Underwater wireless optical communication: why, what, and how? [Invited]

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Foreseeing the proliferation of underwater vehicles and sensors, underwater wireless optical communication (UWOC) is a key enabler for ocean exploration, with strong competitiveness in short-range bandwidth-intensive applications. We provide a tutorial on the basic concepts and essential features of UWOC, as well as an overview of work being conducted in this field. Research challenges, arising from the characteristics of underwater channels, and possible roadmaps are discussed in detail. This review is expected to be of great use for the link designers of this field.

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1. INTRODUCTION

Curiosity and exploration have driven human beings to go deeper into space and the ocean. Nevertheless, till now we know less about the ocean floor than we do about the surface of Mars. Around 70 percent of the Earth's surface is covered by the ocean, and ocean exploration is increasingly attracting global attention due to its scientific, strategic, and economic significance[1]. However, conductive seawater is a natural barrier to most information carriers, such as the commonly used radio waves in this information era. It makes underwater communication a tough nut to crack and imposes significant challenges to ocean exploration. Recently, underwater wireless optical communication (UWOC), as a promising solution to this problem, has gained increasing research interest worldwide[2,3].

This article provides a tutorial on UWOC, as well as an overview of work being conducted in this field. This review does not attempt to cover every single aspect of UWOC. Instead, it introduces the readers the basic concepts and the most noteworthy features of UWOC, attempting to clarify why UWOC is so attractive and essentially what is UWOC. It also identifies how to design a desirable UWOC system, with effort on channel modeling, transmitters, receivers, signal processing, networking, and testing platforms. This review can serve as a quick start to UWOC, and the readers are also referred to some comprehensive and exhaustive surveys of this field[1,4–7] and references therein.

2. WHY IS UWOC VALUABLE IN OCEAN EXPLORATION?

The hostile underwater environment for information transfer is an important factor that inhibits ocean exploration far behind its terrestrial or even space counterpart. Sometimes using underwater cables seems the only viable way for underwater communication. However, such a wired solution normally requires sophisticated and expensive wet-mate connectors. These connectors, especially in the deep water, are generally installed by one or more remotely operated vehicles (ROVs) that have to be carefully controlled by well-trained operators in a mothership. Thus, the deployment and maintenance of a wired underwater communication system is a time-consuming and labor-intensive task. On the other hand, underwater wireless communication, featuring high scalability and flexibility, has garnered more and more attention. Acoustic wireless links are traditionally the dominant option due to the low attenuation of acoustic waves in water[8]. However, they are fundamentally bandwidth limited, with large time latency and bulky antennas. Electromagnetic induction and radio frequency electromagnetic waves can also be adopted for underwater wireless communication. However, the achievable bandwidth and link distance, in conductive seawater, are still quite limited currently[9], especially under the constraint of limited antenna size. The light, as a special band of electromagnetic radiation, can potentially revolutionize the way we communicate in the underwater world. UWOC, with the merits of sufficient bandwidth, high security, compact footprint, and low time latency, has gained considerable interest from both academic and industrial communities during the last years. UWOC offers many intriguing opportunities for a variety of short-range bandwidth-intensive applications, acting as a complementary underwater wireless communication technology to the more established acoustic links.

Figure 1 indicates typical application scenarios of UWOC. As an example of its potential killer applications, a cellular underwater wireless optical multi-access networking prototype was designed, using a series of nodes installed on the seabed as base stations[10]. The underwater unmanned vehicles (UUVs), like autonomous underwater

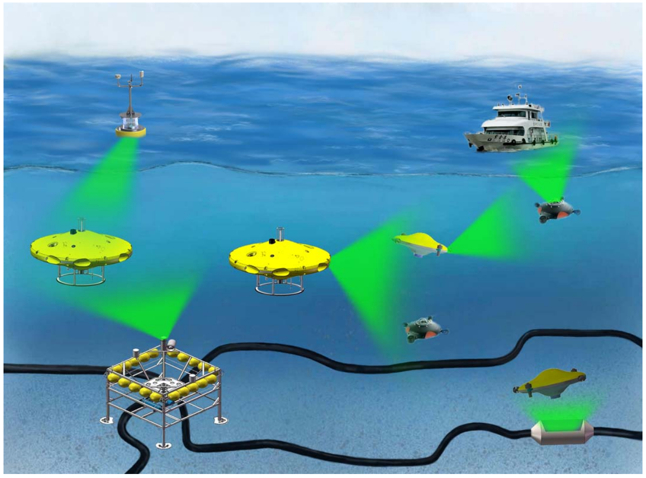

Fig. 1. Typical application scenarios of UWOC.

hovering-vehicles (AUHs), are connected to this network by UWOC. The underwater optical network could be a specific solution for data exchange. Such a network also shows prominent potentiality for simultaneous underwater illumination and high-speed communication, similar to the concept of indoor visible light communication (VLC). Furthermore, if several float stations equipped with a global positioning system (GPS) are connected to the network, an underwater positioning system could be readily constructed using some localization schemes like received signal strength (RSS) and time of arrival (TOA)[11]. On the other hand, by adopting UWOC systems, some seabed monitoring systems no longer need to be directly connected to a wired network linking onshore stations. The information gathered by the sensors can be transferred by an underwater vehicle equipped with UWOC devices. The underwater vehicles can also communicate with a mothership, or even a satellite, albeit extremely challenging. With the real-time UWOC system, a new underwater vehicle was proposed, namely untethered ROV (UTROV), such that some underwater tasks could be accomplished at a much lower cost and risk[12]. In addition, UWOC also has great potential for internal communication among a swarm of UUVs[13]. The high bandwidth and the low latency of the UWOC systems allow the designers to choose a networked multiple-vehicle control system deployed by more flexible algorithms. With the highly cooperated UUV clustering, more challenging tasks could be accomplished than by using a single vehicle.

3. WHAT IS UWOC?

Optical communication is defined as communication at a distance using light to carry information. An optical fiber is the most common type of channel for optical communications, as well as the only medium that can meet the needs for enormous bandwidth in such an information age. Replacing the channel from an optical fiber to free-space underwater, we achieve UWOC that can be regarded as the underwater transmission of unguided optical signals.

Similar to optical fiber communication as well as indoor VLC, UWOC has also opened the possibility for broadband underwater wireless communications, which otherwise cannot be realized by using other information carries, even within a short range. Unfortunately, the propagation of light underwater is attenuated by both absorption and scattering. In addition to energy loss, scattering tends to broaden the laser beam, generates multiple transmission paths, and causes pulse stretching that finally restricts the available channel bandwidth[14]. Since optical fiber communication also faces the similar energy loss problem induced by Rayleigh scattering and absorption, as well as the pulse stretching problem induced by dispersion, one may take it for granted that UWOC is simply a straightforward transformation from optical fiber communication. However, the fiber channel is extremely stable and robust to most changes in the surrounding environment, whereas in real dynamic underwater environment many propagation effects significantly degrade UWOC performance, including turbulence of various scales, bubbles of various sizes, swinging of the transceiver, groups of underwater creatures, to name a few. The propagation of light underwater is tied closely to water optical properties and environmental dynamics, which is the essential feature of UWOC when comparing with optical fiber communication or indoor VLC. In particular, for cross-interface wireless optical communication, say the optical link across the water–air interface, the channel characteristics will be even more complex, considering the effect from turbulence in atmosphere and water, waves, and other perturbations. In addition, the seemingly symmetric uplink from water to air and downlink from air to water are actually not mirror-symmetric, which is an interesting problem that requires future studies.

Besides the unique channel, UWOC also requires unique components, say the transmitters and photodetectors, in contrast to the well-established components in the 1550 nm band for optical fiber communication. Blue–green light has become a common fixture for UWOC systems to minimize absorption in water, while some other wavelengths, ranging from ultraviolet to near infrared, have also been investigated to minimize scattering in water[15,16], realize non-line-of-sight transmission[17], or achieve wavelength-division multiplexing (WDM)[18]. As the waveband suitable for UWOC is totally different from the conventional 1550 nm band, the available transmitters, such as the high-speed directly modulated lasers (DMLs) or external modulators, are still quite limited, while 10 GHz DMLs and 40 GHz external modulators, at 1550 nm, have been commercially available for many years.

Although the operation wavelength of UWOC has significant overlap with that of indoor VLC, they have significantly different requirements on some key components due to different channel properties. A VLC system has to meet both illumination and information transmission requirements in an indoor environment[19]. The illumination requirements inherently guarantee sufficient received optical power (ROP) at the receiver side, and thus, instead of link power budget, VLC focuses more on the achievable bit rate as well as some impairing effects on the high-speed transmission, like reflection-induced multi-path effect. To stay one step in front of some immediate competitors for indoor wireless, like wireless fidelity (WiFi) and 5G networks, the achievable bit rate in VLC normally should be at the gigabits per second (Gbps) level or above. In the underwater world, however, acoustic wireless is the most powerful player but with extremely limited bit rate, implying that UWOC could be readily competitive in terms of bit rate. In addition, link power budget is a major concern for UWOC due to the heavy attenuation of light in water, even adopting the right wavelength. For this reason, light sources with high power and excellent beam quality, as well as photodetectors with high sensitivity, are hungrily desired for the UWOC systems[2,20].

Despite the fact that UWOC shares some similarities with optical fiber communication and indoor VLC, it has its own unique feature and research challenges, fundamentally arising from its unique channel. More attention should be paid to the characteristics of underwater channels for system designers when solving practical UWOC problems via novel technologies.

4. HOW TO DESIGN A UWOC SYSTEM?

Similar to any other communication system, understanding the channel is the first step to design a UWOC system. With the knowledge on the UWOC channel, one can design suitable transmitters, receivers, signal processing algorithms, and networking techniques according to different applications. Last but not least, testing platforms should also be carefully designed to obtain credible experimental data.

A. Channel Modeling

In order to make the most of the UWOC systems, it is necessary to learn how light behaves as it propagates through the water. The overall power loss and the spatial and temporal distribution of light are the most important issues in an underwater communication system, since they are closely related to the communication performances, such as link budgets, signal-to-noise ratio (SNR), multi-path effect, temporal dispersion, and inter-symbol interference (ISI)[1,21].

As the light propagates in water, some of the photons are absorbed with the energy being converted to other forms, such as heat, causing the decrease in the received photon energy and the maximum communication distance. Some photons change the propagation direction because of the variation of the refractive index, resulting in a reduction of received photons and a change in arrival time, i.e., both the energy loss and ISI. The two dominant impairing phenomena are called absorption and scattering, respectively. As a common practice, for simplicity, different water types have been modeled according to the chlorophyll concentration[22,23]. The overall attenuation coefficient c is defined as

$$c = a + b, \tag{1}$$

where a and b represent the absorption and scattering coefficient, respectively. The a, b, and c are the inherent optical properties (IOPs) of waters, and the values of them vary with the water type and wavelength. Typical coefficients of the absorption, scattering, and attenuation for the different water types are shown in Table 1[23].

Combined with Beer–Lambert's law, the overall power loss when light propagates through a specified distance z is given by an expression for the irradiance,

$$I = I_0 \exp(-cz), \tag{2}$$

where I_0 and I are the irradiance at the source and the receiving end, respectively.

However, only the absorption and scattering coefficients are not enough for precise and quantitative description of the spatial and temporal distribution of light in water. Specific system configurations should also be considered, such as the source divergence angle, the emitting energy distribution, and the receiver field-of-view (FOV).

The spatial and temporal distribution of light is closely related to the scattering effect. Volume scattering function (VSF) describes the scattering probability and angle changes when a photon is propagating through an infinitesimal underwater zone. The scattering coefficient b could be derived from the VSF by

$$b = \iint \beta(\theta, \varphi) \sin\theta \, \mathrm{d}\theta \mathrm{d}\varphi, \tag{3}$$

where $\beta(\theta, \varphi)$ is the VSF, and θ and φ are the polar angle and azimuth angle, respectively. The VSF is another major IOP of water[23]. With the VSF and the absorption coefficient, analytical and numerical solutions could be adopted to analyze the light propagation in the water[23–25]. The analytical solutions start from Mie's scattering theory and the Maxwell equations and then give the expression of the light transfer function[25,26]. But, it is a complicated process. Numerical solution is another simple way to solve the problem, such as the Monte Carlo simulation[27]. The Monte Carlo method sends a single photon at a time passing through the water, tracks the absorption-induced loss and the transmission path relying on the VSF, and then judges the boundary conditions of both the channel and the system configurations[16,28,29]. This process will be repeated over millions of photons, and then the spatial and temporal distribution

Table 1. Typical Parameters for Different Water Types

Water Types	a	b	c
Clear water	0.114	0.037	0.151
Coastal water	0.179	0.219	0.398
Harbor water	0.366	1.824	2.190

of light could be obtained by aggregating states from all the photons that meet the boundary conditions. As an example, the intensity distribution of a Gaussian laser beam (divergence angle: 1.7 mrad) is studied by Monte Carlo simulation, after transmitting through 30 m or 60 m in clean sea water. The results are shown in Fig. 2. The intensity reduction is due to both absorption and scattering effect, whereas the beam spread is due to the scattering effect.

However, the VSF of water in certain areas is difficult to measure[30]. Besides, the composition of natural waters varies naturally, with both depth and time, leading to a profound impact on the water characteristics and the VSF. Therefore, it is not always realistic to measure the precise VSF for each communication analysis.

Besides the VSF, there are many aspects of underwater conditions making the channel modelling more challenging for UWOC, such as background light sources, turbulence, and sea bubbles. The background light sources, including sunlight, bioluminescence, and headlights on underwater vehicles, lead to an additive noise and lower SNR. The changes in temperature, density, pressure, and salinity of water lead to the changes of refractive index and then turbulence occurs. Sea bubbles are widely distributed on the sea surface and certain areas. Turbulence and sea bubbles cause the light beam to bend away from the receiver, the scintillation of the optical signal, and then the temporal dispersion, leading to poor communication performance and increased receiver complexity to maintain link alignment[31–33]. In some special applications, such as the water–air/air–water transmission, non-line-of-sight UWOC, the channel model needs to be further studied[30].

B. Transmitters

UWOC usually employs light-emitting diodes (LEDs) or laser diodes (LDs) as the optical source for direct modulation. LEDs and LDs have their own advantages, depending on different application circumstances. LEDs are one of the most robust and cost-effective light sources in spite of their limited modulation bandwidth. Advanced modulation, like quadrature amplitude modulation (QAM) and orthogonal frequency-division multiplexing (OFDM), can be adopted to achieve higher bit rates under the limitation of modulation bandwidth[34]. A UWOC system that can reach 2.175 Gbps through a 1.2 m underwater channel was demonstrated using a commercial LED[35]. A specially designed LED with a 3 dB bandwidth of 807 MHz was also employed in UWOC, enabling a data rate of 1.3 Gbps, even using simple on–off keying (OOK) modulation[36]. An LD has the merits of small divergence angle, high bandwidth, and high power. A 450 nm GaN LD was used to achieve 12.4 Gbps through a 10.2 m water tank[37], where the LD package was carefully designed to maximize the bandwidth of a commercial LD. To further improve the transmitter bandwidth, some methods such as mode injection locking[38] or WDM have been used[18]. By injection locking, a 16 Gbps UWOC system was demonstrated based on a 488 nm LD whose bandwidth was extended to 8.2 GHz via an optoelectronic feedback system. Besides, a 10 m/9.51 Gbps WDM-UWOC was demonstrated using red, green, and blue (RGB) LDs[18], with the experimental setup shown in Fig. 3. The proposed WDM-UWOC has prominent potentiality for simultaneous underwater illumination and high-speed communication.

Despite the great progress made in modulation bandwidth, DMLDs still cannot perform very well in terms of beam quality and output power, limiting the transmission distance of a UWOC system. Directly modulating a diode-pumped solid-state laser (DPSSL) can potentially generate high-speed green light signals with high power and superior beam quality. Figure 4 shows the schematic diagram illuminating the working principle of a DM-DPSSL[39].

UWOC combining with optical fiber communication can solve some limiting problems in complex underwater environment. In particular, a plastic optical fiber (POF) can be effectively used as a reach extender for UWOC because the low-loss transmission window of a POF coincides well with that of water[40,41]. With the proposed underwater fiber–wireless (Fi-Wi) architecture, consisting of a length of POF and some passive collimating lenses at the front end, the transmission distance of UWOC can be significantly extended, as shown in Fig. 5.

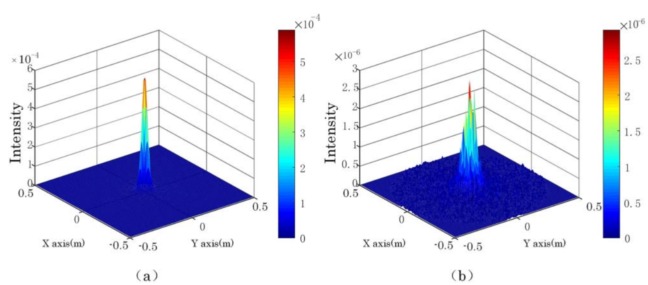

Fig. 2. Intensity distribution of a laser beam after transmitting through (a) 30 m and (b) 60 m in clean sea water.

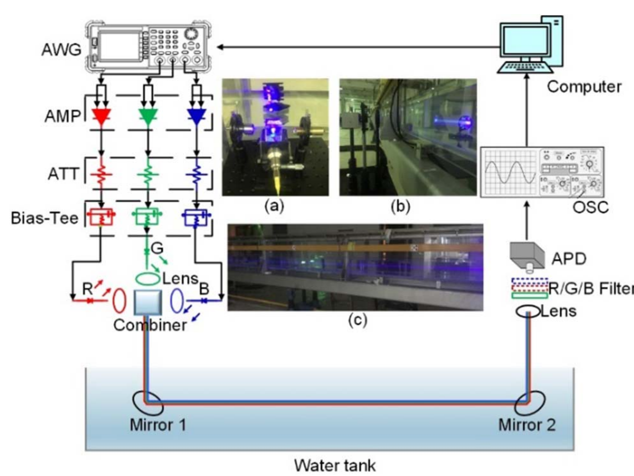

Fig. 3. Experimental setup of the proposed RGB LD-based WDM UWOC system. Inset: (a) the transmitter module, (b) the receiver module, and (c) the water tank[18].

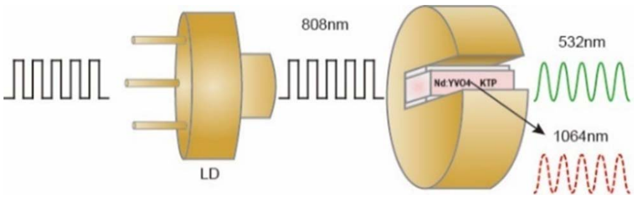

Fig. 4. Schematic diagram of the working principle of a DM-DPSSL[39].

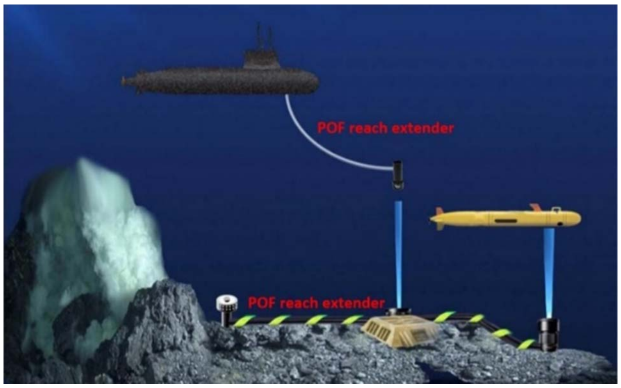

Fig. 5. Possible application scenario of the proposed underwater Fi-Wi system[40].

Properly designed leaky POFs can also be used as the leaky feeder for UWOC, allowing optical radiation to occur along the POF length for uniform coverage of optical signals. Such a leaky POF-based passive distribution system can improve UWOC coverage, especially in hard-to-cover areas of a complex underwater environment[41], as shown in Fig. 6.

C. Receivers (towards Single Photon Detection)

A photodetector is a key component in a UWOC system. Positive-intrinsic-negative (PIN) and avalanche photodiodes (APDs) are widely used[18,42], and an APD generally can get higher SNR due to its internal gain[43]. However, the maximum useful APD gain is limited by the excess noise generated during the avalanche multiplication. The excess noise can be mitigated by operating the APD at Geiger mode, as a single photon avalanche detector (SPAD)[44]. In particular, an SPAD array, like a multi-pixel photon counter (MPPC), can alleviate the nonlinear photoelectric response and ISI caused by the intrinsic dead time of an SPAD[45,46].

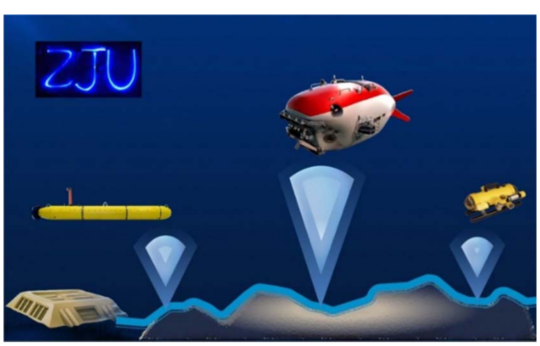

Fig. 6. Leaky POF-based distributed UWOC system[41]. Inset: a "ZJU" symbol generated by a leaky POF originally used for decorative applications.

The feasibility of using MPPC as the receiver in optical communication was preliminarily discussed in Refs. [47,48]. The suitability of employing MPPC in UWOC was further testified with the finding that an MPPC could provide significant performance improvement compared with the case of using an APD[49]. Numerical investigation also proved that SPAD arrays could be used to detect advanced modulation formats and are superior in energy efficiency and reception sensitivity[50,51].

The MPPC is a promising candidate in long-reach UWOC systems with high sensitivity. A 46 m UWOC system based on pulse position modulation (PPM) and MPPC was proposed and experimentally demonstrated with ultra-low transmitting power using the setup shown in Fig. 7[52].

As shown in Fig. 8, at the transmitting side, the required transmitting optical powers into water for different L-PPM signals are quite low to assure a 46 m UWOC. For the 5 MHz 64-PPM signal, at the transmitting side, the optical power fed into the underwater channel even reached below $-27.7\,\mathrm{dBm}$, when the laser worked under a spontaneous state. The corresponding received power at the receiving side was measured to be as low as $-62.8\,\mathrm{dBm}$.

For the MPPC-based UWOC systems, photon equivalent threshold can be properly adjusted such that non-signal counts can be effectively suppressed[53].

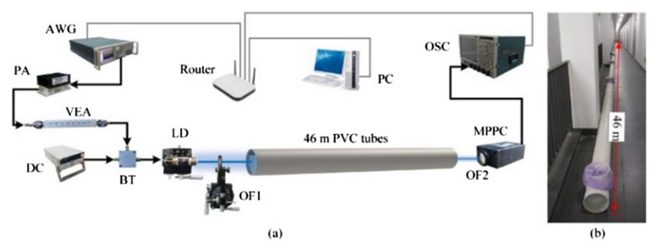

Fig. 7. (a) Experiment setup of the 46 m UWOC system using an MPPC receiver[52]. (b) The 46 m PVC tube filled with tap water to simulate a 46 m underwater channel.

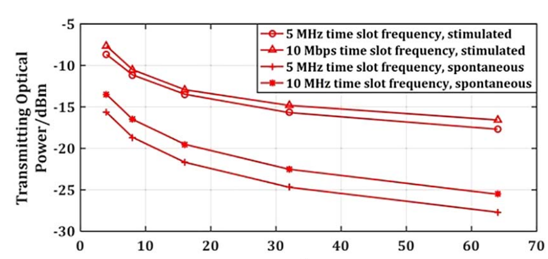

Fig. 8. Transmitting optical power for different L-PPM signals[52]; stimulated/spontaneous: laser worked under stimulated/spontaneous emission state.

An MPPC-based 46 m UWOC was demonstrated, applying merely one 2.3 MHz, 3 W blue light LED as the transmitter, for different PPM signals with a 5 MHz slot frequency. After the 46 m underwater transmission, the ROP can be even lower than 5 pW. Accordingly, less than 100 incident photons were received during each pulse slot, as shown in Fig. 9.

Although the photoelectric response of each individual pixel in the MPPC is nonlinear due to its intrinsic dead time, the output voltage/current of an MPPC consisting of thousands of pixels could be linearly proportional to the incident optical power due to the statistical effect[53,54]. This feature enables MPPC to detect optical signals with multi-valued advanced modulation formats. A 21 m/312.03 Mbps underwater transmission using 32-QAM OFDM and an MPPC with a 3 dB bandwidth of 4 MHz was successfully demonstrated[55], with the captured waveform and spectrum shown in Fig. 10.

UWOC has witnessed the photodetector evolution from PIN, APD to SPAD, with the receiver sensitivity being enhanced toward the single photon level. On the other hand, some new photo detection schemes, although not superior in sensitivity, are also proposed due to their attractive features for certain special applications. As an example, self-powered solar panels, featuring a large receiving area and lens-free operation, have great application prospects in internal communication among a swarm of underwater vehicles, with relaxed requirements on link alignment. With an ordinary solar panel as the detector, a 7 m/22.56 Mbps UWOC using a 64-QAM OFDM signal was demonstrated[56]. In addition, conventional receivers normally require an external power supply, which may arouse some problems in practical scenarios where the energy supply is restricted and battery maintenance is inconvenient. The solar-panel-based UWOC systems can potentially realize simultaneous communication and optical power transmission, enabling fully passive receivers.

It is worthwhile to note the trade-off between aperture and bandwidth on the receiver end. A large active area is desired to relax the link alignment at the expense of poor time response. As discussed earlier, the sacrificed bandwidth can be compensated, at least in part, by some signal processing techniques[16].

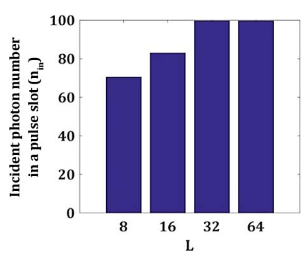

Fig. 9. Histogram of incident photon number in each pulse slot for different L-PPMs[53].

D. Signal Processing

Modulation

The modulation format can greatly affect the performance of UWOC systems. Due to its implementation simplicity, OOK is the most popular modulation format in UWOC. PPM is also widely used because of its energy efficiency. Compared with OOK, PPM can achieve a longer transmission distance. For the PPM scheme, the information is carried in the pulse position. However, it suffers from the shortcoming of low bandwidth efficiency. Digital pulse interval modulation (DPIM) is an improved modulation format of PPM, with higher bandwidth efficiency. The decimal value of the transmitted signal depends on the number of slots between two adjacent pulses. It does not require slot synchronization, but a misjudgment of "0" to "1" will lead to a series of errors. A UWOC system using optical superimposition-based pulse amplitude modulation with 4 levels (PAM-4) was demonstrated[57], with higher bandwidth efficiency and enhanced tolerance to the modulation nonlinearities of LEDs. Recently, owing to its much higher bandwidth efficiency, OFDM receives the attention of researchers worldwide. Power loading and bit loading can also be combined with OFDM to further enhance system performance. With the assistance of bit loading, a 2 m/1.118 Gbps UWOC was demonstrated with a spectral efficiency as high as 6.18 bit $\cdot$ s^{-1} $\cdot$ Hz^{-1}[58]. The impact of bit loading on improving the system performance is illuminated clearly in Fig. 11. Besides, there are some improvements of OFDM for special demands. A novel OFDM symbol structure was proposed for noise suppression and can easily make a compromise between

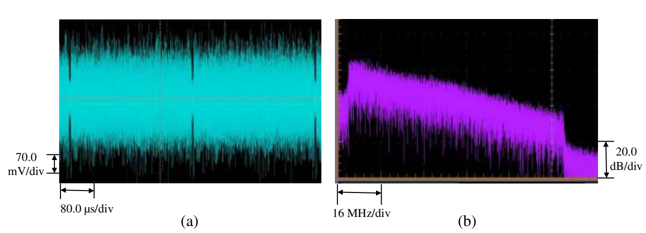

Fig. 10. (a) Waveform and (b) spectrum of the captured 32-QAM OFDM signal with an ROP of −19.9 dBm[55].

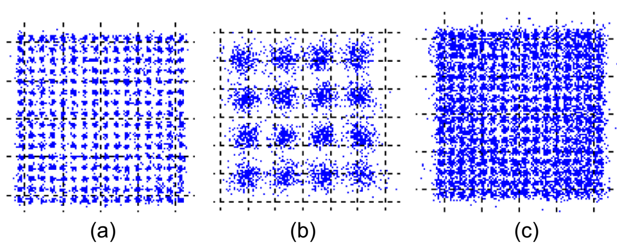

Fig. 11. Constellations after 2 m underwater transmission: (a) 256-QAM with bit loading, (b) 16-QAM with bit loading, (c) 256-QAM without bit loading[58].

transmission capacity and distance[59]. A PS-256-QAM-OFDM was demonstrated for a 35 m UWOC system, and 27.8% capacity improvement was achieved compared with the bit-power loading scheme[60].

Equalization

For the underwater channel, the presence of plankton and suspended particles may induce the scattering of photons, resulting in temporal dispersion, especially in highly turbid environments. Both the bandwidth limitation of devices and scattering will cause ISI and lead to system performance degradation. In order to achieve high bandwidth efficiency in the bandwidth limited system, it is necessary to employ an appropriate equalization algorithm. For the OFDM modulation scheme, equalization is generally implemented in the frequency domain. The commonly used frequency domain equalizers are based on zero-forcing (ZF) or minimum mean square error (MMSE). In the time domain, digital filters with an adaptive algorithm such as least mean square (LMS) or recursive least square (RLS) can be a better fit to the variance of channels. A post nonlinear equalizer based on the simplified Volterra series and RLS method was employed in Ref. [61]. With a 15 m transmission distance, the system capacity was improved by 18% at the forward error correction (FEC) limit. Nonlinear equalizers such as maximum likelihood sequence estimation (MLSE), decision feedback equalization (DFE), or turbo equalization are also classical equalization algorithms, which can effectively compensate the temporal dispersion and reduce the bit error rate (BER). For instance, Gao *et al.* demonstrated 1.1 Gbps OOK-based UWOC using MLSE with only 167 MHz bandwidth[62].

Coding

Transmitting through a high attenuation environment or long distance, the receiver captures the signal with extremely low SNR. In this case, to maintain a stable communication link, channel coding technologies, such as convolutional code, Reed Solomon (RS) code, and low-density parity check (LDPC) code, are indispensable. In general, channel coding can be divided into two categories: block codes and convolution codes. Redundant bits are introduced to the transmitted sequences to correct a certain number of errors. Simpson *et al.* demonstrated a 500 kbps UWOC system with OOK data and a (255,129) RS code. The experimental results show that the coded system has an 8 dB improvement for a BER of 10^{-4}[63]. Furthermore, two codes can be combined to create a concatenated code, which has the advantages of two codes at the same time. Wang *et al.* studied a serial concatenated code with an RS code as the outer code and convolutional code as the inner code[64]. With interleaver, it can outperform the corresponding single code by about 3 dB. Mattoussi *et al.* studied the performance of RS code and LDPC code in the physical and upper layers[65]. The results show that LDPC code has an undeniable advantage in the physical layer, and the data protection in the physical layer is more essential than in the upper layers.

Spatial Diversity

In a turbulent transmission environment, spatial diversity can provide a significant performance enhancement of the communication system. Additionally, employing multiple transmitter apertures can provide a higher total transmission power and get a longer transmission distance. Through numerical calculation and simulation, Dong and Liu proved that the performance degradation caused by turbulence can be alleviated by the multiple-input single-output (MISO) scheme[66]. Jamali *et al.* theoretically and systematically studied the performance of a multiple-in multiple-out (MIMO) UWOC system, and the results show that spatial diversity can considerably enhance the system performance, especially for strong turbulence cases[67]. Song *et al.* experimentally demonstrated a 2×2 MIMO-OFDM UWOC using the setup shown in Fig. 12 and achieved a gross bit rate of 33.69 Mbps after a 2 m transmission[42].

E. Networking

Compared to an underwater acoustic system, the UWOC technique has provided an alternative solution to high-bandwidth and low-latency underwater wireless transmission[5]. However, some physical impairments, such as absorption, scattering, and turbulence, limit the transmission range of UWOC and thus affect its application in wide-range underwater transmissions. Therefore, the underwater optical wireless network (UOWN) technique, which allows multi-hop transmission, has been one of the key enabling technologies for UWOC to enhance its transmission range. Many research efforts have been focused on the UOWN technique[10,68–71]. In Ref. [68], the k connectivity of a UOWN was analyzed with diverse network density and channel conditions. In Ref. [10], the cellular code division multiple-access (CDMA) technique was introduced into UOWNs, and their structures, principles, and performance in different water types were investigated. In Ref. [69], Jamali *et al.* characterized the performance of a relay-assisted wireless optical CDMA network

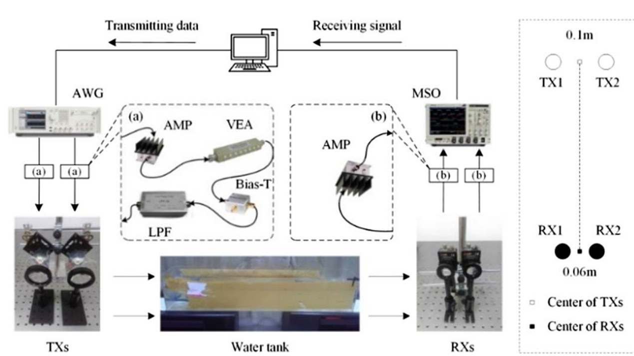

Fig. 12. Experimental setup for the proposed MIMO-OFDM-based UWOC system. The inset shows the schematic arrangement of transmitters (TXs) and receivers (RXs)[42].

employing the decode-and-forward (DF) relaying technique. Similarly, the performance of a multi-hop enabled UWOC system adopting the DF relaying technique was analyzed in Ref. [70]. In Ref. [71], the performance of a multi-hop enabled UOWN employing DF and amplify-and-forward (AF) relaying techniques was analyzed and modeled. Besides, routing algorithms were also developed for DF and AF-based schemes in Ref. [71]. All of the above works focused on the channel characterization and performance analysis for UOWN systems. Noticeably, although two important relaying techniques, DF and AF, have been investigated in UOWN systems, another important relaying technique, bit-detect-and-forward (BDF)[72], is still left unanalyzed in UOWNs.

The underwater routing technique is another important enabling technology for a UOWN. However, very few research works have been done on designing effective routing protocols for UOWN systems, while many routing protocols have been proposed for underwater acoustic wireless networks (UAWNs)[73–75]. The readers are also referred to a comprehensive survey with network layer topics containing relaying techniques and potential routing algorithms[6].

The security issue for a UOWN should also be considered in practical implementation[76]. Due to the inherently nonzero divergence angle of the light beam and the scattering effect of water on light, the gradually diffused light beam over distance may provide eavesdroppers with opportunities to wiretap or modify the transmitting signals[76–78]. Therefore, the level of security that has been traditionally taken for granted on UWOC may not always be there. As shown in Fig. 13, a 5 MHz square wave signal is successfully tapped aside the water tank by an MPPC, which preliminarily verifies the probability of information leakage in UWOC[76].

F. Testing Platform

The ultimate orientation of UWOC is its application in real dynamic underwater environments including oceans, lakes, rivers, and so on, where a UWOC system can be truly tested. However, the field trials, especially the sea trials, are extremely expensive and time consuming[79]. In addition, in field trials, it is difficult to study the effect of each single physical parameter on light propagation, as all parameters affect and contact mutually. Following the fundamental principle of going from simplicity to complexity, from part to whole, numerical simulations and experiments in laboratory environments should be well conducted before the demanding field trials. For this reason, the UWOC community has witnessed the testing platform evolution from ideal static tap water (or even pure water) in an indoor tank, to dynamic tap water with scattering agents in an indoor tank, and finally to the real sea[80,81]. For example, we have demonstrated a 26 m/5.5 Gbps air–water optical wireless communication using a 25 m indoor tank filled with static tap water[82], as shown in Fig. 14. For practical implementation of the air–water optical communication, we envision significant

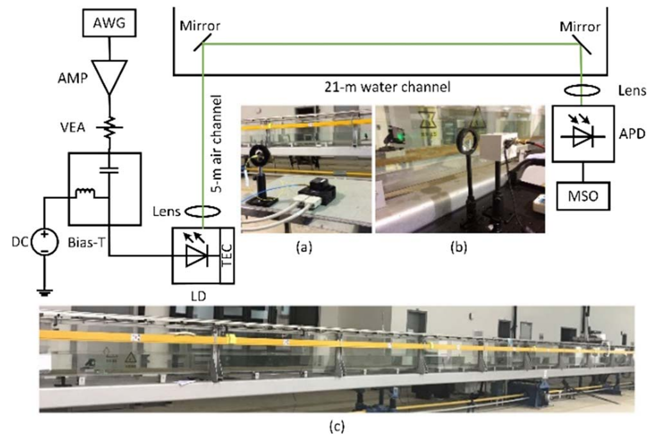

Fig. 14. Experimental setup of the air–water laser communication scheme[82]. Inset: (a) the transmitter module, (b) the receiver module, and (c) the water tank.

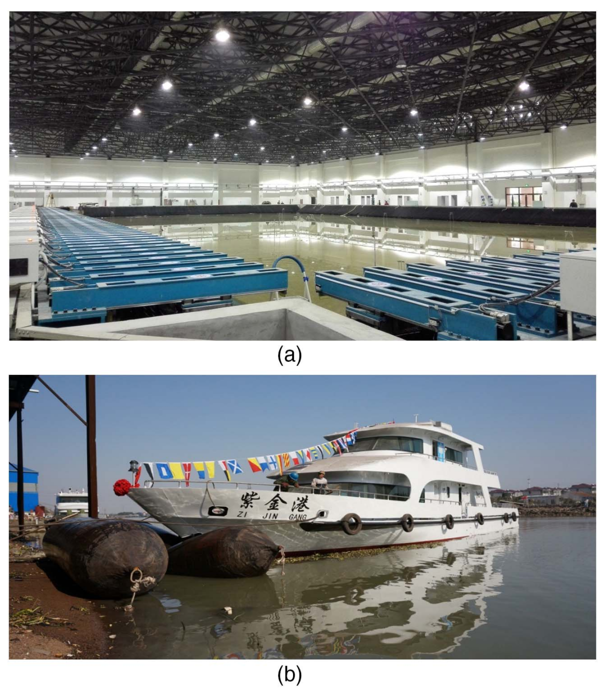

Fig. 15. (a) Wave/current basin (70 m in length, 40 m in width, and 1.5 m in depth). (b) The research vessel named Zijingang (29.8 m in length with a gross tonnage of 100 tons).

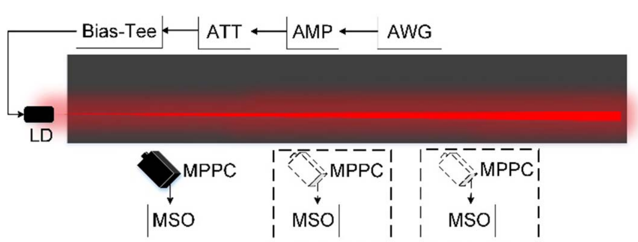

Fig. 13. Experimental setup for verifying information leakage using an MPPC placed aside the light beam[76].

challenges induced by link perturbations, such as turbulence and waves. The acquiring, tracking, and pointing techniques should be further developed to realize a stable cross-interface optical link. The recent availability in our laboratories of a large wave/current basin (70 m in length, 40 m in width, and 1.5 m in depth), as shown in Fig. 15(a), equipped with a three-dimensional (3D) wave generator, tidal generation pipes, and a sediment supply system, enables us to directly measure the environmental effects, arising from wave, tide, and impurities, on the optical link. In addition, further sea trials can be implemented by taking our research vessel shown in Fig. 15(b), which is 29.8 m in length with a gross tonnage of 100 tons.

5. CONCLUSION

We have introduced the basic concepts and essential features of UWOC. More recently, we have seen growing research activities in UWOC because of its strong competitiveness in short-range bandwidth-intensive scenarios with envisioned killer applications. UWOC to a certain extent shares similarities with optical fiber communication and indoor VLC, but with very distinct channel characteristics that also induce unique research challenges. Faced with the challenges, research efforts can be made from different perspectives based on a profound understanding of underwater channels. Link loss is a core feature of the UWOC channel, and thus powerful transmitters and ultra-sensitive receivers are hungrily desired to maximize the transmission distance, with signal processing and networking techniques being valuable additions for this goal. Besides link loss, many propagation effects (such as scattering and scintillation), arising from water optical properties and environmental dynamics, can significantly degrade link performance and should be investigated in detail. It is crucial to recognize that, unlike the link loss, such link performance degradation cannot be substantially improved merely by higher transmission powers or more efficient receivers, for which signal processing and networking techniques could be more powerful players. All in all, the characteristics of underwater channels should be the first consideration when tackling research challenges in the field of UWOC, especially when transplanting some techniques from other fields. The testing platforms should also be developed gradually, from the lab tank to the real sea, to fertilize the growth of this field.

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