Underwater Communication Enabled by Visible Light Semiconductors: Toward Beyond 5G

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***Abstract*—To support seamless network coverage in the Beyond 5G (B5G) era, this paper proposes three practical approaches to extending terrestrial access networks into underwater environments using Underwater Optical Wireless Communication (UOWC) based on visible light semiconductors. First, a Radio-over-UOWC (RoUOWC) method enables low-power LPWA signals in the 920 MHz band to be transparently transmitted underwater. Second, the application of G.hn technology facilitates gigabit-class optical wireless links exceeding 500 Mbps using commercial OFDM-based chipsets. Third, a novel PON-UOWC hybrid architecture is proposed to support multi-terminal underwater access while retaining compatibility with existing OLT/ONU systems. These results demonstrate the feasibility of a cost-effective, scalable, and protocol-transparent underwater extension of terrestrial networks. The proposed methods offer promising pathways for future applications in smart aquaculture, marine infrastructure monitoring, and blue economy initiatives.**

***Index Terms*—Underwater Optical Wireless Communication (UOWC), RoUOWC, G.hn, LPWA, Passive Optical Network (PON), Beyond 5G, Visible Light Communication (VLC).**

I. Introduction

With the commercial rollout of fifth-generation (5G) mobile communication systems progressing, research attention has shifted to Beyond 5G (B5G) and sixth-generation (6G) technologies, with deployment targeted in the 2030s. These next-generation systems aim not only to increase speed and capacity, but also to achieve seamless connectivity across all domains—land, sea, air, and space. Such extended coverage is expected to integrate cyber and physical spaces and enable network infrastructure deployment in previously challenging environments such as oceans and outer space. These capabilities are considered essential to addressing societal issues such as disaster resilience, environmental protection, and industrial advancement [1], [2].

The digital transformation of the ocean is particularly crucial, as oceans account for about 70% of the Earth's surface. The "blue economy," which balances sustainable ocean resource utilization and economic growth, has gained global attention. Key sectors such as offshore wind power, aquaculture, maritime transport, and environmental monitoring are rapidly growing. Offshore wind power, for example, is projected to account for 50% of marine infrastructure investment by 2050. Similarly, smart aquaculture relies heavily on real-time monitoring of water quality and environmental conditions. These developments require high-performance and cost-effective underwater communication infrastructure capable of collecting and transmitting large amounts of data in real time [3]–[5].

Fig. 1 illustrates a conceptual platform for underwater Internet of Things (IoT) services. UOWC enables real-time, high-speed communication among various underwater sensors and cameras deployed in environments such as aquaculture farms and offshore wind power installations. These systems facilitate continuous monitoring of environmental parameters, structural health, and operational status, thereby supporting efficient management and sustainability of marine resources.

To realize such services, a flexible and seamless network infrastructure is required, bridging Over-water and underwater environments. One promising approach is the integration of Underwater Optical Wireless Communication (UOWC), which uses visible light—particularly in the blue-to-green range—with relatively high transmittance in water [6], [7].

As shown in Fig. 2, the feasibility of UOWC depends heavily on the attenuation characteristics of electromagnetic waves in water. While radio frequency (RF) signals suffer extremely high attenuation in seawater, the blue-to-green region (approximately 450–550 nm) exhibits the lowest attenuation, making it highly suitable for underwater optical communication [9], [10].

As summarized in Table I, each existing underwater communication method has trade-offs between bandwidth, range,

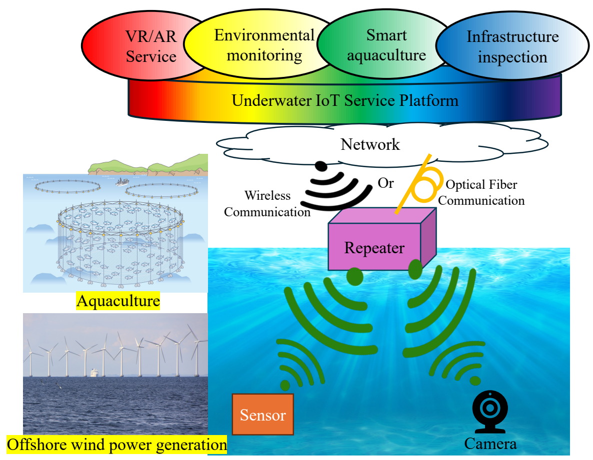

Fig. 1. Underwater IoT Service Platform

TABLE I
COMPARISON OF UNDERWATER COMMUNICATION TECHNOLOGIES [9], [10]

Technology	Bandwidth	Latency	Range	Relative Cost	Key Challenges
Acoustic Communication	kbps	High	Long (km)	High	Low bandwidth, high latency, multi-path, Doppler effects
RF Communication	Mbps–Gbps	Very Low	Very Short (<10 m)	Medium	Severe signal attenuation in seawater
Wired Communication	Gbps–Tbps	Very Low	Short (<100 m)	Very High	High deployment/maintenance costs, immobile

latency, and cost. These limitations highlight the need for new infrastructure solutions that can meet the performance and flexibility requirements expected in the B5G/6G era [11].

UOWC presents a strong candidate to address these gaps, providing broadband, low-latency communication suitable for high-throughput applications such as real-time video transmission and underwater robot control. However, to fully utilize its potential, UOWC should be integrated as part of a broader network architecture rather than being treated solely as a physical-layer solution [12], [13].

In this study, we propose a hybrid architecture that combines UOWC with existing terrestrial access technologies. This enables seamless, cost-effective interconnection between underwater and Over-water domains by leveraging widely available devices and protocols.

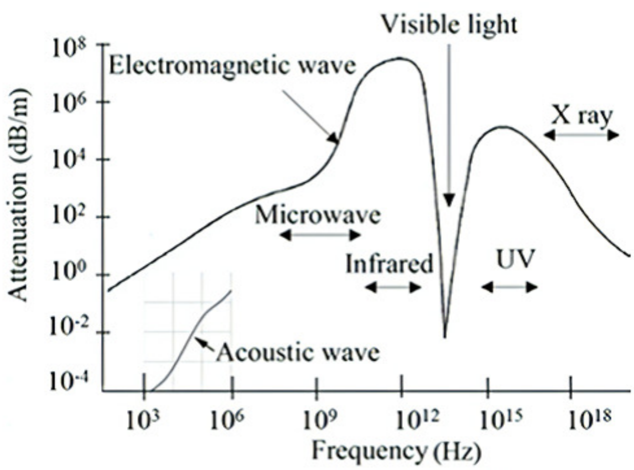

Fig. 2. Attenuations of electromagnetic wave including visible light and acoustic waves in water. [8]

II. SEAMLESS COMMUNICATION APPROACHES

To realize this vision, we propose and evaluate the following three hybrid communication approaches:

- **LPWA Extension for Underwater Use:** Extend Low Power Wide Area (LPWA) technologies to underwater environments to enable efficient deployment of large-scale sensor networks [14].
- **Underwater G.hn Deployment:** Apply the G.hn gigabit communication standard, used in indoor networks, to underwater systems to establish affordable high-speed links [15].
- **Underwater PON Architecture:** Introduce Passive Optical Network (PON) architecture to underwater environments, supporting centralized, passive distribution to multiple underwater terminals.

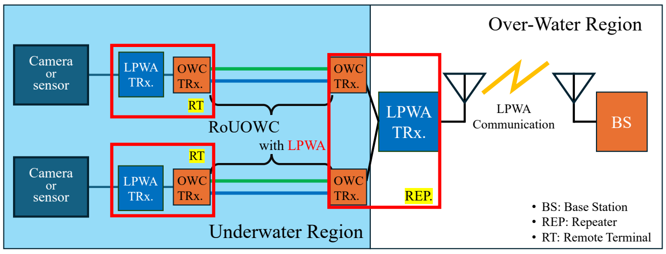

Fig. 3. System configuration of the RoUOWC with LPWA system.

III. UNDERWATER EXTENSION OF LPWA SYSTEMS

Low Power Wide Area (LPWA) communication in the 920 MHz band is widely used for wide-area environmental monitoring and IoT networks due to its low power consumption and multi-hop capabilities. However, its direct application to underwater environments is difficult because electromagnetic waves are severely attenuated in water. Therefore, this study proposes and experimentally validates a novel method for transmitting LPWA signals underwater via Visible Light Communication (VLC).

A. RoUOWC System Overview and Features

The proposed method is a "Radio over Underwater Optical Wireless Communication (RoUOWC)" system, where the LPWA signal (an IEEE 802.15.4g compliant GFSK modulated signal) is directly superimposed on a visible light carrier (450–520 nm). This approach enables end-to-end communication through simple electrical-to-optical and optical-to-electrical conversions without requiring any changes to the modulation scheme or protocol.

The main features of the RoUOWC system are as follows:

- By analogically superimposing the modulation signal onto the optical carrier, it enables low-latency, transparent communication without the need for protocol conversion.
- It allows for a simple and cost-effective implementation using commercially available laser diodes (LDs) and photodiodes (PDs).
- A full-duplex, bidirectional configuration is achievable using wavelength division with blue (450 nm) and green (520 nm) light.

B. System Configuration and Experimental Setup

As shown in Fig. 3, the proposed system consists of a terrestrial base station (BS), an overwater repeater (REP),

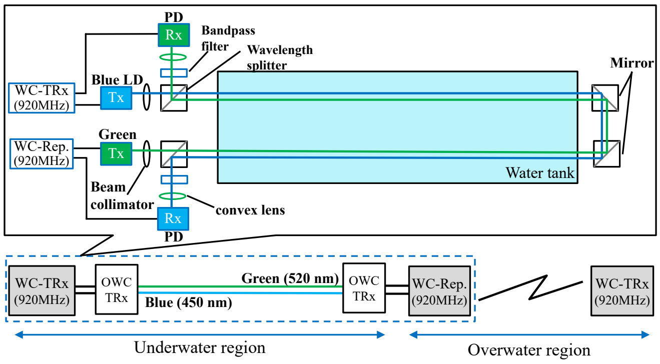

Fig. 4. Experimental setup for the underwater extension of the LPWA system.

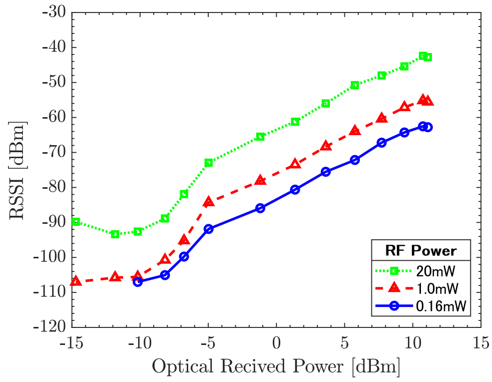

Fig. 5. Received RSSI characteristics in the underwater LPWA extension.

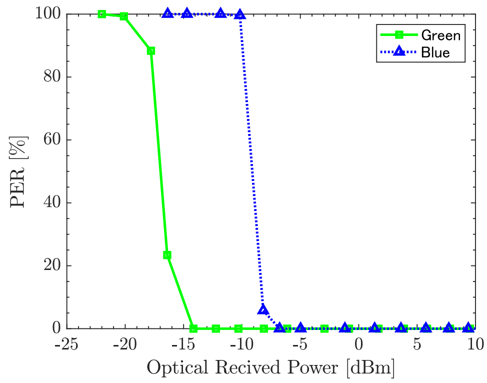

Fig. 6. Packet Error Rate (PER) characteristics in the underwater LPWA extension.

and an underwater terminal (RT). The link between the BS and REP uses conventional 920 MHz LPWA communication, while the link between the REP and RT uses RoUOWC, allowing sensor data to be seamlessly relayed from underwater to the terrestrial network.

The specific experimental setup is shown in Fig. 4. In the experiment, a 1.2 m long water tank was placed between the optical transceivers, and a mirror was used to create a 2.4 m underwater optical path. To achieve full-duplex communication, a blue (450 nm) laser diode (LD) was used for the optical transmitter (Tx) of the overwater repeater (REP), and a green (520 nm) LD was used for the optical transmitter of the underwater terminal (RT). Each optical receiver (Rx) was configured to receive the signal with a photodiode (PD) via optical components such as a beamsplitter, a band-pass filter, and a convex lens. The LPWA signal is transmitted from the terrestrial base station (BS), modulated onto the blue light at the REP, transmitted through the water, and then received and demodulated at the RT.

C. Experimental Results and Discussion

Fig. 5 shows the measured Received Signal Strength Indicator (RSSI) versus the received optical power. For both blue (450 nm) and green (520 nm) light, the RSSI decreased gradually with a reduction in optical power but remained stable above -90 dBm within the measurement range, which is sufficient for establishing LPWA communication. Notably, the system demonstrated a wide optical dynamic range of approximately 20 dB for blue light and 30 dB for green light, including the error-free region discussed below. This result indicates that the RoUOWC system has high tolerance to fluctuations in optical attenuation caused by factors such as water turbidity.

Next, Figure 6 shows the end-to-end Packet Error Rate (PER) characteristics. Both wavelengths exhibited a "waterfall" characteristic, where the PER drops sharply once the received optical power exceeds a certain threshold. Error-free (PER = 0%) communication was achieved at a received optical power of -7.5 dBm or higher for blue light and -14 dBm or higher for green light.

Furthermore, a five-day continuous operation test was conducted to evaluate the system's long-term stability. During this period, the RSSI fluctuation remained stable within the -50 to -60 dBm range, demonstrating its long-term stability for practical applications.

These experimental results demonstrate that the proposed RoUOWC system can seamlessly extend an existing LPWA network into an underwater environment without modifying its protocol. This approach is effective for building multi-point sensor networks for coastal environmental monitoring and smart aquaculture. Future work includes optimizing the media access control (MAC) to efficiently accommodate a large number of underwater sensor nodes.

IV. Underwater Extension of G.hn Systems

While the underwater extension of LPWA systems discussed in Section II is suitable for wide-area environmental sensing, its bandwidth is insufficient for applications requiring larger data transmission, such as remote monitoring of underwater infrastructure and high-definition video feeds. To meet this demand, this section proposes a new approach that applies G.hn (ITU-T Recommendation G.9960), a technology for achieving gigabit-class high-speed communication at low cost, to underwater optical wireless communication.

G.hn is a standardized technology designed for high-speed data communication over existing in-home wiring, such as telephone lines, coaxial cables, and power lines. It is widely adopted in Fiber To The Curb (FTTC) configurations to connect the last mile from the fiber optic terminus to

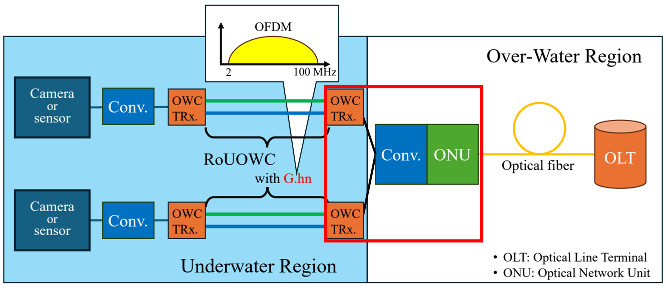

Fig. 7. Network configuration for the underwater G.hn extension.

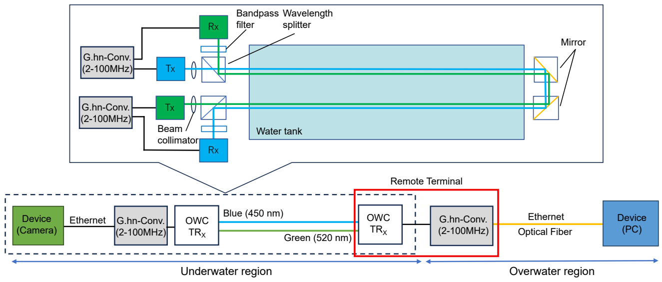

Fig. 8. Experimental setup for the underwater G.hn extension.

individual homes. At its core is Orthogonal Frequency Division Multiplexing (OFDM) technology, which ensures stable communication even in harsh transmission environments. This study aims to leverage the robust physical layer of G.hn and the cost-effectiveness of its standardized chipsets to seamlessly extend terrestrial optical access networks into underwater environments.

A. System Configuration and Operating Principle

The overall architecture of the proposed underwater G.hn extension network is shown in Fig. 7. In this architecture, an existing terrestrial (or overwater) optical fiber access network is connected to the underwater communication domain via a ”Remote Terminal.”

The Remote Terminal consists of an Optical Network Unit (ONU), a G.hn converter that performs bidirectional conversion between Ethernet and G.hn signals, and a visible light transceiver (OWC TRx). The operating principle of this system is as follows:

1) Ethernet frames from the terrestrial network are received by the ONU in the Remote Terminal and passed to the G.hn converter.
2) The G.hn converter transforms the Ethernet frames into an OFDM electrical signal compliant with the G.9960 standard. This OFDM signal consists of numerous subcarriers allocated in the 2 MHz to 100 MHz frequency band.
3) This OFDM signal is fed into the laser driver of the OWC transceiver to directly modulate the intensity of the visible light (e.g., green light at 520 nm). This process transmits the signal underwater as an optical signal while preserving the G.hn signal format.
4) At the underwater terminal, the optical signal is received by a photodiode, converted back to an electrical OFDM signal, and then restored to an Ethernet frame by another G.hn converter.

Reverse communication (uplink) is achieved through a similar process using a different wavelength of visible light (e.g., blue light at 450 nm). The greatest advantage of this method is that by treating the G.hn signal as an analog baseband signal, the underwater transmission path can be used transparently, much like a physical cable. This allows existing G.hn-compliant terminals to be used underwater without any modification, significantly reducing implementation costs and development time.

B. Experimental Setup and Evaluation

To quantitatively evaluate the transmission performance of the proposed system, an experimental setup as shown in Fig. 8 was constructed. In the experiment, a 1.2 m long water tank and a high-reflection mirror were used to create an effective underwater transmission path of 2.4 m by reflecting the laser beam. A commercial G.hn converter was used for signal conversion, with its input/output ports connected directly to the modulation port of the laser driver and the output port of the photodiode module, respectively. Performance was evaluated by conducting end-to-end data transmission between the underwater terminal and an overwater terminal (PC) and measuring the throughput and Packet Error Rate (PER) with a packet analyzer.

C. Experimental Results and Discussion

Fig. 9 shows the measured end-to-end throughput as a function of received optical power. The throughput increased with the received optical power, achieving a maximum throughput of over 500 Mbps in the range of -5 dBm to 0 dBm. This rate is sufficient for transmitting multiple uncompressed HD video streams in real-time, demonstrating that this system can meet the demands of high-capacity underwater communication. Interestingly, when the received optical power exceeded -5 dBm, the throughput tended to decrease. This is likely because the photodiode entered its saturation region, which degrades the modulation depth of the received OFDM signal. This result suggests that for practical applications, it is necessary to optimally control the laser bias current (optical output) according to the transparency of the underwater environment.

Next, Fig. 10 shows the PER characteristics. The system exhibited a clear ”waterfall” characteristic in its PER performance. When the received optical power exceeded the threshold of -15 dBm, the PER dropped sharply, achieving an error-free state of less than 10^{-9}. A wide optical dynamic range of approximately 25 dB exists between the minimum received power required for error-free operation (-15 dBm) and the power at which throughput begins to saturate (approx. +10 dBm). This indicates that the system has a very high margin and stability against fluctuations in optical path loss that may be expected in real-world operational environments, such as those caused by water turbidity or misalignment.

These experimental results demonstrate that the proposed method of applying the G.hn system to underwater optical

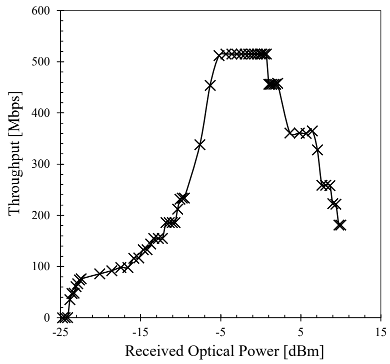

Fig. 9. Throughput characteristics of the G.hn system.

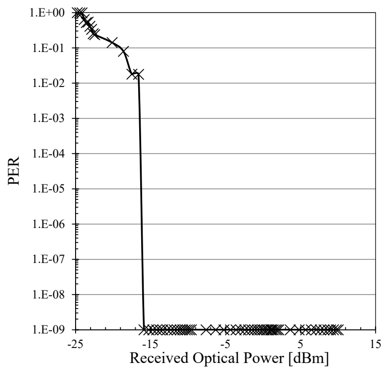

Fig. 10. Packet Error Rate (PER) characteristics of the G.hn system.

wireless communication is an effective approach for achieving stable, broadband communication exceeding 500 Mbps while leveraging existing low-cost communication equipment.

V. Concept for Extending PON to Underwater Environments

This section proposes a concept for extending the Passive Optical Network (PON) architecture to underwater environments. PON has been widely adopted in existing optical access networks, particularly in Fiber To The Home (FTTH) deployments, as a cost-effective and efficient means of accommodating numerous subscriber terminals. In underwater environments as well, the demand for simultaneously connecting and centrally managing multiple nodes is increasing, as seen in applications such as smart aquaculture, underwater sensor networks, and cooperative control of robot swarms. Introducing a scalable network architecture like PON is thus considered highly promising.

We propose two network configurations that integrate Underwater Optical Wireless Communication (UOWC), based on visible light, with PON technology. These configurations aim to establish a flexible and cost-efficient link between above-water and underwater segments.

A. Architecture Combining OLT–ONU with G.hn Based RoUOWC

The first configuration connects the terrestrial Optical Line Terminal (OLT) to an above-water Optical Network Unit (ONU) using conventional optical fiber. Beneath the ONU, a G.hn-based UOWC system is deployed to enable underwater communication. The ONU converts downstream optical signals into Ethernet format, which are then modulated into OFDM signals using a G.hn converter and transmitted to underwater terminals via visible light.

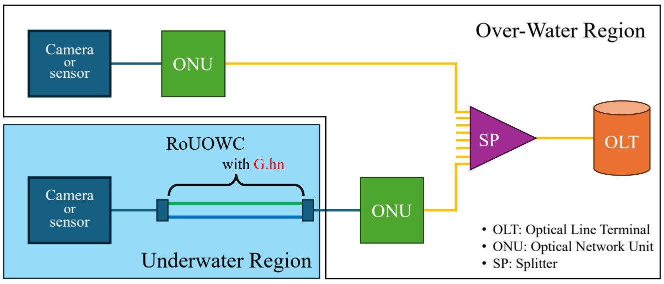

Fig. 11. G.hn-based RoUOWC

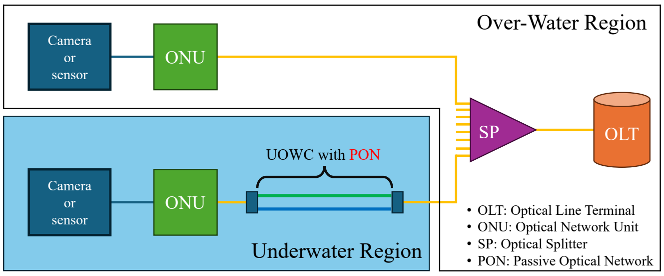

Fig. 12. PON architecture with UOWC inserted between OLT and ONU

Fig. 11 illustrates this architecture. The ONU, located above the water surface, connects to underwater cameras or sensors through a G.hn-over-visible-light RoUOWC (Radio over UOWC) link. This structure takes advantage of existing G.hn test environments and combines the high-throughput performance of G.hn with the dense connectivity of PON. Moreover, since the underwater side does not require dedicated PON control logic, the overall system remains relatively simple and scalable.

B. Architecture with UOWC Inserted Between OLT and ONU

The second configuration replaces a segment of the optical fiber link between the OLT and ONU with a UOWC link. The downstream optical signal from the OLT is first converted to an electrical signal, which is then transmitted underwater using visible light (e.g., 520 nm). At the underwater receiving terminal, the signal is converted back to electrical form and passed to the ONU. Similarly, the upstream signal is transmitted from underwater using visible light (e.g., 450 nm) to the OLT.

Fig. 12 shows the conceptual diagram of this configuration. By treating the UOWC segment as an extension of the physical optical fiber, this approach allows the PON architecture to be preserved without modifying existing firmware or MAC-layer protocols in the OLT and ONU. Additionally, traditional PON technologies such as Time Division Multiple Access (TDMA) and Wavelength Division Multiplexing (WDM) can be directly applied, enabling fair resource allocation and high operational efficiency even with a large number of underwater terminals.

Furthermore, since PON inherently supports symmetrical bandwidth for upstream and downstream traffic, it is well suited for future bidirectional underwater applications, such as video feedback systems and real-time robot control.

C. Future Outlook and Challenges

While the proposed concept is still at the stage of system design and feasibility evaluation, the anticipated growth in underwater multi-terminal communications suggests that PON-based solutions will be crucial in the near future. Key technical challenges that must be addressed include:

- Implementation and stability verification of multiplexing techniques, such as WDM and TDMA, in UOWC
- Evaluation of the compatibility and performance of optical splitters and WDM components in underwater environments
- Assessment of the impact of signal reflection and transmission delay on PON control signals (e.g., Dynamic Bandwidth Allocation)
- Development of automatic alignment and tracking mechanisms for underwater terminals

Overcoming these challenges will enable the deployment of low-cost, highly reliable optical access infrastructure underwater, paving the way for full-scale marine network integration in the Beyond 5G and 6G era.

VI. Conclusion

This study proposed and experimentally demonstrated three approaches to extending terrestrial communication technologies into underwater environments using underwater optical wireless communication (UOWC) based on visible light semiconductors, with a view toward network expansion in the Beyond 5G/6G era.

First, the LPWA-based approach enabled a low-power and environmentally robust underwater sensing network by transparently relaying conventional 920 MHz signals via the proposed RoUOWC (Radio over UOWC) method using visible light. Second, in the G.hn-based approach, gigabit-class OFDM signals were transmitted underwater via visible light, achieving stable high-speed communication exceeding 500 Mbps with only commercial chipsets. Third, the proposed PON-based architectures introduced two configurations that incorporate UOWC links without modifying existing OLT/ONU systems, demonstrating the feasibility of supporting simultaneous underwater multi-terminal connections and centralized management.

These results indicate that UOWC can be elevated beyond a physical-layer solution into a seamless extension of terrestrial access networks, forming the basis of a next-generation underwater communication infrastructure. Future work will explore advanced features such as mobility support, mesh networking, and adaptive control using machine learning, to realize more intelligent and autonomous underwater network platforms. The outcomes of this study are expected to serve as a foundational technology for real-world applications in fields such as the blue economy, marine disaster prevention, and deep-sea exploration.

References

[1] NTT DOCOMO, INC., "6G White Paper," NTT DOCOMO, INC., Tech. Rep., June 2022, (in Japanese).

[2] Samsung Research, "6G Spectrum: Expanding the Frontier," Samsung Electronics, Tech. Rep., 5 2022.

[3] OECD, *The Ocean Economy in 2030*. OECD Publishing, 2016. [Online]. Available: 10.1787/9789264251724-en. DOI: 10.1787/9789264251724-en

[4] World Bank and United Nations Department of Economic and Social Affairs, "The potential of the blue economy: Increasing long-term benefits of the sustainable use of marine resources," World Bank, Tech. Rep., 2017, accessed: 2025-7-17. [Online]. Available: https://openknowledge.worldbank.org/handle/10986/26843

[5] International Energy Agency, "Offshore Wind Outlook 2019," IEA, Tech. Rep., 2019, accessed: 2025-7-17. [Online]. Available: https://www.iea.org/reports/offshore-wind-outlook-2019

[6] Z. Lv, G. He, H. Yang, R. Chen, Y. Li, W. Zhang, C. Qiu, and Z. Liu, "The investigation of underwater wireless optical communication links using the total reflection at the air-water interface in the presence of waves," *Photonics*, vol. 9, no. 8, 2022, DOI: 10.3390/photonics9080525.

[7] D.-C. Li, C.-C. Chen, S.-K. Liaw, S. Afifah, J.-Y. Sung, and C.-H. Yeh, "Performance evaluation of underwater wireless optical communication system by varying the environmental parameters," *Photonics*, vol. 8, no. 3, 2021, DOI: 10.3390/photonics8030074.

[8] T. Sawa, N. Nishimura, K. Tojo, and S. Ito, "Practical Performance and Prospect of Underwater Optical Wireless Communication -Results of Optical Characteristic Measurement at Visible Light Band under Water and Communication Tests with the Prototype Modem in the Sea-," *IEICE TRANS.FUNDAMENTALS*, vol. E102-A, no. 1, pp. 156–167, 4 2022, DOI: 10.1587/transfun.E102.A.156.

[9] I. F. Akyildiz, D. Pompili, and T. Melodia, "Underwater acoustic sensor networks: research challenges," *Ad Hoc Networks*, vol. 3, no. 3, pp. 257–279, 2005, DOI: 10.1016/j.adhoc.2005.01.004.

[10] H. Kaushal and G. Kaddoum, "Underwater optical wireless communication," *IEEE Access*, vol. 4, pp. 1518–1547, 2016, DOI: 10.1109/ACCESS.2016.2552538.

[11] N. Saeed, A. Celik, T. Y. Al-Naffouri, and M.-S. Alouini, "Underwater optical wireless communications, networking, and localization: A survey," *Ad Hoc Networks*, vol. 94, p. 101935, 2019, DOI: 10.1016/j.adhoc.2019.101935.

[12] S. Jaruwatanadilok, "Underwater wireless optical communication channel modeling and performance evaluation using vector radiative transfer theory," *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 9, pp. 1620–1627, 2008, DOI: 10.1109/JSAC.2008.081202.

[13] Z. Zeng, S. Fu, H. Zhang, Y. Dong, and J. Cheng, "A survey of underwater optical wireless communications," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 1, pp. 204–238, 2017, DOI: 10.1109/COMST.2016.2618841.

[14] R. Oikawa, N. Higaki, and N. Yoshimoto, "First Demonstration of End-to-End Wireless Signal Transmission between Over- and Under-water region using Visible Light Sources," in *International Conference on Emerging Technologies for Communications 2023*, 11 2023, pp. P3–16, DOI: 10.34385/proc.79.P3-16.

[15] R. Oikawa and N. Yoshimoto, "End-to-End demonstration of all-optical underwater communication network using G.9960 compliant OFDM technology," in *2024 Conference on Lasers and Electro-Optics Pacific Rim (CLEO-PR)*, 2024, p. P2_072, DOI: 10.1109/CLEO-PR60912.2024.10676561.