A Survey of Underwater Optical Wireless Communications

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***Abstract*—Underwater wireless communications refer to data transmission in unguided water environment through wireless carriers, i.e., radio-frequency (RF) wave, acoustic wave, and optical wave. In comparison to RF and acoustic counterparts, underwater optical wireless communication (UOWC) can provide a much higher transmission bandwidth and much higher data rate. Therefore, we focus, in this paper, on the UOWC that employs optical wave as the transmission carrier. In recent years, many potential applications of UOWC systems have been proposed for environmental monitoring, offshore exploration, disaster precaution, and military operations. However, UOWC systems also suffer from severe absorption and scattering introduced by underwater channels. In order to overcome these technical barriers, several new system design approaches, which are different from the conventional terrestrial free-space optical communication, have been explored in recent years. We provide a comprehensive and exhaustive survey of the state-of-the-art UOWC research in three aspects: 1) channel characterization; 2) modulation; and 3) coding techniques, together with the practical implementations of UOWC.**

***Index Terms*—Channel coding, channel modeling, experimental underwater optical wireless communication (UOWC), hybrid acoustic/UOWC systems, modulation, underwater vehicles.**

NOMENCLATURE

AMOUR	Autonomous Modular Optical Underwater Robot
AOPs	Apparent Optical Properties
APD	Avalanche Photodiode
AUVs	Autonomous Underwater Vehicles
BCH	Bose-Chaudhuri-Hocquenghem
BER	Bit-Error Rate
BPSK	Binary Phase-Shift Keying
CDMA	Code Division Multiple-Access
CDOM	Colored Dissolved Organic Material
CORK-OTS	Circulation Obviation Retrofit Kit Optical Telemetry System
CRC	Cyclic Redundancy Check
CSAIL	Computer Science and Artificial Intelligence Laboratory
DPIM	Digital Pulse Interval Modulation
DPPM	Differential Pulse Position Modulation
DPSK	Differential Phase-Shift Keying
DT	Dynamic Threshold
FEC	Forward Error Correction
FOV	Field of View
FSO	Free Space Optical
Gbps	Gigabit per Second
GMSK	Gaussian Minimum Shift Keying
HDL	Hardware Description Language
HG	Henyey-Greenstein
IM/DD	Intensity Modulation/Direct Detection
IOPs	Inherent Optical Properties
ISI	Inter-Symbol Interference
Kbps	Kilobit per Second
LD	Laser Diode
LDPC	Low-Density Parity-Check
LED	Light-Emitting Diode
LOS	Line-of-Sight
LT	Luby Transform
MAC	Medium Access Control
Mbps	Megabit per Second
MEMS	Micro-Electromechanical System
MIMO	Multiple-Input Multiple-Output
MIT	Massachusetts Institute of Technology
ML	Maximum Likelihood
MPPM	Multi-Pulse Pulse Position Modulation
NLOS	Non-Line-of-Sight
NRL	Naval Research Laboratory
NRZ-OOK	Non-Return-to-Zero On-Off Keying
OFDM	Orthogonal Frequency-Division Multiplexing
OOK	On-Off Keying
OWC	Optical Wireless Communications
PAPR	Peak-to-Average Power Ratio
PC	Personal Computer
PDF	Probability Density Function
PIN	Positive-Intrinsic-Negative
PolSK	Polarization Shift Keying
PPM	Pulse Position Modulation
P-PPM	Polarized- Pulse Position Modulation
PSK	Phase-Shift Keying
PWM	Pulse Width Modulation
QAM	Quadrature Amplitude Modulation

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QPSK	Quadrature Phase-Shift Keying
RF	Radio Frequency
RF-EM	Radio-Frequency Electromegnetic
ROVs	Remotely Operated Underwater Vehicles
RS	Reed-Solomon
RTE	Radiative Transfer Equation
RZ-OOK	Return-to-Zero On-Off Keying
SIM	Subcarrier Intensity Modulation
SIMO	Single-Input Multiple-Output
SISO	Single-Input Single-Output
SNR	Signal-to-Noise Ratio
SPF	Scattering Phase Function
TDMA	Time Division Multiple-Access
UTROV	Untethered ROV
UWC	Underwater wireless communication
UOWC	Underwater Optical Wireless Communication
UWSNs	Underwater Wireless Senor Networks
VSF	Volume Scattering Function.

I. Introduction

A. Overview of Underwater Optical Wireless Communication

TWO THIRDS of the earth surface is covered with water. For the past thousands of years, humans have never stopped exploring the ocean. In recent years, with the ever-increasing global climate change and resource depletion, there has been a growing interest in the research of ocean exploration system. Underwater wireless communication (UWC) technology enables the realization of ocean exploration systems, and thus attracts much attention. UWC refers to transmitting data in an unguided water environment through the use of wireless carriers, i.e., radio-frequency (RF) waves, acoustic waves, and optical waves. Considering the limited bandwidth of RF and acoustic methods and the increasing need for high-speed underwater data transmission, underwater optical wireless communication (UOWC) has become an attractive and viable alternative. In fact, light has been used as a method of wireless communication for thousands of years in various forms. For instance, the ancient Chinese used beacon towers to deliver military information around 1,000 BC, and the ancient Greek and Roman armies used polished shields to reflect sunlight for signaling around 800 BC. In 1880, Alexander Graham Bell developed a wireless telephone system that used sunlight as the transmission medium. This system is regarded as the first optoelectronic communication system in the world [1], [2]. In the 1960s, the invention of laser as an optical source changed the future of optical wireless communication (OWC) [3]. From that time on, a flurry of terrestrial OWC applications appeared. Due to the severe attenuation effects of seawater to visible light and the limited knowledge of aquatic optics, the early development of UOWC was far behind the terrestrial free-space optical (FSO) communications. However, in recent years, there are growing research activities in UOWC. There is an urgent need for a comprehensive survey that can provide researchers with a fundamental understanding of UOWC and knowledge of the state-of-the-art UOWC research.

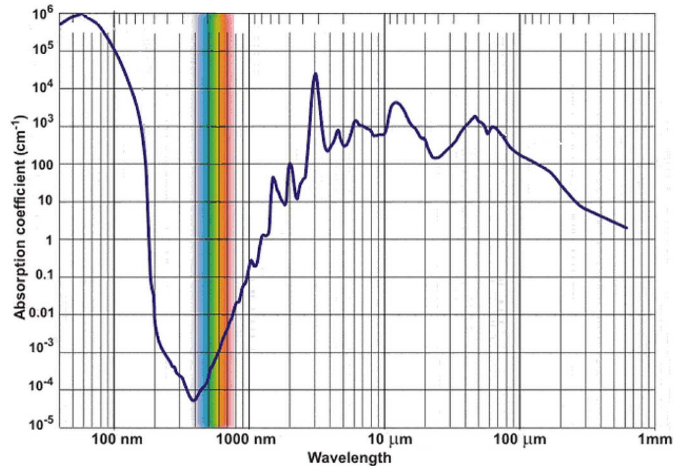


Fig. 1. The "transparent window" for light aquatic attenuation [4].

Based on nearly 20 years experimental and theoretical study of light propagation in the sea, Duntley proposed in 1963 that seawater shows a relatively low attenuation property to light with wavelengths from 450nm to 550nm, which corresponds to the blue and green spectrum (Fig. 1) [5]. This finding was then experimentally confirmed by Gilbert *et al*. [6]. The existence of the blue-green light transmission "window" in water provides a foundation for the development of future UOWC. The early applications of UOWC are mainly for military purpose, especially in submarine communications. In 1976, Karp evaluated the feasibility of optical wireless communications between underwater and above surface (satellite) terminals [7]. In 1977, the researchers from the Lawrence Livermore Laboratory of the University of California proposed a one-way optical communication system from shore to submarine [8]. The transmitter of the UOWC system employed blue-green laser source to generate light pulses. It was flexible to be carried by a land vehicle or an airplane due to its compact architecture. The transmitter can also focus its output light beam on a relay satellite, which then reflects the beam to a submarine [8]. Other UOWC tests such as the plane-to-submarine topology were also established by U.S. Navy in early 1990s [9].

Over the decades, the interest of UOWC is still limited to military applications [8], [10]. The massive market promotion of UOWC has not been achieved so far. Only a few limited UOWC products were commercialized in the early 2010s. These products include the BlueComm UOWC system that can achieve 20 Mbps underwater data transmission over a distance of 200m [11], [12], and the Ambalux UOWC system that can provide 10 Mbps data transmission with a range of 40m [13], [14]. A recent numerical study shows that it is possible to achieve LED-based visible light communication over a link distance of 500m in pure seawater by employing a single photon avalanche diode [15]. In order to satisfy the increasing demands for ocean exploration with efficient high bandwidth data transmission, researchers have proposed the concept of underwater wireless sensor networks (UWSNs). The proposal of UWSNs has greatly facilitated the development of UOWC. Thus, the market of UOWC has begun

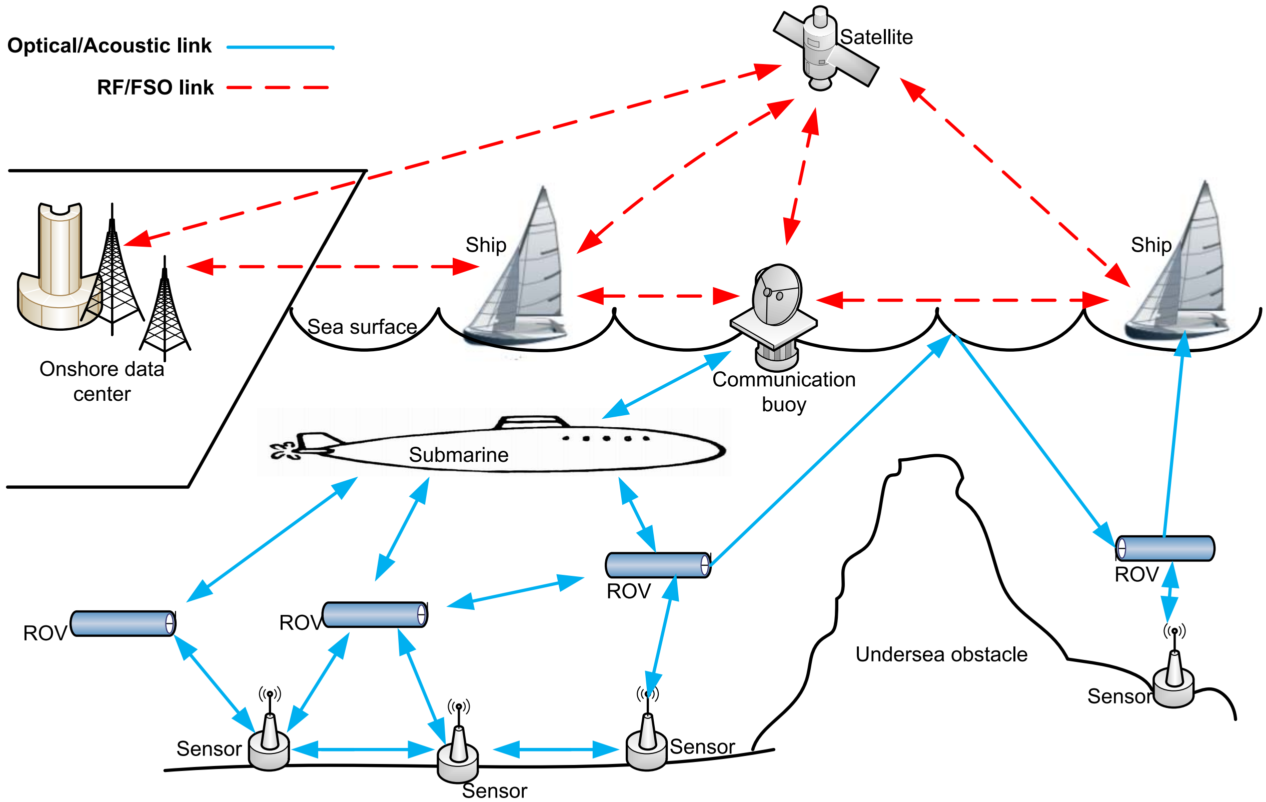


Fig. 2. An underwater wireless sensor network with aerospace and terrestrial communication.

to show a future promise. The basic UWSNs consist of many distributed nodes such as seabed sensors, relay buoys, autonomous underwater vehicles (AUVs) and remotely operated underwater vehicles (ROVs) (Fig. 2). These nodes have the capabilities to accomplish sensing, processing, and communication tasks that maintain the collaborative monitoring to the underwater environment [16]. In Fig. 2, sensors located at the bottom of the seabed collect data and transmit via acoustic or optical links to the AUVs and ROVs. Then, AUVs and ROVs relay signals to ships, submarines, communication buoys and other underwater vehicles. Above the sea surface, the onshore data center processes data and communicates with satellite and ships through RF or FSO links.

B. Review of Related UOWC Surveys and Motivations

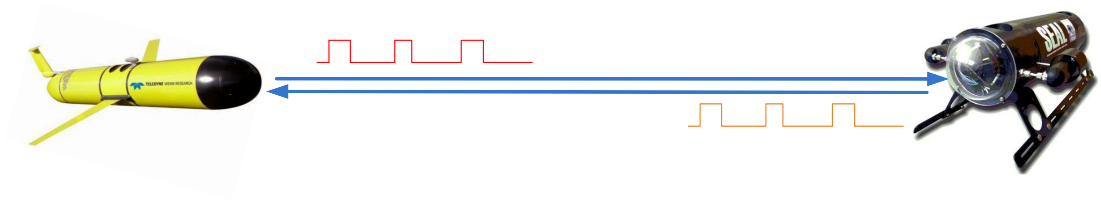
With increasing activities in UOWC research, several brief articles have been published to survey the subject. Khalighi *et al.* [14] briefly reviewed some recent works on UOWC in channel models, modulation and coding schemes, and experimental works. The authors also presented the performance study of a typical UOWC system under several simplified assumptions. Johnson *et al.* [17] conducted a survey on UOWC channel models. Several typical UOWC modeling approaches such as Beer Lambert's law, radiative transfer function, and Monte-carlo method were briefly discussed. Johnson *et al.* [18] introduced UOWC and mainly focused on aquatic optical properties. Arnon [19], evaluated the link performance of a typical UOWC system and introduced a number of challenging issues associated with UOWC systems. In this work, we provide a comprehensive survey of UOWC research from its inception to its current state, and the framework of this survey article follows that in [14]. Besides the fundamentals and highlighted challenges, this survey can facilitate new research in UOWC. Towards the end of this article, we will also suggest a number of research problems and directions in order to invite more UOWC related research, as the underlying transmission problem is extremely challenging.

C. Organization

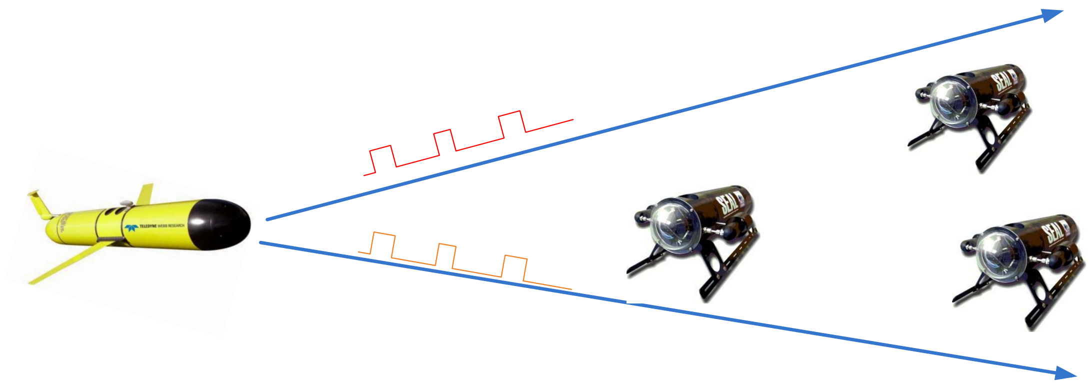
The remainder of this article is organized as follows. Section II introduces the fundamentals of UOWC, which includes the link configurations of UOWC, the advantages and challenges of UOWC, and several light propagation properties in underwater environment. In Section III, we focus on UOWC channel models and cover the modeling of aquatic optical attenuation, link misalignment, and link turbulence. In Section IV, we provide details on modulation and coding techniques that have been implemented in UOWC systems. Section V describes the progress achieved in practical implementations of UOWC, including experimental line-of-sight UOWC systems, non-line-of-sight UOWC systems, retroreflector-based UOWC systems, UOWC smart transceivers, and hybrid UOWC systems. Section VI summarizes the survey and suggests some future directions for UOWC research.

II. FUNDAMENTALS OF UOWC

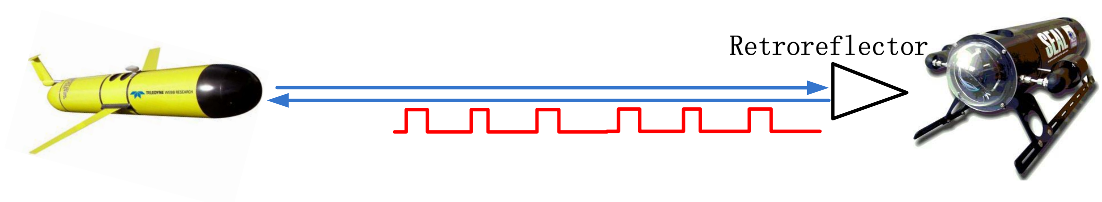
In this section, we will introduce background information which constitutes the basis of UOWC research. First, we



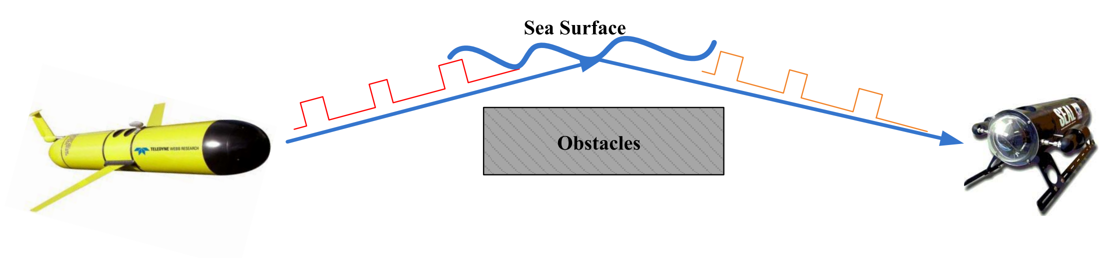
(a) Point-to-point LOS configuration.



(b) Diffused LOS configuration.



(c) Retroreflector-based LOS configuration.



(d) NLOS configuration.

Fig. 3. Four link configurations of UOWC.

will present the link configurations of UOWC. Second, the advantages and challenges of UOWC will be highlighted. At the end of this section, we will present background knowledge related to light propagation properties in underwater environment.

A. Link Configuration of UOWC

Based on link configurations between the nodes in UWSNs, UOWC can be classified into four categories (Fig. 3) [18]: 1) Point-to-point line-of-sight (LOS) configuration, 2) Diffused LOS configuration, 3) Retroreflector-based LOS configuration, and 4) Non-line-of-sight (NLOS) configuration.

1) Point-to-point LOS configuration (Fig. 3(a)) is the most commonly used link configuration in UOWC [19]. In a point-to-point LOS configuration, the receiver detects the light beam in the direction of the transmitter. Since the point-to-point LOS UOWC system commonly employs light sources, such as lasers, with narrow divergence angle, it requires precise pointing between transmitter and receiver. This requirement will limit the performance of UOWC systems in turbulent water environments and can become a severe problem when the

transmitter and the receiver are non-stationary nodes, such as AUVs and ROV [18].

2) Diffused LOS configuration employs diffused light sources, such as high-power light-emitting diodes (LEDs), with large divergence angle to accomplish broadcasting UOWC from one node to multiple nodes (Fig. 3(b)). Broadcasting method can relax the requirement of precise pointing. However, compared with the point-to-point LOS configuration, the diffused-light based link suffers from aquatic attenuation due to the large interaction area with water. Relatively short communication distances and lower data rates are the two major limitations of this configuration.
3) Retroreflector-based LOS configuration, as shown in Fig. 3(c), can be regarded as one special implementation of the point-to-point LOS configuration. This configuration is suitable for duplex UOWC systems with underwater sensor nodes having limited power and weight budget. In modulating the retro-reflector link, the transmitted light is reflected back from a modulated retro-reflector. During this process, the information that the retroreflector responses to the transceiver will be encoded on the reflected light. Since there is no laser or other light sources in the retroreflector end, its power consumption, volume and weight will be tremendously reduced. One limitation of this configuration is that the backscatter of the transmitted optical signal may interfere with the reflected signal, thus degrading the system signal-to-noise ratio (SNR) and bit-error rate (BER). Moreover, since the optical signals go through the underwater channel twice, received signal will experience additional attenuation.
4) NLOS configuration (Fig. 3(d)) overcomes the alignment restriction of LOS UOWC. In this configuration, the transmitter projects the light beam to the sea surface with an angle of incidence greater than the critical angle so that the light beam experiences a total internal reflection [20]. The receiver should keep facing the sea surface in a direction that is approximately parallel with the reflected light to ensure proper signal reception. The major challenge of NLOS links is the random sea surface slopes induced by wind or other turbulence sources [21]. These undesirable phenomena will reflect light back to the transmitter and cause severe signal dispersion.

B. Advantages and Challenges of UOWC

UOWC systems are used for high speed underwater communications between multiple fixed or mobile nodes. They have great potential for applications in the UWSNs. There are three UWC choices for implementing UWSNs: acoustics, RF and optics [22]. In order to emphasize the unique advantages and characterizations of UOWC, we will compare the UOWC with the RF and acoustic methods.

The acoustic method is the most widely used technology in UWC. It has a long application history that can be dated to late 1800s. After an extensive expansion of military applications during the two World Wars, underwater acoustic communication system became a popular proven technology that has been applied to almost every aspect of UWSNs [23]. Considering the extreme broadness of ocean and the strong attenuation effect of seawater to other transmission sources like optical wave and RF wave, the most attractive advantage of underwater acoustic communication is that it can achieve a long link range up to several tens of kilometers [24]. Although acoustic method is the most popular method to achieve UWC, it also has certain intrinsic technical limitations. First, since the typical frequencies associated with underwater acoustics are between tens of hertz and hundreds of kilohertz, the transmission data rate of acoustic link is relatively low (typically on the order of Kbps) [16]. Second, due to the slow propagation speed of sound wave in water (about 1500m/s for pure water at 20 Celsius), the acoustic link suffers from severe communication delay (typically in seconds). Thus it cannot support applications that require real-time large volume data exchange. Third, acoustic transceivers are usually bulky, costly and energy consuming. They are not economical for large scale UWSNs implementations [25]. Furthermore, acoustic technology can also impact marine life which uses sound waves to accomplish communication and navigation [26].

The underwater RF communication can be dealt with as an extension of the terrestrial RF communication. The underwater RF communication has two major advantages. First, compared with acoustic wave and optical wave, the RF wave can perform a relatively smooth transition through air/water interface. This benefit can be used to achieve the cross-boundary communication which combines the terrestrial RF communication system and underwater RF communication system together. Second, RF method is more tolerant to water turbulence and turbidity than optical and acoustic methods [22]. The fatal limitation that impedes the development of underwater RF method is its short link range. Since seawater that contains lots of salt is a conductive transmission medium, the RF waves can only propagate a few meters at extra-low frequencies (30-300Hz) [16]. Moreover, the underwater RF systems also require huge transmission antenna and costly, energy-consuming transceivers.

Compared with the acoustic approach and RF approach, UOWC has the highest transmission data rate, the lowest link delay and the lowest implementation costs. UOWC can achieve a data rate on the order of Gbps over moderate distances of tens of meters [14]. This high-speed advantage will guarantee the realization of many real-time applications such as underwater video transmission. Since the transmission speed of light in water is much higher than acoustic wave, UOWC links are immune to link latency [14], [16], [22]. UOWC also has higher communication security over the acoustic and RF methods. Most UOWC systems are implemented in LOS configuration, rather than the diffused broadcasting scenario like acoustic and RF wave. It becomes more difficult to be eavesdropped. Furthermore, UOWC is much more energy efficient and cost-effective than its acoustic and RF counterparts [22]. Instead of using large and expensive acoustic and RF transceivers which are highly energy consuming, relatively small and low-cost optical underwater

TABLE I
COMPARISON OF UNDERWATER WIRELESS COMMUNICATION TECHNOLOGIES [22]

UWC technologies	Benefits	Limitations
Acoustic	· Most widely used UWC technology · Long communication range up to 20 km	· Low data transmission rate (on the order of kbps) · Large communication latency (on the order of second) · Bulky, costly and energy consuming transceivers · Harmful to some marine life
RF	· Relatively smooth transition to cross air/water boundaries · More tolerant to water turbulence and turbidity · Loose pointing requirements · Moderate data transmission rate (up to 100 Mbps) at close distance	· Short link range · Bulky, costly and energy consuming transceivers
Optical	· Ultra-high data transmission rate (up to Gbps) · Immune to transmission latency · Low cost and small volume transceivers	· Can't cross water/air boundary easily · Suffers from severe absorption and scattering · Moderate link range (up to tens of meters)

transceivers, such as laser diodes and photo diodes, can be implemented in UOWC systems. This benefit can improve the large scale commercialization of UOWC, and accelerate the implementations of UWSNs.

Although UOWC enjoys many advantages over the acoustic and RF methods, achieving UOWC remains as a challenging task. The main challenges of UOWC are listed as follows.

1) Optical signal suffers from severe absorption and scattering. Although the wavelength of transmission light has been carefully selected in the blue and green spectrum [5] to minimize the transmission attenuation effect, due to the inevitable photon interactions with the water molecules and other particulate matters in water, absorption and scattering still severely attenuate the transmitted light signal and cause multi-path fading. Due to the impact of absorption and scattering, UOWC suffers from poor BER performance over a few hundred meters link distance in turbid water environment. In underwater environment, matters such as chlorophyll are capable of absorbing the blue and red lights. These matters and other colored dissolved organic material (CDOM) can increase the turbidity of the water, and thus shrink the propagation distance of the light. Moreover, the concentration of CDOM will also change with ocean depth variations, thus changing the corresponding light attenuation coefficients [27]. These undesirable impacts will increase the complexity of UOWC systems.
2) Underwater optical links will be temporarily disconnected due to misalignment of optical transceivers. In several UOWC systems, blue/green lasers or LEDs have been implemented as the light sources due to their narrow divergence feature; however, a precise alignment condition is required [19]. As the underwater environment is turbulent at relatively shallow depths, link misalignment will take place frequently, especially in the vertical buoy-based surface-to-bottom UOWC applications [27], [28]. Random movements of sea surface will cause serious connectivity loss problem [29].
3) Implementation of UOWC systems requires reliable underwater devices. The underwater environment is complex. The flow, pressure, temperature and salinity of seawater will strongly impact the performance and lifetime of UOWC devices [16]. Considering that no solar energy can be exploited undersea and extended undersea operation time of UOWC devices, the reliability of device batteries and efficiency of device power consumption are critical [16].

In Table I, we summarize the benefits and limitations of the three popular techniques to achieve UWC.

C. Light Propagation in Water

Due to the unique optical characteristics of underwater environment, light propagation in water is sophisticated. In order to derive new channel models for UOWC and implement reliable UOWC network, it is necessary to understand the basic properties of light propagation in underwater environment, which can provide the foundation of UOWC system design.

According to Mobley's statements [30], the optical properties of water can be classified into two different groups: inherent optical properties (IOPs) and apparent optical properties (AOPs). IOPS can be understood as the optical parameters that only depend on the composition of transmission medium [18]. They are independent of the characterizations of light sources. The major IOPs of water are the absorption coefficient, the scattering coefficient, the attenuation coefficient, and the volume scattering function [31]. AOPs, on the other hand, are known as the optical parameters that depend on not only the transmission medium itself, but also the geometrical structure of the light field such as diffusion and collimation [18]. The three major AOPs of water are radiance, irradiance and reflectance [31]. In the UOWC system, IOPs are typically used in determining communication link budgets, whereas AOPs are used to calculate ambient light levels for communication systems near the ocean surface [18]. Since IOPs have a greater impact on the link performance, in the rest of this section, we will focus on IOPs. The details of AOPs that include their definitions and measurements can be found in [30]–[34].

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

In order to derive the absorption and scattering coefficients mathematically, we introduce a simple model shown in Fig. 4. We assume that a volume of water ΔV with thickness ΔD is illuminated by a collimated light beam with wavelength λ. We denote the power of incident light as P_I. A portion of the incident light power P_A is absorbed by water, and another portion of light power P_S[1] is scattered. P_T is the remaining light power that will propagate as desired. According to the law of power conservation, we have [30], [36]

[1]The reflected light component is included in P_S.

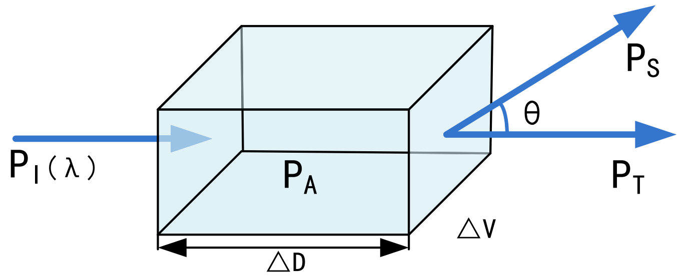


Fig. 4. Geometry of inherent optical properties for a volume ΔV. Fig. 4 is adapted from [30].

$$P_I = P_A + P_S + P_T. \tag{1}$$

Based on (1), we define the ratio between the absorbed power and the incident power, $\frac{P_A}{P_I}$, as absorbance. Similarly, the fraction between the scattered power and the incident power, $\frac{P_S}{P_I}$, as scatterance. The subsequent absorption coefficient and scattering coefficient are then calculated by taking the limit of absorbance and scatterance as water thickness ΔD becomes infinitesimally small [30], [36]

$$a(\lambda) = \lim_{\Delta D \to 0} \frac{P_A}{P_I \Delta D}, \tag{2}$$

$$b(\lambda) = \lim_{\Delta D \to 0} \frac{P_S}{P_I \Delta D}. \tag{3}$$

In underwater optics, the overall attenuation effects of absorption and scattering can be described by the attenuation coefficient[2] $c(\lambda)$ which can be expressed as [38]

$$c(\lambda) = a(\lambda) + b(\lambda) \tag{4}$$

where the unit of attenuation coefficient is m^{-1}. In addition, Jerlov [39] states that the underwater light absorption coefficient can be further represented as the summation of four absorption factors [39]

$$a(\lambda) = a_w(\lambda) + a_{CDOM}(\lambda) + a_{phy}(\lambda) + a_{det}(\lambda) \tag{5}$$

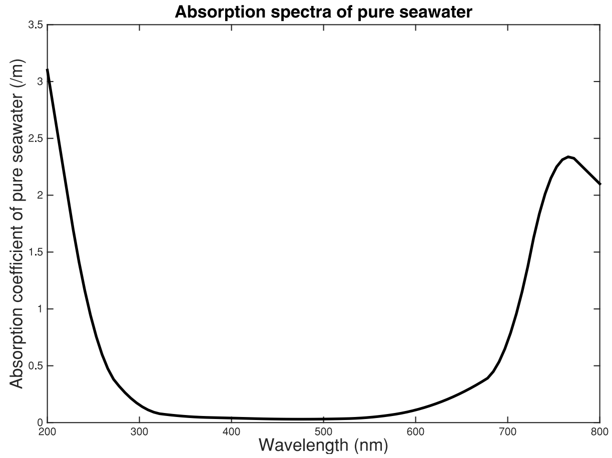
where $a_w(\lambda)$ is the absorption due to pure seawater; $a_{CDOM}(\lambda)$ is the absorption due to CDOM; $a_{phy}(\lambda)$ denotes the absorption due to phytoplankton; and $a_{det}(\lambda)$ represents the absorption due to detritus.

The absorption effect of pure seawater is introduced from two sources: the water molecules and dissolved salt in water such as NaCl, $MgCl_2$, Na_2SO_4, and KCl [40]. Pure seawater is absorptive except around a 400nm-500nm window, the blue-green region of the visible light spectrum. The corresponding absorption spectrum of pure seawater is shown in Fig. 5(a).

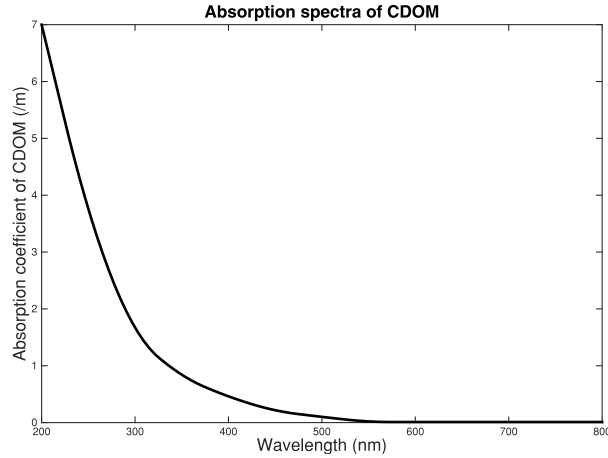
CDOM[3] refers to colored dissolved organic materials with dimension smaller than 0.2 mm [41]. Fig. 5(b) shows that the CDOM is highly absorptive to blue wavelengths (420 nm-450 nm) and less absorptive to yellow and red light [42].

[2]Also known as extinction coefficient in some optical literature [30], [37].

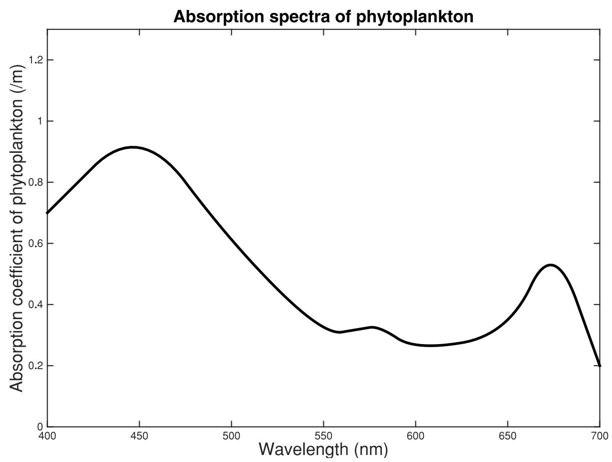
[3]In optical literature, CDOM is also represented as gelbstoff, yellow substances or gilvin.



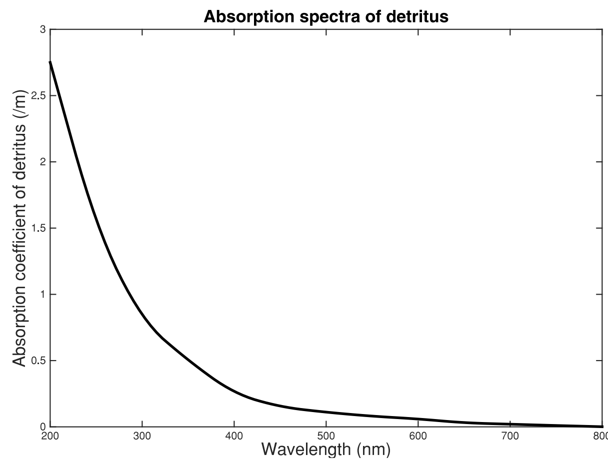
(a) Absorption spectra of pure seawater.



(b) Absorption spectra of CDOM.



(c) Absorption spectra of phytoplankton.



(d) Absorption spectra of detritus.

Fig. 5. Optical absorption spectra for different ocean components. The data in Fig. 5 are taken from [45]–[47].

The absorption effects due to phytoplankton are mainly caused by photosynthesising of chlorophyll. For different phytoplankton species, the characteristics of the absorption effect are also different [43]. Fig. 5(c) shows a typical absorption coefficient profile shared by all species. We can observe that the $a_{phy}(\lambda)$ shows a high absorption in the 400-500 nm region and a further peak at about 660 nm.

Detritus includes living organic particles such as bacteria, zooplankton, detrital organic matter and suspended inorganic particles such as quartz and clay. These substances are grouped together due to their similar absorption behaviour [44]. Fig. 5(d) shows a absorption curve similar to that of CDOM.

The scattering coefficient for underwater light propagation can also be presented as a summation of different scattering factors

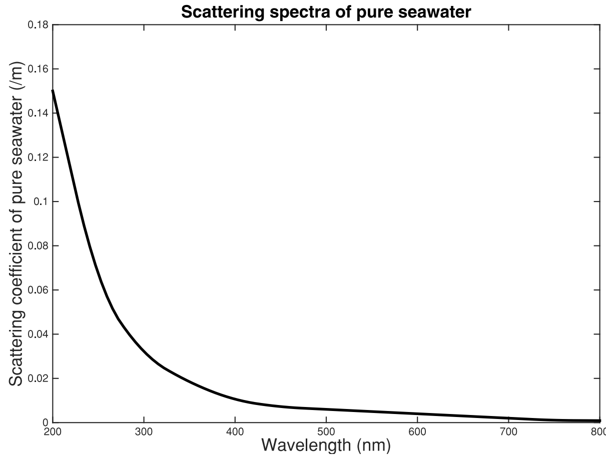
$$b(\lambda) = b_w(\lambda) + b_{phy}(\lambda) + b_{det}(\lambda) \tag{6}$$

where $b_w(\lambda)$ is the scattering due to pure seawater; $b_{phy}(\lambda)$ denotes the scattering due to phytoplankton; and $b_{det}(\lambda)$ represents the scattering due to detritus. Compared with absorption, scattering is relatively independent of wavelength. The dominant factor that impacts scattering is the density of particulate matters.

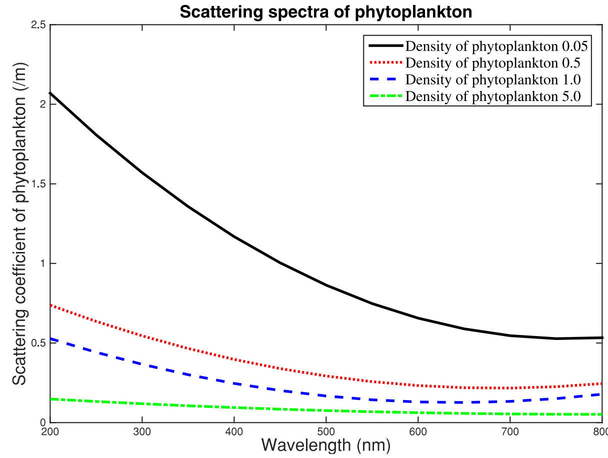
In pure seawater, since the refractive index will change with the variations of flow, salinity and temperature, the scattering coefficient will also change. Compared with the size of water molecules, the wavelength of light is relatively large, thus the Rayleigh scattering model can be used to describe the scattering induced by pure seawater. The corresponding scattering spectrum is shown in Fig. 6(a).

Phytoplankton and detritus account for more than 40% of the total scattering effects [48]. Since the scattering light caused by phytoplankton and detritus propagates mainly in the forward direction, Mie scattering model can be used to approximate these two types of scattering [30]. In practice, the exact scattering coefficient highly depends on the density of phytoplankton and detritus [49]. In Fig. 6(b) and Fig. 6(c), we present the scattering spectra due to phytoplankton and detritus with different densities. A summary of the above discussion on seawater absorption and scattering characteristics is presented in Table II.

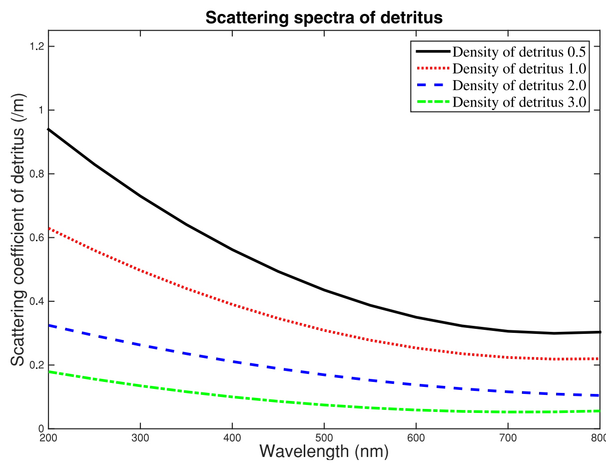
Based on the attenuation coefficient that has been introduced, Beer-Lambert's law provides the simplest and most



(a) Scattering spectra of pure seawater.



(b) Scattering spectra of phytoplankton.



(c) Scattering spectra of detritus.

Fig. 6. Optical scattering spectra for different ocean components. The data in Fig. 6 are taken from [45]–[47].

widely used scenario to describe the light attenuation effects in underwater environment [50] as

$$I = I_0 e^{-c(\lambda)z} \tag{7}$$

where I_0 is the power of transmitted light; z denotes the light transmission distance; I represents the power of light after transmitting z distance; and $c(\lambda)$ stands for the attenuation coefficient. The value of attenuation coefficient $c(\lambda)$ will change with different water types and water depths. The typical values of $a(\lambda)$, $b(\lambda)$, and $c(\lambda)$ associated with four major water types are given in Table III. In pure seawater, absorption is the main limiting factor, the low scattering coefficient makes the beam free from divergence. In clear ocean waters, there is a higher concentration of dissolved particles affecting scattering. In coastal ocean water, high concentrations of plankton, detritus and minerals are the dominant sources of absorption and scattering. Turbid harbor water has the highest concentration of dissolved and in-suspension matters, which will severely attenuate the light propagation [37]. More details of water types and variations of attenuation coefficient with other parameters such as depth, pressure, and salinity can be found in [27], [30], [48], [51], and [52].

From (4) and (7), we know that the Beer-Lambert law contains two implicit assumptions. First, the transmitter and receiver are perfectly aligned. Second, all the scattered photons are lost even though in reality some of the scattered photons can still arrive at the receiver after multiple scattering events. This assumption severely underestimates the received optical power, especially in the scattering dominant situation. In order to describe the scattering effects more accurately, volume scattering function (VSF), which is another important IOP, can be introduced, and it is defined as [36]

$$\beta(\theta, \lambda) = \lim_{\Delta D \to 0} \lim_{\Delta\Omega \to 0} \frac{P_S(\theta, \lambda)}{\Delta D \Delta\Omega} \tag{8}$$

where $P_S(\theta, \lambda)$ is the fraction of incident power scattered out of the beam into a solid angle $\Delta\Omega$ centered on θ (Fig. 4). VSF is the scattered intensity per unit incident irradiance per unit volume of water. In view of the physics, the VSF can also be interpreted as the differential scattering cross section per unit volume [36]. Integrating $\beta(\theta, \lambda)$ over all directions (solid angles) gives the scattering coefficient [36]

$$b(\lambda) = \int \beta(\lambda, \theta) d\Omega = 2\pi \int_0^{\pi} \beta(\lambda, \theta) \sin(\theta) d\theta. \tag{9}$$

TABLE II
SUMMARY OF ABSORPTION AND SCATTERING CHARACTERISTICS OF SEAWATER [39]

Compositions	Absorption coefficient	Scattering coefficient
Water	· Invariant at constant temperature and pressure. · Strongly depends on λ	· Rayleigh scattering. · Small variance compared with absorption. · Strongly depends on λ
Sea salts	· Negligible in visible spectrum. · Increase towards short λ	· Rayleigh scattering. · Not depend on λ
CDOM	· Variable with the density of CDOM. · Increase towards short λ	· Negligible
Plankton and detritus	· Variable with the density of plankton and detritus. · Increase towards short λ	· Mie scattering. · Variable with the density of plankton and detritus. · Increase towards short λ

TABLE III
TYPICAL VALUES OF $a(\lambda)$, $b(\lambda)$, AND $c(\lambda)$ FOR DIFFERENT WATER TYPES [30], [37], [53], [54]

Water types	$a(\lambda)$ (m^{-1})	$b(\lambda)$ (m^{-1})	$c(\lambda)$ (m^{-1})
Pure sea water	0.053	0.003	0.056
Clear ocean water	0.114	0.037	0.151
Costal ocean water	0.179	0.219	0.398
Turbid harbor water	0.295	1.875	2.17

Normalizing (8) with the scattering coefficient, we obtain the scattering phase function (SPF), which is defined as [36]

$$\tilde{\beta}(\theta, \lambda) = \frac{\beta(\lambda, \theta)}{b(\lambda)}. \tag{10}$$

The scattering phase function is also an important IOP. Considering the difficulty in measuring the SPF, the Henyey-Greenstein (HG) function is commonly introduced to present the SPF as [55]–[59]

$$\tilde{\beta}(\theta, \lambda) = P_{HG}(\theta, g) = \frac{1 - g^2}{4\pi\left(1 + g^2 - 2g\cos\theta\right)^{\frac{3}{2}}} \tag{11}$$

where g is the average cosine of θ in all scattering directions.

D. Lessons Learned From Fundamentals of UOWC

In this section, we have introduced four typical link configurations of UOWC. According to the characteristics of each link configuration, different application scenarios for each configuration can be proposed. Point-to-point LOS configuration can achieve high-speed laser UOWC in a moderate distance, but require precise pointing between transmitter and receiver. Thus, this configuration is suitable for UOWC systems that are in clear deep ocean. Diffused LOS configuration can relax the requirement of precise pointing, but suffer from short link distance and low data rate. Thus, shallow turbulent water area is the potential application environment for this configuration. Since retroreflector-based LOS configuration overcomes the limitation of power and weight of UOWC transceiver, small underwater sensor node can take this advantage. NLOS configuration overcomes the alignment restrictions of undersea obstacles. Thus, shallow costal water with lots of reefs can adopt this configuration.

In the second part of this section, we have compared UOWC with RF and acoustic communication method to present the advantages and challenges of UOWC. In summary, UOWC benefits from its capability to achieve high-speed UWC in a moderate distance. But it suffers from several limitations such as severe aquatic optical attenuation, pointing errors, and limited communication distance. Future research on UOWC should focus on overcoming these limitations.

In the third part of this section, we have introduced the concept of absorption and scattering coefficients, Beer Lambert's law, as well as VSF. These concepts provide a theoretical basis for UOWC system design [37]. In a UOWC link, the optical signal launched from the transmitter will experience various losses before reaching the receiver. They include system loss introduced by transceivers, link loss results from water attenuation, geometric misalignment, and water turbulence.

Since the loss introduced by the transceiver is mainly characterized by device parameters and design specifications, it is challenging to characterize the loss in a comprehensive and uniform approach. Thus, in Sections III, we will focus on the channel modeling techniques in UOWC links.

III. UOWC Channel Modeling

Compared with terrestrial FSO communication channels, UOWC channels have several unique characteristics. The existing terrestrial FSO channel models are not suitable for underwater environment; therefore, new reliable channel models must be proposed and studied. In this section, we will present the state-of-the-art of UOWC channel modeling techniques, which include link attenuation modeling, geometric misalignment modeling, and turbulence modeling.

A. Modeling of Aquatic Optical Attenuation in UOWC

As we have presented in Section II-C, without considering the link configuration, transceiver architecture and alignment condition, the two major IOPs that will attenuate light propagation in UOWC systems are absorption and scattering. Thus, the modeling of UOWC aquatic optical link attenuation can be regarded as a task that accurately describes the absorption and scattering effects with specific link configurations. In the remaining of this section, we will introduce the models of aquatic optical attenuation in two categories: LOS configuration and NLOS configuration.

1) Aquatic Optical Attenuation in LOS Configuration: For simplicity, several researchers utilized the Beer-Lambert law to model LOS UOWC. Smart [60] and Giles and Bankman [61] evaluated the performance of a UOWC system based on Beer-Lambert law in different water types and different communication ranges. The impacts of environmental variability, such as variations of refractive index with depth, were taken into account.

Another general theoretical model of aquatic optical attenuation in UOWC is radiative transfer equation (RTE). As we have presented in Section II-C, the VSF is an important IOP that describes the scattering characterizations of photons. However, the VSF is difficult to be measured in practice [62]. Furthermore, the VSF can only determine the scattering properties of a single photon at each refractive index condition. It is not suitable to model the scattering properties of large number of photons [17]. Considering these two facts, most UOWC researchers employ RTE in their UOWC channel modeling research. Without considering the temporal dispersion of light, the typical two-dimensional RTE can be expressed as [63]–[65]

$$\vec{n}\cdot\nabla L(\lambda,\vec{r},\vec{n}) = -cL(\lambda,\vec{r},\vec{n}) + \int_{2\pi}\beta\big(\lambda,\vec{n},\vec{n}'\big)L(\lambda,\vec{r},\vec{n})d\vec{n}' + E(\lambda,\vec{r},\vec{n}) \qquad (12)$$

where $\vec{n}$ is the direction vector; ∇ is the divergence operator; $L(\lambda,\vec{r},\vec{n})$ denotes the optical radiance at position $\vec{r}$ towards direction $\vec{n}$; $\beta(\lambda,\vec{n},\vec{n}')$ is the VSF; and $E(\lambda,\vec{r},\vec{n})$ represents the source radiance. RTE is capable of describing the energy conservation of a light wave passing through a steady medium [64], [65]. The derivations of RTE are complex and lengthy, and they can be found in [36] and [66]. The RTE can be solved both analytically and numerically. Since the RTE is an integro-differential equation involving independent variables [63], [65], it is difficult to find an exact analytical solution. Thus only few analytical RTE models have been proposed in recent years. Jaruwatanadilok [67] devised an analytical solution of RTE employing the modified Stokes vector. This model takes both multiple scattering and light polarization effects into account. Based on this model, numerical results show that the ISI and BER are functions of data rate and link distance. This finding can be further used to predict several performance parameters of UOWC systems such as the maximum communication distance with certain data rate and BER. Cochenour *et al.* [54], [68] proposed a beam-spread function for laser-based UOWC by solving the RTE analytically. The small angle approximation was performed to simplify the derivation. This analytical model reveals the relationship between received optical power versus link range for various transmitter/receiver pointing accuracies. It was also validated by watertank experiments.

Besides utilizing analytical solutions, numerical methods are preferred to solve the RTE. In fact, for many practical UOWC applications, finding an exact analytical solution of RTE is even more challenging [63]. Moreover, since a series of assumptions and approximations have been made to simplify the RTE, the analytical solutions will also suffer from numerous limitations [69]. In view of this, most researchers focused on developing powerful numerical RTE solvers [50], [65]. The most popular numerical approach to solve RTE is Monte Carlo simulation. It is a probabilistic method to mimic the loss of underwater light propagation by sending and tracking large number of photons [70], [71]. The Monte Carlo method benefits from its easy programming, accurate solution and high flexibility, but it also suffers from random statistical errors and low simulation efficiency [36]. Leathers *et al.* [72] from the U.S. Naval Research Laboratory (NRL) reported a practical guide to generate Monte Carlo computer simulations for typical ocean optics applications. This method has been adopted by many other UOWC researchers and has been proved to be robust.

In recent years, researchers have employed Monte Carlo approach to solve the RTE or study the characterization of UOWC channels. Li *et al.* [73] built a Monte Carlo simulator to model the impulse response of UOWC channel. In this simulator, several receiver parameters such as aperture size and field of view (FOV) were taken into account. The authors utilized this Monte Carlo simulator in order to evaluate the channel capacity of a UOWC system with different link distances, water conditions, and transceiver parameters [74]. Simulation results indicate that the bandwidth of UOWC for clean water, coastal water and harbor water are on the order of hundreds of MHz, tens of MHz and MHz respectively [74]. Gabriel *et al.* [37] from Institut Fresnel utilized a Monte Carlo approach to solve the RTE and provided a channel model that can be used to appropriately predict different design parameters of UOWC systems. As a continuance of [37], Gabriel *et al.* [55] proposed a channel impulse response of UOWC system by solving the RTE based on Monte Carlo simulation. The authors quantified the channel time dispersion for different water types, link distances, and transmitter/receiver characteristics. A two-dimensional HG phase function was employed to model the VSF. Based on this numerical channel model, the authors concluded that the channel time dispersion can be neglected when operating at a moderate distance (20 m) in a clean water environment. However in highly turbid water, the channel time dispersion can impact the data transmission when operating over a large distance (100 m). Based on this conclusion, the system will experience less ISI in the received signal when the transmission distance is short and the water is clear. As a result, complex signal modulation and demodulation can be avoided. In order to verify the Monte Carlo approach for UOWC channel modeling, Hanson and Radic [53] made a comparison between the results of Monte Carlo simulation and laboratory experiments. The results of the Monte Carlo simulation and the water-tank experiment exhibited reasonable agreement. Up to one Gbps data rate was achieved in a two-meter long water pipe. Dalgleish *et al.* [75] employed Monte Carlo approach to solve the RTE and calculate the impulse response for a UOWC system over different operation environments. Another similar comparison between Monte Carlo simulation and experimental measurements can also be found in [56]. The authors devised a numerical Monte Carlo simulation tool that is capable of computing received power of a UOWC system by considering the receiver aperture size, FOV, and pointing-tracking losses. This simulator is based on modeling a complex probability density function (PDF) (such as the lightfield distribution underwater) by its known individual components (such as the scattering distance of photons in water) [56]. By randomly sampling these known processes, the unknown PDF can be approximated using these discrete samples [56]. The accuracy of this simulator was validated by comparing the simulation results with the experimental data from [54] and [76]. Cox [77] also attached the Matlab source code of this simulation tool.

Besides the probabilistic Monte Carlo approach, there are also two deterministic methods that can be used to solve the RTE numerically: the discrete ordinates method and the invariant imbedding method [30], [50]. But only few researchers employed these two approaches as alternatives of Monte Carlo simulation. Li *et al.* [64], [65], developed an efficient RTE solver based on the deterministic numerical approach. This solver employs the matrix free Gauss-Seidel iterative method in order to calculate the received power of UOWC systems. It can also process highly forward peaked VSF that can not be handled well by the discrete ordinates approach. According to the simulation results, this method can achieve the same accuracy as the Monte Carlo approach but with a much shorter simulation time. The referred Matlab source code of this method can be found in the Appendix of [64].

The majorities of aquatic optical attenuation models for UOWC are based on solving the RTE. However, instead of solving RTE, several stochastic models have also been proposed from the probabilistic nature of photon trajectory. Zhang *et al.* [78] from Tsinghua University demonstrated a stochastic channel model to represent the spatial-temporal probability distribution of propagated photons for non-scattering and single scattering[4] components of UOWC links. The authors adopted the HG function as the probability density function of light scattering angle to simplify the analysis. The proposed stochastic model also exhibited reasonable agreement with the numerical results of Monte Carlo simulation. Based on [78], the same research group further proposed a more general stochastic UOWC channel model in [79] by taking into account all the three components of propagated photons, which include non-scattering, single scattering and multiple scattering[5] components. This comprehensive channel model fits well with the Monte Carlo simulations in turbid water environment, such as in coastal or in harbor waters. Following the similar stochastic approach of [78] and [79], the Tsinghua researchers also presented a closed-form expression for the distribution of angle of arrival (AOA) in [80]. This AOA model characterizes how the received intensity of ballistic and single scattering components is distributed over AOA with respect to unit transmission power [80]. Numerical results have validated the proposed AOA distribution by Monte Carlo approach in clear and turbid water conditions with relatively short link range.

Semi-analytical modeling approach has also been employed by several UOWC researchers. In [81] and [82], based on the results of Monte Carlo simulation, Tang *et al*. [81], [82] adopted a closed-form double-Gamma function to represent the channel impulse response of the UOWC. This semi-analytical impulse response is capable of describing the temporal dispersion of light in turbid underwater environments. It can be used to carry out BER calculation and 3-dB channel bandwidth evaluation of a UOWC system. As an extension of [81] and [82], the authors applied a similar curve fitting approach to derive the impulse response for LOS UOWC links with multiple-input multiple-output (MIMO) configuration [83]. Weighted double Gamma functions have been derived as the impulse response of a 2-by-2 LOS MIMO UOWC system in turbid water environment. Dong *et al.* [84] also employed the weighted double Gamma functions proposed in [83] to evaluate the capacity of a 2-by-2 LOS MIMO UOWC system. Simulation results suggest that the channel capacity of UOWC MIMO system can be degraded by the increase of symbol rate and enhanced by the increase of average transmission power. Then Zhang and Dong [85] extended the 2-by-2 MIMO UOWC system into a general $M \times N$ MIMO link and developed a weighted Gamma function polynomial to model the impulse response.

During the past ten years, a lot of research has focused on UOWC aquatic optical attenuation modeling. However, to this date, only a few models are capable of providing an end-to-end simulator for the UOWC designers [69]. There are still several "barriers" between the UOWC channel modelers and hardware engineers [69]. Doniec *et al.* [86] presented an end-to-end model that can simulate the signal strength and communication distance in any propagation directions.

[4]Single scattering components refer to photons that experience only one scattering event during the propagation from source to destination.

[5]Multiple scattering components refer to photons that experience more than one scattering event during the propagation from source to destination.

This generic model incorporates all the components of a UOWC system that includes information of light source, detectors, amplifiers, and analog-to-digital converters [86]. The authors also verified this model through an autonomous underwater optical robotic system. Since this model takes into account all the relevant components of a UOWC system as well as the attenuation properties of water, it provides a direct and complete reference for UOWC designers to estimate the overall system performance.

2) Aquatic Optical Attenuation in NLOS Configuration: As shown in Fig. 3(d), in NLOS implementations, transceivers can utilize reflection of the sea surface to overcome link obstacles. Compared with channel modeling of LOS UOWC, investigations of NLOS UOWC channel modeling have received less attention. Light propagation in NLOS configuration experiences the same attenuation effects as those in LOS configuration. The major difference between LOS and NLOS channels is the reflection effects introduced by wavy sea surface. Thus, accurate description of the reflection effect of sea surface is considered as the most critical part of NLOS channel modeling. Several models that describe the slopes of random sea surface can be found in [29], [87], and [88]. Similar to channel modeling work of LOS configuration, channel models of NLOS link can also be derived both analytically and numerically. To the best of authors' knowledge, most channel models of NLOS configuration were derived through numerical approaches such as Monte Carlo simulations. As an example of an analytical approach, Arnon *et al.* [19], [20] proposed a novel concept of NLOS UOWC network. Each node inside this network can communicate with each other through reflection at the ocean-air interface. Communication from one node to multiple nodes can also be achieved. The authors derived a mathematical model for the NLOS channel by considering the link attenuation, sea surface slopes and receiver FOV. Numerical simulation was also performed to test the validity of this NLOS UOWC channel model. Simulation results show that an increase in node separation distance dramatically improves the BER of the NLOS UOWC system. By applying the numerical Monte Carlo method, Tang *et al.* [21] proposed a path loss model for NLOS UOWC links. The effects of both random sea surface slopes and scattering properties of seawater have been taken into account. Numerical results suggest that the random sea surface slopes induced by wind or other turbulence sources may strongly corrupt the received signal. However, this effect can be alleviated when the received signal contains multiple dominant scattering light components. Jagadeesh *et al.* [89], [90] proposed an impulse response for NLOS UOWC based on Monte Carlo simulation. A two-dimensional HG angle scattering function was employed in this simulation process in order to model the multiple scattering effects of light. Based on this impulse response, the authors also evaluated the system performance with different water types and receiver FOVs.

B. Modeling Geometric Misalignment of UOWC

As introduced in Section II-B, the diffused point-to-point UOWC links suffer from temporal misalignment. This undesired effect will degrade the system performance and induce temporal communication interruptions. In fact, link misalignment is inevitable in any UOWC systems, and there are three major reasons that will tighten the system alignment requirements.

1) Limitations of transceivers: Since the scattering in natural waters will diffuse the beam, narrowly directive light sources such as laser are widely applied in high-speed, long-range UOWC system to increase the optical power delivered to the remote underwater terminal [91]. However, due to the narrow divergence angle of laser beam and limited FOV of the receiver, these UOWC systems require precise alignment.
2) Relative motions caused by underwater vehicles, ocean current, and other turbulence sources: UOWC links suffer from severe misalignment when communicating with an AUV or ROV. Since the AUV or ROV keeps moving, the transceivers should always keep tracking with each other. Thus, link misalignment is more likely to occur. Ocean currents and wind can introduce random movements of transceivers in underwater environment, possibly causing link interruptions.
3) Variations of refractive index: The refractive index will change with water depth, temperature, salinity, and other environmental conditions. This phenomenon usually occurs in surface-to-bottom UOWC links and will cause the non-straight light propagation, thus aggravating link misalignment of UOWC [27].

Similar to the modeling work of UOWC aquatic optical attenuation, both analytical and numerical methods can be implemented in the modeling of UOWC link misalignment. For the analytical cases, without focusing on the pointing error caused by slight jitter of the transceivers, Tang *et al.* [92] employed the following beam spread function to model the link misalignment when the receiver deviates in a larger region [54], [92]

$$BSF(L,r) = E(L,r)\exp(-cL) + \int_0^\infty E(L,v)\exp(-cL) \times \left\{\exp\left[\int_0^L bs(v(L-z))dz\right] - 1\right\} J_0(vr)vdv \quad (13)$$

where $BSF(L, r)$ is the irradiance distribution of the receiver plane; $E(L, r)$ and $E(L, v)$ are the irradiance distributions of the laser source in spatial coordinate system and spatial frequency domain, respectively [54]; L presents 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 scattering coefficient and attenuation coefficient respectively; $s(v)$ is the scattering phase function. Through this model, the authors evaluated the BER performance of UOWC under misalignment condition. Numerical results indicated that, regardless of water type, an appropriate amount of misalignment will not cause severe performance degradation with sufficiently large transmission power. A similar conclusion was also drawn from the experiment of [93]. As an extension of [92], Dong *et al.* [29] presented a random sea surface slope model that concerns the link pointing errors caused by slight jitter of the transceivers for a vertical buoy-based UOWC system. The PDF of random sea surface slopes is expressed as a two-dimensional Gaussian distribution [29]. The authors employed this model and beam-spread function to evaluate the BER performance of the system. Numerical results suggest that the BER deteriorates as the pointing errors increase. However, an increase in seawater turbidity will cause less pointing errors (as the light source is diffused by turbid water, it illuminates over a larger area), and thus the BER degradation caused by pointing error can be reduced. Zhang *et al*. employed a similar PDF of random sea surface slope [29] but in the form of angle to model the pointing errors of buoy-based downlink UOWC systems [94]. The authors utilized this model to evaluate the channel capacity of downlink buoy-based UOWC MIMO systems. Numerical results suggest that more turbid water, longer link range and larger inter-spacing may reduce the channel capacity, and meanwhile more turbid water and longer link range can weaken the effects of random sea surface slopes on the channel capacity [94]. Moreover, Zhang and Dong [95] also investigated the link misalignment caused by the light source properties such as the divergence and elevation angles. In their work, the authors evaluated the impacts of light source divergence and elevation angles on the spatial-temporal distribution of light intensity. Numerical results suggest that larger divergence angle and elevation angle can attenuate the received light intensity while more turbid water and longer link range can diminish the sensitivity of each photon to its initial launch angle [95].

Numerical methods have also been employed to model UOWC link misalignment. Using a Monte Carlo approach, Gabriel *et al.* [96] studied the impact of link misalignment on the received power of a point-to-point LOS UOWC system. This numerical model was validated through water-tank experiments. Since misalignment effects in LOS UOWC can also be caused by variations of refractive index. Johnson *et al.* [27], [52] proposed a profile of the refractive index with the variation of depth. This profile was then used in a numerical ray-tracing simulation for evaluating the tolerance of UOWC link offset. From the numerical results, a 0.23m link offset was allowed for 500nm laser with 0.57 degree FOV and 200m link distance. This work provides an effective reference for modeling link misalignment induced by refractive index variations [97].

C. Modeling Link Turbulence of UOWC

Turbulence in UOWC is defined as the event that makes water experience rapid changes in the refractive index [18]. This phenomenon is commonly caused by ocean currents which induce sudden variations in the water temperature and pressure. Most studies on UOWC channel modeling have focused on providing an accurate description of absorption and scattering effects, but the impact of underwater optical turbulence is commonly ignored. In fact, underwater optical turbulence can also cause considerable degradation to the performance of a UOWC system, which may require additional studies. The modeling of underwater optical turbulence is mainly based on research results of atmospheric optical turbulence channel models in free-space optical communications. Considering the similarity of underwater optical turbulence and atmospheric optical turbulence, several researchers directly applied or modified the classical atmospheric optical turbulence models as the underwater optical turbulence models. Hanson and Lasher [98] adopted the Kolmogorov spectrum model to present the underwater optical turbulence. Motivated by [98], Liu *et al.* [99] characterized a UOWC channel model that includes both scattering/absorption and underwater optical turbulence. The proposed underwater optical turbulence model was adopted from the classical lognormal turbulence model used in FSO communication [99]

$$f_I(I) = \frac{1}{\sqrt{2\pi}\sigma_t I}\exp\left(-\frac{(\ln I - \mu)^2}{2\sigma_t^2}\right), \quad I > 0 \tag{14}$$

where I is the received optical irradiance; μ is the mean logarithmic light intensity; and σ_t^2 is the scintillation index. Based on this channel model, the authors developed a single-input-multiple-output (SIMO) UOWC system. Monte Carlo numerical simulation was performed to evaluate the BER performance. Numerical results show that the SIMO scheme can effectively reduce channel fading and extend communication range. Instead of using classical turbulence models of FSO communication, Tang *et al.* [100] employed oceanic turbulence model from [101] and [102] to investigate the temporal statistics of irradiance in the moving ocean with weak turbulence. They derived a closed-form expression that describes the relationship of temporal correlation, propagation distance, and average velocity for the moving medium. Based on this expression, the authors also evaluated the temporal correlation of irradiance in specific turbulent ocean environments. Numerical results show that the velocity of ocean flow is the dominant factor that causes turbulence and affects temporal statistics of irradiance in a UOWC system [100]. Other UOWC studies related to underwater optical turbulence can also be found in [103] and [28].

D. Lessons Learned From UOWC Channel Modeling

In this section, we have presented the state-of-the-art UOWC channel modeling techniques, which include aquatic optical attenuation modeling, geometric misalignment modeling, and turbulence modeling.

Solving the RTE is one viable approach to model the aquatic optical attenuation in LOS UOWC link. Considering the complexity of RTE, its analytical solutions are, however, difficult to be derived. Moreover, since many assumptions and simplifications are made to the RTE during the analyzing process, the derived solutions can only model UOWC channels with limited conditions. Thus, numerical solutions of RTE such as Monte-carlo approach become popular for UOWC researchers. The benefits of Monte-Carlo approach are its easy programming and flexibility. But it also suffers from low simulation efficiency and stochastic errors. One improvement that can be made for this approach is to develop highly efficient new simulation algorithms with minimum stochastic errors. Both analytical and numerical solutions of RTE are

TABLE IV
SUMMARY OF LITERATURES ON UOWC CHANNEL MODELING

UOWC channel models	Related references	Benefits	Limitations
Beer Lambert's law	[60], [61], [105]	Simplest UOWC channel model.	Not accurate.
Chlorophyll-based Monte-Carlo model	[27], [43], [58], [106], [107]	Easy to solve through simulations.	Statistical errors and low efficiency.
Analytical RTE model	[36], [54], [66]–[68], [73]	Accurate.	Difficult to solve.
Numerical RTE model	[36], [37], [50], [53], [55], [63], [64], [70]–[72], [74], [75], [108]–[111]	Accurate and easy to program.	Statistical errors and low efficiency.
Analytical stochastic model	[78], [79]	Flexible to perform performance analysis.	Assumptions limited. Difficult to derive.
Numerical stochastic model	[56], [77], [81]–[83], [85]	Easy to program.	Statistical errors and low efficiency.
End-to-end system model	[86]	Complete and in detail.	Difficult to implement.
NLOS model	[20], [21], [87]–[90], [112]	Model NLOS UOWC.	Inaccuracy in modeling the impact of surface reflection.
Misalignment model	[29], [52], [92], [93], [95], [96], [97]	Model pointing errors of UOWC.	Not include enough environmental parameters.
Turbulence model	[28], [98]–[103], [113], [114]	Model turbulence in UOWC.	Referred from atmospheric turbulence models, not accurate.

based on the classical theory of light propagation in underwater environment. Besides relying on these classical theories, novel approaches such as stochastic channel models have also been proposed based on the probabilistic nature of photon trajectory. One major concern of this newly proposed modeling method is the lack of empirical verification via practical measurements of UOWC channels. Thus, further evaluations on stochastic UOWC channel models need to be performed. The focus on channel models of NLOS UOWC lies in the reflection process occurs at the sea surface; therefore, accurate modeling the random moments of sea surface is critical. However, there is a lack of research on random movements of sea surface. Most of the existing models on sea surface movement are based on experimental measurements, and many important parameters such as water density have not been considered in the models. Thus, more accurate modeling of reflection process is also needed in future investigations on NLOS UOWC modeling.

The modeling of geometric misalignment of UOWC can also be categorized as analytical methods and numerical methods. The representative analytical model is the beam spread function. However, when this model is applied to vertical UOWC links, several important impact factors such as refractive index variations, pressure and water constituent are not included. As a result, the model may lose its accuracy with increasing link distance.

The research of turbulence in UOWC is far behind the counterpart in FSO communication. Compared with the classical models for atmospheric turbulence such as lognormal and gamma-gamma models [104], there is no widely accepted turbulence models in UOWC. Based on the classical FSO turbulence models, researchers simply use lognormal model to describe underwater turbulence. But this model hasn't been confirmed by experimental measurements. In order to develop an accurate mathematical model for underwater turbulence, it is necessary to have deep understanding on aquatic optical properties and perform accurate experimental measurements on underwater turbulence.

We summarize the literature related to channel modeling of UOWC in Table IV.

IV. Modulation and Coding Techniques for UOWC

In this section, we will first give a brief introduction of several digital modulation techniques implemented in UOWC systems. The advantages and limitations of each modulation scheme will be presented. Then, we will discuss the channel coding techniques of UOWC. Finally, we will summarize this section and classify the related literature on modulation and coding schemes for UOWC.

A. Modulation Schemes of UOWC

UOWC channel modulation techniques have attracted much attention in recent years due to its capability to impact the system performance considerably. Since UOWC can be regarded as implementing FSO communication in underwater environment, the conventional intensity modulation (IM) techniques used in FSO communication systems can also be applied to UOWC systems. On-off keying (OOK) modulation is the most popular IM scheme in FSO communication systems. This modulation scheme can also be implemented in UOWC systems. The OOK modulation is a binary level modulation scheme. During an OOK transmission, an optical pulse which occupies part of or entire bit duration represents a single data bit "1". On the other hand, the absence of an optical pulse represents a single data bit "0". There are two pulse formats in OOK modulation scheme: return-to-zero (RZ) format and non-return-to-zero (NRZ) format. In the RZ format, a pulse with duration that only occupies a part of the bit duration is defined to present "1"; however, the pulse occupies the whole bit duration in the NRZ scheme. The RZ-OOK has been shown to achieve higher energy efficiency than the NRZ-OOK, but at the expense of consuming more channel bandwidth. Due to the severe absorption and scattering effects in underwater environment, the transmitted OOK signal suffers from various channel fading. In order to alleviate these impacts and achieve an optimal OOK signal detection, dynamic threshold (DT) techniques can be applied in most UOWC OOK receivers. The DT is determined based on the estimation of channel fading. Several channel estimation techniques of FSO communication systems such as pilot symbol method, symbol-by-symbol maximum likelihood (ML) method, and ML sequence method [104] can also be employed by the UOWC OOK systems. The two major drawbacks of UOWC OOK scheme are low power efficiency and bandwidth efficiency. But due to its simplicity, OOK modulation is still the most popular IM scheme in UOWC. It has been implemented in a number of theoretical and experimental UOWC research works [67], [116], [117].

Pulse position modulation (PPM) scheme is another popular modulation technique used in UOWC systems. Compared with OOK modulation, PPM has much higher energy efficiency and no requirement of dynamic thresholding, but at the expense of lower bandwidth utilization rate and more

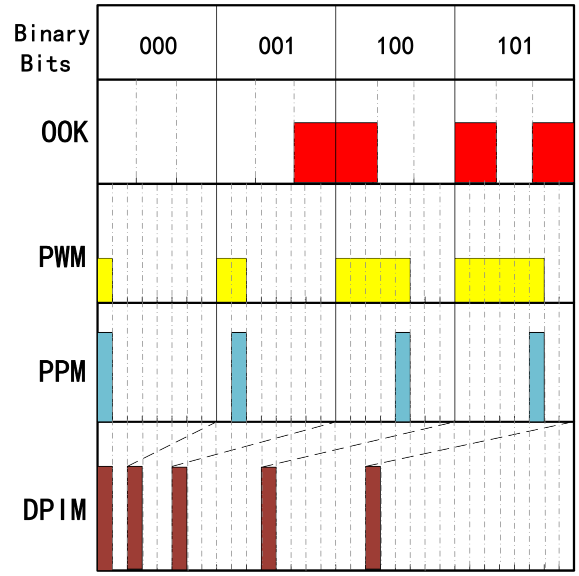


Fig. 7. Illustration of OOK, PWM, PPM and DPIM [115].

complex transceivers. In PPM, every transmitted M bits will be modulated as one single pulse in one of 2^M time slots, and the pulse position represents the transmitted information (Fig. 7). The main drawback of PPM modulation is the tight timing synchronization requirement. Any timing jitters or asynchronization will severely degrade system BER performance. In recent years, several researchers studied the performance of PPM scheme over UOWC channel models. He and Yan [118] investigated the performance of 4-PPM scheme over numerical RTE channel model. They found that the corresponding BER for PPM scheme is almost equal to that of OOK modulation and with much higher energy and spectrum efficiency. More complex PPM such as 8-PPM or 16-PPM can be used to improve higher bandwidth efficiency. Sui *et al.* [119] proposed a modified PPM scheme for UOWC. This modified PPM can maintain the similar power efficiency and anti-noise performance as the conventional PPM. It also has improved the bandwidth utilization rate of the system. Besides theoretical studies, PPM was also applied in several experimental UOWC implementations. The related studies can be found in [120]–[126].

Similar to PPM, pulse width modulation (PWM) also utilizes the relative positions of pulses to represent data symbols. In L-ary PWM, optical pulses will only appear in the first L consecutive time slots to represent one symbol, where L is equal to the decimal of symbol bits (Fig. 7). Since the PWM extends the total pulse time during the transmission of one symbol, the peak transmission power of each pulse is reduced (Fig. 7). The PWM scheme also benefits from better spectral efficiency and stronger resistance to ISI. However, these two advantages will be counterbalanced by higher average power requirements that increase with number of slots per symbol [104].

Digital pulse interval modulation (DPIM) is also widely implemented in UOWC. In this modulation, an "On" optical pulse slot is sent and followed by a number of "Off" slots. The number of "Off" slots depends on the decimal

TABLE V
MODULATION BANDWIDTH AND REQUIRED POWER TO ACHIEVE THE SAME BER AS OOK FOR L-PPM, L-PWM, AND L-DPIM [130], [131]

Modulation Schemes	Modulation Bandwidth (B)	Required Power to Achieve the Same BER as OOK
OOK	R_b	P_{OOK}
L-PPM	$\frac{L}{\log_2 L} R_b$	$\sqrt{\frac{2}{L \log_2 L}} P_{\mathrm{OOK}}$
L-PWM	$\frac{L}{\log_2 L} R_b$	$\frac{L+1}{\sqrt{\log_2 L}} P_{\mathrm{OOK}}$
L-DPIM	$\frac{L+3}{2 \log_2 L} R_b$	$\frac{4\sqrt{\frac{L+1}{\log_2 L}}}{(L+3)\sqrt{2}} P_{\mathrm{OOK}}$

value of the transmitted symbol, and an additional guard slot is commonly added in order to avoid sending consecutive "On" pulses (Fig. 7) [115]. For example, in Fig. 7, the first transmitted binary symbol is "000", which represents decimal "0". According to the mechanism we have stated, an "On" slot is sent followed by "0+1" "Off" slots, and the additional "+1" slot is the guard slot. Similarly, for the second transmitted binary symbol "001", which represents decimal "1", there should be "1+1" "Off" slots following the "On" slot. Compared with PPM and PWM which require slot and symbol level synchronization, digital pulse interval modulation is an asynchronous modulation scheme with variable symbol lengths [104]. Furthermore, with variable symbol length, DPIM also has higher bandwidth efficiency than PPM and PWM [104]. The most critical problem of DPIM is the error propagation in demodulation. From Fig. 7, we notice that if an "Off" slot is demodulated as "On", then all the succeeding symbols will also be wrong. Applications of DPIM can be found in several UOWC applications of ROVs and AUVs such as [127]–[129].

Table V presents the modulation bandwidth (B) for OOK, L-PPM, L-PWM, and L-DPIM in terms of the transmission rate R_b. (the peak bandwidth is used for L-PWM.) The bandwidth efficiency can be simply obtained as R_b/B. Also shown in Table V is the required power to obtain the same BER as OOK. For $L = 2$, 2-PPM has the same power efficiency as that of OOK, but the required bandwidth is doubled. For large L, L-PPM achieves the highest power efficiency at the expense of low bandwidth efficiency. It can also be shown that L-DPIM achieves slightly lower power efficiency than L-PPM, but L-DPIM has much higher bandwidth efficiency than L-PPM.

Figure 8 compares the BER performance versus the achievable link distance (L) for an IM/DD system with OOK, L-PPM, L-PWM, and L-DPIM in clear ocean water using avalanche diode. The system is dominated by the shot noise. As shown in Fig. 8, for a target BER of 10^{-6}, the achievable link distance is 48 m for OOK. For 2-PWM, the link distance is 41 m and it decreases to 37 m for 8-PWM. For 2-DPIM, the link distance is 45 m and it increases to 51 m for 8-DPIM. The 8-PPM achieves the longest link distance at 57 m. While L-PPM has the most power efficiency, L-DPIM is also a suitable choice as it has better bandwidth efficiency and

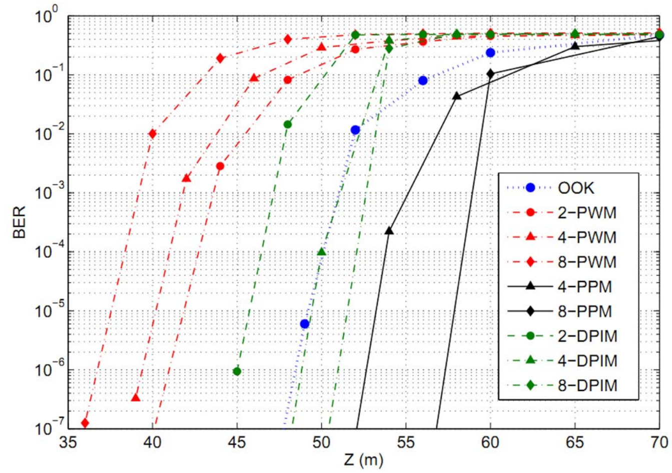


Fig. 8. BER performance for different modulations. Average transmit power $P_{av} = 0.1$ W, transmission bit rate $R_b = 100$ Mbps, APD with carrier cut frequency $f_c = 300$ MHz, Quantum efficiency $\eta = 0.78$, APD maximum Gain $G = 50$. Receiver diameter $D = 20$ cm, focal distance $F = 25$ cm, field-of-view $FOV = 0.69°$ [115].

peak-to-average power ratio (PAPR) [115]. Other comparisons of modulation techniques for UOWC can also be found in [125] and [132].

Coherent modulation schemes have also been implemented in several UOWC systems. In contrast to the direct IM schemes, coherent modulations encode the information on the amplitude, polarization or phase of optical carriers. At the receiver side, the same synchronized optical carrier will mix with the received optical signals and accomplish demodulation. Compared with IM, coherent modulations benefit from higher receiver sensitivity, higher system spectral efficiency and better rejection on background noise, but at the expense of higher implementation complexity and higher cost [104]. Due to the high dispersion effect of seawater, coherent modulation at optical frequencies is difficult to be achieved in UOWC systems. In order to overcome this limitation, intensity modulation has to be imposed on the pre-modulated signals [133]. Typical coherent modulations used in UOWC systems include quadrature amplitude modulation (QAM), phase shift keying (PSK), and polarization shift keying (PolSK).

Cochenour *et al.* [133] presented an experimental comparison study of binary PSK (BPSK), quadrature PSK (QPSK), 16-QAM and 32-QAM in a UOWC system. The authors evaluated the link performance for different coherent modulations with different levels of water turbidity. A summary of constellation diagrams for each modulation techniques was demonstrated. Similarly, Sui *et al.* [134] compared the coherent PSK, frequency shift keying modulations with several IM schemes such as OOK and PPM. Simulation results have demonstrated that PSK modulation performs the best over other modulation schemes in terms of data rate and BER. But it also suffers from poor power efficiency. A binary PolSK (BPolSK) modulation for UOWC has been introduced in [135]. In BPolSK, the signal is modulated by changing the polarization of the light. Since polarization states of light are less sensitive than the amplitude, phase or intensity of optical signals, BPolSK has higher tolerance to underwater turbulence and other channel interference such as ambient light. This property is ideal for UOWC in low SNR environment. PolSK can also be used to suppress backscatter of the transmitter in a duplex system and has better immunity to phase noise of lasers [104], [135]. Although PolSK is ideal for optical wireless communications, it still suffers from short transmission distance and low data rate. To overcome these limitations, Dong *et al*. [136] presented a novel polarized pulse position modulation (P-PPM). This modulation scheme combines conventional PPM and PolSK together by transmitting a series of PPM symbol in different polarization directions. Numerical results show that P-PPM benefits from the virtues of both PPM and PolSK. It can increase the transmission bandwidth and distance of a UOWC system. Zhang *et al.* [137] further presented P-DPPM which is combination of PolSK and DPPM instead of PPM.

Another modulation scheme implemented in UOWC is the subcarrier intensity modulation (SIM). The interest of SIM is the much higher spectral efficiency [115]. But SIM also requires complex modulation/demodulation devices and suffers from poor average power efficiency [138]. By using SIM, orthogonal frequency-division multiplexing (OFDM) can also be achieved in UOWC systems [138], [139].

B. Channel Coding of UOWC

As discussed in the previous sections, due to the severe absorption and scattering effects induced by sea water, the transmitted optical signal will experience considerable attenuation. This undesirable effect will directly degrade the BER performance of UOWC system. In order to mitigate the impact of aquatic optical attenuation and maintain a low BER in low SNR underwater environment, forward error correction (FEC) channel coding techniques can be implemented in UOWC systems.

FEC coding is an error-control technique that adds redundant bits into the transmitted sequence so that the receiver can correct a limited number of errors in the received message. A properly designed FEC code is capable of improving the power efficiency of a communication system, but at the expenses of decreased bandwidth efficiency. For a UOWC system, these benefits are presented as lower transmitter power requirements or extended link range. Generally, FEC codes can be divided into two categories: block codes and convolutional codes [140]. Researchers have employed several classical block codes into the UOWC systems due to their simplicity and robustness. The first block code implemented in UOWC system is the Reed-Solomon (RS) code [141]. Cox *et al.* [141] demonstrated an experimental UOWC system that utilized (255, 129) RS FEC code. This system employed 405 nm laser diode and RZ OOK modulation to achieve a 500 kbps UOWC link in a 3.66 meters long water tank. The experimental results suggested that the coded system can reduce the required power to achieve a BER of 10^{-4} by approximately 8 dB compared with an uncoded OOK system. Based on [141], the same research group from North Carolina State University upgraded their system in [142]. In the upgraded system, a 5-Mbps UOWC link using RS code was established in a seven-meter long water tank. The experimental results show that the (255,129) RS and (255,223) RS codes are capable of improving the SNR of received signals about six and four dB respectively at a given BER of 10^{-6}. Another similar experimental UOWC system that utilizes (2720,2550) RS and SIM can be found in [139]. In this system, the (2720, 2550) RS code performed an error correction that reduced the input BER from 1.5×10^{-3} to 10^{-9}.

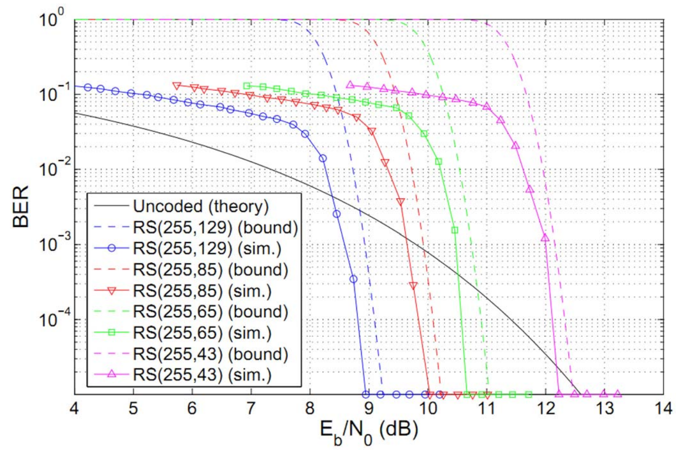


Fig. 9. RS simulation results with code length 255 and various code rates [143].

Several papers have compared the performance of different coding techniques in underwater optical wireless communication. Everett performed channel measurements with an experimental UOWC testbed for various sea water conditions [143], and he concluded that the additive white Gaussian noise channel is a good approximation for the underwater FSO channel. The same author studied the error rate performance of different coding schemes in UOWC via both simulation and measurements. Compared with the uncoded system, the results show that for a BER of 10^{-4}, (255,129) RS code can provide a coding gain of approximately 2.5 dB; Turbo code can provide a coding gain from 6.8 dB to 9.5 dB for code rates ranging from r = 1/2 to r = 1/6; LDPC code can provide a coding gain from 7.7 dB to 9.2 dB for code rates ranging from r = 1/2 to r = 1/4. Take the RS code with code length 255 and various code rates for example, as shown in Fig. 9 [143], the coding gain ranges from −0.79 dB to 2.28 dB.

Besides the RS code, other classical block code and error-detecting code such as Bose-Chaudhuri-Hocquenghem (BCH) code and cyclic redundancy check (CRC) code have also been implemented in UOWC systems to improve the BER performance in low SNR underwater environment. Wang and Zheng [144] simulated the anti-noise performance of BCH and RS codes with simple OOK modulation. Numerical results indicated that the RS code outperformed the BCH code in error correction capability, but at the expense of lowering transmission data rate. In [123], a UOWC system based on hardware description language (HDL) was demonstrated. In this system, the authors referred the architecture of IEEE 802.15.4 and IEEE 802.11 protocols and implemented CRC code in the medium access control (MAC) layer of the system. The BER performance at the receiver was improved over the uncoded systems. Instead of applying one layer of FEC code for byte-level error correction, packet-level error correction coding schemes were also developed to maintain the robustness of the UOWC system. Doniec *et al.* [86], [145] embedded a two-layer error correction coding scheme into a UOWC video transmission system. In this two-layer channel coding scheme, the transmitted video frames were firstly encoded on Manchester codes and Luby Transform (LT) codes to mitigate packet-level losses, then CRC and RS codes will be employed sequentially for byte-level error correction at the physical layer. Experimental results show that this multi-layer coding scheme can greatly improve the robustness of the UOWC system in a turbid water environment. But trade-offs may be taken between system performance and complexity.

Although block codes are simple to be implemented, they are not capable of providing the optimal performance for UOWC, especially in the environment with strong interference. Thus, more complex and powerful channel coding schemes such as low-density parity-check (LDPC) code and Turbo code are employed. LDPC code is a highly efficient linear block code. It is constructed by employing sparse parity check matrices and can provide an error-correction performance close to the Shannon limit [104]. Turbo code is a parallel concatenated code. It combines two or more convolutional codes and an interleaver to produce a block code that can also achieve a BER close to the Shannon limit. Although lots of research works on implementing LDPC and Turbo codes in FSO communication system have been proposed, there is still fewer investigation on applying LDPC and Turbo codes in UOWC. In [143], Everett demonstrated the performance of RS, LDPC and Turbo codes in UOWC systems both theoretically and experimentally. The author explained the mechanism of RS, LDPC and Turbo codes in details, and compared their performance for UOWC such as BER, power efficiency, and link distance extension. This work provides a relatively complete description of implementing channel coding techniques in UOWC.

C. Lessons Learned From Modulation and Coding Techniques for UOWC

In this section we have discussed the modulation and coding techniques that can be applied in UOWC systems.

Since UOWC can be regarded as FSO communication in underwater environment, the conventional intensity modulation techniques used in FSO communication systems can also be applied to UOWC systems. OOK, PPM, PWM and DPIM are the four major intensity modulation techniques implemented in UOWC system. Among these four modulation techniques, OOK has the simplest implementation, but it has low bandwidth efficiency. Several auxiliary techniques such as dynamic threshold technique and maximum likelihood method are integrated into the OOK scheme to increase its reliability. PPM has better power efficiency than OOK, but PPM requires tight timing synchronization and complex transceivers. Compared with PPM and PWM, DPIM has higher bandwidth efficiency, but DPIM suffers from error spread in demodulation process. Coherent modulations outperform IM/DD schemes with higher receiver sensitivity, higher system spectral efficiency and better rejection on background noise, but at the expense of higher implementation complexity and higher cost. The choices of modulation techniques in practical implementations of UOWC require a comprehensive knowledge of the application scenario. For discrete underwater sensor nodes, simple and low cost modulation schemes such as OOK are preferred. But for central node of UOWC such as relay stations, more than one modulation techniques need to be integrated to increase the efficiency and reliability of the system.

Considering the severe aquatic optical attenuation effects in underwater environment, channel coding techniques are necessary to maintain the low BER of the system. Simple block codes have the advantages of low implementation cost, low complexity, and low energy consumption, but also have limited error correction capability. Thus, they are suitable to implement in compact underwater sensors that operate in high SNR underwater environment such as clear water in deep sea. Complex channel coding techniques with higher error-correction capability such as LDPC and Turbo codes can be integrated into central data processing node of UWSNs to increase the robustness of the system.

We now summarize all the related literatures on UOWC channel modulations and coding techniques in Table VI and Table VII, respectively.

V. Experimental Setups and Prototypes of UOWC

In this section, we will survey the experimental setups and prototypes of UOWC. We first introduce several typical LOS/NLOS experimental setups and prototypes of UOWC. Then, we will review the research of UOWC implementations in several specific topics, which include retroreflector, smart transceiver design, UOWC for underwater vehicles and the hybrid UOWC systems. Finally, we will summarize this section and classify the literature on experimental UOWC systems.

A. Typical LOS/NLOS UOWC Systems

As mentioned in Section I, although a few commercial UOWC products were developed in the early 2000s, large scale commercial applications of UOWC systems have not been

TABLE VI
SUMMARY OF LITERATURE ON UOWC MODULATION SCHEMES

UOWC modulations	Literature	Benefits	Limitations
OOK	[67], [116], [117], [132]	Simple and low cost.	Low energy efficiency.
PPM	[118]-[126]	High power efficiency.	High requirements on timing. Low bandwidth utilization rate and more complex transceivers.
DPIM	[115], [127]-[129], [146]	High bandwidth efficiency.	Error spread in demodulation. Complex demodulation devices.
PSK	[133], [134], [138]	High receiver sensitivity.	High implementation complexity and high cost.
QAM	[133]	High system spectral efficiency and better rejection on noise.	High implementation complexity and high cost.
PolSK	[135]–[137]	Higher tolerence to underwater turbulence.	Short transmission distance and low data rate.
SIM	[138], [139]	Increase system capacity and low cost.	Complex modulation/demodulation devices and suffers from poor average power efficiency.

TABLE VII
SUMMARY OF LITERATURE ON UOWC CHANNEL CODING

UOWC channel codes	Literature	Benefits	Limitations
RS	[86], [144], [145], [147]	Simple and robust encoders and decoders.	Limited error correction capability in low SNR environment.
BCH	[144]	Simple and robust encoders and decoders.	Limited error correction capability in low SNR environment.
CRC	[86], [123], [145]	Simple error-detecting codes.	Limited error correction capability in low SNR environment.
LT	[86], [145]	Practical fountain code. Mitigate packet-level losses.	Complex system implementation.
LDPC	[143]	High error correction capability.	Complex encoders and decoders.
Turbo	[143]	High error correction capability.	Complex encoder and decoder.

realized so far. Most of the UOWC systems are experimental demonstrations and prototypes in laboratory environment. In the remaining of this section, we will provide a comprehensive summary of the recent progress on experimental UOWC research. The purpose of this summary is not to introduce all the UOWC experimental literature in details, but to provide a general description of the most recent works on UOWC experiments that concern different applications and approaches.

According to the link configurations, experimental setups and prototypes of UOWC can be divided into two categories: LOS experimental setups and NLOS experimental setups.

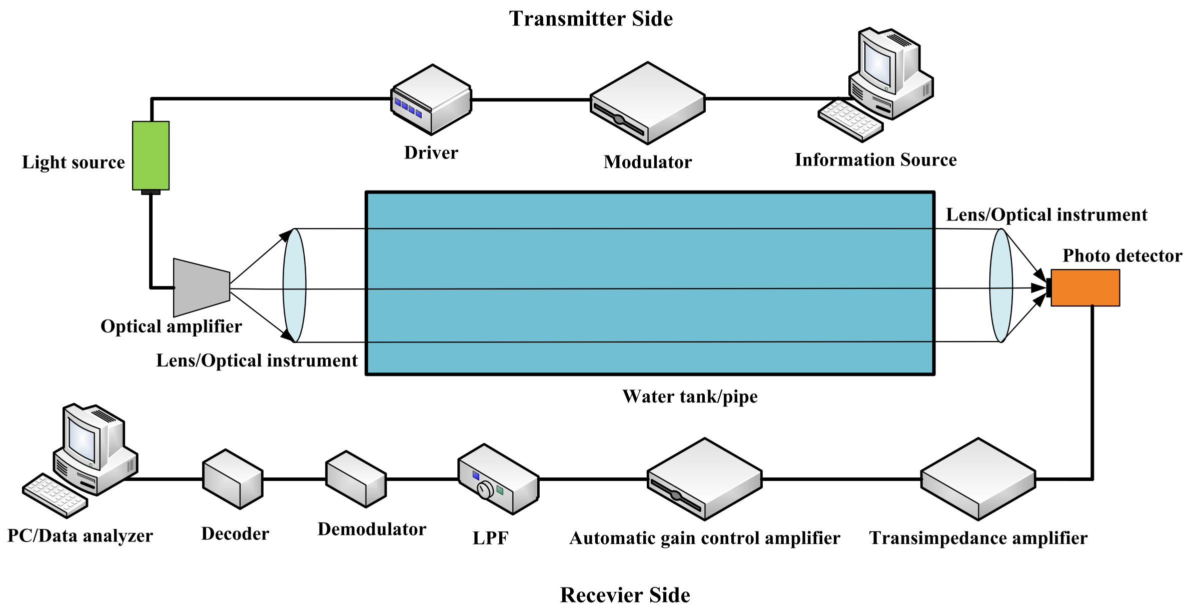


Fig. 10. A typical laboratory LOS UOWC system based on intensity-modulation direct-detection (IM/DD) technique.

Due to the simplicity of implementation, most UOWC experimental systems utilize LOS configuration. In Fig. 10, a typical laboratory LOS UOWC system based on intensity-modulation direct-detection is demonstrated. The configuration of LOS UOWC link is similar to the FSO communication setups [104]. On the transmitter side, the information bits are generated by a personal computer (PC), and then modulated onto optical carriers. In several UOWC experiments, the modulated optical signal will be further amplified by an optical amplifier and then transmitted through lens that are precisely aligned to focus the light. Water tank or pipe is used to model the underwater transmission link. In order to mimic the different refractive condition and turbidity of underwater environment, Maalox is added in the water to act as a scattering agent for attenuating the light beam [105], [147]. On the receiver side, the optical signal will go through an optical filter and focusing lens. It will then be captured by the photon detector. Since photodiode can only transform the variations of light intensity into corresponding current changes, a trans-impedance amplifier is cascaded as the following stage to convert current into voltage. The transformed voltage signals will then go through a lowpass filter to reduce the thermal and ambient noise levels [104]. Further signal processing steps that include demodulation and decoding will be performed at the last two stages of the receiver. The recovered original data will finally be collected and analyzed by a PC or BER tester for evaluating several important performance parameters such as BER.

Two light sources are commonly used in typical UOWC experimental systems: light-emitting diodes (LEDs) and laser diodes (LDs) [68], [93], [120], [148]. As stated in Section I, blue or green wavelength has been chosen for the light sources to minimize the aquatic optical attenuation. Compared with LED, LD has higher output power intensity, better collimated properties, narrower spectral spreading, and much faster switching speeds, but at the expense of higher cost, shorter lifetime and dependence on temperature [149]. Thus, LDs are more appropriate to be implemented in applications of high-speed UOWC that has strict alignment requirement. In several LD-based UOWC applications, optical diffusers are implemented to reduce the system pointing requirements [53], [150], [151]. Compared with the LD-based UOWC systems without diffusers, the diffused LD-based UOWC systems can benefit from both high speed and relatively low pointing requirements [152]. On the other hand, since LEDs offer lower output power intensity, wider divergence angles, and lower bandwidths, they can be installed in several diffused UOWC applications with short-range, low-speed link requirement.

At the receiver, there are also two types of photodiodes that are widely used in UOWC experiments: P-i-N (PIN) diode and avalanche photodiode (APD). The major difference between these two devices lies in the noise performance. For PIN photodiodes, the dominant noise is thermal noise, while for the APDs, the performance is mainly limited by shot noise [104]. Since APD can provide high current gain, it can be implemented in longer UOWC links (tens of meters), but at the expense of more complex auxiliary circuits. Besides PIN diodes and APDs, photomultiplier tubes (PMT) have also been implemented in several UOWC experiments [75], [122], [123], [148], [153]–[155]. Compared with photodiodes, PMT benefits from higher sensitivity, higher optical gain and lower noise levels. But it also suffers from high voltage supplies (on the order of hundred volts) and high unit cost. Moreover, PMT is susceptible to shocks and vibration. It can be easily damaged by the overexposure to light. The cost of PMTs is also much higher than that of photodiodes. Thus PMTs are commonly used in static experimental UOWC systems. Based on the typical LOS UOWC link configuration and the critical devices that we have introduced, a number of experimental UOWC links have been proposed in recent years.

Since LED benefits from its low cost and stable performance in various environments, several researchers preferred to employ LED as the light sources in experimental UOWC systems [126], [139], [144], [156]. Chancey [46] proposed a UOWC system based on high power Gallium Nitride LEDs. This experimental demo is capable of achieving 10 Mbps video transmission over a distance of 12 meters. Also Simpson [47] from the North Carolina State University demonstrated a UOWC system with signal processing capabilities that utilized high-power LED as the light source. Experimental results show that 1 Mbps data rate is achievable over a distance of 3.66 meter long. Similarly, Brundage [157] also developed a UOWC system that utilized a high-power blue LED as transmitter and a blue enhanced photodiode as receiver. This system successfully accomplished a 3 Mbps data transmission in a 13-meter long water tank. By using the mirrors folding architecture, Fair *et al.* [106] tested their LED based UOWC system over a distance of 91 meters, a maximum data rate of 5 Mbps was accomplished. Recently, researchers from the Massachusetts Institute of Technology (MIT) presented a bidirectional UOWC system named AquaOptical [127]. The transmitter of the system consists of six five watts LEDs with 480 nm wavelength. The researchers tested this demo system in both pool and ocean environments. Experimental results showed that in clear pool water, the AquaOptical can achieve a data rate of 1.2 Mbps at distances up to 30 meters; while in turbid water with only three meters visibility, the system achieved a data rate of 0.6 Mbps over nine meters. As an upgraded version of AquaOptical, AquaOptical II can establish a bidirectional underwater communication link between each pair of transceivers [128]. Since AquaOptical II is designed with software defined radio, it has more powerful signal processing capabilities than its previous generation and can also achieve a data rate of two Mbps over a distance of 50 meters. Several theoretical channel models have been validated through this testbed [86]. Furthermore, the MIT researchers also performed a real-time video delivery experiment by employing AquaOptical II [145]. Using the same design approach of software defined radio, Cox *et al*. [138] from North Carolina State University also built a UOWC experiment based on LED. Since software defined radio system is more configurable than conventional hardware implementations, it is convenient to test various modulation formats or digital filtering schemes on UOWC [138]. The authors examined the performance of BPSK and Gaussian minimum shift keying (GMSK) schemes and accomplished a data rate of one Mbps over a range of 3.66 meters. Most recently, a typical cellular UOWC network prototype based on LEDs was demonstrated in [116]. The authors implemented code division multiple-access (CDMA) techniques in this prototype and tested the network performance in various water conditions. Besides the aforementioned experiments, other similar recent experimental UOWC systems and prototypes that utilized LEDs as light sources can also be found in [117], [125], [158], and [159].

Instead of using LEDs, several experimental setups also utilized lasers as the light sources due to high bandwidth and low noise floor [68], [93]. Although laser and laser diodes were invented in the early 1960s, only few early laser-based UOWC experiments have been performed in the 1990s [120], [160]. In recent years, with the cost reduction and popularization of laser devices, there is a surge of laser-based UOWC experimental systems. Cox, Jr. [35] constructed a laboratory testbed based on a 405 nm blue laser diode and PMT. This setup can provide up to one Mbps underwater data transmission in a distance of 12 meters. Hiskett and Lamb [161]. proposed a laser-based UOWC system by utilizing 450 nm laser diode and APD. One 40 Mbps wireless communication link was established over one meter water tank. Sun *et al.* [148] demonstrated a real-time underwater video transmission system by implementing 488 nm blue laser and PMT. A 5-Mbps high-speed video stream was successfully transmitted through 4.5 meters long underwater channel. Nakamura *et al.* [162] demonstrated an IM/DD-OFDM UOWC system using 405 nm blue laser diode. The system can achieve a data rate of 1.45 Gbit/s over a distance of 4.8 m. Oubei *et al* [163], reported a NRZ-OOK UOWC system. The system can operate at data rate up to 2.3 Gbit/s over a 7 m distance. The transmitter of the system is a TO-9 packaged pigtailed 520 nm laser diode and the receiver is an APD module. A BER of 2.23×10^{-4} can be achieved through this system. As a continuance of [163], Oubei *et al.* [164] proposed a 16-QAM-OFDM UOWC system that also employs TO-9 packaged fiber-pigtailed laser diode as the light source. A record data rate of 4.8 Gbit/s over a 5.4 m watertank transmission link can be achieved. To the best of authors' knowledge, this is the highest data rate record for UOWC system up to date. Several researchers have also employed laser to study the spatial and temporal dispersion effects of UOWC links over different modulations, coding schemes and water conditions [150], [151], [165], [166].

Compared with typical LOS UOWC experimental systems, only a few UOWC experiments have focused on the diffused and NLOS link configurations. Pontbriand *et al.* [167] from the Woods Hole Oceanographic Institution (WHOI) demonstrated a broadcasting diffused UOWC system. This system can achieve a data rate up to 10 Mbps over a maximum vertical distance of 200 meters and horizontal radius up to 40 meters [167]. Cochenour and Mullen [152] employed 532 nm laser and a diffuser to generate diffused light. A diffused UOWC link with up to 1 Gbps data rate in 7.72 meters long water tank was established. On the other hand, the experimental NLOS UOWC links are mainly focused on the applications of underwater ranging and imaging. Alley *et al.* [168] proposed a NLOS imaging system that utilized 488 nm blue laser as the illuminator. Experimental results demonstrate that, compared with the conventional LOS imaging system, this NLOS configuration significantly improves the SNR of imaging. A similar experimental approach that employed modulated pulse laser in NLOS configuration for underwater detection, ranging, imaging, and communications was presented in [169].

B. Retroreflectors in UOWC

Retroreflector is an optical device that can reflect arbitrary incident light back to its source (Fig. 11). Utilizing this beneficial characterization, a modulating retroreflector UOWC

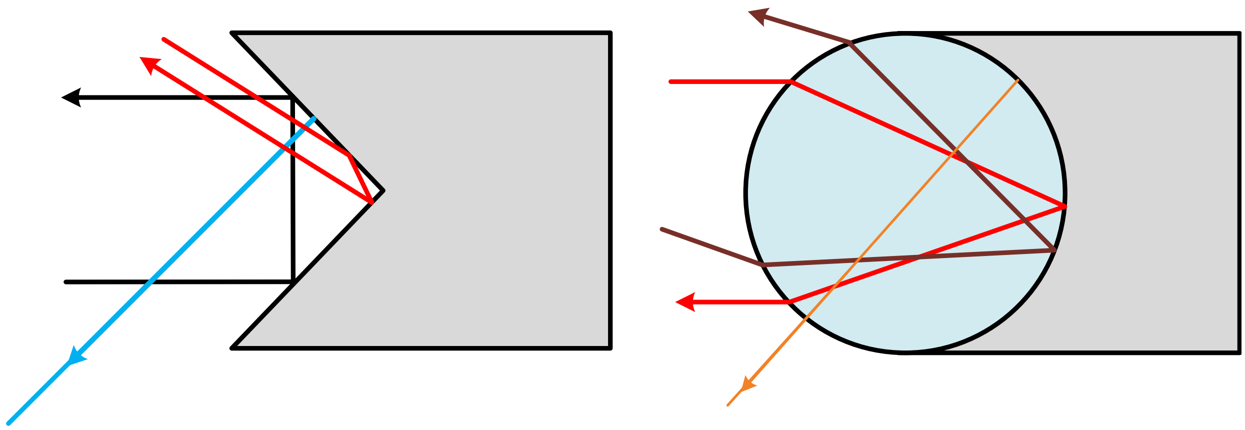


Fig. 11. Demonstration of corner and spherical retroreflectors.

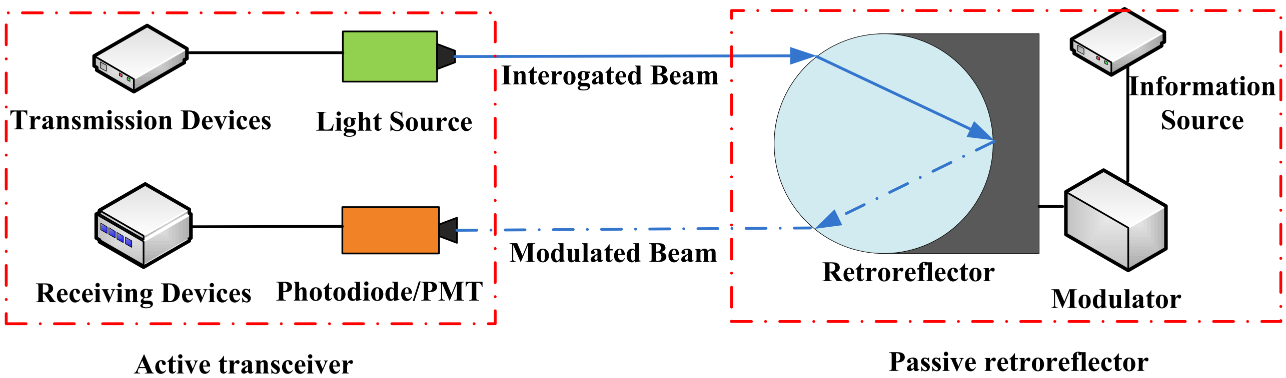


Fig. 12. A modulating retroreflector link.

system was introduced. When modulating the retroreflector link (Fig. 12), an active transceiver projects a light beam into the retroreflector. During the reflection process, the modulator will modulate the light beam and add information to it. This information will later be captured and demodulated by the active transceiver. The most significant advantage of modulating retroreflector UOWC system is that most of the power consumption, device weight, volume and pointing requirements are shifted to the active end of the link, thus the passive end will benefit from small dimensions, relatively low power and pointing requirements [170].

A typical UWSN may contain many sensor nodes and underwater vehicles. Each sensor node and underwater vehicle are required to have long sufficient cruising time due to the difficulty in recharging battery. In such an application, modulating retroreflector becomes an attractive choice. In addition to the challenges involved in a direct UOWC link such as absorption and scattering, retroreflector based UOWC systems have several additional limitations. Unlike the typical UOWC links, the retroreflector based UOWC links have to transmit through the underwater channel twice, so the link will experience higher attenuation and interference. Furthermore, the backscattered light generated from the interrogating beam can be significant in turbid water where it will eventually surpass the desired retro-reflected signals.

Although the concept of implementing retroreflector in FSO communication system has already been proposed for almost 20 years [172], only few research works on UOWC retroreflector system were demonstrated recently. The first institute that implemented retroreflector FSO communication in marine environment is the U.S. Naval Research Laboratory (NRL). Since late 1990s, the NRL began to launch the research of retroreflector applications in FSO communication and successfully achieved shore-to-shore, boat-to-shore and sky-to-ground retroreflector FSO links [170], [173], [174]. Based on these achievements, NRL researchers then applied the retroreflector link to underwater environment. Mullen *et al.* [175] and Cochenour *et al.* [176] employed a polarization discrimination technique to overcome the impact of backscattering on the interrogating light. An experimental test was also performed in laboratory water tank to evaluate the system performance. The authors compared the experimental results of polarized and non-polarized setups with different transceiver FOV and link ranges. Experimental results showed that, by utilizing polarization discrimination technique, the backscatter level can be greatly reduced. This fact will then increase the communication range of retro-reflecting link. Cox *et al.* [147] from North Carolina State University proposed a blue/green retro-reflecting modulator for UOWC based on micro-electromechanical system (MEMS). The authors deployed the retroreflector link in a 7.7-meter long water tank and evaluated the system performance with various water turbidities. Experimental results show that 1 Mbps and 500 kbps data rates can be achieved in

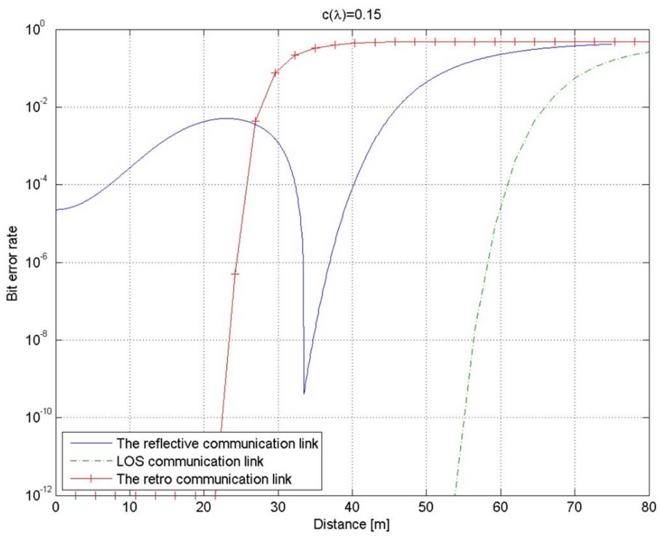


Fig. 13. The BER performance versus link distance for clean ocean with extinction coefficient 0.15 m^{-1} [171].

2.7 attenuation length[6] and 5 attenuation length respectively. Rao *et al.* [177], [178] proposed the design and implementation of an omni-directional retroreflector-based UOWC system. The receiver module in this system uses automatic gain control techniques to enhance its dynamic range.

Noticeably, the retroreflector based UOWC links have to transmit through the underwater channel twice where the forward scattered and back scattered signals interact in terms of link performance. This leads to a more complex environment. In the existing literature regarding retroreflectors in UOWC, Cochenour *et al.* [176] proposed a formulation of radiated power by retroreflector in UOWC. Arnon [171] further compared the BER performance of retroreflector link with some classic communication links in Fig. 13. For a fixed target BER, Fig. 13 indicates that a retroreflector based link configuration achieves shorter link distance than the LOS based link configuration due to extra attenuation caused by the folded transmission path. On the other hand, due to the reflection at the random sea surface, the BER performance curve of a reflective link configuration is, in general, not a monotonic function of link distance.

C. Smart Transceivers of UOWC

As shown in Fig. 10, in a UOWC system, the information waveforms are generated by a source and then transferred by an optical transmitter through the underwater channel to a specific destination. At the other end of the link, the receiver will collect the optical signal and recover the original information. Although the transmission wavelength is carefully selected in blue/green spectrum to minimize the attenuation effect of sea water, several other factors such as misalignment will still severely degrade the link performance. As stated in Sections I and III, most UOWC systems utilize point-to-point configuration, and thus precise pointing and tracking requirements are necessary. However, link misalignment is an inevitable phenomena in underwater environment, any variations of refractive index or turbulence of ocean can cause link misalignment and interrupt communication. Especially in mobile UOWC applications such as AUVs and ROVs, the two ends of a link are all in nonstatic condition, which makes the alignment more difficult to achieve. Conventionally, there are three common methods to relieve the pointing requirements of a UOWC system: using diffused light beam, increasing receiver aperture size, and implementing a dedicated gimbal system. Diffused light beam can effectively increase the illuminated area of a light source, but the communication range also shrinks. Although large aperture can increase the receiver FOV and it has already been implemented in several UOWC systems such as [167], the extra introduced ambient light and limited transceiver size requirement will still restrict the application of this method. Dedicated gimbal system can be used in several applications that have less size limitation and energy requirements, but for compact UOWC systems with limited volume and energy budget, this approach is not practical.

Considering the limitations of each compensation method that we have introduced, a compact adaptive smart UOWC transceiver that can relax the misalignment requirement with minimized volume and energy cost needs to be proposed. Simpson *et al.* [179] proposed a novel UOWC front-end and introduced the concept of smart transmitter and receiver. The smart quasi-omnidirectional transmitter can estimate the water condition according to the backscattered light captured by the adjacent smart receiver. Based on specific water conditions, the transmitter can take several actions such as changing transmission light wavelength to improve link performance. The transmitter can also electronically switch the beam direction according to the angle of arrival of detected signal. On the receiver side, segmented lens array architecture was implemented to increase the total FOV. By using the information of angle of arrival estimation, the smart receiver can also adjust and steer the FOV towards the direction of desired signals to improve the SNR of the received signal. Moreover, the CDMA technique has also been implemented in both transmitter and receiver ends to reinforce the system performance in multi-user environment. The authors installed the prototyping smart transceivers in a 3.66-meter long laboratory water tank to evaluate the system performance. Experimental results demonstrate that the smart system can effectively increase the total FOV of the receiver. The preliminary algorithm for angle of arrival estimation and backscatter estimation was also verified to work properly. Other performance aspects such as diversity combining and multi-user CDMA approach were also tested and proved to be effective. This novel trial of smart transceivers provides an adaptive solution to handle the impact of dynamic nature of underwater environment to the UOWC systems. It can be applied to different underwater platforms such as AUVs, ROVs, and other sensor nodes embedded with UOWC system. Several theoretical research works focusing on smart or adaptive UOWC transceivers were also proposed. Akhoundi *et al.* [116] proposed a smart hexagonal omnidirectional transceiver. This transceiver has an array of optical filters. The received optical signal will go through

[6] The attenuation length is defined as the product of attenuation coefficient and link distance.

the filter arrays and get converted to electrical signals through an array of photodiodes. Then, the received electrical signal, after having passed through filtering and automatic gain control blocks, will be converted to an optical signal and further transmitted to the optical network controller via fiber optic network module. Besides the adaptive gain control scheme, this smart transceiver is capable of achieving omnidirectional signal transmission and reception. Tang *et al.* [124] presented an adaptive gain control scheme for UOWC receivers based on APD. The authors derived a closed-form expression that can describe the relationships of optimal gain of APD, link range and receiver offset distance. This result can be further applied to practical design of UOWC transceiver for improving the link reliability.

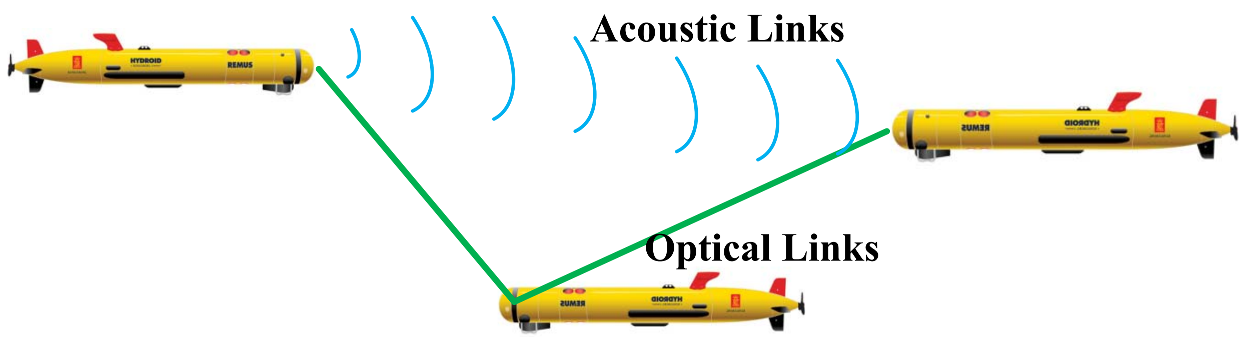
D. UOWC for Underwater Vehicles

With the ever-increasing demands of human underwater activities, underwater vehicles such as AUVs and ROVs have been widely applied to perform different tasks such as undersea resource exploration, wreck rescue missions and maintenance of oil production facilities. In terms of communication methods, underwater vehicles can be divided into three categories: tethered underwater vehicles, wireless underwater vehicles, and hybrid underwater vehicles. Tethered underwater vehicles are usually controlled robots that are connected to the surface control platform through an optical fibre or electrical cable. The tethered system has long endurance time and can provide reliable high-speed data communication, but at the expense of higher manufacture cost and limited operation range. Moreover, high operational and maintenance costs also limit the application of tethered ROVs. Since tethered ROVs are limited to operate within a short range of the surface-mounting boat, the surface-mounting boat has to relocate to achieve a wide mobility of the tethered ROVs. However, the operational cost of the surface-mounting boat is high, thus limiting the applications of tethered ROVs. The maintenance cost of tethered ROVs can be high when the tethering cable is damaged by a large marine animal such as whale or shark. On the other hand, conventional wireless underwater vehicles are usually autonomous operated robots that utilize acoustic wave as the viable communication carrier [180]. Since this kind of vehicle is free from the limitations of connection cable, it has more flexibility and can operate in a vast area. The bottle necks of this approach are the low bandwidth, high latency, and complex energy-consuming acoustic transceivers. Hybrid underwater vehicles that integrate both tethered and wireless systems together were reported in [181] and [182]. While these vehicles enjoy flexibility and reliability, they are, unfortunately, not suitable for large-scale implementations due to high unit cost, bulky instrumentations, and large number of cables.

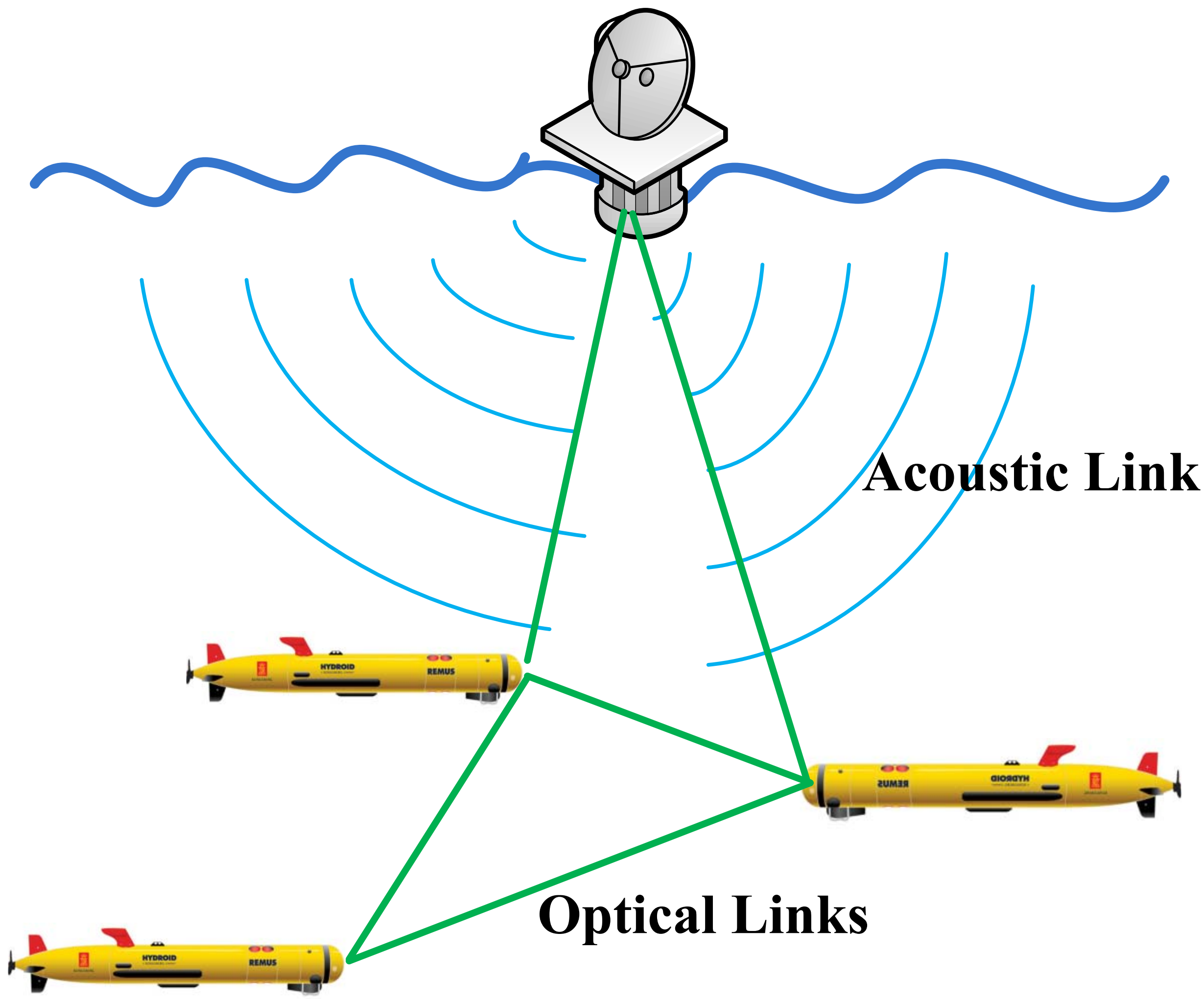
In order to satisfy the needs of UWSNs for compact, endurable, and high-bandwidth underwater vehicles, several researchers have embedded UOWC into AUVs and ROVs to overcome the limitations of conventional underwater vehicles. A team from the Computer Science and Artificial Intelligence Laboratory (CSAIL) at MIT first proposed a prototyping AUV system called autonomous modular optical underwater robot (AMOUR) [183]. The AMOUR was designed to perform tasks including underwater monitoring, exploration, and surveillance. Since AMOUR is based on a stack-up modular design approach, it also has the capabilities to deploy and recover sensor nodes in the sensor networks. The earliest version of AMOUR employs LEDs as the light source and can achieve one Kbps data rate over a distance of two meters. After the presentation of the first AMOUR prototype, CSAIL researchers upgraded the AMOUR system. Several new features based on UOWC such as remote control, localization, and time division multiple-access (TDMA) have been implemented into this underwater vehicle system [184], [185]. In [186], the researchers demonstrated a cooperative UWSN that employed AMOUR, another different kind of AUV named Starbug and several underwater sensor nodes [187]. During the experiment, cooperative tasks such as data transmission, cooperative localization and navigation, as well as physical connection were performed. This work has proved the feasibility of cooperations among different underwater vehicles and sensor nodes as a possible approach to achieve long-term operation of UWSNs. In [129], an upgraded underwater vehicle system AMOUR VI with UOWC module to achieve real-time control link was demonstrated. In this experiment, the CSAIL researchers used blue/green LEDs as light source and tested the system in a shallow swimming pool where ambient light existed. Human input device was used to control the orientation of the vehicle. Compared with the conventional acoustic ROVs which has a data rate up to hundred Kbps and latencies of hundred milliseconds, this UOWC system can achieve data rate on the order of Mbps and latencies on the order of one millisecond in a range of tens of meters. The architecture of the vehicle is compact. Both the transmitter and receiver modules are sealed in a transparent plastic cylinder with approximate length of 30 cm and weight of two kilograms. The vehicles can also move in arbitrary directions with the embedded thruster system. The details of this thruster algorithm and its corresponding configurations were presented in [188]. Besides these research results that were proposed by MIT CSAIL, other UOWC research groups also presented several demos and prototypes on optical wireless underwater vehicles in [45], [189], and [190]. Hybrid communication systems containing both acoustic and optical modules were also implemented in several underwater vehicles [191], [192]. We will introduce them in the following section.

E. Hybrid RF/Acoustic/Optical UWC Systems

The performance of UOWC systems can be severely degraded by the absorption and scattering effects of sea water, channel turbulence, misalignment errors and other impact factors. All of these undesirable factors can cause frequent communication failure. Thus the reliability of UOWC system should be enhanced. Based on hybrid RF/FSO communication systems [104], two plausible methods to increase the reliability of UOWC system are to employ acoustic wave or RF wave as back-up scenarios.



(a) Mutual hybrid UOWC configuration.



(b) Boradcasting hybrid UOWC configuration.

Fig. 14. Two types of hybrid acoustic/optical UWC links.

Compared with UOWC, underwater acoustic communication method benefits from its mature technology, long link range and lower pointing requirements, but suffers from low data rate, low security and bulky instruments. On the other hand, UOWC systems can achieve high speed point-to-point data transmission, but they cannot operate in long distance and turbid environment. Considering the pros and cons of these two methods, two hybrid link configurations have been proposed (Fig. 14). The first configuration (Fig. 14(a)) utilizes both acoustic wave and optical wave as duplex transmission medium. In this configuration, the two ends of the link are all mobile underwater vehicles that are equipped with both acoustic and optical transceivers. When two nodes of the link are in short distance and water condition is clear, the system will use optical wave as carrier to achieve high speed data transmission. If there is large distance between the two nodes

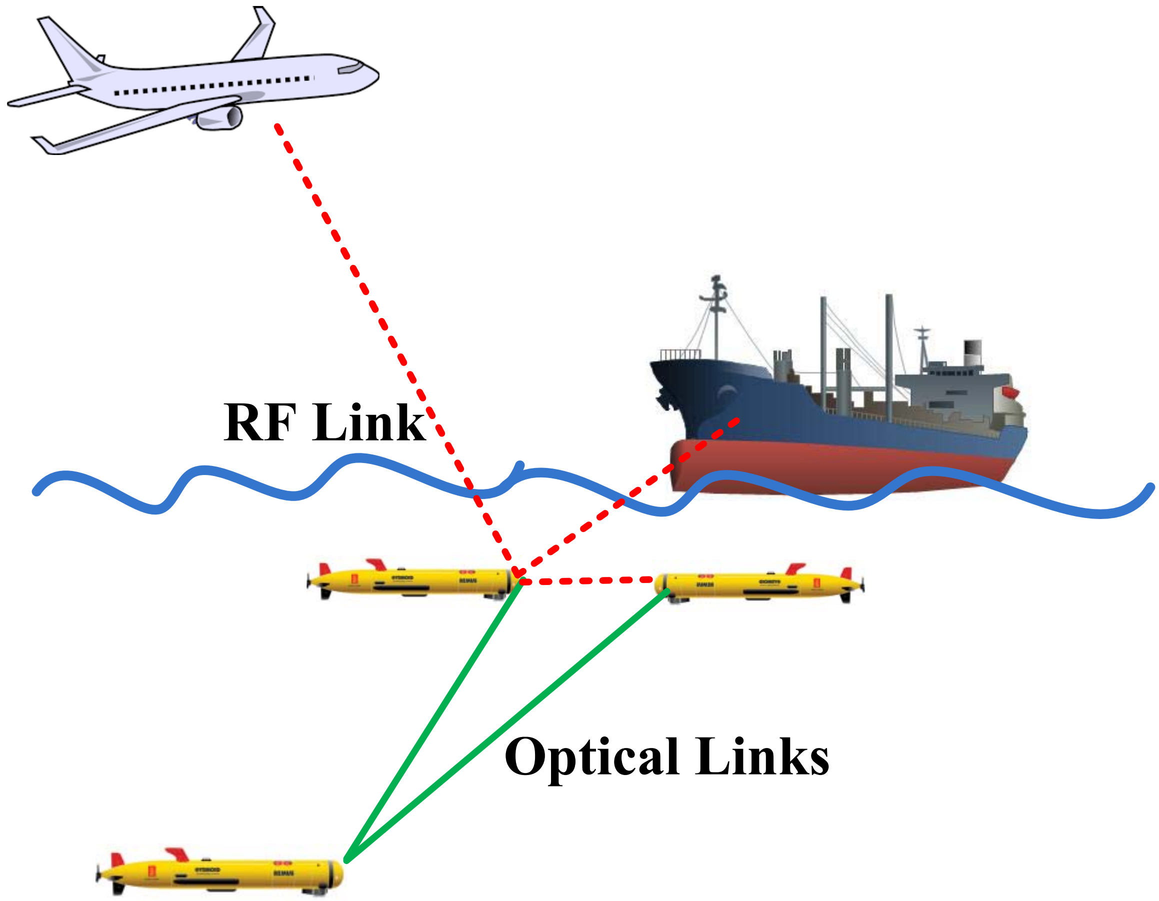


Fig. 15. Demonstration of hybrid RF/acoustic UWC systems.

or the water is turbid, the system will instead employ acoustic methods in order to accomplish connectivity. The virtue of this implementation is the high flexibility and reliability, but at the expense of high power consumption and bulky instruments due to acoustic transceivers on both ends. In the second configuration shown in Fig. 14(b), the system is configured by one static control platform and several mobile sensor nodes. Acoustic wave is used as a broadcasting method to transmit control information in the downlink from control platform to each sensor node. While optical wave is applied in the communication links between each sensor node, as well as uplinks from sensor nodes to main control platform. This hybrid UWC system utilizes the advantages of each communication method. Since acoustic wave has diffusion property and long propagation distance, it can cover the area that is distributed with sensor nodes. Moreover, in the downlink from control platform to sensor nodes, the transmitted information are low-speed control signals, which are suitable for acoustic communication. On the other hand, in the uplink of the system the large volume of oceanic monitoring data is transmitted through high speed UOWC links.

Compared with optical wave, RF wave has limited transmission range, but it can easily cross water-to-air or water-to-earth boundaries following the path of least resistance, and also has higher tolerance to dirty water environment [22]. In this way, a hybrid RF/optical UWC system is proposed in Fig. 15. The underwater vehicles are equipped with both RF and optical transceivers. When the vehicles are in clear deep water, optical wave is used as transmission carrier to optimize the link distance and transmission data rate. When the vehicles are moving to dirty and turbulent shallow water, RF transceivers will operate to achieve short-range UWC with other underwater vehicles, or cross-boundary links with other communication nodes such as aeroplanes and ships.

Based on these hybrid UOWC link configurations, several related research have been proposed in recent years. In [191], researchers from the CSAIL at MIT reported a novel hybrid UWSNs that is capable of accomplishing long-term underwater monitoring tasks including video stream of sea floor, real time data transmission of water temperature, pressure and other parameters. This hybrid UWSNs consist of two types of sensor nodes: static nodes and mobile nodes. Point-to-point communication between two nodes is accomplished using high-speed optical wave, while diffused broadcasting links are achieved through the acoustic method. Moreover, the mobile nodes can also locate and move to the static nodes for data muling. The authors also demonstrated several optimizing algorithms and the corresponding hardware implementations of the system. Experimental results show that this hybrid data collection system can provide a much higher power and data transmission efficiency than the conventional acoustic underwater networks with multihop protocol. Vasilescu *et al.* [193] proposed a more advanced hybrid underwater sensor network. This underwater sensor network consists of several sensor nodes called *AquaNodes*. Each of the nodes contains an RF bluetooth module, an acoustic module and an optical module that operates with green light. Depending on the application environment, the users can communicate with each node through different means, for instance, in clear shallow water using optical signal or in water/air interface using bluetooth method. Furthermore, TDMA and self-synchronization technologies are also implemented in each node. According to the experimental results, this system can achieve a 400-meter long acoustic link with 300 bps data rate in ocean environment and establish an optical link up to eight meters with 330 Kbps data rate. Based on this transmission speed, the data collected through the embedded sensors which include temperature, pressure, and water chemistry information can be continuously transmitted to the communication buoy, which will then relay the information to the onshore data center for following processing and analysis. Except these two hybrid UOWC systems demonstrated by MIT, scholars from other research institutions also proposed several discussions on hybrid UOWC topic. Farr *et al*. from WHOI presented the operation concept of an untethered ROV (UTROV) that employs both optical and acoustic communication methods [194]. This vehicle can accomplish typical survey and reconnaissance tasks over a long distance using a low bandwidth acoustic modem. It can also communicate optically by employing a small ship-based or seafloor-based relay. Based on UTROV, the authors also demonstrated a seafloor borehole observatory system called circulation obviation retrofit kit optical telemetry system (CORK-OTS) in [195]. The CORK-OTS consists of several underwater ROVs and a surface vessel with lowered cable. At the lowered cable end, an acoustic modem was integrated with the optical system to send control information, while optical transceivers were implemented in both ROV and lowered cable end to achieve high speed data transmission. Although the details of testing this platform was not discussed, this research provides a novel method to achieve seafloor observation. Moriconi *et al.* [196] proposed a scenario to achieve hybrid acoustic/optical swarm communication network, which also demonstrated both the acoustic and optical modules of the system node.

Besides the experimental setups of hybrid UOWC, only a few studies have been reported for the hybrid UOWC systems. In [197], the authors proposed a hybrid duplex optical-acoustic communication system. In this system, the downlink from the base station to the AUVs is a diffused acoustic link with low bandwidth and the uplinks are highly directional optical links with high bandwidth. The authors also discussed the factors that limit the performance of system, and those factors include refractive index variation, optical pointing error and acoustic latency. Another theoretical evaluation of hybrid underwater optical-acoustic network can be found in [198]. The researchers proposed a communication node equipped with both acoustic and optical transceivers. A transmission algorithm was designed and applied to each node to ensure the link alignment and connectivity. Simulation results show that the hybrid system has better energy efficiency than the pure acoustic system and is more flexible to be applied in different water conditions.

F. Lessons Learned From Experimental Setups and Prototypes of UOWC

In this section, we have studied the experimental setups and prototypes of UOWC from different aspects: typical LOS/NLOS experimental UOWC system, retroreflector-based UOWC system, smart transceiver design, UOWC for underwater vehicles and the hybrid UOWC systems.

To this end, majority LOS/NLOS experimental UOWC systems are mainly designed to operate in laboratory water tank environment. Maalox is added in the water to act as a scattering agent for attenuating the light. However, compared with the real underwater environment, laboratory water-tank environment cannot truly emulate the variations of refraction index with depth, underwater turbulence, sea surface moments and underwater background noise. Thus, the water-tank-based UOWC systems are only suitable to verify several concepts and algorithms of UOWC modulations, channel coding, network protocols and so on. In order to conclusively study and evaluate a UOWC system, the target UOWC system has to be implemented in realistic underwater environments.

The most significant advantage of modulating retroreflector UOWC system is that most of the power consumption, device weight, volume and pointing requirements are shifted to the active end of the link, thus the passive end will benefit from small dimensions, relatively low power and pointing requirements. However, most experimental tests on retroreflector-based UOWC systems are performed in idealized conditions, there is no conclusive tests on the reliability of retroreflector-based UOWC so far. Thus, future research on retroreflector UOWC system should include implementations of retroreflector-based UOWC systems in realistic underwater environments.

Basically, smart transceivers of UOWC are designed to achieve two goals. First, overcoming the tight pointing requirements of UOWC systems. Second, optimize the energy efficiency of UOWC systems. To achieve the first goal, FOV of UOWC transceivers need to be increased physically or electrically. The physical method to increase transceiver's FOV is to implement omnidirectional LED arrays or photodiodes arrays in the UOWC transceivers. On the other hand, the electrical method to increase transceiver's FOV is to adaptively control the pointing directions of the LEDs of transmitter and photodiodes of receiver. To achieve the second goal of smart transceiver, dynamic gain control mechanism is proposed in UOWC transceivers. In this mechanism, the transceivers will firstly sense the underwater environment to evaluate the water condition. If the water condition is not optimal, higher output power will be performed, and if the water condition is clear, then lower output power will be performed. Besides the aforementioned techniques that have been implemented in current UOWC smart transceivers, adaptively switching of modulations and coding techniques to optimize system performance is another plausible function of future smart transceivers.

Underwater vehicles that are equipped with UOWC devices can achieve high-speed data transmission and increase the total throughput of UWSNs. The major concern of optical wireless underwater vehicles is the system energy efficiency. Due to the difficulty in recharging battery, underwater vehicles are energy

TABLE VIII
SUMMARY OF LITERATURES ON EXPERIMENTAL SETUPS AND PROTOTYPES OF UOWC

Specified topics	Literatures	Commments
Typical LED-based LOS UOWC	[106], [86], [116], [117], [122], [123], [125]–[128], [138], [139], [144], [145] [46], [47], [155]–[158], [199], [200]	Relatively low cost; easy to be implemented; moderate speed and communication range.
Typical Laser-based LOS UOWC	[68], [93], [120], [148], [35], [160], [161], [150], [151], [165], [166], [201], [202] [203]	Higher cost; high speed; long communication range; Strict pointing.
Diffused LOS UOWC	[167], [152]	To achieve broadcasting UOWC.
NLOS UOWC	[168], [169]	To overcome underwater obstacles; few experiments were performed.
Retroreflector-based UOWC	[147], [175]–[178]	Light and compact architecture with low cost and energy budget.
UOWC smart transceivers	[179], [124]	Adaptive transmission to improve link performance.
UOWC in underwater vehicles	[45], [129], [183]–[190]	With higher speed and less instruments budgets than acoustic method.
Hybrid UOWC systems	[191]–[198], [204]	Improve system reliability.

limited systems. Thus, energy efficient modulations and coding techniques need to be integrated into the vehicles to maintain longer cruising time.

Hybrid RF/acoustic/optical UWC utilizes the advantages of each communication carriers to increase the reliability of the system. One major challenge of hybrid RF/acoustic/optical UWC system is to adaptively and smoothly switch from one communication method to another. To achieve this function, sophisticated environment detection protocol and algorithm need to be implemented in the hybrid UWC system.

We now summarize all the discussed experimental UOWC systems in Table VIII.

VI. CONCLUSIONS AND PERSPECTIVES FOR FUTURE RESEARCH

A. Summary and Conclusion

In this article, we provided a comprehensive survey for UOWC research. This survey covers three aspects of the state-of-the-art of UOWC research from the perspective of communication engineering: UOWC channel modeling, modulation and coding technologies, and experimental UOWC prototypes. With the help of this survey, the readers can have a comprehensive understanding of UOWC channel characteristics and various related factors that limit the performance of UOWC systems. Besides providing the readers with the necessary technical background and big picture of UOWC systems, we also highlighted the challenges of UOWC and provided insights into the design of UOWC systems. Unlike FSO communication, UOWC is a much less explored subject, and the underlying problem is inherently far more challenging. With the stated advantages, we strongly believe that UOWC is a viable technology for underwater wireless communication in the presence of the hostile communication channel. The holy grail question remains to be how to achieve reliable underwater optical wireless communication over a long link distance (preferably on the order of Km). To achieve this ultimate goal, more research need to be done on UOWC, and this research area is still in its infant stage. In the following, we will suggest some possible future research directions for UOWC research.

B. Future Research Directions

1) Future Research Directions on UOWC Channel Modeling: Although lots of modeling works focusing on the horizontal LOS configuration have been published, few channel models have considered the vertical link. Compared with the horizontal link configuration, vertical links take into account the variations of refractive index with the depth and temperature. Numerical models of link misalignment have not been fully studied. In particular, it is of interest to develop a general nonzero boresight pointing error model for a vertical buoy-based UOWC system with different jitter variances at the receiver aperture.

While stochastic channel models have been proposed from the probabilistic nature of photon trajectory, one major concern of this newly proposed modeling method is the lack experimental verification. Thus, further proof and evaluation on stochastic UOWC channel models need to be performed.

The modeling of LOS UOWC is relatively mature, and several close-to-reality models have been proposed. However, accurate channel models for NLOS UOWC have yet been proposed. To do this, it is crucial to accurately model the random movement of the sea surface. The existing model on sea surface movement are mostly based on rough experimental measurements, and important parameters such as water density have not been considered.

Since there is no widely accepted turbulence models in UOWC, researchers simply borrow the classical turbulence models from FSO communication literature to model the underwater turbulence channels. However, the validity of these turbulence models is questionable because FSO communication and UOWC are fundamentally different. There is an urgent need to develop an accurate and tractable mathematical model for the underwater turbulence channel. Such a model can facilitate theoretical performance studies of UOWC links.

2) Future Research Directions on Modulation and Coding Techniques of UOWC: The design of appropriate modulation and coding schemes that can adapt the characterizations of underwater environment is another potential research direction of UOWC. In recent years, researchers have implemented a number of conventional optical modulation and coding techniques in UOWC. These schemes have been proved useful and can improve the system performance. However, few implementations have considered to design adaptive modulation or coding schemes for UOWC. Since most UOWC systems are embedded on a battery-powered platform, the energy efficiency is thus important.

3) Future Research Directions on Transmission Schemes of UOWC: UOWC can provide high-speed data transmission in moderate underwater links. However, many real-time applications require the covering area of UOWC to be large. For example, to monitor an undersea oil pipeline, the sensors need to be located along with the pipeline; to build a coastal tsunami alarm system, the warning sensors need also to be distributed along the coast. In order to extend the covering area of UOWC and improve the system performance, various transmission schemes for UOWC system need to be proposed. The applicability of MIMO technology has been investigated by several UOWC researchers [85], [94], [205], [206]. Compared with the single-input single-output (SISO) system, UOWC MIMO system benefits from higher power efficiency, higher reliability, and higher capacity [85]. But the extra device complexity introduced by MIMO scheme also limits its applications, especially for several compact underwater sensors. Thus, developing a novel UOWC MIMO transceiver architecture can be one potential research problem.

Cooperative communication (or relay-assisted communication) scheme is one viable approach to extend the coverage of UOWC systems. Several theoretical investigations have been proposed on this topic [116], [205], [207]; however, multi-hop cooperative communication has not been fully investigated for UOWC. An interesting problem is how to optimally place these relay nodes so that the overall end-to-end link performance can be optimized.

Multiple access techniques have been considered as viable solutions to extend the capacity of UOWC system. For example, optical CDMA technology enables high-volume data collection from multiple underwater sensors, and it has attracted some recent interests [205], [207], [208]. It is of interest to compare optical CDMA with some other multiple access schemes.

Coherent FSO has proven to be an effective technology for long distance FSO terrestrial and space communication due to its high sensitivity and noise rejection capability. Therefore, it is of interest to apply the coherent FSO technology to UOWC systems. In order to make coherent FSO effective, one important problem is to study the effects of phase noise caused by underwater turbulence channels.

4) Future Research Directions on Practical Implementations of UOWC: Link misalignment is an inevitable phenomenon for UOWC. Although a few research works on smart transceivers for overcoming link misalignment have been proposed, there is a need to develop highly intelligent UOWC transceivers. The next generation UWSNs require high bandwidth, energy-efficient, and compact UOWC transceivers to be implemented in AUVs, ROVs, and underwater sensor nodes. Thus, there is huge research potential for developing more advanced and low-cost transmission light sources, receiving devices, as well as energy preservation system for the next-generation UWSNs. Most importantly, future UOWC prototypes need to be tested in a realistic underwater environment.

One major challenge of hybrid RF/acoustic/optical UWC system is to adaptively and smoothly switch from one communication method to another. To achieve this goal, sophisticated environment detection protocol and algorithm need to be developed and implemented in the hybrid UWC system.

5) Future Research Directions on UOWC Networks: To this end, most research works on UOWC have mainly focused on the physical layer issues. Only few studies on UOWC networks have been published so far [205], [207], [209]–[211]. However, it is important to design an UOWC system with extended boundaries and high user capacity. In order to achieve these goals, efficient network architectures and protocols need to be developed. One approach is to modify the cellular network architecture of terrestrial wireless communication systems in order to adapt the unique characterization of underwater environment. Considering the strong attenuation effect of sea water, the coverage of each cell in UOWC system can be limited, and the communication links among nodes are vulnerable to environmental factors. Thus, new network protocols that can overcome these limitations must be properly designed.

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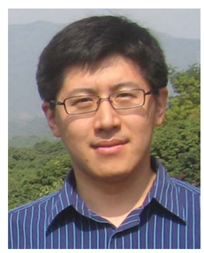

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