Underwater Wireless Optical Communications: From the Lab Tank to the Real Sea

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Abstract: This paper introduces the recent progress of underwater wireless optical communications (UWOC). Studies in channel dynamics and link alignment issues contribute to the mature applications of UWOC in real sea environments.

1. Introduction

More extensive ocean explorations enhance human understanding of the ocean and demand for more advanced ocean technology, say ocean wireless communication. Reliable underwater wireless communication systems with a high data rate are of great significance for real-time data exchange among underwater vehicles, sensor networks and mother ships. For its advantages like high bandwidth, low latency and moderate transmission distance, underwater wireless optical communication (UWOC) has emerged as a promising technology in underwater communication [1]. To promote the deployment of UWOC, many efforts have been devoted to overcoming the large link loss caused by the absorption and scattering in seawater. With the breakthrough in high-performance transceivers and signal processing technologies, the link distance and data rate have been extended to hundreds of meters and several tens of Gbps, respectively [2]. Furthermore, not all experiments are confined to controlled smooth environments like water tanks in labs, and some have already moved to practical environments existing dynamic factors and link alignment issues [3]. The success in sea trials has also become an important benchmark for system performance evaluation.

This paper presents an overview of the recent progress in improving the transmission distance and data rate of UWOC systems. Studies in channel dynamics and link alignment issues are also highlighted in this paper. With these advancements, UWOC systems have more opportunities for wide applications and deployment in real sea environments.

2. Progress in Transceivers and Signal Processing

Employing blue-green light to achieve lower attenuation is a common method for UWOC systems. However, devices operating in these wavebands normally have limitations in modulation bandwidth and transmitting power. Injection locking for laser diodes [4] and pre-emphasis circuits [5] for light-emitting diodes (LEDs) can effectively enhance the bandwidths of transmitters. On the other hand, the master oscillator power amplifier fiber laser is a promising solution to realize high average and peak powers [6]. Another useful method is to combine several high-speed outputs, to form a high-power output. A 3×1 fiber combiner was used in [7] to reach a total power of 2.4 W, achieving a 100-m/8.39-Mbps UWOC link.

High-sensitivity detectors have significantly extended the link distance of UWOC, and they have been widely used in recent UWOC transmissions over 100 m. The single photon avalanche diode exhibits sensitivity close to the quantum limit but its bandwidth is limited by the dead time [8]. While maintaining a high sensitivity, both multi-pixel photon counters [9] (MPPCs, also known as silicon photomultipliers, SiPMs) and photomultipliers (PMTs) [10] can achieve Gbps-level UWOC links. PMTs and MPPCs can typically operate in two modes: counting mode and analog mode. The analog mode supports higher data rates with high-order modulation, while the counting mode enables greater sensitivity. A 312.03-Mbps orthogonal frequency division multiplexing (OFDM) link was demonstrated using an analog MPPC with a 3-dB bandwidth of 4 MHz [11]. While using a photon-counting PMT and pulse position modulation (PPM), a receiving sensitivity of 3.32 bits/photon was achieved to overcome a link loss of 136.8 dB [12].

Appropriate signal processing techniques based on the transceiver properties can lead to further breakthroughs in UWOC. For bandwidth-limited systems, modulations with high spectrum efficiency boost the data rate effectively. An LED-based UWOC transmission with a data rate exceeding 3 Gbps, within about 500-MHz bandwidth, was achieved by discrete multitone modulation [12]. For long-distance systems, PPM combined with high-peak-power pulsed lasers and photon-counting detectors can realize optimal energy efficiency. A distance record of 35.88 attenuation lengths was achieved using 256-PPM and a pulsed transmitter with a 100-kW peak power [12]. In addition, signal processing is often adopted to mitigate signal distortion [14]. A compressed Volterra nonlinear equalizer was proposed to mitigate the nonlinear impairments and inter-symbol interference, reaching a data rate of 500 Mbps over

200 m in a swimming pool, which is the longest physical distance [15]. Furthermore, artificial neural network-aided signal processing has also recently emerged as a valuable and effective tool in UWOC [16,17].

Recent long-distance results are depicted in Fig. 1(a) [5-9, 12, 14, 15, 18-21] and the attenuation lengths are noted for comparison. The transmission distance of UWOC systems has reached a level of several hundred meters at a data rate of several hundred Mbps, implying that studies in UWOC can enter a new stage for promoting practical applications.

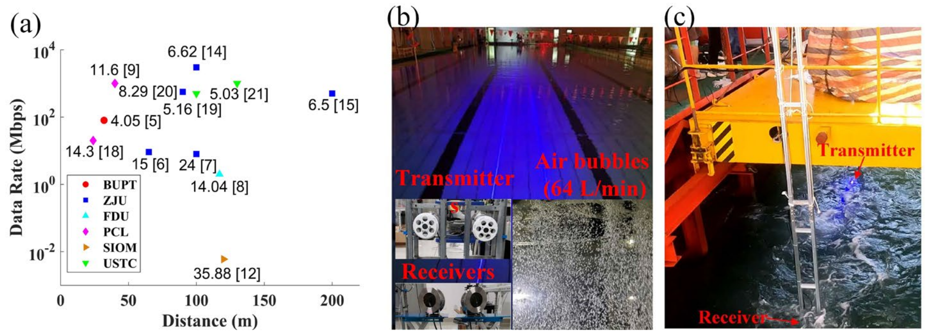

Fig. 1. (a) Recent long-distance demonstrations of UWOC systems, (b) a 2×2 MIMO-UWOC system in a swimming pool with air bubbles, and (c) the sea trial scene of the UWOC system based on beam-shaped LEDs.

3. Studies in Practical UWOC

The design of practical UWOC systems should consider hostile dynamic factors in real sea environments, like turbulences and air bubbles. The dynamic factors usually lead to scintillations and their effects on communication have been widely investigated theoretically and experimentally [3, 22-24]. Multiple-input multiple-output (MIMO) is considered to be one of the most effective methods to mitigate scintillation. For most UWOC systems, repetition coding and maximum ratio combining can lead to the best bit error rate performance [25-27]. In [25], a 2×2 MIMO-UWOC system was demonstrated to counter air bubble-induced scintillation, achieving a 50-m/233-Mbps underwater link with an air intensity of 64 L/min, as shown in Fig. 1(b). A 100-m/1-Gbps sea trial of UWOC also adopted the MIMO technique to improve link stability [28]. In addition, methods such as polarization modulation [29] and the employment of low-coherence light sources [30] can also improve the system's robustness against scintillation.

Transceiver movement and beam wandering will disturb link alignment, especially when using lasers with narrow divergence angles. Existing solutions can be divided mainly into two categories: using acquisition, pointing, and tracking (APT) systems and developing systems with relaxed alignment requirements. Precise ATP relies on the accurate analysis of sound signals [31], marker images [32], and light spot images [33], which contain location information. For easy alignment, reported research includes diffused laser [34], LED array [35], fisheye lens-based receiver [36], and omnidirectional photoluminescence-based receiver [37]. A sea trial of UWOC based on beam-shaped LED was carried out on an offshore platform in the East Sea, China, as shown in Fig. 1(c) [38]. Despite the hostile sea condition and gale (force 8), it was still able to establish a stable UWOC link.

Apart from the aforementioned works, studies in water-air links [1], non-line-of-sight links [3], and new components for beam shaping or steering [39-41], will also contribute to the development of practical UWOC. With the continuous technological advancement, practical UWOC systems require more sea trials for verifications.

4. Conclusion

In summary, this paper reviews the recent progress of UWOC in transceivers and signal processing. Methods to overcome dynamic channels and misalignment are also introduced. It can be foreseen that improving the robustness of UWOC and validating it through sea trials will be an important trend in this field. This work was supported by National Key Research and Development Program of China (2022YFC2808200, 2022YFB2903403) and Key Research and Development Program of Hainan Province (ZDYF2023GXJS016).

5. References

[1] L.-K. Chen *et al*., “Underwater and water-air optical wireless communication,” J. Lightw. Technol **40**, 1440-1452 (2022).
[2] S. Zhu *et al*., “Recent progress in and perspectives of underwater wireless optical communication,” Prog. Quant. Electr. **73**, 100274 (2020).
[3] X. Sun *et al*., “A review on practical considerations and solutions in underwater wireless optical communication,” J. Lightw. Technol **38**, 421-431 (2020).
[4] W.-S. Tsai *et al*., “A 30 Gb/s PAM4 underwater wireless laser transmission system with optical beam reducer/expander,” Sci. Rep. **9**, 8605 (2019).

[5] H. Zhou *et al*., “Design and implementation of more than 50m real-time underwater wireless optical communication system,” J. Lightw. Technol **40**, 3654-3668 (2022).
[6] C. Zhang *et al*., “9.14-Mbps 64-PPM UWOC system based on a directly modulated MOPA with pre-pulse shaping and a high-sensitivity PMT with analog demodulation,” Opt. Express **30**, 30233-30245 (2022).
[7] M. Zhao *et al*., “Long-reach underwater wireless optical communication with relaxed link alignment enabled by optical combination and arrayed sensitive receivers,” Opt. Express **28**, 34450-34460 (2020).
[8] H. Chen *et al*., “Toward long-distance underwater wireless optical communication based on a high-sensitivity single photon avalanche diode,” IEEE Photon. J. **12**, 1-10 (2020).
[9] L. Zhang *et al*., “Over 10 attenuation length gigabits per second underwater wireless optical communication using a silicon photomultiplier (SiPM) based receiver,” Opt. Express **28**, 24968-24980 (2020).
[10] K. Nakamura *et al*., “Over 1 Gbit/s NRZ-OOK underwater wireless optical transmission experiment using wideband PMT,” in *2019 24th OECC and 2019 PSC*, (IEEE, 2019), 1-3.
[11] J. Wang *et al*., “Underwater wireless optical communication based on multi-pixel photon counter and OFDM modulation,” Opt. Commun. **451**, 181-185 (2019).
[12] S. Hu et al., “35.88 attenuation lengths and 3.32 bits/photon underwater optical wireless communication based on photon-counting receiver with 256-PPM,” Opt. Express 26, 21685-21699 (2018).
[13] Y. Zhou *et al*., “Common-anode LED on a Si substrate for beyond 15 Gbit/s underwater visible light communication,” Photon. Res. **7**, 1019-1029 (2019).
[14] C. Fei *et al*., “100-m/3-Gbps underwater wireless optical transmission using a wideband photomultiplier tube (PMT),” Opt. Express **30**, 2326-2337 (2022).
[15] Y. Dai *et al*., “200-m/500-Mbps underwater wireless optical communication system utilizing a sparse nonlinear equalizer with a variable step size generalized orthogonal matching pursuit,” Opt. Express **29**, 32228-32243 (2021).
[16] H. Lu *et al*., “Deep learning aided robust joint channel classification, channel estimation, and signal detection for underwater optical communication,” IEEE Trans. Commun, **69**, 2290-2303 (2020).
[17] N. Chi *et al*., “Visible light communication in 6G: Advances, challenges, and prospects,” IEEE Veh. Technol. Mag. **15**, 93-102 (2020).
[18] Z. Chen *et al*., “Experimental demonstration of over 14 AL underwater wireless optical communication,” IEEE Photon. Technol. Lett. **33**, 173-176 (2021).
[19] J. Wang *et al*., “100 m/500 Mbps underwater optical wireless communication using an NRZ-OOK modulated 520 nm laser diode,” Opt. Express **27**, 12171-12181 (2019).
[20] Z. Du *et al*., “90-m/660-Mbps Underwater Wireless Optical Communication Enabled by Interleaved Single-Carrier FDM Scheme Combined with Sparse Weight-Initiated DNN Equalizer,” J. Lightw. Technol (2023).
[21] C. Tu *et al*., “First demonstration of 1Gb/s PAM4 signal transmission over a 130m underwater optical wireless communication channel with digital equalization,” in *2021 IEEE/CIC ICCC*, (IEEE, 2021), 853-857.
[22] Y. Baykal *et al*., “Underwater turbulence, its effects on optical wireless communication and imaging: A review,” Opt. Laser. Technol. **156**, 108624 (2022).
[23] F. Xing *et al*., “Performance characterization of two-way multi-hop underwater networks in turbulent channels,” Chin. Opt. Lett. **17**, 100005 (2019).
[24] J. Zhang *et al*., “Monte-Carlo-based optical wireless underwater channel modeling with oceanic turbulence,” Opt. Commun. **475**, 126214 (2020).
[25] X. Chen *et al*., “Demonstration of a 2× 2 MIMO-UWOC system with large spot against air bubbles,” Appl. Opt. **61**, 41-48 (2022).
[26] W. Liu *et al*., “Experimental Investigation of Underwater Optical Wireless Communication for Correlated SIMO Channel Under Temperature-Induced Turbulence,” IEEE Photon. J. (2023).
[27] L.-K. Chen *et al*., “Robust UOWC systems against bubble-induced impairments via transmit/receive diversities,” Chin. Opt. Lett. **17**, 100006 (2019).
[28] S. Ishibashi and K.-I. Susuki, “1Gbps × 100m Underwater Optical Wireless Communication Using Laser Module in Deep Sea,” in *OCEANS 2022, Hampton Roads*, (IEEE, 2022), 1-7.
[29] W. Liu *et al*., “Multilevel polarization shift keying modulation for turbulence-robust underwater optical wireless communication,” Opt. Express **31**, 8400-8413 (2023).
[30] C. T. Geldard *et al*., “Empirical study of the underwater turbulence effect on non-coherent light,” IEEE Photon. Technol. Lett. **32**, 1307-1310 (2020).
[31] Y. Weng *et al*., “Pointing error control of underwater wireless optical communication on mobile platform,” IEEE Photon. Technol. Lett. **34**, 699-702 (2022).
[32] J. Lin *et al*., “Machine-vision-based acquisition, pointing, and tracking system for underwater wireless optical communications,” Chin. Opt. Lett. **19**, 050604 (2021).
[33] J. Tang *et al*., “Monocular vision aided optical tracking for underwater optical wireless communications,” Opt. Express **30**, 14737-14747 (2022).
[34] C. Yu *et al*., “Experimental verification of diffused laser beam-based optical wireless communication through air and water channels,” Opt. Commun. **495**, 127079 (2021).
[35] B. Han *et al*., “Experimental demonstration of quasi-omni-directional transmitter for underwater wireless optical communication based on blue LED array and freeform lens,” Opt. Commun. **434**, 184-190 (2019).
[36] Y. Hua *et al*., “Fisheye lens-based UWOC system with an FOV of±90°,” Opt. Express **31**, 26888-26897 (2023).
[37] C. H. Kang *et al*., “Ultraviolet-to-blue color-converting scintillating-fibers photoreceiver for 375-nm laser-based underwater wireless optical communication,” Opt. Express **27**, 30450-30461 (2019).
[38] X. Yang *et al*., “50-M/300-Mbps Underwater Wireless Optical Communication Using Incoherent Light Source,” J. Lightw. Technol (2023).
[39] C.-W. Chow *et al*., “Actively controllable beam steering optical wireless communication (OWC) using integrated optical phased array (OPA),” J. Lightw. Technol 41, 1122-1128 (2022).
[40] Y. Shen and X. Luo, “Efficient bending and focusing of light beam with all-dielectric subwavelength structures,” Opt. Commun. 366, 174-178 (2016).
[41] M. Wu *et al*., “Super-focusing of center-covered engineered microsphere,” Sci. Rep. 6, 31637 (2016).