A Review on Practical Considerations and Solutions in Underwater Wireless Optical Communication

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(Invited Paper)

***Abstract*—Underwater wireless optical communication (UWOC) has attracted increasing interest in various underwater activities because of its order-of-magnitude higher bandwidth compared to acoustic and radio-frequency technologies. Testbeds and pre-aligned UWOC links were constructed for physical layer evaluation, which verified that UWOC systems can operate at tens of gigabits per second or close to a hundred meters of distance. This holds promise for realizing a globally connected Internet of Underwater Things (IoUT). However, due to the fundamental complexity of the ocean water environment, there are considerable practical challenges in establishing reliable UWOC links. Thus, in addition to providing an exhaustive overview of recent advances in UWOC, this article addresses various underwater challenges and offers insights into the solutions. In particular, oceanic turbulence, which induces scintillation and misalignment in underwater links, is one of the key factors in degrading UWOC performance. Novel solutions are proposed to ease the requirements on pointing, acquisition, and tracking (PAT) for establishing robustness in UWOC links. The solutions include light-scattering-based non-line-of-sight (NLOS) communication modality as well as PAT-relieving scintillating-fiber-based photoreceiver and large-photovoltaic cells as the optical signal detectors. Naturally, the dual-function photovoltaic–photodetector device readily offers a means of energy harvesting for powering up the future IoUT sensors.**

***Index Terms*—Energy harvesting, fiber detector, non-line-of-sight, turbulence, underwater wireless optical communication.**

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I. Introduction

Over 70% of the Earth's surface is covered by oceans. Underwater oil exploration, oceanographic studies, and subsea military activities are examples of the growing need to explore the oceans for industrial, scientific, and military purposes. For instance, Saudi Aramco, which is the largest oil and gas company in the world, has over 43,000-km offshore oil pipelines to be monitored, thereby requiring an efficient, secure, and high-speed underwater wireless communication technology. Acoustic communication, which is the most common technology in underwater wireless communication, dates back to 1490 when Leonardo da Vinci suggested detecting ships in the distance by acoustic means [1]. Today, studies of the physical layer of underwater acoustic communication have reached a certain level of maturity. Numerous sea trials have demonstrated such communication over tens of kilometers or beyond [2] and transmission rates of tens of kilobits per second or higher [3]–[7], the latter being a substantial advance on the few tens of bits per second in the early stage [8], [9]. Acoustic-based video transmission has also been demonstrated [6]. Figure 1 shows the published experimental performance of underwater acoustic telemetry systems regarding their data rates versus their ranges, with a range-times-rate bound to estimate the existing performance envelope [10]. As the physical layer verifications become proven, calls are emerging to integrate acoustic modems into networks. Some platforms (e.g., SUNRISE [11], LOON [12], and SWARMs [13]) require network technologies such as medium access control (MAC) [14], multiple input and multiple output (MIMO) [15], [16], localization [17], [18], route discovery [19], and energy harvesting [20].

Considering the limited data rate of the acoustic method regardless of its maturity, the increasing need for high-speed underwater data transmission is driving the development of high-bandwidth communication methods. Radio-frequency (RF) technology typically delivers digital communication or full-bandwidth analog voice communication with rates of tens of megabits per second in terrestrial environments over the kilometer range [21]. However, researchers are also attempting to deploy RF technology in unconventional environments, such as (i) underground to monitor soil properties and build underground

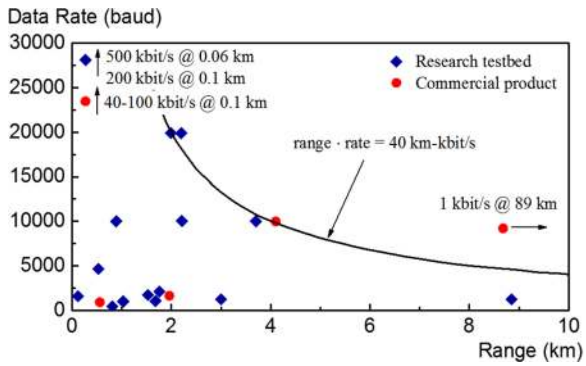

Fig. 1. Data rate versus transmission range of published experimental work on underwater acoustic systems (from [10]).

TABLE I
EXEMPLARY PREDICTED DATA RATES FOR DIFFERENT RANGES (FROM [24])

	Seawater	Fresh water
0.2 m	10–100 Mbit/s	10–100 Mbit/s
1–2 m	1–10 Mbit/s	5–20 Mbit/s
10 m	20–50 kbit/s	100–200 kbit/s
50 m	1–10 kbit/s	3–10 kbit/s
200 m	50–100 bit/s	100–200 bit/s

Mbit/s: megabits per second; kbit/s: kilobits per second; bit/s: bits per second.

networks [22], [23], and (ii) underwater to build underwater sensor networks. Though the considerable RF attenuation in water that increases drastically with frequency [24], there are still a few prior works on underwater RF communications [25]–[27]. In these works, a long transmission distance is always achieved by sacrificing the bandwidth (40 m and 100 bit/s at 3 kHz) [26] or vice versa (16 cm and 11 Mbit/s at 2.4 GHz) [25]. Table I summarizes the realizable ranges and data rates of underwater RF communication systems [24].

Given the limited performance of underwater acoustic and RF communication, underwater wireless optical communication (UWOC) has become a transformative alternative. Optical wireless communication (OWC) is data transmission in an unguided propagation medium through an optical carrier, namely ultraviolet (UV), visible, or infrared. Unlike the expensive, licensed, and limited electromagnetic spectrum in RF, the largely unlicensed spectrum (100–780 nm, or ∼30 PHz) in OWC enables wireless data transmission at extremely high data rates of up to gigabits per second (Gbit/s) [28]. In fact, the development of OWC has been ongoing since the very early years of human civilization. Signaling by means of beacon fires, smoke, ship flags, and semaphore telegraph can be considered as being historical forms of OWC [29]. In 1880, Alexander Graham Bell invented the photophone based on modulated sunbeams, thereby creating the world's first wireless telephone system that allowed the transmission of speech [30]. The recent development of high-speed power-efficient optoelectronic devices has offered the promise of OWC data rates of up to 100 Gbit/s [31] with transmission links of a few kilometers [32]. Such devices include light-emitting diodes (LEDs) [33], superluminescent diodes [34], lasers diodes (LDs) [35], photodetectors [36], modulators [37], and the integration of these devices [38]. Furthermore, because of the high energy efficiency of these high-speed optical emitters, OWC with dual functionality, such as light fidelity (Li-Fi), has been proposed for simultaneous lighting and communication purposes [39].

However, because of the complexity in aquatic environments, the early development of UWOC lagged far behind terrestrial OWC. The first experimental UWOC demonstration was made by Snow *et al.* in 1992, achieving a data rate of 50 Mbit/s over a 5.1 m water channel with a gas laser [40]. In 2006, by using a 470 nm blue LED, Farr *et al.* achieved a 91 m UWOC link with a rate of 10 Mbit/s [41]. The first gigabit (1 Gbit/s) UWOC system was implemented by Hanson *et al.* in 2008 using a diode-pumped solid-state laser [42]. However, more considerations are needed for the physical layer of UWOC to mature, one being the selection of a light wavelength that is suitable for use underwater. In the presence of underwater microscopic particulates and dissolved organic matter in different ocean waters, absorption and multiple scattering cause irreversible loss of optical intensity and severe temporal pulse broadening, respectively [43], which in turn degrade the 3 dB channel bandwidth [44]. Because of the low attenuation coefficients, blue-green light is preferable in clear and moderately turbid water conditions [45]. For highly turbid water, the channel bandwidth can be broadened by using a red-light laser because of the lower scattering at a longer wavelength, as investigated numerically by Xu *et al.* [46]. Based on that study, Lee *et al.* demonstrated the performance enhancement experimentally by utilizing a near-infrared laser; they showed that the overall frequency response of the system gains an increment of up to a few tens of megahertz with increasing turbidity [47]. These investigations led to the demonstration of real-time ultra-high-definition video transmission over underwater channels with different turbidities [48].

Besides the selection of a suitable transmission wavelength, recent years have seen much consideration of modulation schemes, system configurations, and optoelectronic devices. Efficient and robust modulation schemes and system configurations such as orthogonal frequency-division multiplexing (OFDM) [49], pulse-amplitude modulation (PAM) [50], discrete multitone (DMT) with bits and power loading [51], and injection locking [52] are now used to achieve high data rates. Highly sensitive photodetectors such as photomultiplier tubes (PMTs) [53], single-photon counters [54], and multi-pixel photon counters are now used for long-haul communication [55]. Figure 2 summarizes the recent advances of laser-based UWOC systems [40], [42], [46], [49]–[70]. In that plot, the extinction length, which is defined as the product of the transmission range and the attenuation coefficient of the water channel, is used to normalize the effect of water turbidity.

Despite the aforementioned previous investigations, if UWOC is to be used in real oceanic environments, then we must consider how UWOC systems are affected by oceanic

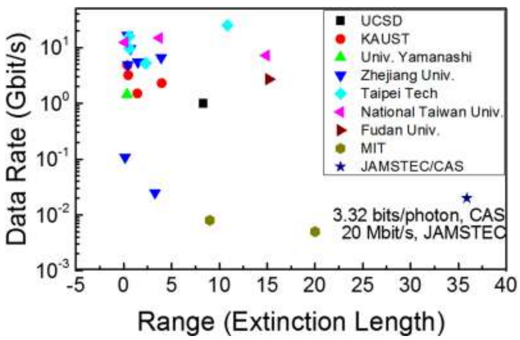

Fig. 2. Plot of data rate versus range (in terms of extinction length) of recent experimental work on laser-based UWOC.

turbulence. One of the main challenges with conventional UWOC systems is posed by the strict requirements on positioning, acquisition, and tracking (PAT). It is especially challenging to maintain PAT in the presence of oceanic turbulence because of optical beam fluctuations and, thus, misalignments. To build robust UWOC links to mitigate the effect of turbulence, we highlight herein our solutions, including non-line-of-sight (NLOS) UWOC modality, scintillating-fiber-based photoreceivers, and photovoltaic (PV) cells with a large active area as signal detectors to ease the PAT requirement. Furthermore, by using highly sensitive PV cells as photodetectors, we show simultaneous energy harvesting and signal detection in an underwater environment, thereby also providing solutions to the question of how to supply energy to an underwater data transceiver.

II. Oceanic Turbulence

In the presence of oceanic turbulence, the optical signal suffers random variations that are commonly known as scintillations. This phenomenon is due to random changes in the refractive index along the path of propagation, which in turn causes random changes in the direction of photons traveling through the water medium. Because the active areas of commonly used photodetectors are small to ensure fast communication links, even slight variations in the direction of the beam can cause signal fading. Underwater turbulence, which can persist for a relatively long time, can be induced by variations in temperature, salinity, or pressure, and by air bubbles in the water channel. Understanding this turbulence-induced fading is critical to establishing long-distance yet stable UWOC links, which is the primary motivation for the vast amount of previous research into water turbulence and its effects on optical links. This research examined the statistical characteristics of underwater turbulence, its impact on the propagation of light, and potential techniques to mitigate those effects.

One way to quantify the strength of the turbulence is to determine the scintillation index σ_I^2 of the received signal, which is defined as the variance of the received normalized intensity and is expressed as

$$\sigma_I^2 = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}, \tag{1}$$

where I is the received intensity and $\langle \cdot \rangle$ denotes the average taken over a long duration. High values of the scintillation index correspond to strong turbulence, which results in poorer performance of UWOC links.

A study conducted in the Tongue of the Ocean in the Bahamas measured the refractive-index structure constant C_n^2 to quantify the strength of the turbulence [71]. Other experiments have been conducted in emulated laboratory environments to statistically study the histogram of the received intensity in the presence of turbulence-induced fading caused by random and gradient changes in temperature and salinity, and by air bubbles in the water channel [72]–[74]. In those studies, the experimentally obtained histograms were fitted with well-known statistical distributions, and the goodness of fit was reported in each case. Such statistical results allow underwater turbulence to be modeled in calculations and simulations and facilitate methods to counter the associated performance degradation. For example, a model was developed to produce a closed-form expression of the bit error ratios (BERs) in vertical underwater channels and was verified using computer simulations [75]. Numerical calculations have also been used to study turbulence and to confirm that increasing the aperture size improves the performance under turbulence-induced fading [76]. Similarly, it was also shown experimentally that using wider beams can improve the performance of UWOC links in the presence of air bubbles [77]. Using beam expansions and aperture averaging is analogous to using spatial diversity in MIMO systems because the light beam travels through a wider space compared to a narrower beam. Moreover, spatial diversity can be achieved by using multiple transmitters. For example, the performance of a multiple-input single-output system has been evaluated [78], in which the transmitters were arranged in a uniform circular array, and it was shown that such a system improves the performance of UWOC links in turbulent water channels. A comprehensive study of the performance of MIMO systems has also been presented [79], and the performance of different wavelengths in the presence of temperature and salinity gradients has been studied [80]. The results showed that the scintillation index decreases significantly with wavelength, which suggests improved performance by using longer wavelengths because they are more immune to scintillation. However, it is important to note the critical tradeoff between using longer wavelengths that suffer from higher attenuation and using shorter wavelengths that suffer from stronger turbulence-induced fading. Furthermore, the reciprocity of the effects of underwater turbulence on the UWOC performance has also been studied [81]. The importance of the reciprocity of the channel lies in the fact that it alleviates the need for feedback to the transmitters to provide the channel state information in duplex links because they can extract it from the received signals.

To show how turbulence affects the beam position, we used a quadrant detector sensor head (PDQ90A; Thorlabs) with its auto aligner cube (KPA101; Thorlabs) to monitor the change in beam position in the presence of a 0.1 °C/cm temperature gradient. Figure 3 shows the relative position recorded over 100 s with a sampling rate of 1 kHz.

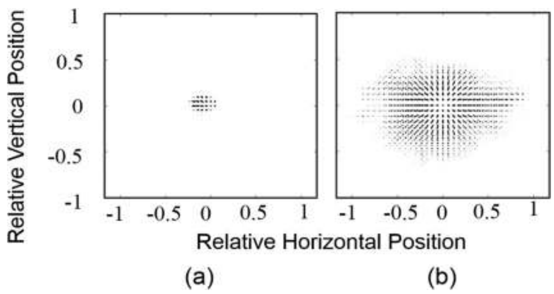

Fig. 3. (a) Beam position on the receiver side with no temperature gradient. (b) Beam position on receiver side with a 0.1-°C/cm temperature gradient.

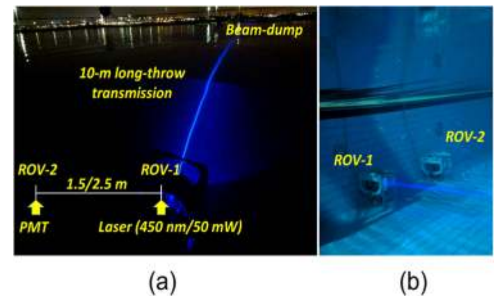

Fig. 4. (a) Pool testbed for deployment of 450 nm laser-based non-line-of-sight (NLOS) UWOC modality based on two ROVs. (b) Photograph of transmitter and receiver pointing in parallel direction to form an NLOS configuration.

Based on Fig. 3, we note that the beam position in the presence of turbulence changes randomly with time, thereby potentially degrading the performance of UWOC. We also note that the change on the horizontal axis (-1 – 1) exceeds that on the vertical axis (-0.4 – 0.4), this being due to the deformation of the beam by the vertical temperature difference, which gives the beam profile an oval shape. And the oval shape is mathematically related to the variance of the relative horizontal/vertical position, which is 0.06 for the horizontal and 0.02 for vertical.

III. Non-Line-of-Sight Underwater Wireless Optical Communication

Because of the complexity of the oceanic environment, including turbulence [80], turbidity [82], and undersea obstacles [77], severe signal fading occurs if a misalignment of the optical link happens in line-of-sight (LOS) UWOC, leading to degraded information transfer. By contrast, NLOS UWOC [83], a modality that relieves the strict PAT requirements, promises robust data-transfer links in the absence of perfect alignment. An NLOS UWOC system relies on either reflection from the water surface [84] or light scattering [85] from molecules and particles in the water (e.g., plankton, particulates, and inorganics). Compared with reflection-based NLOS, that based on scattering is more robust because it avoids the possibility of signal fading from the wavy surface. Furthermore, to receive the signal, reflection-based NLOS requires a certain pointing angle to the water surface for making the reflection light travel into the field-of-view (FOV) of the receiver. Therefore, we focus herein on scattering-based NLOS, which entirely relieves the PAT requirements. In such links, the transmitting photons are redirected multiple times by the molecules in the water before being detected by the photoreceiver. Therefore, a light beam with high scattering properties is favorable in NLOS UWOC. Cox *et al.* measured the total light-scattering cross sections for microscopic particles against the entire visible spectrum [86]. They showed that shorter wavelengths exhibit higher scattering for both Rayleigh and Mie scattering. Therefore, blue light (400–450 nm), which is the shortest visible wavelength, is preferred for use in NLOS UWOC. However, having constrained by the development of devices in general, previous works on NLOS UWOC mainly relied on simulations. Monte Carlo simulations [87] and the Henyey-Greenstein (HG) phase function [88] were used to develop models describing the transmitted photons' trajectory. The impulse response [85], BER performance [89], and the effects of channel geometry on path loss [83], [90] have also been predicted based on theoretical simulations. Herein, for the first time, we experimentally demonstrated a high-speed blue-laser-based NLOS UWOC system in a diving pool.

In our pool deployment, we used as the transmitter a 450 nm blue LD (PL TB450B; Osram) operating at 0.18 A with an optical emission power of 50 mW enclosed in a remotely operated vehicle (ROV-1), and as the receiver we used a PMT (PMT R955; Hamamatsu) with a high sensitivity of 7×10^5 A/W carried by ROV-2. As shown in Fig. 4(a), the laser and PMT were separated by either 1.5 or 2.5 m. At the far end of the laser beam, a beam dump made of black silicon was used to minimize the light reflected from the pool wall and to ensure that all the received light was due to the scattering process. As shown in Fig. 4(b), the laser and PMT pointed in parallel to fully relieve the alignment requirements. At the transmitter side, an alternating current (AC) signal was generated by a pattern generator (ME522A) with a pseudorandom binary sequence that was $2^{10}-1$ pattern modulated with non-return-to-zero on-off keying (NRZ-OOK). The PMT was operated at 15 V with a high voltage-controller voltage of 2 V, and an OD2 neutral-density filter was placed in front of the PMT window to control the incident power within the detection range of the PMT. The water was pool water with an absorption coefficient of 0.01 and a scattering coefficient of 0.36 m^{-1}.

Figure 5 shows that a data rate of 48 Mbit/s was achieved with a BER of 2.6×10^{-3} when the transmitter-receiver separation distance was 1.5 m, which is below the forward error correction (FEC) limit of 3.8×10^{-3}. Meanwhile, for the separation distance of 2.5 m, a maximum data rate of 20 Mbit/s was obtained with a BER of 2×10^{-4}. The corresponding eye diagrams are shown in Fig. 6. Upon increasing the data rate, the eyes become closer, inducing higher BER. Besides, compared with the eyes for the separation distance of 2.5 m, those for 1.5 m are noiseless. This is due to the weaker received light and increased inter-symbol interference caused by the multipath scattering with greater separation. Nevertheless, we have demonstrated, for the first time, a high-speed NLOS UWOC link with the PAT requirements fully relieved by using a blue laser. Furthermore, we envisage that a longer-haul NLOS UWOC could be developed in the future based on photon-counting modes using algorithms for pulse-counting, synchronization, and channel estimation [91].

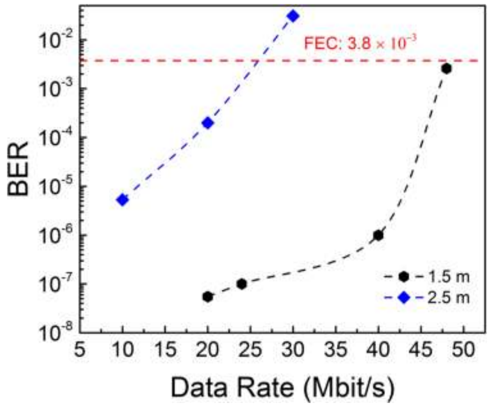

Fig. 5. BER versus data rate for NLOS UWOC pool testbed for transmitter-receiver separation distances of 1.5 (black) and 2.5 m (blue).

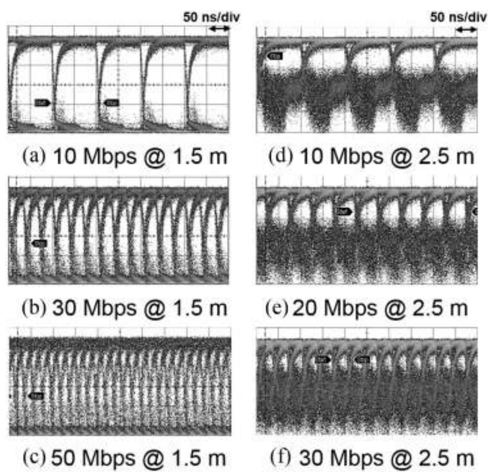

Fig. 6. Eye diagrams for data rates of: (a) 10 Mbit/s, (b) 30 Mbit/s, and (c) 50 Mbit/s with a separation distance of 1.5 m and (d) 10 Mbit/s, (e) 20 Mbit/s, and (f) 30 Mbit/s with a separation distance of 2.5 m.

IV. Omnidirectional Fiber Photodetector With Large Active Area

Paving the way for the upcoming era of the Internet of Underwater Things (IoUT), developments on the transmitter side have enabled transmission of up to gigabits per second in underwater environments [92]. However, on the receiver side, the small detection area of conventional photodiodes impedes the practicality in this regard. Although commercial photodiodes have demonstrated high modulation bandwidths of up to gigahertz, the detection areas of these photodiodes are limited to only a few square millimeters. This is largely attributed to the resistance-capacitance limit of the photodiode [93]. Considering the severe conditions in underwater environments and to relieve the strict PAT requirement, large-area photoreceivers with higher modulation speeds are essential for both practicality and to improve the connectivity among trillions of IoUT devices.

Scintillating fibers, which rely on the photon conversion process of the doped molecules in the fiber to propagate the converted light to the fiber end, were used as the optical receivers for corona discharges in early work [94], [95]. Having similar working principles to those of luminescent solar concentrators [96]–[99], scintillating fibers rely on the doped molecules in the core of the fiber to absorb the incoming light and re-emit it at a longer wavelength. The re-emitted light then propagates effectively along with the core of fiber to the fiber end. The first demonstration of using scintillating fibers as the photoreceiver for free-space optical communication (FSO) was reported by Peyronel *et al.* in 2016 [100]. The design was devised for indoor visible-light communication under eye-safe conditions. The advantages of scintillating fibers include the flexibility to form large-area photoreceivers of various sizes with no significant deterioration in response speed. Inspired by these prior studies, we aim to demonstrate the fundamental potential of scintillating fibers as large-area photoreceivers for UV-based UWOC. Compared to traditional photodiodes, this would eventually improve the practicality of UWOC in actual ocean environments with a large angle of view and omnidirectional detection [101].

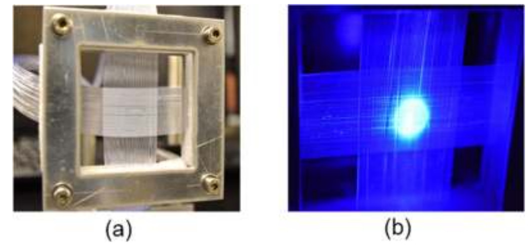

Fig. 7. Scintillating-fiber-based photoreceiver with an effective planar detection area of $\sim$5 cm^2 under: (a) no illumination and (b) collimated illumination of a 375-nm UV laser diode (similar to [101]).

As a proof of concept, a large-area photoreceiver made of commercially available scintillating fibers was constructed, as shown in Fig. 7. As shown in Fig. 7(a), the photoreceiver comprises around 90 strands of scintillating fibers and thus forms a planar detection area of roughly 5 cm^2. To demonstrate the modulation capabilities of the scintillating-fiber-based photoreceiver, we used a 375 nm UV LD (NDU4116; Nichia) as the transmitter to send a modulated optical signal over a 1.5-m-long water channel. The photoreceiver was placed at the other end of the water tank, and the strands of the fiber end were coupled into a commercial avalanche photodetector (APD) (APD430A2; Thorlabs) through a series of condenser lenses. Figure 7(b) shows the collimated UV light beam incident on the planar detection area of the large-area scintillating-fiber-based photoreceiver. It is apparent that the photoreceiver is sufficiently large to cover the entire profile of the collimated beam with no additional lenses. In addition, the small-signal frequency response of the large-area scintillating-fiber-based photoreceiver was tested over the same water channel. Figure 8 shows the small-signal frequency response of the photoreceiver with a 3-dB bandwidth of 91.91 MHz, which is relatively high compared to a conventional photodiode with the same detection area. The modulation bandwidth is primarily governed by the recombination lifetime of dye molecules [100], [104], and thus eliminating the need to balance the design trade-off between the detection area and the modulation bandwidth as in conventional photodiodes. Besides, with a conventional photodiode, although

TABLE II
COMPARISON OF PHOTODETECTION TECHNIQUES USED IN UWOC

Type of photoreceiver	Area size	Wavelength of transmission	-3 dB bandwidth	Modulation speed (Transmission format)	REF.
PIN	0.8 mm^2	685 nm	150 MHz	1.324 Gbit/s (128-QAM-OFDM)	[46]
APD	0.2 mm^2	520 nm	1 GHz	2.3 Gbit/s (NRZ-OOK)	[67]
APD	1 cm^2	470 nm	11 MHz	10 Mbit/s (Manchester-encoded)	[102]
APD	0.2 mm^2	450 nm	1 GHz	1.5 Gbit/s (NRZ-OOK)	[59]
Solar Panel	~ 5 cm^2	405 nm	<1.5 MHz	22.56 Mbit/s (64-QAM-OFDM)	[103]
Scintillating-fibers	5 cm^2	375 nm	91.91 MHz	250 Mbit/s (NRZ-OOK)	Similar to [101]

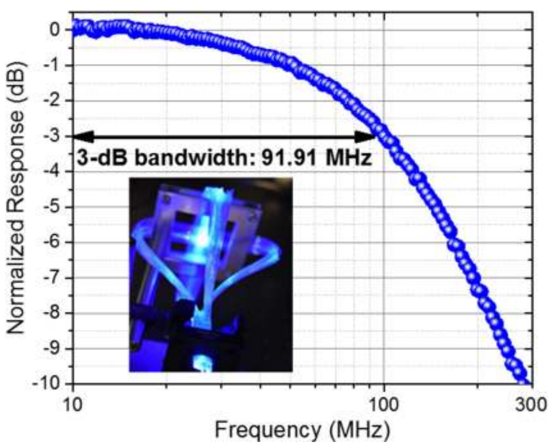

Fig. 8. Measured small-signal frequency response of large-area scintillating-fiber-based photoreceiver over a 1.5-m-long water channel. The inset shows a photograph of the spheroid-like omnidirectional scintillating-fiber-based photoreceiver (similar to [101]).

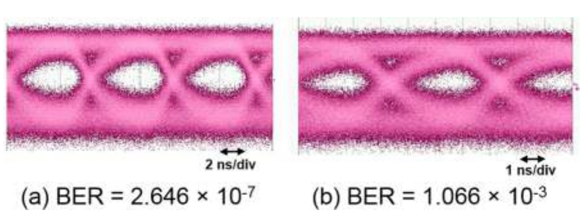

Fig. 9. Received BER and eye diagrams at: (a) 150 Mbit/s and (b) 250 Mbit/s over a 1.5-m-long water channel using a 375-nm UV laser as the transmitter (similar to [101]).

the angle of view can be improved by using additional receiver lenses, it is challenging to attain flexibility and omnidirectional detection. The inset of Fig. 8 shows a photograph of the large-area scintillating-fiber-based photoreceiver with high flexibility to form a spheroid-like photoreceiver for omnidirectional detection.

Moreover, the data rate of the scintillating-fiber-based photoreceiver in an underwater communication link was tested by modulating the 375 nm UV laser. The transmitter was connected to a BER tester (J-BERT N4903B; Agilent) for OOK signal generation. The signals were transmitted through a 1.5-m-long water channel to the scintillating-fiber-based photoreceiver before coupling into an APD. The APD was then connected back to the J-BERT. Figure 9(a) and (b) show the eye diagrams and corresponding BER below the FEC limit at 150 Mbit/s and a maximum attainable rate of 250 Mbit/s, respectively. Thus, the potential of a large-area and high-bandwidth scintillating-fiber-based photoreceiver is shown for establishing UV-based data transmission in underwater channels. By using a more-complex modulation scheme (e.g., PAM, OFDM, DMT) coupled with bit-loading and pre-equalization techniques, higher data rates of up to gigabits per second could be expected with the large-area scintillating-fiber-based photoreceiver.

Table II summarizes the photodetection techniques used in UWOC. Comparatively, the photodetection scheme based on scintillating fibers offers large modulation bandwidth as compared to other prior works, without sacrificing the detection area. Moreover, as compared to conventional photoreceivers based on Si-based photodiodes [46], [59], [67], [102] and solar panels [103], the use of scintillating fibers render large area detection while preserving the modulation bandwidth of the accompanying Si-based photodiode. This could also alleviate the costly and timely development path for a UV-based photoreceiver with a large detection area and high response speed [104]–[107]. Hence, the approach can accelerate the realization of UV-based NLOS communication modality to obviate the strict PAT requirements in UWOC.

V. PHOTOVOLTAIC CELLS FOR SIMULTANEOUS SIGNAL DETECTION AND ENERGY HARVESTING

Following the vigorous development of information technology and popularization of the IoUT concept, energy issues have become a bottleneck for power-hungry UWOC devices. To support the underwater equipment for massive data processing and long-distance communication, it is essential to develop and use sustainable energy resources and explore advanced energy-storage technologies. As a renewable and green energy, solar energy is undoubtedly an alternative to resolve these energy issues. In recent years, PV cells, which are increasingly popular alternatives to traditional photodetectors, have been studied extensively in the field of OWC [108]–[113]. Apart from harvesting the energy through the direct current (DC) component of the light source, a PV cell can also convert AC signals superimposed on

TABLE III
COMPARISON OF SEVERAL OWC SYSTEMS BASED ON DIFFERENT KINDS OF PV CELLS

Type of solar cell	Bandwidth	Distance	Data rate	Ref.
Silicon	10 kHz	40 cm	3 kbit/s	[114]
Silicon	350 kHz	24 cm	7.01 Mbit/s	[115]
Silicon	350 kHz	95 cm	11.84 Mbit/s	[116]
Silicon	120 kHz	10 cm	17.05 Mbit/s	[110]
Organic	1.3 MHz	1 m	34.2 Mbit/s	[111]
Silicon	-	80 m	20 Mbit/s	[117]
GaAs	24.5 MHz	2 m	0.5 Gbit/s	[113]

the light source back to electrical signals for signal detection. Table III summarizes the communication performance of several OWC systems based on different kinds of PV cells. Most of the previous works on PV cells for OWC have been focused on improving the data rate and bandwidth by using various novel PV cells. In [111], 34.2-Mbit/s signals were received by using organic PV cells and a red laser over a 1-m air channel. In addition to using LEDs or lasers operating in visible-light band and silicon wafer-based PV cells for OWC [108]–[111], researchers also employed mature near-infrared laser sources and GaAs PV cells to implement efficient energy harvesting and high-speed FSO communication [113]. However, an essential prerequisite for realizing long distances and high speeds is strict alignment, which limits the use of conventional OWC for mobile underwater platforms. Consequently, work remains lacking in resolving the above issues.

Inspired by these previous studies, PV cells with the dual functions of signal acquisition and energy harvesting show good prospects for application in energy-hungry marine environments. In Ref. [103], the authors first stressed the importance of PV cells for UWOC to resolve underwater energy issues in underwater environments. Considering the complexity in underwater channels, the authors also highlighted the superiorities of PV cells with large detection areas, which can significantly alleviate the alignment issues caused by mobile transmitters and receivers. To promote the application of PV cells in practical UWOC scenarios. In the following, we use a white laser with a large divergence angle for simultaneous lighting and optical communication in UWOC [118]. We explore PV cells with large detection areas that are capable of detecting weak light, which can alleviate the alignment issues and lays the foundation for future implementation of long-distance underwater communication.

Figure 10 shows the schematic of the PV-cell-based UWOC system. Because the measured bandwidth of the PV cell is only around 290 kHz, a highly spectral-efficient modulation format (i.e., OFDM) was used in the experiment to improve the data rate. The OFDM signals were generated offline. The bit number of the pseudorandom binary sequence was $2^{20}-1$. The size of the inverse fast Fourier transform was 1024. The number of efficient subcarriers and subcarriers for the frequency gap near DC were 93 and 10, respectively. The number of OFDM

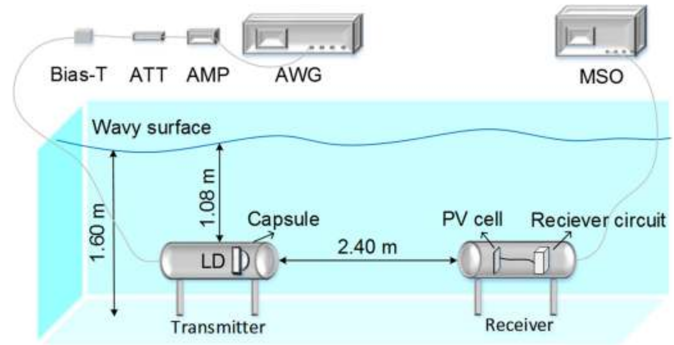

Fig. 10. Schematic of UWOC system based on a PV cell.

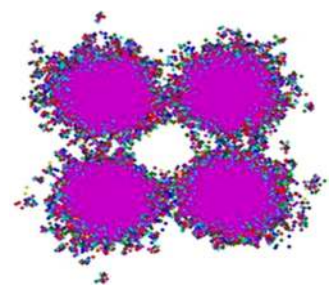

Fig. 11. Constellation map of received 908.2 kbit/s 4-QAM-OFDM signals with a BER of 1.01×10^{-3} over a 2.4 m underwater channel.

symbols was 150, including four training symbols for channel equalization and two for timing synchronization. The cyclic prefix number was 10. Four-quadrature amplitude modulation (4-QAM)-OFDM signals were sent from an arbitrary-waveform generator (AWG) with a sampling rate of 5 MHz. After being adjusted by an amplifier (APM) and an attenuator (ATT), the OFDM signals were superposed on a white LD via a bias tee. Over a 2.4 m transmission distance in the diving pool, the optical signals were detected by a PV cell with a detection area of 36 cm^2 (6 cm $\times$ 6 cm). Note that the experiment was conducted in daytime, and thus the main background noise is attributed to sunlight and the underwater channel. To separate the AC signals from the DC signals, a receiver circuit was designed for the PV cell. Besides, an amplifier and a filter were included to amplify the signals and filter the noise outside of the detection band. Finally, the signals were captured by a mixed-signal oscilloscope with a sampling rate of 25 MHz and processed offline.

After transmission through the 2.4-m underwater channel, the achieved gross data rate of the OFDM signals was 908.2 kbit/s. The constellation map of the received 4-QAM-OFDM signals is shown in Fig. 11, which is well converged. The corresponding BER was 1.010×10^{-3}.

VI. FUTURE WORK

Beyond the challenges and solutions mentioned above, areas remain that require extensive investigation in practical UWOC deployment. An example is the physical layer of UWOC, which still requires considerable effort before networking construction. Apart from the required compact, high-speed, and low-power optoelectronic devices, solid understandings and further investigations are needed urgently of water channels and modem algorithms, along with both analytical and computational exploratory studies. Higher layers of networking technologies are also in demand, which includes MAC, localization, route discovery, and multihop communication. Furthermore, a low-power and compact computing technology is a major consideration when designing a practical UWOC system for field deployment. This includes digital signal processors (DSPs), field-programmable gate arrays (FPGA), and future general-purpose computing platforms.

VII. Conclusions

While UWOC offers high-speed data transfer and complements the existing RF and acoustic technologies, its ultimate performance is affected by the complex underwater environment. The main concerns are (i) alignment loss under oceanic turbulence and (ii) energy supply for power-hungry underwater devices. The oceanic turbulence, which is induced by temperature or salinity gradients in the waters, will cause time-varying characteristics of seawater channels, and thus result in a severe distortion of received signals with large pointing errors, and even failure of communication. However, such PAT issues and energy harvesting in underwater environments can be addressed by several novel system configurations and device innovation. NLOS UWOC, by taking advantage of underwater light scattering, significantly eased the PAT requirements. The demonstration of a 20-Mbit/s/2.5-m blue-laser-based NLOS UWOC proves the feasibility of alignment-free optical communication by establishing an NLOS UWOC link. Besides innovating the communication system configuration, it is also promising to mitigate such pointing errors by using novel photodetectors with a large active area. The study of 250-Mbit/s/1.5-m scintillating-fiber-based photoreceiver link with a 5-cm^2 active area, shows the capability of simultaneously easing the alignment issues while still maintaining high-speed communication. The PV cell, with a large active area of 36-cm^2 as a photoreceiver, on the other hand, shows great potential for simultaneous signal detection and energy harvesting for underwater sensors. Beyond the considerations and solutions mentioned, there are other core areas of research interest for field deployment, such as theoretical models and algorithms for randomly varying water channels, higher layers of networking technologies, and a low-power computing system for underwater environments. It can be envisaged that the above comprehensive suite of technologies may soon revolutionize the technology of underwater communication to meet the demands for comprehensive undersea interconnectivity under the framework of IoUT.

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