic communication still poses various hurdles for effective communication. This is because the underwater environment is far more vibrant and challenging as there cannot exist any typical type of underwater acoustic channel i.e., a system designed to work in one environment (say shallow water) may fail in another environment (say deep ocean). Moreover, these waves are characterized by three major factors: frequency dependent attenuation, time varying multipath propagation and high latency. The multipath phenomenon leads to delay spread which is around 10 ms but it can be as large as 50 to 100 ms [31], [32]. These values of delay spread result in inter-symbol interference (ISI) which may extend over 20 - 300 symbols at a data rate of 2 - 10 kilo-symbols per second and thereby, limiting the data rate [24].
(II) **RF waves**: The use of RF waves in underwater wireless communication has been explored for further improvement in data rates as it provides higher bandwidth and faster velocity in underwater environment. Depending upon the system design architecture, the RF waves can range from as low as few tens of Hz to GHz. Electromagnetic waves operating at extremely low frequency (ELF) i.e., 30 - 300 Hz are extensively used in military applications or in

establishing communication paths between terrestrial and underwater bodies. They are used for long distances propagation and are successfully deployed for communication with naval submarines. The first ELF project was developed in 1968 for communication between deeply submerged submarines. In this project, an alerting system was used to call the submarine to the surface for high bandwidth communication using terrestrial radio links [33]. It has been reported in [34] that RF frequencies in MHz range are capable of propagating in sea water up to distance of 100 m by using dipole radiation with high transmission powers in the order of 100 W. However, it requires sophisticated antennas design and high transmission power.



(a)



(b)

FIGURE 1. Underwater RF system design architecture (a) Buoyant RF communication system (b) Direct RF communication System.

For RF system design which involves a communication link between underwater and terrestrial transceiver, any frequency range from MHz to GHz works effectively. Such communication systems are called buoyant RF communication system as shown in Fig. 1 (a) and they are not truly underwater communication. Other design configuration involves direct RF communication link between two transceivers submerged underwater or one set inside the water and other set in the air. This type of system design is called direct RF communication system as shown in Fig. 1 (b) and it makes use of ELF or low frequency (LF) for communication.

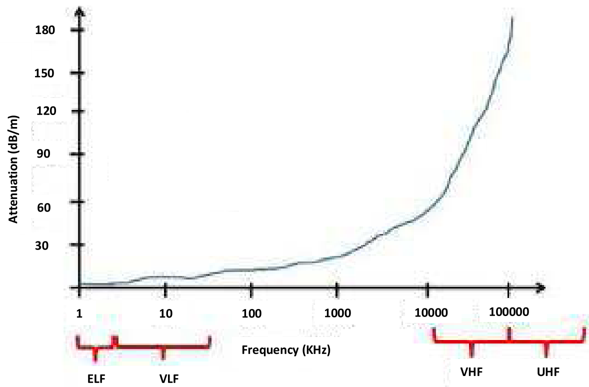


FIGURE 2. RF attenuation in sea water [41].

A comparison of RF and acoustic communication is carried out in [35] which gives maximum propagation distances for several frequency ranges (6 m at 100 kHz, 16 m at 10 kHz, and 22 m at 1 kHz). Data rate in RF communication can be improved using multiple input multiple output (MIMO) schemes. It has been reported in [36] that quadrature phase shift keying (QPSK) modulation scheme with four transmit antennas is capable of transmitting 48 kbps at 23 kHz bandwidth over a distance of 2 km. Lot of research has been carried out at RF frequencies for underwater communication [37]–[40] but they suffer from the high losses due to conductivity of sea water. Average conductivity in sea water is 4 mhos/m which is almost two orders higher than the conductivity in fresh water. This increases the absorption loss at high frequencies in sea water as shown in Fig. 2. Note that the absorption coefficient of sea water is related to conductivity as

$$\alpha_{sea\,water} \approx \sqrt{\pi f \mu \sigma}, \tag{1}$$

where α is the absorption coefficient, f the operating frequency, μ the permeability and σ the conductivity. For this reason, most of the work is carried out at low frequencies in order to support long distance communication.

On the contrary, the absorption coefficient of fresh water is essentially frequency independent and given by

$$\alpha_{fresh\,water} \approx \frac{\sigma}{2}\sqrt{\frac{\mu}{\epsilon}}, \tag{2}$$

where ϵ is the permittivity. Therefore, RF wave communication in fresh water is good choice, however, it requires very large size antenna (the wavelength is 10 km at 30 kHz). Further, in order to compensate for high antenna losses, high transmitter power is required. Recently in [42], an experiment for Wi-Fi network in freshwater using 700 MHz, 2.4 GHz and 5 GHz

TABLE 3. Summary of UOWC with transmission distance, power and data rates specifications.

Distance	Power	Source	Data Rate	Ref.
30 - 50 m	1 W	Laser	1 Gbps	[56]
20 - 30 m	500 mW (avg)	Blue LED	$\approx$ kbps	[57]
2 m	10 mW	Laser diode	1Gbps	[54]
31 m (deep sea) 18 m (clean ocean) 11 m (coastal)	0.1 W	LED	1 Gbps	[58]
30 cm tank (turbid)	6 V_{pp} (vol.)	Semiconductor Laser	5 - 20 Mbps	[59]
30 m (pool) 3 m (ocean)	5 W	LED	1.2 Mbps 0.6 Mbps	[60]
64 m (clear ocean) 8 m (turbid harbor)	3 W	Laser	5 Gbps 1 Gbps	[61]
7 m (coastal)	12 mW	Laser	2.3 Gbps	[62]
20 - 30 m	30 mW	LED	1 Mbps (30m) 10 Mbps (20 m)	[47]
200 m	5 W	LED	1.2 Mbps	[63]
4.8 m	40 mW	Laser	1.45 Gbps	[64]
5.4 m	15 mW	Laser	4.8 Gbps	[65]

was demonstrated for its applicability to underwater communication with rate adaptive algorithm. It was shown that the system operating at 700 MHz is capable for long distance communication while providing low data rates. High data rates can be achieved at 2.4 GHz and 5 GHz but at short ranges as the path loss in water increases with the increase in propagation distance. Besides absorption loss, the refraction loss at air-water interface is nearly 60 dB at low frequencies and decreases with the increase in frequency. It is seen that refraction loss drops down to 27 dB at 1.8 MHz which is quite attractive from an amateur radio point of view.

(III) **Optical waves**: As RF signals require huge antenna size, large transmitter power in fresh water and suffers from high attenuation in sea water, the next obvious choice for underwater communication to support high data rate is using optical signal. UOWC is capable of exceeding Gbps at a distance of few hundreds of meters due to high frequency of optical carrier. Although optical signals in underwater environment face several extreme challenges due to water absorption or scattering caused by suspended particles or due to strong disturbance caused by the Sun, there are still many evidences for broadband optical link underwater over moderate ranges. Various theoretical and experimental studies have been carried out for observing the behavior of optical beam underwater [43]–[45]. All these literatures provide an evidence of high capacity underwater wireless optical transmission over moderate ranges. In 1992, an experimental work was demonstrated using argon-ion laser operating at 514 nm for 50 Mbps over a distance of 9 m [46]. In 1995, LED based theoretical analysis of UOWC was carried out for 10 Mbps at a distance of 20 m and for 1 Mbps at a distance of 30 m [47]. Later this work was extended in 2005 wherein theoretical analysis for varying data rates in different underwater environments suggested the operating range to vary from less than 10 m to over 25 m [48]. An unidirectional optical wireless link capable of sending data at 320 kbps up to a distance of 2.2 m for an underwater sensor network was presented in [49] and later in 2006, an omnidirectional LED based optical communication link was tested for seafloor observatories [50]. In [51], a short range underwater optical wireless communication link up to 5 m was established at 10 Mbps using FM modulation. J. A. Simpson et al. extended the work of [51] and investigated fundamental issues like modulation techniques, error correction, high speed communication channels, etc. for UOWC [52], [53]. In [54], a 1 Gbps laser based communication over 2 m range has been demonstrated in laboratory environment. In most of the work carried out so far, underwater optical communication link distance ranges from few meters to tens of meters. In 2010, a bidirectional communication link using high power LED arrays at 470 nm and discrete pulse interval modulation was developed to achieve a communication range of 50 m with high data rate [55]. Table 3 summaries various UOWC till 2015.

III. OPTICAL BEAM PROPAGATION UNDERWATER

The propagation of optical beam underwater is very challenging as the fundamental characteristic of different water bodies (varying from shallow water to deep ocean) are quite different and requires thorough understanding of the complex physio-chemical underwater environment. The properties of different water bodies vary with geographical location (from the deep blue ocean to littoral waters near land) and with concentration of dissolved substances. In general, following different water types are considered:

(I) Pure sea water: The absorption in pure sea water is considered as a sum of absorption in pure water (absence of suspended particulate matter) and absorption by salts in pure salt water. The latter is assumed to negligible in visible spectrum (400 - 700 nm). The absorption is the main limiting factor here which increases with the increase in wavelength. Therefore, the red wavelength of 500 nm is attenuated more than blue light and for this reason the deep clear ocean water appears rich blue in color. The water absorption coefficient in pure sea water is given as [66]

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

where λ is the operating wavelength, K is the diffuse coefficient and b is the scattering coefficient. Due to low value of b and K in this case, the propagation of optical beam is mainly in straight line.

(II) Clear ocean water: Ocean water have higher concentration of dissolved particles like dissolved salts, mineral components, colored dissolved organic matter, etc. Based on the concentration of suspended particles and their geographical location, they are further categorized into Type 1 - III (based on Jerlov water type) [67].

(III) Coastal ocean water: They have much higher concentration of dissolved particles and thus increase the turbidity level. The effect of absorption and scattering is more in this water type.

(IV) Turbid harbor: It has the highest concentration of dissolved and suspended particles and therefore, limits the propagation of optical beam due to absorption and scattering.

The optical properties of water are divided into two groups namely: inherent optical properties and apparent optical properties. Inherent optical properties are dependent only on the medium specifically the composition and particulate substance present in the medium, whereas apparent properties are dependent on both the medium as well as the geometric structure of the illumination such as collimated or diffused beam. The inherent optical properties include absorption coefficient, scattering coefficient, attenuation coefficient and volume scattering function which are used to determine the link budget in UOWC. Apparent properties define the directional property of the optical beam and are used to evaluate the ambient light levels for communication near the water surface [68]. The common apparent properties are radiance, irradiance and reflectance. The apparent property can only be formed from regular and stable sources of illumination. Therefore, the downwelling irradiance from Sun is not an apparent property as it may change with time of day and cloud cover. In such scenarios, either a ratio of properties which are equally affected by the environment is considered or a normalized derivative is evaluated as shown in Eq. (4) below

$$K(z,\lambda) = -\frac{1}{E(0,\lambda)}\frac{dE(z,\lambda)}{dz}, \tag{4}$$

where E is the original apparent property such as downwelling irradiance from Sun.

The physical properties of water not only vary geographically but also according to vertical depth. The topmost layer is called the euphotic zone and since it receives sufficient amount of sunlight, therefore, large photosynthetic life is found in this zone (as chlorophyll is the main component of phytoplankton). This zone is up to 200 m deep in clear ocean water, 40 m in continental shelves and 15 m in coastal water [69]. The variation of chlorophyll with depth forms a skewed Gaussian profile from surface to the bottom [70]. The peak on skewed Gaussian chlorophyll-depth profiles is known as deep-chlorophyll maximum where attenuation coefficient is at its maximum value as shown in Fig. 3. Few kilometers below this zone where the sunlight is not sufficient for photosynthetic growth is called dysphotic zone. Further below this zone where no light ever reaches is called aphotic zone. Each of these zone have their own physical characteristics and requires unique link budgeting from zone to zone. A model that expresses the inherent properties of sea water (i.e., concentration of colored dissolved organic matter and suspended scattering particles) by the concentration of chlorophyll is discussed in [71].

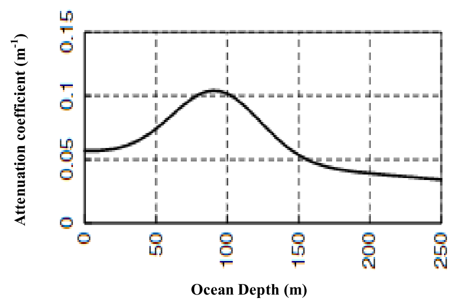


FIGURE 3. Attenuation curve with increasing optical depth [72].

The important factors that affect the UWOC are (i) absorption and scattering, (ii) beam spreading, (iii) turbulence, (iv) alignment (v) multipath interference (vi) physical obstruction and (vii) background noise.

A. ABSORPTION AND SCATTERING

The two main phenomenon that result in the loss of intensity or change in direction of optical signal underwater are absorption and scattering, respectively. In order to understand the absorption and scattering coefficients, a simple geometrical model considering an elemental volume of water ΔV with thickness Δr is shown in Fig. (4). When the water is illuminated with a light beam of incident power P_i having a wavelength λ, then a small fraction of the incident

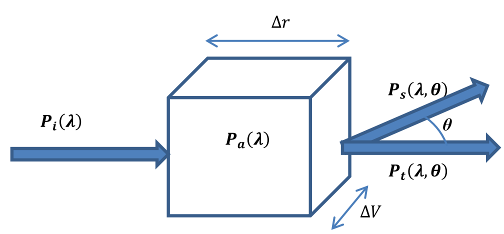


FIGURE 4. Geometry of inherent optical property [69].

light is absorbed by the water denoted by P_a and other fraction is scattered denoted by P_s. The remaining light power, P_t will be passing through the water unaffected. Therefore, according to conservation of energy, it can be stated as

$$P_i(\lambda) = P_a(\lambda) + P_s(\lambda) + P_t(\lambda). \tag{5}$$

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

$$A(\lambda) = \frac{P_a(\lambda)}{P_i(\lambda)}, \quad B(\lambda) = \frac{P_s(\lambda)}{P_i(\lambda)}. \tag{6}$$

The absorption and scattering coefficients are found by taking the limit as thickness, Δr becomes infinitesimally small and is given as

$$a(\lambda) = \lim_{\Delta r \to 0} \frac{\Delta A(\lambda)}{\Delta r} = \frac{dA(\lambda)}{dr}, \tag{7}$$

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

The overall attenuation underwater can be expressed as a beam extinction coefficient, c which is the linear combination of absorption and scattering coefficients given as

$$c(\lambda) = a(\lambda) + b(\lambda), \tag{9}$$

Typical values of absorption and scattering coefficients are mentioned in Table 4. The propagation loss factor, L_P as a function of wavelength and distance, z is then given as

$$L_P(\lambda, z) = exp^{-c(\lambda)z}. \tag{10}$$

TABLE 4. Typical values of absorption and scattering coefficients [54].

Water Type	$a\left(m^{-1}\right)$	$b\left(m^{-1}\right)$	$c\left(m^{-1}\right)$
Clear ocean	0.114	0.037	0.151
Coastal ocean	0.179	0.220	0.339
Turbid harbor	0.366	1.829	2.195

Clearly, it shows that light propagation in turbid harbor is far more challenging than in pure sea or clean ocean. The overall absorption in sea water is due to intrinsic absorption from inorganic material (such as water molecules, suspended particles and dissolved salts) and absorption from organic substances (phytoplankton- small microscopic plant with chlorophyll, gelbstoff - decaying marine matter or yellow substance from broken plant tissue). Hence, the overall absorption coefficient in sea water is split into four factor expressed as [73]

$$a(\lambda) = C_w a_w(\lambda) + C_{phy} a_{phy}(\lambda) + C_g a_g(\lambda) + C_n a_n(\lambda) \tag{11}$$

where C is the concentration of inorganic and organic particles, $a_w(\lambda)$ is absorption due to pure water, $a_{phy}(\lambda)$ due to phytoplankton, $a_g(\lambda)$ due to gelbstoff and $a_n(\lambda)$ due to non-algal material suspensions.

Pure sea water is composed of many dissolved salts like NaCl, KCl, $CaCl_2$, etc. that results in absorption spectrum which causes a dip around blue-green region of the visible spectrum i.e., 400 nm - 500 nm [66]. Phytoplanktons are microscopic organisms that resides only that part of the ocean where sunlight can propagate, also known as photic zone. Its range varies from 50 m to 200 m in clear ocean water, up to 40 m in continental shelves and 15 m in coastal water [74]. It contain colored pigment due to chlorophyll, carotenoids, phaeophytins, chlorophillides and phaeophorbides, etc. which absorb large amount of optical light. Chlorophyll is the significant source of absorption showing peaks around blue-green region and a further peak at 670 nm. High concentrations of chlorophyll are observed along the equator, on the coastlines (specifically east-facing) and in high latitude oceans. For this reason, areas with high organic matter such as near coastal region appear yellow-green in color. Chlorophyll concentrations for open ocean fall within the range 0.01-4.0 mg m^{-3}, whereas near-shore levels may be up to 60 mg m^{-3} [70]. Further, the phytoplankton distribution varies with depth underwater where only 1% of the sunlight reaches [74]. This implies the variation of attenuation coefficient with depth, geographical location, time of day and season. Gelbstoff, also called color dissolved organic material (CDOM) contains dead plant tissues or decaying organic matter, therefore, produces humic and fulvic acids that shows high absorption peak around blue region and therefore makes yellow-red color to be more dominant. It is generally present in low concentration in open waters and in higher concentration in coastal waters. Non-algal material is a composite of living organic particles

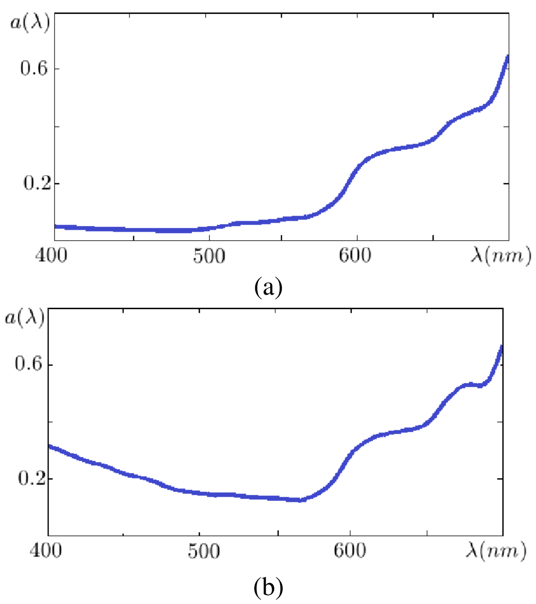


FIGURE 5. Combined absorption spectra of different water types (a) open ocean and (b) coastal waters (absorption coefficients in m^{-1}) [18].

such as bacteria, zooplankon, detrital organic matter and suspended inorganic particles such as quartz and clay. Fig. (5) shows the combined absorption spectra of open ocean and coastal water. Since the chlorophyll, humic and fulvic concentration is low in open oceans, the absorption spectrum is dominated by the attenuation due to pure water. In this case, the minimum attenuation window is around 400-500 nm which is blue-green region of visible light. For coastal regions, chlorophyll and gelbstoff concentration is much higher and therefore, the minimum absorption window is shifted between 520 and 570 nm which means yellow-green region.

As different factors affect the absorption in underwater environments, the minimum attenuation window for various water types will be different. Ideal transmission wavelengths for different water types are listed in Table 5.

TABLE 5. Ideal transmission wavelength for different water types.

Water Type	Chlorophyll conc.	Humic and Fulvic Conc.	Operating Wavelength
Pure sea/clear ocean	Less	Less	450-500 nm (blue-green)
Coastal ocean	High	High	520-570 nm (yellow-green)
Turbid harbor	Very high	Very high	520-570 nm (yellow-green)*

'*' implies performance limited by absorption and scattering coefficients

Scattering results in the deflection of the optical beam from the original path caused by the suspended particles or by the change in the density or refractive index which leads to reflection or refraction process. It leads to the reduction in the intensity of the received signal and causes ISI if the bit rate is not lowered to accommodate for temporal scattering. It is largely independent of wavelength and depend mainly on various particulates present underwater. Therefore, its effect is more pronounced in coastal areas than open oceans. For modeling the scattering of light by suspended particles, a volume scattering function (VSF), $\beta(\theta, \lambda)$ is defined which describes the angular distribution of scattered light to the incident irradiance per unit volume. Assuming the incident light to be unpolarized and the water to be isotropic, then the scattering becomes angular dependent. It is described as fraction of scattered power through an angle θ into a solid angle $\Delta\Omega$ and the corresponding VSF is expressed as

$$\beta(\theta, \lambda) = \lim_{\Delta r \to 0,\ \Delta\Omega \to 0} \frac{\Delta B(\theta, \lambda)}{\Delta r \Delta\Omega}. \tag{12}$$

The total scattered power per unit irradiance i.e., scattering coefficient, $b(\lambda)$ is obtained by integrating $\beta(\theta, \lambda)$ over all angles as given below

$$b(\lambda) = 2\pi \int_0^{\pi} \beta(\theta, \lambda) \sin\theta d\theta. \tag{13}$$

The scattering phase function (SPF) which gives the angular distribution of light intensity scattered by a particle at a given wavelength is defined as

$$\tilde{\beta}(\theta) = \frac{\beta(\lambda, \theta)}{b(\lambda)}. \tag{14}$$

Generally, the Henyey-Greenstein (HG) function which was originally proposed for galactic scattering is used to represent SPF as [75], [76]

$$\tilde{\beta}(\theta) = P_{HG}(\theta, g) = \frac{1 - g^2}{4\pi \left(1 + g^2 - 2g\cos\theta\right)^{\frac{3}{2}}}, \tag{15}$$

where g is the the HG asymmetry parameter that depends on the medium characteristics and is equal to the average cosine of the scattering angle β in all scattering directions. Based on the Petzold's measurements of VSF [77], various values of g for clean ocean, coastal, and turbid harbor are given as 0.8708, 0.9470, and 0.9199, respectively [78]. These values are calculated considering a divergent beam. For a collimated beam, the phase function does not affect the channel characteristics and therefore, the average value of $g = 0.924$ is considered a good approximation for most practical underwater scenarios [69], [79]. Although HG function is easy and simple to compute, however, it fails to provides adequate results for light scattering with small ($\theta < 20°$) and large angles ($\theta > 130°$) [79]. Therefore, a modified phase function, called the two-term Henyey-Greenstein (TTHG), was proposed in [76] that provides a better match with the experimental results and is given as

$$P_{TTHG}(\theta) = \alpha P_{HG}\left(\theta, g_{fwd}\right) + (1 - \alpha) P_{HG}(\theta, -g_{bk}), \tag{16}$$

where P_{HG} is HG function, α is the weight of the forward-directed HG function, and g_{fwd} and g_{bk} are the asymmetry factors for the forward and backward directed HG phase functions, respectively.

Fig. 6 shows the plot of VSF as a function of angular distribution for different water types. The effective received power as a function of attenuation co-efficient (sum of absorption and scattering coefficient) and VSF, $\beta(\theta)$ is given as

$$P_r(\lambda, z, \theta) = P_0 exp^{-c(\lambda)z} \beta(\theta). \tag{17}$$

The change in the direction of optical beam due to scattering is dominated by size of particulates matter. Rayleigh scattering occurs if the particulate size is smaller than the wavelength of light and Mie scattering occurs due to interaction of particles larger than the wavelength of light. Scattering has different effects on different water types. Scattering in pure sea water is well described by Rayleigh scattering as it is more pronounced at shorter wavelengths due to the presence of salts and ions in it [80]. In this case, both forward and backward scattering takes place. Rayleigh scattering coefficient by pure sea water, b_w is given as

$$b_w(\lambda) = 0.005826 \left(\frac{400}{\lambda}\right)^{4.322}, \tag{18}$$

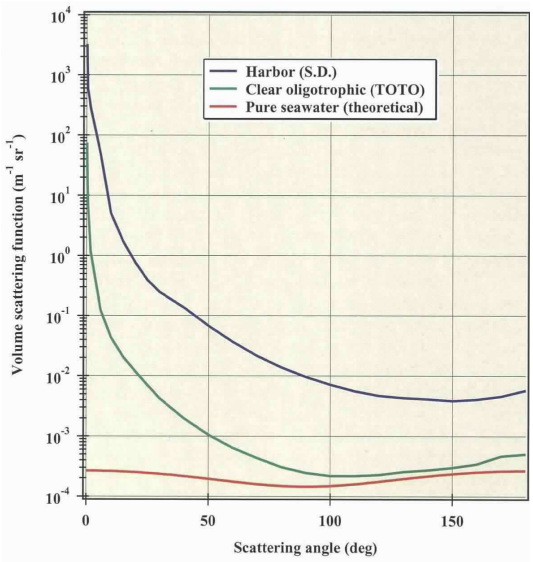


FIGURE 6. VSF as a function of angular distribution [17].

where λ is wavelength in nm. For an isotropic scattering, where the probability of forward and backward scattering are equal, the VSF is empirically expressed as [51]

$$\beta_w(\theta) = 0.06225\left(1 + 0.835cos^2\theta\right). \tag{19}$$

Although scattering plays a significant role in lower wavelengths, however, the overall attenuation in pure sea water is dominated by absorption. Regions closer to land water where excess of particulate and organic matter are found, attenuation is dominated by scattering and minimum attenuation window shifts from blue (∼470 nm) to green (∼550 nm).

Scattering in ocean water is due to organic and inorganic particles present in the water. Other factors that cause scattering in ocean water is temperature, pressure, salinity as it changes the refractive index forming at optical boundary and thus, deviates the beam from the propagation path. In this case, the probability of forward scattering is several order higher than backward scattering and is best described by Mie scattering whose scattering coefficients for large and small particles of ocean water are given as [81]

$$b_l(\lambda) = 1.151302\left(\frac{400}{\lambda}\right)^{1.17} \tag{20}$$

$$b_s(\lambda) = 0.341074\left(\frac{400}{\lambda}\right)^{0.3} \tag{21}$$

where b_s and b_l are the scattering coefficients for small and large particles, respectively.

In case of turbid harbor, the effect of scattering causes the collimated optical light to appear as diffuse source after propagating short distance. In [82], the effect of multiple scattering in turbid water has been investigated using frequency agile modulated imaging system (FAMIS). FAMIS is a novel system developed at the Naval Air Warfare Center, Patuxent River that attempts to combine the transmission characteristics of optical energy, with the well-established signal processing techniques of RF and radar systems. The spatial and temporal effects of scattering in turbid underwater environment using phase shift keying (PSK) and quadrature amplitude modulation (QAM) is analyzed in [83] and have shown the utility of laser link for short distances up to 100 m only. In [84], the authors present the spatial and angular effects of scattering on a laser link using the radiative transfer equation (RTE). It showed that Beer's Law of exponential power loss does not hold for large attenuation lengths as scattered light is captured by the receiver. More literature on absorption and scattering in UOWC can be found in [85]–[89].

From the above discussion, it implies that both absorption and scattering collectively impacts the optical beam underwater, however, each of these phenomena has a dominance depending upon the underwater environment. For example, in pure sea water or clear oceans, initially, the absorption will be the limiting factor and as the water approaches closer to the land, where organic matter and suspended particulates are present, scattering dominates. Therefore, the choice of optical wavelength with minimum absorption window will shift from blue-green to yellow-green. This implies that a single wavelength is not a good choice for wavelength-dependent underwater environment. A multi-wavelength adaptive scheme combined with rate adaptive transmission is proposed in [90] mitigating the randomly changing underwater environment.

B. TURBULENCE

Variation in the refraction index along the propagation path caused due to fluctuations in the density, salinity and temperature of the underwater environment leads to large fluctuations in the intensity of the signal at the receiver. This phenomenon is called scintillation and degrades the performance of UOWC. There is as such no specific model for underwater turbulence like in the case of free space optical (FSO) communication, due to the dynamic nature of underwater environment. Since the physical mechanism of underwater turbulence is almost similar to FSO, the classical Kolmogorov spectrum model of FSO can be applied to underwater environment and is given as [91], [92]

$$\Phi_n(\kappa) = K_3\kappa^{-11/3}, \tag{22}$$

where $K_3\left(=\chi\epsilon^{-1/3}\right)$ is a parameter similar to C_n^2 (in FSO communication) and it reflects the optical turbulence strength underwater. The other parameters are: χ is the dissipation rate of temperature or salinity variances, ϵ the kinetic energy dissipation rate (typical ranges from 10^{-3} to 10^{-11} m^2s^{-3} in natural water) and κ the scalar spatial frequency (in rad/m). The received intensity fluctuations are represented by lognormal distribution owing to the aperture averaging effect due to larger aperture dimension of the optical lens (in front of detector) than the coherence length of the light. The probability density function of lognormal distribution is given as

$$f_I(I) = \frac{1}{I\sqrt{2\pi\sigma_I^2}} exp\left\{-\frac{\left(ln(I/I_0) + \sigma_I^2/2\right)^2}{2\sigma_I^2}\right\}, \quad (23)$$

where I_0 is the mean received intensity and σ_I^2 the scintillation index given by

$$\sigma_I^2 = \frac{\langle I^2\rangle - \langle I\rangle^2}{\langle I\rangle^2} = \frac{\langle I^2\rangle}{\langle I\rangle^2} - 1, \quad (24)$$

where I is the intensity at some point in the detector plane and the angle bracket $\langle\rangle$ denotes an ensemble average.

Though very little work has been carried out to understand the fading characteristics due to turbulence, however, recently some reports have been published to characterize the underwater turbulence. Measurement of turbulence strength at varying depths inside water for analyzing its impact on underwater imaging is carried out in [93] and [94]. A UOWC channel model that takes into account absorption, scattering and turbulence is presented in [92]. Based on lognormal channel model, BER performance was evaluated for SIMO UOWC system using Monte Carlo simulation. It was observed that SIMO is effective to reduce the effect of channel fading and thereby increase the communication range. An oceanic model for weak and strong turbulence in case of plane, spherical and Gaussian light waves is presented in [95]. An accurate power spectrum for refractive index fluctuations in turbulent seawater has been derived in [96]. Statistical properties of Gaussian beam propagation through turbulent water are studied in [95] and [97]– [100]. Temporal correlation of irradiance in moving turbulence ocean water has been investigated in [101] and results suggested that the average velocity of the moving ocean would be the main factor affecting the temporal statistics of irradiance while link distance has negligible effect. The use of adaptive optics is discussed in [102] to overcome underwater turbulence for imaging and communication. In [103], the scintillation indices of plane and spherical optical waves propagating in underwater turbulent media were evaluated by using the Rytov method and it was reported that turbulence effect would become significant at 5 - 10 m for plane wave and 20 - 25 m for spherical wave. Scintillation index of a focused Gaussian beam for weak oceanic turbulence has been studied in [104] for BER calculations. The RTE of optical light at λ = 400 - 600 nm in turbulent ocean water was simulated in [105] for different flow, temperature, and salinity conditions in order to analyze the irradiance fluctuations due to turbulence. Implementation of spatial diversity or aperture averaging schemes reduces the fading caused by underwater turbulent environment and improves BER of the system. In [92], Monte Carlo based statistical simulation methods were carried using a single LED transmitter and multiple detectors (single input multiple output - SIMO scenario) for BER evaluation of the system. Tremendous improvement in BER and communication range was observed. The performance of 3×1 multiple input single output (MISO) transmission in 25 m coastal water with weak turbulence yields 9 dB performance improvement at BER = 10^{-12}. In a recent report by Jamali et al., the performance of relay-assisted underwater optical wireless code division multiple access (CDMA) networks over lognormal turbulent channel has been analyzed which shows an improvement of 32 dB at BER = 10^{-6} for 90 m point-to-point clear ocean link. The effect of aperture averaging was analyzed in [44] for ocean water in case of weak underwater turbulence which showed tremendous reduction in the value of scintillation index and thereby, improving the system performance. It was shown that the effect is more pronounced in plane waves than in spherical waves. The semi-analytical expression for on-axis scintillation index of a partially coherent flat-topped laser beam has been derived in [106] and its effect on underwater oceanic turbulence has been investigated for varying turbulence profile. Reduction in scintillation index has been observed for partially coherent flat-topped beam in comparison to Gaussian beam.

C. POINTING AND ALIGNMENT

Since the optical beam is very narrow, maintaining the LOS for reliable optical link is very critical in UOWC. Due to the movement caused by underwater vehicles, ocean current or other turbulent sources, a constant tracking between transceivers is very essential to maintain a uninterrupted reliable link. Pointing errors in UOWC include two components: bore-sight and jitter [107]. Bore-sight is a fixed displacement between the beam center and the center of detector whereas jitter is the random displacement of the beam center at the detector plane. Link misalignment in UOWC system is modeled using a beam spread function and is expressed as

$$\begin{aligned} &BSF(L,r) \\ &= E(L,r)exp(-cL) + \int_0^\infty E(L,v)exp(-cL) \\ &\quad\times\left\{exp\left[\int_0^L b\tilde{\beta}(v(L-z))dz\right] - 1\right\} J_0(vr)vdv, \quad (25) \end{aligned}$$

where $BSF\,(L,r)$ is the irradiance distribution of the receiver plane, $E\,(L,r)$ and $E\,(L,r)$ are the irradiance distributions of the laser source in spatial coordinate system and spatial frequency domain, respectively, L is the distance between the source and the receiver plane, r is the distance between the receiver aperture center and the beam center on the receiver plane which is assumed to be perpendicular to the beam axis, b and c are the attenuation and scattering coefficients, respectively, $\tilde{\beta}$ is the scattering phase function.

Pure sea water requires tight pointing requirements as the optical beam is likely to follow collimated path. On the other hand, in turbid harbors, scattering is the significant contributor causing the optical beam to spread in different directions, and it therefore relaxes the system pointing requirements. The effect of pointing requirements as a function of beam scattering function for various water types is discussed in [108]. A misalignment of 3 degree reduces the detector response by a factor of 100. An experimental work for analyzing the effect of optical link misalignment in a pool of 3.5 m length is studied in [109]. The effect of misalignment caused due to light source properties such as the divergence and elevation angles is analyzed for spatial temporal distribution of light using Monte Carlo simulations [110]. Pointing error due to slight jitter of the transceivers for a vertical buoy-based UOWC system using random sea surface slope model is presented in [87]. A similar model is used in [111] to evaluate the pointing error and channel capacity of downlink UOWC MIMO systems. Results suggest that the channel capacity of the system is reduced in case of highly turbid water, larger link range, and larger inter-spacing. For eluding the pointing requirement in UOWC, some systems make use of photomultiplier tubes (PMTs) as they provide large field-of-view (FOV) of the receiver due to large aperture size ranging from 10 mm to 500 mm (∼20 inch). But this system is not only expensive and bulky but also not suited for multi-user environment. In order to improve the system reliability, electronic switched pointing and tracking is implemented where the optical front end of the receiver is capable of varying its FOV in accordance with the angle of arrival of the optical signal. In [112], the use of smart transmitters and receivers have been reported in order to improve the pointing accuracy of UOWC system. The smart transmitters can estimate the quality of the water from back scattered light collected by the receiver. The smart receivers have segmented wide FOV and electronic beam steering mechanism to align the FOV towards the wanted signal. This approach is very beneficial in multi-platform environment. The smart transmitter emits CDMA codes that improves the capability to work in the presence of other optical signals in multi-platform environment. Various scenarios as presented in [112] employing smart transmitters and receiver for pointing and tracking requirements in UOWC is shown in Fig. 7.

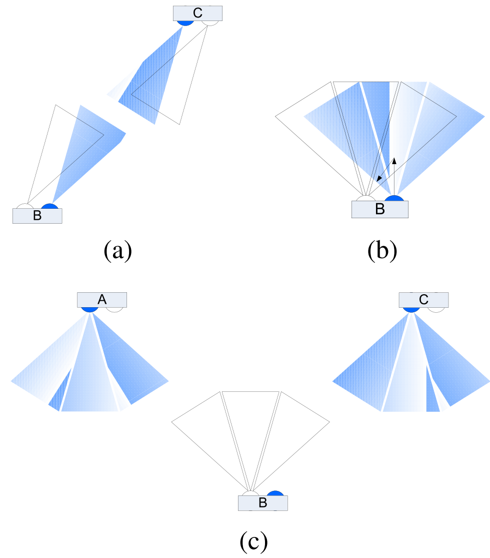


FIGURE 7. Smart transmitters and receiver for UOWC system (a) electronic switched pointing and tracking (b) optical back scatter estimation (c) segmented FOV for duplex multi-platform system [112].

Modulating retro-reflectors (MRR) are also used to reduce the pointing and tracking requirements by retro-reflecting the modulated light back to the interrogating source. MRR couple passive optical retro-reflectors with electro-optic shutters to allow short distance FSO communication between a laser and pointing system. MRR based on ferro-electric liquid crystals [113], micro-electro-mechanical systems (MEMS) [114] and multiple quantum well (MQW) [115] electro-absorption modulators have been demonstrated recently. MQW has the advantage of providing fast temporal response, thereby, provides data rates up to 10 Mbps. Liquid crystals modulators are almost three order of magnitude lower than MQW and therefore, not suitable for high data transfer [116]. Two different configurations of MRR are (i) corner-cube configuration: the optical modulation is integrated with corner-cube to provide the modulated light back to the source (ii) focal plane configuration: the modulator is placed at the focal plane of the collecting optics as shown in Fig. 8. The corner-cube retro-reflector has the advantage of large acceptance angle when compared to focal plane configuration, making corner-cube configuration more relaxed in terms of pointing and tracking accuracy. However, focal plane configuration can support high data rates due to its small response time. Implementation of spatial light modulators (SLMs) in MRR are also used for steering the optical beam, beam shaping or adaptive optics.

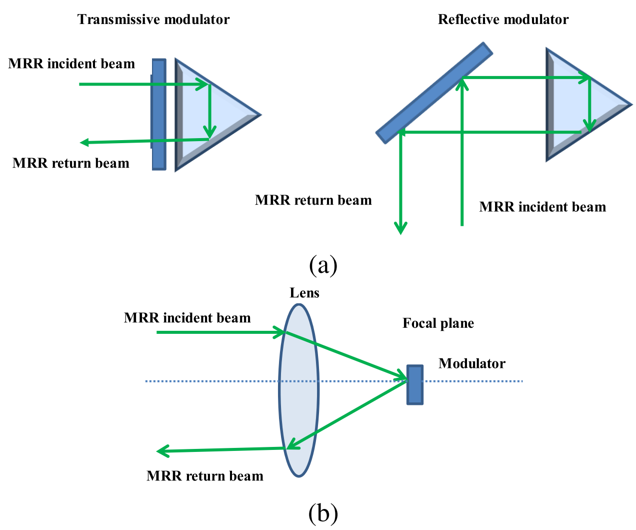
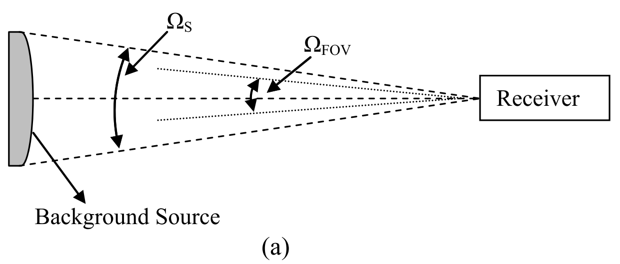


FIGURE 8. MRR configurations (a) Corner-cube (b) focal plane.

Pointing and misalignment issues are relaxed in case of NLOS communication that uses the air-water interface as a diffusive reflector as this will lead to the spread of power over larger areas. However, the diffuse reflector causes loss of power and therefore, lesser number of photons will fall on the receiver. In [117], UOWC is achieved with less pointing accuracy by using NLOS links or a diffuser to de-collimate the laser beam. Pulse shapes were examined for collimated laser beam and a diffused laser beam with 20° FOV. It is observed in [117] that the diffused NLOS link requires less pointing accuracy and at least 30 dB more transmission power to achieve a similar signal strength at the receiver. In many literatures, LEDs are used instead of lasers to reduce the pointing requirements [55], [118]–[120]. The effect of misalignment caused due to refractive index variation is shown in [121]. Here, numerical ray tracing simulation is used to evaluating the maximum link offset for transmission wavelengths of 500 - 650 nm. It is found that for a link distance of 200 m, 0.23 m link offset is tolerated for 500 nm laser with 0.57° full angle FOV.

D. BACKGROUND NOISE

Background noise must be taken into account while designing UOWC link. Noise is strongly dependent upon operating wavelength and geographical location. In general, deep ocean is less noisy than harbor side (such as marine work site) due to man made noise. Most of the noise sources in underwater environment are described as continuous spectrum and Gaussian profile. The main sources of background noise are: (i) diffused extended background noise, (ii) background noise from the Sun or other stellar (point) objects and (iii) scattered light collected by the receiver.



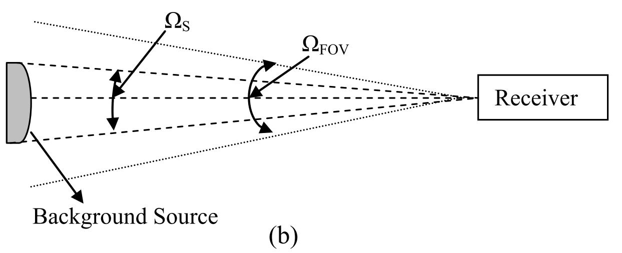


FIGURE 9. Geometry of (a) extended source when $\Omega_{FOV} < \Omega_S$ and (b) stellar or point source when $\Omega_{FOV} > \Omega_S$ (Ω_{FOV} is the solid angle of receiver field-of-view of the receiver and Ω_S is the solid angle field-of-view of the source).

Fig.9 shows the geometry of point and extended sources relative to the receiver. Solar interference is the major contributor of background noise that limits the performance of optical links operating in the euphotic zone of the ocean (at the depth of tens of meters). At larger depths, biological luminance/blackbody radiation is the principle source of optical noise. The peak of the biological luminance is centered on the blue-green region and potentially increases the noise present in the system. The total background noise is given as [56]

$$P_{BG} = P_{BG\_sol} + P_{BG\_blackbody}. \tag{26}$$

In the above equation, solar background noise power, P_{BG_sol} is expressed as

$$P_{BG\_solar} = A_R \left(\pi FOV\right)^2 \Delta\lambda T_F L_{sol}, \tag{27}$$

where A_R is the receiver area, $\Delta\lambda$ the optical filter bandwidth and T_F the optical filter transmissivity. The solar radiance, L_{sol} (W/m^2) is given by

$$L_{sol} = \frac{ERL_f e^{-Kd}}{\pi}, \tag{28}$$

where E is downwelling irradiance (W/m^2), R is the underwater reflectance of downwelling irradiance, L_f is the factor describing the directional dependence of underwater radiance, K is the diffuse attenuation coefficient and d is the underwater depth. For a wavelength of 532 nm, $E = 1440$ W/m^2, $R = 1.25\%$, and $L_f = 2.9$ in the horizontal direction [48]. Noise from blackbody radiation is given as

$$P_{BG\_blackbody} = \frac{2hc^2 \gamma A_R \left(\pi FOV\right)^2 \Delta\lambda T_A T_F}{\lambda^5 \left[e^{(hc/\lambda kT)} - 1\right]}, \tag{29}$$

where $c = 2.25257 \times 10^8$ is the speed of light in water, h is the Planck's constant, $T_A = \exp(-\tau_\circ)$ is the transmission in water, k is the Boltzmann's constant, and $\gamma = 0.5$ is the radiant absorption factor. The use of narrow band spectral filter in front of detection system helps in reducing the background noise. In [122], adaptive rate controller for submarines laser communication is used in blue-green wavelength with very narrow band optical filter to reduce the background solar noise. Besides background noise, other sources of noise including photodetector noise (detector dark current noise), preamplifier noise, shot noise and thermal noise are present. Back-scattered light radiated by the medium also contributes to background noise. An adaptive optics system helps in optimization the UOWC system wherein the amount of background light is minimized by reducing the overall FOV while maximizing the amount of desired signal energy captured.

E. MULTIPATH INTERFERENCE AND DISPERSION

Just like in acoustic communication, multipath interference is produced in optical underwater channel when an optical signal reaches the detector after encountering multiple scattering objects or multiple reflections from other underwater bodies. This eventually leads to waveform time dispersion (time spreading) and decreases the data rate due to ISI. However, the effect of multipath interference is not much pronounced in UOWC in comparison to acoustic communication due to very large speed of light. The amount of multipath interference depends upon system specifications and the propagation environment. For shallow water environment, optical waves reflected from surface or bottom generate multiple signals at the detector. For deep oceans, these surface and bottom reflections can be ignored. Advanced signal processing techniques such as channel equalization and adaptive optics are used at the receiver to suppress interference. Although channel equalization for fast varying underwater channel seems to be a big challenge, however, careful characterization of underwater optical channel can help to choose appropriate system design parameters for reliable and high quality optical link. Work done by authors in [54] and [56] is focused on channel time dispersion leading to ISI. In [56], a polarized light is used to analyze the effect of transmission distance on time dispersion and it has been concluded that ISI is very substantial for long range communication (50 m) at high data rate (1 Gbps). The effect of system design parameters like transmitter beam divergence and receiver aperture size is studied in [54] to quantify channel time dispersion in UOWC. In [123], the authors used Monte Carlo simulation method to characterize UOWC and concluded that except for highly turbid environment, the channel time dispersion can be neglected when working over moderate distances. Therefore, UOWC is capable of supporting high data rates at moderate distances. The effect of ISI on the performance of 25 m coastal water link at two different data rates i.e., 0.5 Gbps and 50 Gbps with spatial diversity is considered in [124]. It is observed that spatial diversity helps in reducing the effect of multipath interference by partially compensating for ISI degradation, especially for low data rates. However, its performance degrades at high data rates specially for high signal to noise ratio (SNR).

F. PHYSICAL OBSTRUCTIONS

As the optical beam is very narrow, any living organism such as school of fish or marine animals will cause momentary loss of signal at the receiver. This requires the use of appropriate error correction techniques, signal processing techniques and redundancy measures to ensure re-transmission of data when lost. The two most widely used error correction techniques in underwater environment is automatic repeat request (ARQ) and forward error correction (FEC). ARQ allows for re-transmission of data after data time out session. However, it does not provide constant throughput which decreases rapidly during high BER cases [125]. In FEC, source coding is performed where redundant bits are encapsulated with data bits to increase the robustness of the message. However, this process increases the payload of the transmission. Another technique called hybrid ARQ which is a combination of ARQ and FEC is used to improve the reliability of UOWC system. Signal processing techniques also help in improving the optical link quality and make the system robust against physical obstruction. A 1 Mbps UOWC system was developed using signal processing capabilities to enhance the propagation distance in [126]. Hop-to-hop communication approach is beneficial in error prone underwater network. A multi-hop underwater optical communication system is developed in [127] that can support a bandwidth up to 100 kHz for communication range of 1 m.

IV. OPTICAL LINK CONFIGURATIONS

There are three basic types of underwater optical link configurations: (i) direct LOS links, (ii) NLOS links and (iii) retro-reflector links.

A. DIRECT LOS LINKS

Direct LOS link is the most simple, unobstructed and point-to-point underwater connection between transmitter and receiver. This link is fairly well to implement in case of static transmitters and receivers such as two sensor nodes at the bottom of the ocean. For mobile platforms such as AUVs, very sophisticated pointing and tracking mechanism is required to keep both transmitter and receiver bore-sighted. It works well in clear oceans where the transmitter directs a narrow beam signal towards the receiver. However, there are large chances of obscuration due to marine life growth, schools of fish or other obstacles. Therefore, in order to establish a LOS link, it is important to design a system which discourages the marine life from blocking the propagation path. The lights that are considered optimal for optical communication underwater also attract schools of fish. Ocean water fishes prefer blue-green wavelengths whereas fresh water fishes prefer yellow-green wavelengths. Therefore, in order to avoid fishes entering the LOS region, flashing or erratic lights are preferred [128].

The received signal power, P_R in a LOS link is given by [15]

$$P_{R\_LOS} = P_T \eta_T \eta_R L_P \left(\lambda, \frac{d}{cos\,\theta}\right) \frac{A_R cos\,\theta}{2\pi d^2 \left(1 - cos\,\theta_d\right)}, \tag{30}$$

where P_T is the average transmitter optical power, η_T and η_R are optical efficiencies of the transmitter and receiver, respectively, d is the perpendicular distance between the transmitter and receiver plane, θ is the angle between the perpendicular to the receiver plane and the transmitter-receiver trajectory, A_R is the receiver aperture area and θ_d is the laser beam divergence angle. Typically, the value of $\theta_d \ll \pi/20$ [15].

The laboratory experiments for LOS links in [129] and [130] have been carried out using LEDs with green and blue light spectra in order to investigate the characteristics of laser beam propagation through different water types such as turbid level. It is found that the viewing angle, propagation distance and turbid level play a significant role in the behavior of the blue light. Their results show the loss of communication above threshold viewing angle when one of the devices is rotated with respect to their LOS alignment. Ambalux in [130] demonstrated a 10 Mbps LOS link up to 40 m depending on different water types. In [131], a LOS link employing different modulation techniques i.e., binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), 8-PSK, 16-quadrature amplitude modulation (QAM), 32-QAM was studied in a laboratory environment using 70 MHz carrier and 3 W solid state

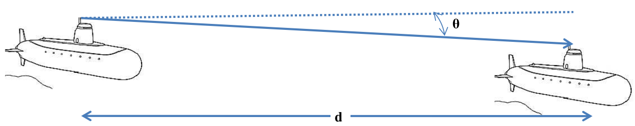


FIGURE 10. LOS configuration.

continuous wave (CW) laser. It was observed that even in turbid water, 5 Mbps can be achieved using high power laser. Cox et al. [132] presented back-scatter suppression in LOS link using polarization shift keying along with channel coding. LOS link configuration is shown in Fig. 10.

B. NLOS LINKS

LOS link is not always possible in practical systems as it requires very tight pointing and tracking system and there are chances of beam blockage due to underwater marine life, bubbles and suspended particles. Therefore, a NLOS underwater communication link is proposed in [133] where an optical link is implemented by means of back-reflection of the propagating optic signal at the ocean-air interface. These types of links are also called reflective links. Other way to implement NLOS links is to spread or diffuse the optical light from the LEDs or lasers in order to increase the FOV of the receiver. Such type of links are also called diffuse links. Both reflective and diffuse scenarios are presented in Fig. 11.

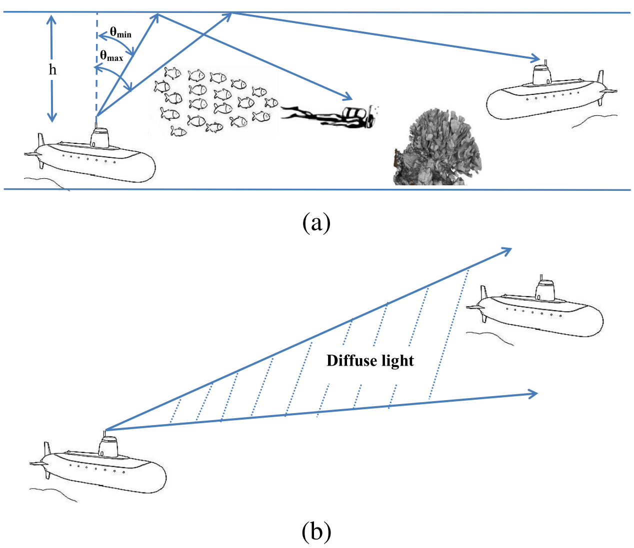


FIGURE 11. NLOS configuration: (a) reflective (b) diffuse.

Compared to LOS links, these links do not require stringent pointing and tracking requirements especially in a turbid environment that causes spatial dispersion of collimated light. For clear lake or ocean water, the divergence of laser beam has to be increased by making use of array of LEDs or lasers to form a cone of light defined by inner and outer angles θ_{min} and θ_{max} in the upward direction as shown in Fig. 11 (a). When the angle of transmitted light is greater than the critical angle, the transmitted light strikes the ocean-air interface and is reflected back into the water due to total internal reflection (TIR). When the transmitter is at depth h, the illuminated annular surface with equal power density at depth x will be given by [15], [133]

$$A_{ann} = 2\pi\, (h+x)^2 \,(cos\,\theta - cos\,\theta_{max})\,. \tag{31}$$

The received power would then be given by

$$P_{R\_NLOS}\,(\theta) = A_R f_R\,(\theta)\,, \tag{32}$$

where $f_R\,(\theta)$ is a auxiliary function dependent on P_T, A_{ann}, η_T, η_R, $(h+x)$ and angle of transmission, θ_t.

The effect of multi-scattering in NLOS is studied in [134] and [135]. A comparison of LOS and NLOS carried out in [136] showed that the 100 MHz bandwidth available for LOS link in turbid environment decreases to almost 20 MHz in NLOS environment even in clear water. Penguin automated systems (ON, Canada) developed a high bandwidth UOWC system for tele-roboting operations consisting of array of LEDs in hemi-spherical configuration to enable larger FOV of the transmitter [137]. In this experiment, first wireless underwater video pictures were transmitted at 1.5 Mbps up to around 15 m in turbid water environment. Other geometrical configuration used for NLOS link is icosahedron which is widely used in UOWC system due to its geometrical simplicity and its ability to provide complete free space coverage using LEDs. Other possible geometrical configurations are employing directional transmitters and omni-directional receivers or both transmitter and receiver being omni-directional. The latter case eases the pointing and tracking requirement and is mechanically the simplest solution. One such scenario is demonstrated by Fair et al. [50], where omni-directional LEDs are used to provide the diffusion of light over full region of operation and are able to achieve omni-directional UOWC for 10 m. This work is particularly focused for AUV and fixed node applications in seafloor observatories. Link budget analysis is carried out for NLOS geometries considering attenuation only due to attenuation coefficients. Their investigation does not take into account multipath interference, dispersion (spatial and time) and multiple scattering. Therefore, the results are only valid for clear ocean or lake water.

C. RETRO-REFLECTOR LINKS

Retro-reflector links are used in limited duplex communication where receivers have low power to support full transceiver operations. Here, the source has more power and payload capacity than the receiver, therefore, it serves as an interrogator which sends modulated light signals towards the remote receiver. The receiver is equipped with a small optical retro-reflector which upon sensing the incoming interrogating beam from the source reflects it back to the source. The received power in this case is given as

$$P_{R\_Retro} = P_T \eta_T \eta_R \eta_{Retro} L_P \left(\lambda, \frac{d}{cos\theta}\right) \frac{A_{Retro} cos\theta}{2\pi d^2 (1 - cos\theta_d)} \times \left[\frac{A_R cos\theta}{\pi (d tan\theta_{Retro})^2}\right] \tag{33}$$

where η_{Retro} is the optical efficiency of the retro-reflector, A_{Retro} is the retro-reflector aperture area, θ_{Retro} is the divergence angle of retro-reflector and other parameters are defined earlier. Link budgeting of underwater optical communication using retro-reflector is presented in [138].

The retro-reflector underwater works in two scenarios: (i) photon limited and (ii) contrast limited. The photon limited scenario occurs in clear ocean water or lakes. In this case, the link range and capacity is limited by the amount of photons falling on the detector due to absorption underwater. Moreover, pointing and tracking is crucial in this case as the information bearing retro-reflected signal is dependent upon the density per unit area of interrogating photons incident on the retro-reflector. Contrast limited scenario occurs in turbid harbors where scattering plays an important role in link range and capacity. This is a critical problem for applications related to underwater laser imaging. Here, the increased back-scatter component leads to reduction of photons and thereby, decreases the contrast of the image. The back-scatter component can be significantly reduced by using polarization discrimination [139], [140]. Fig. 12 shows retro-reflector configuration.

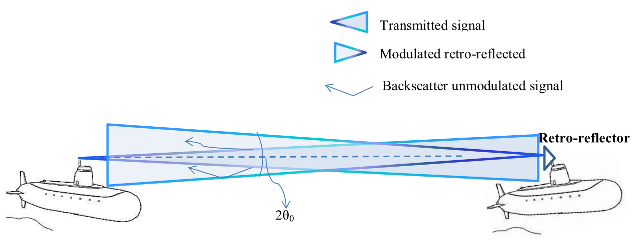


FIGURE 12. Modulating retro-reflector configuration.

V. MODELING OF AQUATIC OPTICAL ATTENUATION

The modeling of UOWC helps to determine the optical signal strength taking into account all the losses (i.e., attenuation, multipath, turbulence, etc.) as the signal propagates through underwater channel. An accurate model incorporates various system design parameters so that it provides a best fit for underwater environment. The model provides a good estimate of range, data rate and coverage angles for changes in underwater environment and optical components. In [56], a channel model for UOWC is proposed using vector radiative transfer theory. Comprehensive modeling of UOWC based on Monte Carlo simulation were carried out to quantify time dispersion for various ranges, water types, transmitter/receiver parameters [141]. In [48], authors presented an underwater model for evaluating transmission range considering various parameters such as transmitted power, detector's sensitivity as well as extinction through the water. The models of aquatic optical attenuation can be classified into two categories: LOS configuration and NLOS configuration. Light propagation in both the configurations experience the same attenuation effects, however, in case of NLOS channel, reflection from the surface of water is considered as a critical part of modeling UOWC.

A. AQUATIC OPTICAL ATTENUATION FOR LOS CONFIGURATION

Modeling of LOS configuration makes use of Beer Lambert's law that evaluates the communication range and angle for different water types. However, it assumes that the scattered photons are lost although in reality some fraction of the scattered photons are captured by the receiver when light beam undergoes multiple scattering. So in that case, Beer Lambert's law severely underestimates the received power especially in the scattering dominant regime. Therefore, in most of the cases, RTE is estimated to model aquatic optical attenuation in UWOC as it takes into account the effect of multiple scattering as well as light polarization. RTE describes the energy conservation of light as it passes through a vibrant underwater environment. However, mathematical computation of RTE is difficult as it involves complex integro-differential equations of several variables. Therefore, very few researchers have proposed an analytical model of RTE [56], [61], [142] as it involves large number of assumptions and approximations to simplify the result. Some researchers have solved RTE numerically using discrete ordinates method and invariant imbedding method. In [143], the authors have numerically evaluated RTE based on the deterministic numerical approach. It employs the matrix free Gauss-Seidel iterative method in order to calculate the received power of UWOC systems.

Another popular approach to model UOWC employs numerical methods with Monte Carlo simulation [123], [136], [139], [142], [144], [145] as it is flexible, easy to program and provide accurate solution. However, there are certain drawbacks of Monte Carlo simulations: i) it cannot address wave phenomena, ii) poor simulation efficiency and iii) suffers from random statistical errors. A practical and robust method of Monte Carlo simulation for ocean optic applications is given in [146]. Channel capacity for various link distances, water types and transceiver parameters are evaluated using Monte Carlo simulations in [147]. A channel model using Monte Carlo approach was used to predict different design parameters for UWOC system in [141]. Further, the work in [141] was extended to study the channel impulse response by solving the RTE through Monte Carlo simulation [123] using TTHG function. It is shown that except for highly turbid water, the channel time dispersion due to scattering can be ignored for moderate distances. A comparison between experimentally collected data and Monte Carlo simulation were carried out in [148]. Received power was calculated using numerical Monte Carlo simulation taking into account receiver aperture size, FOV, and pointing-tracking losses. The simulation results were validated by comparing the results with the experimentally collected data from [84]. A semi-analytic Monte Carlo radiative transfer model is proposed for addressing oceanographic lidar systems [149]. Here, an analytical estimate is made for probability of scattered or emitted photons at appropriate points in the stochastically constructed underwater photon trajectory. Results indicate substantial reduction in variance and computer resources using this approach as compare to conventional Monte Carlo approach. In [150], a closed form expression of double Gamma function is used to represent the channel impulse response of optical beam propagation in sea water. The results fit well with Monte Carlo simulations in turbid water environment and show the degradation of BER performance due to temporal pulse spread. The zero-forcing (ZF) equalization was used to combat the temporal spread and improved the UOWC system performance. In [151], weighted double Gamma functions were adopted to derive a closed form expression of impulse response of 2×2 MIMO UOWC system in turbid water environment.

A stochastic model for UOWC has been suggested by various authors due to the random nature of optical beam as it propagates through underwater channel. A stochastic channel model is used to evaluate the spatial and temporal distribution of photons only for non-scattering and single scattering components of UOWC links by adopting the HG function [152]. Their work was further extended for long distance communication in [153] that takes into account all the three components of photon propagation i.e., non-scattering, single scattering and multiple scattering due to various suspended particles in UOWC. A stochastic channel model was proposed that fits well with Monte Carlo simulations in turbid water environment such as coastal and harbor water and was used to evaluate path loss scattering richness, and attenuation in UOWC. An end-to-end generic model of signal strength is presented in [119] that provide insights into optimization approaches for underwater optical modem. The results were also verified in a suite of pool experiments that provide a good estimate of overall system performance.

B. AQUATIC OPTICAL ATTENUATION FOR NLOS CONFIGURATION

The channel modeling in a NLOS link is more complex than a traditional LOS link as it includes the attenuation effects (as in LOS configuration) as well as back-reflection effect from the water-air interface. In addition to wavelength and device characteristics, NLOS path loss is a function of system geometry, including transmitter beamwidth, communication range, receiver FOV, the pointing elevation angles, as well as the optical properties of the underwater channel. Most of the channel models for NLOS configuration are based on Monte Carlo simulations. The concept of NLOS network was proposed in [133], where a mathematical model was derived for underwater sensor networks taking into account link attenuation, reflection from ocean-air interface and receiver FOV. BER performance versus sensor node separation was studied and it demonstrated an increase in BER with an increase in node separation distance. In [154], NLOS configuration based on Monte Carlo simulation and HG function is analyzed for different water types and receiver FOV. A path loss model of NLOS link using Monte Carlo simulations taking the effects of both random sea surface slopes and scattering properties of seawater is presented in [155]. The numerical results show that the random surface slopes induced due to turbulent underwater environment degrade the quality of received signal. This effect is further alleviated when the received signal contains multiple dominant scattering light components. Channel impulse response for NLOS link in UOWC system is investigated experimentally using collimated and diffuse laser light up to 1 Gbps in [117].

VI. UOWC SYSTEM DESIGN

The system design for UOWC is shown in Fig. 13. It consists of a source that generates the information to be transmitted which is then modulated on the optical carrier to be transmitted to longer distances with a high data rate. The transmitter is equipped with projection optics and beam steering elements in order to focus and steer the optical beam towards the position of the receiver. The information bearing signal is then allowed to propagate through the underwater channel whose characteristics vary according to the geographical location and time. At the receiving end, the collecting optics collects the incoming signal and passes it to the detector for optical-to-electrical conversion. The electrical signal is then allowed to pass through a signal processing unit and a demodulator for recovering the originally transmitted signal.

A. TRANSMITTER

The market for optical components is already very mature and is being widely used in optical fibers and FSO communication system. Therefore, UOWC have the advantage of technological maturity that exists in the wavelength of interest. Depending upon the requirement and keeping in mind that underwater systems have power and mass constraints, the choice of LED or laser may vary in the blue-green portion of the spectrum. Generally, for buoy system operating in shallow water, blue-green LEDs are preferred. In case of systems operating in deep clear ocean water, laser based systems are preferred. The output power of lasers or LEDs in blue-green spectrum ranges from 10 mW to 10 W. Both LEDs and lasers have their own pros and cons while making decision for the source in UOWC system. Lasers have fast switching time and high optical power but LEDs are cheap, simple, less temperature dependent and more reliable. LED-based system is less susceptible to underwater effects as compare to laser owing to their large viewing angles. The performance of LED based system is

TABLE 6. Types of lasers operating in blue-green spectrum.

Types	Wavelength	Advantages	Disadvantages
Argon-ion laser	455-529 nm	- High output - Less life time	- Very less efficiency (∼ 0.1%) - Requires high input power - Requires cooling arrangements
Diode pumped solid state (double Nd:YAG)	532 nm (green) 473 nm (blue)	- Very high output power - Long life time - Compact	- Efficiency varies from 20-50 % for green lasers & 3-5 % for blue laser - Costly
Doubled Ti: Sapphire	455 nm	- Ultra fast output pulses - Frequency tunable	- Costly - Sensitive to vibrations
Flashlamp pumped frequency doubled Nd:YAG	532 nm	- High Power	- Hard to modulate
Metal vapour laser	441.6 nm, 570 nm and 578 nm	- High power (40 mW - 100 mW) - Long life time	- Requires cooling arrangements
Liquid dye laser	450 nm - 530 nm	- Very high power (MW-peak value) - Tunable depending upon dye - Support high data rate (pulse width ns to ps)	- Costly - Requires cooling arrangements
Semiconductor laser	405 nm & 450 - 470 nm (InGaN) 375 nm to 473 nm (GaN)	- High power (hundreds of mW) (405 nm) - Less power (450 - 470 nm) - Very less power < 200 mW (GaN) - Highly efficient - Compact	- Costly - Easily damage due to over current
Fiber laser	518 nm	- Rugged, - Compact size - High efficiency - High output power (∼ 140 mW)	- Costly - May require external modulator

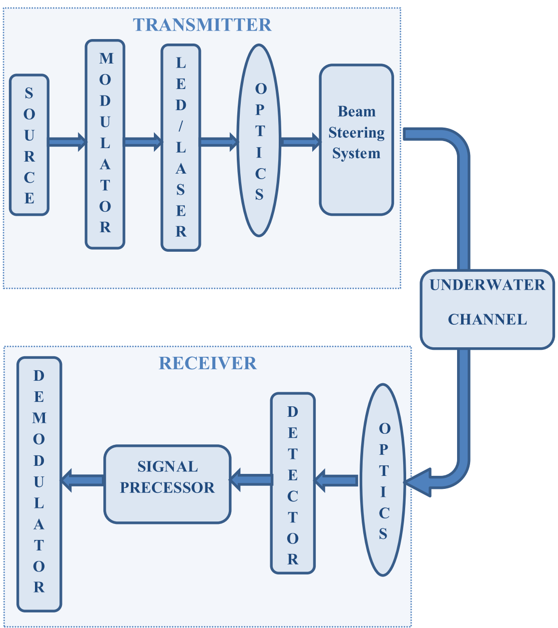


FIGURE 13. Block diagram of typical underwater optical communication system.

determined by geometric effects due to beam divergence, FOV of the receiver and dynamic range. The implementation of LED is cheap and easier in UOWC system, however, the link range is very limited due to incoherent optical beam and omnidirectional coverage of light. The link range can be increased by either using a high power LED (operating in Watts) or converting the omnidirectional coverage to unidirectional link with the help of focusing optics or by using array of LEDs. LEDs such as those fabricated from Gallium Indium Nitride (InGaN) on a silicon carbide (SiC) substrate provides an output power of 10 mW that can be configured into arrays in order to increase the optical power. Further, the light from one or more LEDs can be collimated using lens arrangement to focus its beam. The use of multi-wavelength scheme combined with rate adaptive scheme is presented in [90] to combat with wavelength dependent underwater environment and improve the system performance .

Laser-based systems have been demonstrated for long ranges, high data rates and low latencies. The first duplex laser communication between aircraft and submarine is discussed in [156]. The coherent laser beam provides a good quality output which however, is rapidly degraded by underwater scattering and turbulence. The link distance up to 100 m under clear water and 30 - 50 m under turbid conditions is achievable using laser based UOWC system. A design and tradeoff for directional and omnidirectional UOWC link using laser diode and arrayed LEDs is presented in [50]. The tight pointing requirement using laser beam is relaxed using retro-reflector. In order to meet the application requirements for deep submarine communication, lasers are used as they possess high power, high efficiency, and long life. Moreover, lasers are capable of supporting high data rates due to large modulation bandwidth (>1 GHz) as compare to LEDs whose modulation bandwidth is almost less than 200 MHz. A comparison of various lasers operating in the blue-green spectrum is shown in Table 6.

Argon ion laser falls within the blue green transmission window of underwater communication. A continuous wave argon ion laser can produce high peak power pulses at high repetition frequencies when operated in a synchronized cavity-dumped, mode-locked manner. Commercial power levels vary from less than 100 mW to over 15 W. Krypton laser can also be used in the yellow to red region but it lases over a very wide range of the visible spectrum (462 nm to 676 nm). Its output power is about 100 mW in yellow to red region of the spectrum [157]. When operating in blue region, its output is comparatively smaller than argon laser. Bulk solid-state lasers have found wide utility in applications with high power and compact size requirements. Solid state blue-green lasers are based on non-linear frequency conversion of near infrared lasers such as Neodymium yttrium aluminum garnet (Nd:YAG or Nd:$Y_3Al_5O_{12}$) or Titanium Sapphire (Ti:Al2O3) [158]. Diode pumped solid state laser generates a frequency doubled output of near-infrared Nd: YAG laser. Another approach for generating blue - solid state lasers is based on multi-photon pumped gain medium [159]. These lasers absorb two or more near-infrared photons to generate a single blue photon. The life of these lasers depends on the operating life of replaceable flash lamps. Metal vapor laser gives radiation in the blue-green region at 441.6 nm (He Cd) and 570, 578 nm (Cu). These are high power lasers and require proper cooling arrangements. Liquid dye laser can tune over a wide range of frequencies and are capable of working in CW or pulsed mode. It produces very large peak powers (up to MW) in the pulsed operation though average power is larger in the CW mode. The output of these lasers is tunable over a specific range depending upon dye material. Pumping in these lasers is carried out by argon or krypton laser for CW operating and by Nd:YAG or Xe flash-lamps for pulsed operations [157], [160]. Semiconductor laser such as InGaN gives an output power of few hundreds of milliwatt at 405 nm and the output power reduces to few tens of milliwatt at longer wavelengths i.e., 450 nm to 470 nm. High power infrared fiber laser sources are also good candidates for underwater optical communication. A direct conversion of an Er : Yb co-doped fiber source operating at 1500 nm into blue-green output is a good choice for optical sources as they provide high power, good efficiency and support a high data rate. In [161], third harmonic generation of pulsed fiber laser at 1500 nm using lithium Niobate intensity modulator is used to develop a fully integrated eye-safe transmitter operating at 65 Mbps data rate. Solid state and fiber lasers are preferred for large platforms where size is not a major concern.

The use of blue-green array of LEDs has been widely used in UOWC. LEDs can support variable data rates up to Mbps and have high electrical to optical efficiency. The main issue with LEDs is its wide spectral bandwidth i.e., 25 - 100 nm and therefore, it requires wide bandpass filters which in turn causes solar background noise to enter the system. Therefore, LEDs are only used for short range communication e.g., to connect underwater sensors and divers. For long range applications such as AUV to satellite connection, lasers are the preferred choice. Table 7 gives the comparison of high power LEDs for UOWC [162].

TABLE 7. Comparison of blue-green LEDs [162].

Manufacturer	Wavelength (nm)	Luminous Flux (Im)
Lamina Atlas NT-42C1-0484	460 - 470	63
AOP LED Corp PU-5WAS	455 - 475	54
Kingbright AAD1-9090QB11ZC/3	460	35.7
Ligitek LGLB-313E	460 - 475	30.6
Toshiba TL12B01(T30)	460	6
Lumex SML-LX1610USBC	470	5

B. RECEIVER

The receiver in UOWC should possess wide FOV, high gain and provide high SNR. Most common photo-sensors in the blue-green region are: PMT, semiconductor photo-sensors and biologically inspired quantum photo-sensors. PMT is type of vacuum tube that is very sensitive to light. It is characterized by high gain, low noise, high frequency response and large collection area. However, their large size, more power consumption and fragility make them a poor choice for UOWC. Further, PMTs can be damaged if exposed to excessive light. In [163], PMT is used along with a variable gain amplifier at the receiver to establish a communication link in a laboratory setup for 500 kbps in return-to-zero format and 1 Mbps in non-return-to zero format for a distance of 3.66 m. An omni-directional transmission and reception of optical signal using PMT in conjunction with diffuser in hemi-spherical configuration is presented in [164] for 100 m range at a data rate of 1 Mbps.

Semiconductor photo-sensors include PIN and avalanche photodiode (APD). PIN photodiode is characterized by fast response time, low cost, unity gain and good tolerance to ambiance light whereas APD has large internal gain and high quantum efficiency (70 - 90%). APD is potentially faster and has a higher internal gain than PIN, but requires high bias voltage, complex control circuitry and are more sensitive to ambiance noise. Further, the quantum efficiency of APD depends upon the thickness of the material e.g., Silicon has very limited sensitivity in the 400 - 500 nm range. For this reason, at shorter wavelengths, PIN photodiode seems to be a more promising technology than APD for UWOC system. In [54], APD has been used as a receiver using 532 nm laser at 7 W for demonstrating 1 Gbps data rate over 2 m propagation path. In [60], three different models for long, short and hybrid propagation ranges were investigated using PIN and APD receivers. PIN photodiodes are used for short and hybrid ranges, while APDs are used for long ranges in order to achieve an error free communication at 4 Mbps over 2.2 m and 2.4 m.

Biologically inspired quantum photo-sensors take advantage of photosynthetic life underwater. The biological life underwater is able to absorb and process the dim light coming from the Sun and other hydrothermal vents. Their biological organism captures the solar radiations and use quantum coherence to transport the energy to the reaction center where biochemical reaction for photosynthesis begins. Unlike semiconductor devices (such as PMT, PIN and APD) that are based on semi-classical charge transport theory and suffers strong absorption by diffused surface layer in blue-green region, these quantum photo-sensors are highly efficient candidates for UOWC. A lot of research is going on to invent biologically inspired quantum devices that work effectively in underwater environment [41], [165]–[167].

C. MODULATORS

The selection of a modulation technique is a very critical decision for designing any communication system. Modulation can be carried out either directly or by using external modulator. Direct modulation is the easiest way to realize where the current driving the light source is directly modulated. Direct modulation of lasers via pump source is very simple, however, it suffers from the phenomenon called chirping which limits the data rate and link range in UOWC system. In case of optically pumped solid state lasers, the non-linearities in the system lead to relaxation oscillations that prevent the direct modulation of the laser. The potential of directly modulated semiconductor laser is not fully explored due to the long-term challenge of stretching the emission wavelength of semiconductor lasers toward green [168]. The first truly green-light nitride laser at ∼532 nm did not appear until 2009 and for this reason, most of the work reported in UOWC is with directly modulated blue semiconductor laser. A 4.8 Gbps data rate transmission using 16-QAM-OFDM over 5.4 m tap water is demonstrated in [65] using direct modulated blue laser. As blue light suffers from high absorption and scattering losses in underwater environment, therefore, researchers are putting greats efforts to investigate the feasibility of directly modulated green laser diode in UOWC system. A high speed underwater optical link up to 2.3 Gbps over 7 m using directly modulated 520 nm laser diode is experimentally demonstrated in [62]. In external modulation, the light from the laser which is emitting a constant power passes through an external modulator (which is voltage driven device) to achieve modulated optical power at the output of external modulator. These systems are capable of utilizing full power of the source. However, external modulators limit the modulation range and requires relatively high drive current. In [54], an externally modulated laser operating at 532 nm is used to establish 1 Gbps underwater optical link.

Modulation in UOWC is broadly classified into two categories: intensity modulation or coherent modulation. The most widely used modulation is the intensity modulation in which the source data is modulated on the intensity of the optical carrier which can be achieved by varying the driving current of the optical source either directly with the message signal to be transmitted or by using an external modulator. When the intensity modulated signal is detected by a direct detection receiver, then the scheme is known is intensity modulated/direct detection (IM/DD) or non-coherent detection. Due to low cost and less complexity of IM/DD systems, they are widely used in UOWC systems. In this case, only the presence or absence of power is ascertained and no phase information is required. The other approach of detecting the modulated optical signal is coherent detection. It makes use of local oscillator to down convert the optical carrier to baseband (homodyne detection) or to RF intermediate frequency (heterodyne detection). This RF signal is subsequently demodulated to baseband via conventional RF demodulation process. The strong field of local oscillator raises the signal level well above the noise level of the electronics circuit which improves the sensitivity of the system. Due to complexity and high cost, coherent systems are not popularly used in UOWC system. Also, most of the coherent modulation schemes are always transmitting symbols for bit "1" or bit "0" and therefore, consume large power than any other non-coherent modulation schemes, making it undesirable option for underwater communication.

The choice of modulation technique is based on the type of application being used and design complexity. The wireless system can be either power limited (such as for long distance communication, battery operated optical wireless devices, etc.) or bandwidth limited (due to multipath channel, diffuse link or photodetector limited bandwidth, etc.). Underwater optical communication is very much influenced by turbidity and the dimensions of the dissolved particles in water. Also, multipath propagation due to reflection of optical signal from surface and bottom of sea water leads to ISI and limits the available channel bandwidth. Therefore, a lot of research is going on for both intensity modulation techniques such as on-off keying (OOK), pulse position modulation (PPM) as well as for phase shift keying techniques e.g., BPSK, QPSK and QAM. Details of these modulation techniques can be studied in [169] and [170]. OOK and PPM modulation formats are typically used in direct detection schemes and comparatively simple to implement than coherent techniques. The PPM modulation technique has a better power efficiency than OOK and therefore, it is a good choice for long distance communication or for battery operated underwater sensors where low power consumption is the major concern. Many variants of PPM scheme such as differential PPM (DPPM) [171], digital pulse interval PPM (DPI-PPM) [172], differential amplitude PPM (DAPPM) and multilevel digital pulse interval modulation schemes [173] are used to improve the bandwidth efficiency of the wireless communication system.

Different intensity modulation techniques are investigated in [174] for UOWC. A 2.3 Gbps high-speed UOWC system is experimentally demonstrated in [62] using OOK modulated laser at 520 nm over 7 m distance. In [175], the BER performance for different modulation techniques using APD receiver has been theoretically analyzed for aligned LOS geometry model of Jerlov water type. The effect of chlorophyll concentration and the propagation distance is also investigated. A modified version of PPM with improved bandwidth utilization is demonstrated in [176]. A low cost laser transmitter operating at 405 nm (blue) and 635 nm (red) using OOK modulation schemes was designed to test the feasibility of UOWC. It was observed that blue laser has longer propagation length and can support larger data rate (1 Mbps) than red laser using PMT receiver [163]. A comparison of intensity (OOK and PPM) and phase modulation techniques such as frequency shift keying (FSK) and differential phase shift keying (DPSK) schemes was presented in [177]. It was shown that OOK modulation scheme is simple and cost effective but its BER performance was 10^{-2} for SNR = 25 dB which is very poor. Out of all the schemes i.e., OOK, DPSK, FSK and PPM, the performance of DPSK was the best in terms of BER performance ($\sim 10^{-5}$ for SNR = 25 dB) and is well suited for bandwidth limited systems. However, it requires larger power and complex design circuitry. FSK is undesirable for underwater applications as it is always on and consumes more power. PPM modulation is a good option for power limited undersea applications. The performance of OOK modulation using MIMO in UOWC to reduce the effect of underwater turbulence is presented in [124]. An underwater speech communication using pulse modulated laser at 5 mW output power has been demonstrated in [178] for short range applications. Although the received speech quality was not good, but it can be used for transmission of short message service from a fixed installation such as sea bed habitat, between divers or between AUVs. The effect of modulated light at high frequencies (up to GHz) has been investigated in [179] for forward scattering in ocean water and its impact on underwater optical imaging and communication system has been studied. Short range underwater optical links employing BPSK, QPSK, 8-PSK, 16-QAM, and 32-QAM modulation are implemented in [131] for turbid water environment, yielding data rates up to 5 Mbps. It was able to send 10^6 symbols per second, and upgraded the initial speed of 1 Mbps using BPSK to 5 Mbps using 32-QAM, in a 3.6 m water tank. A new technique of intensity modulated pulsed laser is investigated in [180], for detection, ranging, imaging and underwater communication. The laser transmits a variety of intensity modulated waveforms, from single-tone to pseudo random code in order to work in turbid environment in the presence of back-scatter light. In [181], the author introduced the PPM modulation by a single chip computer for improving the synchronization and coding efficiency of the laser in underwater environment. For low power consumption in underwater sensor networks, a decision feedback equalizer (DFE) is applied to the phase shift silence keying (PSSK) [182] and phase shift-PPM (PSPPM) [183]. The effect of changing chlorophyll concentration versus the depth of sea water is considered in [184] for evaluating the BER performance of four different modulation techniques which includes PPM, OOK, FSK, and DPSK using 470 nm blue laser at 2.59 mW output power. The results show that PPM is the preferred choice for long distance underwater vertical propagation. Nakamura et al. [64] have demonstrated a 1.45 Gbps optical wireless transmission at 450 nm using optical intensity modulated/direct detection (IM/DD) OFDM signals through a 4.8 m underwater channel. Adaptive modulation scheme for UOWC is studied in [185]. An underwater communication over a 3 m link using BPSK has been investigated in [82] for 1 Mbps data rate using frequency agile modulated imaging system FAMIS. A comparison of BER performances for OOK, PPM, pulse width modulation (PWM), and digital pulse interval modulation (DPIM), where a PIN or an avalanche photodiode is used at the receiver is presented in [174]. Subcarrier intensity modulation (SIM) is another coherent modulation technique used in UOWC which provides high spectral efficiency but suffers from poor average power efficiency. An experimental UWOC system was demonstrated in [186] that utilized (2720,2550) RS and SIM. It was shown that the BER was reduced from 10^{-3} to 10^{-9}. An experimental demonstration of OFDM based system was carried out in [187] where data rates of 161.36 Mbps using 16-QAM, 156.31 Mbps using 32-QAM, and 127.07 Mbps using 64-QAM were achieved for a link distance of 2 m in underwater channel. The use of error correction coding schemes along with modulation techniques improves the reliability of UOWC.

D. CHANNEL CODERS

In order to mitigate the effect of underwater attenuation, FEC channel coding schemes such as Turbo, low density parity check (LDPC), Reed Solomon (RS), convolutional, etc., are implemented in UOWC systems. Here, redundant bits are systematically introduced into the transmitted bit sequence in such a way that the receiver can correct a limited number of errors in the received message. A properly designed FEC coding technique improves the power efficiency and the link range of the system but at the cost of reduction in bandwidth efficiency. Generally, FEC codes can be divided into two categories: block codes and convolutional codes. Block codes implemented in UOWC system are RS codes, Bose-Chaudhuri-Hocquenghem (BCH) codes and cyclic redundancy check (CRC) codes. The first block code that was used in UOWC is (255, 129) RS FEC code in [53]. It was shown that RS coded system reduces the power requirement by approximately 8 dB relative to an uncoded OOK system to achieve a BER = 10^{-4}. Their work was extended in [52] where a base transmission rate of 5 Mbps is achieved in 7 m long underwater optical link using (255,129) and (255, 223) RS codes and the results show an improvement in SNR of 6 dB and 4 dB, respectively at BER = 10^{-6}. A real time digital video transmission through a unidirectional underwater channel is demonstrated using (255, 239) Reed-Solomon (RS) as inner code for byte-level error correction coupled with a systematic Luby Transform (LT) [188] as an outer code to mitigate packet-level losses. A high quality video transmission up to 15 Hz within the bandwidth limit of 4

Mbps of the AquaOptical II modem and almost negligible communication latency of 100 ms is presented in [189]. In [190], comparison of RS (Reed-Solomon) code and BCH (Bose Chaudhuri Hocquenghem) code was evaluated for underwater optical communication and it was shown that around 4 dB improvement was achieved using RS codes in comparison with uncoded systems. The improvement in SNR was at the cost of decrease in data rate. The design and implemention of various hardware modules using hardware description language (HDL) for UOWC is carried out in [122] and [196]. An improvement in BER has been observed over uncoded systems using IEEE 802.15.4 and IEEE 802.11 protocols with CRC and carrier sense multiple access/collision detect (CSMA/CD) in the medium access control (MAC) layer of the system.

Although block codes are simple and robust, they are not capable of providing the optimal performance for UWOC system, especially in case of highly turbid water or multiple scatterers. In such cases, more powerful and complex codes such as LDPC and Turbo codes are employed. These codes can achieve performance close to the optimal power efficiency as given by information theory for a given bandwidth efficiency [192], [193]. However, perfect knowledge of transmitted sequence is required in order to obtain the estimates of received SNR for both of the coding schemes. LDPC is the most powerful coding scheme with sparse parity check matrix, H, i.e., density of 1's is low relative to zero. Standardized LDPC codes utilize block lengths on the order of 10^4 bits which make the encoding computationally intensive. Therefore, certain structures must necessarily be imposed on the H matrix to both facilitate the description of codes and reduce encoding complexity. Performance improvement in UOWC is observed using LDPC codes with PPM modulation technique in [194]. LDPC designed for second generation digital video broadcasting satellite standard (DVB-S2) is investigated using OOK modulation technique at code rates ranging from $r = 1/2$ to $r = 1/4$ in [195]. It was shown that DVB-S2 LDPC codes provide coding gains of approximately 8.4 dB, 8.9 dB, and 9.2 dB over the uncoded system at a BER of 10^{-4} for code rates of 1/2, 1/3, and 1/4, respectively. Also, it provides lower latency option that is attractive for future real-time implementation.

Turbo code is a parallel concatenated code that combines two or more convolutional codes and an interleaver to produce a block code in order to achieve a BER close to the Shannon limit. In [196], Turbo codes are used along with PPM modulation scheme to ensure reliable data transmission for underwater diver using optical communication. Turbo codes from the universal mobile telecommunications system (UMTS) standard and the consultative committee for space data systems (CCSDS) standard provide coding gains ranging from 6.8 dB to 9.5 dB for code rates ranging from 1/2 to 1/6 [195], [197]. A comprehensive list of modulation techniques and coding schemes is given in Table 8.

VII. COOPERATIVE DIVERSITY IN UOWC

UOWC provides high capacity links with low latency, however, they are not capable of long distance transmission due to various characteristic of underwater channel. Therefore, in order to achieve full benefit of optical carrier in underwater environment, there is a need to extend the short range of its coverage. Various techniques have been studied inorder to overcome this limitation by exploiting the spatial as well as multipath diversities in UWOC systems (such as MIMO, OFDM, spatial modulation techniques [203], etc.). Cooperative diversity (or relay-assisted diversity) is another technique to combat the challenging effects of UOWC and extend the range of optical communication. This diversity technique was introduced for terrestrial radio systems [204]–[206] and these days used in FSO systems [207], [208] as well. Although this scheme is extensively studied in underwater acoustic communication [209]–[213] but it has received relatively less attention in case of UOWC systems. It takes advantage of the signal being overheard by the neighboring nodes (also called relays) that was originally transmitted by the source node. The source and the relay nodes collectively work on the transmitted system to create a virtual antenna array although each of the nodes is equipped with a single antenna. Multi-hop transmission is a kind of relay-assisted transmission where relays are configured in serial fashion in order to split up a relatively longer distance into shorter distance with reduced absorption, scattering and fading effects. This helps in improving the link coverage with limited transmitted power. For example, in case of the underwater wireless sensor network, the main challenge is to forward the data from the source node to the remotely located control station. In this case, a hop-by-hop approach is very beneficial where the relay close to the network detects the data and forwards the data to the next relay until it reaches the control station in the last hop. This scheme not only covers a larger distance but also conserves energy, otherwise, it would not be possible for battery operated source nodes to reach relatively far located control stations due to the adverse effect of underwater channels. In [214], multi hop transmission with decode-and-forward (DF) relaying is demonstrated that outperforms the direct transmission due to reduced path loss. Recently, Akhoundi *et al.* [215] investigated a cellular underwater wireless optical code division multiple-access (OCDMA) network based on optical orthogonal codes (OOC) for different water types. Their work is extended in [216] using cooperative diversity in underwater environments where each source node uploads its own data via relays to a remotely located optical base transceiver station (OBTS) using OCC-OCDMA technique as shown in Fig. 14. BER performance of relay-assisted OCDMA was investigated and it was observed that even a dual-hop transmission in 90 m point-to-point clear ocean link gave a performance advantage of 32 dB over direct transmission.

Multi-hop transmission is very advantageous in case of the mobile underwater sensor network where the topology

TABLE 8. Summary of modulation and coding schemes used in UOWC system.

Modulation	Coding	Comments	Ref.
OOK	-	Simple but low efficiency	[54], [62], [127]
OOK	RS	Robust block code	[53]
OOK	BCH	Robust block code	[195], [203]
OOK	CRC	Simple and robust error detecting codes	[122]
OOK	Turbo	Complex decoding algorithm	[200]
PPM	-	Improved power efficiency but bandwidth inefficient	[180], [185], [204], [205]
PPM	LDPC	Provides near optimal performance but relatively complex decoding	[199], [200]
PPM	CRC	Improved power efficiency and simple error detecting code	[16]
Polarized PPM	-	Improved power efficiency and data rate than conventional PPM	[206]
PSK	-	Increased sensitivity and power efficient	[134], [181], [207]
QAM	-	Good immunity to noise and robust	[64], [65], [134], [192]
SIM	-	Good spectral efficiency but reduced power efficiency	[207]
SIM	RS	Robust code and improved BER performance	[191]

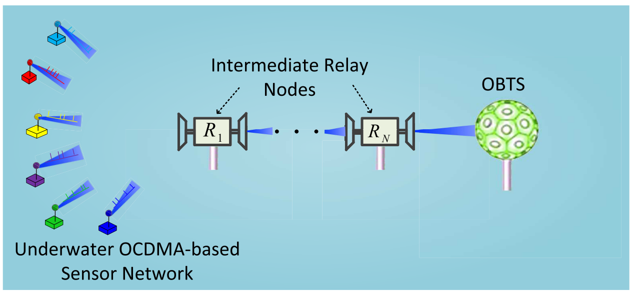


FIGURE 14. Relay-assisted OCDMA based UOWC [216].

changes very rapidly with time. In such cases, multi-hop transmission in conjunction with geographic routing protocol are employed to increase the robustness of the system. Nicolaou et al. [217] proposed a hop-by-hop approach using a geographic routing protocol i.e., vector-based forwarding (VBF) to forward the packet from the source to the target node using a routing vector. Further, delay tolerant networking [218] with store-and-forward technique also helps in underwater link outrages especially when there is no physical end-to-end connectivity due to channel turbulence or any obstacle (e.g. ships). Performance improvement of 5 dB is observed using amplify-and-forward (AF) protocols in cooperative diversity for underwater wireless communication systems [219]. In [220], an effective path loss model is analyzed for long distance underwater communication where information is transferred through a series of intermediate nodes acting as relays. This model takes into account the deterioration of the optical power as it propagates through the dense network configuration and determines the transmission range to satisfy the long distance connectivity criteria assuming IM/DD with OOK modulation technique. Although not much work is carried out in this direction for underwater optical communication, it seems to be a promising technology to improve the link coverage and geographical connection for remote cluster of nodes.

VIII. HYBRID ACOUSTO-OPTIC SYSTEM

Underwater optical wireless communication has high bit rate, low power requirement and less latency, but its transmission range is only few meters. On the other hand, acoustic communication has less bit rate, larger power consumption, significant latency but a longer range. Acoustic modems can operate between 100 and 5000 bps over moderate link distances or at higher data rates for shorter distances. Therefore, in order to take advantage of both of the technologies, a hybrid system is necessary. The hybrid system will complement the existing acoustic system by providing high data rate and low latency when operating within optical range and with long range and robustness when operating outside optical range. The purpose of underwater AUVs or sensors underwater is to relay a high volume of data to the central base station where the information is processed. These AUVs are equipped with both acoustic and optical modems. The acoustic modem is used for long distance communication and the optical modem is used for short distance communication after the alignment is assisted by acoustic communications. Therefore, in hybrid systems, optical transmitters occupy most of the uplink bandwidth by transmitting highly-directional high bandwidth signals. The downlink signal from the base station or ship to AUVs is a low frequency acoustic signal with wide FOV for the purpose of pointing or tracking of the AUVs. In the linear regime of optical-acoustic conversion [221], the laser beam incident at the air-water boundary is exponentially attenuated by the medium, creating an array of thermo-acoustic sources relating to the heat energy and physical dimensions of the laser beam in water, thus producing local temperature fluctuations that give rise to volume expansion and contraction [222]. The volume fluctuations in turn generate a propagating pressure wave with the acoustic signal characteristics of the laser modulation signal [16]. The hybrid acoustic optic system has significant advantages in terms of throughput and energy efficiency as shown in Fig. 15. It is seen from Fig. 15 (a) that the throughput of acoustic channel saturates as the offered load increases. The throughput increases drastically with only optical as well as hybrid channel models though the hybrid model outperforms the other two. Fig. 15 (b) clearly indicates the increase in power consumption of acoustic signals with data rate. In this case, both hybrid and optical models yield comparable results. Therefore, the hybrid acousto-optic system provides some degree of freedom to select the optimal transmission method within least transmission time depending upon the load and water type.

Hybrid acousto-optic system has been investigated in [223], where optical signals are used for uplink transmission of high data rate from submersed AUVs or divers to base station and acoustic signals are used for wide angle low data rate downlink. It was asserted in [223] that the maximum data rate by a hybrid model is greater than a traditional acoustic link by a factor of 150. The hybrid model is used in operating a unmanned self powered remotely operated vehicle (ROV) without requiring a physical connection to the ROV in [224]. Otherwise, sending ROVs thousands of meters below the surface of sea water for fetching data from oil resources is expensive and time consuming. This model is also useful in real time video streaming that requires high bandwidth as well as low latency. High capacity video streaming without underwater optical cables is studied in [225] that allows smooth transitions between the acoustic and optical video delivery mode using image processing algorithms. In [226], the authors present a multi-level Q-learning-based routing protocol, MURAO, using hybrid acoustic/optical communication for underwater wireless sensor networks. The experiment results show that MURAO is more robust to changes of network topology, and achieves much higher delivery rates as well as shorter delays in a dynamic network than the flat Q-learning routing.

IX. FUTURE SCOPE

UOWC is a complementary technology to conventional acoustic links as it provides high data rates with no latency over moderate distances. This helps in reducing power consumption and thereby, promotes reliable underwater monitoring and surveillance applications for longer time durations. UOWC finds its applications in environmental monitoring, data collection (such as water temperature, pH,

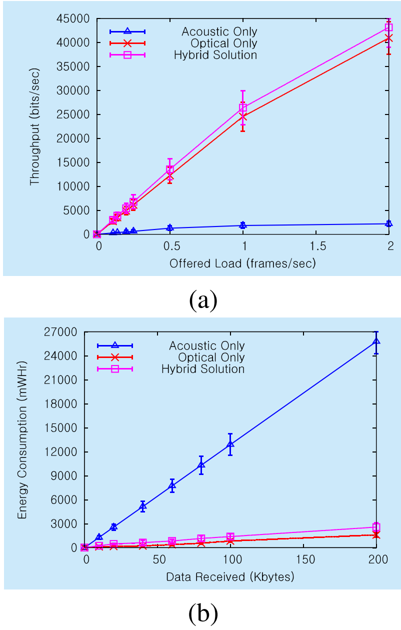


FIGURE 15. **Comparison of (a) throughput and (b) energy efficiency for acoustic, optical and hybrid systems [227].**

etc.), oil/gas monitoring and security. With the ongoing research and developments in this field, UOWC will provide an efficient and robust way of communication between surface vehicles, underwater devices and seafloor infrastructure. Due to low cost, small size, less power consumption and compatibility with other optical systems, it finds its application in heterogeneous network environments or in dense underwater wireless sensor networks. A hybrid communication system using a dual mode (acoustic and optics) transceiver is capable of providing very high data rates and can be used for assisting underwater robotic sensor networks. In case of high turbid underwater environment, the system can switch to low data rate acoustic transceiver, thereby, increasing the reliability of the communication link.

There are still many areas that require extensive research and investigation for long term survival of UOWC. There is need to dig more into fundamental insights and develop new approaches in communication to make UOWC a reality in near future. For this, there is a need for further investigation and analysis of new theoretical models (both analytical and computational) to better understand the laser beam propagation through randomly varying underwater channel. It may also include the modeling of solar penetration, multiple scattering mechanisms and reflections from sea surface, etc. Extensive field experiments and use of testbeds are essential to have better understanding of underwater environment and channel characterization. In order to improve the overall robustness in different underwater conditions, there is a need to explore adaptive techniques that can optimize communication efficiency and save more energy. As there are many obstacles to establish end-to-end communication links between source and destination nodes, there is a need to investigate more into spatial diversity techniques and routing protocols (such as proactive protocols, geographical routing protocols, reactive protocols, etc.). Higher layers of network architecture that include medium access, data link control, transport control and application layers need to be investigated for designing a practical UOWC link. Though there is little work carried out with different modulation or multiple access techniques [215], [228], [229], however, it has been shown that UOWC are capable of providing high speed optical links for short range applications. Further, the reliability of wireless optical communication in unreliable oceanography environment can be improved with the use of error control coding techniques.

There is a lot of work being done to produce simple, cost effective, low powered, robust and real time sensor systems. Various non-acoustic sensors such as optical sensor, electro-mechanical sensor [230], bio-inspired sensors [231] and MEMs based sensors [232] have also been developed for underwater applications. All these sensors are tailored for specific applications and are specially designed to withstand the underwater environmental conditions such as bio-fouling, limited energy resource, corrosive nature of sea water, pressure resistant enclosures, etc. Besides all these remarkable efforts, there is still room for future developments in producing more robust, cheap, adaptive and highly stable underwater optical sensors. This will not only guarantee long term survivability under dynamic conditions but will also avoid frequent and costly rescue operations.

X. CONCLUSION

An improvement in underwater communication system is needed due to increased number of unmanned vehicles in space and underwater. Traditional underwater communication is based on acoustic signals and despite the substantial advancement in this field, acoustic communication is hard pressed to provide sufficient bandwidth with low latency. RF signals for UOWC can only be used at ELF due to the high absorption of electromagnetic signals at radio frequencies. The use of optical fibers or co-axial cables limit the range and maneuverability of underwater operations. Optical underwater communication provides great potential to augment traditional acoustic communication due to its high data rates, low latency, less power consumption and smaller packaging. Also, this technology can benefit meaningfully from the progress made in the terrestrial optical wireless communication. However, the distance and scope of optical beam underwater is affected by water type, abortion, scattering and various other propagation losses. UOWC makes use of blue-green wavelength of visible spectrum as it offers low attenuation window and provides high bandwidth communication (in the order of MHz) over moderate distances (10 - 100 m). Moreover, a typical UOWC having point-to-point link requires strict pointing and tracking systems specially for mobile platforms. The use of smart transmitter and receivers, segmented FOV or electronic beam steering can relax the strict requirement of point and tracking for narrow optical beam. Also, in order to make the link workable for different underwater scenarios and prevent the loss due to LOS, various link configurations like retro-reflective, diffused and NLOS links are discussed in this survey. For an efficient and reliable underwater optical link, a profound knowledge of channel model, system architecture, system components and materials, modulation techniques, operating wavelength and it influence in underwater environment has to be well understood.

We conclude that though acoustic waves are the robust and feasible carrier in today's scenario but with rapid technological development and active ongoing research in UOWC, this technology will be more promising with game-changing potentials in the near future.

NOMENCLATURE

AF	Amplify-and-Forward
APD	Avalanche Photo-Diode
ARQ	Automatic Repeat Request
AUV	Autonomous Underwater Vehicle
BCH	Bose Chaudhuri Hocquenghem
BCH	Bose-Chaudhuri- Hocquenghem
BPSK	Binary Phase Shift Keying
CCSDS	Consultative Committee for Space Sata Systems
CDMA	Code Division Multiple Access
CDOM	Color Dissolved Organic Material
CRC	Cyclic Redundancy Check
CSMA	Carrier Sense Multiple Access / Collision Detection
CW	Continuous Wave
DAPPM	Differential Amplitude Pulse Position Modulation
DF	Decode-and-Forward
DFE	Differential Feedback Equalizer
DPI-PPM	Digital Pulse Interval- Pulse Position Modulation
DPIM	Digital Pulse Interval Modulation
DPPM	Differential Pulse Position Modulation
DPSK	Differential Phase Shift Keying
DVB-S2	Digital Video Broadcasting Satellite Standard
ELF	Extremely Low Frequency
EM	Electro-magnetic
FAMIS	Frequency Agile Modulated Imaging System
FEC	Forward Error Correction
FOV	Field-of-View
FSK	Frequency Shift Keying
FSO	Free Space Optics function Beam Spread Function
HDL	Hardware Description Language
IM/DD	Intensity Modulated/Direct Detection
ISI	Inter-Symbol Interference
LDPC	Low Density Parity Check

LF	Low Frequency
LOS	Line-of-Sight
MAC	Medium Access Control
MEMS	Micro-Electro-Mechanical Systems
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
MQW	Multiple Quantum Well
MRR	Modulating Retro-Reflector
OBTS	Optical Base Transceiver Station
OCDMA	Optical Code Division Multiple Access
OFDM	Optical Frequency Division Multiplexing
OOC	Optical Orthogonal Codes
OOK	On-Off Keying
PMTs	Photo-Multiplier Tubes
PPM	Pulse Position Modulation
PS-PPM	Phase shift-Pulse Position Modulation
PSK	Phase Shift Keying
PSSK	Phase Shift Silence Keying
PWM	Pulse Width Modulation
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
ROVs	Remotely Operated Vehicles
RS	Reed Solomon
RS	Reed-Solomon
RTE	Radiative Transfer Equation
SIM	Subcarrier Intensity Modulation
SIMO	Single Input Multiple Output
SLMs	Spatial Light Modulators
SNR	Signal to Noise Ratio
SPF	Scattering Phase Function
SSB	Single Side Band
TIR	Total Internal Reflection
TTHG	Two-Term Henyey-Greenstein
UMTS	Universal Mobile Telecommunications System
UOWC	Underwater Optical Wireless Communication
UUV	Unmanned Underwater Vehicle
VBF	Vector-Based Forwarding
VSF	Volume Scattering Function
ZF	Zero Forcing

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