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REVIEW

Underwater Acoustic Communication: Technology Advances for Practical Marine Applications

Botao Xie [1], *Bigui Huang* [1]*, *Tao Liu* [1], *Jiwen Song* [2], *Feida Zhao* [2]

[1] *China National Offshore Oil Corporation Research Institute, 100024 Beijing, China*

[2] *China National Offshore Oil Corporation Information Technology, 100010 Beijing, China*

ABSTRACT

Key areas such as marine resource exploration, real-time monitoring of ecological environments, and national defense security systems urgently require reliable underwater information transmission capabilities as a foundation. Underwater acoustic communication (UAC), leveraging its unique advantages as the most effective method for long-range data transfer in aquatic environments, has become an indispensable enabling technology for supporting these core applications. This review systematically examines recent advancements in UAC technology and their critical role in enabling modern marine initiatives. The analysis covers key developments in both non-coherent and coherent communication systems, including single-carrier and multi-carrier modulation schemes such as OFDM. It highlights their respective advantages in terms of robustness and high-data-rate transmission. The significant impact of challenging underwater channel characteristics, notably severe multipath fading, time-varying Doppler shifts, limited bandwidth, and environmental noise, is discussed alongside corresponding mitigation strategies. Furthermore, the integration of machine learning for sophisticated channel estimation, adaptive equalization, and intelligent system optimization is explored as a promising frontier. Emerging technologies like spread-spectrum, full-duplex, and covert UAC are also evaluated for their potential in specialized and high-stakes applications. The paper concludes by identifying persistent challenges, including

*CORRESPONDING AUTHOR:
Bigui Huang, China National Offshore Oil Corporation Research Institute, 100024 Beijing, China; Email: frhbg2025@163.com

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regulatory constraints, physical-layer security issues, interoperability across platforms, and energy efficiency demands. Finally, it outlines future research directions aimed at developing more intelligent, secure, and efficient next-generation underwater networks.

Keywords: Underwater Acoustic Communication; Marine Applications; Channel Characteristics; Coherent Communication; Multi-carrier Modulation

1. Introduction

The ocean accounts for about 71% of the Earth's surface and is the core support for the Earth's life system and human development. Its importance runs through many key areas, such as resource supply, economic support, global governance, and geo-security. From the perspective of resources and economic value, the fishery resources, deep-sea polymetallic nodules, and combustible ice in the ocean directly support the process of global food security and energy transformation. According to OECD data, the contribution of the global marine economy in 2010 reached US$1.5 trillion [1,2]. The European Union regards the "blue economy" as the core growth engine, which is expected to contribute more than 500 billion euros and create 5.4 million jobs each year [3]. In the field of trade and transportation, more than 80% of the world's goods trade depends on sea transportation. Taking the automotive industry as an example, the automotive industry chain of Germany, Japan, and the United States highly depend on intermediate maritime transportation and key channels, such as the Mandel Strait and the Suez Canal. Route risk not only directly affects the industrial cost but also threatens the stability of the supply chain. To avoid the diversion of high-risk channels, the average daily cost of a single vessel may increase by $10,000–$35,000 [4].

From the perspective of global governance and geo cognition, the global ocean observing system (GOOS) has built an ocean "data twin" through satellite, Argo buoy and other technologies, and NASA's "eternal ocean" visualization project relies on its data to present global ocean currents and promote human's global cognition of ocean dynamics. However, even if the coordinating body, the International Olympic Committee, is committed to scientific governance, the system is still affected by geopolitics (such as the suspension of financial support by the United States due to political differences), highlighting the key role of the ocean in connecting scientific objectives with international governance [5]. In addition, the delimitation of the exclusive economic zone and the promotion of the application for the continental shelf under the framework of the United Nations Convention on the Law of the Sea have reshaped the composition of national territory. Disputes such as the "Nine Segment line" in the South China Sea have become the geographical focus due to the demands for resources and sovereignty, which further confirms that the ocean is not only an economic space for resources, but also a core area of the game and rulemaking of major powers [1,6]. It is worth noting that with the continuous extension of the scope of human activities from the coast to the deep sea, whether it is the precise exploration of deep-sea resources, the dynamic guarantee of trans ocean shipping, or the real-time monitoring of the global marine environment, higher requirements are put forward for the supporting technical system, especially in the process of exploring, utilizing and protecting the marine environment, which is increasingly dependent on efficient technical tools [7].

This technical demand is particularly prominent in the field of communication: the normalized application of autonomous underwater vehicles (AUVs) [8], distributed sensor networks and real-time environmental monitoring platforms urgently needs a reliable and efficient underwater wireless communication system as a support, and this demand fundamentally promotes the transformation of human exploration and utilization of the ocean [7]. Among the existing wireless communication schemes, underwater acoustic communication (UAC) is one of the most feasible solutions for medium and long-range underwater information transmission - because electromagnetic waves and light waves will suffer serious attenuation in the aquatic environment (**Table 1**) [9–16], it cannot meet the communication requirements of deep-sea scenes. It can be seen that the maturity of UAC technology directly determines the upper limit of the efficiency of AUVs, distributed sensor networks, and other equipment, which is of key significance in improving the accuracy of marine exploration and ensuring the safety of marine development.

Table 1. Different ways of underwater communication.

Modes	Transmission Rates	Transmission Distance	Influence Factor
Electromagnetic induction	Fast	10 meters	Dielectric constant, conductivity.
Optical	Fast	10–100 meters	The absorption and scattering of light by medium.
Acoustic	Slow	up to 10^3meters	Medium temperature, pressure.

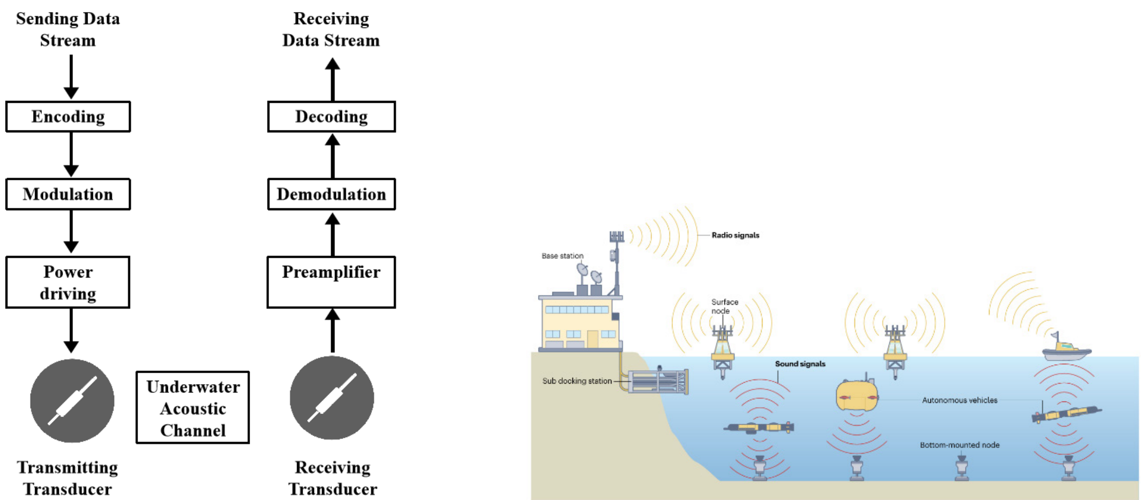
The development of underwater acoustic communication has long been driven by the needs of specific applications. During World War II, underwater acoustic communication technology began to develop due to military requirements. In 1945, the U.S. Naval Research Laboratory developed an underwater telephone based on single-sideband modulation technology for communication between submarines over distances of several kilometers. Since then, the United States has maintained a leading position in underwater acoustic communication technology on the international stage, while countries such as Germany, the United Kingdom, France, and Japan have been accelerating their efforts to catch up. Underwater acoustic communication technology has developed rapidly in the context of the arms race. To date, these countries have multiple manufacturers producing a range of underwater acoustic communication products, which are widely applied in both civilian and military fields. Overall, the technological level has made significant progress compared to several decades ago.

In recent years, extensive research has been conducted internationally on distributed underwater bi-directional communication and sensor networks, with sea trials of acoustic networks conducted to verify schemes and simulate their performance [17]. A prominent example is the Seaweb network developed by the U.S. Navy beginning in the 1990s [18,19]. The Seaweb network is currently the largest practical underwater acoustic network under development, primarily used for underwater battlefield monitoring, ocean remote sensing, and control of underwater unmanned vehicles. It enables high-quality data transmission in harsh shallow-water environments and possesses a certain degree of adaptive organizational capability, allowing it to adjust transmission power based on environmental conditions.

From a practical application perspective, underwater acoustic communication is the most effective means for surface ships [20], submarines [21], and other equipment to achieve two-way information transmission. For example, it enables communication between combat units and between combat units and command ships, ensuring that command ships can direct battlefield operations and issue orders to combat units, or facilitate coordinated operations among combat units. In underwater special operations, underwater acoustic communication can be used as a method of communication between frogmen, frogman transport vehicles, and their mother ships, enabling the exchange of operational information and sharing of the operational situation underwater. This ensures the timely issuance of orders and consistency in team actions, forming an interconnected operational group.

In the civilian sector, underwater acoustic communication is primarily used for marine surveys, marine engineering construction, and the development and utilization of seabed mineral resources [22,23]. In marine surveys, underwater acoustic communication technology can transmit real-time data collected by seabed instruments, significantly reducing the data acquisition cycle while lowering costs effectively. In deep-sea exploration, underwater acoustic communication equipment is an indispensable component of manned deep-sea submersibles [24]. Beyond data transmission, it enables deep-sea divers to maintain real-time communication with surface scientists, enabling them to respond promptly to underwater emergencies and complete scientific research tasks. In the offshore oil extraction industry, underwater acoustic communication equipment is used for monitoring underwater environmental parameters, platform attitude, and earthquake and tsunami prevention, ensuring the safety of construction and extraction sites [25,26].

From a technical implementation perspective, while the UAC system architecture is similar to that of ground-based radio systems, the physical medium is fundamentally different. The UAC system follows an architecture similar to that of ground-based radio communication systems, encompassing signal generation, modulation, transmission, reception, demodulation, and decoding. However, the core distinction lies in the physical medium. As shown in **Figure 1**, unlike ground systems that rely on electromagnetic waves and antennas, the UAC system uses sound waves and sensors converting electrical signals into sound at the transmitter end and reversing this process at the receiver end. This architecture enables communication across complex marine environments, including shallow-water ports, offshore oil fields, and polar sub-ice zones.



(**a**) (**b**)

Figure 1. (**a**) Underwater acoustic communication system; and (**b**) A vision of an underwater acoustic network [17].

From an engineering perspective, the development of underwater acoustic communication has undergone three major technological phases. In the 1940s, analog amplitude modulation (AM) was applied to short-range naval voice telephones. By the 1970s, digital non-coherent modulation methods such as frequency-shift keying (FSK), had become practical solutions for mitigating multipath interference. A landmark example is the digital acoustic telemetry system developed by the Massachusetts Institute of Technology and the Woods Hole Oceanographic Institution in 1981, which achieved a transmission speed of 1.2 kbps at a distance of 200 meters using multi-frequency shift keying (MFSK) [27]. This laid the foundation for low-speed environmental data transmission systems used in moored sensors and profiling floats [28].

The real breakthrough in its performance and application occurred in the late 1980s with the emergence of coherent communication technology, which began to meet the demand for real-time, high-speed underwater data exchange. The decision feedback equalizer (DFE) and digital phase-locked loop (DPLL) solutions proposed by Stojanovic's team in 1993 reduced the bit error rate by two orders of magnitude, thereby enabling the development of early UAC systems with multimedia capabilities [29]. Since then, the trajectory of underwater communications has gradually followed the evolutionary logic of terrestrial systems (**Figure 2**) from analog to digital, from non-coherent to coherent, from single-carrier to multi-carrier modulation, and from point-to-point links to scalable network architectures.

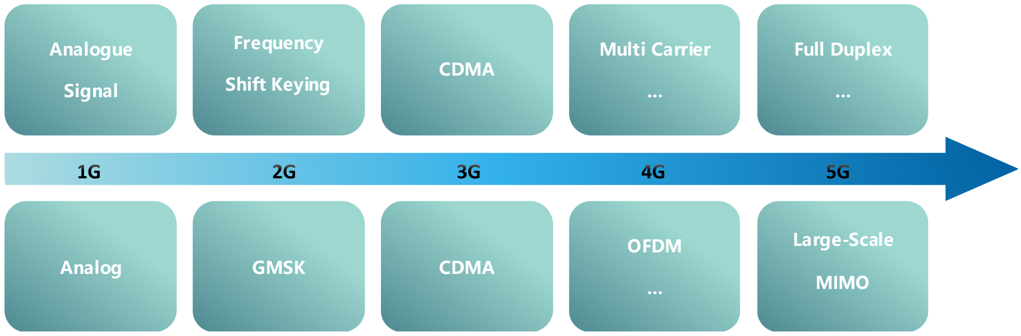


Figure 2. Underwater acoustic communication system.

Recent advances continue to enhance UAC performance across several domains. In signal processing, the integration of time reversal mirror (TRM) techniques with orthogonal frequency-division multiplexing (OFDM) has enabled stable communications with bit error rates as low as 10^{-4} under significant Doppler distortion [30]. In channel coding, modern schemes such as low-density parity-check (LDPC) codes and polar codes improve error correction performance by 3–5 dB [31], promoting reliability in highly dynamic channels [32]. Hardware innovations are equally impactful: the introduction of broadband vector sensors has expanded usable bandwidth beyond 60 kHz while reducing power consumption by up to 40% [33,34], enabling larger and longer-lasting network deployments.

Together, these advances are enabling the transition of underwater communications from niche research tools into scalable infrastructure supporting real-time ocean observation networks, AUV coordination [35], and offshore smart sensing systems. Despite these advancements, the field of UAC grapples with several persistent research gaps that hinder the transition from laboratory breakthroughs to robust, large-scale deployment. Firstly, there is a critical scarcity of open-source, well-annotated underwater acoustic channel datasets [36,37]. This lack of public data severely impedes the development, benchmarking, and independent validation of advanced algorithms, particularly data-driven machine learning models. Secondly, many studies remain confined to idealized simulations or limited field trials, failing to fully address the compounded challenges of real-world environments, such as hardware imperfections, extreme spatial and temporal variability, and non-Gaussian noise. Lastly, there is a discernible disconnect between purely technological research and the critical cross-disciplinary constraints of environmental impact, regulatory compliance, and energy sustainability. This review systematically explores the underlying channel characteristics, modulation and coding techniques, and system integration strategies, aiming to bridge these gaps by synthesizing not only the technological advances but also providing a critical analysis of the practical implementation challenges, thereby offering a holistic perspective on the current state and future trajectory of UAC systems.

The structure of this review is as follows: Section 2 analyzes the impact of underwater channel characteristics on system performance. Section 3 reviews non-coherent and coherent UAC technologies, including single-carrier and multi-carrier systems, as well as other relevant technologies. Section 4 explores machine learning enhancements in UAC. Section 5 outlines technical challenges and future prospects. Finally, Section 6 concludes the paper.

2. The Impact of Channel Characteristics on Underwater Application Performance

Underwater acoustic communication systems serve as critical infrastructure for marine scientific exploration, resource development, and national defense applications. The performance of these systems is fundamentally constrained by the unique physical properties of the underwater acoustic channel [38], which differ significantly from terrestrial radio channels. This section provides a comprehensive analysis of these key constraints and their practical implications for real-world systems such as AUV coordination networks and seabed monitoring installations [39].

2.1. Propagation Delay and Its Operational Impacts

The slow propagation speed of sound in water (approximately 1,500 m/s, which is only 1/20,000 the speed of light) introduces substantial transmission delays [40]. These delays typically range from 0.67 ms/m to 0.75 ms/m depending on water temperature, salinity, and pressure conditions, creating significant challenges for time-sensitive applications. In practical systems, this manifests as: In AUV formation control, round-trip delays of 2–3 seconds over 1 km distances can cause instability in collision avoidance algorithms; For seabed monitoring networks, event detection and response times are extended by hundreds of milliseconds, compromising real-time monitoring capabilities; In military surveillance systems, target tracking accuracy degrades proportionally with increasing delay. The time-varying nature of sound speed due to diurnal thermal variations (causing delay fluctuations of 20–50 ms in typical shallow water environments) further complicates system synchronization, particularly affecting coordinated AUV operations and distributed sensor networks [41].

2.2. Bandwidth-Distance Trade Off: Fundamental Capacity Limitations

The available bandwidth in underwater acoustic communications is severely constrained by frequency-dependent absorption losses, primarily due to relaxation mechanisms of magnesium sulfate and boric acid molecules [42]. This creates a fundamental trade-off where achievable bandwidth decreases dramatically with distance: Systems operating at 1–10 km ranges typically achieve 20–50 kHz bandwidth, enabling data rates of 100–500 kbps; At 100 km ranges, available bandwidth drops to 1–5 kHz, limiting data rates to 10–50 kbps; For very long-range communications (> 500 km), bandwidth is typically limited to 1 kHz or less, supporting only basic telemetry at rates below 1 kbps [43]. These limitations directly impact application performance. High-resolution seabed imaging systems require compressed data formats and extended transmission times. AUV swarm coordination must utilize efficient control command encoding schemes. Real-time video transmission remains impractical for most operational scenarios beyond short ranges.

2.3. Multipath Effects and Signal Degradation

Multipath propagation occurs due to reflections from surface and bottom boundaries, as well as refraction through water layers with different sound speed profiles [44]. This results in time delay spread—the temporal dispersion of arriving signal components—which causes intersymbol interference (ISI) where symbols overlap and interfere with subsequent symbols [45]. The severity of this effect is environment-dependent: In shallow water environments (50–100 m depth), delay spreads typically range from 2–20 ms, with extreme cases reaching 50–100 ms in highly reflective environments; In deep water, delay spreads are generally shorter (1–5 ms) but still significant for high-rate communications [46]. Experimental measurements show that in a typical 50 m deep channel with four reflections, path differences of 200 m can occur, corresponding to approximately 130 ms of delay spread [47]. This distortion mechanism particularly affects coastal monitoring systems operating in shallow, reflective environments; underwater construction and maintenance operations with strong multipath; and military communications requiring reliable, low-probability-of-intercept transmission.

2.4. Environmental Noise and Interference

The underwater acoustic environment contains multiple noise sources with distinct spectral characteristics: Natural noise including turbulence (dominant below 10 Hz), shipping traffic (most significant in the 10–200 Hz range), wave action (affecting the 100–100,000 Hz range), and thermal noise (becoming dominant above 100 kHz) [48]. Biological noise from marine life, particularly snapping shrimp that produce impulsive noise with sound pressure levels reaching

70 dB in the 2–20 kHz band [49]. The resulting signal-to-noise ratio (SNR) constraints are severe: Tropical shallow-water environments often exhibit SNRs below 20 dB due to biological activity; Harbor and coastal regions experience SNR degradation of 10–15 dB due to anthropogenic noise; Arctic environments provide comparatively better SNRs but present unique challenges from ice-generated noise. These conditions necessitate sophisticated signal processing techniques, including adaptive equalization algorithms to combat time-varying multipath spread spectrum techniques for interference mitigation and advanced forward error correction codes capable of operating at low SNRs.

In summary, as illustrated in **Table 2** and **Figure 3**, the acoustic channel is inherently complex and multipath in nature, with each acoustic path experiencing varying degrees of attenuation. These channel characteristics pose significant challenges for practical system implementation: AUV collaborative systems must integrate predictive control algorithms to compensate for latency and intermittent connectivity; seafloor monitoring networks require sophisticated medium access control protocols to cope with limited bandwidth and high latency; military systems demand robust waveform designs capable of operating in complex multipath and noisy environments. Current research focuses on developing integrated solutions, including intelligent adaptive modulation techniques that dynamically respond to channel conditions, multiple-input multiple-output (MIMO) configurations to mitigate multipath effects, and cross-layer optimization frameworks that jointly address physical-layer constraints and application requirements.

Table 2. Summary of key underwater channel impairments and mitigation strategies.

Impairment	Typical Values	Impact on UAC	Mitigation Techniques
Propagation Delay	0.67–0.75 ms/m	Real-time coordination impaired	Predictive algorithms,time-stamping
Bandwidth-Distance Tradeoff	1–50 kHz (1–100 km)	Data rate limits	Adaptive modulation,multi-carrier systems
Multipath Delay Spread	2–100 ms	Intersymbol interference	Equalization, OFDM, time-reversal
Environmental Noise	SNR: 5–20 dB	Signal detection reliability	Spread spectrum, FEC, beamforming

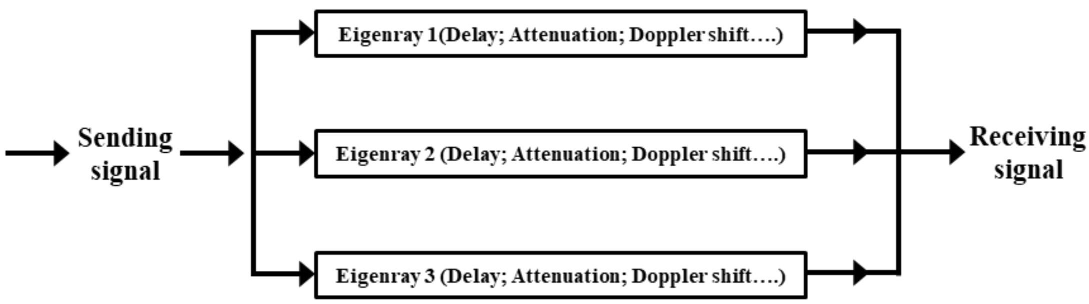


Figure 3. Acoustic channel model.

Faced with system-level challenges such as latency constraining coordination efficiency, bandwidth limiting information density, and multipath and noise threatening reliability, ongoing efforts are concentrated on developing intelligent signal processing frameworks and novel modulation mechanisms. These are specifically designed to mitigate channel impairments in practical applications such as AUV swarm collaboration and real-time seabed monitoring. Such technological advances aim to overcome existing physical limitations, enhance transmission rates and link stability, and lay the technical foundation for strategic applications, including deep-sea resource exploration, distributed AUV cooperative networks, real-time marine environmental monitoring, and underwater defense information systems.

This chapter provides a deep analysis of the unique physical characteristics of the underwater acoustic channel and its fundamental constraints on system performance. Propagation delay, bandwidth-distance tradeoff, multipath effect, and environmental noise constitute the main challenges of underwater acoustic communication. These channel characteristics not only limit the data transmission rate and communication distance, but also affect the system's performance in terms of real-time operation, reliability, and adaptability. Understanding these constraints is the premise of designing an efficient underwater acoustic communication system, and also provides a theoretical basis and optimization direction for various modulation, coding, and signal processing technologies introduced in the following chapters.

3. Application of Underwater Acoustic Communication Technology

Due to the unique transmission structure and channel characteristics of underwater environments, underwater acoustic communication heavily relies on signal demodulation during the receiving process. According to whether the demodulation relies on the precise phase information of the carrier wave, underwater acoustic communication technology can be divided into coherent and incoherent systems.

3.1. Non-Coherent Underwater Acoustic Communication: Application Assurance in Extreme Environments

Non-coherent underwater acoustic communication technology, as a widely adopted robust solution, offers the key advantage of significantly reducing the stringent requirements for carrier phase synchronization [50]. This design philosophy enables the establishment of a highly survivable communication paradigm, particularly suited to the unpredictable and extreme conditions commonly encountered in underwater environments. Unlike coherent communication systems that rely on precise synchronization between the transmitter and receiver, non-coherent technology primarily achieves information transmission by analyzing the energy distribution or frequency domain characteristics of the demodulated signal. Although this approach typically results in a 30–50% loss in spectral efficiency, it compensates for this by offering exceptional adaptability to critical underwater damage factors, such as rapid Doppler shifts caused by relative platform motion and severe multipath effects resulting from strong reflections from the sea surface, seabed, and underwater objects. It is this high tolerance for adverse channel dynamics that establishes the indispensable application value of non-coherent technology in dynamic marine environments.

The core application value of non-coherent technology is most prominently demonstrated in its exceptional ability to maintain link reliability in dynamic and difficult-to-model acoustic channels. This capability is critical in various typical scenarios, such as: continuously transmitting environmental parameters from a network of ocean data buoys drifting with ocean currents; ensuring covert and reliable communication during tactical missions by submarines and divers; and establishing acoustic links in polar ice-covered waters, where the harsh environment makes precise synchronization nearly impossible. In engineering practice, frequency-shift keying (FSK) and its derivative technologies, such as multi-frequency shift keying (MFSK) and differential frequency shift keying (DFSK), constitute the mainstream modulation schemes for non-coherent systems (**Table 3**). These schemes achieve information demodulation by detecting energy within discrete frequency intervals, significantly simplifying the receiver design process and avoiding the challenge of precisely estimating the highly unstable signal phase in underwater environments.

Table 3. Comparison of typical non-coherent modulation schemes.

Type	Robustness	Typical Applications
FSK	High	Environmental monitoring, emergency beacons
MFSK	Very High	Drifting buoys, tactical communication
DFSK	High	Shallow-water networks, diver communication

In the field of marine environmental monitoring, the application of non-coherent technology has a long history and has proven to be practical and effective. In 1981, the 16-FSK modulation system developed by the Massachusetts Institute of Technology (MIT) in collaboration with the Woods Hole Oceanographic Institution (WHOI) was a landmark application example that laid the foundation for the subsequent development of marine observation infrastructure [51]. The system successfully achieved a communication rate of 1.2 kbps at a distance of 200 meters, providing the first compelling technical proof of the feasibility of non-coherent modulation schemes for environmental sensing platforms and remote underwater instruments. Modern non-coherent systems often integrate multi-carrier frequency strategies (such as MFSK) along with coding protection intervals, time diversity, and cyclic prefixes to effectively counteract frequency-selective fading and intersymbol interference caused by strong multipath propagation in shallow water channels. These enhanced measures have demonstrated significant benefits in practical applications such as port security monitoring, coral reef ecosystem health assessment, and coastal search and rescue systems. Although the data throughput of such systems is typically limited to hundreds of bits per second, they can maintain a stable bit error rate (BER) below 10^{-3} in highly reverberant environments, with data recovery success rates often exceeding 95%, fully validating their practicality and reliability in complex offshore environments.

In commercial applications, non-coherent underwater acoustic communication technology reached maturity in the mid-1990s, with representative products such as the Datasonics ATM series acoustic modems (later acquired by Benthos Company), whose design core focused on achieving high robustness and long-term deployment stability. Typical devices, such as the ATM-845 and ATM-850, can provide reliable low-bit-rate communication links under full ocean depth conditions and have been widely applied in critical mission scenarios, including underwater emergency beacon triggering, autonomous underwater vehicle (AUV) telemetry data transmission, and structural health monitoring of underwater oil and gas facilities. The core engineering value of these commercial systems lies in their tolerance for highly dynamic and unstable acoustic channel fluctuations, as well as their minimal reliance on precise time synchronization or complex signal processing algorithms, ensuring long-term reliable operation in harsh environments.

Although non-coherent systems are renowned for their exceptional robustness, their inherent low spectral efficiency (typically not exceeding 0.5 bps/Hz) constitutes the primary limitation of their application boundaries. Additionally, international regulatory frameworks limiting acoustic emission power and stringent requirements for energy efficiency in underwater devices further constrain the practicality of non-coherent technology in data-intensive tasks. These tasks include the real-time transmission of high-resolution geophysical imaging data from the seabed, coordinating multi-autonomous underwater vehicle (AUV) clusters to perform collaborative operations, and telemetry of large volumes of scientific data from seabed observation stations. Addressing these challenges requires ongoing technological innovation, with exploration directions including but not limited to: combining modulation schemes such as MFSK with advanced time-frequency hopping (TFH) strategies; studying novel coding and detection mechanisms such as non-orthogonal signal transmission or non-coherent detection based on polar coordinate encoding; and integrating adaptive intelligent algorithms to dynamically optimize system performance under channel uncertainty.

In summary, non-coherent acoustic communication technology, as a foundational technology, continues to provide reliable, low-complexity, and highly survivable data exchange capabilities in underwater environments. Although its inherent performance limits may restrict its dominant role in ultra-high-bandwidth demand scenarios, this technology remains a key pillar of foundational marine communication infrastructure, particularly in applications where environmental unpredictability is high and energy efficiency takes precedence over data throughput. Ongoing research into hybrid modulation architectures (combining the advantages of coherent and non-coherent systems) and AI-enhanced receiver algorithms demonstrates the immense potential to extend the practical value and influence of non-coherent systems into next-generation intelligent marine networks.

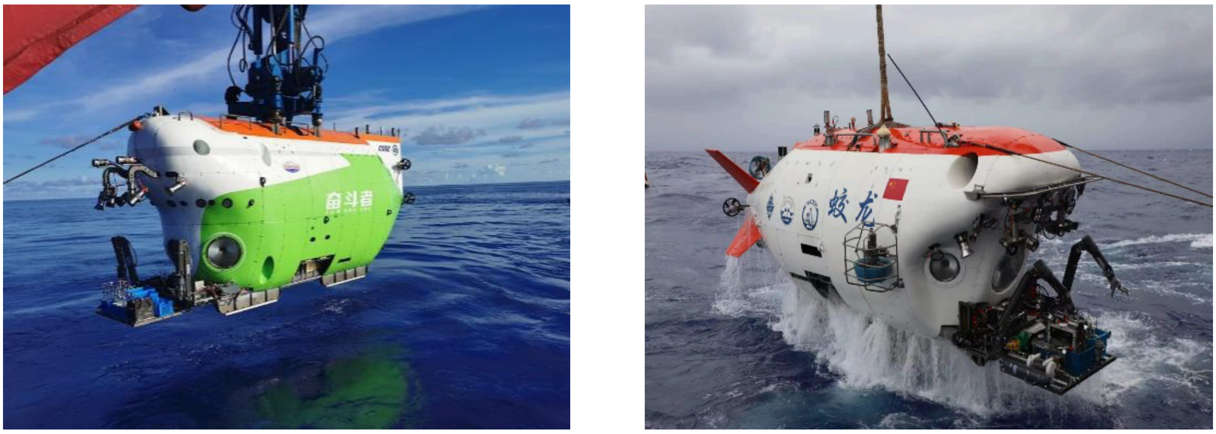
3.2. Coherent Underwater Acoustic Communication: High-Speed Information Channel for Deep-Sea Exploration and Coordinated Operations

Coherent underwater acoustic communication technology establishes a core transmission system for high-bandwidth underwater operations through precise carrier phase synchronization mechanisms. Its engineering value is primarily reflected in three aspects: the receiving end must accurately recover signal phase to achieve coherent demodulation; the use of efficient modulation techniques such as PSK and QAM enhances spectral efficiency to 1–5 bps/Hz (5–10 times higher than non-coherent technologies); providing critical support for high-value applications such as high-definition video transmission for deep-sea manned submersibles, collaborative control of AUV swarms, and three-dimensional mapping of the seabed. The following sections will analyze the technical characteristics and application progress of two architectural categories: single-carrier (suitable for high-reliability point-to-point scenarios, such as the remote monitoring of deep-sea manned submersibles) and multi-carrier (adapted for high-speed mobile networks such as naval vessel fleets and AUV swarms).

3.2.1. Single-Carrier Underwater Acoustic Communication

Single-carrier underwater acoustic communication technology realizes efficient and reliable data transmission by modulating information onto a single frequency carrier signal [52]te>. It has long served as the foundational solution for point-to-point high-fidelity communication in underwater scenarios where link stability and real-time responsiveness are of paramount importance. Typical application domains include manned deep-sea submersible missions, long-endurance underwater gliders, and collaborative underwater robotic platforms operating in extreme marine environments. Unlike multi-carrier schemes that rely on multiple subchannels, the single-carrier approach simplifies system structure, making it particularly advantageous in low-power, low-latency, and spatially constrained underwater applications. Its core engineering value lies in its ability to address two major impairments of underwater acoustic channels: large multipath delay spread and dynamic Doppler frequency shifts. These distortions are effectively mitigated through time-domain and frequency-domain equalization techniques, which restore signal integrity and maintain data fidelity over long distances and under variable oceanic conditions.

Among these techniques, frequency-domain equalization (FDE) has emerged as the mainstream method for high-performance underwater acoustic systems [53]. Compared with traditional time-domain approaches, FDE significantly reduces computational complexity by nearly 50% while maintaining strong robustness against multipath interference. This makes it especially suitable for deployment on platforms such as the Jiaolong manned submersible and distributed deep-sea observation networks (**Figure 4**), where computational resources are limited but high transmission reliability is required. However, when operating in highly time-varying channels, such as those affected by seasonal monsoons or rapidly shifting ocean currents, the conventional equalizer combinations, like Decision Feedback Equalizers (DFE) combined with Digital Phase-Locked Loops (DPLL), often face performance degradation. For example, bit error rates can abruptly increase due to fast-varying Doppler spreads, undermining system stability. To overcome these limitations, joint processing paradigms that combine equalization with channel decoding have emerged as critical breakthroughs. While early joint schemes, such as the 1989 trellis-coded modulation (TCM)-based equalization and decoding [54], were limited by hardware capabilities, they laid the conceptual groundwork. The subsequent introduction of Turbo equalization in 1995 marked a major leap forward, enabling iterative optimization between equalizer and decoder modules [55]. This innovation extended the communication range beyond 50 km, allowing real-time data transmission from ultra-deep environments, such as the Mariana Trench, for the first time. Continued advancements, including the Maximum A Posteriori (MAP) Turbo equalizer (2001) [56] and the linear MMSE-Turbo version (1997) [57], greatly enhanced shallow-water performance and computation feasibility, accelerating engineering deployment in industrial and scientific applications.



(**a**) (**b**)

Figure 4. (**a**) Jiaolong manned submersible; and (**b**) Fendouzhe Striver deep-sea manned submersible.

China's engineering innovations have further advanced the practical application of single-carrier systems in real-world field conditions. For instance, He Chengbing et al. proposed a hybrid scheme combining frequency-domain pre-equalization with time-domain Turbo decoding [58], achieving 4 kbps reliable communication over a 10.8 km link in the Danjiangkou Reservoir. This supported the ecological sensor network of the South-to-North Water Diversion Project, demonstrating long-range, high-integrity transmission under reservoir multipath conditions. In the Bohai oilfield, Yan's bidirectional Turbo equalization algorithm successfully reduced command error rates to below 10^{-7} [59], enabling robotic arms on underwater vehicles to achieve millimeter-level operation precision during critical inspection and maintenance tasks. Extensive open-sea trials conducted by the Chinese Academy of Sciences' Institute of Acoustics further validated the adaptability of MMSE-Turbo schemes to deep-sea channels exceeding 10,000 meters [60,61], providing reliable communication support for the Fendouzhe Striver deep-sea manned submersible (**Figure 4b**) and future 11,000-meter-class deployments.

Currently, single-carrier acoustic communication technology has been widely and maturely applied in three high-value domains: (1) real-time geological data and HD video transmission from deep-sea manned submersibles, such as the Jiaolong's 20 kbps video stream in hydrothermal vent regions of the South China Sea (**Figure 5**); (2) real-time coordination among autonomous underwater vehicles (AUVs) for collaborative missions such as pipeline inspection, mine detection, and sensor array deployment; and (3) long-range communication in deep-sea environmental monitoring networks, such as the 6,000-meter-class buoy arrays established in the western Pacific. Despite remaining challenges such as the high computational load of iterative equalization algorithms and sensitivity to dynamic channel fluctuations, research into AI-powered blind equalization and model-driven deep learning techniques is opening new frontiers. These technologies are expected to drive the next generation of single-carrier systems, offering enhanced adaptability and making them suitable for even more demanding tasks, including polar under-ice research base communications and deep-ocean seismic early warning systems. As the underwater information infrastructure evolves toward higher intelligence, security, and resilience, single-carrier systems will continue to be a critical pillar of mission-critical marine operations.

Figure 5. Some of the underwater photos were transmitted back by the Jiaolong manned submersible via its underwater acoustic communication device.

3.2.2. Multi-carrier Underwater Acoustic Communication

Multi-carrier modulation technology fundamentally breaks through the rate bottleneck of underwater acoustic communication by decomposing high-speed data streams into parallel low-speed subcarriers, serving as the core engine for constructing the "transparent ocean" information infrastructure. Its revolutionary value lies in: significantly extending symbol duration to suppress inter-symbol interference, leveraging the spectral superposition characteristics of orthogonal subcarriers to maintain high spectral efficiency (1–5 bps/Hz) while overcoming multipath effects and Doppler shifts (**Table 4**) [62,63], and providing disruptive solutions for deep-sea exploration, high-speed naval communications, underwater IoT, and other complex, bandwidth-limited marine scenarios. Compared with traditional single-carrier approaches, multi-carrier technology offers better scalability, robustness, and real-time response, especially in scenarios with long-range, time-varying, and noisy channels. This makes it an essential enabler for constructing next-generation underwater information infrastructures that can support intelligent perception, real-time control, and big data exchange.

Table 4. Comparison of multi-carrier modulation techniques.

Type	Robustness	Complexity	Typical Applications
OFDM	Moderate	Low	Deep-sea communication, submersible links
OTFS	High	High	High-mobility naval operations
FBMC	Moderate-High	Medium	Crowded sensor networks, island monitoring
GFDM	High	Medium-High	Underwater 5G, military networks

Recent breakthroughs in interference cancellation algorithms, dynamic channel compensation, and intelligent signal processing have driven the development of a comprehensive application ecosystem for the three major technological routes: OFDM, OTFS, and FBMC [64–66]. From real-time monitoring of the South China Sea's combustible ice extraction zones to high-speed networking for aircraft carrier battle groups and offshore platform clusters, multi-carrier technology is reshaping the communication paradigm for marine development and security operations. Its compatibility with AI-based adaptive modulation and coding schemes also provides the foundation for self-optimizing underwater networks, which can evolve according to mission requirements and channel dynamics.

As the most mature engineering routing scheme, OFDM replaces cyclic prefixes with orthogonal subcarrier design and zero-filling technology, converting frequency-selective channels into flat-fading subchannels. In 2005, Zhou's team conducted OFDM testing in shallow water areas [67], as shown in **Figure 6**. In 2021, Harbin Engineering University achieved a 100 km/199 bps deep-sea communication link at a depth of 3,700 meters in the South China Sea [68], setting a global benchmark for emergency communication ranges for deep-sea submersibles and establishing a lifeline data channel for the Deep Sea No. 1 Energy Station. To address the long-standing challenge of Doppler sensitivity, Ebihara's team developed OSDM technology [69], which improves the system's Doppler tolerance by 40% through joint time-frequency domain equalization. The improved D-OSDM system demonstrated stable transmission with a bit error rate < 10^{-3} in strong Doppler environments, such as nuclear submarine maneuvering scenarios.

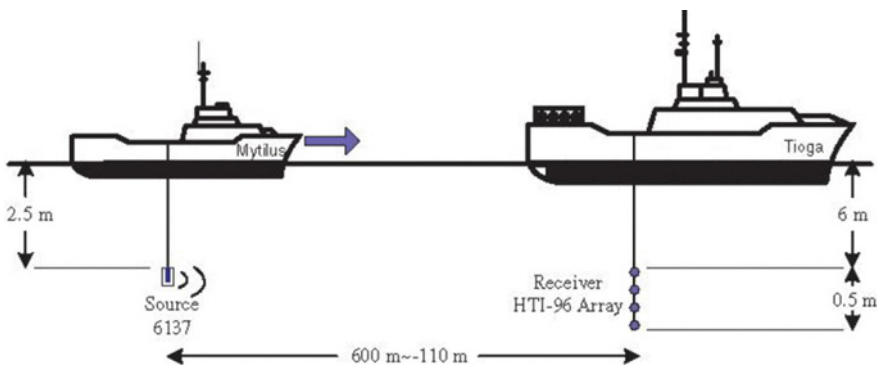


Figure 6. OFDM experiment.

To adapt to spectrum constraints and dense sensor deployment environments, the University of Utah's FBMC scheme suppresses subcarrier interference and spectral leakage [70], improving spectral containment and interference isolation for sensor networks deployed on South China Sea islands. Meanwhile, GFDM technology provides a reconfigurable waveform platform suitable for underwater 5G military-dedicated networks [71,72], enabling flexible resource allocation and robust anti-jamming capabilities, especially for mobile and multi-node communication [73–75].

The breakthrough of OTFS lies in the construction of a delay-Doppler domain signal representation that enables a dual-immunity mechanism. The cross-domain Turbo iterative equalization algorithm developed by Xi'an Jiaotong University in 2022 [76] achieves a spectral efficiency of 5 bps/Hz—eight times that of traditional FSK—on a 4-knot patrol vessel, meeting the requirements for real-time command and high-definition image transmission during law enforcement missions. In parallel, the optimized prototype filters in the newly developed C-FBMC technology reduce signal distortion and inter-symbol interference by more than 50% under dual-expansion channel conditions, such as typhoon-induced fluctuations in sea conditions.

Enhanced interference resistance stems from innovative signal integration. Qiao's orthogonal M-ary spread spectrum method enables error-free 10 kbit-level secure transmission [77], ensuring the confidentiality of strategic military commands in sensitive zones, such as the Xisha Islands. Similarly, MC-CDMA subcarrier coding enhances resistance to narrowband interference by up to 20 dB [78], enabling underwater monitoring networks on the Yongshu Reef to maintain a bit error rate below 10^{-4} even in the presence of strong electromagnetic disturbances.

Dynamic channel compensation and advanced coding technologies are expanding the horizon of underwater communications. Wan's grid-based delay estimation method [79] leverages Bayesian inference to reduce residual Doppler error to 0.3 dB, thereby enhancing the positioning and communication accuracy of aircraft carrier-based aircraft in active submarine operations. The Polar Code and LDPC [80] concatenated scheme achieves an 8–10 dB coding gain, supporting China's strategic goal of achieving stable 30 km/4000 bps error-free underwater communication by 2025, aiming to surpass NATO's current anti-submarine communication benchmark. Additionally, the Lagrange interpolation compensation algorithm drastically reduces the 8PSK error rate from 10^{-1} to 10^{-4} at a cruising speed of 10 knots.

MIMO-multi-carrier fusion introduces a revolutionary spatial dimension to underwater acoustic communications [81,82]. At the same time, deep learning-powered channel prediction algorithms have resolved long-standing array interference issues, enabling the coordinated operation of kilometer-scale underwater unmanned vehicles within the Fujian aircraft carrier battle group. To overcome the computational complexity bottleneck of large-scale multi-carrier deployments, quantum entanglement carrier modulation has been explored to further improve the encryption and anti-interception capabilities of strategic platforms, such as the Type 094 submarine. In tandem, intelligent reflective surface (IRS) technology expands the spatial coverage of communication networks such as the coral reef ecological monitoring system, laying the groundwork for a future deep-sea–space–air integrated intelligent communication framework.

As multi-carrier technology continues to converge with 6G networks, quantum computing, and underwater robotics, it is expected to trigger a new wave of technological breakthroughs. These will be particularly transformative in high-value scenarios such as underwater digital oilfields, seabed mining control networks, polar shipping route surveillance, and autonomous underwater exploration systems—helping establish an intelligent, secure, and transparent marine communication infrastructure on a global scale.

3.3.Other Underwater Acoustic Communication

In addition to mainstream modulation schemes such as multi-carrier modulation, a new generation of advanced technologies—including spread-spectrum communication [83], full-duplex transmission [83] and covert communication [84]—is progressively forming a diverse and application-oriented ecosystem for underwater communication technology. These emerging solutions are not merely theoretical breakthroughs; they are being increasingly tailored to meet the complex, high-performance demands of real-world scenarios, such as deep-sea resource development, military reconnaissance, intelligent underwater robot swarms, and offshore energy infrastructure monitoring. In this context, new communication paradigms that focus on interference resistance, real-time responsiveness, and information security are becoming the foundation of next-generation underwater networks, offering robust support for mission-critical operations in dynamic and unpredictable marine environments.

Among them, spread-spectrum communication has shown great promise in scenarios requiring strong anti-interference capability and low detectability [85]. By expanding the signal across a much wider frequency spectrum using pseudo-random (PN) or pseudo-noise (PR) sequences, this technique effectively disperses energy, enhancing resistance to narrowband jamming while simultaneously reducing the likelihood of signal interception. The evolution of this technology has proceeded through distinct generational stages. The first-generation Direct Sequence Spread Spectrum (DSSS) utilized time-domain Gold sequences to achieve up to 32 dB of spreading gain [86]; however, its performance degraded significantly in multipath environments, with bit error rates increasing to the order of 10^2. The second-generation Frequency Hopping Spread Spectrum (FHSS) introduced random frequency switching to lower the risk of interception by up to two orders of magnitude [87]. However, due to the inherent coherent bandwidth limitations of underwater acoustic channels, the hopping rate is generally restricted to below 200 hops/s, which limits its performance in dynamic spectral environments. To overcome these constraints, the third-generation hybrid spread-spectrum schemes combine both time and frequency domain strategies. Notably, Zhou Feng's team proposed a burst hybrid spread-spectrum approach that integrates random duty-cycle pulse modulation, achieving an interception probability below 10^{-4} while reaching a high spectral efficiency of 3.7 bps/Hz through adaptive frequency selection [88]. This method is particularly suited to applications requiring stealth and agility, such as coordinating swarming AUVs or clandestine seabed surveys [89]. More recently, the integration of multi-carrier spread spectrum is blurring the traditional boundaries of spectrum efficiency and reliability, making it feasible to deploy these methods in complex underwater networks where multiple devices require simultaneous low-profile communication with robust interference mitigation.

Parallel to this advancement, full-duplex communication is redefining the latency-performance landscape of underwater information exchange. Traditional half-duplex systems [90], which alternate between transmitting and receiving, typically suffer from high end-to-end delays of 2–5 seconds, making them unsuitable for real-time applications such as cooperative autonomous vehicle control, bidirectional sensing-actuation loops, or urgent event-based alerting in marine operations. To address this challenge, In-Band Full-Duplex (IBFD) underwater acoustic communication has emerged as a key enabling technology, allowing bidirectional information exchange over the same frequency band without increasing bandwidth usage [91]. Central to IBFD is the self-interference cancellation (SIC) algorithm, which enables simultaneous two-way transmission by removing echoes of transmitted signals at the receiver. Qiao et al. designed a vector sensor-based full-duplex acoustic modem employing zero-point beamforming to suppress transceiver crosstalk by 45 dB [92]. Combined with adaptive power control algorithms and dynamic channel adaptation, the system can support error-free two-way communication at 1096.8 bps within a 20 kHz bandwidth, significantly improving both throughput and communication robustness in time-varying environments. The Institute of Acoustics, Chinese Academy of Sciences, further contributed by developing a time-varying channel estimation framework based on compressive sensing, which reduced the estimation delay to just 0.8 ms under four-throttle modulation conditions. Their ongoing research into Concurrent-Channel Full-Duplex (CCFD) technology leverages quantum noise injection to achieve in-band isolation up to 60 dB. A prototype built on this principle has already demonstrated a 2.4 kbps symmetric throughput in controlled environments, suggesting a viable path toward dense deployment of underwater Internet of Things (IoT) networks with ultra-low latency and full-band efficiency.

Simultaneously, the evolution of covert communication is being actively shaped by real-world needs such as military stealth, strategic surveillance, and the protection of sovereign marine territories. Traditional low probability of detection (LPD) techniques suppress the power spectral density of signals to below −160 dB/Hz via spread-spectrum gain, yet remain susceptible to identification by advanced broadband sonar systems, especially at close ranges or in hostile detection environments. To address this vulnerability, researchers are turning to biomimetic covert communication, which draws inspiration from the acoustic behavior of marine life to embed communication signals within natural soundscapes—such as ambient noise or biological vocalizations—thereby improving ecological compatibility and reducing the risk of detection. Yin et al. proposed a novel scheme using M-ary dolphin whistle coding to embed digital information in bionic signals [93]. This technique maps data to dolphin-like whistles via a signal selector, while the receiver employs passive time-reversal mirrors to equalize the underwater channel and recover the embedded message. Wang et al. further enhanced concealment by selectively utilizing authentic marine mammal call pulses to verify the security and imperceptibility of bionic signaling [94]. While most existing approaches are limited by the fidelity of their dolphin whistle emulation, Lee et al. introduced a machine learning-driven bionic acoustic communication system that significantly improves imitation accuracy and reduces signal distortion, paving the way for high-fidelity covert communication under complex acoustic conditions [95]. This line of development has immediate potential in applications ranging from submarine coordination in contested zones to surveillance of marine protected areas.

This chapter comprehensively summarizes the principles, characteristics, and applications of incoherent and coherent underwater acoustic communication technology in the actual marine environment. Incoherent technology plays an important role in extreme environments due to its high robustness and low complexity, while coherent technology supports high-speed data transmission through high-frequency spectral efficiency, making it suitable for high-bandwidth demand scenarios such as deep submersibles, AUV clusters, and seabed monitoring networks (**Table 5**). In addition, the emerging technologies such as spread spectrum, full duplex, and covert communication are also introduced, showing the diversified application prospects of underwater acoustic communication technology in military, industrial, and scientific research fields. The continuous evolution and integration of these technologies are promoting the development of the underwater communication system to be more intelligent, more reliable, and more secure. A comprehensive understanding of these underwater acoustic channel constraints will help develop more efficient communication systems for key applications, such as distributed AUV operation, real-time environmental monitoring, underwater infrastructure inspection, and naval defense systems.

Table 5. Performance comparison of emerging UAC technologies.

Technology	Data Rate	Range	Robustness	Primary Challenge
Spread-Spectrum (DSSS)	1–10 kbps	1–5 km	High	Multipath interference
Full-Duplex (IBFD)	1–2.4 kbps	0.5–2 km	Moderate	Self-interference cancellation
Covert (Bionic)	0.1–1 kbps	0.5–3 km	Very High	Low data rate, bio-compatibility

4. Machine Learning-Enhanced UAC

In recent years, machine learning (ML) methods have emerged as a powerful tool for addressing the complex and highly nonlinear challenges inherent in underwater acoustic communication (UAC). By leveraging data-driven approaches, ML techniques offer promising solutions for channel estimation, signal equalization, and adaptive receiver design, significantly enhancing the performance and robustness of UAC systems in dynamic oceanic environments.

Channel estimation is a critical component in UAC systems, especially for coherent and multi-carrier communication schemes, where accurate knowledge of the channel state information (CSI) is essential for reliable data recovery. Traditional methods often struggle with the time-varying, multi-path, and sparse nature of underwater acoustic channels. Machine learning, particularly deep learning models, has demonstrated significant potential in learning channel characteristics directly from data, thereby improving estimation accuracy and system adaptability.

For instance, Chen et al. (2018) proposed a multilayer perceptron (MLP)-based receiver for orthogonal frequency-division multiplexing (OFDM) systems, which was validated using real data from the Swan River, Australia. The model demonstrated superior bit error rate (BER) performance by effectively extracting channel features [96]. In 2019, Zhang et al. developed a five-layer DNN for channel estimation and equalization, outperforming traditional least-squares methods in Bellhop-simulated channels [97]dNote>. Further advances include the integration of compressed sensing with DNNs [98,99], meta-learning for rapid environmental adaptation [100], and data augmentation techniques to combat overfitting in small-sample scenarios [101]. Recent work by Wang et al. introduced a bias-free denoising neural network for robust channel estimation under noisy conditions [102].

These methods highlight the ability of ML models to handle non-linear channel distortions, though challenges remain in real-time deployment and generalization across varying acoustic environments.

Machine learning is being increasingly integrated with conventional UAC technologies, such as OFDM, single-carrier coherent systems, and spread-spectrum communications. For example, in 2023, Zhang et al. combined deep learning with expert knowledge in an OFDM receiver, using super-resolution networks for channel estimation and attention-based LSTMs for signal detection, achieving lower BER and improved interpretability [103]. Similarly, Liu et al. applied convolutional neural networks (CNNs) to exploit temporal and frequency-domain features in doubly selective channels [104].

These hybrid approaches leverage the strengths of both model-based signal processing and data-driven learning, resulting in more adaptive and efficient UAC systems.

Despite promising results, the application of machine learning to UAC faces significant hurdles. Data scarcity is paramount. The USTC Underwater Acoustic Dataset and ISI Dataset provide valuable insights, but they are often region-specific and fail to cover the full range of dynamic environmental conditions that affect underwater communication [105–108]. These datasets typically lack the diversity needed to train robust ML models capable of handling different challenges, such as varying salinity, temperature gradients, marine life interference, and moving platforms. This scarcity stifles the development of generalizable models. Furthermore, the "black-box" nature of complex models, such as deep neural networks erodes trust and complicates debugging in safety-critical applications. The computational complexity and high energy consumption of training and running these models are at odds with the severe power constraints of underwater nodes. For instance, running a real-time DNN-based channel estimator on an embedded modem can consume an order of magnitude more power than conventional algorithms, drastically reducing network lifetime [97]. Future research should focus on developing lightweight, explainable AI architectures. Integrating physical knowledge into models through Physics-Informed Neural Networks (PINNs) offers a path to improved generalization with less data [109]. Similarly, leveraging self-supervised and semi-supervised learning can reduce the dependency on vast labeled datasets, which are impractical to obtain at sea.

Machine learning also complements other advanced UAC technologies such as spread-spectrum, full-duplex, and covert communications. For example, ML can optimize frequency hopping patterns in FHSS, improve self-interference cancellation in full-duplex systems, and enhance the realism of bio-inspired covert signals. The integration of ML with these technologies is pushing the boundaries of what is possible in underwater networking, enabling more intelligent, adaptive, and secure communication systems.

This chapter explores the innovative applications of machine learning technology in underwater acoustic communication, with a focus on the significant potential demonstrated in channel estimation, signal equalization, and adaptive receiver design. Through data-driven methods, ML models can effectively handle the nonlinear and time-varying characteristics of underwater acoustic channels, significantly improving system performance and robustness. Although there are still challenges in terms of real-time performance, interpretability, and data dependency, the combination of machine learning and traditional communication technologies has become an important direction for promoting the intelligent development of underwater acoustic communication. In summary, machine learning represents a paradigm shift in underwater acoustic communication, providing new avenues for addressing long-standing challenges. In the future, it has broad application prospects in fields such as AUV networks, underwater Internet of Things (IoT), and real-time environmental monitoring.

5. Technical Challenges and Prospects

While significant progress has been made in underwater acoustic communication technologies, several critical challenges remain that hinder their widespread deployment and effectiveness in real-world applications. Beyond the technical limitations discussed previously, practical implementation faces additional constraints related to regulatory frameworks, environmental considerations, and system integration challenges.

5.1. Regulatory and Environmental Constraints

The deployment of underwater acoustic communication systems is increasingly constrained by a complex web of international and regional regulations designed to mitigate anthropogenic noise pollution in the marine environment. Key regulatory bodies include the International Maritime Organization (IMO), which has issued guidelines for reducing underwater noise from commercial shipping [110]. These guidelines, while primarily targeting vessel noise, set a precedent for regulating acoustic emissions and influence the permissible transmission power and frequency bands for UAC systems, especially in busy shipping lanes and ecologically sensitive Marine Protected Areas (MPAs). In regions like the European Union [111], the Marine Strategy Framework Directive (MSFD) explicitly includes underwater noise as a form of pollution that member states must monitor and reduce to achieve "Good Environmental Status".

The ecological impact of acoustic emissions is a primary driver of these regulations. Bioacoustic studies have conclusively shown that anthropogenic underwater sound can cause a range of adverse effects on marine life, from masking biologically critical cues to causing physiological stress, hearing loss, and behavioral displacement[112]. For instance, a seminal study demonstrated that mid-frequency military sonar can cause blue whales to cease foraging and initiate avoidance behaviors, leading to significant energetic costs[113]. The frequency bands most effective for long-range UACs critically overlap with the hearing ranges of many commercially important fish species and cetaceans, such as porpoises and beaked whales[114].

Therefore, future UAC systems must be designed with a "Green UAC" paradigm. This involves developing waveforms that minimize energy in ecologically sensitive frequency bands or use intermittent, low-duty-cycle pulses to reduce overall acoustic energy input. Furthermore, implementing real-time Environmental Impact Mitigation algorithms is crucial; these systems would use onboard sensors or network-shared data to detect the presence of sensitive species via passive acoustic monitoring and dynamically reduce power or halt transmissions accordingly [115]. Finally, conducting comprehensive Environmental Impact Assessments before large-scale deployments is essential, modeling the potential acoustic footprint and its overlap with known animal distributions and migration routes.

5.2. Data Security and Policy Considerations

As underwater networks become integral to national security and economic infrastructure, they become high-value targets for espionage, jamming, and spoofing attacks. The shared nature of the acoustic medium makes eavesdropping particularly facile compared to terrestrial radio. The security challenge is multifaceted, requiring assurance of data confidentiality to prevent unauthorized access, data integrity to prevent tampering, and robust authentication to verify the identity of the sender.

The geopolitical dimension adds another layer of complexity. Data sovereignty issues arise when information collected in a country's Exclusive Economic Zone is transmitted through international waters, potentially subject to interception by other state actors. Furthermore, the use of UAC technology in disputed regions transforms communication systems into instruments of geopolitical strategy, where denial-of-service attacks on sensor networks could be considered acts of hybrid warfare [116].

To address these challenges, a multi-layered security architecture is essential. Cryptography remains a cornerstone, with research pushing towards lightweight [117] and post-quantum cryptographic algorithms that are feasible for the computational constraints of underwater modems. Alongside cryptography, Physical-Layer Security offers a promising complementary approach by leveraging the unique properties of the underwater channel itself as a security feature. Techniques such as channel-based secret key generation, where two legitimate parties derive identical keys from the reciprocal channel impulse response, and artificial noise injection, designed to degrade an eavesdropper's channel, are areas of active investigation [118]. The development and deployment of robust authentication protocols are equally critical to prevent node impersonation and Hello flood attacks, which pose significant threats to the integrity of mobile AUV swarms and distributed sensor networks.

5.3.Integration and Interoperability Challenges

The underwater domain lacks the universal standards that have enabled the explosive growth of terrestrial IoT. The UAC landscape is a fragmented ecosystem of proprietary systems from different manufacturers, each with its own modulation schemes, multiple access protocols, and data formats. This heterogeneity creates significant barriers to achieving the vision of a seamlessly connected "Internet of Underwater Things".

The NATO STANAG 4748 standard, known as JANUS, is a notable exception [119]. It defines a common digital signaling format for basic interoperability, primarily intended for distress signaling and vessel discovery. However, JANUS is a low-rate, low-throughput protocol unsuitable for high-bandwidth applications, such as video transmission or AUV control, highlighting the limitations of current standardization efforts.

The interoperability challenge manifests in several ways across network layers. Incompatible routing and medium access control protocols prevent different networks from forming a unified topology. At the data layer, the absence of common data formatting means that even received data may not be interpretable without custom translation software. Furthermore, a lack of standardized interfaces for remote configuration, diagnostics, and health monitoring complicates the management of mixed-vendor networks.

Addressing this requires a concerted effort towards developing open APIs and middleware that can translate between different proprietary protocols, an initiative pursued by projects like the EU's SUNRISE [120]. Promoting community-accepted standards beyond JANUS, covering higher data rates, security, and network management, is another critical path forward, facilitated by standardization bodies like the IEEE Ocean Engineering Society. Finally, promoting modular and software-defined modem designs, where waveform processing and protocols are implemented in software, would allow a single modem to be reconfigured to communicate with different systems as needed, greatly enhancing flexibility and interoperability.

5.4.Energy Efficiency and Sustainability

Energy is the single most limiting factor for untethered underwater systems. A typical modem in receive mode can consume 1–5 Watts, while transmitting at high power can demand 10–50 Watts or more [121]. For an AUV, communication can account for over sixty percent of the total energy consumed during a mission, beyond simple navigation [122], a figure that underscores the critical nature of energy constraints.

This constraint dictates every aspect of system design, from the use of ultra-low-power application-specific integrated circuits and microcontrollers to the adoption of energy-efficient MAC protocols that minimize the time nodes spend in idle listening mode. The computational complexity of advanced algorithms, particularly machine learning-based ones, poses a major challenge, as a sophisticated equalizer might improve performance but could drain the battery orders of magnitude faster than a simpler algorithm.

The path forward lies in cross-layer energy optimization and energy harvesting. Systems must be designed for adaptive fidelity, dynamically adjusting their performance and communication strategies based on energy availability. Supplementing batteries by harvesting energy from the environment is critical for long-term sustainability. Promising techniques include triboelectric nanogenerators that convert mechanical energy from ocean waves into electricity, with recent designs achieving power densities sufficient for low-duty-cycle sensor nodes [123]. A system-wide perspective is ultimately required, optimizing not just the modem but also the connected sensors, data compression algorithms, and operational scheduling to align with the available energy budget, whether from batteries or harvested sources.

5.5.Research Gaps and Future Directions

Several important research gaps require attention to advance the field of underwater acoustic communications. The scarcity of comprehensive, open-source underwater acoustic channel datasets continues to hinder the development and validation of machine learning algorithms. Most existing studies rely on simulated data or limited field measurements, which may not fully capture the complexity and variability of real-world underwater environments. Collaborative efforts to create large-scale, annotated datasets encompassing diverse environmental conditions would significantly accelerate progress in data-driven approaches.

The assumption of ideal conditions in many theoretical studies represents another limitation. Real-world systems must contend with practical constraints such as hardware imperfections, calibration errors, and environmental variability that are often overlooked in simulation-based research. Future work should prioritize robust algorithm design that accounts for these non-ideal conditions and validates performance through extensive field testing.

Looking ahead, several promising research directions emerge. The integration of artificial intelligence with underwater acoustic communications offers particular potential for addressing long-standing challenges. AI algorithms can enhance real-time Doppler compensation through adaptive filtering techniques that continuously learn and predict channel variations. Machine learning-based error correction systems can dynamically adjust coding schemes based on channel conditions, improving reliability without excessive redundancy. For multi-carrier systems, neural network-based channel estimation can provide more accurate and computationally efficient alternatives to traditional methods.

The convergence of underwater acoustic communications with emerging technologies such as 6G networks, quantum computing, and advanced materials science presents exciting opportunities. Quantum-inspired algorithms could revolutionize secure underwater communications through quantum key distribution, while metamaterials and intelligent reflective surfaces may enable more efficient signal propagation and coverage extension. The development of biodegradable or environmentally neutral sensor platforms would address growing concerns about the ecological impact of marine deployments.

In summary, while significant technical challenges remain, the continued advancement of underwater acoustic communication technology holds tremendous promise for enabling new applications in ocean exploration, environmental monitoring, and defense systems. By addressing the multidisciplinary challenges spanning technical performance, environmental compatibility, and regulatory compliance, future research can unlock the full potential of underwater communications as a foundational technology for marine science and industry.

6. Conclusion

Underwater acoustic communication technology has emerged as a cornerstone for enabling diverse marine applications, bridging the gap between technological innovation and real-world needs. From non-coherent systems that ensure robust connectivity in dynamic environments to coherent OFDM and MIMO architectures, which facilitate high-data-rate transmission for deep-sea submersibles and autonomous underwater vehicle (AUV) swarms, the technology has demonstrated remarkable adaptability. Key applications span marine resource exploration, ecological monitoring, and national defense, leveraging advancements like spread-spectrum coding for anti-jamming and biomimetic signaling for stealth.

However, practical deployment still faces critical bottlenecks. The underwater acoustic channel's inherent limitations—multipath fading, bandwidth scarcity, and ambient noise—constrain data rates and reliability, particularly in long-range scenarios. For instance, while OFDM has achieved 199 bps over 100 km in deep-sea trials, the transmission of real-time high-definition video remains challenging. Additionally, integrating technologies, such as full-duplex communication and AI-driven adaptive equalization requires overcoming the computational complexity and power consumption hurdles associated with mobile platforms.

This review also acknowledges certain limitations, including the reliance on simulation-based validations in some studies, the scarcity of open-source underwater acoustic datasets for machine learning, and the need for more holistic performance metrics that account for ecological impact and regulatory compliance. Future work should prioritize real-world validation, collaborative data-sharing initiatives, and the development of energy-efficient, environmentally sustainable communication solutions.

In the future, the fusion of multi-carrier modulation with emerging technologies (e.g., 6G networks, quantum computing, and machine learning) holds promise for transformative applications. AI-enhanced real-time systems could dramatically improve Doppler compensation, error correction, and channel prediction, thereby enabling robust communications in highly dynamic environments. Non-coherent systems, hybrid modulation architectures, and biomimetic covert communication will continue to play vital roles in ensuring reliability and stealth in challenging scenarios.

Future breakthroughs may enable "transparent ocean" infrastructures, supporting autonomous marine operations, distributed underwater IoT networks, and resilient communications for deep-sea energy stations. By addressing spectral efficiency, real-time processing, security, and ecological sustainability, underwater acoustic communication will continue to underpin humanity's exploration and stewardship of the oceans, driving innovation from tactical defense systems to sustainable marine resource management.

Author Contributions

Conceptualization, B.X., B.H., and T.L.; investigation, B.X., T.L., J.S., and F.Z.; validation, F.Z.; writing—original draft preparation, B.X. and T.L.; writing—review and editing, B.H., T.L., J.S., and F.Z.; visualization, B.X.; supervision, B.H.; project administration, B.H. All authors have read and agreed to the published version of the manuscript.

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