

Review

Underwater Drone-Enabled Wireless Communication Systems for Smart Marine Communications: A Study of Enabling Technologies, Opportunities, and Challenges

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Highlights

What are the main findings?

- This paper reviews underwater wireless communication methods, including acoustic, optical, and RF communication, in marine applications, and explores the potential of existing underwater drones.
- This paper examines the opportunities and challenges of hybrid wireless communication systems for underwater drones.

What is the implication of the main finding?

- This paper considers the integration of underwater drones, IoUT, AI-driven data, VR, and DT for smart marine communications.

Abstract

Underwater drones such as autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs) are revolutionizing underwater operations and are essential for advanced marine applications like environmental monitoring, deep-sea exploration, and marine surveillance. In this paper, we concentrate on the enabling technologies and wireless communication strategies for underwater drones. Specifically, we analyze acoustic, optical, and radio frequency (RF) approaches, along with their respective advantages and disadvantages. We investigate the potential of integrating underwater drone-enabled wireless communication systems for smart marine communications. The study highlights the benefits of combining acoustic, optical, and RF methods to improve connectivity and data reliability. A hybrid underwater communication system is ideal for underwater drones because it can reduce latency, increase data throughput, and improve adaptability under various underwater conditions, supporting smart marine communications. The future direction involves developing hybrid communication frameworks that incorporate the Internet of Underwater Things (IoUT), AI-driven data, virtual reality (VR), and digital twin (DT) technologies, enabling a next-generation smart marine ecosystem.

Keywords: underwater drones; AI-driven data; internet of underwater things; virtual reality; digital twin; smart marine communications



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1. Introduction

Marine communications include various methods and technologies used to transmit information between ships, underwater vehicles, coastal stations, satellites, and other maritime infrastructure [1]. These systems are crucial for navigation, safety, environmental monitoring, military operations, and commercial maritime activities. Marine communication systems can generally be categorized as an integrated network of space, air, ground, and sea, which includes satellite communications, air-to-sea (A2S) communications, and underwater communications, as shown in Figure 1. A2S communications mainly depend on space and satellite systems, used for short- to medium-range communication between air and ships or underwater vessels [2–4]. They are commonly employed in maritime navigation and emergency situations. Satellite communication uses geostationary and low-Earth-orbit (LEO) satellites to provide global maritime connectivity, supporting navigation, internet access, and emergency coordination. Unlike A2S and satellite communications, underwater communication faces major challenges due to water's physical properties, which hinder the effectiveness of traditional RF signals [5]. Typically, underwater communication technologies include acoustic, optical, and RF methods [6–8].

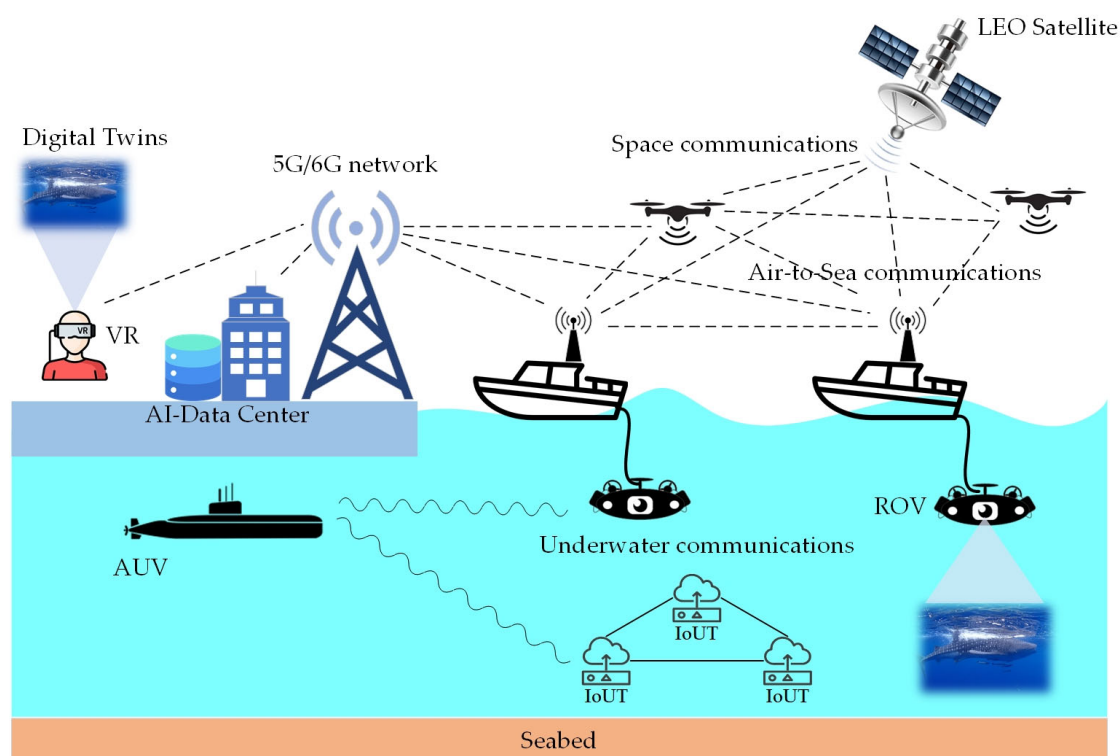


Figure 1. Schematic of an integrated space-air-ground-sea network for smart marine communications.

Innovative marine communications involve integrating advanced technologies like IoUT, AI-driven data, VR, DT, and hybrid communication networks to enhance real-time, efficient, and autonomous data exchange in maritime environments [9,10]. These systems support various applications, including autonomous ships, underwater drones, maritime security, environmental monitoring, and offshore oil and gas operations.

Underwater drones, including ROVs and AUVs, as shown in Figure 2, are vital for innovative marine communications by enabling efficient, real-time data exchange in underwater settings. ROVs are typically tethered to a surface vessel or controlled remotely by a human operator, making them suitable for missions that require human involvement, such as surveillance, patrolling, and environmental surveys. Conversely, AUVs are designed to operate autonomously without continuous human control. Military and scientific ROVs,

such as Revolution [11], H1000 [12], PIVOT [13], Boxfish [14], and SRV-8 [15], are compared with AUVs like REMUS 300 [16], COMET-300 [17], and NemoSens [18]. These underwater drones serve as a bridge between surface ships, satellites, and underwater infrastructure, enhancing connectivity, surveillance, and environmental monitoring. Their integration with advanced communication technologies, such as IoT, AI-driven data, VR, DT, and hybrid communication networks, makes them crucial for upcoming maritime operations.

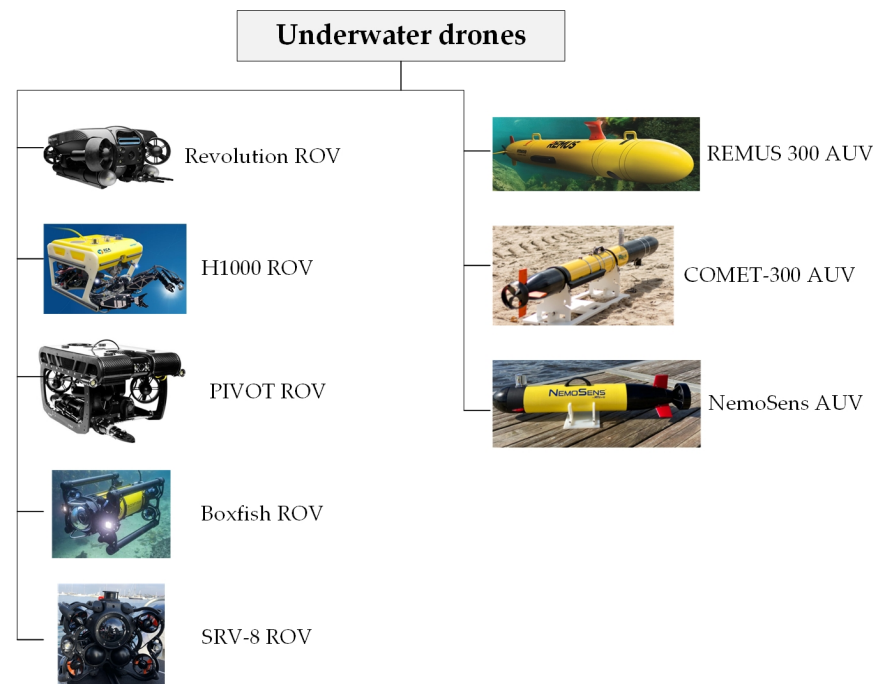


Figure 2. The current classification of underwater drones into ROVs and AUVs. Reference images include ROVs such as Revolution [11], H1000 [12], PIVOT [13], Boxfish [14], and SRV-8 [15], as well as AUVs like REMUS 300 [16], COMET-300 [17], and NemoSens [18].

To enhance underwater communication networks, underwater drones can serve as relay nodes between surface stations and submerged assets, including ocean sensors, submarines, and offshore installations [19]. They enable real-time data transfer between deep-sea environments and command centers, boosting operational efficiency. Additionally, several applications of underwater drones can support autonomous marine operations, including surveillance, security, smart navigation, and collision avoidance [20]. For real-time oceanographic data collection [21], IoUT can be equipped with multiple sensors to monitor ocean conditions, including temperature, salinity, pH, and marine biodiversity. By collecting real-time environmental data, they can aid climate research, pollution detection, and deep-sea exploration. Moreover, underwater drones serve as data collectors and transmitters within the IoUT frameworks [22], enhancing port management, ocean resource exploration, and offshore infrastructure monitoring [23].

Trends in underwater drones rely on AI-driven data processing and innovative marine communications. They are vital for advancing marine communication, enabling real-time, autonomous, and intelligent data exchange underwater. By combining hybrid communication networks, AI, VR, IoUT, and digital twins, fields such as ocean surveillance, environmental monitoring, maritime security, and disaster management can be greatly improved. As technology progresses, AI-driven ROV or AUV networks will continue to transform marine communication, making operations safer, more efficient, and highly interconnected [24]. Digital twins (DTs) represent a revolutionary step in networked vir-

tual reality, enabling the real-time digital visualization of underwater environments and facilitating the optimization of communication network performance [25].

The enabling technologies for underwater communications, including acoustic, optical, RF, and magneto-inductive (MI) communications, are crucial for underwater drones in the marine ecosystem. Many review papers have examined and discussed the new aspects of marine communications.

In [10], Theocharidis et al. provided a comprehensive review of current underwater communication technologies. The authors highlighted the challenges and innovations across various applications, including scientific research, exploration, environmental monitoring, and security. It emphasizes the evolution and interplay of acoustic, optical, quantum, and hybrid communication methods, along with their limitations and potential solutions in the complex underwater environment. Additionally, novel research directions, such as AI-driven dynamic communication systems, bio-inspired communication models, and hybrid communication approaches, have been proposed.

In [26], Dai et al. provided a comprehensive overview of the development and implementation of integrated sensing, communication, and computing networks (ISCCNs) designed for innovative ocean applications. They systematically explore collaboration across space, air, ground, and sea networks, focusing on four main layers: the space layer, the aerial layer, the sea surface layer, and the underwater layer. Integrating sensing, communication, and computing within a unified framework is vital for advancing innovative ocean initiatives. By leveraging a multilayered network architecture, ISCCNs can provide extensive coverage and data collection capabilities, which are essential for effective ocean management and research. However, challenges such as system interoperability, energy efficiency of deployed sensors, and the harsh marine environment require ongoing research and innovation. Additionally, addressing security vulnerabilities is crucial to protect the integrity and confidentiality of ocean data. The authors highlighted physical-layer security (PLS) with cooperative jamming and artificial noise (AN) as the core mechanism for securing mobile edge computing (MEC) offloading across various paths, including space, air, ground, and sea. Beyond confidentiality, adjacent layers strengthen the stack: Federated learning (FL) keeps raw data local to protect privacy and reduce communication load, and has been applied in air-sea networks. Blockchain provides tamper-evident logs and distributed authentication, enhancing integrity and trust among marine devices.

In [27], Qu et al. provided a thorough analysis of various communication methods for underwater environments, emphasizing their respective advantages, limitations, and potential applications. They note that while acoustic communication remains the standard for long-distance underwater communication, its bandwidth and data rate limitations drive the search for alternative methods. Electromagnetic and optical communications offer higher data rates but are limited by range and environmental conditions. Hybrid systems and emerging technologies, such as underwater wireless sensor networks (UWSNs) and IoUT, hold significant promise for overcoming these challenges and creating more resilient, efficient underwater communication networks.

In [28], Nomikos et al. provided a comprehensive overview of integrating uncrewed aerial vehicles (UAVs) into maritime communication networks. This integration aims to improve connectivity for naval operations, addressing the shortcomings of traditional shore-based and satellite communication systems. Incorporating UAVs into maritime communication offers a promising solution to the limitations of conventional systems, including limited coverage and high latency. However, it also presents challenges that require interdisciplinary research and innovation. Overcoming these challenges involves developing robust physical-layer designs, efficient resource management strategies, and advanced computing paradigms. Additionally, optimizing UAV trajectories and incorpo-

rating emerging technologies, such as machine learning and swarm intelligence, are vital for advancing UAV-assisted maritime communications.

In [29], Wibisono et al. provided a comprehensive overview of the technologies and methodologies that enable wireless power and data transmission in underwater environments. The survey highlights that although significant progress has been made in underwater wireless power and data transfer systems, ongoing research and development remain necessary to address existing challenges. Advances in this area will be crucial for developing sustainable and efficient underwater networks with a wide range of applications, from environmental monitoring to industrial processes.

In [30], Petritoli et al. analyzed the development, functionality, and applications of autonomous underwater gliders (AUGs). The comprehensive review highlights the transformative effect of AUGs on underwater exploration and monitoring. Their unique propulsion system and autonomous operation have opened up new avenues in oceanographic research, enabling continuous data collection over large areas without the need for constant human oversight. However, the review also highlights challenges, such as the need for improved navigation systems to enhance maneuverability and for more reliable communication methods for real-time data transmission. Addressing these issues is crucial for enhancing the capabilities of AUGs and ensuring their effectiveness across diverse applications.

In [31], Alqurashi et al. presented a survey on enabling technologies, opportunities, and challenges for maritime communications. The survey examines technological advancements, potential applications, and the inherent difficulties in marine communication. It highlights the vital role of advanced communication technologies in transforming maritime operations. Although significant progress has been made, ongoing research and development are crucial to overcoming existing challenges and fully realizing the potential of marine communications.

In [32], Hasan et al. provided a comprehensive review of the advancements and challenges in developing AUVs. They highlight the interdisciplinary nature of AUV development, combining insights from biology, engineering, and computer science to address the unique challenges of underwater exploration. By using biomimetic designs, AUVs can achieve more efficient propulsion and maneuverability. Advanced control systems enhance autonomy and adaptability, enabling AUVs to perform complex missions with minimal human intervention. Improved navigation and sensing technologies allow precise operation without relying on traditional positioning systems, thereby broadening the potential uses of AUVs in scientific research, environmental monitoring, and industrial operations.

In [33], Sun et al. provided a comprehensive overview of ocean-sensing technologies and their applications in critical underwater scenarios. These scenarios include geological surveys, navigation and communication, marine environmental monitoring, and underwater inspections. The key technologies discussed are acoustic, optical, and electromagnetic sensing. The application highlighted the following areas: geological surveys, navigation and communication, marine environmental monitoring, and underwater inspections. The authors predict advancements in sensor miniaturization, increased autonomy of underwater vehicles, and improved data processing capabilities. These developments are expected to address current limitations and meet the future needs of ocean exploration.

In [34], Luo et al. provided a comprehensive review of recent advancements in air/water cross-boundary communications, a critical area for the next-generation 6G wireless networks aiming for seamless global coverage and the Internet of Everything (IoE). They presented a thorough review of recent progress in air/water cross-boundary communications, categorizing existing works into three main types: optical direct communication, relay-based communication, and non-optical direct communication. The review highlights

that penetrating the air/water interface seamlessly poses significant challenges due to the harsh environment and complex channel characteristics. It also discusses the misalignment caused by channel dynamics, which severely degrades performance and limits practical applications.

In [35], Pal et al. provided a detailed technical overview of various underwater communication technologies, specifically acoustic, magnetic, and visible light. They included an analysis of RF, acoustic, optical, and MI communications. The paper concludes that no single technology is optimal for all conditions, underscoring the need for multimodal solutions.

In [36], Ali et al. provided a comprehensive literature review of various underwater wireless communication (UWWC) techniques. The review covers RF, optical, MI, and acoustic communication methods, aiming to elucidate their key aspects. The paper presented a detailed comparison of four primary UWWC techniques across various parameters, including communication range, data rates, propagation speed, bandwidth, stealth operation, impact on marine life, immunity to noise, air-water interface transition, latency, antenna size, bit error rate (BER), and key factors affecting channel performance. They have highlighted several research gaps, such as the need for improved channel estimation using advanced modulation and coding techniques, addressing high energy consumption and delay in certain models, and enhancing throughput by reducing processing time.

Then, Wang et al. [19] provided a survey of reinforcement learning-based approaches for future underwater networking. To enhance the communication quality of underwater networking and address challenges in the design of optimization schemes, reinforcement learning (RL) can optimize spectrum resource allocation and deployment, improve throughput, reduce delay, enhance reliability, promote energy savings, maximize energy efficiency, facilitate data sensing and processing, and enable intelligent cluster networking. The authors have identified challenges and research directions for RL-enabled underwater communication networking in the future.

As mentioned above, in the related works [10,19,26–36], we summarize the comparison between this study and the related works, as shown in Table 1.

Advancements in marine communications are vital for improving maritime safety, environmental monitoring, and autonomous underwater operations. However, underwater communication networks face significant challenges, including high signal attenuation, limited bandwidth, short range, and power constraints, which hinder the transfer of real-time, high-bandwidth data. Traditional wireless communication methods, such as low-frequency electromagnetic waves and acoustic signaling, have inherent drawbacks in terms of data transfer speed, flexibility, and reliability, especially when connecting AUVs, ROVs, and smart maritime infrastructure.

As reliance on autonomous marine systems grows, so does the need to develop robust, efficient, and adaptable wireless communication technologies to address these challenges. Underwater drones are essential for connecting surface and subsea communication networks, acting as mobile relays, data gatherers, and intelligent nodes within hybrid marine communication systems. Incorporating IoUT, AI-driven data, VR, and DT technology offers significant potential to enhance underwater connectivity, facilitate seamless interactions between maritime assets, and improve real-time decision-making in dynamic marine environments.

This paper examines the enabling technologies, opportunities, and challenges of wireless communication systems for underwater drones, with a focus on their applications in marine environmental monitoring and marine tourism. It also outlines future directions for advancing underwater drones, IoUT, AI-driven data, VR, and DT.

Table 1. Comparison between related works [10,19,26–36] and this study.

Reference	Main Contributions	IoUT	AI	VR	DT
[10]	■ The recent underwater communication technologies.	✓	✓	×	×
[26]	■ The comprehensive overview of developing and implementing ISCCNs tailored for smart oceans.	✓	✓	×	×
[27]	■ The comprehensive analysis of various communication methods utilized in underwater environments.	✓	×	×	×
[28]	■ The integration of UAVs into maritime communication networks.	✓	✓	×	×
[29]	■ The various technologies and methodologies that enable wireless power and data transmission in underwater environments.	✓	×	×	×
[30]	■ The transformative impact of AUGs on underwater exploration and monitoring.	✓	×	×	✓
[31]	■ The technological advancements, potential applications, and inherent challenges in marine communications.	×	×	×	✓
[32]	■ The comprehensive examination of the advancements and challenges in developing AUVs.	✓	×	✓	×
[33]	■ The various ocean sensing technologies and their applications in critical underwater scenarios.	✓	✓	×	×
[34]	■ The comprehensive review of recent advancements in air/water cross-boundary communications.	✓	×	×	×
[35]	■ The comprehensive summary of underwater sensor networks.	✓	×	×	×
[36]	■ The comprehensive literature review of various underwater wireless communication (UWWC) techniques.	✓	×	×	×
[19]	■ The survey of reinforcement learning-based approaches for future underwater networking.	×	✓	×	×
This work	■ The enabling technologies, opportunities, and challenges of wireless communication systems of underwater drones and their applications for smart marine.	✓	✓	✓	✓

The key objectives of this paper are as follows:

1. To review underwater wireless communication methods, including acoustic, optical, RF, and MI communication, in marine applications, and to explore the potential of existing underwater drones.
2. To examine the opportunities and challenges of hybrid wireless communication systems for underwater drones.
3. To identify future research directions, where we consider the integration of underwater drone, IoUT, AI-driven data, VR, and DT for smart marine communications.

As shown in Figure 3, this paper is organized as follows. Section 2 covers the enabling technologies for underwater wireless communications. Section 3 discusses the challenges in underwater drone-enabled wireless systems. Section 4 provides an overview of the enabling

technologies for underwater drone communication networks. The research directions are outlined in Section 5, and Section 6 summarizes the conclusions.

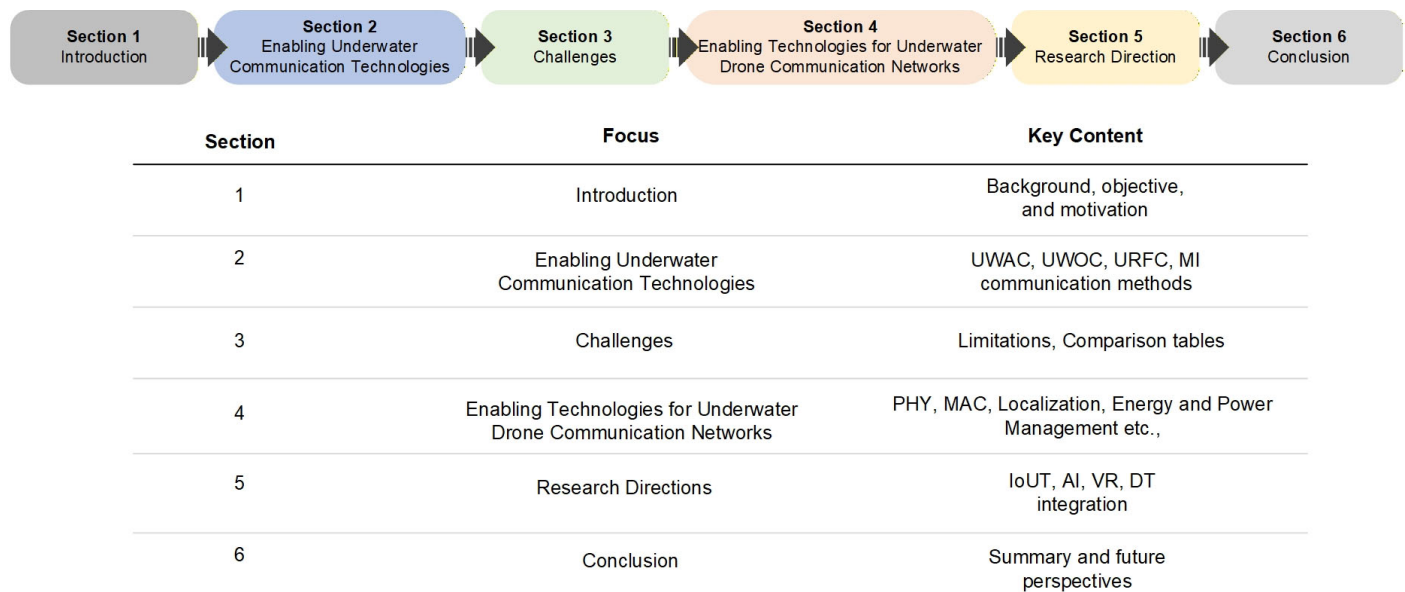


Figure 3. The structure and organization of this paper clearly emphasize the focus and main points of each section.

2. Enabling Underwater Communication Technologies

The benchmarking framework introduced here serves as a foundation for the analysis presented in this section, where prior studies are systematically compared based on normalized performance indicators. The results are consolidated into Tables and Figures to guide the selection of underwater drone communication systems.

2.1. Acoustic Communications

2.1.1. Underwater Wireless Acoustic Communication

There are many questions about research methodologies. How is acoustic communication used for underwater drones? Acoustic communication is the most effective and widely employed method for underwater drones because electromagnetic waves rapidly attenuate in water. It allows real-time communication, navigation, and data transfer for various underwater activities. Acoustic communication uses sound waves rather than radio waves for data transmission. It operates at frequencies from a few kHz to hundreds of kHz, enabling communication over distances up to 20 km. The data rate ranges from 1 kbps to 100 kbps. Its advantages are long-distance capability and good water penetration, but it has a low data rate and high latency.

Early experiments in underwater sound transmission date back to the mid-20th century, when acoustic telemetry was explored for oceanographic and naval applications. Since then, advances in transducer design, modulation schemes, and signal processing have established underwater acoustic communication (UWAC) as the primary means of wireless data exchange beneath the sea surface. Then, Vaccaro [37] tested the speed of sound in lake water in 1998. UWAC can achieve a data rate of 8 kbps over distances of up to 13 km [38]. Recent work [39] has reported that a data rate of up to 125 kbps using 32-QAM modulation is achievable under low-multipath conditions, such as in deep or calm waters, where the acoustic channel remains sufficiently stable for coherent detection. However, in shallow or turbulent environments, multipath propagation and Doppler shifts cause rapid phase fluctuations, which reduce coherence and make non-coherent or adaptive modulation schemes more practical for maintaining link reliability. Additionally, the UWAC channel

is more complex than terrestrial communications. The first reason is that the wave speed varies with factors such as temperature, salinity, and depth, all of which influence acoustic wave speed. For example, if the temperature increases by 1 °C, the acoustic wave speed can increase by 4 m/s. If salinity increases by one practical salinity unit, the speed can increase by 1.4 m/s. If depth increases by 1 km, the wave speed can increase by 17 m/s. These are factors affecting UWAC, as described in [27], where the acoustic model can be found. The primary factor influencing wireless UWAC is acoustic propagation, which encompasses attenuation, noise, multipath, and Doppler shift [40]. Attenuation depends on the signal frequency, and channel capacity depends on distance. Figure 4 shows the schematic of underwater wireless acoustic communications.

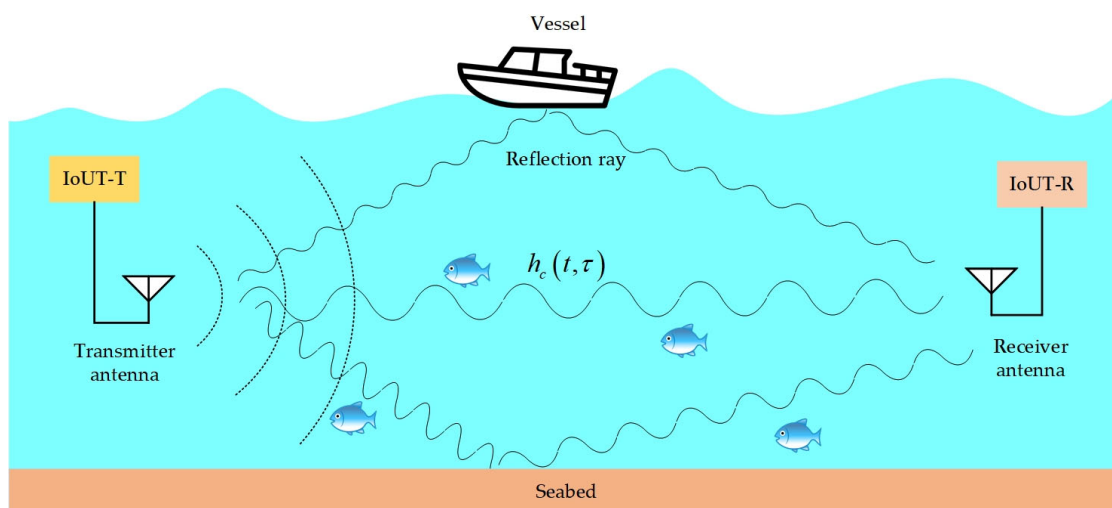


Figure 4. Underwater wireless acoustic communication.

Several commercial UWAC systems are currently available and widely used in marine monitoring, offshore operations, and defense applications. Examples include EvoLogics S2C modems, Teledyne Benthos ATM series, and Kongsberg cNODE systems, which support acoustic communication over distances ranging from several hundred meters to 6–10 km, with data rates between 100 bps and 15 kbps, depending on the channel conditions.

The overall attenuation or path loss of the acoustic channel is given by

$$A(d, f) = \left(\frac{d}{d_0} \right)^k a(f)^{d-d_0} \quad (1)$$

where f denotes the signal frequency, and d is the transmission distance, taken as the reference distance d_0 . The path loss component k models are between 1 and 2 for cylindrical and spherical spreading. The absorption coefficient $a(f)$ can be obtained using an empirical formula [41].

Scattering loss occurs when sound waves encounter obstacles during propagation. These obstacles can be stationary objects or a group of fish in the water, whether fixed or moving. Both spreading and absorption losses contribute to the overall transmission loss, which is described by a simplified model expressed in dB as

$$10 \log A(d, f) = 10 \log d_0 + 10k \log d + d \cdot 10 \log a(f, S, T, c, pH, z) \quad (2)$$

where S represents the salinity of water (ppt), z denotes the depth of water (km), pH represents the acidity and alkalinity of the water, T denotes channel temperature (°C), and c represents the sound speed of acoustic wave propagation (m/s).

While acoustic attenuation increases with frequency, the effective propagation range also depends strongly on sound-speed gradients within the ocean. Determining and optimizing propagation paths based on the measured sound speed profile (SSP) is therefore crucial for achieving satisfactory link performance. Proper SSP-based modeling enables identification of optimal ray paths, such as convergence zones, surface ducts, or deep sound channels, that minimize transmission loss and enhance the stability of long-range communication links [41].

The SSP describes how the speed of sound varies with ocean depth. Sound speed in water depends mainly on temperature (T), salinity (S), and depth (z). It is mathematically expressed as

$$c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.01T)(S - 35) + 0.016z \quad (3)$$

Figure 5 shows the transmission loss in seawater as a function of frequency, covering the range from 1 kHz to 100 kHz. The following distances are set: $d = 0.5$ km, $d = 1$ km, $d = 5$ km, and $d = 10$ km. Quantitatively, the transmission loss at 10 km increases from about 25 dB at 1 kHz to 110 dB at 100 kHz; at 5 km, it rises from 16 dB to 60 dB, while at 1 km, it grows from 0 dB to 9 dB across the same frequency range. These results highlight the fundamental trade-off in underwater acoustics: low frequencies enable long-range propagation, whereas high frequencies are limited to short-range, high-resolution applications.

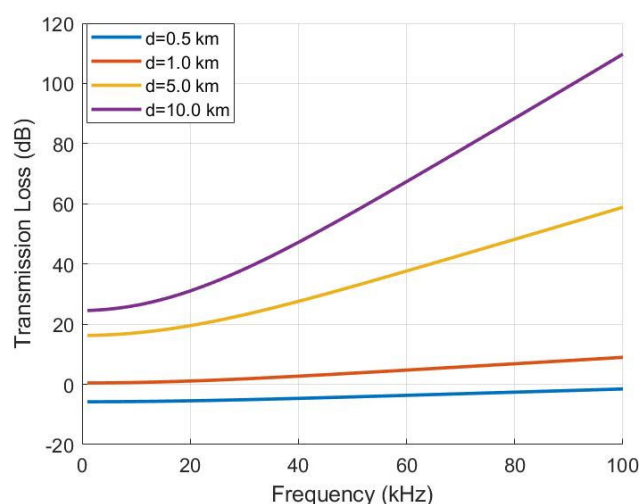


Figure 5. Acoustic communication transmission loss versus frequency in seawater.

The signal-to-noise ratio (SNR) [41,42] is a key indicator of ensuring channel quality. The SNR can be expressed as

$$SNR(d, f) = \frac{S(f)}{A(d, f)N(f)} \quad (4)$$

where $S(f)$ is the power spectrum density, and $N(f)$ is the noise power, where the noise in the acoustic channel consists of ambient noise and site-specific noise. Ambient noise is the background of the quiet deep sea. Site-specific noise, in contrast, is limited to specific locations.

Time-varying channel model of the underwater physical channel at baseband is expressed

$$h_c(t, \tau) = \sum_i a(t) e^{j\theta_i(t)} \delta(\tau - \tau_i(t)) \quad (5)$$

where $\delta(\cdot)$ denotes Dirac delta function, and the index i denotes the i -th cluster of rays arriving coherently with commonly delay $\tau_i(t)$, sound amplitude $a(t)$, and phase $\theta_i(t)$.

It is essential to acknowledge that the multipath effect in the ocean encompasses sound reflection off the seabed, refraction at the surface and through obstacles, as well as refraction within the water. The speed of sound (c) is roughly 1500 m/s. This slow speed, combined with propagation through multiple paths, creates significant challenges. Delay spreading, which can last tens or even hundreds of milliseconds, results in frequency-selective signal distortion between the floating transmitter and the floating receiver.

The echo is a result of sound propagation underwater. In [42], Onasami et al. introduced the echo state network (ESN) to improve the echo in UWAC. They showed that the ESN can achieve higher accuracy and lower computational costs than deep neural networks (DNNs) and long short-term memory (LSTM) networks. The ESN achieved a mean absolute percentage error (MAPE) of 15.96%, significantly lower than that of DNNs (56.54%) and LSTMs (52.10%). Therefore, using ESN for modeling underwater environments, especially in chaotic settings, can help reduce echo channeling.

While fish shoals are an obstruction caused by UWAC, Duane et al. [43] demonstrated the significant impact of fish shoals on long-range, wide-area acoustic sensing in the ocean. The study provides experimental evidence and theoretical validation for how these shoals attenuate acoustic signals, affecting various underwater applications. The study found that large fish shoals can substantially block acoustic sensing over vast areas, covering entire sectors of more than 30 degrees horizontally and reducing detection ranges by approximately an order of magnitude. This phenomenon presents significant challenges for underwater acoustic remote sensing, surveillance of underwater vehicles and marine life, geophysical studies, and underwater communication.

The influence of the underwater acoustic channel on acoustic transmission was thoroughly reviewed in [44]. The paper provides a detailed review and analysis of topology discovery in underwater acoustic sensor networks (UASNs), addressing a key challenge in the research and development of these networks. It examines the main channel and network characteristics of UANs, highlighting the importance of understanding these factors in designing effective network protocols.

Signal interference from natural sources and human activities impacts the underwater channel, mainly causing problems for signal detection at the receiver. The paper in [45] presents a filter that effectively reduces short interference for both single-carrier and multi-carrier UWAC systems without needing prior knowledge of the interference. The least trimmed square (LTS) equalizer is introduced for robust regression-based estimation and shot-interference mitigation.

2.1.2. UWAC for Underwater Drones

A wireless-powered communication network (WPCN) is a common setup for the UWAC application. In [46], the authors studied the performance of WPCN-based UWAC systems, focusing on factors that affect the average bit error rate (BER), outage probability, and achievable data rate. The average BER and outage probability of these systems increase with increasing transmission distance because path loss increases with distance. While Doppler shift negatively affects BER, BER increases as Doppler shift increases. The authors suggest that increasing the signal bandwidth helps reduce interference caused by Doppler shift, making the system more resilient. For example, increasing Doppler shift from 0.2 Hz to 0.6 Hz resulted in a 1.69% rise in BER with a 20 kHz bandwidth, but a 35.21% rise with a 5 kHz bandwidth. This is because larger subcarrier spacing broadens the bandwidth and reduces interference between adjacent subcarriers. Consequently, Xing et al. [46] confirm that transmission distance, transmit power, time allocation, signal frequency, and Doppler shift all significantly influence the performance of WPCN-based UWAC systems. Optimal choices of signal frequency and time allocation can be identified to minimize BER and

maximize data rate, highlighting the importance of careful parameter selection for system design in challenging underwater environments.

In [47,48], the development and implementation of a real-time orthogonal signal-division multiplexing (OSDM) system for UWAC were described. The OSDM MODEM combines both hardware and software components. The hardware includes a digital signal processor (DSP), a power amplifier, an analog-to-digital converter (ADC), a digital-to-analog converter (DAC), preamplifiers, and a bandpass filter. The software manages channel coding, Doppler estimation and correction, channel estimation, channel equalization, and maximum ratio combining (MRC). The system proved to be robust against Doppler shifts and complex multipath effects common in underwater acoustic channels. The Doppler shifts observed were generally small.

Recently, the higher-modulation cognitive model was introduced as an end-to-end (Floating transmitter to Floating receiver) deep learning solution for underwater acoustic signal modulation [49]. GIQNet is a deep learning framework that features a temporal large kernel convolution (TLKC) module. This module is essential for extracting long-range temporal features from signals. Its ability to identify these dependencies is critical for accurate modulation recognition, especially in the presence of multipath effects and Doppler shifts in underwater acoustic channels. The authors in [50] confirm that GIQNet maintains a lightweight architecture with fewer parameters, making it highly suitable for deployment on resource-constrained AUV edge devices. Its efficient design ensures high recognition accuracy while reducing computational complexity and power consumption, which are vital for underwater applications.

Table 2 presents nine representative works on UWAC, summarizing their tested communication ranges, achievable data rates, system complexity levels, and distinctive contributions.

Figure 6 presents a scatter plot of existing works [46–54] by UWAC range and data rate. The scatter plot shows that UWAC systems span from short-range, high-throughput links to long-range, low-data-rate connectivity, each addressing different aspects of underwater drone operations. At short to medium ranges, high data rates are reported by Lodovisi et al. [47], Wang X. et al. [49], and Wang H. et al. [53], achieving up to 100 kbps over distances of 100 to 1000 m. It is suitable for AUV swarms requiring real-time coordination, short-range data offloading to support vehicles, or docking/charging stations. At medium range and moderate data rates, Yang et al. [48] and Xing et al. [46] achieve a throughput of 1–4 kbps over a distance of 3 km. For underwater drones, it is suitable for long-endurance AUVs that need reliable telemetry, health monitoring, and command uplinks during exploration. At long range and low data rate, Huang et al. [51] can operate at 10 km but are limited to 700 bps. This involves strategic command and control of AUV fleets for basin-scale deployments (e.g., defense, climate monitoring). In lower-bound cases, Manicacci et al. [50] and Zhu et al. [54] provided results suitable for proof-of-concept AUV/ROV testbeds at short ranges.

Table 2. Performance analysis of recent UWAC studies, highlighting range, data rate, complexity, and key contributions for underwater drones.

Reference	Range	Data Rate	Complexity	Contribution
Xing et al. [46]	2–3 km	1 kbps	Medium	WPCN-UWAC enabling energy harvesting for IoUT
Lodovisi et al. [47]	200 m	100 kbps	High	A hybrid optical–acoustic system achieving Mbps throughput in clear waters
Yang et al. [48]	5 km	4.35 kbps	Medium	OSDM modem robust to multipath and Dropper
Wang, X. et al. [49]	1 km	100 kbps	Medium	Deep learning–based adaptive modulation classification (GIQNet AMC)

Table 2. Cont.

Reference	Range	Data Rate	Complexity	Contribution
Manicacci et al. [50]	300 m	100 bps	Low	Real-time acoustic positioning system with buoy relays
Huang et al. [51]	100–700 km	37–400 bps	High	Adaptive modulation for ultra-long-range UWAC
Cai et al. [52]	100–500 m	10 kbps	Medium	AUV formation networking under intermittent acoustic links
Wang, H. et al. [53]	0.5–2 km	100 kbps	Medium	RIS-assisted acoustic comms are improving reliability and rate
Zhu et al. [54]	500 m	2–3 kbps	Medium	Shared IoUT acoustic layer with testbed validation

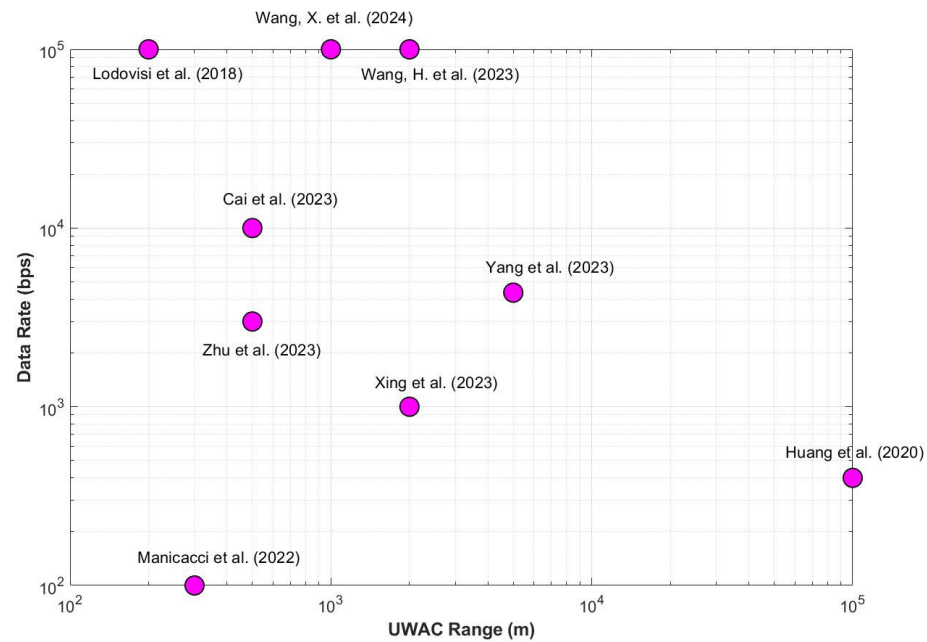


Figure 6. Scatter plot of existing works [46–54] by UWAC range and data rate.

2.2. Optical Communications

2.2.1. Underwater Wireless Optical Communication

Underwater wireless optical communication (UWOC) is an innovative technology that uses visible light to transmit data through water, offering significant advantages over traditional acoustic communication methods [55]. UWOC systems are known for their higher bandwidth and lower latency, making them suitable for a range of underwater applications, including environmental monitoring, underwater exploration, and communication between AUVs and ROVs [56].

The channel model [56–58] of underwater optical links is governed by absorption $a(\lambda)$ and scattering $b(\lambda)$, with attenuation coefficient $c(\lambda) = a(\lambda) + b(\lambda)$. Beer–Lambert’s law gives the intensity decay:

$$I(d, \lambda) = I_0 e^{-c(\lambda)d} \quad (6)$$

A convenient line-of-sight (LOS) channel model for narrow beams is

$$H_{LOS}(d, \lambda) = \frac{A_r}{d^2} \cos \phi T_s(\psi) g(\psi) \cos \psi e^{-c(\lambda)d} \quad (7)$$

where ϕ and ψ are irradiance/incidence angles, $T_s(\psi)$ is optical filter gain, and $g(\psi)$ is concentrator gain within its field of view. The received power is

$$P_{i,O} = \eta_t \eta_i P_{t,O} H_{LOS}(d, \lambda) \quad (8)$$

with transmitter/receiver optical efficiencies η_t, η_r . A simple electrical SNR approximation is

$$SNR_O = \frac{(P \cdot P_{i,O})^2}{N_0 B + \sigma_{\text{shot}}^2 + \sigma_{\text{th}}^2} \quad (9)$$

where P denotes the photodetector responsivity, and the denominator group noise terms are as follows: σ_{shot}^2 is shot noise variance, σ_{th}^2 is thermal noise variance. $N_0 B$ is background light and ambient noise within bandwidth B .

Beam divergence and misalignment introduce geometric loss $G_{\text{geo}}(d)$; for a beam with half-angle θ_{div} ,

$$G_{\text{geo}}(d) = \frac{A_r}{\pi d^2 \tan^2 \theta_{\text{div}}} \quad (10)$$

These equations capture the high-rate, low-latency but distance and clarity-limited behavior of UWOC.

The communication system of UWOC technology uses laser diodes (LDs) or light-emitting diodes (LEDs) as signal transmitters, combined with advanced modulation techniques. These include orthogonal frequency-division multiplexing (OFDM), non-return-to-zero on-off keying (NRZ-OOK), and optical code division multiple access (OCDMA), all of which are carefully designed to enhance data transmission speeds, efficiency, and system resilience [57]. At the core of UWOC are underwater optical modems, specialized devices that transmit and receive optical signals. These modems support omnidirectional communication over approximately 100 m and data rates exceeding 1 Mbps [57,58]. Their performance depends on the integration of optical transmitters and receivers, which are key components that send and receive optical signals, respectively [38,59]. In practice, Sonardyne BlueComm optical modems achieve up to 5–10 Mbps over distances of 100–150 m in clear water.

A key element of UWOC is the non-line-of-sight (NLOS) scattering channel, which is common in underwater environments where direct visibility between the transmitter and receiver is often obstructed. The characteristics of this channel have a significant impact on the performance of optical communication systems [60]. To examine these features, researchers employ Monte Carlo ray tracing, an advanced modeling approach that provides insights into the impulse response and path loss under various water conditions [61,62]. This method is vital for understanding how light behaves in various underwater scenarios, which directly influences the design and optimization of UWOC systems. Furthermore, the underwater attenuation coefficient is crucial for determining the amount of light absorbed or scattered in water, thereby affecting the performance of UWOC systems [63].

The BER is a crucial performance metric in UWOC, indicating the number of errors per transmitted bit relative to the total number of bits sent. A lower BER indicates a more reliable communication link, which is essential for applications requiring high data integrity [64]. By continuously monitoring and optimizing system parameters, researchers can enhance UWOC's overall performance, ensuring effective underwater communication across different conditions [65,66].

2.2.2. UWOC for Underwater Drones

The implementation of UWOC includes several key components, including a directly modulated semiconductor laser serving as the transmitter. This technology enables the transmission of pseudo-random binary sequence signals at bit rates of 5, 10, 15, and 20 Mbps across different channels [67–69]. Its high transmission bandwidth makes UWOC an appealing option for short-range underwater applications, where traditional acoustic systems often encounter limitations due to low data rates and high latency caused by the speed of sound in water [70].

A practical use of UWOC involves combining an LED lighting communication system with a Bluetooth module to enable underwater-to-air communication. This integration enhances the infrastructure necessary for efficient communication between underwater wireless systems and command ship networks, thereby improving monitoring capabilities [67,69,71]. Underwater visible light communication (UVLC) is particularly effective in underwater environments because blue-green light undergoes less absorption, resulting in clearer data transmission [72]. Moreover, the successful transmission of error-free images and text at 230.4 kbps demonstrates the reliability and practicality of UWOC in real-world scenarios [71]. This capability is essential for the IoUT, which envisions a network of interconnected underwater devices that can communicate both with each other and with surface systems. The IoUT aims to monitor large, unexplored water regions, utilizing dependable underwater communication technologies to explore and safeguard natural underwater resources [73].

In summary, the implementation of UWOC systems, characterized by high data rates and low latency, is transforming underwater communication. By integrating advanced technologies such as LED lighting systems and Bluetooth modules, UWOC is paving the way for improved monitoring and exploration of underwater environments, ultimately supporting the broader goals of the IoUT [67,71,73].

Recent studies indicate that most UWOC systems are limited by short range, sensitivity to alignment, and limited connectivity beyond the water column. To overcome these challenges, we introduce a hybrid architecture that links UWOC connections between underwater drones (AUVs and ROVs) with relay links via surface vessels, aerial unmanned vehicles (UAVs), and LEO satellites, as illustrated in Figure 7. This multi-domain integration enhances coverage, minimizes reliability issues, and enables seamless communication between underwater and internet networks. Such an architecture creates new opportunities for real-time ocean monitoring, offshore energy and aquaculture operations, and defense applications, where continuous underwater-to-satellite connectivity is vital for situational awareness and informed decision-making.

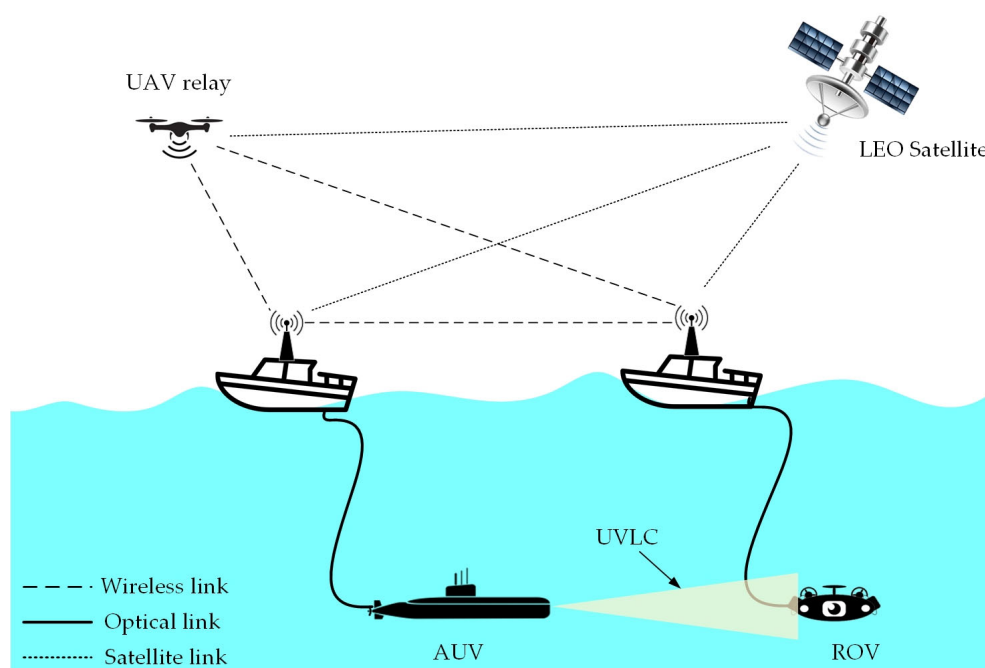


Figure 7. Underwater wireless optical communication between an AUV and ROV, connected through wireless links via surface vessels, a UAV, and a LEO satellite.

Table 3 shows seven representative studies on UWOC, summarizing their communication ranges, data rates, system complexity levels, and unique contributions. The UWOC range data rate chart illustrates the capability of optical systems to deliver ultra-high throughput, up to 10 Gbps, over ranges from 10 m to nearly 1 km, depending on water clarity and alignment stability. While short-range systems are well-suited to docking and swarm coordination, medium- and long-range deployments enable real-time AUV-to-buoy video uplinks and subsea infrastructure monitoring. These results affirm UWOC as the most promising modality for bandwidth-intensive underwater drone applications, though hybrid integration remains essential to mitigate turbidity and alignment constraints.

Figure 8 shows a scatter plot of existing works [67–73] by UWOC range and data rate. At short range and moderate-to-high data rates, references such as Kottilingal et al. [67] and Liu et al. [73] demonstrated laboratory or short-range field trials achieving 30–100 Mbps. These are suitable for ROV docking systems, near-field AUV telemetry, and swarm communications where precise alignment is feasible. At medium range and high data rates, Luo et al. [71] and Xu et al. [68] achieve data rates of 100 Mbps to 1 Gbps at ranges of 10 to 100 m. These works highlight the effectiveness of advanced optical modulation and error correction in extending the reach of UWOC. At long range and very high data rates, Suzuki et al. [70] achieved Gbps transmission over ranges approaching 1 km, representing the upper performance bound of UWOC in clear-water conditions. This shows the feasibility of long-range HD video streaming from AUVs and oceanographic sensors, but requires precise beam alignment. In ultra-high data rate demonstrations, Chen et al. [69] achieved 10 Gbps over 100 m using an advanced laser-based UWOC. While highly promising, such systems are highly sensitive to turbidity and misalignment, requiring stable platforms and adaptive optics to function effectively.

Table 3. Performance analysis of recent UWOC studies, highlighting range, data rate, complexity, and key contributions for underwater drones.

Reference	Range	Data Rate	Complexity	Contribution
Kottilingal et al. [67]	1–5 m	2–30 Mbps	Medium	Proposed real-time duplex video transmission using multiple wavelengths
Xu et al. [68]	100–300 m	100 Mbps	High	Demonstrated multi-hop UWOC feasibility with field validations
Chen et al. [69]	100 m	10 Gbps	High	Proposed a hybrid UWOC, enabling seamless IoUT
Suzuki et al. [70]	100–900 m	1 Gbps	High	Proposed multi-beam transmitters and multi-PMT receivers, proving high-speed robustness
Luo et al. [71]	10–100 m	50 Mbps	Medium	Proposed AUV swarm-based UWOC relaying with adaptive beam/power control for scalable IoUT
Ali et al. [72]	50 m	100 Mbps–1 Gbps	Medium	Proposed UVLC trends and optimizing energy-efficient protocols and 5G/6G for IoUT network
Liu et al. [73]	10 m	100 Mbps	Medium	Developed a lemniscate-shaped LED array, improving BER and uniformity; simulation and validation for robust UWOC links

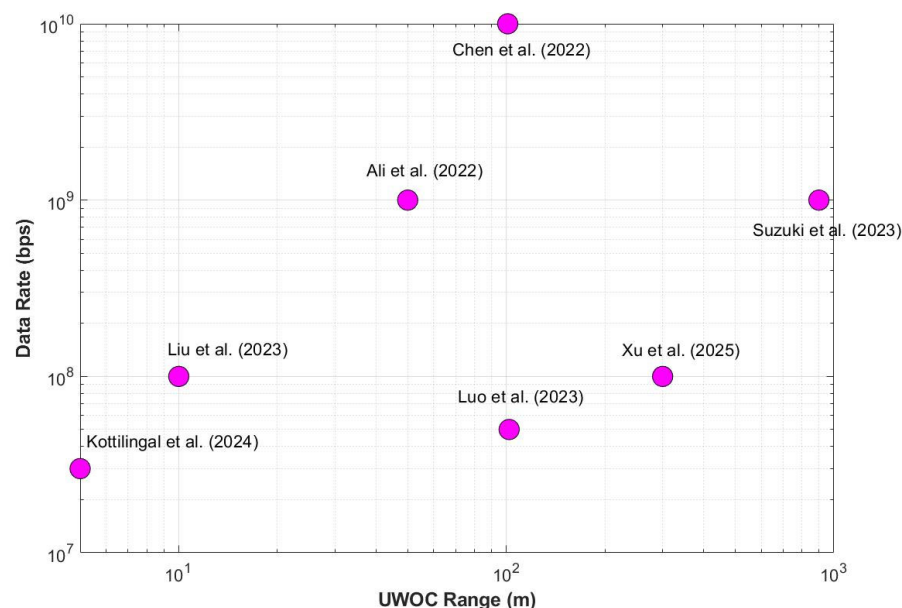


Figure 8. Scatter plot of existing works [67–73] by UWOC range and data rate.

In this regard, UWOC clearly outperforms UWAC in raw throughput, achieving gigabits per second (Gbps). High throughput is feasible at short to medium ranges, while km-scale links often trade stability for water clarity and precision. It is summarized that short-range communication, which can be used for docking, formation control, and swarm networking, is suitable for ROVs/AUVs within a range of 20 m. For medium range, 50–200 m is suitable for real-time sensor data offloading and AUV-to-buoy relay. Over long distances of 500 m or more, strategic high-capacity uplinks, such as those used for subsea infrastructure monitoring, are employed.

2.3. RF Communications

2.3.1. Underwater RF Communication

Underwater radio frequency communication (URFC) is a challenging yet essential area of research, especially for applications involving AUVs and UWSNs. This approach uses electromagnetic waves to transmit data, but it faces significant hurdles due to the high attenuation of radiofrequency signals in seawater, which restricts their effective range and reliability [74,75]. URFC can provide higher throughput than UWAC but lower than UWOC [76]. However, the effectiveness of URFC in underwater environments is constrained by factors such as water salinity, temperature, and the presence of obstacles, which can greatly attenuate radio signals [77]. In [5], Alahmad et al. investigated RF communication in seawater using an AUV equipped with three types of antennas: a loop, a wire, and a helical antenna. The helical antenna demonstrated superior performance in the coverage area, enabling the AUV to move freely and successfully capture live video streaming, highlighting the potential of RF systems for underwater operations.

The received power over distance $P_{i,RF}$ can be expressed as a modified Friis formula [5] with conductive loss

$$P_{i,RF} = P_{t,RF} G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2 e^{-2\alpha d} \quad (11)$$

where G_t and G_r represent the antenna gain of the transmitter and receiver.

In conductive media [74,75], the complex permittivity is $\epsilon_c = \epsilon - j\sigma/\omega$. The propagation constant is

$$\gamma = \alpha + j\beta = \sqrt{j\omega\mu(\sigma + j\omega\epsilon)} \quad (12)$$

For seawater where $\sigma \gg \omega\epsilon$, a good-conductor approximation gives

$$\alpha \approx \beta \approx \sqrt{\pi f \mu \sigma} \quad (\text{Np/m}), \quad \delta = \frac{1}{\alpha} \quad (\text{skin depth}) \quad (13)$$

These relations exhibit severe attenuation at high frequencies in seawater, which explains why underwater RF links are typically short-range and are used for near-field control, wake-up signaling, or specialized low-frequency systems.

The schematic of the URFC features an integrated underwater-to-surface communication architecture that links ROVs on the seabed to a surveillance center via hybrid RF, optical, and aerial communication, as illustrated in Figure 9. Underwater segment: Two ROVs (Transmitter: ROV-Tx and Receiver: ROV-Rx) exchange signals using RF modules with wavelet-OFDM modulation [5]. Each ROV is equipped with a transmitter and receiver antenna, a battery, and a processing module. Surface communication: surface gateway buoys connect the ROVs via optical cabling, ensuring reliable coupling of underwater signals to the air surface domain. Aerial and terrestrial segment: The floating units relay data wirelessly to the UAV via ground-to-air (G2A) [78] and air-to-ground (A2G) [79] communication, and then to a 5G network tower. Ultimately, the 5G infrastructure connects to a surveillance center, enabling real-time monitoring and control of underwater operations [80]. This architecture showcases a multi-domain communication system that bridges underwater RF links with terrestrial 5G and UAV relays, enabling reliable and scalable marine monitoring.

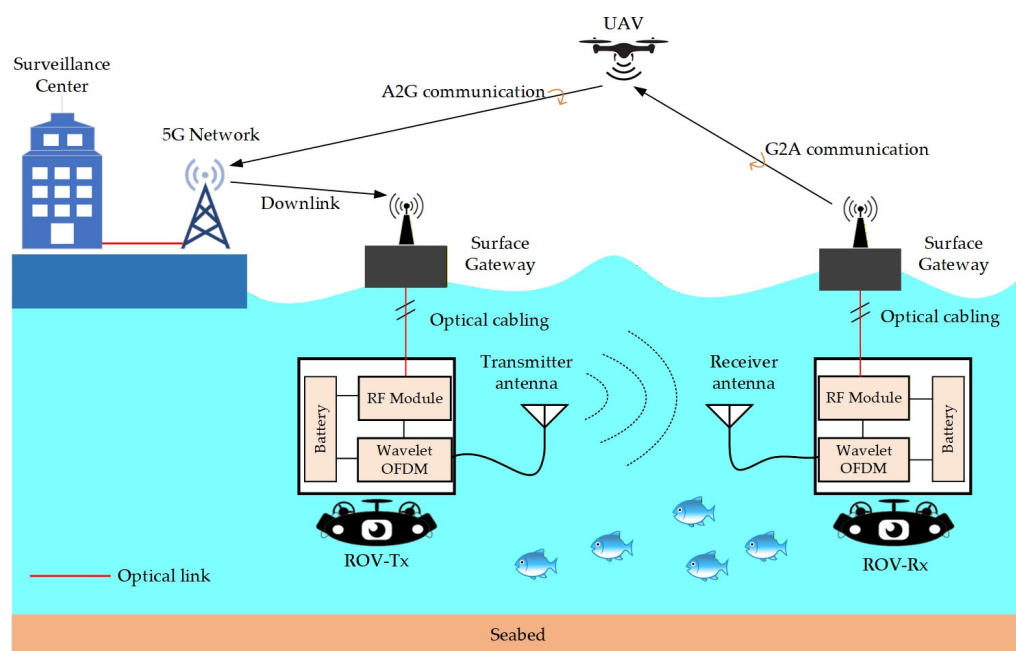


Figure 9. Hybrid underwater-surface-aerial communication system connecting ROV-based RF links with floating optical units, UAV relays, and a 5G network for real-time seabed monitoring.

2.3.2. URFC for Underwater Drones

The implementation of URFC systems utilizes various techniques and technologies to address challenges in underwater drones, including reducing high attenuation and limited range. Using a wavelet-orthogonal frequency-division multiplexing (OFDM) wireless communication system offers a solution for an RF module optimized for underwater deployment in AUVs [81]. The authors in [81] demonstrated that URFC, especially with loop antennas and Wavelet OFDM, provides resilience against issues such as biofouling and positional misalignment, enabling reliable, high-speed data transfer over lossy media.

Different antenna types, including loop, wire, and helical antennas, have been tested for URFC. Notably, the helical antenna has demonstrated superior performance in terms of coverage area and data transmission, enabling the successful live streaming of video from AUVs [5]. Furthermore, the use of bowtie antennas in multi-hop sensor networks has extended communication ranges and enhanced network longevity [82].

In oceanography, URFC can improve the monitoring of ocean conditions and environmental parameters. For example, it can be integrated into UWSNs to gather and transmit data on temperature, salinity, and pollution levels, giving researchers timely information to evaluate marine ecosystems [21]. The ability to transmit large amounts of data quickly is crucial for applications such as remote sensing and environmental monitoring, where a rapid response to changing conditions is essential [83]. By deploying AUVs or ROVs with URFC systems, researchers can collect extensive data on marine species in their natural habitats without human interference [84]. This technology enables the collection of high-resolution imagery and biological data, which can be transmitted back to the surveillance center in real-time, allowing for immediate analysis and informed decision-making.

Kelley et al. [85] introduced an RF multi-carrier method for URFC that could benefit underwater drones. It features an integrated system that uses broadband RF antennas and multi-carrier digital radio technologies, supporting data rates of up to 1 Mbps over distances of 100–1000 m. This approach adapts techniques from 4G communications for underwater applications, addressing challenges such as severe attenuation and multipath effects, which are crucial for reliable communication in underwater drone operations. Then, Wang et al. [86] discussed an electrocommunication system for underwater robots that employs binary frequency shift keying (BFSK) modulation and a deep learning-based demodulation method. Hasaba et al. [87] demonstrated that RF signals can be effectively used for communication in seawater, achieving a maximum data rate of 6.8 Mbps. The study measured the insertion loss between antennas submerged in seawater, yielding promising results that suggest RF communication is feasible for AUVs in marine resource exploration, complementing existing methods such as acoustic and laser communication.

Recently, hardware implementation has been based on the universal underwater software-defined radio (UniSDR) architecture, which supports multi-mode communication, including RF for underwater applications [88]. This architecture enables underwater drones to utilize URFC alongside other modes, such as acoustic and optical, thereby boosting flexibility and performance. By facilitating joint operations and data exchange across different communication modes, UniSDR can reduce transmission latency, improve energy efficiency, and enhance overall reliability, making it well-suited for various underwater drone communication tasks. Then, Zhang et al. [89] implemented underwater electric-field communication using direct-sequence spread spectrum (DSSS) and BPSK modulation, rather than RF communication. It highlights the advantages of electric field communication, such as stability in complex waters and resistance to environmental interference, which are critical for underwater operations. While it does not specifically address underwater radio-frequency communication for drones, the findings suggest that DSSS-BPSK could improve underwater robot communication capabilities.

In summary, implementing URFC depends on overcoming challenges related to signal attenuation, antenna design [5], modulation techniques [81,86,87,89], and regulatory compliance [88]. By harnessing the strengths of RF technology, especially in shallow water environments [74], researchers can create more effective underwater communication systems, such as dynamic magnetic induction for AUV-assisted underwater IoT [90]. The integration of wireless power and data transfer systems for AUVs further boosts underwater drone capabilities, enabling high-speed, full-duplex communication and alleviating voltage stress on data channels [91].

Table 4 presents seven important studies on URFC, summarizing their tested communication ranges, achievable data rates, system complexity levels, and unique contributions. The URFC range and data rate indicate that RF systems can deliver Mbps-level throughput at very short ranges and at rates of kbps to Mbps up to 100 m, making them a complementary technology to acoustic and optical links. Although high attenuation in seawater limits their scalability, URFC is especially suitable for underwater drone docking, short-range data offloading, and inter-vehicle control links.

Figure 10 illustrates the operational window of URFC, which bridges the gap between UWAC (long-range, low-rate) and UWOC (short-range, high-rate). The studies plotted reveal the inherent trade-offs between attenuation in conductive seawater and the potential for localized high-rate transmissions. At short ranges and high data rates, Alahmad et al. [5] and Hasaba et al. [81] reported data rates of 1–10 Mbps at a few meters, demonstrating the suitability of URFC for short-range, high-throughput links. These are promising for ROV docking stations, diver-to-ROV communication, and payload data offload. At medium range and moderate data rates, Wang et al. [86] and Zhang et al. [89] achieved throughputs of 1–10 kbps at a distance of 10 m. This performance is well-suited for control signaling, telemetry, and localization beacons in multi-drone operations. At extended ranges and lower data rates, Zhilin et al. [88] demonstrated Mbps rates up to 100 m, while Kelley et al. [85] extended the range towards several hundred meters with reduced throughput. These demonstrate the potential for robust mid-range links but require careful optimization of frequency and antenna due to the effects of seawater conductivity losses. Lastly, in lower-bound cases, Wei et al. [90] reflect trade-offs made in favor of energy efficiency or experimental simplicity.

Table 4. Performance analysis of recent URFC studies, highlighting range, data rate, complexity, and key contributions for underwater drones.

Reference	Range	Data Rate	Complexity	Contribution
Alahmad et al. [5]	2 m	4 Mbps	Medium	Real-time video with AUVs
Hasaba et al. [81]	2–3 m	6.8 Mbps	High	Developed Wavelet-OFDM with loop antennas, providing robust short-range RF links for AUVs
Kelley et al. [85]	100–1000 m	1 Mbps	Medium	Proposed RF signaling with LDPC framework for medium-range RF UWAC
Wang et al. [86]	10 m	5 kbps	Medium	Proposed BPSK and deep learning demodulation, achieving BER with low power
Zhilin et al. [88]	100 m	10 Mbps	High	Designed a universal multimode SDR modem (UniSDR) for IoUT, enabling adaptive, hybrid underwater networking
Zhang et al. [89]	11.2 m	10 kbps	Medium	Proposed DSSS-BPSK communication system, compact and interference-resistant for underwater robots
Wei et al. [90]	2 m	100 kbps	High	Developed a dynamic MI channel model, ensuring stable, power-efficient AUV-assisted IoUT links

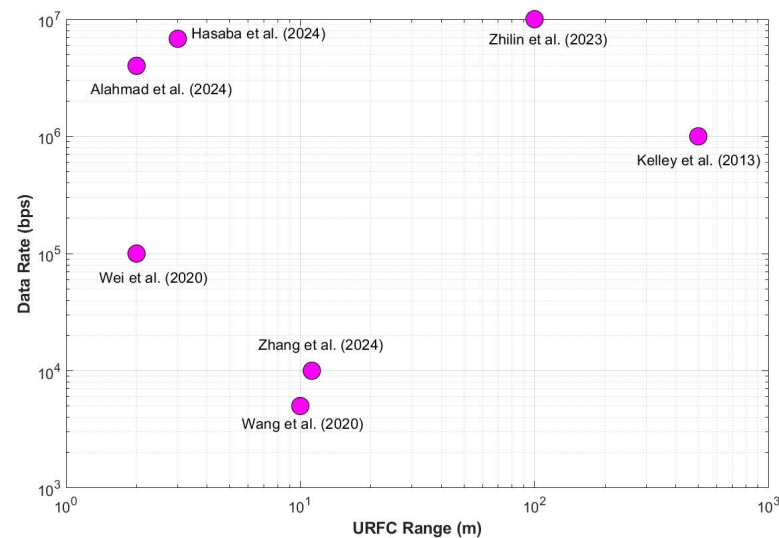


Figure 10. Scatter plot of existing works [5,81,85,86,88–90] by URFC range and data rate.

The functionality of URFC can serve as a middle ground between acoustic and optical channels, enabling short- to medium-range control and data links where line-of-sight (LOS) optics are impractical. Short-range communication ranges, such as those used for ROV docking, diver-ROV/AUV communications, and payload offload, can provide data rates of Mbps. For mid-range at 10 m and data rates of 1 kbps to 10 Mbps, it is suitable for formation control, localization, and inter-drone messaging. At a range of up to 100 m, it is suitable for backup commands and sensor relay, such as IoUT. Future trends in URFC include integrating wavelet-OFDM [81], multiple-input multiple-output (MIMO) antennas, and hybrid RF-acoustic or optical schemes, which can facilitate reliable deployment in underwater drone networks. These findings [5,81,85,86,89,90] suggest that URFC, when integrated into hybrid architectures, can enhance the robustness and flexibility of next-generation underwater drone communication systems.

Beyond qualitative summaries of existing surveys, we normalize prior results along comparable axes, ranges, and data rates. We then map these literature data points to the drone-centric baselines used throughout this paper. Specifically, for UWAC, our synthesis aggregates recent field and tank reports into Table 2. It visualizes the range–rate trade-off in Figure 6, enabling a side-by-side comparison of short, medium, and long-range acoustic links used by AUVs and ROVs. For UWOC, we likewise collect reported ranges and data rates into Table 3 and plot them in Figure 8 to highlight where optical links enable Mbps to Gbps telemetry and where water clarity and alignment constraints affect deployment. For URFC, peer results are consolidated in Table 4 and summarized in Figure 10 to show the short-range, high-throughput operating window and its role as a low-latency control and offload channel. This benchmarking layer clarifies how earlier surveys and point studies translate into actionable baselines for underwater drone networks.

2.4. MI Communications

MI communication is emerging as a promising technology for underwater networking, offering solutions to the limitations faced by traditional communication methods such as acoustic and electromagnetic (EM) waves. MI communication leverages the properties of magnetic fields to transmit data, which is particularly advantageous in underwater environments where other methods suffer from high attenuation and unpredictable channel conditions, as discussed in [34–36,90]. This technology is characterized by its low power consumption, predictable channel behavior, and minimal propagation delay, making it suitable for various underwater applications, including the IoUT and AUVs.

In [92], the author presented a network coverage using MI waves for IoUT in a shadowing environment. Unlike EM waves, in MI-based communication, the effect of shadow fading on the obtainable transmission distance is not as pronounced. The simulation results showed the path loss of the channel model between the transmitter and receiver, based on coil antennas, the operating frequency, and obstacles in a seawater environment. It can be observed that MI communication has a low data rate in underwater environments.

In [93], Ren et al. presented the MIMO technique for underwater MI-assisted acoustic wireless sensor networks. The simulation results demonstrate that the cooperative MIMO system size can enhance energy efficiency and ensure the connectivity of underwater nodes and surface base stations. Additionally, implementing cooperative MIMO communications in underwater environments is challenging due to difficulties in synchronizing the received signal. While MI communication helps reduce synchronization errors caused by slow acoustic propagation, synchronization remains a complex issue. The large wavelength in underwater environments makes it difficult to place multiple acoustic transducers on a single device while ensuring spatial independence, which is necessary for cooperative MIMO.

Then, the performance analysis and design of quasi-cyclic low-density parity check (QC-LDPC) codes for underwater MI communications was presented by Xu et al. [94]. The study demonstrates that using QC-LDPC codes significantly improves the BER performance compared to uncoded communication, proving their effectiveness in underwater MI communication. The study confirms the significant performance improvement offered by QC-LDPC codes and provides a robust framework for designing reliable and energy-efficient underwater MI communication systems.

Advantages of MI Communication provide a stable and predictable channel response, which is less affected by environmental factors such as multi-path fading and high propagation delays that typically affect acoustic communications. Despite its advantages, however, MI communications faces several challenges that need to be addressed to fully realize its potential in underwater drones. These include optimizing antenna design for better performance, developing robust networking protocols, and addressing issues related to range extension and capacity enhancement [90–94].

3. Challenges

In this section, we outline the challenges of using underwater drones to facilitate wireless communication systems. Underwater wireless communication (UWC) is a fundamental technology for the development of underwater drones such as AUVs and ROVs. Each communication method, including UWAC, UWOC, URFC, and MI, offers specific benefits while facing inherent challenges due to the complex and changing nature of the aquatic environment. To better understand their relative potential, we summarize the advantages, challenges, limitations, and opportunities of UWAC, UWOC, URFC, and MI when used with underwater drones, as shown in Tables 5–8.

Table 5. Perspective on UWAC use with underwater drones.

Aspect	Details
Advantages	■ Longest communication range (1–100 km) ■ Resistant in murky, deep-water conditions ■ Sound waves penetrate well against throwing obstacles
Challenges	■ Limited bandwidth (bps–kbps) ■ High latency caused by slow sound speed ■ Affected by multipath, Doppler effect, and ambient noise

Table 5. *Cont.*

Aspect	Details
Limitations	■ Cannot support real-time video streaming ■ Vulnerable to interference in noisy environments
Opportunities	■ Coordinate a swarm of AUVs over large ocean areas ■ IoUT backbone for connecting AUVs ■ AI-driven data adaptive modulation and equalization to enhance reliability

Table 6. Perspective on UWOC use with underwater drones.

Aspect	Details
Advantages	■ Extremely high data rates (Mbps–Gbps) ■ Low latency, ideal for real-time video ■ Compact, lightweight transceivers (LEDs, lasers)
Challenges	■ Unreliable in murky or very turbulent waters ■ Narrow beamwidth hampers drone mobility ■ Power-hungry at long ranges and high rates
Limitations	■ Severely affected by turbidity, scattering, and biofouling ■ Requires accurate pointing and alignment ■ Limited range (100 m)
Opportunities	■ Real-time HD/4K video streaming for drone-based inspection and mapping ■ Optical relaying in drone swarms to increase coverage. ■ DT and VR or Augmented Reality (AR) in underwater environments for next-generation AUV missions

Table 7. Perspective on URFC use with underwater drones.

Aspect	Details
Advantages	■ Low latency, ideal for control and command signals ■ Compact antennas (loop, helical) facilitate drone integration ■ High throughput achievable over short ranges
Challenges	■ Severe attenuation in conductive seawater ■ Range usually less than or equal to 10 m ■ Weak robustness in deep oceans
Limitations	■ Not suitable for long-distance communication ■ Limited stability when seawater conductivity varies
Opportunities	■ Short-range communication for AUV docking and charging ■ Backup low-latency links within hybrid systems ■ AUV-to-surface gateways via buoys/UAVs to support IoUT integration ■ Underwater localization with wavelet OFDM

Table 8. Perspective on use of MI communication with underwater drones.

Aspect	Details
Advantages	■ Robust in conductive media ■ Low latency, deterministic channel ■ Simple PHY and MAC layer design
Challenges	■ Rapid path loss ■ Large coil antennas ■ Efficient matching and resonant design
Limitations	■ Lower throughput than UWAC and UWOC ■ Short effective range ■ Not suitable for wide-area networking
Opportunities	■ Docking and charging stations ■ Localization and navigation ■ Hybrid stacks ■ Relayed and resonant networks

3.1. Hybrid Communication Systems

The hybrid approach typically combines UAWC, UWOC, and URFC, each selected for its benefits and the specific requirements of underwater wireless communication methods and applications [95]. In this subsection, we examine the key aspects of hybrid communication systems for underwater drones, as discussed in existing research.

3.1.1. UAWC-UWOC

An optical-acoustic hybrid network for real-time video streaming was introduced by Han et al. [96]. They proposed a hybrid communication solution for underwater sensors that combines acoustic and optical methods. Optical communication provides high-quality, real-time video streaming, while acoustic communication ensures a reliable network topology and acts as a backup for video delivery when optical signals are unavailable. This approach enables smooth transitions between the two modes by using image processing algorithms to compress key frames for transmission over the acoustic channel, thereby enhancing the efficiency of underwater operations without relying on optical cables. Later, Gauni et al. [97] proposed a hybrid model combining acoustic and optical communication for underwater applications, particularly beneficial for underwater drones. The hybrid approach leverages the strengths of both technologies, enhancing underwater drone communication capabilities across various fields, including climate monitoring and military operations. In [98], Islam et al. introduced green underwater wireless communications using hybrid optical-acoustic techniques. They confirmed that the proposed hybrid optical-acoustic underwater wireless communication method effectively conserves power while maintaining network throughput. Simulation results showed up to 35% energy savings compared with conventional approaches, demonstrating potential for long-term AUV/ROV missions with limited power resources. For applications of localization and tracking for AUVs, Zhang et al. [99] proposed a hybrid acoustic-optical communication scheme for autonomous underwater vehicles (AUVs) to improve the localization and tracking of moving target ships. They discussed the acoustic link, which enables non-line-of-sight (NLOS) localization, while the optical link supports high-rate line-of-sight (LOS) data transmission. By integrating these technologies, the system overcomes individual limitations, ensuring accurate tracking and reliable communication.

Although hybrid UWAC and UWOC systems offer numerous benefits, they still face challenges such as the complexity of integrating two different technologies and the

requirement for advanced control algorithms to switch between communication modes. In [100], Luo et al. introduced a Q-learning-based adaptive switching scheme for hybrid acoustic-optical communication in AUVs. This scheme enhances network throughput by leveraging both acoustic and optical channels and addresses partial optical channel observations using a blind estimation method that employs the extended Kalman filter (EKF). Combining these technologies enables high-bandwidth, low-latency operations, which are crucial for effective communication in challenging underwater environments, considering factors such as AUV mobility and environmental conditions. Nonetheless, ongoing research and technological advancements continue to enhance the capabilities and reliability of hybrid communication systems, making them more practical for robust underwater conditions.

3.1.2. UWOC-RF

Hybrid UWOC and RF communication systems for underwater drones offer a promising solution to underwater communication challenges by combining the strengths of both technologies to enhance data transmission. The advantages of hybrid UWOC and RF communication include high data speeds, low latency, a more extended range, and improved energy efficiency. In [101], Agheli et al. introduced the UWOC system for AUVs and UWSNs, while the RF systems for AUVs and UAVs were connected via a free-space optical (FSO) channel. They examined a triple-hop UWSN in which AUV and UAV relays enable end-to-end communication between the sensor networks and the terrestrial access point (AP). The outage probability and average bit-error rate (ABER) performance were evaluated for the UWOC and URFC, demonstrating reliable and stable AUV–UAV FSO communication.

Utilizing relay nodes, such as floating buoy sensors or aerial drones, can enhance communication by bridging underwater and terrestrial systems. These relays can utilize visible light communication (VLC) and FSO for efficient data transfer. In [102], the authors examined a hybrid communication system for AUVs that uses VLC for underwater links and combines RF and FSO for terrestrial connections. A floating buoy sensor acts as a relay node, enabling data transfer from the AUV to a land-based station. The results showed that the VLC-FSO combination outperforms the VLC-RF setup in terms of BER, especially at low signal-to-noise ratio (SNR). Additionally, an adaptive modulation based on optimal SNR for the air-to-underwater channel was introduced in [103]. The authors developed a new optical wireless communication system using 850 nm optical signals for IoUT devices, with a mirror-equipped aerial drone serving as a relay. The study focused on high-speed data transfer, SNR-based adaptive modulation, and successful 4K video streaming in shallow seawater; however, it does not explore the incorporation of RF communication into the system.

Combining terrestrial, aerial, and underwater communication systems, such as the integrated terrestrial-air-underwater (TAU) architecture, can greatly enhance data rates and decrease outage probabilities compared to traditional RF systems. Singh et al. [104] proposed an integrated TAU communication system that utilizes hybrid FSO and UWOC technologies, explicitly designed for AUVs. This system utilizes UAVs to enhance performance compared to conventional RF systems. They examine the optimization of the optical beam divergence angle using a new cognition-based divergence angle tracking (CODAT) algorithm, demonstrating improved data rates and lower outage probabilities for the integrated TAU communication system.

In practice, fiber-coupled optical wireless communication devices can be used for the remote control of underwater drones, providing reliable communication over approximately 100 m, as introduced by Sawa et al. [105].

Although hybrid UWOC and RF communication systems offer significant benefits for underwater drones, they also face challenges that must be addressed. A mixed UWOC-RF system [106] that uses a UAV as a mobile aerial base station to communicate with an AUV remains challenging to implement. Performance factors, such as UAV height, air bubbles, temperature gradients, and water salinity, must be considered alongside key metrics, including outage probability, ABER, and channel capacity. Furthermore, integrating the UWOC-RF system requires careful design and optimization to ensure smooth operation and reduce computational complexity [98,107]. In [107], Bolboli et al. introduced a hybrid long-range (LoRa)/optical relay node designed for underwater communication, tackling challenges such as signal attenuation and the air-water interface. The experimental results demonstrate the effectiveness of this hybrid LoRa/optical relay node for providing reliable, energy-efficient communication in underwater applications, making it suitable for drones that require robust connectivity. Additionally, LoRa technology is being explored for use in smart marine IoT applications. The performance of the communication link between the LoRa module and the aerial relay station has been studied in [108] under seawater conditions.

3.1.3. Hybrid Underwater Communication Mathematics Model

Hybrid underwater communication combines two or more modalities [88], typically UWAC, UWOC, URFC, and MI, to leverage their complementary strengths in terms of transmission range, bandwidth, latency, and robustness. Let $R = \{A, O, R, M\}$ represent the available communication modes. Note that A is the UWAC model, O is UWOC, R is URFC, and M is the MI model. At a given time t , the optimal mode $r(t)$ is selected based on a utility-based decision formulation expressed as

$$r(t) = \underset{r \in R}{\operatorname{argmax}} U_r(t) \quad (14)$$

where $U_r(t)$ denotes the utility score of mode r , capturing the trade-off between capacity, latency, and energy efficiency. A generic utility function may be defined as

$$U_r(t) = \alpha_1 C_r(t) - \alpha_2 L_r(t) - \alpha_3 E_r(t) \quad (15)$$

where $C_r(t)$ is the achievable capacity, $L_r(t)$ the end-to-end latency, and $E_r(t)$ the energy consumption per bit. The weighting parameters ($\alpha_1, \alpha_2, \alpha_3 \geq 0$) can be adjusted according to mission requirements, such as high throughput for data offloading or low latency for real-time control of underwater drones.

Representative link models for the hybrid system may be expressed as follows.

Acoustic Link Capacity:

$$C_A = B_A \log_2(1 + \text{SNR}_A) \quad (16)$$

This indicates modest bandwidth but longer propagation range and higher reliability in turbid or deep-sea environments.

Optical Wireless Link Attenuation:

$$P_{i,O} = P_{t,O} e^{-c(\lambda)d} \cdot G \quad (17)$$

where $P_{t,O}$ and $P_{i,O}$ are the transmitted and received optical powers, $c(\lambda)$ is the wavelength-dependent attenuation coefficient, d the underwater distance, and G the geometric/alignment loss factor.

MI Path-Loss:

$$PL_M(d) \propto d^3 \quad (18)$$

This reflects a limited range but high robustness to turbidity, salinity, and non-line-of-sight (NLoS) conditions.

To avoid unnecessary frequent mode switching, a switching threshold is applied such that a mode transition from m_1 and m_2 occurs only if

$$U_{r_2}(t) - U_{r_1}(t) > \delta \quad (19)$$

where δ is a small positive constant. This mathematical model provides a clear framework for explaining how hybrid systems dynamically select and transition between communication modes to sustain optimal performance under varying underwater channel conditions.

3.1.4. Multimodal System

In [88], Zhilin et al. proposed UniSDR for IoUT. It combines acoustic, optical, magnetic induction, and RF technologies. This design offers flexibility in building a radio system that can use multiple modes simultaneously, thereby boosting communication capabilities for underwater drones. By leveraging the complementary features of these modes, the UniSDR architecture addresses challenges such as high system costs and coordination issues, ultimately improving transmission latency and energy efficiency. Subsequently, DURIUS was introduced in [109]. It is a novel multimodal approach that integrates hybrid acoustic, optical, and RF methods for underwater communication. It strategically chooses the most suitable communication technology based on the AUV's movement, optimizing data throughput and reducing energy consumption. This design addresses the challenges of reliable, energy-efficient broadband wireless communication underwater and significantly outperforms existing state-of-the-art methods.

Although the design of multimodal underwater communications was introduced in [88,109], its application to underwater drones is still being developed and presents challenges. These include the complexity of coordinating different communication modes and the potential for increased system costs. Additionally, environmental factors such as water turbidity and temperature can affect the performance of each communication method differently, necessitating adaptive strategies to maintain optimal performance. Despite these challenges, the potential benefits of integrated communication systems make them a promising area for further research and development in underwater exploration and monitoring.

Table 9 summarizes recent works on hybrid and multimodal wireless communication approaches for underwater drones, classifying them by modality (e.g., UWAC–UWOC, UWOC–RF, multimodal), application domains, and associated challenges. The comparison highlights common limitations, including limited optical range, acoustic latency, energy consumption, mobility-induced misalignment, and environmental turbulence. It identifies specific gaps in synchronization, outage reliability, and secure data transfer. This classification offers a structured overview of current research trends and future challenges in developing robust and adaptive underwater communication systems.

Table 9. Modality of hybrid UWC methods for underwater drones: Applications and challenges.

Reference	Modality	Main Application	Challenges
Han et al. [96]	UWAC–UWOC	Real-time video streaming	- Short optical range - Limited equipment installation space - Seamless switching delays
Gauni et al. [97]	UWAC–UWOC	- Cooperative networking - Environmental monitoring	- Multipath fading - Acoustic noise - Limited restrictions in turbid water

Table 9. Cont.

Reference	Modality	Main Application	Challenges
Islam et al. [98]	UWAC–UWOC	■ IoUT framework ■ Energy-aware communication	■ High acoustic energy use ■ Optical scattering ■ Limited endurance
Zhang et al. [99]	UWAC–UWOC	■ Localization and tracking of AUVs	■ Maintaining LoS under mobility ■ Tracking sensitivity ■ Current disturbances
Luo et al. [100]	UWAC–UWOC	■ Adaptive networking ■ Throughput optimization	■ Channel prediction errors ■ Switching inefficiency ■ AUV mobility
Agheli et al. [101]	UWOC-RF	■ Relay-assisted networking ■ Air–sea interface	■ UAV pointing/alignment errors ■ Turbulence ■ High relay energy demand
Ali et al. [102]	UWOC-RF	■ Cooperative relays ■ Secure communications	■ VLC turbulence ■ Salinity/temperature effects ■ BER degradation
Kodama et al. [103]	UWOC-RF	■ High-resolution video ■ Secure optical communication	■ Relay stability ■ Turbidity impact ■ Eavesdropping and confidentiality risks
Li et al. [106]	UWOC-RF	■ Relay-based networking ■ UAV–AUV coordination	■ Optical scattering/absorption ■ UAV pointing errors ■ Outage probability
Bolboli et al. [107]	UWOC-RF	■ IoUT telemetry ■ Cross-interface relays	■ LoRa attenuation underwater ■ Interface reflection ■ Seabed blockage
Zhilin et al. [88]	Multimodal	■ Generalized IoUT framework ■ Multi-mode coordination	■ Multi-mode synchronization ■ Interference ■ Energy overhead ■ Water conductivity effects
Loureiro et al. [109]	Multimodal	■ Energy-efficient networking ■ Adaptive AUV communication	■ Optimum power consumption with AUV ■ Optimal switching for RF/optical ■ Handover decision reliability ■ High data rate ■ Robust interference

3.2. Role of Underwater Drones in Smart Marine Applications

Underwater drones play a crucial role in monitoring the marine ecosystem. Most applications include pollution detection and biodiversity assessment, which are studied.

3.2.1. Pollution Detection

Recent technological advancements in underwater drones have significantly enhanced environmental monitoring capabilities, particularly in pollution detection. Underwater drones can combine multi-sensors, AI-edge computing, and autonomous systems to provide more accurate, efficient, and cost-effective solutions for monitoring pollutants in water [110–114].

Microplastics (MPs) are the most common pollutants in the marine environment. MPs are plastic particles smaller than 5 mm, often too tiny for the naked eye to see. They are widespread in daily life, including in salt, water, and air, and pose a serious threat to

marine ecosystems due to their resistance to natural breakdown and ability to carry toxic chemicals. MPs can enter marine life, potentially disrupting marine ecosystems. Recent work in [110] presented a systematic review of the potential for AUVs to detect MPs in marine environments. Most researchers highlight emerging methods for detecting MPs using AUVs. Spectroscopy, sensors, machine learning, and in situ methods are key for AUV detection. Therefore, AUVs are an attractive platform for in situ detection of MPs with hyperspectral imaging (HSI), electrochemical sensors, and AI-assisted UWOC.

In [111], marine litter could be monitored using UAVs and ROVs in shallow coastal waters. The study tested UAVs and ROVs for monitoring floating, submerged, and seafloor items using artificial plastic plates. It assessed how water conditions (transparency, color, depth, bottom substrate), item characteristics (color and size), and method settings (flight/dive height) influence detection accuracy. As a result of the factors influencing detection accuracy, the study found that floating items larger than 5 cm could be detected with over 90% accuracy at flight heights of up to 20 m, with item color and water color playing a significant role in detection. For submerged items, those larger than 10 cm were best detected with over 90% accuracy at a flight height of 20 m. Water transparency, water depth, and water color were identified as key factors influencing water quality.

In [112], underwater drones were used in field applications to monitor water quality and ecology. They provide three-dimensional data and underwater footage, enabling the mapping of vegetation and the assessment of water-quality variations with depth. ROVs can be equipped with deep learning systems for environmental monitoring [113]. Using YOLOv4 neural network architectures, these ROVs can effectively detect underwater rubbish. The integration of image enhancement and noise reduction techniques improves detection accuracy, enabling real-time analysis and recognition of pollution. In [114], advancements of the aerial-aquatic speedy scanner (AASS) can effectively address limitations in current monitoring technologies, thereby improving pollution detection in aquatic environments. It combines high-quality image capture with super-resolution reconstruction (SRR) and an improved YOLOv8 detection network, significantly boosting detection accuracy.

The role of underwater drones extends beyond mere detection; they are also instrumental in monitoring marine litter, as noted in [110–114]. By tracking and analyzing the accumulation of marine debris, underwater drones support efforts to preserve marine environments.

3.2.2. Biodiversity Assessment

Underwater drones have become a transformative tool for biodiversity assessment [115–119], providing innovative solutions to the challenges posed by traditional methods. These tools offer a non-invasive, cost-effective, and efficient means of gathering data in aquatic environments, thereby enhancing the ability to track biodiversity and assess ecosystem health. The integration of advanced technologies in these drones enables high-resolution data collection, which is vital for understanding and managing aquatic ecosystems.

Recent studies show the increasing usefulness of underwater drones as effective tools for biodiversity assessment across various marine and freshwater ecosystems. On coral reefs, semi-autonomous vehicles equipped with stereo-video cameras produced biodiversity metrics that were largely comparable to those from diver surveys, though with distinct detection biases related to body size and species richness [115]. In multi-use marine protected areas, ROVs offered non-destructive, cost-effective assessments that confirmed protection benefits in terms of fish abundance and diversity [116]. Figure 11 illustrates the Genneino T1 ROV model, used to monitor fish in reservoirs [116]. In freshwater reservoirs,

ROV surveys revealed depth-related patterns in native and invasive fish communities, linking species distributions to bathymetric and environmental gradients [117]. Post-disaster assessments utilized UAVs and ROVs in conjunction to identify megafauna hotspots and substrate associations in affected estuarine and coastal systems, highlighting the importance of multi-platform surveillance in long-term ecological recovery monitoring [118]. Lastly, combining unmanned surface vehicles (USVs), ROV imagery, and multi-metric indices enabled standardized evaluation of benthic habitat quality across various seabed types, making drone-based monitoring more consistent with policy frameworks [119].

Collectively, these works [110–119] demonstrated the versatility of AUVs, ROVs, UAVs, and USVs in detecting biodiversity patterns across different scales and settings. Despite challenges such as turbidity, detection biases, and limited short-term data, combining multi-platform drone technologies with ecological indices offers a scalable and consistent approach to biodiversity monitoring. We emphasize the potential of underwater drones to become essential tools for ecosystem assessment, conservation efforts, and adaptive marine management in the era of smart marines.



Figure 11. ROV model Genneino T1 used for monitoring fish in reservoirs [116].

For underwater wireless communication systems suitable for underwater drones used in monitoring and environmental conservation missions, UWAC systems can be employed, providing low-data-rate telemetry that is well-suited for relaying data from distributed drone sensors and fixed nodes within the monitoring network. Meanwhile, the implementation of the UWOC system can support short-range, high-capacity data transfer, making it suitable for detecting oil spills, plastics, and chemical waste, enabling underwater drones to transmit visual evidence of polluted areas effectively.

For biodiversity assessments, including coral reef health [115], fish assemblages [116], and benthic habitat quality [117], high-throughput communication is essential, as it enables the transmission of video and imaging data from underwater drones. Therefore, UWOC is the most suitable choice for transmitting HD imagery and stereo video in clear-water habitats, which is crucial for species recognition and habitat mapping.

3.2.3. Oil and Gas Exploration

ROVs and AUVs play a vital role in oil and gas exploration. ROVs are equipped with high-definition cameras and manipulator arms, enabling precise inspections and maintenance of offshore infrastructure, including pipelines and platforms [24,25]. In contrast, AUVs operate independently to gather data on seabed topography and marine life, making them essential for mapping potential hydrocarbon reservoirs and monitoring environmental impacts. To ensure reliable control and data transmission in complex underwater environments, these systems utilize hybrid communication architectures combining UWAC

for long-range telemetry, UWOC for high-speed data transfer and video streaming, and URFC for short-range command and localization. These links are often integrated with surface buoys, USVs, and LEO satellite relays, enabling real-time monitoring and remote decision-making from onshore control centers [26]. Advanced subsea networks developed by industry leaders such as Schlumberger further enhance these operations by coupling sensor data with digital-twin analytics for predictive maintenance and production optimization [24]. Routine AUV/ROV inspections detect corrosion, leaks, and anomalies before they lead to failure, ensuring the integrity of critical infrastructure and minimizing environmental risks [30]. Collectively, these technologies enhance safety, efficiency, and sustainability in offshore energy exploration and production.

3.2.4. Maritime Security

AUVs and ROVs have become indispensable tools for maritime security and defense operations [31]. They are employed in mine countermeasures (MCM), anti-submarine warfare (ASW), critical infrastructure protection, and harbor surveillance. AUVs equipped with synthetic aperture sonar (SAS), multibeam sonar, magnetometers, and high-definition cameras can autonomously detect, classify, and identify mines or underwater threats over large areas [32]. In security operations, ROVs perform hull and keel inspections, port sweeps, and protection of subsea cables or pipelines. Reliable hybrid communication systems by combining UWAC for long-range control, UWOC for high-speed imagery transfer, and URFC for short-range coordination that ensure connectivity with surface buoys, USVs, UAVs, and LEO satellite relays for real-time command and data fusion [33].

Recent research focuses on AI-enabled autonomy [2,3], swarm coordination [4], and PLS to enhance situational awareness while minimizing communication latency and detection risk [9]. These advances enable persistent surveillance, rapid response, and the protection of national maritime assets, making underwater drones a cornerstone of next-generation naval and coastal security systems.

3.3. Cybersecurity and Eavesdropping Risks in Underwater Networks

Cybersecurity is emerging as a fundamental requirement for underwater communication networks [120], particularly as unmanned underwater vehicles (UUVs) and fixed sensor nodes increasingly exchange mission-critical data for scientific, commercial, and defense operations. Among the various cyber threats [121], eavesdropping represents one of the most pervasive risks. Due to the broadcast nature of underwater acoustic channels, adversaries equipped with passive hydrophones can intercept signals over long distances without revealing their presence, making acoustic communications highly susceptible to covert surveillance [122,123]. In UWOC and URFC-based underwater systems, interception remains possible at shorter ranges, especially when links are weakly secured or poorly aligned [7,68].

Traditional cryptographic solutions used in terrestrial networks are challenging to apply underwater because of limited bandwidth, high propagation delay, high bit-error rates, and energy-constrained nodes, which restrict the use of heavy encryption and frequent key exchanges [120]. As a result, eavesdroppers may extract sensitive navigation data, control commands, environmental measurements, or classified information, potentially compromising mission integrity or enabling hostile situational awareness [124]. To mitigate these risks, researchers are exploring lightweight encryption [123], PLS techniques [125], secure modulation [39], and covert communication strategies that exploit channel characteristics to enhance confidentiality without increasing overhead [120]. Strengthening cybersecurity against eavesdropping is therefore essential for ensuring resilient and trustworthy underwater drone communication networks.

4. Enabling Technologies for Underwater Drone Communication Networks

Reliable, efficient, and scalable communication between underwater drones and other network entities requires multiple technological components that span the physical, link, and system layers. To support autonomous mission execution, cooperative operations, and end-to-end data exchange across underwater, surface, aerial, and satellite domains, a range of enabling technologies must jointly operate to overcome the unique constraints of the underwater environment. This section provides an overview of the key enabling technologies that empower modern underwater drone communication networks, including physical-layer techniques, MAC and network layer mechanisms, localization and synchronization, power and energy management, intelligent and adaptive systems, and emerging hybrid technologies.

4.1. Physical Layer Enabling Technologies

Effective physical-layer (PHY) technologies are essential for establishing reliable underwater communication links under dynamic and harsh ocean channel conditions. These technologies aim to optimize data transmission, mitigate channel impairments, and ensure signal robustness across varying environmental scenarios [125,126].

In [125], Junejo et al. provided a review of PHY enabling technologies for underwater communications, focusing on enhancing link robustness, improving spectral efficiency, and mitigating interference within the constraints of underwater channels. Core enabling techniques include modulation and coding schemes, adaptive waveform design, channel equalization, PLS, and the use of diverse transmission media.

Modulation and coding techniques [39,51,72,81] play a central role in enhancing communication reliability and efficiency. Non-coherent modulation schemes such as frequency shift keying (FSK) and differential phase shift keying (DPSK) are widely adopted due to their resilience to phase distortion and Doppler effects. Meanwhile, coherent schemes such as phase shift keying (PSK), QAM, and multicarrier approaches, including OFDM, can support higher data rates under favorable channel conditions. Channel coding (e.g., Turbo, LDPC, convolutional codes) further strengthens resilience by enabling error detection and correction [127].

Adaptive waveform and channel equalization techniques enhance PHY performance by dynamically adjusting transmission parameters in response to variations in the channel. Equalization strategies compensate for multipath and delay spread, while filter bank multicarrier systems based on offset quadrature amplitude modulation (FBMC/OQAM) in underwater acoustics schemes improve packet reliability [128].

PLS is a crucial capability that leverages channel characteristics for authentication and confidentiality [125]. Techniques such as cooperative jamming, artificial noise, and channel-based key generation enhance data protection without heavy cryptographic overhead, making them suitable for resource-constrained underwater nodes.

Medium-specific enabling technologies also contribute to PHY performance. UWAC remains the most prevalent due to long propagation ranges, while UWOC links enable high data rates over short distances with low latency. URFC and MI communication provide short-range alternatives when UWAC or UWOC links are unsuitable, especially in turbid or noisy environments. MI communication [90–94], in particular, offers robustness in conductive seawater and confined environments such as ports, pipelines, or submerged structures, and is gaining increasing research interest for underwater drone operations.

To support multi-domain missions, hybrid PHY solutions are emerging that combine two or more media, such as UWAC, UWOC, or URFC-MI, to enable adaptive switching or simultaneous data transfer. Such hybrid PHY designs improve link reliability and

mission flexibility, especially when operating across varying depths, water conditions, or structural environments.

4.2. Medium Access Control and Network Layer Technologies

Medium access control (MAC) and network layer technologies are essential for coordinating access to the shared underwater communication medium and enabling reliable data delivery across multi-hop and heterogeneous underwater drone networks. These technologies aim to optimize channel utilization, minimize collisions and latency, and ensure end-to-end connectivity in dynamic underwater environments [129].

In [129], Jiang S. described that MAC technologies for underwater communication must consider long propagation delays, low bandwidth, and the spatial–temporal variability of the underwater channel. Traditional terrestrial MAC schemes, such as carrier-sense multiple access/collision avoidance (CSMA/CA), perform poorly underwater because of high latency and collision risks. Therefore, underwater-optimized MAC protocols have been developed, including ALOHA-based, reservation-based, TDMA, CDMA, and hybrid MAC schemes. ALOHA-based and contention-free MAC variants are ideal for sparse networks with low traffic, while TDMA and CDMA mechanisms offer structured access for deterministic or high-traffic scenarios. Hybrid MAC approaches combine contention-based and scheduled access to strike a balance between flexibility and efficiency.

At the network layer, routing protocols are critical for supporting multi-hop communication among underwater drones, surface nodes, and gateways. Geographic, depth-based, vector-based, and cluster-based strategies are widely explored to cope with mobility, dynamic topology, and intermittent connectivity. Delay/disruption tolerant networking (DTN) [130] is particularly relevant, as it tolerates link instability and provides store–carry–forward mechanisms for reliable data transfer in sparse or intermittently connected underwater networks. Cross-layer approaches that jointly optimize MAC and routing decisions enhance performance by adapting to changes in channel state, mobility, and energy availability.

To support large-scale IoUT deployments, Zhu et al. [54] described adaptive network layer protocols that leverage real-time link quality estimation, mobility prediction, and autonomous path selection. Networking for autonomous underwater drones requires support for mission-task routing, where communication paths adapt to mission objectives, drone roles, and environmental context. QoS strategies ensure differentiated service for mission-critical, safety-related, and bulk data transmissions.

Interoperability among underwater, surface, aerial, and satellite segments further increases network complexity [31,78]. Multi-domain networking frameworks enable seamless data exchange across these domains by integrating UWAC, URFC, UWOC, and MI-based links into a unified routing and coordination architecture. Heterogeneous network gateways, such as USVs acting as relay nodes, provide protocol translation, buffering, interface management, and cross-domain routing. These mechanisms are essential for achieving reliable and scalable communication in collaborative maritime operations involving multiple autonomous assets [54,129,130].

4.3. Localization and Synchronization Technologies

Accurate localization and synchronization [131] are essential for coordinating underwater drone operations, enabling navigation, data fusion, and cooperative mission execution. Since GPS signals do not propagate underwater, specialized techniques are required to determine the position, orientation, and timing of underwater platforms.

In [132], Miller et al. described how localization technologies for underwater drones can be broadly classified into acoustic positioning systems, vision-aided navigation meth-

ods, and cooperative or algorithmic localization techniques. Acoustic positioning systems, including long baseline (LBL), short baseline (SBL), and ultra-short baseline (USBL), are widely used for high-precision localization. LBL provides high accuracy over large areas using seabed transponders, while USBL and SBL systems are installed on vessels or surface platforms for real-time tracking. Doppler velocity logs (DVL) and inertial navigation systems (INS) are frequently integrated to enhance dead reckoning and improve localization accuracy, especially in dynamic environments. Simultaneous localization and mapping (SLAM) techniques, which leverage sonar, optical, or inertial measurements, enable AUVs to construct maps of unknown environments while simultaneously estimating their own position.

In [133], Shams et al. described that time synchronization is crucial for effective coordination, sensor fusion, and communication scheduling among underwater nodes. Synchronization is typically achieved through acoustic signaling, with protocols designed to minimize the impact of long and variable propagation delays. Mobility-aware and clock-drift compensation methods are increasingly employed to maintain synchronization accuracy. Recent advancements leverage machine learning (ML) and cooperative exchange of timing information to improve synchronization robustness without increasing signaling overhead [134].

4.4. Energy and Power Management Technologies

Effective energy and power management technologies are critical for extending mission duration, supporting long-term deployments, and ensuring operational reliability of underwater drones and sensor networks [135]. Due to limited battery capacity and the high cost of retrieval or recharge, underwater systems require energy-efficient communication, sensing, processing, and mobility strategies.

Energy-efficient hardware design [46] and power-aware communication protocols [91] form the foundation of underwater energy management. Low-power modem architectures, adaptive transmission power control, and sleep-wake scheduling significantly reduce energy consumption. Duty cycling, topology control, and traffic-aware scheduling further extend network lifetime. Energy-aware routing techniques also balance load across multiple nodes to avoid early depletion of critical relays [101].

In [136], Khan et al. described that energy harvesting technologies have emerged as promising solutions to support persistent underwater operations. Surface-tethered or hybrid drones can harvest solar or wind energy at the surface, while seabed stations can utilize ocean thermal, wave, or microbial fuel cell energy sources for recharging. Underwater charging docks and contactless inductive charging platforms are being increasingly developed to enable AUVs to autonomously replenish their energy without human intervention, allowing for long-endurance missions and persistent surveillance.

In [137], Yang et al. discussed that an energy-optimized and tracking control method is closely linked to mission planning for AUVs. Intelligent energy budgeting allocates resources based on mission priority, environmental conditions, and expected link quality. Computational offloading to surface or edge nodes, along with adaptive sensing, reduces onboard processing loads, conserving energy for critical tasks. With increasing autonomy, energy-aware AI-based decision-making allows underwater drones to optimize navigation paths, communication schedules, and sensing frequency based on predicted energy consumption and mission value.

4.5. Intelligent and Adaptive Technologies

Intelligent and adaptive technologies are increasingly integrated into underwater drone systems to enhance autonomy, communication efficiency, and mission resilience.

These technologies enable underwater networks to dynamically respond to changing environmental conditions, channel variations, and operational requirements without relying on continuous human intervention [138].

AI and ML techniques support adaptive decision-making across communication, navigation [139], and coordination functions. ML-driven channel prediction models improve communication reliability by anticipating channel fluctuations and proactively adjusting transmission parameters. Cognitive communication approaches enable underwater drones to sense the communication environment and autonomously select the most suitable communication modality, such as UWAC, UWOC, URFC, or MI, based on range, turbidity, bandwidth requirements, and energy availability. Adaptive data compression, semantic communication, and event-triggered data reporting further optimize bandwidth usage by prioritizing mission-relevant information [140].

At the network level, AI facilitates cooperative mission planning, swarm coordination, and multi-agent communication strategies. Distributed intelligence enables underwater drones to share situational awareness, jointly avoid obstacles, and coordinate sensing or mapping tasks. In [141], Popli et al. described that edge computing and an FL framework for enhanced data security and cyber intrusion detection approaches bring computation closer to underwater drones, reducing reliance on surface-based processing and minimizing communication overhead. These technologies enable models to be trained or updated locally, enhancing autonomy and protecting data privacy.

Self-optimization and self-healing capabilities also enhance network resilience. Autonomous reconfiguration of communication topology, rerouting around failed nodes, and predictive maintenance of hardware components reduce downtime and increase mission continuity [138–141]. As underwater networks evolve toward greater autonomy, intelligent and adaptive technologies will play a foundational role in enabling persistent, efficient, and resilient multi-domain marine operations [2,24,26,31].

4.6. Emerging and Hybrid Enabling Technologies

Emerging and hybrid enabling technologies [142] are expanding the operational scope, performance, and reliability of underwater drone communication networks. These technologies integrate new communication modalities, multi-domain connectivity, and advanced system concepts that bridge underwater, surface, aerial, and satellite platforms.

MI communication has gained growing attention as a complementary method for underwater communication [88,90–94]. MI systems utilize low-frequency magnetic fields to transmit data over short to medium ranges. They are particularly effective in conductive seawater, confined environments, and areas with high acoustic noise or optical attenuation. MI communication is well-suited for operations near submerged structures, pipelines, harbors, or under ice. Recent developments demonstrate its potential for low-latency command and control, localization, and robust short-range data exchange for autonomous underwater vehicles [90].

Hybrid communication solutions combine multiple media, such as UWAC-UWOC [98–100] and UWAC-RF [101–103,106,107], along with multimodal approaches [88,109], to leverage their complementary strengths. For example, optical links provide high data rates for short-range data transfer or data offloading, while acoustic links enable long-range connectivity. Thus, MI communication links serve as a reliable alternative communication channel in environments where UWAC or UWOC signals are degraded or unavailable. These hybrid approaches allow dynamic switching between communication modes based on environmental conditions, bandwidth demands, energy constraints, or mission priorities, significantly improving communication availability and robustness.

Interoperability across domains is further strengthened by emerging technologies that integrate underwater networks with maritime, aerial, and satellite systems. USVs often serve as gateways, bridging UWAC or MI communication links with terrestrial cellular, Wi-Fi, or LEO satellite networks. LEO satellite constellations, non-terrestrial 5G networks, and maritime mesh systems expand the reach of underwater networks beyond local areas, enabling real-time monitoring and global data exchange [31,143].

Digital twin (DT) concepts are increasingly applied to underwater systems, enabling real-time mirroring of physical assets and processes in a virtual environment [144]. DTs enhance predictive maintenance, operational planning, and training for underwater missions. In addition, semantic communication, where transmitted data is compressed based on meaning rather than raw content, is emerging as an efficient strategy for underwater AI-enabled networks, reducing bandwidth use while preserving mission-critical information.

Collectively, these emerging and hybrid technologies represent the next evolutionary phase of underwater communication, enabling greater autonomy, resilience, and integration of underwater drone networks into broader multi-domain communication ecosystems.

5. Research Directions

Building on hybrid underwater communication systems, the next generation of underwater drone networks must evolve into intelligent, immersive, and interconnected architectures. This section highlights four key research areas—IoUT, AI-driven data, VR, and DT—that collectively shape the future of marine communication systems.

5.1. IoUT

Kabanov et al. [145] introduced marine IoT (MIoT) platforms, including IoUT for interoperability of marine robotic agents. The robotic agents include AUVs, ROVs, active and passive marine sensors, buoys, underwater sonar stations, coastal communication posts, and other components of the platform. It is necessary to use a hybrid communication system within the platform. Therefore, the integration of underwater drones into the IoUT platforms marks a paradigm shift in marine communication and exploration [146]. This solution creates a dynamic, intelligent network of interconnected devices capable of autonomous data collection, real-time processing, and seamless communication across aquatic, surface, and aerial domains [147]. AUVs or ROVs can serve as the mobile backbone of the IoUT. In [148], Wei et al. presented an AUV-assisted magnetic induction and acoustic hybrid IoUT, in which the AUV served as the central data-collection point for IoUT sensors, resulting in a power-efficient system. In this context, AUVs can be highly beneficial for IoUT applications.

Mohsan et al. [149] and Adam et al. [124] introduced the latest IoUT frameworks. They outline data accuracy, transmission efficiency, and security, which are essential for effective deployment. The IoUT extends the terrestrial IoT, forming a network of smart, interconnected underwater objects. Additionally, IoUT is a connected multi-sensor system for an underwater network model [150].

Later, Mohsan et al. [151] introduced the role of AUVs in IoUT. The advantages of IoUT greatly enhance AUV capabilities by enabling real-time data collection and communication. AUVs serve as essential components within the IoUT framework, providing mobility and enhanced energy storage capabilities compared to traditional sensor nodes. They can connect sensors to other devices or the internet, supporting various applications such as environmental monitoring and naval surveillance. However, challenges like latency and communication reliability remain significant concerns for the effective use of IoUT with underwater drones.

5.1.1. Communication Technologies and Challenges

IoUT networks depend on various communication technologies, including UWAC, UWOC, and UWOC-RF, as well as magnetic induction-based solutions, to ensure reliable data transmission. Each technology has its advantages and limitations, such as range, bandwidth, and energy use, which must be considered when designing IoUT systems. Including IoUT, aided by intelligent reflection surfaces (IRS), presents a challenge for underwater communication [127]. Interestingly, Nkenyereye et al. [152] noted that the integration of 5G technology with AUVs and IoUT is still in its early stages, but it shows potential to improve communication capabilities. Simulation tools are being used to explore the feasibility of 5G-based AUV-IoUT networks, addressing latency, bandwidth, and energy constraints through hybrid UWOC-RF networking.

5.1.2. Energy Efficiency and AUV/ROV Assistance

The harsh underwater environment poses significant challenges for energy management in IoUT networks. Battery-operated sensor nodes are difficult to replace or recharge, necessitating energy-efficient solutions. AUVs/ROVs can assist by providing energy-efficient wake-up solutions that activate underwater sensor nodes on demand, thereby conserving energy [153]. Energy-efficient routing architectures, such as the AUV-assisted optimization approach, have been proposed to enhance data collection from underwater sensor nodes [154]. These architectures use energy-harvesting nodes and AUVs to mitigate the hot-spot problem and extend the network's operational period.

5.1.3. Data Management and Big Marine Data

The IoUT generates large amounts of data, known as big marine data (BMD), which presents challenges for processing and analysis. At the data plane, AI-powered data solutions are being explored to handle the volume, speed, and diversity of data, enabling efficient knowledge extraction and decision-making [147]. While blockchain acts as a backend for data management and security of BMD, Blockchain IoT (BIoT) and marine IoT (MIoT) are expanding IoUT solutions [155]. The main features of BMD include sensors, cameras, tags, aerial remote sensing, and various interdisciplinary data types, such as physical, chemical, biological, environmental, and economic data. However, developing IoUT-based BMD remains a significant challenge.

5.1.4. Applications and Future Directions

IoUT has a broad range of applications, including naval surveillance, natural disaster prevention, archaeological expeditions, and environmental monitoring. The technology is set to revolutionize industries such as oil and gas exploration and maritime security [156]. Future research directions include developing standardized communication protocols, energy-efficient data routing techniques, and advanced AI-driven data processing for BMD [157], as well as creating a reliable delay-sensitive communication mechanism [158]. These advancements will improve the resilience and efficiency of IoUT networks, enabling more extensive and dependable underwater exploration. While integrating IoUT with AUVs/ROVs offers significant potential, it also presents challenges that must be addressed to realize its full capabilities. Energy efficiency [154], communication reliability [159,160], and data management are critical areas requiring ongoing research and innovation. As the field progresses, developing standardized protocols and advanced technologies will be key to overcoming these challenges and unlocking the full potential of AUV-assisted IoUT for underwater exploration and monitoring.

5.2. AI-Driven Data

The integration of AI-driven data is significantly enhancing the capabilities of underwater drones, enabling more efficient and autonomous operations in challenging marine environments. AI-driven data for underwater drones is being utilized to enhance navigation, control, perception, and environmental monitoring, addressing key challenges such as energy constraints, complex underwater terrains, and data processing limitations. We examine the diverse applications and innovations of AI-driven underwater drones, focusing on their impact on ocean exploration, environmental protection, and search and rescue (SAR) operations.

5.2.1. Autonomous Navigation and Control

AI technologies are being integrated into underwater drones to enhance navigation and control in complex marine environments. These systems employ model learning, advanced control techniques, and perception capabilities to operate autonomously, even in dynamic and unpredictable conditions [161]. The use of AI planning frameworks improves the autonomy of underwater drones by generating efficient action sequences for subsea operations [162].

5.2.2. Environmental Monitoring and Protection

AI-powered drones are being developed to explore and protect waterways by collecting data on water quality and pollution levels. These drones are equipped with cameras and sensors for data collection and can identify and clean contaminated waste using object detection and AI-controlled movement [162]. Additionally, AI-driven underwater drones are used for large-scale mapping and monitoring the health and disease status of ocean organisms, contributing to environmental impact assessments and sustainable marine resource management [163].

5.2.3. Search and Rescue Operations

AI-driven underwater drones are utilized in SAR missions [164], employing LiDAR sensors, SLAM algorithms, and deep learning for real-time environment mapping and navigation. These drones can autonomously explore new areas and make informed decisions, helping identify and locate objects or people underwater. Benchmarking You Only Look Once (YOLO) models for marine SAR under various weather conditions using the SeaDronesSee and AFO datasets is discussed in [165]. This challenge demonstrates that YOLOv10 and YOLOv11 provide faster inference speeds, albeit with a slight reduction in precision for marine object detection in SAR missions.

5.2.4. AI-Driven Underwater Drones

One significant challenge for underwater drones is limited endurance due to energy constraints. Innovations such as wireless power transfer [46] and energy-efficient AI models [137] are being explored to overcome these limitations, enabling longer and more sustainable operations. Meanwhile, underwater environments pose challenges for data processing and communication due to limited bandwidth and computational resources. Lightweight AI models, designed for efficiency and robustness [166], are being developed to function effectively in these extreme conditions. Techniques such as a lightweight two-stage underwater structural damage detection model and a low-light marine image enhancement model are used to optimize AI models for underwater applications [167–169].

AI-powered underwater drones have made significant progress in autonomy and efficiency; however, challenges persist, including the need for more robust and explainable AI models, increased data availability, and overcoming hardware limitations. Future research

includes developing self-healing systems [170], combining AI with emerging technologies such as blockchain and FL [171], and exploring new applications in environmental monitoring and disaster response.

5.3. VR and Digital Twin

The integration of VR and DT technologies in underwater drones for wireless communication presents a transformative approach to enhancing smart tourism. These technologies provide immersive experiences and efficient management of underwater environments, which are essential for activities such as diving and exploring underwater cultural heritage sites. Utilizing VR and DT in underwater drones not only enhances their operational capabilities but also improves the tourist experience by providing real-time data and interactive environments.

5.3.1. Digital Twin Technology in Underwater Drones

DT systems enhance teleoperation and navigation by providing a dynamic view of the underwater drone, thereby improving situational awareness and reducing operator workload. This facilitates more straightforward navigation through complex underwater terrains [172–174]. For instance, projects like SUSHI DROP utilize DT to develop precise digital replicas of underwater ecosystems, supporting sustainable fishing and environmental monitoring. Such methods are vital for smart tourism as they help conserve marine life while enabling safe exploration for tourists. Moreover, integrating DT with IoUT networks enables the real-time monitoring and management of underwater environments, leveraging federated learning models that enhance data privacy and model precision—key factors for protecting tourist sites [175]. The integration of advanced communication systems, including IoUT, VR, AR, AI-driven data, and underwater drones, lays the groundwork for a new marine industry built on a DT-CPS platform [176].

5.3.2. VR Applications

In [177], Li et al. proposed that a VR-based docking station is an important solution for controlling and navigating AUVs. This expansion aims to equip the VR with additional functions, enabling it to address hazardous conditions or challenging situations that AUVs may encounter in real-world scenarios. The future direction involves enhancing the on-line AUV simulator with VR diagnostic features, providing tools to mitigate hazardous underwater scenarios, and ultimately improving the safety and efficiency of AUV operations. Moreover, the use of VR offers archaeologists and the public a new perspective on reconstructed archaeological sites, allowing for direct analysis of virtual sites and immersive exploration [178]. VR technology enables the creation of virtual diving experiences, allowing tourists to explore underwater sites without the need for physical diving. This is particularly beneficial for sites that are difficult to access or require preservation.

5.4. AI and Digital Twin Implementation

The integration of AI and DT technologies is expected to play a transformative role in the evolution of underwater communication systems and autonomous marine operations. As underwater drone networks become more complex and mission-critical, AI-driven decision-making and DT-based virtualization offer promising pathways to enhance adaptability, resilience, and operational efficiency across diverse maritime environments. The following research directions outline key opportunities for advancing AI and DT implementations within underwater drone communication networks [140,174].

AI provides the potential to significantly enhance communication performance, autonomy, and network intelligence in underwater systems [19,26,28,33]. Future research should focus on developing AI-enabled channel prediction models capable of estimating

underwater channel dynamics [100], such as multipath effects, Doppler spreading, and environmental variability, to support proactive modulation [49,51], coding, and routing adjustments [153]. ML-driven cross-layer optimization could further enhance QoS, allowing underwater drones to adjust communication parameters with minimal human intervention autonomously. AI-based cooperative routing [165,166] and mobility-aware network control offer promising research avenues for enhancing connectivity in dynamic multi-AUV networks, particularly during collaborative missions, environmental monitoring operations, and time-sensitive SAR scenarios.

Advancements in edge AI and FL present additional opportunities to enable distributed learning and decision-making within underwater networks. Due to limited bandwidth and energy constraints, traditional centralized AI training is inefficient for underwater systems [171]. Future research should explore lightweight ML models that can be trained locally on resource-constrained AUVs while maintaining high inference accuracy. FL approaches [167] may allow multiple underwater nodes to collaboratively update AI models without exchanging raw data, improving privacy, energy efficiency, and communication overhead. Another promising direction is semantic communication, where AI is used to transmit only mission-relevant information rather than raw data, thereby reducing bandwidth usage and improving efficiency in low-capacity underwater links.

DT technology [172] offers a complementary yet distinct research pathway for underwater drone communication networks by providing a virtual representation of physical assets, communication processes, and mission environments. DT-based mission rehearsal environments can enable pre-deployment scenario testing and optimization, allowing operators to simulate communication performance, vehicle coordination, and ecological influences before execution. Additionally, DTs can support real-time system monitoring and predictive maintenance by forecasting component degradation, detecting network anomalies, and suggesting corrective actions [173].

AI-DT convergence represents a high-impact research direction, enabling closed-loop optimization for underwater drones [174]. Future studies should explore architectures where DTs continuously feed real-time system state information into AI models for adaptive control. At the same time, AI enhances DT fidelity by learning from real mission data. This model could facilitate self-healing communication networks, autonomous fault recovery, and continuous performance optimization in large-scale IoUT deployments. Integrating DT with hybrid communication networks, including UWAC, UWOC, URFC, and MI communication links, also presents new opportunities for performance benchmarking, interoperability enhancement, and multi-domain coordination [175,176].

Overall, AI and DT represent promising research directions for advancing autonomous, resilient, and scalable underwater drone communication networks. Their effective integration will play a crucial role in shaping the next generation of intelligent marine systems.

5.5. Integration of Underwater Drones, IoUT, AI, VR, and Digital Twin in Smart Marine Communications

The integration of underwater drones, IoUT, AI, VR, and DT into smart marine systems marks a significant step forward in marine technology. This integration aims to improve the efficiency, accuracy, and sustainability of marine operations by utilizing advanced technologies. Combining these tools enables better data collection, analysis, and communication in challenging underwater environments, supporting applications such as environmental monitoring, resource exploration, and the management of marine ecosystems [1–3,26,34].

Underwater drones play a crucial role in marine exploration and monitoring [117–126]. They can be equipped with IoUT [54,127–137] and AI-driven data [154–170], which enhance their adaptability and efficiency in complex marine environments. Underwater drones equipped with IoUT capabilities can monitor water quality, pollution levels, and marine

Figure 12 illustrates the challenges of integrating a hybrid communication framework for underwater drones, IoUT, AI-driven data centers, VR platforms, and DT technologies, including UWAC, UWOC, and URFC, using UAV relays, LEO satellites, and terrestrial 5G/6G networks. It also combines underwater, surface, aerial, and terrestrial networks into a seamless ecosystem for real-time, resilient, and adaptive connectivity. Underwater layers, ROVs, AUVs, and IoUT sensors communicate via UWAC for long-range control and UWOC for high-throughput data transfer. While IoUT nodes extend coverage for environmental sensing and collaborative AUV missions, enabling distributed monitoring of ecosystems, infrastructure, or defense zones. Surface layers, including several vessels and buoy sensors as communication gateways, forward underwater data streams to the surface, where URFC links provide short-range, rapid control, and UWOC-RF hybrids enhance performance in mixed conditions. Aerial layers, such as UAVs with A2A and G2A links, serve as agile, mobile relay nodes that reduce latency and expand coverage. Meanwhile, LEO satellites offer wide-area connectivity, linking offshore assets to global data centers. This enables remote mission control and real-time situational awareness across ocean basins. On the terrestrial and cloud layers, 5G/6G infrastructure [180] provides high-capacity backhaul for data-heavy missions. AI-driven data centers process large data streams, optimizing routing, error correction, and decision-making. DT models simulate marine operations, supporting predictive maintenance, scenario rehearsal, and resilience planning. Meanwhile, VR interfaces offer immersive monitoring for operators, enabling applications in tourism, defense, and offshore industries.

6. Conclusions

This study examined the enabling technologies, opportunities, and challenges related to underwater drone-enabled wireless communication systems for smart marine communications. By analyzing acoustic, optical, RF, and MI communication methods, we highlighted their strengths and inherent limitations, as well as the need for hybrid frameworks to achieve reliable, low-latency, and high-throughput performance across various aquatic conditions. The integration of underwater drones, IoUT, AI-driven data, VR, and DT technologies offers a transformative path toward more autonomous, adaptable, and intelligent marine operations. Our findings emphasize that while UWAC remains vital for long-range missions, UWOC systems provide unmatched bandwidth for high-resolution sensing, and URFC or MI communication links offer valuable low-latency control over short distances. Hybrid and multimodal solutions, such as UWAC-UWOC and UWOC-RF integrations, will be essential to ensuring resilience and scalability in future underwater drone systems. Additionally, cross-domain connectivity via surface buoys, UAVs, and LEO satellites is a crucial enabler for seamless integration among the undersea, surface, and space domains.

Future developments, such as channel modeling for space–air–ground–sea integrated networks (SAGSIN) [181], AI-driven channel estimation, and energy-efficient multimodal architectures, will be essential for addressing the evolving challenges in marine environments. These advancements will accelerate the development of intelligent marine ecosystems, enabling applications such as environmental monitoring, offshore energy operations, maritime safety, defense, and smart tourism. Over time, underwater drones equipped with intelligent hybrid communication systems will play a key role in shaping the future of ocean exploration, resource management, and sustainable marine growth.

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