

Underwater Wireless Communication Systems and Networks: A Survey, Future Directions, and Novel Proposals

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ABSTRACT In recent years, underwater wireless sensor networks (UWSNs) have attracted significant attention due to their wide range of civil and defense applications. However, underwater environments impose severe challenges, including dynamic channel conditions, lack of accurate three-dimensional localization, spatial sparsity, high propagation delays, limited bandwidth, energy-constrained sensor nodes, interference, and strong background noise. Addressing these challenges requires efficient and integrated network stack designs spanning the physical, medium access control (MAC), and routing layers. Furthermore, additional performance gains can be achieved through the integration of heterogeneous communication technologies, such as acoustic and optical systems. This paper first presents an up-to-date comprehensive survey of UWSN protocols, covering the physical, MAC, and routing layers, with a detailed analysis of their design trade-offs and performance limitations. In addition, existing network stack protocols, underwater modems, and network security threats are reviewed, with particular emphasis on the Smart Adaptive Long- and Short-range Acoustic (SALSA) stack and its operational challenges. Building on this comprehensive survey, the paper identifies key research gaps and outlines future directions to enhance the development and integration of different network layers. Building on the insights derived from this survey, two main contributions are introduced. First, novel Developed-SALSA (D-SALSA) stack protocols are proposed, designed to enhance adaptability, energy efficiency, throughput, and communication reliability in dynamic underwater environments. Second, a heterogeneous network architecture is presented that leverages the complementary advantages of acoustic and optical communication technologies, with a novel management protocol adopted within the proposed D-SALSA stack protocols to support high-rate and large-scale marine data transmission. By combining research directions built on an up-to-date comprehensive survey with the design of novel stack protocols and heterogeneous networking paradigms, this work provides a unified framework for advancing UWSN performance and addressing persistent challenges in underwater communications.

INDEX TERMS Underwater wireless sensor networks, physical layer, medium access control layer, routing strategies, network stack protocols, network security threats, JANUS and SALSA stack protocol, underwater modems, heterogeneous networks, big marine data transmission.

I. INTRODUCTION

THE global interest in oceans has been increasing, particularly in the areas of climate change observation, marine ecosystems, utilization of natural resources, and security

missions [1]. These tasks are carried out through the deployment of underwater wireless sensor networks (UWSNs) [1]. UWSNs represent a fascinating and challenging field at the intersection of marine technology, networking, and sensor

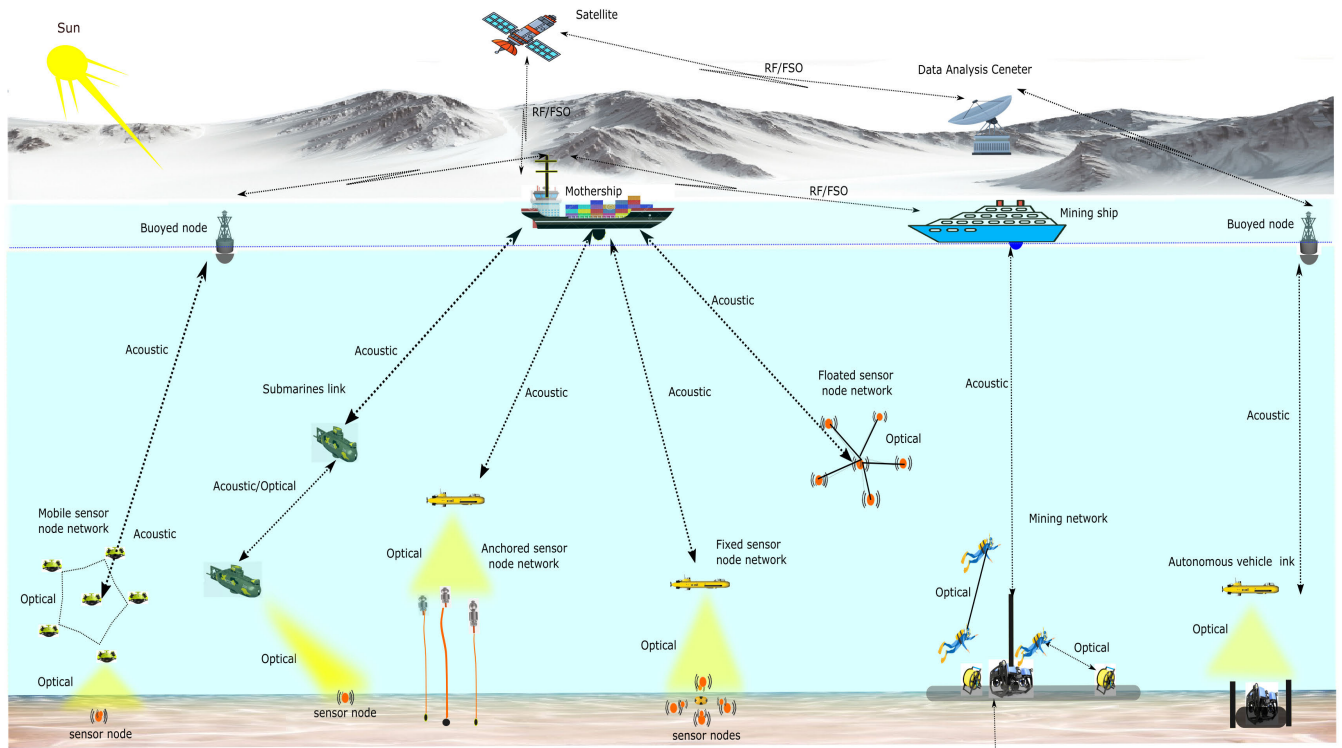


FIGURE 1. General network architecture of the underwater wireless communication systems and networks.

systems. These networks consist of interconnected underwater sensor nodes equipped with sensing, computing, and communication hardware, integrated into a network stack designed to collect and transmit data from the underwater environment.

Figure 1 illustrates various underwater wireless network scenarios, each tailored for specific applications and operational requirements. The fixed and anchored sensor nodes are strategically deployed on the seabed or attached to underwater structures to monitor environmental parameters, ocean currents, or structural integrity. In contrast, floated sensor nodes drift with ocean currents, enabling large-scale data collection over expansive areas. Mobile sensor nodes, including underwater robots, enhance flexibility by actively navigating to collect and relay data. Mining networks employ a mix of these nodes to monitor underwater excavation sites, ensuring safety and operational efficiency. Additionally, submarines and autonomous underwater vehicles (AUVs) establish communication links using acoustic and optical communication systems. While acoustic waves offer long-range but low-bandwidth transmission, optical communication enables high-speed data transfer over shorter distances, making it ideal for real-time applications. These integrated communication technologies enhance underwater exploration, surveillance, and resource management.

However, UWSNs face significant challenges in harsh underwater environments. The underwater environment is disrupted by ocean currents and sea waves, causing spatial

uncertainty. In addition, GPS cannot resolve this uncertainty due to the inefficacy of RF signals in seawater. This spatial uncertainty makes line-of-sight (LoS) communications challenging underwater, as perfect alignment is not achievable. It leads to ambiguity in node location information, increasing the probability of collisions when multiple devices access the medium simultaneously. Furthermore, the lack of precise location information complicates the selection of efficient, obstacle-free routing paths.

Additionally, underwater communication is inherently broadcast in nature, leading to power wastage and elevated network power budgets. This broadcast characteristic causes signals to travel long distances and reach multiple receivers, resulting in packet collisions and network congestion. This, in turn, increases the routing protocol overhead, which negatively impacts network scalability.

Adding to these challenges, marine topography, structures, and natural elements introduce severe signal attenuation, scattering, and dispersion. These challenges lead to multi-path fading, beam bending, and Doppler shift, all of which degrade communication reliability and reduce channel capacity. Furthermore, the underwater environment is non-uniform, influenced by pressure and temperature, adding further complexity to signal transmission, MAC, and routing techniques.

Moreover, the energy constraints of underwater sensors present substantial obstacles. Unlike terrestrial sensors, underwater devices cannot easily be recharged or replaced, making energy efficiency a critical consideration. Moreover, hardware limitations, including size, weight, battery life,

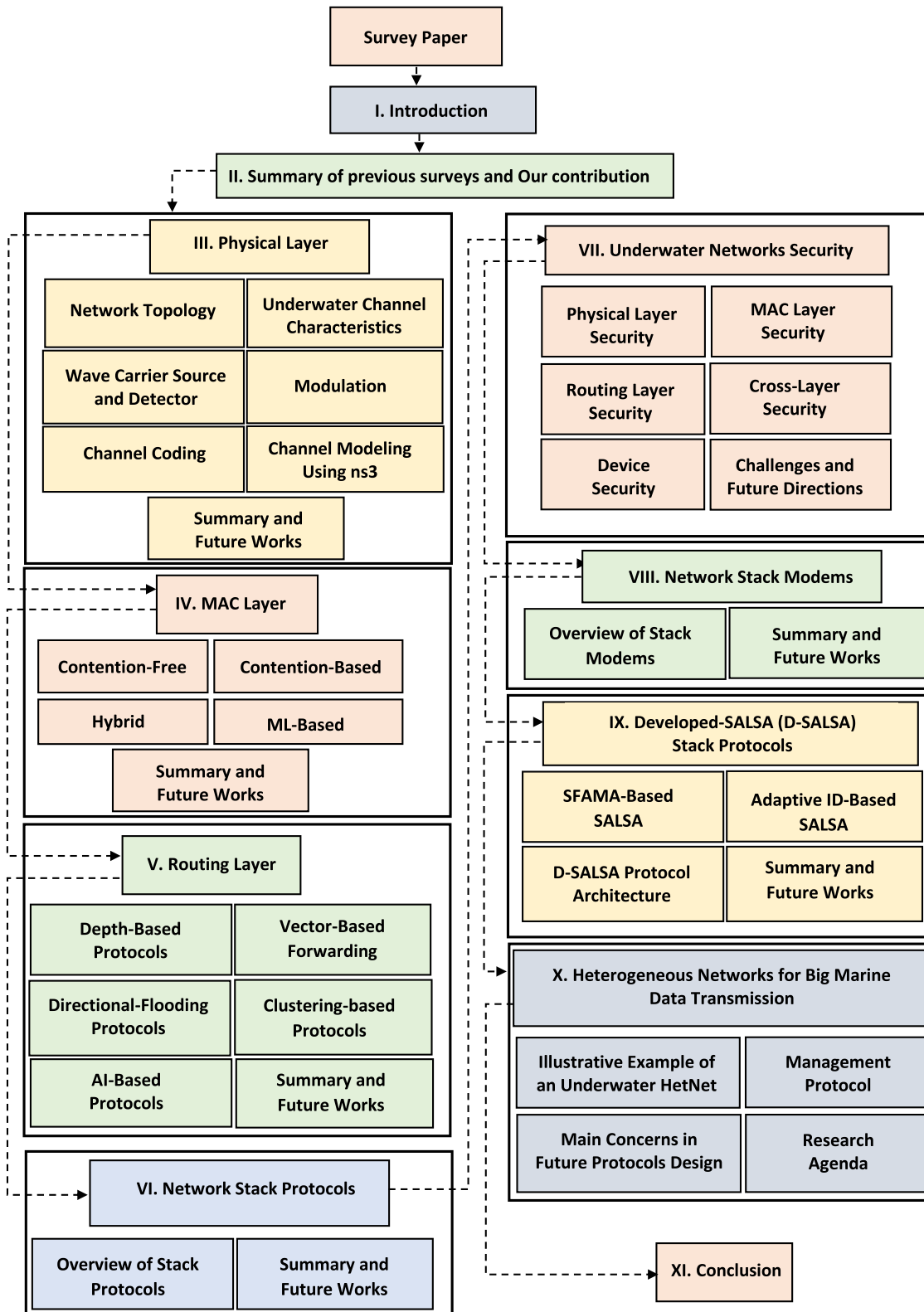


FIGURE 2. Paper Organization.

memory, and processing constraints, contribute to the challenges of hardware implementation [2], [3], [4].

To address these challenges, new methodologies must be developed for underwater networks, as their unique

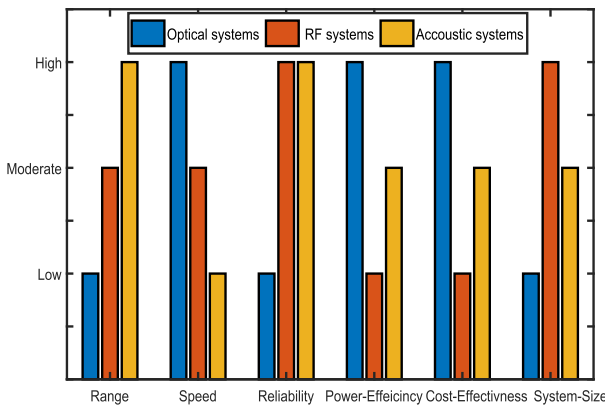


FIGURE 3. Trade-off between the wireless communication technologies for UWSNs. This figure is reproduced from [10].

characteristics make free-space communication techniques unsuitable for underwater environments. For instance, while RF carriers are highly effective for free-space communication between sink nodes and satellites, they are unsuitable for underwater channels. Figure 3 illustrates the carriers used with UWSNs, namely RF, optical, and acoustic carriers.

RF carriers offer moderate speed rates with moderate communication ranges; however, they are not power efficient, and are implemented with large sizes and high costs. In contrast, optical carriers are characterized by high-speed, high-energy efficiency, and compact size at low cost. Nevertheless, due to the dynamic nature of underwater environments and the directivity of optical sources, optical systems are limited to short-range communications and exhibit low reliability. As a result, neither RF nor optical carriers alone are suitable for reliable long-range underwater networks.

On the other hand, acoustic carriers can propagate over long distances with relatively low attenuation in seawater, enabling communication ranges of up to 20 km. Additionally, acoustic systems are implemented with moderate sizes and affordable costs. Due to these advantages, acoustic systems are predominantly used for underwater communication. However, they are limited by narrow bandwidths in the range of a few kHz, offering low-speed communications on the order of a few Kbps [5], [6], [7]. As a result, modulation techniques must be both spectrally and energy-efficient to accommodate the limited bandwidth and hardware capabilities [8].

Despite extensive research efforts, a comprehensive and universally accepted protocol stack for underwater networks, integrating the physical, MAC, and routing layers, remains elusive [9]. To address this gap, we survey key techniques for each layer and explore the design of network stack protocols. We focus on the SALSA stack, which addresses limitations in existing protocols, and introduce our own D-SALSA stack to enhance the efficiency and reliability of underwater networks. Finally, we propose future directions, emphasizing heterogeneous network architectures for large-scale marine data transmission.

The rest of the paper is organized as follows: Section II reviews the most recent survey papers, highlights their

contributions, and compares them to our contributions. Sections III, IV, and V discuss the physical, MAC, and routing layers, respectively. Section VI covers network stack protocols, and Section VIII examines underwater modems. Section VII discusses underwater security. Section IX provides a detailed discussion of the proposed developed D-SALSA network stack and presents numerical results demonstrating its performance. Section X discusses Heterogeneous Networks for Big Marine Data Transmission, and Section XI concludes the paper. Figure 2 illustrates the organization of the paper. Table 1 provides a comprehensive list of the main acronyms used throughout the paper for ease of reference.

II. SUMMARY OF PREVIOUS SURVEYS AND OUR CONTRIBUTION

This section presents a summary of up-to-date surveys, followed by a discussion of our contributions.

A. RELATED WORKS

Here, the literature on UWSNs is reviewed to identify gaps and opportunities for enhancing UWSN applications. Table 2 provides an overview of the scope of the considered survey works.

1) MAC LAYER

The author in [11] provides a comprehensive comparative analysis of various MAC protocols for UWSNs, evaluating their topology, synchronization requirements, advantages, and disadvantages. In [12], the authors provide an extensive overview of underwater acoustic communication (UWAC) MAC protocols, introducing an enhanced reference model that simplifies these protocols into core components such as time synchronization, channel access, routing, and topology management. Building on this, [13] categorizes MAC designs into two primary domains, resource-based performance (e.g., allocation, delay) and energy-efficiency, offering a deeper understanding of how these factors influence protocol performance. On the other hand, [14] presents a comparative study of four MAC protocol approaches, identifying the most suitable solution for underwater oil and gas pipeline applications by analyzing key metrics such as end-to-end delay (E2ED), energy consumption (EC), and packet delivery ratio (PDR). Finally, [15], [16] extend this discussion by exploring the challenges and opportunities for optimizing energy-efficient, collision-avoidance MAC protocols in UWSNs, focusing on specific requirements for underwater applications.

2) ROUTING LAYER

Taking an experimental approach, the authors in [17] evaluated several routing protocols for underwater acoustic sensor networks (UASNs), focusing on key factors such as energy efficiency, latency, load balancing, and robustness. Additional routing techniques and strategies, particularly those enhancing scalability and adaptability, were briefly discussed in [18]. Further advancements and specialized protocols, such

TABLE 1. List of Main Acronyms.

Acronym	Definitions
ACK	Acknowledgment
ARQ	Automatic Repeat Request
AUC	Acoustic Underwater Communication
AUV	Autonomous Underwater Vehicle
BMD	Big Marine Data
c-ACK	Cumulative Acknowledgment
CDMA	Code Division Multiple Access
CH	Cluster Head
CLDs	Cross-Layer Designs
CM	Cluster Member
CSMA	Carrier Sense Multiple Access
CSMA/NAV	Carrier Sense Multiple Access with Navigation
DACAP	Distance-Aware Collision Avoidance
DBR	Depth-Based Routing
DCB-TDMA	Dynamic Cluster-Based TDMA
DFR	Directional Flooding-based Routing
DSSS	Dynamic Slot Scheduling System
DTN	Delay Tolerant Network
E2ED	End-to-End Delay
EC	Energy Consumption
FAMA	Floor Acquisition Multiple Access
FDD	Full-Duplex Directional
FEC	Forward Error Correction
FH-BFSK	Frequency Hopped Binary FSK
FRSS	Frequency-Repetition Spread Spectrum
FSK	Frequency Shift Keying
GSFM	Generalized Sinusoidal Frequency Modulation
GUAMANET	Gossiping in Underwater Acoustic Mobile Ad-hoc Networks
GUWAL	Generic Underwater Application Language
IBFD	In-Band Full-Duplex
IoUT	Internet of Underwater Things
ISI	Intersymbol Interference
L2-ABF	Layer-by-Layer Angle-Based Flooding Protocol
L3EACH	Low-Latency Low-Energy Adaptive Clustering Hierarchy
LDB	Localization with Directional Beacons
LEACH	Low-Energy Adaptive Clustering Hierarchy
LED	Light-Emitting Diode
LoS	Line-of-Sight
MAC	Medium Access Control
MCSS	multicarrier Spread-Spectrum
MDP	Markov Decision Process
ML	Machine Learning
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OOK	On-Off Keying
OWC	Optical Wireless Communication
PCAP	Propagation-delay-tolerant Collision Avoidance Protocol
PDR	Packet Delivery Ratio
PMAC	Power Management MAC
PPM	Pulse Position Modulation
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase-Shift Keying
QoS	Quality of Service
RAT	Radio Access Technology
RF	Radio Frequency
RL	Reinforcement Learning
RS	Reed-Solomon
Rx	Receiver
SALSA	Smart Adaptive Long- and Short-range Acoustic
SDCS	Software Defined Communication Stack
SIC	Self-interference Cancellation
SNR	Signal-to-Noise Ratio
SFAMA	Slotted-Floor Acquisition Multiple Access
SVM	Support Vector Machine
TDMA	Time Division Multiple Access
T-Lohi	Tone-Lohi
Tx	Transmitter
UASNs	Underwater Acoustic Sensor Networks
UWA	Underwater Acoustic
UWAC	Underwater Acoustic Communication
UWOC	Underwater Wireless Optical Communication
UWSN	Underwater Wireless Sensor Network
VBF	Vector-Based Forwarding
VoI	Value of Information
WALL	Wireless Acoustic Line Link
WOSS	World Ocean Simulation System

as opportunistic routing and energy-efficient designs, were explored in [19], [20], and [21].

3) CROSS-LAYER DESIGN (CLD)

CLDs are crucial for optimizing resource utilization and enhancing network performance. Several studies have surveyed advancements in UWSNs, focusing on the physical, MAC, and routing layers. In [22], MAC protocols were categorized into hybrid and cross-layer protocols. The authors in [23] highlighted intelligent algorithm-based cross-layer schemes for solving complex, non-linear problems. In [24], energy-efficient and reliable MAC and routing protocols are discussed, emphasizing the trade-offs between energy

consumption, reliability, and latency. Finally, [25] provides a comprehensive survey on energy-efficient MAC and routing protocols in UWSNs, addressing various approaches and challenges to reduce energy consumption while maintaining network reliability and performance.

Several studies have also explored advancements in UWSNs by considering not only the MAC and routing layers but also the physical layer, which plays a significant role in addressing the unique challenges of underwater communication. In [26], the authors reviewed the latest developments in UASNs, discussing future trends and challenges across the physical, MAC, and routing layers. In [27], a survey of UWSNs was presented, addressing techniques at the

TABLE 2. Summary of Existing Surveys on Underwater Wireless Communication Systems and Networks.

Year	Ref.	Physical	MAC	Routing	CLD	Stack	Summary
2012	[22]	×	✓	✓	✓	×	In-depth survey of MAC and routing protocols for UASNs, addressing their challenges and solutions.
2014	[11]	×	✓	×	×	×	Survey of MAC protocols for UWSNs, covering various techniques and performance metrics.
2014	[26]	✓	✓	✓	✓	×	Survey on advances and future trends in physical, MAC, and routing layers in UWSNs.
2015	[17]	×	×	✓	×	×	Review of routing protocols for UWSNs with emphasis on energy efficiency and scalability.
2015	[27]	✓	✓	✓	✓	×	Survey on UWSN at physical, data link, and network layers, discussing protocols and their practical implications.
2016	[23]	×	✓	✓	✓	×	Categorization of UASN routing protocols and introduction of intelligent algorithm-based approaches.
2016	[24]	×	✓	✓	✓	×	Focus on energy-efficient MAC and routing protocols for UWSNs, assessing performance based on energy and communication efficiency.
2017	[12]	×	✓	×	×	×	Detailed review of MAC protocols for UWANs with a structured reference model and key research directions.
2017	[28]	✓	✓	✓	✓	×	Exploration of challenges in UASN design across OSI layers, focusing on network architecture and acoustic channel characteristics.
2020	[13]	×	✓	×	×	×	Analysis of algorithmic design for UASNs, covering communication modeling, localization, and routing protocols.
2020	[14]	×	✓	×	×	×	Survey on MAC protocol approaches for UWSNs, with focus on performance metrics and protocol classification.
2020	[18]	×	×	✓	×	×	Survey on energy-efficient routing protocols in UWSNs, focused on applications like environmental monitoring and pollution detection.
2021	[15]	×	✓	×	×	×	Survey of energy-efficient collision-free MAC protocols for UWSNs, providing a detailed classification of strategies.
2021	[19]	×	×	✓	×	×	In-depth survey on routing protocols for UWSNs, providing insights on performance and optimization techniques.
2021	[20]	×	×	✓	×	×	Survey on recent advancements in energy-efficient routing protocols for UWSNs.
2021	[29]	✓	✓	✓	✓	×	In-depth review of CLD in UWSNs, emphasizing energy efficiency, QoS, and network lifetime.
2021	[30]	✓	✓	×	✓	×	Review of full-duplex physical and MAC layer-based UWSNs, exploring opportunities, challenges, and future directions.
2022	[16]	×	✓	×	×	×	Comprehensive survey on MAC layer protocols for UASNs, including challenges and solutions.
2022	[25]	×	✓	✓	✓	×	Overview of energy-efficient MAC and routing protocols for UWSNs, categorized under a new taxonomy.
2023	[21]	×	×	✓	×	×	Review of opportunistic routing protocols in the Internet of Underwater Things (IoUT), covering key challenges and future directions.
2025	Our paper	✓	✓	✓	✓	✓	We present an up-to-date, comprehensive review of physical, MAC, routing, and network stack protocols, as well as security threats and underwater modems, highlighting existing gaps and future research directions. Furthermore, we propose enhanced SALSA-based stack protocols (D-SALSA) and introduce a novel management protocol for heterogeneous network architectures that leverages hybrid acoustic and optical communication, integrated into the D-SALSA framework.

physical, data link, and network layers to improve network performance and overcome underwater communication constraints. In [28], the protocol design for signaling, MAC, and routing in UASNs was explored, emphasizing the necessity for hybrid and cross-layer solutions. Finally, [29] examined cross-layer design approaches in UWSNs, highlighting the

integration of multiple network layers to optimize resource utilization and network performance.

B. OUR CONTRIBUTIONS

There are two main areas of contribution in this paper. The first is bridging the gaps in previous surveys, and the second

is proposing a new stack protocol and a new management protocol for underwater heterogeneous networks. The details of our contributions are as follows:

- **Up-to-Date Comprehensive Survey with New Research Directions:**
 - **Physical, MAC, and Routing Layer Protocols:** We conduct a comparative analysis of state-of-the-art protocols at the physical, MAC, and routing layers, emphasizing their strengths, limitations, and practical applications, and proposing future research directions.
 - **Stack Protocol Evaluation:** Unlike previous studies that focus on individual layer protocols, our survey examines contemporary stack protocols, evaluating their interoperability, trade-offs, real-world performance, and proposes future research directions.
 - **Security in Underwater Wireless Networks:** We conduct a comparative analysis of state-of-the-art security threats and solutions across physical, MAC, and routing layer protocols and devices, and propose future research directions.
 - **Underwater Modems:** While most prior works focus on protocol-level optimizations, they overlook the critical role of underwater modems in enabling efficient communication. We address this by analyzing modem technologies, their design challenges, and their impact on network performance, and by proposing future research directions.
- **Proposed New Stack Protocols:** Existing surveys do not explore specific protocol enhancements. This paper provides an in-depth analysis of the conventional SALSA protocol and introduces enhanced versions, the Developed-SALSA (D-SALSA) stack protocols, demonstrating significant advancements in design and performance.
- **Proposed Two-Tier Management Protocol:** This paper proposes a novel two-tier management protocol for heterogeneous underwater networks, where the acoustic channel serves as a control plane and optical wireless communication as a high-capacity data plane. The protocol is integrated into the proposed D-SALSA stack architecture.

III. PHYSICAL LAYER

The physical layer of underwater wireless communication systems significantly impacts link reliability, data throughput, and energy efficiency. However, robust performance remains difficult due to severe absorption, scattering, multipath propagation, Doppler spread, and turbulence, all of which distort and attenuate transmitted signals. Mitigating these impairments requires adaptive transmission, signal processing, and suitable coding techniques.

Beyond channel impairments, system performance is influenced by network topology, which determines energy consumption, connectivity, and synchronization efficiency

under dynamic conditions. Also, channel characteristics driven by the spatial, temporal, and frequency variability of seawater and the differing propagation behaviors of acoustic and optical waves establish the fundamental limits of communication. Operating within these constraints requires efficient wave carrier generation and detection using optimized piezoelectric projectors, optical emitters, and sensitive hydrophone or photodetector receivers.

Given these constraints, modulation schemes encode information onto carriers while balancing spectral efficiency, robustness, and energy usage. Channel coding techniques further enhance reliability by mitigating errors due to multipath and Doppler effects, with both conventional and machine learning-based adaptive approaches increasingly adopted. Moreover, high-fidelity simulation tools such as ns-3 enable accurate modeling of underwater channels and support performance evaluation of modulation, coding, and topology strategies under realistic conditions.

Accordingly, this section examines key physical layer components, including topology, channel characteristics, wave carrier sources and detectors, modulation, channel coding, and ns-3-based modeling, to provide a unified view of their combined impact on system performance and reliability.

A. NETWORK TOPOLOGY

Physical and logical arrangement of communication infrastructures connecting devices, sensors, and nodes plays a decisive role in determining performance metrics such as energy consumption, latency, reliability, and network lifetime, particularly in power-constrained underwater environments. Considering that most underwater nodes are battery-powered and difficult to recharge or replace, energy efficiency is a major design concern. multi-hop topologies, where packets are relayed through intermediate nodes, were previously reported to conserve energy by reducing the required transmission range [31]. However, this benefit comes at the cost of increased communication complexity, synchronization overhead, and latency, particularly in high-traffic or dynamically changing underwater environments. These trade-offs underscore the need to balance energy consumption with throughput and latency.

Choice of network topology depends on deployment area, device count, and reliability requirements. In ad hoc network applications, a critical bottleneck is the lack of prior knowledge about node locations, energy status, or link quality. This necessitates robust neighbor discovery protocols, which are foundational for efficient network initialization [32], [33], [34]. Centralized topologies, such as the CDMA-based discovery scheme led by a master node [32], [35], offer orderly coordination but suffer from single points of failure and poor scalability. By contrast, distributed discovery algorithms [36], [37] and multi-hop architectures, promote scalability and fault tolerance with energy balance [38], [39] though requiring complex coordination protocols [40].

Recent studies emphasized topological flexibility, through topology-aware or adaptive networking, as a resilience

strategy, especially under conditions of node drift, disconnections, and path loss due to ocean currents, marine organisms, or human activity [41], [42], [43]. Here, the topology evolves based on environmental feedback and application needs. Previous efforts to optimize topological structures mainly focused on enhancing QoS and energy efficiency of a network. Some proposed schemes were based on complex network theory [44] and time-varying channel-aware models better representing the dynamic acoustic environment [45]. Importantly, approaches using dynamic location-based energy models [46], [47], [48] showed promise in aligning network structure with spatio-temporal communication demands. Despite these advances, many existing schemes remain limited by assumptions of static node behavior or perfect channel knowledge. For instance, while Expectation Maximization and Vickrey–Clarke–Groves (VCG) auction mechanisms [49] offer theoretical energy gains through optimal relay selection, these mechanisms may struggle with practical deployment under variable node mobility or partial observability.

More recent innovations integrate machine learning (ML) into improving topology discovery. For example, optimal directional transmission based on adaptive reinforcement learning (RL) and a Q-learning-based topology-aware routing protocol were used to achieve lower energy usage, shorter discovery latency, and longer network lifetime [50], [51]. However, in harsh and unpredictable underwater conditions, reliance on training data and environmental predictability can limit real-world effectiveness.

B. CHANNEL CHARACTERISTICS OF SEAWATER

The underwater communication environment is strongly affected by physical and chemical characteristics of seawater that, in turn, vary across geographical locations and depths. Unlike ideal laboratory conditions, real-world underwater channels are highly dynamic and heterogeneous, which introduces significant challenges for signal propagation.

1) IMPURITY DISTRIBUTION AND TURBIDITY

Seawater is a complex medium composed of saline water mixed with various dissolved and suspended impurities such as mineral salts, organic matter, and biological materials [52], [53]. These impurities contribute to turbidity, which directly impacts signal attenuation, particularly for optical wireless communication (OWC). Higher turbidity leads to increased scattering and absorption losses, reducing the maximum achievable communication range. Generally, seawater is classified into pure, clear, coastal, and turbid [54]. However, albeit practical, this classification is overly simplistic. For example, mixing of riverine and seawater (e.g., estuaries) introduces gradients of turbidity that could change over horizontal distance [55], thereby complicating link reliability in fixed-topology networks. Similarly, for vertical channels, from sediment-laden seabeds to relatively clearer surfaces, turbidity changes with depth [56], thus requiring adaptive

modulation or beam-steering mechanisms for deployed systems like sensor arrays.

2) SEA ICE AND SNOW LAYERS

In polar regions, oceans are frequently covered by sheets of sea ice that, during winter, are further layered with thick snow [52], [57], [58]. This introduces multi-layered inhomogeneities affecting both acoustic and optical signal propagation. Sea ice is not uniform, as it contains brine pockets, air bubbles, and solid salts, each contributing to different scattering behaviors. Importantly, environmental factors, such as soot deposition, result in stratified layering, while seawater influences the base, leading to bio-contamination such as green algae growth in lower layers [59].

This layered structure creates a non-linear and anisotropic propagation path, which may become particularly problematic for vertical communication channels. Modeling sea ice as homogeneous or static, as was previously done in several earlier studies, ignores its dynamic and location-specific nature, potentially leading to inaccurate system performance predictions. A more realistic model would treat ice sheets as multi-layered media with spatially varying reflectivity and scattering coefficients.

3) REFLECTIVITY AND OPTICAL INTERFERENCE

Concentration of impurities in sea ice and snow affects their reflectivity to incident light. Furthermore, this significantly affects OWC systems operating near or through the sea surface area. To accurately model vertical channels through sea ice, ice should be represented as multiple layers with varying degrees of whiteness. For instance, white or snow-covered ice has a high albedo, reflecting most incident light, which can interfere with upward optical communication or limit energy harvesting systems relying on surface light penetration. Conversely, transparent or partially transparent ice types offer better optical transmission, but are less common and highly localized [59].

Furthermore, trade-offs arise between system positioning and transmission efficiency. While locating sensors beneath reflective snow-covered ice ensures environmental protection, it also increases the optical path loss and limits LoS communications. The choice of wavelength becomes critical, as shorter wavelengths suffer more from scattering, while longer ones are more absorbed, thus requiring a balanced selection tailored to the ice type and impurity profile.

C. CHANNEL CHARACTERISTICS FOR UWAC

Acoustic waves are the most conventional communication technique in deep or long-range underwater scenarios. However, several channel characteristics significantly impact propagation and reception of acoustic signals in underwater environments, presenting challenges that affect system design, reliability, and energy efficiency. For instance, path loss due to the attenuation of acoustic signals as they travel through water is a dominant factor, driven by absorption, scattering, and geometric spreading. Also, when signals

reflect off underwater surfaces and objects, they cause variations in signal strength and frequency shifts, compromising communication reliability. The refraction and scattering of signals lead to misalignment and distortion, particularly in long-range transmissions. Interference from other acoustic sources or ambient noise further degrades communication quality, bringing about the need for robust modulation and coding techniques for error mitigation. Apart from these, noise sources such as thermal, wind-generated, and biological noise contribute to overall signal degradation, which requires sophisticated signal processing algorithms for reliable data recovery in UWAC systems.

1) PATH LOSS AND MULTIPATH FADING

Modeling of an acoustic channel as time-invariant is based on its response to channel geometry and sound-speed profile [60]. The path loss of the channel, along with the link range, is affected by the signal frequency due to absorption and spreading losses [60], [61], [62].

Typical path loss of an acoustic signal of frequency f transmitted over a range l is given by the following equation [63]:

$$A(l, f) = A_0 l^k a(f)^l, \quad (1)$$

where A_0 is a scaling constant, k is the spreading loss factor, and $a(f)$ is the absorption coefficient.

Fading of received signals arises as sound waves arrive from multiple propagation paths. These paths result from reflections due to the presence of boundaries (e.g., sea surface and sea floor) and refraction from spatially varying sound speed profiles, affected by changes in temperature, salinity, and pressure [60]. These multipath components frequently exhibit longer delays, variable amplitudes, and non-stationary behavior, thus significantly degrading communication quality through inter-symbol interference (ISI) and time-varying distortion.

For P multipath components, any p -th path ($p = 0, 1, \dots, P - 1$), can be modeled assuming a low-pass filter with transfer function as shown below [64]:

$$\bar{H}_p(f) = \frac{\Gamma_p}{\sqrt{A(\bar{l}_p, f)}}, \quad (2)$$

where \bar{l}_p is the nominal length of the paths and Γ_p is the cumulative reflection coefficient along the path [60].

Several previous studies have proposed other models for multipath fading. For instance, in [65], the authors developed a channel model specifically tailored for shallow underwater environments, incorporating the effects of surface reflection coherence loss and seabed roughness, which are critical for improving short-range and low-frequency applications. Furthermore, a geometry-based stochastic model applicable to both horizontal and vertical link configurations was proposed in [66], with consideration of link orientation. A complementary model is the fast time-delay estimation algorithm based on linear frequency modulation signals introduced in

[67]. This enables low-latency multipath detection, which is particularly suitable for AUVs.

To mitigate the adverse effects of multipath-induced ISI, several signal processing techniques were proposed, each offering distinct trade-offs in complexity, robustness, and adaptability. For instance, in [68], the authors explored a time-domain equalization technique, a relatively low-complexity solution for ISI suppression; the proposed technique was shown to be effective in static or slowly varying channels. However, it depends on accurate and real-time channel estimation, which is frequently challenging in dynamic underwater environments. In another relevant study [69], the authors employed Direct Sequence Spread Spectrum (DSSS), which improves resilience against multipath fading and jamming by introducing redundancy through spreading codes. However, it requires more bandwidth and increased power consumption, making it less suitable for energy-constrained nodes. In [70], the authors proposed ML-based models to address multipath fading by capturing non-linear and dynamic channel behaviors. Although ML was found to offer adaptive capabilities and improved performance under varying conditions, it could incur computational overhead, especially from training large datasets.

2) DOPPLER EFFECTS

Movements of the sea surface or transceiver platforms in UWAC systems generate Doppler spread, which causes time-varying frequency shifts. If not properly addressed, these shifts degrade system performance by distorting the channel impulse response and destroying subcarrier orthogonality in multicarrier systems like OFDM [61], [69], [71].

In [72], the authors proposed a hybrid Doppler power spectrum model combining both Gaussian and spike profiles. The proposed model took into account diffuse sea-surface scattering, which captures the sharp contributions from transceiver motions. This model was found to provide a more realistic representation of the composite nature of Doppler in UWAC; yet, it still simplifies the inherently non-stationary behavior of the channel over time. By contrast, several classical models approached Doppler as a time-invariant or block-stationary phenomenon offering analytical tractability, but falling short in capturing short-term transients and frequency-selective mobility [61], [71].

The physical depiction of Doppler is a frequency-dependent compression or expansion of the acoustic waveform. This becomes particularly problematic in OFDM systems, where even slight Doppler shifts compromise the orthogonality of subcarriers, leading to severe inter-carrier interference [73], [74]. The low-complexity channel tracking approach proposed in [74] is foundational to enhance the detection of multiple-carrier signals; however, it does not scale well under high mobility or in shallow water environments with strong reverberations.

More recent efforts focused on dynamic estimation and compensation schemes, revealing a shift from static

channel assumptions to adaptive Doppler-aware frameworks. For instance, several previous studies [75], [76] explored a pilot-assisted Doppler tracking, achieving moderate complexity but limited performance in rapidly fluctuating channels. In another relevant study [77], the authors introduced a time-domain compensation strategy tailored to low signal-to-noise ratio (SNR) conditions, though it trades off computational efficiency. While ML-based approaches offer promising adaptability by learning channel behavior [78], they require extensive training data and raise concerns about generalization across environments. A comparative review suggests a trade-off between modeling precision and real-time feasibility [79]. Highly adaptive algorithms (e.g., ML-based or iterative estimation frameworks [80], [81]) were reported to deliver superior performance under harsh Doppler scenarios, but at the cost of increased computational burden, latency, and hardware demands. Conversely, simpler approaches are easier to implement in embedded systems, but offer limited resilience in highly dynamic or shallow-water deployments.

3) RAY BENDING AND POINTING ERROR

Spatial variability of the sound speed profile (SSP) due to temperature, salinity, and pressure gradients results in ray bending at a constant rate, particularly over long-range, low-speed or vertical transmission links [82], [83]. Unlike electromagnetic waves, which generally follow linear trajectories, acoustic rays refract through an inhomogeneous medium and follow curved paths, often modeled as a circular arc with radius $R = 1/gE$, where g is the linear gradient of the medium and E is a ray-specific parameter [84]. This deviation causes displacement from the expected receiver location and results in signal attenuation, uncertainty about arrival times, and poor localization precision.

Several modeling schemes analytically characterized ray trajectories based on sound speed gradients; however, this body of work often assumed static or layered SSPs, which oversimplifies dynamic ocean environments [82], [83]. In practice, environmentally induced SSP fluctuations result in highly non-linear ray paths that undermine these models' predictive accuracy. To address the localization challenge posed by ray bending, in [85], the authors integrated SSP and transmission delay estimation into their simulation framework. However, while this approach enhanced robustness in 2D scenarios, it could have limited scalability in deep-water 3D environments where multipath and bending interaction are more complex. An experimental demonstration of direct-path recognition for high-precision node localization was undertaken in [86], with the results showing practical feasibility under controlled conditions. However, such methods largely depend on a clear LoS, which is frequently unavailable in turbid or cluttered underwater settings. In [87], the authors introduced a correction-based approach, vital in distributed networks, to address node synchronization errors in bending cases, though with computational trade-offs in real-time deployment.

Aside from ray bending, because of transmitter-receiver (Tx-Rx) misalignment that may arise from the swerving nature of the water bodies, instability of mobile communication platforms, and other factors, pointing errors occur as the transmitted signal deviates from the intended center of a receiver [88]. This error introduces an angular deviation that reduces the beamforming gain, particularly in narrow beam or highly directional acoustic systems [89], [90]. In a recent study, the pointing error was modeled for buoy-to-IRS-to-AUV-based acoustic links, accounting for real-time environmental disturbances such as tide and wind [91]. However, although this framework is insightful for attempting to couple environmental modeling with geometric misalignment, its practical implementation is limited by the relative cost and complexity of integrating intelligent reflective surfaces (IRS) in underwater networks.

Another solution to the pointing error problem was proposed in [92], where the authors introduced a track-and-point control scheme using a mobile acoustic transducer capable of angular rotation based on the ray trajectory. Nevertheless, despite being promising in dynamic conditions, this approach introduces mechanical complexity, latency, and energy overhead, making it less suitable for small or resource-constrained platforms. Comparatively, array-based receivers offer passive mitigation by spatially capturing misaligned beams, trading off complexity for robustness. However, this scheme may suffer from increased hardware cost, size, and calibration requirements, particularly in swarm-based or miniaturized AUV deployments.

4) NOISE AND INTERFERENCE

Noise in a UWAC channel introduces signal distortion, hence compromising the reliability of the received data. Typically, such noise can be categorized into radiated noise, self-noise, ambient noise, reverberation noise, and target noise [93]. Another classification of noise in underwater environments is based on background and location dependence [61]. Background noise, frequently caused by ambient sources like wind waves, is typically modeled as Gaussian (non-white) with a power spectral density that decays over frequency. By contrast, location-dependent noise, arising from region-specific sources such as seismic activity near tectonic boundaries, tends to exhibit non-Gaussian characteristics [61], [94]. Yet, while this layered classification enables more targeted modeling strategies, it comes at a major challenge of efficient mitigation strategy, as many existing techniques rely on stationary or simplified noise assumptions that are rarely valid in practical deployments.

To suppress ambient noise, the authors in [93] used the Gabor Wavelet transform to exploit time-frequency localization. However, this method is computationally heavy and struggles with non-stationary and impulsive noise. These limitations can be addressed with an S-transform-based denoising algorithm, as previously proposed in [95], which

demonstrates superior SNR improvements. However, both aforementioned methods are sensitive to parameter tuning and may perform inconsistently in channel realizations.

Using a statistical approach, Feng et al. [96] introduced a sparse Bayesian learning framework for joint noise suppression and channel state estimation. This technique is highly adaptive and robust to noise uncertainty; however, it incurs high computational costs, thereby limiting its applicability in real-time systems. Furthermore, without prior knowledge of channel state information, the authors in [97] used a deep learning (DL) scheme to mitigate the impact of noise. This model was found to perform well under unknown or dynamic channel conditions; yet, it requires extensive training data and computational resources, raising concerns about generalization and deployment feasibility in resource-constrained AUVs or sensor nodes.

Noise is sometimes represented as interference, especially for relatively high signal-to-interference-plus-noise-ratio and desirable BER [98]. An extended delay spread from multiple path propagation causes intra- and inter- interference among transmitted symbols. To detect these interfered symbols, in [99], the authors developed an adaptive sliding window interference detection algorithm that dynamically adjusts based on estimated delay profiles. This technique enhances detection in multipath-dominant channels, but becomes difficult to calibrate in rapidly changing environments. On the other hand, in [100], the authors modeled interference into physical and protocol-level components. Building on this evidence, an enhanced acoustic protocol interference model was proposed to provide a more integrated view of interference in MAC-layer and physical-layer interactions [98]. This approach is conceptually promising, but still relies on idealized assumptions about node behavior and spatial distribution.

To improve the practicality of most interference assumptions, especially on spectral efficiency, several previous studies focused on self-interference. In [101], the authors proposed an adaptive self-interference cancellation (SIC) scheme based on the normalized least mean-square algorithm for an in-band full-duplex (IBFD) UWAC system. Yet, while this improves self-interference suppression, the adaptation rate is limited under strong reverberation. To increase flexibility, in another relevant study [102], a variable step-size least mean squares (LMS) algorithm was developed to enhance convergence speed and performance. However, this approach may introduce parameter sensitivity and over-adapt in low-noise regions. A possible complementary approach is the geometry-aware SIC model previously proposed in [103], which incorporates the physical layout of the transceivers. This structural insight is valuable, but requires precise localization and modeling, which may not always be available. For systems without prior interference knowledge, a Least Trimmed Squares (LTS) equalizer based on robust regression was introduced in [99], for application in both single and multicarrier scenarios. Yet, while LTS is statistically robust to outliers, its iterative nature may limit its suitability for low-latency applications.

D. CHANNEL CHARACTERISTICS FOR OPTICAL COMMUNICATION

In contrast to acoustic systems, optical communication systems using intensity-modulation/direct-detection (IM/DD) schemes offer high data rates and superior power efficiency, with compact transceivers design [5], [6]. However, their performance is significantly constrained by the limitations of the physical layer.

On the physical layer, several factors critically affect optical signal propagation and reception, including channel impairments, link misalignment, system noise, the non-linearity of opto-electronic components, and eye safety. Path loss, caused by absorption, scattering, and beam divergence, results in significant signal attenuation as light propagates through water. Because of scattering and reflections from suspended particles and underwater surfaces, multipath effects occur, causing signal distortion and temporal spreading. Driven by temperature variations in the water, turbulence fading introduces amplitude fluctuations that degrade system performance. Under the impact of seawater waves, currents, and tides, link misalignment and pointing errors further impact signal quality, particularly in long-range transmissions. In addition, ambient noise from sources such as solar radiation, bioluminescence, and artificial light can interfere with signal detection.

The following subsections provide a detailed discussion of these impairments in optical communication systems.

1) ABSORPTION AND SCATTERING

Propagation of optical rays in sea ice and seawater is significantly affected by interactions between photons and the surrounding medium, including molecules and suspended particles [5], [6]. These interactions cause substantial absorption of ray intensity and alter the direction of propagation, leading to scattering, both of which degrade signal transmission. While absorption can be mitigated by increasing transmitted power, scattering requires an efficient solution to the induced multipath effects that lead to pulse dispersion and beam spreading at the receiver [104], [105], [106]. These effects are particularly detrimental in high-speed and long-range optical communication, as they contribute to ISI and limit the number of photons successfully detected by the receiver [54].

The severity of absorption and scattering is strongly affected by the composition of sea ice sheets and seawater [52], [107]. In snow-covered sea ice sheets, the optical beam experiences severe diffusion, significantly reducing transmission quality. Due to the presence of brine pockets and air bubbles, the sheets exhibit lower absorption, but higher scattering [108], [109]. In seawater, particulate and dissolved organic matter contribute to increased absorption, while suspended sediments further enhance scattering. However, the concentration of chlorophyll is classically considered. Importantly, these effects also depend on wavelength (λ) and are characterized by coefficients (in m^{-1}), denoted as $a(\lambda)$ and $b(\lambda)$, for absorption and scattering, respectively.

For instance, in clear seawater, the lowest optical attenuation occurs at the blue-green region (approximately 460 nm) due to the negligible concentration of water particulates, allowing for longer communication ranges and higher transmission speeds. However, in more turbid waters, shorter wavelengths are degraded by increased chlorophyll absorption and sediment scattering, shifting the optimal transmission range to longer wavelengths (around 540 nm), where the impact of scattering is mild [110].

Coefficients $a(\lambda)$ and $b(\lambda)$ are collectively characterized (i.e., $a(\lambda) + b(\lambda)$) by the beam extinction attenuation coefficient $c_e(\lambda)$ for collimated light and the diffuse attenuation coefficient $K_d(\lambda)$ for diffuse light sources [6], [111], [112], [113], [114]. In scenarios with minimal scattering and where $c_e(\lambda)$ remains constant over a given range L , propagation loss h_c is typically modeled using Beer's Law, which describes an exponential decay of intensity with a constant h_l , given by the following:

$$h_c(\lambda, L) = h_l \exp[-c_e(\lambda) \cdot L].$$

However, for long-range transmissions where multipath scattering becomes significant, a two-term exponential loss model is proposed to characterize these effects accurately, assuming perfect symbol synchronization [115]. It distinguishes between attenuation loss at distances shorter and longer than the diffusion length, with the following expression:

$$h_c = h_{l1} \exp[-c_{e1} \cdot L] + h_{l2} \exp[-c_{e2} \cdot L], \quad (3)$$

where the channel impulse response results across L are obtained using Monte Carlo simulation. Parameters $h_{l1}, c_{e1}, h_{l2}, c_{e2}$ can be determined through an LMS fitting algorithm [54], [110], [115], [116].

2) LINK MISALIGNMENT

In addition to the peculiarities of absorption and scattering effects on signals from collimated and diffused light sources, they are vital deployment considerations due to the Tx-Rx classical point-to-point requirement for efficient optical wireless communication [113], [114]. Errors caused by this pointing constraint, particularly in the absence of precise localization and alignment mechanisms, become significant in dynamic underwater environments due to ocean currents, waves, wind speeds, and mobile Tx-Rx nodes hosted on platforms such as AUVs and buoys. In such scenarios, the narrow divergence angle of laser diode beams makes the system easily prone to Tx-Rx link misalignment, hence hindering long-range transmissions. This misalignment, even between mobile nodes, can be mitigated by using the wide divergence angle of LED beams, ensuring broader optical coverage at the Rx plane. However, due to geometric spread, this approach remains more reliable for short-range communication. Therefore, for pointing errors at relatively minimal dynamic aquatic medium or nodes mobility (e.g., buoy transceiver due to wind-speed of 1-5 m/s), a more directed beam, with its low

geometric loss, achieves better link performance as compared to that of a wider beam [117].

In modeling link misalignment, in [118], the authors proposed a dynamic angular pointing error model for a laser source, fundamentally following the Beckmann distribution, which accounts for geometric loss in the presence of scattering. The results in [118] revealed the link performance, the relaxing effect of scattering on misalignment, and its attenuation on the channel. More recently, the authors in [119] introduced a laser misalignment channel model based on the beam spread function; in this study, the authors considered the impact of multiple scattering for application in underwater Internet of Things communications. The model was found to foster improvement of network topology design, routing techniques, and security algorithms. In [120], misalignment was modeled by the Rayleigh distribution for a massive multiple-input multiple-output (MIMO) system. To minimize the cause of sub-channel correlation of the system, an interference cancellation algorithm based on partition space-time block coding was proposed. This algorithm adopts the receiver signal-sequencing detection scheme with minimum misalignment severity to improve the link performance. For a multiple-input single-output (MISO) system, a cross-medium focused phased array model was proposed and experimentally demonstrated to compensate for misalignment between communication nodes [121]. It can be exploited in reorienting beamforming to adjust the detection area without re-positioning the node. Fundamentally, as presented in [122], most models were derived from the characterization of link misalignment, h_p . The misalignment model accounted for attenuation due to geometric spread, where the radial displacement r_p of the transmitted beam spot (following a Rayleigh distribution) was defined relative to the receiver's detection center, with a parameter w_{Leq} . Given A_0 as the maximum fraction of received power at $r_p = 0$, h_p is expressed as follows [122], [123]:

$$h_p = \exp(-2r_p^2/w_{Leq}^2) A_0.$$

3) TURBULENCE

Random variations in the refractive index of the aquatic medium, particularly due to sea currents, lead to turbulence-induced fading on propagating optical signals. This causes average signal fluctuations in intensity and phase at the Rx plane [5], [114]. Indicators of these gradient variations in water properties include pressure, temperature, salinity, and air bubbles. These changes along the sea depth, especially for temperature and salinity, are stepwise in pattern rather than uniform, which prompts their modeling as a cascade of layers. Specifically, there are layers where these properties remain relatively stable over several meters, after which they are separated by thin, strong gradient sheets about a few centimeters thick, where rapid changes occur [123], [124].

For optical signals along a vertical oceanic-turbulent link, in [125], the authors introduced a cascaded-layer model of the channel, considering temperature and salinity changes with depth. In such a vertical multi-layer scenario, in [126], the

authors gave a unified evaluation of link performance for turbulence modeled as generalized Gamma (GG), exponential GG, exponentiated Weibull, and Gamma-Gamma. Another unified approach based on experimental data was explored in [127], where the authors statistically modeled fading effects due to air bubbles and temperature changes. The aforementioned study of the channel irradiance variations was based on mixture exponential-GG distribution. Furthermore, in [128], the authors experimentally analyzed intensity fluctuations caused by variations in temperature, salinity, and air bubbles. This study employed a beam-expander-and-collimator at the Tx and an aperture-averaging lens at the Rx to validate the Generalized Gamma and exponentiated Weibull distributions using experimental data. Overall, turbulence is classified as weak or moderate/strong based on the scintillation index, which indicates fading severity. Weak turbulence aligns with the Lognormal distribution (e.g., $h_t = \exp(T)$, where T is the log-amplitude coefficient of turbulence that follows a Gaussian distribution), while moderate to strong turbulence follows the Gamma-Gamma distribution [123], [125], [128].

4) NOISES AND INTERFERENCES

A variety of noise sources, such as dark current, shot noise, thermal noise, and background noise, affect optical receivers [129]. Dark current refers to the small electrical current that flows through photodiodes (PDs) when no photons are received. In most cases involving Positive-Intrinsic-Negative (PIN) PDs, dark current is typically negligible as it is overshadowed by other noise sources [130]. Shot noise, which is signal-dependent, arises from the quantum properties of PDs, specifically the random fluctuations in the arrival of photons [129]. When photon arrival rates are low, such as in turbid seawater or white sea ice channels, shot noise is modeled using the Poisson probability distribution function. However, when the photon arrival rate is high, as in clear seawater channels, the random behavior of shot noise is well approximated by a Gaussian distribution [130].

Furthermore, thermal noise is generated by the thermal effects in the PD circuits, particularly in the load resistors of transimpedance amplifier modules [129]. This noise increases with the temperature of the circuits. In underwater environments, the temperature is the highest at the surface of seawater and decreases with depth [130]. However, undersea ice sheets generally maintain seawater temperatures below zero degrees Celsius [108], with temperatures increasing with depth. Under such conditions, thermal noise is less severe than other noise sources [59].

Background noise primarily arises from solar radiation during the day, with its intensity affected by factors such as weather conditions, the zenith angle of the sun, surface conditions, sea ice types, and the depth of the receiver [130]. At the same depth, background radiation is generally higher in non-frozen oceans than in frozen ones, which is largely due to the effects of sea ice and cold weather [112], [130]. At the surface, background radiation is at its peak; however, as light scatters and is absorbed in the water, the impact

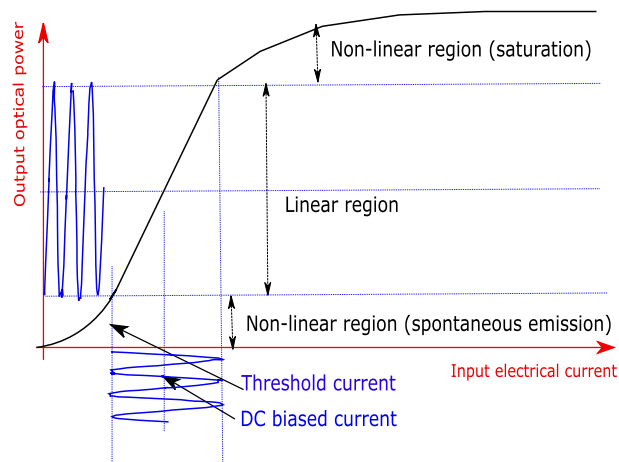


FIGURE 4. Non-linearity characteristics of LD sources (the figure reproduced from [132]).

of background radiation decreases with depth, reaching its lowest point at the seabed [58]. In addition, background radiation depends on the wavelength of the optical carrier source and is the highest within 480 – 532 nm [112].

For deployment considerations, ultraviolet light sources such as the LUMA X-UV and BlueComm 200 UV can be used for transmission in the presence of ambient light. However, this comes with the tradeoff of reduced transmission range caused by increased scattering at shorter wavelengths and greater water absorption outside the blue-green optical window. For shallow waters exposed to sunlight and short-range transmissions, PIN PDs and avalanche photodiodes are ideal. In high-speed, low-light detection applications, photomultiplier tubes and silicon photomultipliers are more suitable, but are sensitive to high light levels. In addition, optical bandpass filters are frequently used to reduce sunlight interference, while newer solutions, such as liquid crystal displays as dynamic optical filters or adaptive optical apertures, help to mitigate ambient light and multi-user interference [131].

5) NON-LINEARITY OF OPTO-ELECTRONIC COMPONENTS

Although laser diodes (LDs) can provide broadband communications in the Gbps range, their transmitted power and communication speed are practically limited due to the non-linearity of opto-electronic components in IM/DD systems (see Fig. 4). Figure 4 illustrates the relationship between the electrical current applied to the LD input and the optical power emitted from the output. LDs operate linearly within a dynamic range in which the optical intensity increases proportionally with the driving current; this is the linear region in the figure.

However, when the driving current exceeds this range, LDs behave non-linearly, and the optical intensity no longer increases with the driving current, as can be seen in the saturation region of the figure. In addition, LDs exhibit non-linearity when the driving current is smaller than a threshold,

at which point the LDs are considered off; this is referred to as the spontaneous emission region in the figure. The non-linearity of LD sources in IM/DD systems is a phenomenon known as “clipping” [132], [133].

Furthermore, opto-electronic components have limited bandwidths, which restrict the modulation speed of LD sources. At high-speed modulation, the optical carrier of the LD suffers from a phenomenon called chirping [134], where the optical carrier frequency shifts up and down instantaneously. Compared to coherent systems, due to the effects of noise clipping and chirping, IM/DD systems are typically suited for low-speed applications with limited power (i.e., in the Mbps and mW ranges, respectively). However, as discussed in the subsequent sections, MIMO systems, multicarrier techniques, and high-order modulations offer promising solutions to increase communication speeds to the Gbps range. For example, in [135], the authors used the OFDM scheme to demonstrate a wireless optical link with a data rate of up to 4.8 Gbps over a 5.4-meter distance in water.

6) EYE-SAFETY

Due to its low absorption in the visible spectrum (400 – 700 nm), the visible window is the preferred range for underwater communications [111]. However, the high directivity and narrow beamwidth of LD sources limit the permissible transmitted power due to the maximum permissible exposure (MPE) level for eye safety [136], [137]. When using LD sources, eye safety should be carefully considered to ensure the protection of humans and animals underwater. Moderate to high transmitted power levels can be hazardous, potentially causing eye and skin damage to divers and marine life. For example, a laser point source with a wavelength of 840 nm is restricted to a power of below 0.24 mW to remain eye-safe; it is classified as a Class II laser according to industry safety standards [138]. Furthermore, a laser point source with a wavelength of 530 nm and a power level of 100 mW is restricted to specific applications, such as medical surgery, and is classified as a Class IIIb laser [138]. The MPE level depends on the wavelength and beamwidth of the LD sources. Therefore, point source LDs are not recommended for communication purposes [138].

Using transmitter optics (e.g., a diffuser cascaded with collimator lenses) with LD sources can transform the point beam into a wider beam, which relaxes the MPE restrictions to some extent. For example, using a holographic diffuser, Khoo et al. increased the allowable transmitted power from 0.24 mW to 1.1 mW (i.e., a five-fold increase) for a laser point source at a wavelength of 840 nm [139]. In addition, the underwater channel itself can help mitigate these risks, as the scattering in seawater diffuses the LD beam, thus reducing the potential risks to the eyes and skin [59].

E. WAVE CARRIER SOURCE AND DETECTOR

A vital consideration in the design of wireless communication systems is the choice of efficient wave carrier source

and detector modules, exploited to enable the bidirectional conversion between electrical signals and propagating carrier waves. In this case, they are either in the acoustic or optical domain (see Fig. 5) [64], [140], [141]. At the transmitter, the information-bearing signal is modulated onto a carrier wave, for instance, either through a piezoelectric projector for acoustic transmission or a light-emitting diode (LED) for optical systems. The piezoelectric projector converts electrical signals into mechanical pressure waves through the inverse piezoelectric effect, offering mechanical robustness and good efficiency over low-frequency bands typical of long-range UWAC [142], [143]. However, this results in limited bandwidth and slow propagation speed, making acoustic systems less suitable for high data rate transmission. By contrast, LEDs operate at much higher carrier frequencies, enabling high data rate transmission of light intensity modulated signals, but with limited link range and strong sensitivity to water turbidity and misalignment [144], [145].

To improve the efficiency of wave propagation, especially in focusing the signal, carrier source components are paired with enhancing acoustic or optical elements such as horns or lenses. Acoustic horns are designed to improve impedance matching between the transducer and the aquatic medium, thereby enhancing acoustic directivity and reducing transmission losses [146], [147]. However, while these horns can significantly improve directional radiation, their bulkiness can limit application in compact AUV systems. For optical systems, lenses such as collimators, parabolic reflectors, or telescopes are used to manipulate the coverage and direction of the emitted light beam, especially to minimize beam divergence and maximize the received power [88], [148].

Furthermore, due to the possible movement of transmitter-receiver platforms, beam steering mechanisms are used to adaptively direct the carrier wave towards the intended receiver, which is particularly valuable in high-frequency UWAC and directional UWOC systems. In acoustic systems, this is typically achieved using phased-array projectors controlled by phase or time-delay circuits, thus enabling beam directional control without physically rotating the transducer [149], [150]. On the optical side, mechanical gimbals, microelectromechanical systems (MEMS) mirrors, or liquid crystal-based beam directors are used to steer the beam along a line-of-sight path [151], [152]. This combination of projection horns or optics with beam steering not only improves directionality but also significantly reduces channel fading and multipath spread by ensuring that the energy is concentrated along the intended path. However, despite improving directionality, these enhancements introduce mechanical complexity and alignment sensitivity, particularly in mobile underwater scenarios.

On the receiver side, the incoming signals are first collected and directed using receiving horns (acoustic) or collecting optics (optical) before being captured by detector components to convert the received waveform back into electrical signals. In acoustic reception, hydrophones, frequently based on piezoelectric or MEMS technology, can be used

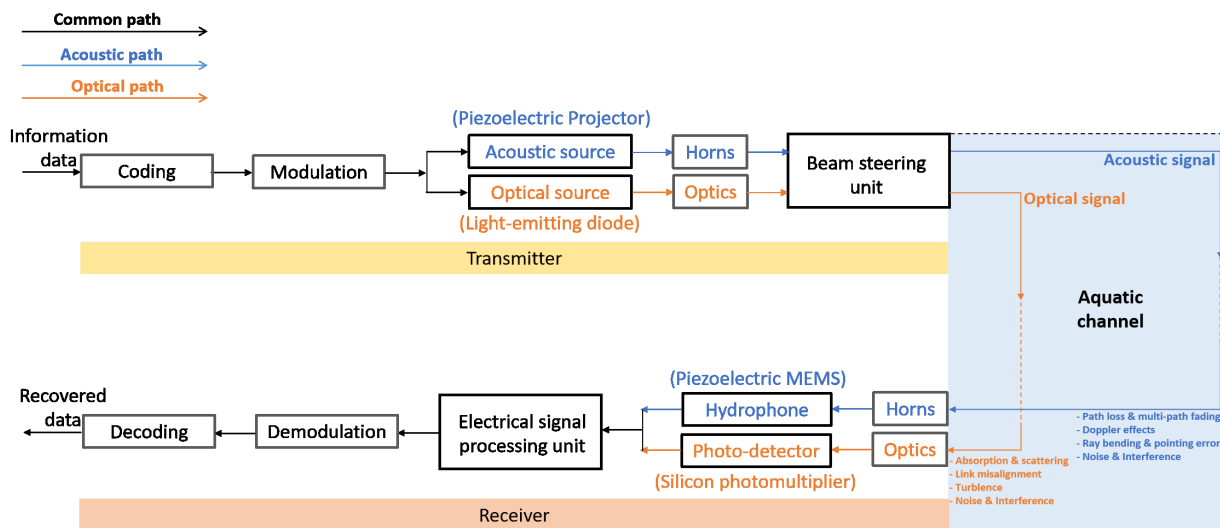


FIGURE 5. General block diagram of an acoustic and an optical underwater wireless communication system.

to transduce underwater pressure waves back into electrical signals [143], [153]. Yet, although these MEMS hydrophones enable miniaturization and integration with compact platforms, they often require enhanced signal conditioning due to higher inherent noise [154]. For the optical reception, the photodetector, particularly the silicon photomultiplier (SiPM) or avalanche photodiode (APD), is used to detect weak or scattered light signals and convert them into electrical form [155], [156]. SiPMs are advantageous in low-intensity applications due to their high gain; yet, they also exhibit limited dynamic range and are sensitive to temperature variations [88], [157].

Following signal detection, the resulting electrical signals are passed through a signal conditioning and digital processing unit for filtering, amplification, synchronization, etc. The output signal is demodulated and decoded to recover the originally transmitted signal. This post-detection block is critical for mitigating the distortions introduced by the channel, particularly those caused by solar radiation, Tx-Rx misalignment, multipath fading, Doppler spread, scattering, and noise from the receiver circuitry [88], [130], [158]. To mitigate these underwater impairments, advanced signal processing algorithms such as equalizers, ML-based demodulators, and decoders are used to further improve robustness and real-time adaptability, particularly in mobile underwater networks [159], [160], [161], [162]. For instance, various equalization and error correction coding strategies were previously shown to improve system robustness in underwater environments significantly, and considerable focus was placed on reducing computational complexities [163], [164], [165], [166].

F. MODULATION

1) TRADITIONAL MODULATION TECHNIQUES

Due to random fluctuations in transmitted signals introduced by the aforementioned channel characteristics, the choice

of modulation technique becomes crucial, as it significantly influences system performance, particularly in terms of data rate, power efficiency, and resilience to interference. Generally, modulation schemes are categorized into single-carrier and multicarrier systems. Although single-carrier systems offer low complexity and resilience in fast-fading channels, they frequently require complex equalization to mitigate ISI, limiting scalability for high-data-rate applications [89], [90]. By contrast, multicarrier techniques demonstrate better handling of long delay spreads and frequency-selective fading, thus achieving higher spectral efficiency and simpler equalization [88], [167].

In UWAC systems, some typical digital modulation techniques include Amplitude-Shift Keying (ASK), Frequency-Shift Keying (FSK), and Phase-Shift Keying (PSK) [168]. The FSK and PSK schemes are predominantly employed due to their resilience in highly dispersive and fading channels. More specifically, a noncoherent FSK system is widely adopted in rapidly time-varying channels where phase coherence is difficult to maintain. These systems typically mitigate ISI by introducing guard intervals to allow multipath reverberations to decay between transmissions. Though this comes at the cost of reduced spectral efficiency from lower data throughput, this approach offers significant benefits in terms of receiver simplicity and resilience [89].

However, to meet the growing demand for higher data rates and improved spectral efficiency, several phase-coherent modulation schemes, such as coherent PSK and Quadrature Amplitude Modulation (QAM), were introduced [89]. Such schemes are characterized by enhanced resilience to phase-induced distortions, enabled by advanced synchronization techniques (typically based on differentially coherent or purely phase-coherent [89]) and channel estimation, which often exploit the sparse nature of multipath acoustic channels [169]. This makes these schemes capable of supporting high-speed transmissions over severely time-dispersive

channels, albeit with a trade-off of system computation complexity [170].

To further enhance bandwidth utilization and mitigate frequency-selective fading, in recent years, multicarrier modulation techniques such as orthogonal frequency division multiplexing (OFDM) have been explored [171]. OFDM splits the available acoustic spectrum into multiple orthogonal subcarriers, thus reducing ISI and simplifying equalization, which would otherwise be complex in single-carrier systems. However, due to their sensitivity to time-varying channels, OFDM systems can suffer from intercarrier interference. These systems also suffer from a high PAPR, which may pose challenges in popular power-constrained underwater applications.

Possible solutions to these challenges are ICI equalization methods and orthogonal signal-division multiplexing (OSDM) [169], [172]. The OSDM offers not only comparable spectral efficiency to OFDM but also a lower PAPR, enhancing practicality in real-world deployments. In addition, novel variants such as orthogonal chirp division multiplexing (OCDM) and orthogonal time-frequency space (OTFS) modulation were explored to address motion-induced frequency offsets and severe Doppler spread, especially for highly mobile applications [172].

In practice, for optical carrier communication systems, intensity modulation with direct detection (IM/DD) is widely adopted over coherent modulation schemes. Characterized by simplicity, lower cost, and efficiency, IM/DD typically involves modulating the intensity of an optical source by directly varying its drive current using the base-band signal. Alternatively, an external modulator can be used to control the optical output, allowing full source power utilization, but with limited modulation range and higher drive current requirements [5].

A common IM technique is on-off keying (OOK) modulation, where the presence or absence of an optical pulse represents binary data “1” or “0” respectively. There are two OOK variants: Return-to-Zero (RZ) and Non-Return-to-Zero (NRZ); the former variant offers better energy efficiency at the cost of increased bandwidth usage. Given the simplicity of IM-based signaling, for transmissions with data rates above 2.5 Gbps, an external modulation was proposed [173]. However, with high-level signaling, direct modulation can achieve higher data rates. For instance, using 16-QAM-OFDM, data rates beyond 4 Gbps were achieved [135].

On the other hand, IM/DD systems are susceptible to intensity attenuation caused by absorption and scattering, particularly in challenging environments like underwater or foggy atmospheres. Furthermore, eye safety regulations limit the maximum allowable transmit power, particularly in indoor settings. To overcome these limitations, adaptive detection techniques using channel state information and pilot-based estimation were developed [6], [174]; yet, these techniques still require real-time adaptability and low-complexity algorithms.

2) ML-BASED MODULATION TECHNIQUES

A recent trend gaining traction is the integration of ML to enhance modulation performance in both UWA and UWOC systems. For instance, a DL-coded index modulation-spread spectrum approach, proposed in [175], encodes data in spreading code indices, thereby significantly improving spectral efficiency and energy savings. Its use of an environment-independent DL detector reduces the burden of real-time retraining and proves robust in complex multipath conditions. Similarly, a two-stage index-modulated Universal Filtered multicarrier (UFMC) system integrated with a DL detector (TSIMNet) introduced in [176] demonstrated improved resilience to carrier and symbol time offsets, offering a viable alternative to OFDM for IoUT applications.

In the optical domain, ML showed promising results for modulation classification and demodulation. For instance, in [177], the authors explored the use of AI algorithms such as decision trees, k-nearest neighbors, support vector machines, and a convolutional neural network to classify modulation schemes. A 95% accuracy at SNRs above 6.3 dB was achieved with performance associated with the number of symbols, suggesting design flexibility. Similarly, in [178], the authors compared deep belief networks and adaptive boosting (AdaBoost) for signal demodulation, with AdaBoost achieving superior robustness across varying SNRs and modulation orders, further underscoring the adaptability and accuracy of ML-based solutions.

Considering that conventional modulation techniques face fundamental trade-offs between complexity, spectral efficiency, and environmental robustness, it becomes important to focus on ML-enhanced systems that offer a compelling pathway to adaptively balance these trade-offs. This being said, challenges remain in terms of training data requirements, generalization across diverse underwater environments, and computational overheads, all of which require further investigation for real-time and scalable deployment.

G. CHANNEL CODING

Although modulation techniques play a critical role in ensuring the efficient and robust transmission of signals over underwater acoustic and optical communication systems, their performance is fundamentally constrained by the physical limitations of the channel. To address this concern, channel coding serves as a complementary strategy by introducing controlled redundancy to detect and correct errors introduced during transmission. The major trade-off in channel coding lies between redundancy (overhead) and error correction capability, which impacts both spectral efficiency and reliability.

Channel coding schemes can be broadly categorized into block codes and convolutional codes, with more recent developments extending to turbo codes, low-density parity-check (LDPC) codes, and polar codes, each with distinct trade-offs in terms of decoding complexity, latency, and performance near channel capacity [6], [179], [180].

1) BLOCK CODES

Block codes, such as the Reed-Solomon (RS) codes and Hamming, are easy to implement and offer reliable error correction for burst errors, which makes them particularly useful in UWOC systems where attenuation and scattering can cause short bursts of errors [181].

In [182], a (255,129) RS code was employed to improve the performance of a UWOC system using 405 nm OOK-RZ modulation. Experimental results revealed an 8 dB SNR gain at a BER of 10^{-4} as compared to the uncoded system, exceeding the theoretical 6 dB gain. In addition, the RS-coded system can tolerate a 0.25 higher attenuation coefficient, indicating improved resilience in turbid water.

For a UWOC system subject to the intense and directional varying solar noise impact at the Rx, in [183], the authors studied the improved system performance using RS coding. Stronger RS codes minimize high solar irradiance but incur greater computational and energy costs. This suggests that a fixed RS configuration is sub-optimal across varying orientations, thus requiring an efficient adaptive RS coding strategy for better energy efficiency and error resilience.

To improve the reliability of a time-varying UWAC system, another relevant study [184] proposed the integration of optimized Hamming distance into OTFS index modulation to reduce index redundancy. The results from optimized index mapping revealed achieving a BER of zero at SNRs of 22 dB and 26 dB for one and two active sub-grids, respectively, thus substantially outperforming randomly selected mappings. This gain is especially evident at high SNRs (≥ 15 dB), where Hamming optimization improves BER performance even when the lower-complexity greedy detection algorithm is used, which then rivals the performance of ML detection without optimization.

Considering both RS and Hamming coding techniques for a hybrid OFDM-MIMO-based underwater wireless communication system, the authors in [185] reported achieving a BER of 10^{-3} using RS codes with QAM, whereas Hamming with QPSK was found to improve BER to 10^{-6} at the same SNR, showing better energy efficiency and reliability for real-time underwater transmission. However, their fixed-length structure limits their adaptability to time-varying channel conditions.

2) CONVOLUTIONAL CODES

Convolutional codes, frequently decoded using the Viterbi algorithm, are better suited for streaming underwater applications and offer improved performance in slowly fading channels [90]. However, this coding scheme suffers from high decoding complexity for long constraint lengths, making it less ideal for low-power or real-time applications. In [186], the authors integrated convolutional coding with a constraint length of 7, generator polynomials [171, 133] (octal), and a coding rate of 1/2, into a Hadamard-Viterbi joint decoding framework for an MFSK-based UAC. The results revealed that soft-decision Viterbi decoding significantly outperformed hard-decision decoding and standalone Hadamard coding.

Under additive white Gaussian noise (AWGN), the joint Hadamard-convolutional coding scheme achieved the lowest BER across all tested E_b/N_0 values. For example, at $E_b/N_0 = 3$ dB, the joint scheme showed a BER close to 10^{-4} , while the hard-decision convolutional code remained around 10^{-2} . This order-of-magnitude improvement highlights the value of soft decoding-based convolutional codes in ensuring communication reliability in multipath and Doppler-affected underwater channels.

Across the AWGN channel of a UWAC operating in noisy and multipath environments, convolutionally coded MFSK was previously used to achieve a 4 dB gain in E_b/N_0 over the uncoded frequency-hopped (FH)-FSK approach used in the JANUS standard, for the same PER [187]. Despite a ~ 1 dB implementation loss as compared to theoretical bounds, the simulation for a memory length of 8 demonstrated performance well within acceptable margins. This evidence suggests that the interleaving mechanism appears to play a key role in channel clearing and reducing error propagation, particularly under channel-induced bursts typical in underwater scenarios. Furthermore, in more challenging environments, uncoded FH-FSK suffers from a BER floor of 3.5%, whereas the proposed convolutionally coded MFSK was found to reduce PER below 10^{-3} at 10 dB lower E_b/N_0 than JANUS, indicating an improved alternative for energy efficiency and error correction.

Another relevant investigation [188] evaluated the impact of zero-tailing (ZTC), direct-truncation (DTC), and full tail-biting (FTB) convolutional codes to ensure reliability of short message transmission in multipath underwater acoustic channels. The results across AWGN channels showed that FTB codes closely matched ZTC performance, with only a 0.1 dB gap at $BER = 10^{-5}$, thereby confirming that FTB can offer comparable protection without the redundancy overhead of tail symbols. By contrast, DTC codes consistently underperformed, especially at short block lengths ($L = 12, 25$), due to weak protection at the code ends. In real ocean experiments, under severe multipath without equalization, the FTB codes using (3,1,6), which corresponds to a 1/3 code rate and a constraint length of 6 at $L = 25$, were found to outperform ZTC and DTC ($BER = 6.5 \times 10^{-3}$ compared to 1×10^{-2} , 2.4×10^{-2} , respectively). This evidence illustrates that, despite the lack of explicit tail bits or equalization, FTB coding can maintain strong error resilience in practical, interference-laden UAC environments.

Considering the dynamic environmental factors affecting the performance of UWOC systems, including the challenges introduced by underwater motion-induced fluctuations, in [189], the authors investigated the mitigating role of convolutional coding. The results showed sensitivity of BER performance to code rate and motion parameters, especially for an expanded motion area than for increased transmission distance. Convolutional coding was found to significantly reduce the required SNR to achieve an acceptable BER of 10^{-3} , with improvements ranging from 7 – 9 dB in static cases to as much as 55 – 72 dB in dynamic scenarios. More

specifically, lower-rate convolutional codes (e.g., rate 1/3) offer superior error correction at the expense of throughput, a trade-off that is well justified in harsh underwater conditions.

3) TURBO CODES

To achieve near-Shannon-limit performance, turbo codes and LDPC codes are increasingly used in both UWA and UWOC systems. With their iterative decoding and use of interleavers, turbo codes offer exceptional error correction even at low SNRs, making them highly effective for long-range UWA links where SNRs are typically low. Considering a single-carrier UWAC system, in [190], the authors studied the error-correction and near-capacity performance of iterative turbo decoding in the presence of multipath, Doppler shift, and low SNR. Using the coded scheme, error-free decoding (0% BER) at multiple transmission points was achieved for over 70% of tested (modulation, position) pairs when SNRs exceeded 10 dB. Some dependency on SNR was also observed. For instance, in turbo-coded transmissions, single-hydrophone SNRs exceeding 8 dB resulted in reliable decoding, while SNRs below 6 dB led to increased BERs (up to 5-10%), particularly at longer ranges (4.5 km). This highlights the SNR threshold (~8 dB) below which turbo decoding starts to degrade.

When decoding signals from 4 or 8 hydrophones, BERs significantly dropped, even at lower per-hydrophone SNRs. This spatial diversity improves decoding convergence in turbo iterations, effectively extending the operational range and increasing prediction accuracy (85 – 90% accuracy with 8 hydrophones). Similarly, the results reported in [191] showed that using 8 hydrophones and turbo coding, error-free communication was predicted at $\text{SNR} \geq 19$ dB and achieved experimentally in 10 of 14 modulation-source combinations, even at higher modulations such as 64-QAM (3.72 kbaud). By contrast, with only the top receiver, success dropped to 3 of 10 predicted cases, showing turbo coding's reliance on spatial diversity to fully exploit soft decoding gains. In addition, the STBC-SCFDE system with Turbo coding was reported to benefit from spatial diversity, with BER decreasing as the number of transmit antennas increased [192]. This observed synergy between spatial diversity and coding makes this joint strategy ideal for scalable and robust underwater networks, especially in low-to-moderate SNR regimes and dynamic environments.

Furthermore, in [193], the authors conducted performance analysis of turbo-coded MIMO-OFDM systems for underwater communication over a realistic shallow water acoustic channel model characterized by multipath delay spread, Doppler shift, and ambient noise. The results highlighted that turbo coding significantly enhanced the BER performance in underwater environments, with the coded system requiring far lower SNRs than its uncoded counterpart in achieving a BER of 10^{-3} at just 5.1 dB SNR with a zero-forcing ordered successive interference cancellation (ZF-OSIC) detector, as compared to 38 dB without coding. Furthermore, performance was found to improve with the use

of a Minimum-Mean-Square-Error-OSIC detector, yielding a BER of 10^{-4} at an SNR as low as 5.1 dB and outperforming the ZF detector by approximately 1.6 dB at the same BER target. This demonstrates the exploitable coding gain from turbo codes with optimized detection algorithms.

Moreover, the use of iterative Log-MAP decoding and soft decision processing allows the turbo-coded system to effectively mitigate ISI and channel-induced degradation, thereby offering substantial improvements in reliability without compromising data throughput. However, the iterative nature of turbo codes results in high latency and power consumption, which is undesirable for delay-sensitive or battery-operated systems. Accordingly, a fully parallel scheme can be exploited to improve the decoding throughput, making it suitable for high-speed applications, though with a compromise to hardware efficiency [192].

4) LDPC CODES

Due to parallel decoding architecture and scalable sparse parity-check matrices, LDPC codes outperform turbo codes in both latency and power-constrained scenarios [194]. However, their performance depends on code design, channel estimation accuracy, and requires large block lengths for optimal performance, which may introduce delay and vulnerability to synchronization errors prevalent in underwater channels.

For an OFDM-based underwater acoustic system, a non-binary LDPC scheme over GF(16) and GF(64) was used in [195]. The results revealed strong error correction under both AWGN and Rayleigh fading, with high-order modulations (e.g., 16-QAM at rate 5/6) yielding substantial gains over lower-rate codes, particularly when uncoded BER is below 0.1. This approach was also found to reduce OFDM's peak-to-average power ratio (PAPR) by leveraging the dense generator matrix, thus enhancing practical applicability without added complexity. Meanwhile, compared to conventional LDPC, a protograph-based spatially coupled LDPC code for OFDM acoustic channels achieved dB gain at 10^{-3} BER under equal latency constraints (1536 information bits) [196]. Furthermore, increasing the sliding window size from $W=4$ to $W=8$ was found to reduce the required SNR from 5 dB to 3.65 dB, thus highlighting a trade-off between decoding latency and error performance.

On the optical side, in [197], the authors considered LDPC-coded OFDM UWOC systems under moderate turbulence (scintillation index 0.05). At an SNR of 12 dB, the system demonstrated a four-order magnitude BER reduction as compared to uncoded systems. The authors observed that longer code lengths (e.g., 1024) and higher-order modulations enhance performance, though requiring appropriate parameter tuning to maintain resilience against fading. In addition, considering reduced computational complexity, the quasi-cyclic LDPC-coded MPPM scheme proposed in [198] achieved 10.7 – 13.6 dB coding gains for various levels of turbulence-induced fading. Particularly, 12.3 dB gain was achieved at $\text{BER} = 10^{-4}$ in weak turbulence (scintillation

index of 0.2073), outperforming OOK and PPM. This scheme is particularly relevant under conditions where channel state information is unavailable. However, the improvement comes with a trade-off in spectral efficiency as the MPPM format shifts to favor power efficiency.

5) POLAR CODES

Originally celebrated for the capacity-achieving properties over symmetric binary-input memoryless channels, polar codes have increasingly gained traction in underwater communication systems due to their low-complexity encoding and decoding structures and strong error correction potential in structured, static environments.

In OFDM-based underwater acoustic systems, the integration of polar codes demonstrated remarkable improvements over traditional LDPC schemes. Under sea trial conditions, a Monte Carlo-constructed polar code with OFDM yielded up to 1.7 dB SNR improvement and 98% frame success rate, significantly outperforming LDPC-coded systems that achieved only 78.5% frame recovery [199]. This not only demonstrates the importance of the construction method, but also highlights the adaptability of polar codes to multipath and Doppler-induced distortions. Meanwhile, in downlink multi-user OFDM systems, a nested polar code structure was proposed in [200], enabling CSI-independent decoding and eliminating the need for successive interference cancellation. Simulation results showed that users with code rates of 7/16 and 1/4 achieved BER values effectively near zero at 17 dB SNR, thus outperforming a conventional 7/8 rate polar code by up to 2 dB. In tank experiments, these findings were verified with BERs of 10^{-5} to 10^{-4} at just 9.79 dB SNR, allowing for error-free image reconstruction.

In optical domains, polar codes combined with PPM modulation (Polar-PPM) proved to be particularly effective in UWOC links. In [201], under both Gaussian and weak turbulence (scintillation index of 0.1), Polar-PPM was found to achieve 1–2 dB coding gain over uncoded PPM systems at a BER of 10^{-3} , with longer code lengths (e.g., $N = 1024$) providing superior BER due to stronger polarization. However, the gains in decoding performance from the increase in list size in successive cancellation list (SCL) decoders begin to taper off beyond $L = 8$, pointing to a practical trade-off between complexity and gain. Extending this to hybrid laser-acoustic systems, in [202], the authors confirmed a 2 dB gain at BER = 10^{-3} for Polar-PPM with $N = 512$. The authors also showed that higher PPM orders (e.g., 16-PPM) compromise performance due to slot ambiguity and increased demodulation errors, emphasizing that modulation order must be chosen carefully.

The above studies establish polar codes as a promising low-latency, low-complexity alternative to LDPC in shallow-water and cross-medium underwater links, particularly where CSI is limited and power efficiency is paramount. However, improvements in decoding under high-order modulation and turbulent conditions remain an open challenge.

6) ML-BASED AMC FRAMEWORKS

Adaptive modulation and coding (AMC) schemes jointly optimize modulation order, coding rate, and power allocation to achieve significant gains in spectral efficiency and energy consumption over fixed schemes, especially when guided by effective SNR or post-equalization SNR metrics reflecting the complex underwater channel dynamics [203].

In recent years, coded modulation techniques such as bit-interleaved coded modulation (BICM) have become essential for enhancing spectral efficiency and robustness in underwater communications, particularly in multicarrier systems like OFDM, where BICM mitigates burst errors caused by frequency-selective fading [204]. However, the performance of BICM largely depends on precise channel estimation and interleaver design, which are challenging under highly dynamic and noisy underwater environments. Also, traditional threshold-based AMC approaches suffer from rigid switching criteria and require explicit CSI, which is frequently outdated or inaccurate in UWA scenarios. To address these limitations, recent studies used ML techniques to enable data-driven and adaptive AMC frameworks. For example, RL-based AMC schemes demonstrated remarkable improvements in both energy efficiency and throughput by learning transmission policies online without prior CSI models, adapting swiftly to channel variability, and reducing energy consumption by over 20% as compared to benchmark algorithms [205].

Similarly, deep neural networks for BER estimation combined with deep RL algorithms such as double deep Q-networks were reported to provide near-optimal energy efficiency (approximately 560 bit/J) despite BER estimation errors (MAPE = 0.43). This was achieved by employing robust channel classification methods that reduce the state space complexity inherent in UWA channels modeled as finite-state Markov chains [206]. Moreover, these data-driven approaches identified critical system parameters, such as optimal feedback link SNR (~ 12 dB), that balance classification accuracy and feedback overhead, overlooked by conventional schemes. Collectively, these ML-enhanced AMC methods offer scalable, low-complexity, and robust solutions capable of real-time adaptation to challenging and uncertain acoustic environments, thereby outperforming fixed modulation and classical Q-learning-based methods in practical deployments.

H. CHANNEL MODELING USING NS3

In the domain of underwater communications, channel modeling is essential for understanding and simulating the propagation characteristics of signals underwater. Simulator ns3 enabled the creation of realistic underwater environments by incorporating various channel models that account for the complex interactions between sound/light waves and the underwater medium [207]. These models consider factors like attenuation, multipath propagation, scattering, and Doppler effects, providing valuable insights into signal degradation and path loss across different distances and depths.

By simulating these channel characteristics within ns3, researchers can evaluate the performance of communication protocols and signal processing techniques under realistic underwater conditions. This enables optimization of system parameters and development of robust communication solutions tailored to the challenges of underwater communications.

1) ACOUSTIC CHANNEL MODELING USING NS3

The ns3 simulator offers three models for acoustic channels: ideal, Thorp, and Bellhop models [208], [209], [210]. The ideal model does not consider channel impairments and is unsuitable for modeling practical scenarios. For the Thorp model, it accounts only for path loss as a function of frequency and distance, neglecting other impairments like Doppler and time spreading. Both the ideal and Thorp models are readily available for use and can be easily integrated into simulated networks.

The Bellhop model, on the other hand, is a realistic channel model that considers all channel impairments, including path loss, beam bending, multipath propagation, and Doppler effects. This model employs ray tracing techniques to trace acoustic rays from the transmitter to the receiver, considering all intermediate interactions such as ray refraction, reflection, bending, and scattering. The Bellhop model uses temperature and pressure profiles of seawater environments to compute accurate channel parameters. While not directly available in ns3, the Bellhop model can be integrated with third-party tools such as the World Ocean Simulation System (WOSS). The WOSS is a multi-threaded C++ framework that facilitates the integration of existing underwater channel simulators, requiring environmental data as input and providing channel realizations as output.

2) OPTICAL CHANNEL MODELING USING NS3

The underwater optical communication module for the ns3 simulator named "UOC module," has an extension to the ns3 core libraries to study the performance of the optical physical layer and its impact on the network layer [211], [212]. The UOC module consists of: `ns3::Channel`, `ns3::PropagationLossModel`, `ns3::NetDevice`, and `ns3::ErrorModel`, all necessary for enhancing the simulating capabilities of the UOC ns3. The `ns3::Channel`, and `ns3::PropagationLossModel`, components aids to emulate the distinct characteristics of an underwater optical system. It can simulate optical systems in different water types, including pure sea, coastal ocean, clean ocean, and turbid harbor, demonstrating the impact of varying water conditions such as turbidity, attenuation, and temperature on the received optical signal.

The `NetDevice` component is divided into `UOC_NetDeviceTX` (transmitter) and `UOC_NetDeviceRX` (receiver), enabling precise modeling of bidirectional communication. Also, the module accounts for the evaluation of point-to-point UOC system performance

through SNR, BER, and packet error rate (PER) models for a given modulation. For instance, the `UOC_SNR` class models the signal-to-noise ratio, while `UOC_ErrorModel` refines error handling for the underwater optical channels. These structured inheritance ensures modularity, reusability, and extensibility, thus providing a robust simulation framework tailored to underwater optical communication [207].

Generally, for mobility applications, such as for AUVs, ns3 uses modules such as random waypoint and saw-tooth movements for modeling. Random waypoint movements are suitable for AUVs like REMUS, while saw-tooth movements are more appropriate for seaglider AUVs. Researchers can configure the speeds, directions, depths, and pitches of AUVs, which are equipped with Li-Ion battery models. The power profile of micro-modems, such as those from the Woods Hole Oceanographic Institute, is assumed in the simulation, and the energy model of AUVs can be either REMUS or seaglider AUV models.

I. SUMMARY AND FUTURE WORKS

In summary, the physical layer of wireless communication systems, though it exploits the complementary strengths from acoustic and optical channels, remains fundamentally constrained by the hostile and highly dynamic underwater environment. Significant progress has been made in topology optimization, channel modeling accuracy, and adaptive signal processing (especially in modulation and coding), but achieving a robust balance across reliability, data rate, and energy efficiency of the system remains an open challenge. Recent research explores the deployment of hybrid acoustic-optical communication, which leverages the long-range reliability of acoustics with the high data rates of optical links to improve the overall achievable system performance. Also, machine learning techniques, such as reinforcement learning-based adaptive modulation and deep neural network-assisted channel estimation are emerging as promising solutions for handling the uncertain underwater environments. To further provide a holistic overview of the discussions in this section, Table 3 consolidates the key takeaways from network topology, channel characteristics, modulation, coding, and channel modeling perspectives.

To foster significant system enhancements, future works should focus on the development of unified cross-layer frameworks that adapts the physical layer with MAC and network layers, as well as real-time, low-complexity ML models deployable on resource-constrained underwater nodes. Beyond the hybrid acoustic-optical setup, the integration of optical and magneto-inductive communication should be leveraged to trade off use cases with water salinity and turbidity. Additionally, there is a critical need for experimentally validated, standardized simulation platforms that integrate realistic acoustic and optical channel models, enabling reproducible and scalable performance evaluation. Advances in energy-efficient strategies for wireless power transfer, energy harvesting, and hardware design, such as

low-power transducers and high-sensitivity photodetectors, alongside in situ validation across diverse ocean conditions, will be essential to transition these approaches from theory to practical internet-of-Underwater-Things deployments [131], [213], [214], [215].

IV. MEDIUM ACCESS CONTROL LAYER

The design of MAC protocols in UWSNs is shaped by the characteristics of the acoustic channel, particularly long propagation delays, limited bandwidth, and time-varying link conditions. These factors make medium access inherently dependent on trade-offs among collision avoidance, energy efficiency, and delay tolerance.

In addition to classical wireless challenges such as hidden and exposed terminals, underwater environments introduce more severe impairments that directly influence medium access decisions. The *hidden node* problem is significant in UWSNs, where a node cannot detect others, leading to potential collisions [14]. Conversely, *exposed nodes* may unnecessarily defer transmission even when no actual interference would occur [14]. The *Doppler effect* introduces frequency shifts due to relative motion in water, complicating communication and increasing collision risk [12]. In addition, the *near-far effect* can cause signals from nearby nodes to dominate weaker distant ones, reducing SINR and increasing packet loss.

These impairments limit the effectiveness of conventional terrestrial MAC strategies and call for protocols that explicitly account for delayed feedback, uncertain channel sensing, and heterogeneous link conditions.

Under these conditions, MAC design must also address several system-level requirements:

- **Energy Efficiency:** Energy management is critical, as battery replacement in underwater environments is often impractical. Reducing retransmissions, optimizing sleep scheduling, and limiting control overhead are key to extending network lifetime [11], [12], [14], [223].
- **Robustness to Propagation Delay:** Long and variable propagation delays complicate synchronization and increase collision likelihood, requiring protocols that remain effective under delayed coordination [12].
- **Adaptability:** Network topology may change due to node mobility and environmental dynamics, making real-time adaptation essential for maintaining stable communication [14].
- **Scalability:** Large-scale deployments introduce additional coordination complexity, requiring MAC schemes that maintain efficiency while limiting computational and signaling overhead [12].

Taken together, these requirements indicate that no single MAC protocol can optimize all performance objectives simultaneously. Different design paradigms therefore emphasize distinct aspects of system performance, which motivates the classification and comparative analysis presented in the following subsections.

A. CONTENTION-FREE MEDIUM ACCESS CONTROL PROTOCOLS

Contention-free MAC protocols rely on pre-scheduled or pre-allocated access to the medium, thereby eliminating collisions and reducing the need for control exchanges such as RTS/CTS or Hello/Reply signaling. They are particularly well-suited to applications with periodic traffic and relatively stable network conditions.

A key limitation, however, is resource underutilization. When nodes have no data to transmit, reserved slots remain idle, which lowers channel utilization. Consequently, these approaches are more effective in dense or structured deployments, whereas their performance degrades in sparse or highly dynamic scenarios [11], [12], [14], [223].

1) TIME DIVISION MULTIPLE ACCESS (TDMA)

TDMA-based protocols divide time into frames and assign each node a dedicated transmission slot, ensuring collision-free communication. In underwater environments, guard times are essential to compensate for long and variable propagation delays, but they also reduce channel utilization, making efficient slot design a critical challenge.

In practice, due to the low propagation speed of acoustic signals (approximately 1500 m/s), propagation delays can reach hundreds of milliseconds or even seconds over typical communication ranges, often exceeding packet transmission durations. As a result, guard intervals must be dimensioned according to worst-case delays, which significantly reduces effective channel utilization, particularly in low data-rate regimes (on the order of 10–100 kbps) [12].

Several TDMA variants have been proposed to improve performance under underwater constraints by incorporating topology awareness, delay adaptation, or scheduling optimization. For example, Wave-Adapted TDMA (WA-TDMA) dynamically adjusts time slots and incorporates adaptive slot reallocation mechanisms to improve slot utilization and reduce initialization overhead [224]. Location-Based TDMA MAC (LT-MAC) exploits spatial information to minimize waiting time and improve delay performance, particularly in small-scale or single-hop networks [216], [217]. Staggered TDMA Underwater MAC Protocol (STUMP) leverages propagation delay diversity to enable partially overlapping transmissions that remain collision-free at the receiver, thereby improving channel utilization compared to conventional TDMA scheduling [218], [225]. Similarly, Depth-Based Layering MAC (DL-MAC) introduces hierarchical slot allocation based on node depth, which reduces contention and improves both throughput and latency in structured deployments [219], [220].

Other approaches focus on improving energy efficiency and scalability. UW-FLASHR reduces idle listening and control overhead by combining reservation and data transmission phases, thereby improving energy efficiency in mobile scenarios [226]. Cellular MAC (C-MAC) introduces a cell-based structure that spatially reuses time slots, improving scalability and throughput in larger networks [227]. Efficiency

Reservation MAC (ER-MAC) exploits centralized scheduling and propagation delay information to enhance bandwidth utilization while avoiding collisions [228]. Spatial-Temporal MAC (ST-MAC) models scheduling as a conflict-graph optimization problem and demonstrates improved throughput and reduced energy consumption compared to conventional schemes by explicitly accounting for spatial-temporal interference [229]. SBMAC further enhances reliability by proactively blocking potentially interfering transmissions based on predicted collision regions [230].

Overall, TDMA-based protocols provide high reliability and predictable performance, but their efficiency strongly depends on accurate synchronization and traffic regularity. In particular, the requirement for network-wide synchronization—already challenging in underwater environments due to variable delays and clock drift—introduces additional overhead and limits scalability [12].

They are less effective in sparse or bursty traffic scenarios, where fixed slot allocation leads to poor channel utilization. This limitation stems from the mismatch between static slot assignment and dynamic traffic patterns, resulting in idle slots and reduced spectral efficiency despite the absence of collisions.

2) ORTHOGONAL FREQUENCY DIVISION MULTIPLE ACCESS (OFDMA)

OFDMA-based MAC protocols extend contention-free access to the frequency domain by dividing the available bandwidth into orthogonal subcarriers, allowing multiple nodes to transmit simultaneously. This approach is particularly suitable for underwater acoustic channels, where severe multipath propagation and limited bandwidth strongly affect performance. In such environments, OFDMA mitigates ISI through guard intervals and improves robustness to frequency-selective fading.

For instance, UW-OFDMAC supports simultaneous transmissions from multiple nodes and dynamically adapts transmit power, subcarrier spacing, and guard intervals to channel conditions, achieving gains in both energy and bandwidth efficiency. Simulation results indicate that such adaptive designs can reduce energy consumption by up to 96% compared to fixed-parameter OFDMA schemes, while improving bandwidth utilization [231]. Similarly, adaptive OFDMAC protocols optimize modulation and power allocation across subcarriers to enhance reliability and reduce BER [232].

The main advantage of OFDMA lies in its ability to combine parallel transmission with robustness against multipath distortion, which makes it attractive in bandwidth-constrained underwater networks. At the same time, these gains come with non-negligible implementation constraints. Maintaining subcarrier orthogonality requires accurate synchronization and careful control of subcarrier spacing relative to Doppler-induced frequency shifts. In underwater environments, where relative node motion can produce noticeable Doppler spreads, even small frequency offsets may cause ICI and degrade performance.

Guard interval design also involves a direct trade-off between interference mitigation and channel utilization. Larger guard intervals improve resilience to delay spread, but they increase overhead and reduce the effective spectral efficiency.

Therefore, the performance of OFDMA-based MAC protocols depends not only on parallel access itself, but also on reliable channel estimation, Doppler compensation, and adaptive parameter selection. These protocols are most effective when channel state information can be estimated with sufficient accuracy and used for resource allocation.

3) CODE DIVISION MULTIPLE ACCESS (CDMA)

CDMA-based MAC protocols allow multiple nodes to access the channel simultaneously using distinct spreading codes, removing the need for strict time synchronization. This property is particularly advantageous in asynchronous and dynamic underwater environments. Unlike TDMA, CDMA utilizes time and frequency resources concurrently, and system capacity is primarily constrained by interference and transmission power rather than available bandwidth.

A key limitation of CDMA is the near-far problem, which necessitates effective power control to ensure balanced signal reception. In UWSNs, differences in propagation distance lead to significant variations in received signal power, allowing nearby transmissions to dominate weaker signals. Consequently, the signal-to-interference ratio (SIR) is influenced by both multi-user interference and path-loss-induced power imbalance, making power control a central design requirement. Protocols such as POCA-CDMA-MAC address this issue through dynamic power adjustment and structured code assignment, reducing interference and improving throughput and delay performance [233].

PLAN adapts transmission parameters to channel conditions, improving performance in multi-hop scenarios [234]. In contrast, simpler approaches such as CDMA-B rely on fixed spreading codes, which reduce implementation complexity but limit control over multi-user interference [235]. More advanced schemes explore structured or path-aware code allocation strategies, which improve scalability by reducing code length and limiting interference between independent communication paths.

These approaches highlight a fundamental trade-off between parallel transmission and interference. While multi-code transmission enables simultaneous packet delivery and increases theoretical throughput, it also intensifies mutual interference, which can degrade the effective data rate. Under interference-limited conditions, single-code CDMA schemes may outperform multi-code schemes due to reduced interference. CDMA-based protocols have also been shown to achieve higher throughput and lower packet drop ratio compared to handshake-based protocols such as Slotted FAMA, particularly under moderate to high traffic loads.

Overall, CDMA provides robustness to synchronization constraints, but its scalability remains limited by multi-user

TABLE 3. Key Takeaways - Physical Layer in Underwater Wireless Communication Systems.

Aspect	Insights and Takeaways
Dominant Challenges and Impairments	<ul style="list-style-type: none"> ● Energy and Topology: Limited battery life, synchronization issues, and node mobility lead to frequent disconnections. ● Channel Conditions: Acoustic links suffer from multipath fading and Doppler spread; optical links face strong absorption, scattering, and turbulence. ● Hardware Constraints: Bandwidth limits, optical misalignment, and detector temperature sensitivity reduce performance and scalability. ● Modeling Limitations: Simplified ns-3 models (Ideal/Thorp) lack temporal variation; realistic Bellhop-WOSS coupling increases computational cost.
Mitigation and Design Strategies	<ul style="list-style-type: none"> ● Topology Optimization: ML-based topology control (e.g., Q-learning) and adaptive neighbor discovery improve scalability and energy balance. ● Channel Estimation and Equalization: Time-reversal, adaptive filtering, and wavelet-based denoising mitigate multipath and Doppler distortion. ● Wave Source and Detection: Directional transducers, MEMS hydrophones, and adaptive beam steering enhance link robustness and alignment. ● Modulation: OFDM, OTFS, and OOK-PPM increase data rate and Doppler tolerance; ML-assisted modulation offers adaptive robustness. ● Channel Coding: RS and Hamming counter burst errors; convolutional, turbo, LDPC, and polar codes approach Shannon limits with varied latency and complexity. ● Adaptive Modulation and Coding (AMC): AMC dynamically adjusts coding and modulation based on real-time SNR for optimal throughput and power use. ● Simulation Frameworks: Bellhop acoustic and UOC optical modules in ns-3 enable realistic, environment-aware link and AUV performance evaluation.
Trade-offs and Limitations	<ul style="list-style-type: none"> ● Reliability improvements frequently increase energy, latency, and computational cost. ● Optical directionality enhances range, but increases alignment sensitivity. ● ML-based physical-layer adaptation requires training data and processing power often unavailable in situ.
Emerging and ML-Based Approaches	<ul style="list-style-type: none"> ● Reinforcement learning-based AMC enables channel adaptation without explicit CSI, saving up to 20% energy. ● Deep learning models support real-time modulation and coding optimization under dynamic ocean conditions. ● Hybrid acoustic-optical systems and cross-layer ML integration enhance reliability and energy efficiency for IoUT networks.
Open Research Challenges	<ul style="list-style-type: none"> ● Unified acoustic-optical modeling within ns-3 for hybrid channel simulation. ● Real-time ML-driven topology and coding adaptation under partial observability. ● Low-latency, energy-efficient decoding for IoUT and AUV applications. ● Cross-layer feedback integration for physical-MAC co-optimization. ● Experimental validation of ML-based adaptive physical-layer methods in realistic sea conditions.

interference, making efficient code design and adaptive power control essential in dense UWSNs.

4) HYBRID APPROACHES

Hybrid contention-free MAC protocols integrate multiple access mechanisms, such as TDMA, CDMA, and graph-based scheduling, to improve resource utilization and adaptability in UWSNs. By jointly exploiting temporal, spectral, and spatial dimensions, these approaches aim to

overcome the limitations of single-access schemes under severe channel constraints.

Graph-based scheduling represents a prominent class of hybrid designs. For instance, GC-MAC employs a distributed graph coloring mechanism to allocate transmission opportunities while ensuring collision-free operation within two-hop neighborhoods [221]. By enabling controlled spatial reuse, this approach improves channel utilization compared to strictly orthogonal access schemes. Simulation results show that GC-MAC can achieve throughput gains of up to

38% compared to TDMA-based schemes and over 70% compared to contention-based protocols under high traffic load. Similarly, ACMENet combines TDMA scheduling with centralized coordination to optimize data collection in tree-based network topologies [236], improving reliability through deterministic access.

These designs introduce a trade-off between coordination efficiency and signaling overhead. While combining multiple access dimensions improves spectral efficiency and reduces collisions, it requires additional control for scheduling, synchronization, and topology awareness. Consequently, performance depends on the availability and accuracy of network state information, as well as the ability to adapt to topology dynamics and propagation delays.

Hybrid approaches therefore offer improved flexibility and efficiency compared to pure TDMA or CDMA schemes, particularly in dense or high-load scenarios where spatial reuse becomes critical. However, these benefits come at the cost of increased computational complexity and control overhead, which can limit scalability in highly dynamic underwater environments.

B. CONTENTION-BASED MEDIUM ACCESS CONTROL PROTOCOLS

Contention-based MAC protocols allocate channel access on demand rather than through fixed scheduling, making them well-suited to irregular, bursty, or event-driven traffic. This flexibility is particularly relevant in UWSNs, where node activity is often sporadic and topological conditions vary over time.

However, in underwater acoustic environments, this flexibility introduces significant limitations. Long propagation delays reduce the effectiveness of carrier sensing and feedback-based collision avoidance, while retransmissions and control packet exchanges increase both energy consumption and E2ED. In addition, the extended vulnerable period inherent to acoustic channels increases collision probability, leading to reduced channel utilization as network load grows. As a result, contention-based protocols offer higher adaptability than contention-free schemes, but at the cost of lower channel utilization under moderate to heavy contention [11], [12], [14], [223].

1) ALOHA VARIANTS

ALOHA-based protocols constitute the simplest class of contention-based MAC schemes and are widely adopted in UWSNs due to their low implementation complexity and adaptability to sporadic traffic. However, their performance is fundamentally limited by high collision probability, which is further exacerbated by long propagation delays in underwater acoustic channels. This leads to rapid throughput saturation as the offered traffic increases, making scalability a key limitation.

Numerous ALOHA variants have been proposed to address these limitations by targeting specific aspects of underwater communication constraints.

Time-structured approaches, such as Slotted ALOHA (S-ALOHA), introduce slot synchronization to reduce collisions and improve channel utilization. In underwater environments, however, propagation-induced timing uncertainty limits the effectiveness of synchronization, reducing achievable gains [237]. Extensions such as Slotted-CS-ALOHA combine slotting with carrier sensing, but remain constrained by outdated channel state information under long propagation delays [238].

Control-assisted schemes, including ALOHA with Advance Notification (ALOHA-AN), introduce short signaling phases prior to data transmission to reduce collisions. While this improves transmission success probability, the additional overhead may offset gains in dense or highly dynamic networks [239].

Delay-aware adaptations, such as Propagation Delay Tolerant ALOHA (PDT-ALOHA), explicitly account for long propagation delays to better schedule transmissions and reduce packet overlap, leading to improved coordination and throughput compared to conventional slotted schemes [240]. Traffic-adaptive mechanisms, including Buffered ALOHA (B-ALOHA) and Variable Interval ALOHA (VI-ALOHA), regulate transmission timing based on network load, improving stability and reducing collision frequency under varying traffic conditions [241], [242].

Energy-aware extensions, such as ST-Slotted-CS-ALOHA, incorporate sleep scheduling to reduce idle listening and extend network lifetime, although often at the expense of increased delay or reduced responsiveness [243]. Carrier-sensing variants such as ALOHA-CS attempt to reduce collisions by monitoring channel activity prior to transmission, but their effectiveness remains limited by delayed channel perception [244].

Despite these enhancements, Pure ALOHA (P-ALOHA) remains a useful baseline, illustrating the fundamental trade-off between simplicity and collision-induced performance degradation in high-delay environments. Even at moderate traffic levels, collision probability remains significant, limiting achievable throughput [245].

More recent approaches explore structured randomness to mitigate collisions. For example, Underwater Seeds Exchange (UW-SEEDEX) employs pseudorandom time-slot scheduling derived from shared seeds, enabling implicit coordination without explicit control signaling and reducing both collision probability and energy consumption [246].

2) CSMA VARIANTS

Carrier Sense Multiple Access (CSMA) protocols mitigate collisions by sensing channel activity prior to transmission. While effective in terrestrial wireless systems, their performance is fundamentally limited in underwater acoustic environments due to long propagation delays, which result in outdated channel state information and reduce the reliability of carrier sensing.

Several adaptations have been proposed to address these limitations by improving channel awareness, reducing

TABLE 4. Summary of Recent Contention-Free MAC Protocols for UWSNs.

Ref.	Year	Scheduling Parameter	Main Contributions
TDMA-Based Protocols			
[219] [220]	2015 2016	Distance-to-sink rank	LT-MAC / LTM-MAC: Location-based TDMA assigns earlier slots to nodes closer to the sink; reduces end-to-end delay in relatively stable, large-scale deployments.
[221]	2016	Propagation-delay estimate	SuperTDMA: Staggered TDMA that interleaves slots based on delay to avoid collisions and improve reliability in high-delay environments.
[222] [223]	2017 2018	Depth level	DL-MAC: Depth-based slot scheduling that prioritizes deeper nodes; lowers latency and improves throughput in hierarchical networks.
[224]	2018	Conflict-graph coloring	GC-MAC: Graph-coloring-based collision-free scheduling where nodes sharing a color transmit simultaneously; improves throughput and fairness.
[225]	2024	Hop index	RAP-MAC: Robust, adaptive pipeline scheduling with fault recovery for large-scale multi-hop UASNs; enhances reliability and throughput under harsh conditions.
OFDMA-Based Protocols			
[12]	2017	Subcarrier assignment	OFDMA-based approaches: Orthogonal subcarrier allocation enabling parallel transmissions; more resilient than FDMA under Doppler and narrowband constraints.
CDMA-Based Protocols			
[14]	2020	Spreading-code assignment	CDMA-based approaches: Code-division access without tight time synchronization; emphasizes power control to mitigate near-far interference.

collision probability, and refining contention resolution under delayed feedback conditions.

Baseline approaches such as CSMA/CA combine carrier sensing with RTS/CTS handshaking to reduce collisions. In UWSNs, however, long round-trip propagation delays significantly increase handshake duration, reducing channel utilization and leaving residual hidden terminal effects. Control overhead can also dominate channel occupancy under moderate to high traffic loads, degrading throughput [263].

Preamble-based schemes, such as P-MAC, introduce an initial signaling phase that enables nodes to estimate channel conditions and propagation delays before data transmission. This improves scheduling decisions and reduces collision probability, particularly in structured or clustered topologies [264], [265]. Priority-based adaptations, such as CS-MAC, allow high-priority nodes to interrupt ongoing transmissions, improving responsiveness while mitigating hidden and exposed terminal effects.

Hybrid schemes such as CSMA-ALOHA combine carrier sensing with random access to balance adaptability and coordination overhead. In sparse deployments, these approaches benefit from reduced handshake latency and can achieve higher throughput, although their performance remains sensitive to network density and propagation delay due to residual collisions [266].

More recent work focuses on backoff optimization. For example, the Short Signal Backoff MAC (SSB-MAC) protocol applies game-theoretic principles to adjust contention behavior during the reservation phase. By replacing purely random backoff with probabilistic decision strategies, it reduces unnecessary waiting times and improves channel utilization, achieving throughput gains on the order of 30–40% under dense network conditions [248].

Overall, CSMA-based protocols exhibit a trade-off between coordination overhead and collision avoidance. While enhancements such as preamble signaling, priority access, and adaptive backoff improve performance, their effectiveness remains constrained by propagation delay and the difficulty of obtaining timely channel state information.

3) MACA VARIANTS

MACA-based protocols extend contention-based access by introducing explicit handshake mechanisms, typically through RTS/CTS exchanges, to mitigate collisions caused by hidden terminals. While this improves reliability compared to pure CSMA schemes, its effectiveness in UWSNs is constrained by long propagation delays. When delays become comparable to packet transmission time, control overhead and latency increase significantly, reducing overall channel utilization.

Several variants have been proposed to address these limitations by refining channel reservation mechanisms and adapting protocol behavior to underwater conditions.

Foundational approaches such as Floor Acquisition Multiple Access (FAMA) enforce a stricter reservation process, ensuring that a node acquires the channel before data transmission. This reduces collision probability under large propagation delays, but introduces longer control phases [267]. Slotted extensions such as S-FAMA introduce temporal structuring to improve coordination, although contention during the reservation phase—particularly at the RTS stage—remains a limiting factor [268].

Other designs adapt the timing of control exchanges to propagation conditions. Protocols such as PCAP and

APCAP adjust RTS/CTS scheduling to better match delay characteristics, improving reliability in long-range and deep-sea scenarios [239], [269].

Scalability-oriented approaches focus on reducing contention and improving resource utilization. For instance, MACA-MCP exploits multi-channel operation to distribute traffic in dense deployments, while MACA-U incorporates synchronization and transmission power control to better handle spatial variability [270], [271]. Additional variants, such as PI-MACA and MACA-PC, respectively, rely on fixed transmission intervals and distance-aware power adaptation to stabilize access and reduce interference in large-scale networks [247], [272].

Despite these improvements, MACA-based protocols remain sensitive to propagation delay. The separation between control and data phases introduces non-negligible overhead, and residual collisions may still arise due to asynchronous reception of control packets. As a result, while these protocols provide more reliable collision avoidance than CSMA, their efficiency remains fundamentally limited in underwater environments dominated by latency and spatial uncertainty.

4) OTHER PROTOCOLS

Beyond conventional ALOHA-, CSMA-, and MACA-based schemes, alternative contention-based protocols have been proposed to address the limitations imposed by handshake overhead and long propagation delays in UWSNs.

Tone-based approaches, such as Tone-Lohi (T-Lohi), replace conventional control packets with short reservation tones, enabling fast contention resolution with minimal signaling overhead. This mechanism is particularly effective in dynamic or mobile scenarios, where repeated control exchanges would otherwise degrade performance [273], [274].

Distance-aware protocols, such as DACAP, exploit knowledge of node separation to adapt RTS/CTS timing, reducing unnecessary waiting periods and improving channel utilization in networks with heterogeneous propagation delays [275].

These approaches illustrate a shift toward lightweight and context-aware contention mechanisms, where implicit coordination (e.g., tones or distance information) replaces explicit control signaling. By reducing reliance on handshake-based exchanges, they alleviate delay-induced inefficiencies and enable faster contention resolution under dynamic conditions.

C. HYBRID MAC PROTOCOLS

Hybrid MAC protocols combine contention-free and contention-based access schemes to balance efficiency and adaptability. In UWSNs, where traffic load, topology, and channel conditions vary significantly, purely deterministic or purely random access mechanisms often fail to provide consistent performance.

1) RESERVATION-BASED PROTOCOLS

A major class of hybrid protocols relies on reservation mechanisms, where nodes dynamically acquire transmission opportunities based on demand while retaining contention phases when needed.

Early approaches, such as Traffic-Adaptive Reservation Multiple Access (TRAMA), introduce dynamic scheduling that adapts to traffic variations, enabling transitions between contention-free and contention-based operation [276]. Similarly, Reservation-MAC (R-MAC) allows nodes to reserve slots with variable duration, increasing flexibility and reducing collisions under congestion [277].

Receiver-driven designs, such as Receiver-Initiated Packet Train (RIPT), shift channel access control to the receiver, improving coordination in stable or predictable conditions [278]. Extensions like RC-SFAMA combine reservation with RTS-based contention, providing more robust access control under dynamic network conditions [279].

More recent work focuses on traffic- and context-aware scheduling. Protocols such as DSSS adjust transmission opportunities according to real-time traffic demand, while Flow-Aware Medium Access (FLAMA) incorporates traffic-awareness to improve energy efficiency in constrained deployments [280], [281].

Recent developments further introduce learning and service differentiation. RAP-MAC enhances robustness through adaptive scheduling and recovery mechanisms, while SSH-MAC incorporates service-aware scheduling by combining centralized and distributed coordination strategies [222], [282], [283].

In this direction, MR-SFAMA-Q integrates reinforcement learning to optimize multi-receiver handshaking and scheduling decisions. By exploiting observed traffic patterns and channel conditions, it reduces idle periods and improves channel utilization, highlighting the growing role of data-driven adaptation in underwater MAC design [284].

Overall, reservation-based hybrid protocols provide a flexible trade-off between deterministic access and dynamic adaptation. However, this flexibility introduces additional control complexity and signaling overhead, which must be carefully managed in delay-sensitive underwater environments.

2) CLUSTER-BASED AND MULTI-CHANNEL PROTOCOLS

Cluster-based and multi-channel MAC protocols improve scalability, energy efficiency, and collision mitigation by introducing spatial organization and frequency diversity. In UWSNs, where node density, limited bandwidth, and long propagation delays constrain performance, these approaches offer an alternative to flat single-channel architectures.

Cluster-based protocols organize nodes into hierarchical structures, where a cluster head coordinates intra-cluster communication. For instance, ERCA-MAC adapts cluster formation and scheduling to network conditions, reducing redundant transmissions and improving energy efficiency in dynamic environments [285]. Cooperative designs such

TABLE 5. Summary of Recent ALOHA/CSMA-Based MAC Protocols for UWSNs.

Ref.	Year	Key Parameter	Main Contributions
[247]	2016	Offered load, throughput, re-transmissions	Carrier Sense Pure ALOHA: Evaluates ALOHA with carrier sensing using Monte Carlo simulation; reduces collisions and improves medium utilization.
[241]	2016	Energy consumption, throughput, alive/dropped nodes	Slotted-CS-ALOHA: Hybrid scheme with buffering, slot checking, and RTS/CTS carrier sensing; decreases collisions and energy use, increases throughput and node lifetime, but does not reduce delay.
[245]	2018	Localization coverage, packet loss, localization time	VI-ALOHA: Poisson-based variable interval slots for beacon broadcasting; reduces collisions and improves localization coverage by over 20% as compared to equal-interval ALOHA.
[246]	2019	Delay, energy consumption, throughput	ST-Slotted-CS-ALOHA: Time-saving slotted ALOHA with carrier sensing; reduces average delay and energy use, increases throughput.
[250]	2016	Power control, interference, throughput	MACA-PC: MACA with power control; uses low power for data packets and high-power notification signals during transmission to prevent collisions; reduces energy use while maintaining throughput.
[251]	2023	Channel contention, backoff optimization, delay	SSB-MAC: Game-theoretic short-signal backoff without handshake; improves throughput, reduces delay, and increases delivery ratio in long-delay UWSNs.

as CR-MAC further exploit intra-cluster collaboration, allowing neighboring nodes to assist in retransmissions and thereby improving reliability under adverse channel conditions [258].

Multi-channel protocols rely on frequency diversity to reduce contention and increase parallelism. UAMC-MAC enables dynamic channel switching to distribute traffic across available bands, alleviating congestion in dense deployments [286]. More structured approaches, such as GCMAC, use graph-coloring strategies to assign channels while limiting interference between neighboring nodes, which is particularly effective against hidden terminal effects [257].

These approaches enable spatial reuse and parallel transmissions, improving throughput and scalability. However, they introduce additional coordination requirements, including channel assignment, synchronization, and cluster management, which can result in significant overhead in resource-constrained underwater environments.

3) FREQUENCY, SPATIAL, AND TEMPORAL REUSE PROTOCOLS

Protocols based on frequency, spatial, and temporal reuse increase network capacity by enabling concurrent transmissions while controlling interference. In UWSNs, where bandwidth is scarce and propagation delays are significant, such reuse mechanisms are key to improving spectral efficiency and scalability.

Temporal reuse relies on time-domain scheduling to regulate channel access. Protocols such as Z-MAC and D-MAC dynamically alternate between contention-based and scheduled operation depending on traffic conditions, balancing flexibility and coordination. Fairness-oriented schemes, including SF-MAC and WSF-MAC, refine this approach by introducing equitable or priority-based access among nodes.

Reuse can also be achieved in the frequency domain through multi-channel and OFDMA-based designs. For example, TLAO-MAC allocates subcarriers according to traffic demand, while GO-MAC combines OFDM with georouting to jointly optimize resource allocation and forwarding

decisions [255], [256]. Similarly, JRSPA-MAC integrates relay selection and power allocation in multi-hop transmissions to improve overall efficiency [253].

Spatial reuse enables simultaneous transmissions across different regions of the network. Protocols such as TSR-SIC exploit successive interference cancellation to decode overlapping signals, increasing throughput without strict orthogonality. Directional or full-duplex designs, such as FDD-MAC, further extend this capability by allowing concurrent transmission and reception while limiting interference [254].

Additional mechanisms combine synchronization and power control to regulate interference. TSPC aligns transmissions through time synchronization and adaptive power adjustment, while TDTSPC-MAC extends this principle to three-dimensional deployments, improving performance in multi-layer UWSNs [260], [261].

More recent approaches explore non-orthogonal access to further increase reuse efficiency. HN-MAC employs NOMA to enable power-domain multiplexing, increasing user capacity without additional bandwidth, while TF-MAC integrates traffic-aware scheduling with multi-channel allocation to improve both throughput and fairness [259], [262].

Overall, reuse-based MAC protocols enhance network capacity and spectral efficiency by exploiting multiple access dimensions. However, these gains depend on accurate synchronization, effective interference management, and advanced receiver capabilities such as SIC, which increase system complexity and implementation cost in underwater environments.

D. ML-BASED MAC PROTOCOLS

Unlike conventional MAC protocols based on fixed rules and static parameter settings, ML-based approaches introduce adaptive decision-making mechanisms suited to the dynamic and uncertain nature of UWSNs. Variations in channel conditions, node mobility, and traffic patterns limit the effectiveness of predefined schemes, whereas learning-based protocols adjust transmission strategies based on observed interactions with the environment.

TABLE 6. Summary of Multi-Channel / Frequency-Reuse MAC Protocols for UWSNs.

Ref.	Year	Channel/Reuse Parameter	Main Contributions
[252]	2015	Frequency division; time-slotting	H-MAC: Combines frequency separation with coordinated time slots to cut collisions in bandwidth-limited UASNs.
[253]	2018	Dual-channel RTS/CTS (acoustic & optical)	O-A Handshake MAC: Slot-reservation using dual handshakes; adapts data-period length to contenders and falls back to acoustic data when optical data are infeasible.
[254]	2019	Acoustic handshake (idle check, location); optical handshake (beam alignment, channel test); postponed access (CSMA/CA); SDMA spatial reuse; slot-based contention; acoustic fallback	OA-CMAC: Hybrid contention + SDMA with dual handshakes; improves throughput (up to 2× when optical success >50%) and extends lifetime (~30%) versus acoustic-only MAC.
[255]	2019	Successive interference cancellation; temporal/spatial reuse	TSR-SIC: Enables concurrent transmissions decoded via SIC, maximizing throughput in large-scale networks.
[256]	2020	Joint relay selection; power allocation for parallel multi-hop paths	JRSPA-MAC: Uses metaheuristics to pick relays/powers, increasing parallel capacity and reducing delay.
[257]	2022	Full-duplex operation; directional/beamformed links	FDD-MAC: Simultaneous TX/RX with directional beams lowers interference and boosts throughput.
[258]	2021	Adaptive subcarrier allocation (OFDMA); traffic-awareness	TLAO-MAC: Dynamically allots subcarriers by load, lowering latency and raising throughput under fluctuating demand.
[259]	2023	Cross-layer OFDM with geo-routing; resource allocation	GO-MAC: Integrates geo-routing with OFDM to improve reliability and energy efficiency in congested UASNs.
[260]	2023	Conflict-graph coloring; collision minimization	GCMAC: Assigns channels via graph coloring to reduce hidden-terminal collisions and increase throughput/energy efficiency.
[261]	2023	Cooperative retransmissions; virtual backoff	CR-MAC: Nearby nodes assist retransmission and use a virtual backoff to prevent collisions in high-error, long-delay settings.
[262]	2023	Traffic-aware slotting; multi-channel allocation	TF-MAC: Assigns resources by traffic load and uses multiple channels for higher throughput and fairness.
[263]	2022	Time synchronization; transmit power control	TSPC: Synchronizes to a reference clock and tunes power to lower collisions; suited to precise-timing deployments.
[264]	2023	3D layered topology; synchronized slots & power management	TDTSPC-MAC: Extends TSPC to 3D UASNs to mitigate collisions in deep or multi-layer networks.
[265]	2024	Power-/code-domain NOMA; interference management	HN-MAC: Dynamically groups users and applies NOMA to increase multi-user capacity while reducing interference.

Early work has focused on augmenting ALOHA-based protocols with learning capabilities. Learning-ALOHA (L-ALOHA) adapts transmission timing, enabling nodes to progressively identify collision-free opportunities [287]. Reinforcement learning (RL) extensions further improve adaptability. For example, DR-ALOHA-Q reports channel utilization gains ranging from 13% to 106% in static scenarios and up to 126% in mobile environments [288]. UW-ALOHA-QM demonstrates even larger improvements, reaching up to 300% higher utilization in highly dynamic settings [289].

These improvements arise from the ability of RL agents to learn transmission policies that capture underwater-specific constraints, including long propagation delays and space-time uncertainty. Such approaches operate in a distributed and

asynchronous manner, avoiding the need for global synchronization or explicit exchange of network state information.

ML techniques have also been applied to more structured MAC designs. In MACA-based schemes, RL-PC-MACA adapts transmission power to reduce interference, while MACA-EEQL employs Q-learning to optimize scheduling under energy constraints [290], [291].

More generally, learning-based MAC protocols enable cross-layer adaptation by jointly considering access decisions, power control, and scheduling under uncertain channel conditions.

These advantages come with important trade-offs. Learning requires exploration, which can temporarily degrade performance during convergence. Convergence time may be significant in large or rapidly varying networks, and practical

implementations must also account for computational cost, memory usage, and energy consumption.

Overall, ML-based MAC protocols represent a shift toward adaptive and data-driven medium access. They offer clear benefits in terms of robustness and channel utilization in non-stationary environments, but their deployment remains constrained by convergence behavior and resource limitations.

E. SUMMARY AND FUTURE WORKS

Overall, MAC protocol design in UWSNs is driven by fundamental trade-offs between reliability, energy efficiency, delay, and scalability, all of which are strongly influenced by the characteristics of the underwater acoustic channel. Contention-free schemes offer deterministic access and high reliability, but often lack adaptability and may leave resources underutilized. In contrast, contention-based protocols provide greater flexibility, although their performance degrades under long propagation delays due to increased collision probability and control overhead. Hybrid approaches attempt to balance these aspects by combining scheduling and random access, but this typically comes with additional coordination complexity.

Learning-based MAC protocols further extend this design space by enabling adaptive and context-aware decision-making. They are particularly promising in non-stationary environments, where predefined strategies become ineffective. However, their practical use remains constrained by convergence time, computational overhead, and energy consumption, which are critical factors in underwater systems.

Looking ahead, several research directions emerge. A first challenge lies in the design of delay-aware and propagation-resilient MAC mechanisms that explicitly account for long and variable propagation delays, which directly affect synchronization, collision avoidance, and channel sensing. Improving spectral efficiency is also essential, especially in dense deployments, and will likely rely on more effective reuse strategies across time, frequency, and space.

Another important direction concerns cross-layer design, where tighter interaction between the physical and MAC layers can enable more efficient adaptation to channel variability, Doppler effects, and environmental dynamics. Finally, learning-based MAC protocols are expected to play an increasing role, particularly in distributed and lightweight forms. Their effectiveness, however, will depend on the ability to control convergence behavior and limit their computational and energy footprint.

V. ROUTING LAYER

Routing in UWSNs must address a set of tightly coupled challenges arising from the unique characteristics of the acoustic channel and the network topology. In particular, routing decisions are strongly influenced by long propagation delays, limited bandwidth, high bit error rates, and dynamic topology changes due to node mobility and water currents.

Unlike terrestrial networks, where shortest-path routing is often sufficient, underwater routing protocols must balance multiple conflicting objectives, including E2ED, PDR, energy consumption, and robustness to link failures. The slow propagation speed of acoustic signals (approximately 1500 m/s) further complicates route selection, as multi-hop paths may significantly increase latency while reducing transmission reliability.

In addition, UWSNs are characterized by sparse deployments, frequent void regions, and limited localization capabilities, which make traditional topology-based routing approaches less effective. As a result, routing protocols must rely on localized decision-making, redundancy control, and adaptive forwarding strategies to ensure reliable communication under uncertain and time-varying conditions [1], [8], [17], [19], [23], [292].

To address these challenges, a wide range of routing protocols have been proposed, each targeting specific performance trade-offs such as throughput, delay, reliability, and energy efficiency.

Rather than optimizing a single metric, modern routing strategies aim to jointly optimize multiple performance criteria under realistic underwater constraints.

In this work, routing protocols are classified into five main categories based on their forwarding strategy and required network information: depth-based, vector-based, flooding-based, clustering-based, and learning-based approaches. For each category, we analyze its design principles and discuss its strengths and limitations in the context of UWSNs.

A. DEPTH-BASED ROUTING (DBR)

Depth-Based Routing (DBR) protocols are widely used in UWSNs due to their simplicity and independence from full localization information. Instead of relying on global topology knowledge, DBR uses depth as a local metric to guide packet forwarding toward surface sinks.

Figure 7 illustrates the basic concept of DBR protocols, where packets are routed from source nodes to sink nodes by progressively forwarding them upwards toward nodes at lower depths (d_2 , d_3 , and d_4), with $d_2 > d_3 > d_4$. This upward forwarding strategy ensures that packets move toward the surface without requiring explicit route discovery [293].

Sensor nodes determine packet forwarding based on two parameters: their own depth and the depth of the previous sender. These nodes are equipped with pressure sensors that allow them to estimate their depth in seawater [294]. The depth information is embedded in the packet before transmission. Upon receiving the packet, a forwarding node retrieves the sender's depth and compares it with its own. If the forwarding node's depth is shallower than the sender's ($d_f \leq d_s$), it considers itself a suitable candidate to forward the packet; otherwise, it refrains from forwarding.

This localized decision process eliminates the need for route maintenance and reduces control overhead, making DBR suitable for dynamic and sparse underwater deployments.

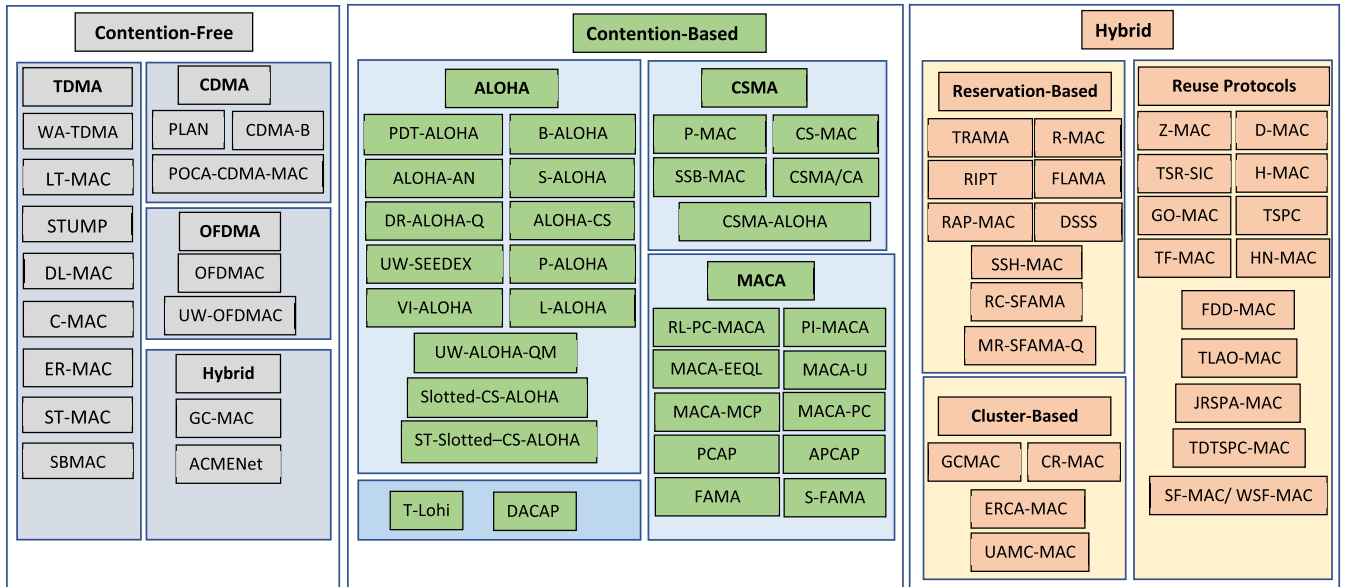


FIGURE 6. MAC Protocols for UWSNs.

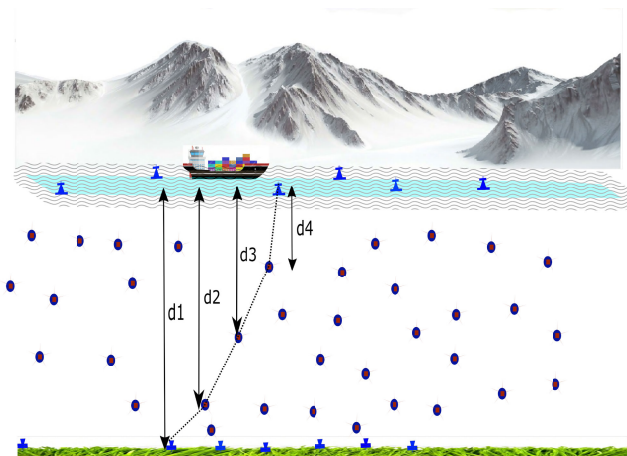


FIGURE 7. General topology of DBR protocols.

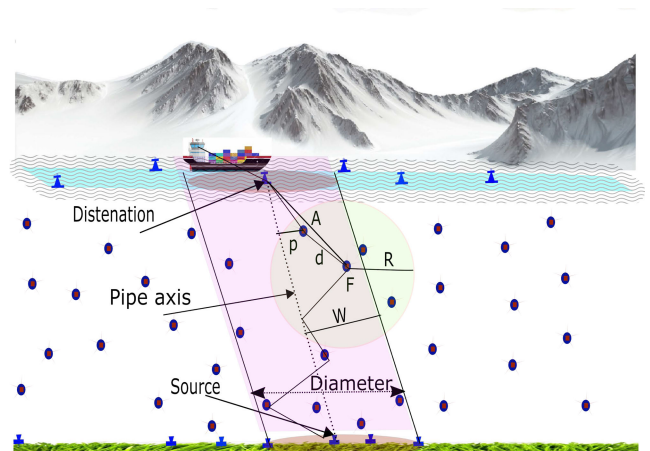


FIGURE 8. General topology of VBF protocols.

During routing, two common phenomena frequently occur. The first is multipath routing, where multiple neighboring nodes are eligible to forward a packet to the next hop. If all these nodes attempt to transmit simultaneously, it can lead to increased collisions, higher energy consumption, and redundant transmissions. The second phenomenon is *multiple-time transmissions*, where a node may receive the same packet multiple times due to the broadcast nature of DBR, leading to unnecessary retransmissions.

To mitigate these issues, several enhancements have been proposed, including holding-time mechanisms, priority-based forwarding, and redundancy suppression techniques that limit the number of forwarding nodes while maintaining reliability.

Overall, DBR provides a robust and low-complexity routing solution, particularly suitable for environments with limited localization capabilities. However, its broadcast-based forwarding can introduce redundancy

and energy inefficiency in dense networks if not properly controlled.

Many protocols have been developed based on the DBR concept, adapting its principles to suit specific network requirements. Table 7 summarizes representative DBR-based routing protocols and their key features [295], [296], [297], [298], [299], [300], [301], [302], [303], [304], [305], [306], [307], [308], [309], [310], [311], [312], [313], [314], [315], [316], [317].

B. VECTOR-BASED FORWARDING PROTOCOL (VBF)

Vector-Based Forwarding (VBF) protocols extend depth-based routing by introducing spatial constraints to improve forwarding efficiency and reduce redundant transmissions.

Figure 8 illustrates the basic topology of VBF, where the routing area is represented as a virtual “pipe” centered along the routing vector from the source to the destination. The size of this pipe is determined by its routing diameter [293], [318],

which controls the number of nodes participating in packet forwarding. Nodes located within this pipe are eligible to forward packets, while those outside the region discard them, reducing redundant transmissions and improving energy efficiency.

The VBF protocol has been proposed to address challenges related to node mobility and energy constraints [293], [318]. To support mobility, packets include information about the positions of the source, destination, and forwarding nodes. Nodes estimate their relative position using signal characteristics such as received signal strength and angle of arrival [319], [320].

Forwarder selection is based on a desirability factor that evaluates a node's suitability based on its proximity to the routing vector and its ability to advance the packet toward the destination. Candidate nodes delay transmission using a holding time inversely related to this factor, allowing the most suitable node to transmit first while others suppress redundant transmissions.

Compared to DBR, VBF reduces unnecessary packet replication by restricting forwarding to a spatial region, improving energy efficiency and channel utilization. However, this improvement introduces additional complexity and relies on position estimation, which may be inaccurate in some underwater environments.

Further comparative analyses between DBR and VBF routing protocols can be found in [321], [322], [323], and [324].

C. ROUTING BASED ON DIRECTIONAL-FLOODING

Directional-flooding-based routing protocols extend traditional flooding by introducing spatial selectivity in packet dissemination, aiming to improve efficiency and reduce unnecessary interference.

In conventional omnidirectional flooding, acoustic signals are radiated uniformly in all directions, allowing multiple neighboring nodes to receive and forward packets. While this broadcast nature increases PDR through redundancy, it limits spatial reuse, as only one transmission can effectively occur within a given interference region at a time. As a result, omnidirectional flooding often leads to reduced throughput, increased E2ED, and inefficient channel utilization [1], [19], [325], [326].

Directional-flooding protocols address these limitations by employing directional acoustic antennas. These antennas are implemented using arrays of elements whose amplitudes and phases can be adjusted to steer the transmitted beam toward a specific direction. The transmitted beam is confined within a limited spatial region (e.g., a cone), allowing multiple neighboring nodes to transmit simultaneously within the same communication range, a feature known as spatial reuse.

By restricting transmissions to specific directions, directional routing improves channel utilization, reduces interference, and enhances network capacity compared to omnidirectional approaches.

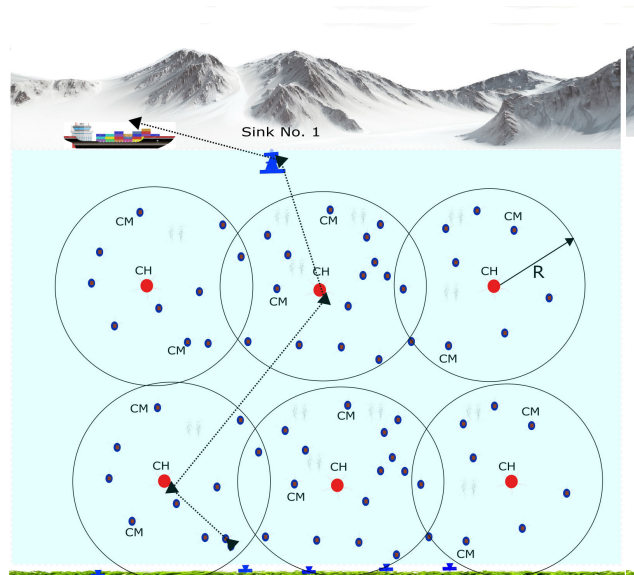


FIGURE 9. Network topology of LEACH protocol (some cliparts are reproduced using [329], [330], [331]).

Directional routing also helps mitigate several challenges in UWSNs, including hidden-node and exposed-node problems, as well as near-far effects. By directing transmissions toward the destination, these protocols can reduce propagation distance, improve signal quality, and lower energy consumption per bit, resulting in higher throughput and reduced E2ED [1], [326], [327].

However, these benefits come with increased system complexity. One major challenge is the *deafness problem*, where a receiving node may not detect incoming transmissions due to antenna misalignment. In such cases, transmitting nodes may repeatedly retransmit packets, increasing latency and reducing fairness.

Directional routing also requires accurate neighbor discovery and alignment, often involving sequential beam scanning or multiple transmissions across antenna sectors, which introduces additional overhead and delays.

Furthermore, these protocols depend on localization or relative positioning information to determine transmission directions. Inaccurate positioning or environmental constraints, such as non-line-of-sight conditions, can degrade routing performance and connectivity [325], [326], [327], [328].

Compared to omnidirectional flooding, directional approaches improve spatial efficiency and capacity but require more complex coordination and are sensitive to alignment and localization errors.

D. CLUSTERING-BASED PROTOCOLS

Clustering-based routing protocols organize the network into hierarchical structures to improve scalability and energy efficiency in UWSNs.

Figure 9 illustrates the basic concept of clustering protocols, where nodes self-organize into clusters. Within each

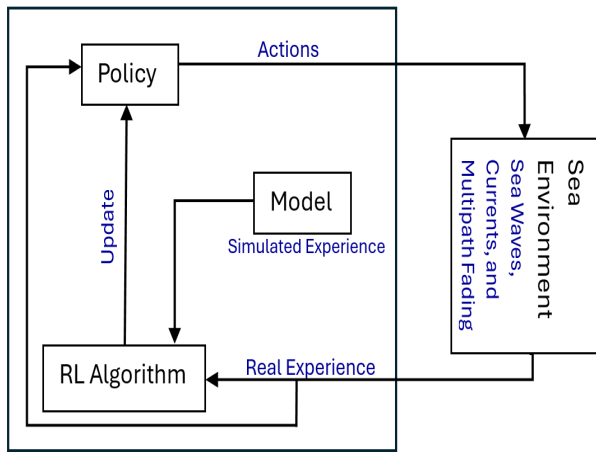


FIGURE 10. General framework of RL techniques.

cluster, one node acts as the cluster head (CH), while the remaining nodes function as cluster members (CMs). CMs sense and transmit data to the CH, which then aggregates and forwards the data toward surface sinks. This approach reduces long-distance transmissions by relying on short-range intra-cluster communication and fewer inter-cluster transmissions, thereby improving energy efficiency.

In traditional clustering protocols, CHs may be predetermined and remain fixed throughout the network lifetime [332]. However, since CHs are responsible for data aggregation and long-range communication, they consume significantly more energy than regular nodes, which can lead to early energy depletion and reduced network lifetime [333].

To address this limitation, dynamic CH selection and rotation mechanisms have been introduced, where the role of CH is periodically reassigned based on criteria such as residual energy or network conditions. This helps balance energy consumption among nodes and prolong network lifetime.

Among clustering protocols, the Low-Energy Adaptive Clustering Hierarchy (LEACH) is one of the most representative schemes. LEACH operates in rounds, each consisting of a setup phase and a steady-state phase. During the setup phase, CHs are selected and clusters are formed, while the steady-state phase is dedicated to data transmission from CMs to CHs and subsequently to the sink. To improve efficiency, the steady-state phase is typically designed to be longer than the setup phase [332].

Although LEACH provides significant energy savings, its direct application to underwater environments is limited by long propagation delays, dynamic topology changes, and the high cost of acoustic communication. As a result, several adaptations have been proposed to address these constraints.

Overall, clustering-based routing reduces redundant transmissions and improves scalability, particularly in moderately dense networks. However, it introduces additional overhead related to cluster formation and maintenance, and its performance depends on efficient CH selection and cluster stability in dynamic underwater environments.

E. AI-BASED ROUTING PROTOCOLS

AI-based routing protocols aim to address the limitations of traditional strategies by enabling adaptive and data-driven decision-making in dynamic underwater environments, with RL emerging as one of the most widely adopted approaches.

In RL, an agent learns a decision policy through interaction with an environment using reward feedback, which makes it suitable for UWSNs where network conditions such as topology, channel quality and traffic exhibit strong temporal variability [350].

Figure 10 illustrates the general RL framework, where agents iteratively interact with the environment by observing states, selecting actions, and receiving rewards. During learning, nodes balance exploration and exploitation to progressively refine their forwarding strategies.

In routing applications, each node can be modeled as an agent that selects the next-hop node based on the current network state. The state typically includes parameters such as residual energy, link quality, node depth, queue length, or position, while the action corresponds to selecting a forwarding node. The reward function encodes routing objectives such as energy efficiency, delay, or PDR.

As shown in Table 8, most existing RL-based routing protocols predominantly rely on Q-learning with handcrafted reward functions that combine multiple performance metrics such as energy, delay, and link quality. This approach enables adaptive and distributed routing decisions without requiring explicit channel or topology models, while remaining primarily driven by locally observed state information [351], [352], [353].

However, RL-based approaches introduce several challenges, including slow convergence, exploration overhead, and increased computational complexity. Moreover, the design of state representations and reward functions remains critical, as it directly affects learning stability and overall performance.

Overall, RL-based routing represents a shift from rule-based mechanisms to data-driven adaptation. Nevertheless, its effectiveness is still constrained by the reliance on predefined state and reward formulations, which may limit robustness and generalization in highly dynamic underwater environments.

F. SUMMARY AND FUTURE WORKS

Despite substantial progress in routing protocol design for UWSNs, several challenges remain due to the intrinsic characteristics of underwater environments, including long propagation delays, limited bandwidth, energy constraints, and dynamic topology. Existing approaches, such as DBR, VBF, directional flooding, and clustering, improve performance through geometric or heuristic mechanisms but remain limited in their ability to adapt to rapidly changing conditions.

A key limitation of current protocols is their reliance on predefined metrics and static decision rules, which restrict

TABLE 7. Summary of Recent Routing Protocols for UWSNs.

Ref.	Year	Main Contribution
DBR-Based Protocols		
[318]	2020	Determines forwarding probabilities based on node depth, residual energy, and forwarding number.
[319]	2020	Minimizes EC and prolongs network lifetime with greedy and opportunistic techniques.
[320]	2021	Uses IoT-enabled sink nodes, power-efficient mechanisms, and cloud computing for scalable routing.
[321]	2023	Introduces angle estimation and a fuzzy forwarding strategy to enhance node status accuracy.
[322]	2023	Extends Epidemic routing with an energy-aware condition and introduces a probabilistic forwarding strategy.
VBF-Based Protocols		
[339]	2024	Incorporates uncertainty management and energy efficiency to improve performance, focusing on energy-efficient routing and robust adaptability to underwater mobility.
Flooding-Based Protocols		
[340]	2020	Enhanced flooding-based routing by avoiding unnecessary retransmissions, improving PDR, and reducing delay.
Clustering-Based Protocols		
[341]	2020	Improves energy efficiency by using data aggregation, which reduces redundant data transmission and enhances the lifetime of UASNs
[342]	2021	Uses mobile sinks to collect data from CHs, reducing EC.
[343]	2022	Utilizes mobile sinks to improve data reception in two dense areas, reducing packet loss.
[344]	2022	Applies virtual layers with clustering and CH rotation for better data collection.
[345]	2022	Employs a bias reward function and distributed decision-making to optimize CH selection and routing efficiency, hence enhancing energy utilization and extending network lifetime.
[346]	2023	Optimizes routing by guiding network communication based on clustering, reducing EC.
[347]	2023	Combines hybrid and opportunistic routing techniques to improve routing reliability and energy efficiency in underwater networks.
[348]	2023	Utilizes link-quality-based clustering and mobile sink mechanism to optimizes source node selection and data transmission, hence improving energy efficiency and network lifetime.
[349]	2024	Uses Fuzzy C-means clustering for uniformity and energy efficiency and optimizes CH selection with Sobol sequence-based algorithm
[350]	2024	Utilizes core node set-based clustering and shortest transmission path tree to improve reliability, reduce EC, and minimize delay.
[351]	2024	Uses arithmetic progression for asymmetrical clustering without precise localization; enhances network longevity by reducing energy use.
[352]	2024	Focuses on reliable opportunistic routing for better performance and energy efficiency in underwater networks.
[353]	2024	Optimizes energy-efficient cluster routing using a shuffled frog leaping algorithm, which improves network stability and extends operational lifetime.
[354]	2024	Balances EC across nodes, preventing premature energy drain in clusters, which stabilizes the network's energy usage and improves longevity.

their effectiveness in non-stationary environments. Although AI-based routing introduces adaptability, challenges related to convergence speed, scalability, and computational complexity still hinder practical deployment.

Future research should focus on adaptive and distributed routing frameworks capable of operating under uncertainty and partial information. In this context, federated learning (FL) enables collaborative model training without raw data exchange, reducing communication overhead and improving scalability in bandwidth-constrained underwater networks [354].

Another promising direction is the use of digital twin technology (DTT), which provides high-fidelity virtual representations of UWSNs for real-time monitoring and network optimization [355]. However, its practical implementation requires accurate channel and network modeling, reliable synchronization between physical and virtual systems, and efficient real-time data acquisition.

Additional challenges include cross-layer routing design that jointly optimizes MAC and routing decisions, energy-aware multi-hop strategies under strict lifetime constraints,

and mobility-aware routing mechanisms. Hybrid approaches combining geometric, probabilistic, and learning-based techniques also represent a promising avenue for improving robustness and efficiency.

Overall, future routing protocols for UWSNs are expected to evolve toward adaptive, learning-enabled, and cooperative frameworks that balance performance gains with low complexity and energy efficiency.

VI. NETWORK STACK PROTOCOLS

In this section, we present a range of network stack protocols developed for underwater communication systems. We provide a comprehensive comparison of their designs and performance across different layers. The section concludes with an outline of key future research directions with a particular focus on the integration of advanced technologies to enhance underwater networking capabilities.

A. OVERVIEW OF STACK PROTOCOLS

In this subsection, we provide an overview of existing underwater network stack protocols.

TABLE 8. Summary of AI-Based Routing Protocols for UWSNs.

Paper	Year	ML Method	Contributions
[361]	2020	RL	<ul style="list-style-type: none"> Introduces a holding time mechanism and multipath suppression to optimize routing and reduce transmissions.
[362]	2020		<ul style="list-style-type: none"> Combines Q-learning and artificial ants for optimal routing with energy and latency awareness.
[356]	2021		<ul style="list-style-type: none"> Uses Q-learning with optimal next-hop selection to improve energy efficiency and reduce delay.
[363]	2021		<ul style="list-style-type: none"> Uses artificial ants to optimize routing with power and latency-based rewards.
[364]	2021		<ul style="list-style-type: none"> Utilizes Q-learning to enable proactive path precalculation and dynamic rerouting, while addressing void hole detection and energy depletion through transmission failure recovery mechanisms.
[365]	2021		<ul style="list-style-type: none"> Combines Q-learning and cooperative communication for energy-efficient routing.
[366]	2021		<ul style="list-style-type: none"> Uses RL for relay node selection and recovery, reducing EC and packet loss.
[367]	2021		<ul style="list-style-type: none"> Proposes a Q-learning-based cooperative routing protocol for underwater optical-acoustic hybrid networks, integrating cluster-based topology and TDMA for efficient relay selection. Optimizes routing by considering packet size and link type, ensuring adaptive transmission and improved performance.
[368]	2022		<ul style="list-style-type: none"> Introduces a reward function that combines energy, distance, and density.
[369]	2022		<ul style="list-style-type: none"> Proposes fuzzy control for routing based on residual energy and density.
[370]	2022		<ul style="list-style-type: none"> Optimizes transmission paths using Q-learning and data prioritization while balancing residual energy and preventing void node formation through dynamic CH node adjustments.
[371]	2022		<ul style="list-style-type: none"> Implements a two-hop check to prevent void areas and enhance routing reliability, while leveraging opportunistic routing with Q-value-based waiting to optimize data forwarding efficiency.
[372]	2022		<ul style="list-style-type: none"> Selects neighboring nodes based on environmental conditions and remaining energy, with the best path determined by maximizing cumulative rewards, thereby ensuring efficient energy usage and improved path selection.
[357]	2023		<ul style="list-style-type: none"> Combines opportunistic routing and RL to enhance energy efficiency and reliability, with void recovery and dynamic scheduling for optimized packet delivery.
[373]	2023		<ul style="list-style-type: none"> Uses RL for global routing optimization to improve reliability through layered routing.
[51]	2023		<ul style="list-style-type: none"> Utilizes Q-values and network topology to select the optimal forwarding node.
[374]	2023		<ul style="list-style-type: none"> Uses Q-learning for optimal relay and CH selection while proposing hierarchical routing for energy balancing and sink node isolation.
[375]	2023		<ul style="list-style-type: none"> Balances low- and high-power routing for energy efficiency, improving network lifetime through critical node energy allocation.
[358]	2024	<ul style="list-style-type: none"> Uses Stackelberg game theory with Q-learning for energy optimization while proposing cooperative communication to prevent outages. 	

1) AQUA-NET

Peng et al. [386] introduced Aqua-Net, a flexible and extendable stack protocol designed to support underwater research and applications. It addresses underwater challenges using

acoustic modems (e.g., Micro-Modem, Benthos Modem) for data transmission, considering high attenuation, long propagation delays, and low bandwidth. The MAC layer employs UW-ALOHA, an Aloha-based protocol with ACKs and

TABLE 8. (Continued.) Summary of AI-Based Routing Protocols for UWSNs.

Paper	Year	ML Method	Contributions
[376]	2024	RL	<ul style="list-style-type: none"> Introduces initial Q value selection, adaptive discount factor, and dynamic learning rate mechanisms to minimize unnecessary exploration, reduce EC, and decrease E2ED.
[377]	2024		<ul style="list-style-type: none"> Leverages Q-values and RL to dynamically select optimal routes, addressing energy constraints, unstable links, and high transmission delays, while reducing packet loss, EC, and delays.
[378]	2024		<ul style="list-style-type: none"> Leverages Q-learning, cluster-based topology, and TDMA/CDMA protocols to reduce EC and mitigate the impact of redundant nodes.
[379]	2024		<ul style="list-style-type: none"> Minimizes EC by reducing redundant links and applying a proactive routing protocol with sink attraction to avoid loops and optimize energy balance.
[380], [381]	2024		<ul style="list-style-type: none"> Dynamically updates Q-values to optimize load balancing, reduce delay, reduce collisions, and ensure stable network performance in dynamic conditions.
[382]	2024	SVM	<ul style="list-style-type: none"> Proposes an RL-based RVC method with K-means++ for node organization and energy-efficient routing. Balances EC, extends network lifetime, and outperforms other methods in efficiency.
[383]	2023		<ul style="list-style-type: none"> Proposes an adaptive SVM-based routing protocol to reduce packet loss and E2ED in sparse UASNs by selecting optimal forwarding nodes based on depth, energy, and node sparsity, improving routing reliability.
[384]	2020	MARL	<ul style="list-style-type: none"> Proposes a MARL routing protocol for UOWSNs, leveraging multi-hop data transmissions with enhanced reward functions considering energy, link stability, and transmission quality. Implements deep RL to enhance real-time adaptability in dynamic underwater environments.
[385]	2023		<ul style="list-style-type: none"> Prioritizes data based on depth, energy, congestion, and Value of Information (VoI) to optimize relay node selection, reducing delay for high-VoI data and improving energy efficiency for low-VoI data.
[386]	2024		<ul style="list-style-type: none"> Enhances PDR by selecting optimal nodes, optimizing performance through a reward function that incorporates delay, congestion, distance, and energy, and accelerates convergence with adaptive learning and Q-value initialization.
[387]	2021	DQL	<ul style="list-style-type: none"> Proposes a hybrid DL and dynamic biased tracking method for UWSN routing, improving throughput, PDR, and reducing packet loss and EC
[388]	2023		<ul style="list-style-type: none"> Uses an MDP model to optimize energy, depth, and routing decisions, balancing energy efficiency, E2ED, and network lifetime.
[389]	2024		<ul style="list-style-type: none"> Combines broadcast/unicast for energy efficiency, with a hybrid model for residual energy and depth to limit E2ED. Uses asynchronous updates for dynamic topologies and supports extensions for node density and noise.
[390]	2024	GNN	<ul style="list-style-type: none"> Optimizes routing by integrating current and future node/link states, enhancing energy efficiency, E2ED, and network lifetime through spatiotemporal relationships. Reduces overhead and improves flexibility by dynamically adjusting the prediction validity period to balance PDR and energy efficiency.

backoff schemes (Binary Exponential, Poisson) to manage retransmissions. The routing layer utilizes VBF for robustness, energy efficiency, and high PDR, with variants like HH-VBF and VBVA enhancing 3D network performance. The Major Characteristics of the Aqua-Net stack protocol could be listed as follows:

- Layered Architecture: Aqua-Net follows a layered design with cross-layer optimization, allowing

protocols and applications to configure system parameters dynamically.

- Standardizing Interfaces for Acoustic Modems: Aqua-Net provides a unified interface that abstracts details of the physical layer to support various acoustic modems.
- Real-World Implementation and Interface Support: Aqua-Net is implemented using Micro-Modem and Gumstix on embedded Linux. It offers a pseudo-BSD

socket interface for applications and a queue management system for protocols.

- **Case Study (Evaluating UW-ALOHA):** A case study tests UW-ALOHA in Aqua-Net, validating its effectiveness through lab experiments, aligning experimental results with analytical predictions.

As a pioneering stack protocol, AquaNet has been a foundational component of UWSN research, enabling seamless protocol integration and device compatibility for practical underwater applications.

2) SEALINX

Le et al. [387] proposed SeaLinX, a protocol stack using underwater acoustic modems for data transmission. The MAC layer supports multiple protocols: UW-ALOHA for random access, S-FAMA for collision reduction via handshaking, and PMAC for scheduled transmissions, optimizing channel usage. This flexibility allows adaptation to various network conditions.

For routing, SeaLinX integrates both dynamic and static protocols. Dynamic routing adjusts in real time for changing conditions, while static routing uses predefined paths for stable networks. This dual approach enhances reliability and efficiency for underwater applications.

3) IP-COMPATIBLE ARCHITECTURE

Sun et al. [388] proposed a networking architecture ensuring interoperability with traditional TCP/IP stacks for underwater modems. An adaptation layer between the data link and network layers preserves TCP/IP while handling header compression, data fragmentation, and auto-configuration via router proxies.

The physical layer employs underwater acoustic modems (e.g., Teledyne Benthos SM-75), while the MAC layer uses CSMA/NAV for medium access, with ARQ and c-ACK for reliability. The mesh-based routing layer supports multi-hop communication, optimizing energy efficiency and enabling seamless integration with conventional internet infrastructure.

4) AQUATIC MONITORING PROTOCOL STACK

Muppalla et al. [389] proposed a protocol stack for IoUT, integrating hardware and communication systems. The hardware includes a task manager, power manager, sensing manager, acoustic module, peripheral interface, and power supplier, ensuring efficient underwater operation.

The communication system consists of:

- **Application Management** uses REST architecture for client-server interaction.
- **Routing Management** employs delay-tolerant network (DTN) protocols to handle long delays and limited bandwidth.
- **Localization Management** uses localization with directional beacons (LDB) for underwater node positioning.

This stack enables efficient communication and data management for IoUT applications like fish farming and environmental monitoring.

5) UNETSTACK

Chiter et al. [390] presented UnetStack, a flexible network stack designed for underwater communication challenges like low bandwidth, long delays, and high packet loss. It employs an agent-based architecture, replacing traditional layers with software agents for cross-layer sharing and low-overhead protocols, making it suitable for both simulation and deployment.

The physical layer is implemented using modem drivers and simulated modems, with precise transmission timing through 'TIMEDTX' and 'TIMESTAMPEDTX'. The MAC layer supports channel reservations via 'ReservationReq' and optional reliability mechanisms like 'TxAckReq'. The routing layer provides multi-hop communication, with route maintenance services generating discovery/change notifications.

UnetStack includes UnetSim, a network simulator supporting discrete-event and real-time simulations. Field-tested in MISSION 2012 and 2013, it has proven its effectiveness in real underwater environments. Implemented on the Java Virtual Machine, UnetStack is portable and customizable, with an online community version encouraging contributions. Its seamless transition from simulation to deployment makes it a powerful tool for underwater network research.

6) SOFTWARE DEFINED COMMUNICATION STACK

Valerio et al. [391] introduced a self-adaptive, cross-layer Software Defined Communication Stack (SDCS), which autonomously selects optimal protocols for each network layer using a policy engine with RL techniques to optimize PDR, E2ED, and EC.

The physical layer employs underwater acoustic links, addressing challenges like long delays and low bandwidth. The MAC layer supports CSMA (low latency, high collisions), T-Lohi (collision reduction via TONE packets), and DACAP (RTS/CTS handshaking for higher PDR at increased latency). The routing layer integrates the policy engine, dynamically selecting the best MAC protocol via a feedback-control loop (MAPE-K) and RL (N-armed bandit problem). Simulations validate SDCS's adaptability, offering an efficient solution for dynamic underwater networks.

7) ENERGY-EFFICIENT STACK

Dohngdi et al. [392] proposed a cross-layer protocol stack for 3D underwater networks, enhancing energy efficiency and network performance for long-term ocean monitoring.

The physical layer employs underwater acoustic channels, with transmission loss, noise, and multipath effects considered. Optimal frequency is ~30 kHz, with power levels dynamically adjusted (e.g., 0.01 W for 500 m vertical links, 10^{-6} W for 10 m horizontal links). BPSK is recommended for its lower bit error probability.

The MAC layer introduces Dynamic Cluster-Based TDMA (DCB-TDMA), adjusting power based on node roles and supporting node addition/removal. It includes a master cycle with sleep/wake periods and employs a multi-hop Tri-message protocol for time synchronization.

The routing layer uses cluster-based routing, where CH nodes rotate to balance EC. The transport layer ensures reliability via scheduled transmissions and FEC schemes, avoiding retransmissions through spatial redundancy. The application layer supports both regular and query-based data collection.

The protocol manages localization (pre-programmed node locations), clustering (EC-based CH selection), time synchronization (Tri-message protocol), and power management (dynamic power adjustments, sleep-wake scheduling).

Implemented in UnetSim [390], simulations confirmed improvements in EC, E2ED, throughput, and channel utilization. DCB-TDMA significantly outperformed Basic-TDMA in energy efficiency and network performance, making this stack a promising solution for energy-efficient UASN applications.

8) QOS-AWARE STACK

Emokpea et al. [393] proposed a cross-layer routing algorithm that integrates the physical, data-link, and network layers to optimize network performance. The approach enhances single-hop performance while ensuring QoS requirements, reducing E2ED, and improving energy efficiency.

The physical layer employs underwater acoustic links, addressing bandwidth limitations, long propagation delays, and multipath effects. The MAC layer utilizes slotted CSMA/CA to efficiently manage medium access and minimize collisions. The routing layer adopts wireless acoustic line link (WALL) routing, a unicast technique based on a planar graph of node positions. It selects energy-efficient routes that satisfy throughput constraints while minimizing E2ED. Simulation results demonstrated that WALL routing improves energy efficiency, throughput, and hop-count performance compared to existing protocols, validating the potential of cross-stack designs for enhanced network reliability.

9) SECURE COMMUNICATION STACK

Tronchin et al. [394] explored security mechanisms for UASNs, addressing challenges such as multipath effects, high packet error rates, and frequency-selective noise. Traditional security measures, like public key infrastructure, are impractical; instead, the study suggests a watchdog layer for overhearing packets and a reputation system to detect and exclude malicious nodes.

The MAC layer employs UWPOLLING, a polling-based protocol ideal for data muling applications. A sink node sends trigger packets to sensor nodes, which respond with probe packets, allowing the sink to allocate transmission time efficiently. To mitigate resource exhaustion attacks, the protocol incorporates a HASH freshness index for packet validation and a reputation-based blacklisting system. The routing layer employs the SUN protocol, a hop-count-based Dynamic Source Routing scheme. Security is reinforced by using a watchdog layer to detect sinkhole attacks and blacklist untrustworthy nodes, ensuring secure and reliable routing.

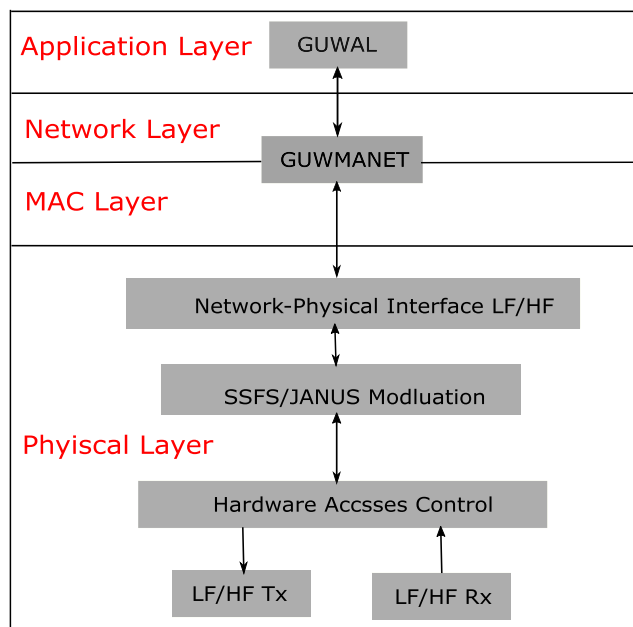


FIGURE 11. Architecture of SALSA stack protocol indicating; application, network, MAC, and physically layers.

10) L3EACH & L3EACH-V2

Ghazy et al. [395] introduced the Low-Latency Low-Energy Adaptive Clustering Hierarchy (L3EACH) and its enhanced version, L3EACH-V2, designed to reduce latency and EC through optimized ID assignment, time slot reservation, packet routing, and self-network organization.

The physical layer utilizes underwater acoustic links, addressing path loss, interference, and noise. The MAC layer combines TDMA for intra-cluster time slot allocation and CDMA for inter-cluster collision avoidance. The routing layer employs a cluster-based approach where CHs handle intra-cluster communication and relay data to the sink. L3EACH dynamically assigns local IDs and time slots within clusters, minimizing overhead and improving energy efficiency. L3EACH-V2 further enhances this by embedding IDs in the preamble signal, reducing overhead and boosting throughput. Compared to protocols like DIVE [38], L3EACH and L3EACH-V2 significantly reduce ID length and EC per packet, making them highly suitable for dense underwater networks.

11) CONVENTIONAL SALSA STACK PROTOCOL

Figure 11 illustrates the structure of the Conventional Smart Adaptive Long- and Short-range Acoustic (SALSA)¹ stack protocol, which is a four-layer architecture consisting of the physical, MAC, network, and application layers. The SALSA stack protocol integrates core components, including JANUS and FRSS at the physical layer, the cross-layer protocol

¹The commercial name of the conventional SALSA protocol is simply SALSA. However, in this paper, we refer to it as Conventional SALSA to distinguish it from the Developed-SALSA (D-SALSA) stack protocols proposed in Section IX.

GUAMANET (Gossiping in Underwater Acoustic Mobile Ad-hoc Networks) for the MAC and routing layers, and the Generic Underwater Application Language (GUWAL) at the application layer. The SALSA stack adapts the transmission power, data rate, message size, frequency band, and modulation according to network and environmental conditions [396], [397], [398].

In this section, we discuss in detail the layers of the SALSA protocol stack, as shown in Fig. 11.

a: PHYSICAL LAYER

SALSA incorporates forward error correction (FEC) schemes to detect and correct errors. Additionally, it adopts two primary modulation schemes: Frequency-Repetition Spread Spectrum (FRSS), which employs a coherent modulation technique [399], and JANUS, which utilizes a non-coherent modulation scheme [400]. Furthermore, SALSA enhances throughput and reduces latency by leveraging multiple frequency bands (low frequency and high frequency, i.e., LF and HF) and efficient header architectures. In the following, we discuss these two physical layer approaches.

FRSS: The FRSS modulation [399], [401], developed jointly by TNO (The Netherlands Organization for Applied Scientific Research) and FFI (Norwegian Defense Research Establishment), has been integrated into TNO's software-defined underwater acoustic modem, serving as lightweight underwater sensor platforms. During 2014-2015, several FRSS modems were successfully employed in various FRSS communication experiments. FRSS employs a multi-band spread-spectrum modulation approach, with repetition coding applied to contiguous frequency bands. At the receiver, a multi-channel equalizer is utilized to jointly equalize the rate-1/2 convolutionally encoded Quadrature Phase-Shift Keying (QPSK) symbol streams in separate bands, with tap updates determined by the LMS algorithm.

The FRSS modulator includes a training preamble and periodic training symbols for equalization reference. Subsequently, the rate-1/2 'soft' symbols are decoded using a Viterbi decoder. The FRSS method derives from the MCSS (multicarrier Spread-Spectrum) method. All FRSS transmissions utilize an approximately 4-kHz wide frequency band, typically between 4-8 kHz, but also operating between 5-9 kHz.

SALAS Physical adaptivity encompasses the self-reconfigurability of various elements, including data rate flexibility (four distinct data rates), message length adaptability, frequency band selection, and modulation choice. Tailored specifically for FRSS-SALSA modulation, the development entails various components such as profile-encoded preamble and frame header for Physical Service Data Units, and computation of acoustic descriptors involving ambient noise level assessment for adjusting transmit power, output SNR for rate adaptation, degree of clipping for gain adjustment, and delay spread analysis.

JANUS: JANUS [400], [402], [403], a non-coherent modulation scheme standardized by NATO,² serves various purposes, particularly in facilitating initial communication between different modems. Employing a simple FSK method, JANUS can be easily implemented on legacy systems. It utilizes the Frequency Hopped Binary FSK (FH-BFSK) scheme, where binary data is mapped to 13 evenly spaced tone pairs across the passband transmission bandwidth. These frequency pairs periodically change according to a predetermined pattern to combat ISI caused by multipath propagation or collisions. Further robustness is ensured through a convolutional encoder (rate 1/2) and a random bit interleaver, with 8-bit Cyclic Redundancy Checks employed for data corruption detection.

Flexibility is maintained by deriving all relevant parameters in the JANUS modulation from the center frequency (f_c) and bandwidth (B_w), with their ratio ($Q = f_c/B_w$) typically around 3. Although the default frequency band is 9.44-13.6 kHz, it is anticipated that other bands will be proposed and established to meet different ranges and application requirements in the future (ANEP-87). Alternatively, the frequency band for NATO voice communications (STANAG 1074, 8,087.5-11,087.5 Hz) can be utilized, as all present NATO underwater telephones support this band, or a non-overlapping band (e.g., 11-14 kHz or 5-8 kHz) to prevent interference. The likelihood of interference is mitigated by the included MAC mechanism, albeit at a lower throughput. Baseline JANUS packets consist of 64 bits, with 34 bits allocated for user application data. For larger data payloads, additional cargo data packets may follow the baseline packet, each with a default capacity of 64 bits in the public JANUS Toolkit implementation.

b: MAC LAYER

The MAC layer is represented by the GUWMANET module, which operates at both the MAC and network layers. The SALSA protocol uses the ALOHA protocol extended with CSMA or a CSMA/CA via Binary Exponential Backoff with Global Awareness, depending on the modulation scheme used at the physical layer. The FRSS modulation is paired with the ALOHA protocol, extended with carrier sensing [400]. Similarly, the JANUS standard incorporates a MAC protocol that features a CSMA mechanism with Collision Avoidance via Binary Exponential Backoff with Global Awareness [400]. Additionally, other contention-based MAC schemes, such as the SFAMA MAC scheme, could be explored within the SALSA stack protocol.

c: NETWORK LAYER

The network layer of the SALSA stack protocol is meticulously designed to meet the demanding requirements of underwater communication, offering robust, adaptive, and efficient capabilities that pave the way for enhanced connectivity and exploration in marine applications [396], [397], [398]. At the core of this network layer lies the GUAMANET,

²NATO stands for the North Atlantic Treaty Organization.

which serves as the backbone of SALSA's communication framework. GUWMANET facilitates seamless communication between underwater nodes, providing a flexible and adaptable platform for data exchange.

One of the key strengths of the SALSA network layer is its customization and extensibility. Developers have the freedom to incorporate additional functionalities and tailor the protocol to suit specific application requirements through plug-ins. This flexibility enables adaptation to diverse underwater scenarios, ensuring optimal performance in various environments. The SALSA project's network layer development also encompasses the creation of several adaptivity modules.

These modules include the *First-Contact* module, which leverages JANUS for dynamic address allocation, and the *Data Mule* module, which facilitates buffered transfer of large messages between mobile nodes. Additionally, the *Multi-Topology-Routing* module enables efficient message routing across different bands and modalities, while the *Adaptive Modem Configuration* module allows for on-site reconfiguration of transmit power and modulation settings based on environmental factors.

Adaptivity is a cornerstone of the SALSA network layer, with mechanisms implemented at both the physical and network levels. The AMC module governs adaptivity, utilizing acoustic descriptors measured and computed at the PHY level to make informed decisions. This ensures efficient resource utilization and optimal communication performance, even in challenging underwater conditions.

Overall, the SALSA network layer represents a significant advancement in underwater communication technology, offering unparalleled adaptability, resilience, and efficiency. By integrating these advanced capabilities, SALSA enables transformative advancements in marine exploration and connectivity.

d: APPLICATION LAYER

SALSA utilizes the GUWAL at the application layer, which interfaces directly with GUWMANET [396], [397], [398]. Within the application layer, users can schedule data transmissions and control packets to mimic GUWAL behavior, with adaptability to various scenarios based on user requirements. Adaptations and their synchronization across the network to ensure interoperability are managed by an adaptivity module within the network layer.

B. SUMMARY AND FUTURE WORKS

Table 9 compares the stack protocols discussed in the previous subsection. On the physical layer, the systems vary significantly in terms of carrier frequency, modulation techniques, and communication ranges. For example, traditional acoustic-based systems such as those proposed in [386] and [388] use carriers in the 10–60 kHz and 9–14 kHz ranges, respectively, supporting up to 9.6 kbps and 15.36 kbps with modulation schemes such as BPSK, FSK, and PSK. In contrast, more recent protocols, such as the one outlined in [395],

emphasize low-power, short-range operation (0.9–2.8 km) at low bit rates (80 bps), making them suitable for dense clustered deployments.

At the MAC layer, a range of access techniques is applied depending on expected delays and energy constraints. For example, UW-ALOHA with backoff and acknowledgment (e.g., [386], [387]) supports random access, while TDMA and CDMA, described in [395], enhance intra- and inter-cluster scheduling efficiency. Other studies (e.g., [389]) rely on Delay-Tolerant Networking (DTN) for intermittent links, and [394] incorporates security mechanisms such as UW POLLING and HASH.

In the routing layer, there is a clear contrast between geographic/cluster-based approaches (e.g., [392], [395]) and dynamic/multi-hop schemes (e.g., [388], [390]). Protocols like VBF and its variants [386] use vector-based forwarding, while [393] adopts WALL routing for planar, energy-efficient paths. Furthermore, [394] introduces reputation-based trust to reinforce security during routing decisions.

For short-range, high-speed applications, an optical communication-based protocol stack can be proposed to leverage the advantages of optical carriers. On the physical layer, the system would operate in the blue-green light spectrum (approximately 450–550 nm), which offers minimal absorption in water. Modulation techniques such as OOK, PPM, or advanced schemes like OFDM can achieve high data rates in the megabits-per-second range. Considering the directional nature and limited range (typically 10–100 meters), the MAC layer should employ TDMA or reservation-based strategies to avoid collisions and ensure efficient channel usage. Low-latency acknowledgment mechanisms would further enhance reliability. On the network layer, routing strategies should leverage opportunistic or table-driven approaches tailored for short-range, line-of-sight links, possibly with relay-assisted or multi-hop capabilities to extend communication in clustered environments. This protocol stack is well-suited for applications requiring high-throughput, low-latency communication between closely positioned underwater nodes, such as AUVs, sensors, or diver systems. Moreover, incorporating ML techniques can significantly boost performance by enabling adaptive modulation selection, dynamic MAC scheduling, and intelligent routing decisions based on real-time environmental conditions, traffic patterns, and historical link performance—ultimately improving throughput, reducing latency, and enhancing robustness in dynamic underwater environments.

Despite its effectiveness, the conventional SALSA stack protocol has several limitations that motivate the development of an improved protocol. In particular, SALSA relies on static node identifications and the ALOHA MAC protocol, which can lead to increased collisions, inefficient resource utilization, and limited adaptability in dynamic underwater environments. Additionally, SALSA does not fully exploit cross-layer optimization or heterogeneous network architectures, which restricts its performance in large-scale or high-throughput applications. These limitations underscore

TABLE 9. Comparison of Underwater Network Stack Protocols: Physical, MAC, and Routing Layers.

Ref.	Physical Layer	MAC Layer	Routing Layer
[386]	Carrier: ~10–60 kHz Bit rate: 80 bps–9.6 kbps Modulation: BPSK, FSK Power: ~2–20 W Range: up to 4 km	UW-ALOHA with backoff and ACK	VBF and its variants (HH-VBF, VBVA)
[387]	Carrier: 20–30 kHz (typical) Bit rate: 600 bps Modulation: OFDM Range: 2–5 km	UW-ALOHA, SFAMA, PMAC	Dynamic and static routing to adapt to network changes or stable topologies
[388]	Carrier: 9–14 kHz Bit rate: 15,360 bps Modulation: PSK, FSK Power: Up to 20 W Range: 2-6 km Transducer: Omnidirectional (upper hemisphere)	CSMA/NAV with ARQ and c-ACK for reliability	Mesh routing with multi-hop capabilities for underwater subnets
[389]	Sensors: Acoustic sensors Carrier: Not specified Modulation: Directional beacon signaling Range: Varies by application	DTN for handling delays	Routing management integrated into IoT architecture for seamless data transfer
[390]	Carrier: 10–60 kHz Bit rate: 200–500 bps Modulation: OFDM, FSK, PSK, QPSK	Reservation-based MAC with optional reliability features	Multi-hop routing using routing tables and discovery mechanisms
[391]	Carrier: 24500 Hz Bandwidth: 4000 Hz Modulation: BPSK Power: 3.3 W	CSMA, T-Lohi, DACAP (RTS/CTS and WARNING packets)	Policy engine dynamically selects optimal MAC protocols based on conditions
[392]	Carrier: 25 kHz Bandwidth: 4 kHz Modulation: BFSK, BPSK, QPSK, 16-QAM Bit rate: 2.4 kbps Power/Range: 0.01 W	Dynamic Cluster-Based TDMA with energy-efficient cycles	Cluster-based routing with CHs relaying to BS using geographic addressing
[393]	Carrier: 1 kHz Range: 150 m Power: 20 dB	Slotted CSMA/CA for collision avoidance	WALL routing using planar graphs and energy-efficient paths
[394]	Carrier: 7-17 KHz Bit rate: 500 bps Range: 4 Km	UWPOLLING with HASH for securing medium access	SUN protocol for dynamic source routing with reputation-based trust mechanisms.
[395]	Carrier: 12 kHz Bandwidth: 4 kHz Bit rate: 80 bps Power: Low-power optimized Range: 0.9-2.8 Km	TDMA for intra-cluster; CDMA for inter-cluster collision avoidance	Cluster-based routing with dynamic ID assignment and time slots

the need for a more flexible and adaptive stack protocol, forming the foundation for the proposed Developed-SALSA (D-SALSA) stack protocols and their integration into heterogeneous network architectures, as introduced in the following sections, i.e., Sections IX and X, respectively.

VII. SECURITY IN UNDERWATER NETWORKS: ISSUES AND SOLUTIONS

Owing to their broadcast-based communication and remote deployment, UWSNs are vulnerable to numerous security threats across the physical, MAC, and routing layers [404],

[405], [406]. This section highlights these threats and provides an overview of emerging mitigation strategies.

A. PHYSICAL LAYER SECURITY

The physical layer is the most vulnerable in UWNs, particularly susceptible to eavesdropping, jamming, and impersonation. To date, several methods have been proposed to mitigate these threats. These methods are briefly outlined below.

Spatial Techniques: Beamforming and directive antennas restrict signal spread. Beamforming uses MIMO and Single Input Multiple Output (SIMO) systems to optimize power directionality, enhancing secrecy. Reference [407] proposes compact acoustic arrays to increase directivity and reduce sidelobes. In [408], the authors presented a secure beamforming method for wireless optical systems based on semidefinite programming, improving robustness under imperfect channel state information. IRSs, which reconfigure the phase of incoming signals, demonstrated secrecy rate improvements up to 300% [91]. IRSs are passive, energy-efficient alternatives to relays and are particularly suited for dynamic underwater environments [409]. Prior works [410], [411], [412] evaluated IRS feasibility, floating deployment, and environmental challenges like salinity and bubbles. The authors in [413] proposed an ML-assisted buoyed IRS system for underwater AUV communications that adapts to ocean conditions to improve security and reliability. Numerical results show that it significantly enhances channel secrecy, achieving about a 400% improvement over a conventional RL-assisted buoyed-AUV system under strong wind conditions.

Jamming Techniques: Cooperative jamming introduced trusted interference to reduce eavesdropper signal quality [414]. Reference [415] used random jammer selection and signal alignment. Reference [416] maximized secrecy rate via artificial noise. References [417], [418], and [419] proposed a three-stage jammer power allocation model. Reference [420] compared performance against half-duplex jamming. Preventive jamming methods, such as RL-based power control [421], evolved to Deep Q-Network models [422]. [423] extended this to relay-based strategies, while [424] and [425] used Deep Deterministic Policy Gradient in UAV-aided systems.

Physical Layer Authentication (PLA): PLA uses features such as Channel Impulse Response (CIR), time-reversal (TR), Angle of Arrival (AoA), Time of Arrival (ToA), and Power Delay Profile (PDP). Cooperative PLA without feedback was introduced in [426] and [427] applied Mahalanobis distance on AoA; extended with CIR and TR in [428], [429], [430]. [431], [432], and [433] combined AoA, ToA, and distance in binary hypothesis testing. Kalman-filter PLA using innovation metrics appears in [434]. A dynamic database approach was found to improve performance in changing environments [435]. ML-based PLA offers high adaptability. Two-stage neural network models with relative root mean square and CIR statistics were previously used in [436] and [437].

Reference [438] added long short-term memory prediction to track channel changes. Reference [439] combined PDP features and convolutional neural networks for spoofing detection. Reference [440] used support vector machine classification with real sea-trial CIRs.

Modulation and Coding: Modulation and coding play a key role in securing UWNs by enhancing reliability and confidentiality. Spread Spectrum (SS) methods like DSSS and FHSS lower interception risk and resist jamming. In multi-user setups, CDMA supports concurrent secure access via orthogonal codes. Several previous studies [441] and [442] explored secure multicarrier SS in low-SNR underwater settings, while [443] proposed multiband OFDM for better resistance to interception. Reference [444] presented SSE-OFDM, merging SS and encryption to improve SNR and eavesdropper suppression. Channel coding schemes such as LDPC and polar codes add both error correction and secrecy. LDPC codes were found to reduce eavesdropping potential in wiretap channels [445], with [446] optimizing them for AWGN channels using low-density generator matrices. Recent trends focused on hybrid modulation-coding schemes with artificial noise, boosting both security and energy efficiency—critical for battery-limited UWSNs.

B. MAC LAYER SECURITY

The MAC layer is susceptible to spoofing, replay, back-off manipulation, and resource exhaustion attacks [447], [448]. In IEEE 802.11 request to send (RTS)/clear to send (CTS) handshaking, malicious nodes can send repeated RTS messages or fake Acknowledges (ACKs), forcing legitimate nodes to waste energy and bandwidth. These attacks are particularly harmful due to the energy-constrained nature of underwater devices. Accordingly, [449] proposed a Secure Clustered MAC (SCMAC) protocol that creates dynamic clusters with mutual authentication. It uses pairwise keys for unicast messages and digital signatures for broadcast security. However, SCMAC suffers from high computational overhead and lacks scalable rekeying protocols. Furthermore, [450] suggested a symmetric-key MAC with RTS/CTS handshakes for low-complexity encryption. Yet, symmetric key distribution and rekeying remain open challenges, especially in decentralized UWSNs. While these MAC-layer defenses improve reliability, they need further integration with trust and anomaly detection systems to address insider threats.

C. ROUTING LAYER SECURITY

Routing Attacks, such as sinkholes, blackholes, Sybil, and selective forwarding, can distort routing tables or disrupt data delivery [405], [406]. Reference [451] shows Depth-Based Routing is vulnerable to location spoofing. Reference [452] highlights key distribution difficulties in cryptographic-based defenses due to the absence of centralized management in underwater networks. Secure FLOOD [453] secures routing with encrypted control messages. It uses Link-Key Tables and Cluster Key Tables for peer-to-peer and broadcast authentication, avoiding heavy key exchange protocols like Elliptic

Curve Diffie-Hellman [454] and Blundo's scheme [455]. However, it still faces challenges with node compromise and key renewal. Reference [456] introduced Resilient Pressure Routing, which validates packet forwarding using geographic constraints and signature filtering. This defends against spoofed pressure levels and fake hop counts. Yet, since attackers may possess cryptographic keys, trust-based methods are necessary. R-CARP [457] was used to strengthen the Channel-Aware Routing Protocol by combining Boneh-Lynn-Shacham digital signatures with reputation scores derived from packet delivery ratios. It provides enhanced detection of insider misbehavior like route manipulation and packet drops [458], though maintaining accurate reputations in highly mobile networks remains a challenge.

D. CROSS-LAYER SECURITY

To strengthen the security and privacy of entire communication networks efficiently, cross-layer approaches have been explored, where security mechanisms are integrated across multiple layers of the protocol stack [459], [460], [461], [462]. Unlike the previous methods that focus on securing a single layer, cross-layer designs consider inter-layer interactions to protect data as it traverses the stack. While such strategies showed promise in other domains, they remain largely unexplored and may offer significant potential to enhance security in these environments.

E. DEVICE SECURITY

Threats to underwater devices primarily stem from physical tampering and unauthorized access. Given their deployment in remote and harsh underwater environments, these devices are particularly vulnerable to physical damage, theft, and manipulation. Malicious actors may gain physical access to sensitive data, disrupt operations, or implant malicious firmware. To counter these risks, tamper-resistant enclosures and anti-tamper mechanisms are essential defenses [463], [464], [465]. A critical concern is hardware compromise, such as the insertion of malicious components during manufacturing or through supply chain attacks, which can jeopardize the entire security infrastructure [466]. Key device-level security metrics include tamper resistance, which evaluates a device's resilience to physical interference, and intrusion detection, which evaluates the effectiveness of unauthorized access monitoring mechanisms [467]. Enhancing device security involves using ruggedized, tamper-proof casings and integrating Hardware Security Modules for secure cryptographic operations and key management. Anti-tamper technologies—such as embedded sensors and alarms—can detect and respond to tampering attempts, adding an additional layer of physical protection [468].

F. CHALLENGES AND FUTURE DIRECTIONS

Despite progress in security mechanisms, UWNs continue to face key challenges such as balancing security with energy efficiency, developing real-time and adaptive security protocols, standardizing underwater security frameworks,

and integrating ML for intelligent threat detection. Securing UWNs requires a comprehensive, layered approach that would adequately address vulnerabilities at the physical, MAC, and routing layers. Future research should prioritize lightweight, adaptive, and intelligent security solutions capable of operating effectively within the dynamic and resource-constrained underwater environment.

Table 10 provides a concise summary of various underwater threats and the corresponding security countermeasures designed to mitigate them.

VIII. NETWORK STACK MODEMS

This section explores performance characteristics and trade-offs of various acoustic modems used for underwater communications [469], [470], [471], [472], [473], [474], [475], [476], [477], [478], [479], [480], [481], [482], [483], [484], [485], [486], [487], [488], [489], [490], [491], [492], [493], [494], [495], [496], [497], [498], [499], [500], [501], [502], [503], [504], [505], [506], [507], [508], [509], [510], [511], [512], [513], [514], [515], [516], [517], [518], with a particular focus on modulation schemes, range, data rate, as well as their advantages and disadvantages. The section concludes with an outline of key future research directions, focusing on the integration of advanced technologies to enhance underwater modem capabilities.

A. OVERVIEW OF NETWORK STACK MODEMS

Table 11 provides a comprehensive review of the existing literature on stack modems tailored for underwater communications and networking, highlighting different approaches and their respective trade-offs. Figures 12 and 13 illustrate the device layout and block diagram of two stack modems: the micro-modem [470] and the BASS modem [505]. As shown, the micro-modem is compact and cost-effective, making it suitable for low-speed, short-range applications. In contrast, the BASS modem is larger and more expensive; however, it supports higher data rates and longer communication ranges. Specifically, while the micro-modem is typically used for low-rate telemetry over a few hundred meters, the BASS modem enables higher-speed communication (e.g., voice/data at 8 kbps) over several thousand meters. In the remainder of this subsection, we discuss the key differences between the stack modems summarized in Table 11.

1) MODULATION SCHEMES

Table 11 reveals that FSK is the most commonly employed modulation scheme. This widespread use is due to FSK's robustness, simplicity, and energy efficiency, which make it suitable for a range of underwater communication applications. Conversely, less common modulation schemes such as OOK (On-Off Keying) and PPM (Pulse Position Modulation) are designed to meet specific needs, such as achieving high data rates or enhancing energy efficiency. Modulation schemes like OFDM represent a median in popularity, offering a balance between adaptability and high data rates. The prevalence of FSK reflects its reliability for underwater

TABLE 10. Summary of Underwater Threats and Security Countermeasures.

Security Level	Threats	Security Techniques	Metrics
Physical Layer	Jamming, eavesdropping, signal attenuation, multipath fading	Spread spectrum, frequency hopping, beamforming, channel coding and modulation	SNR, BER, detection probability, covert rate
MAC Layer	Unauthorized access, data breaches, data integrity attacks	Encryption, hash functions, redundancy techniques	Data confidentiality, data integrity, data availability
Routing Layer	Eavesdropping, DoS, MitM attacks	Firewalls, VPNs, IDSs	Latency, throughput, packet loss rate
Device	Physical tampering, unauthorized access, hardware compromise, supply chain attacks	Tamper-resistant enclosures, anti-tamper mechanisms, HSMs	Tamper resistance, intrusion detection
Cross-Layer	Vulnerabilities across protocol layers, e.g., eavesdropping (physical layer), spoofing (network layer), or DoS attacks (application layer)	Mechanisms across layers to detect, prevent, or reduce threats, such as encryption, authentication, beamforming, jamming detection, or secure routing	Secrecy capacity, detection accuracy, computational overhead, or energy consumption.

conditions, while the increasing adoption of OFDM highlights a shift toward advanced technologies for more demanding applications.

A new optical wireless modem using VLC was tested in La Spezia harbor, achieving 10 Mbit/s Ethernet transmission over 10 m despite high turbidity and sunlight. Integrated with the SUNRISE testbed and a remote-controlled robot, the modem, built with commercial components, offers a foundation for practical deployment.

2) COMMUNICATION RANGE

The communication ranges of the modems vary widely, with the shortest range being 1 meter for the modem in [476], which uses FSK. This range is suitable for highly localized, low-power applications. On the other extreme, the longest communication range is 15,000 meters, achieved by the modem in [508], which combines FSK and PSK for deep-sea communications, demonstrating its suitability for long-range applications such as oceanographic studies. The average communication range lies around 5,000 meters, as evidenced by modems like [494] and [504]. This average range reflects a balance between power efficiency and operational capabilities, making these modems versatile for both shallow and mid-depth underwater communication tasks.

3) DATA RATE

In terms of data rates, the highest two bit rates, 10 and 2 Mbps, are achieved by optical carrier-based modems and by systems employing amplitude modulation schemes and MIMO techniques [519], [520], [521]. Then, a bit rate of 1 Mbps is achieved by acoustic carrier-based modems in [474] and [475] using OOK modulation, designed for short-range, high-speed applications. Conversely, the lowest bit rate is 10 bps, observed in [504] with DSSS modulation, optimized for long-range, energy-efficient communication in challenging environments. The average bit rate lies between 5,000 and 10,000 bps, as seen in modems like [490] and [505]. This range offers a practical balance between

speed and reliability, addressing typical underwater communication requirements without excessive power consumption.

4) ADVANTAGES AND DISADVANTAGES

Table 11 outlines diverse advantages and disadvantages across the listed modems. Optical-based Modems like [519], [520], [521], and [522] emphasize compactness, low cost, and energy-efficiency, making them ideal for small underwater vehicles, budget-conscious operations, and long life-cycle sensor nodes. On the other hand, Modems like [488], [502], and [509] emphasize network capabilities, making them ideal for harsh network conditions. High-performance modems such as [507] and [508] excel in data rates and reliability, suitable for demanding deep-sea applications but often at the expense of high power consumption. Similarly, modems like [494] and [517] offer adaptive technologies and versatile capabilities but face challenges in energy efficiency. While the advantages include energy efficiency, high data rates, and modular designs, disadvantages such as limited range, high power demands, and low data rates in specific contexts highlight the trade-offs that must be considered when choosing an underwater modem. Optical-based models, such as those in [519], [520], [521], and [522], face significant challenges in maintaining precise or loose alignment between communication nodes due to the dynamics of the underwater environment.

B. SUMMARY AND FUTURE WORKS

The analysis of various underwater acoustic modems in Table 11 reveals a considerable diversity in design trade-offs, particularly in modulation schemes, communication range, and achievable data rates. FSK remains the most widely adopted modulation due to its robustness and efficiency, while emerging methods such as OFDM and MIMO-based schemes aim to push data rates higher. Communication ranges vary from a few meters to 15 km, with optical-based systems dominating the short-range, high-speed end of the spectrum, and acoustic systems excelling in long-range reliability. Similarly, data rates span from 10 bps to 10 Mbps,

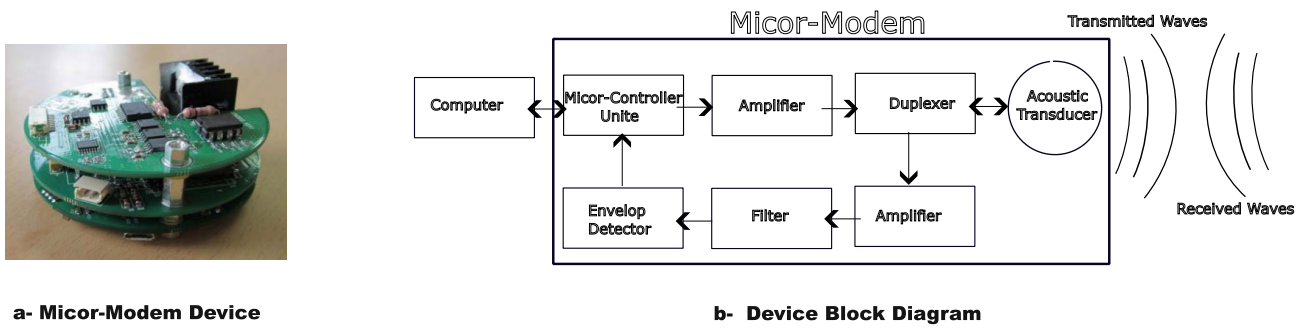


FIGURE 12. Device Layout and Block Diagram of a Micro-Modem, [470], illustrating the transmitter and receiver chains, signal processing modules, and interface components. This modem is compact in size and low in cost; however, it is used only in low-speed, short-range applications (e.g., telemetry within a few tens meters). Sub-figures (a) and (b) are reproduced from [470].

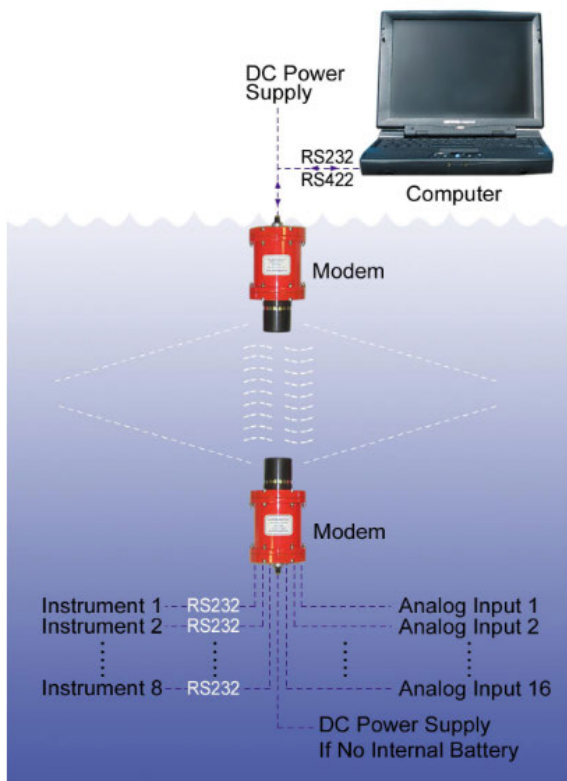


FIGURE 13. Device layout and link architecture of the BASS modem [505]. Compared to the micro-modem shown in Fig. 12, this modem is larger in size and more expensive; however, it is used in high-speed, long-range applications (e.g., voice/data transmission at 35 kbps over several thousand meters, e.g., 10 km). The figure is reproduced from [505].

modulation schemes, power levels, and routing decisions based on environmental feedback, enhancing resilience and efficiency. Moreover, incorporating cybersecurity mechanisms, such as physical-layer encryption and lightweight authentication protocols, will be critical for protecting data integrity and access in mission-critical underwater applications. A new generation of modems combining these technologies—optical carriers for speed, ML for intelligence, and built-in security for trustworthiness—will significantly advance the capabilities of future underwater communication networks.

IX. DEVELOPED-SALSA (D-SALSA) STACK PROTOCOLS

In this section, we propose novel developed models for the conventional SALSA stack protocol, namely Developed-SALSA (D-SALSA) stack protocols. D-SALSA stack protocols enhance the conventional SALSA protocol through key improvements at both the MAC and physical layers. Specifically, the traditional ALOHA-based MAC mechanism is replaced with the more efficient Slotted FAMA (SFAMA) protocol, which employs a handshake-based channel access strategy to mitigate collisions, improve contention management, and enhance channel utilization, resulting in higher throughput and improved delivery performance. In addition, the physical layer is optimized by replacing long MAC addresses (i.e., long static IDs) with adaptive short node identifiers (i.e., short-adaptive IDs), thereby reducing per-packet overhead and enhancing the transmission throughput. This optimization leads to improved energy efficiency and a significant reduction in E2ED, making the protocols more suitable for resource-constrained underwater environments. These enhancements give rise to two developed variants: (i) **SFAMA-Based SALSA Stack Protocol**, which focuses on channel access optimization and throughput improvement, and (ii) **Adaptive ID-Based SALSA Stack Protocol**, which enhances packet efficiency, throughput, scalability, and energy performance. The effectiveness of these improvements will be demonstrated numerically in the next subsections through performance gains in energy efficiency, latency, throughput, and scalability.

clearly distinguishing between energy-efficient deep-sea links and high-speed local networks.

Looking forward, there is a substantial potential for innovation in underwater modem design. Future modems can increasingly use optical wireless communication technologies, particularly visible light communication, to achieve gigabit-level throughput for short-range scenarios such as AUV swarms or diver communications. Integrating ML into modem firmware could enable real-time optimization of

TABLE 11. Comparison of Underwater Modems.

Ref.	Modulation Schemes	Communication Ranges (m)	Data Rates (bps)	Advantages	Disadvantages			
[474]	PPM	1000	150	Energy efficient, low power	Limited range			
[475]	ASK	60	500-5000	Versatile, adaptive	Limited range			
[476]		70	200	Low-cost, simple				
[477]		1.2	2000	Low-cost, simple				
[478]		100	1000-500	Versatile, adaptive				
[479]	OOK	20	256k-1M	High data rate, versatile	Limited range			
[480]		100	1M					
[481]	FSK	1	1200	Low-cost, simple	Limited range			
[482]		9	2000					
[483]		10-50	20-600					
[484]		20	20					
[485]		90	1000					
[486]		140	10-200					
[487]		240	1000					
[488]		350	200					
[489]		-	1200					
[490]		1000-4000	6000			High data rate, deep water capability	High power consumption	
[491]		2000	500			Reliable, high range	Low data rate	
[492]		GMSK	1			7500-15000	High data rate, adaptive	Limited range
[493]		MFSK	400			750, 1500, 2250	Low-cost, network capability	High power consumption
[494]	BPSK	1000-8000	78-1200	Compact, suitable for shallow waters	Low data rate			
[495]	QPSK	2000-5000	200-9000	Reliable, high data rate	High power consumption			
[496]		1000	770					
[497]		8000	8000					
[498]		25	1200			Limited range		
[499]	OFDM	5000	375-9000	High data rate, suitable for AUVs	High power consumption			
[500]		800	1875-10000	High data rate, Adaptive	Limited range			
[501]		2	-					
[502]		400	400-9000					
[503]		2	-					
[504]		5000	3041	High data rate, Reliable	High power consumption			
[505]		10000	4000					
[506]		3000	3200-6400					
[507]	SS	1000	100	Lightweight, suitable for ROVs	Low data rate			
[508]		500	40	Low power, compact				
[509]	DSSS	5000	10-1200	Long range, versatile applications	Low data rate			
[510]	BASS	350-10000	5000-35700	High data rate, low BER	High power consumption			
[511]	MCSS	212	300	Reliable, low power	Limited range			
[512]	S2C	300-8000	6900-62500	High data rate, reliable	High power consumption			
[513]	FSK, PSK	5000-15000	20-24600	High data rate, deep water capability	High power consumption			
[514]	FSK, DPSK, PPC	250-5000	25-2000	Versatile applications, deep water capability	Low data rate for PPC			

In this section, we evaluate the SFAMA-based and architecture and algorithm of the D-SALSA stack protocols, Adaptive ID-based SALSA stack protocols, introduce the and discuss the research agenda for D-SALSA.

TABLE 11. (Continued.) Comparison of Underwater Modems.

Ref.	Modulation Schemes	Communication Ranges (m)	Data Rates (bps)	Advantages	Disadvantages
[515]	FSK, OFDM	3000	15000	High data rate, Versatile	High power consumption
[516]	MFSK, PSK	2000-6000	140-15360	High data rate, Reliable	High power consumption
[517]	MFSK, MPSK	-	1000-10000	Versatile, Adaptive	Limited range
[518]	MFSK, M-ary SS	25-1000	48-1200		
[519]	MFSK, OFDM	100	208-3730	Versatile, multi-mode	Limited range
[520]		1200-1950	7000-10000	High data rate, Deep-sea capability	High power consumption
[521]	OFDM, SS	3000	710-10	High data rate, Versatile	High power consumption
[522]	OFDM, DSSS	200	104k, 260k	High data rate, Adaptive	High power consumption
[523]		3000-8000	100-1000	High data rate, Reliable	
[524]	Manchester-Coded Signal	10-40	10M	Compact size, Low cost, and Energy-Efficient	Alignment is required
[525]	Amplitude Modulation-MIMO	100-150	10M	Compact size, Low cost, and Energy-Efficient	Alignment is required
[526]	Adaptive Modulations	3	2M	Compact size and Energy-Efficient	Alignment is required
[527]	OOK-MIMO	10	20-200 k	Compact size, Low cost, and Energy-Efficient	Alignment is required

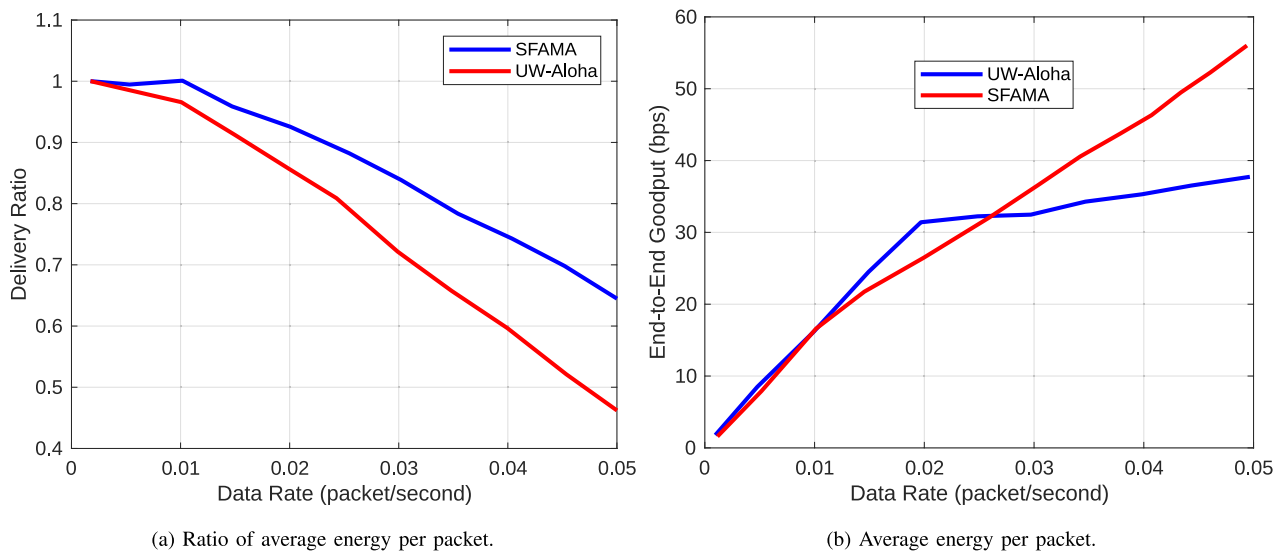


FIGURE 14. Performance of the UW-Aloha and SFAMA MAC schemes; (a) the delivery ratio versus data rate in packets per second; (b) the end-to-end Goodput in pbs vs. data rate in packets per second.

A. SFAMA-BASED SALSA STACK PROTOCOL

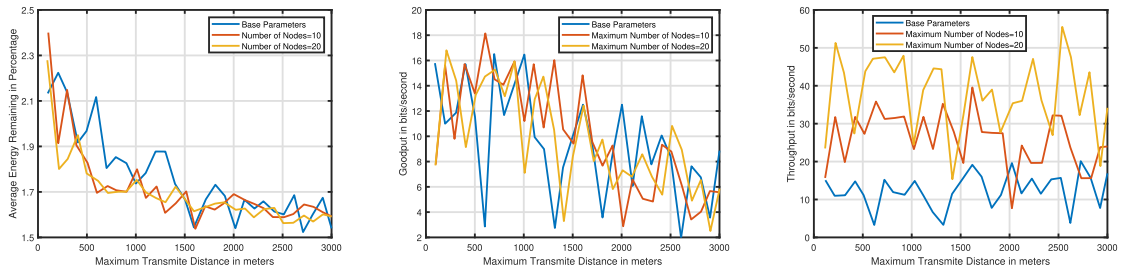
In this subsection, we compare the performance of the SFAMA and UW-Aloha MAC schemes and then present the performance evaluation of the proposed SFAMA-based SALSA Stack Protocol.

1) SFAMA SCHEME VERSUS UW-ALOHA SCHEME

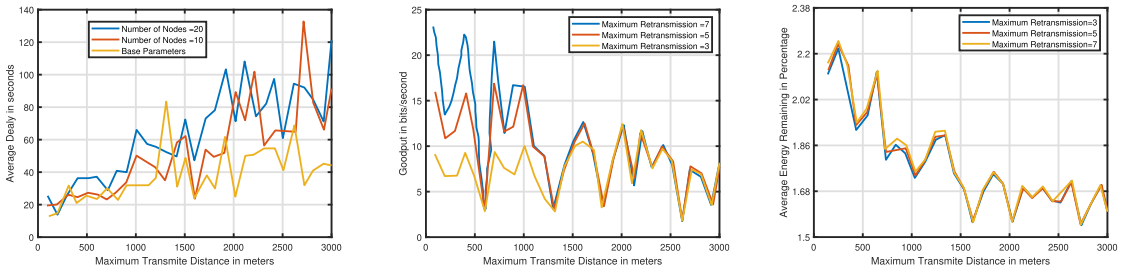
Figure 14 compares the performance of the SFAMA and UW-Aloha MAC protocols, as previously reported in [387]. The data were obtained from a laboratory testbed using the SeaLinx platform, consisting of three network nodes placed in a water tank. Each node was equipped with an AquaSeNT OFDM modem operating at an acoustic data rate of 600 bps. The nodes were logically configured in a string topology

using routing tables, although all nodes were within acoustic range of each other. To evaluate protocol performance, the packet generation rate varied from 0.001 pkt/s to 0.05 pkt/s, with a fixed packet length of 200 bytes. Each protocol was tested for 2 hours, with data transmitted from one end of the string to the other.

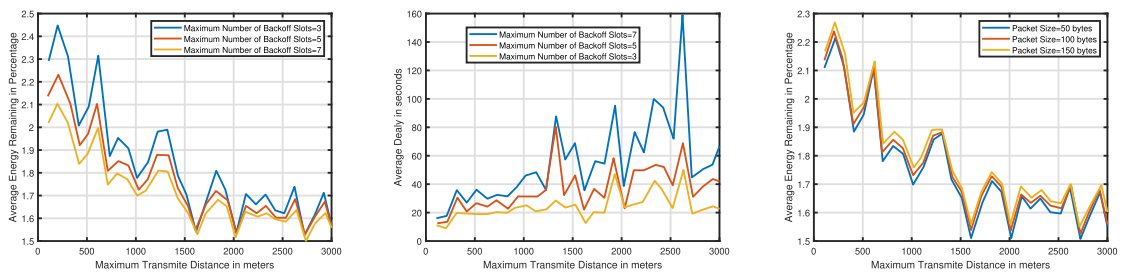
Figure 14 illustrates how the SFAMA scheme, a handshaking-based access protocol, could enhance the performance of the SALSA protocol compared to the UW-Aloha scheme, which uses random access. Two key performance metrics are evaluated: the delivery ratio, shown in Fig. 14a, defined as the fraction of non-duplicate packets received over the total generated packets; and the end-to-end goodput, shown in Fig. 14b, calculated as the average data



(a) Impact of number of nodes on the average remaining energy. (b) Impact of number of nodes on the Goodput. (c) Impact of number of nodes on the Throughput.



(d) Impact of number of nodes on the average delay. (e) Impact of maximum retransmission on the Goodput. (f) Impact of maximum retransmission on the average remaining energy.



(g) Impact of backoff on the average remaining energy. (h) Impact of backoff on the average end-to-end delay. (i) Impact of packet size on the average remaining energy.

FIGURE 15. Performance of the proposed SFAMA-Based SALSA Stack Protocol; subfigures (a)-(d), (e)-(f), (g)-(h), and (i) show the average remaining energy, average delay, goodput, and throughput, respectively, versus maximum transmission distance.

rate of successfully delivered non-duplicate packets over the experiment duration. Figure 14a shows that at low packet rates, both protocols perform similarly, with UW-Aloha performing slightly worse. However, when the packet rate exceeds 0.02 pkt/s, SFAMA significantly outperforms UW-Aloha in delivery ratio. Similarly, Fig. 14b indicates that while performance is comparable at low packet rates, SFAMA achieves higher goodput beyond the 0.02 pkt/s threshold.

2) PERFORMANCE OF THE SFAMA-BASED SALSA STACK PROTOCOL

We evaluate the performance of the MAC layer of the proposed SFAMA-based SALSA Stack Protocol using ns3³, a discrete event simulator developed in C++. In our setup, we consider one sink buoyed on the sea surface and five

³ns-3 is a simulation tool built in C++ and is introduced in the Physical Layer section of this paper.

sensor nodes floating in the seawater. We utilize fixed short node IDs both for the sink and sensor nodes, aiming to enhance energy efficiency and reduce E2ED by minimizing overhead. Bidirectional communication occurs between the source and sink nodes during the RTS/CTS/ACK/NACK handshake; however, data transmission occurs only from the sensor nodes to the sink.

The sensor nodes compete for channel access to send data packets, facilitated by the SFAMA-MAC protocol. Key attributes of the SFAMA MAC protocol include *GuardTime* to accommodate potential clock drift, *maximum number of retransmissions*, *minimum number of backoff slots*, *maximum number of backoff slots*, *maximum packet size in bytes*, *the maximum transmit distance*, *the maximum number of packets in a train*, and *node ID* corresponding to the MAC address of the device. Table 13 shows the simulation parameters used for setting the configuration of the ns3 simulator. The parameters are selected based on preliminary discussions and refined

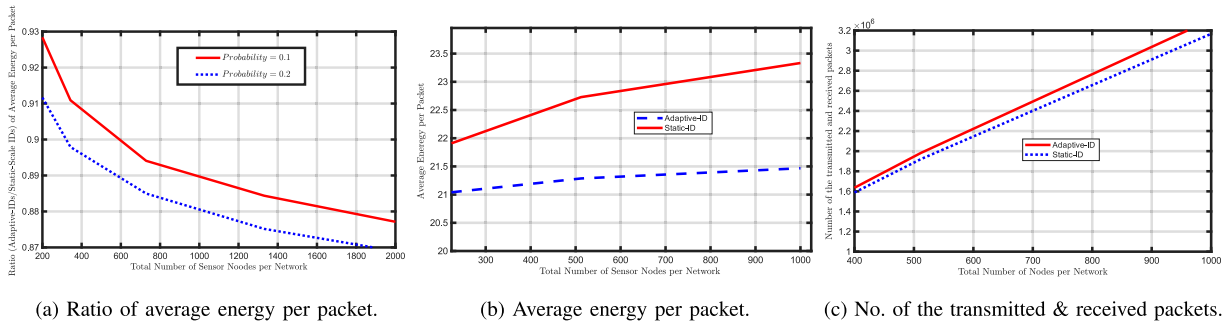


FIGURE 16. Performance of the proposed adaptive ID-based SALSA protocol stack compared with the conventional (i.e., static-ID) SALSA protocol stack: (a) ratio of average energy per packet, (b) average energy per packet, and (c) number of transmitted and received packets vs. the number of sensor nodes per network.

TABLE 12. Simulation Parameters Used in ns3 to Produce the Results in Figure 15.

Parameter	Value
Network Dimension	$10 \times 10 \times 10 \text{ Km}^3$
Number of Nodes	5 nodes
Minimum Inter-distance between the Sensor Nodes	2 km
Network Topology	Random
Mobility Model	Static model
Maximum Transmit Distance	3 Km
Simulation Period	24 Hours
Data Period	2 Seconds
Guard Period	0.2 Seconds
Period to Generate New Data	2 Hours
Time to Finish Data Generation	0
Packet Size	100 Bytes
Maximum Packet Size	∞
Maximum Number of Packets in the Train	DSP Maximum
Maximum Number of Retransmissions	5 transmissions
Minimum Slots in Backoff	0 slots
Maximum Slots in Backoff	5 slots
Routing Scheme	Static routing

TABLE 13. Simulation Parameters of the Numerical Results for Fig. 16, References [302], [523], and [524].

Network Parameters	
Network dimension	$10 \times 10 \times 10 \text{ Km}^3$
Number of nodes	[200, 216, ..., 2000] nodes
Network topology	3-D Square Grids
Mobility model	3-D Gaussian
Variance in the x, y, and z axes	{0.05, 0.05, 0.005} of the grid length
Transceiver Parameters	
Bit Rate	80 bps
Payload	32 bits
Overheads (preamble+packet type+CRC)	$14 + 2 + 8 = 24$ bits
Maximum transmitted power	6.3492×10^{-12} Watt
Power threshold of the receiving packet	6.3492×10^{-20} Watt
Energy of bit aggregation	5×10^{-9} Joule/bit
Spreading factor of the acoustic beam	1.5
Acoustic carrier	12 kHz
Bandwidth	4 kHz

through iterative adjustments to balance computational efficiency and accuracy.

Table 12 presents the simulation parameters used in ns-3 for a small-scale, static sensor network. The network operates in a $10 \times 10 \times 10 \text{ km}^3$ area with 5 randomly placed static nodes, each maintaining a minimum inter-node distance of 2 km and a maximum transmission range of 3 km. The simulation runs for 24 hours, with nodes generating new data every 2 seconds, using 100-byte packets and a guard period of

0.2 seconds to prevent collisions. There is no limit on packet size, and a dynamic scheduling policy (DSP Maximum) governs the number of packets in a train. Each packet can be retransmitted up to 5 times, with a backoff mechanism allowing between 0 and 5 slots to reduce collisions. The routing scheme is static, ensuring predictable communication paths. These parameters emphasize network reliability, congestion control, and data transmission efficiency while evaluating link stability in a small-scale, energy-conscious setup.

Figure 15 shows the performance of the SFAMA-based SALSA Stack Protocol as a function of the maximum transmit distance, aiming to identify the optimal transmit distance for the considered scenario. We evaluate performance metrics including average remaining energy, average delay, goodput, and throughput. While presenting these metrics against the maximum transmission distance, we also investigate the impact of parameters such as the number of sensor nodes, maximum number of retransmissions, maximum number of backoff slots, and packet size.

a: NUMBER OF NODES

Firstly, we examine the variation in the number of sensor nodes, considering values of 10 and 15, as this is an important parameter for evaluating SFAMA performance. As the number of sensor nodes increases, competition for channel access intensifies. Subfigure 15a shows the average remaining energy percentage. On average, the remaining energy percentage is higher in simulation rounds with fewer sensor nodes. This trend aligns with the fact that a smaller number of sensor nodes results in less competition, leading to more energy being conserved.

Subfigure 15b shows the Goodput performance. As the number of sensor nodes increases, competition for channel access intensifies. Although the average throughput tends to be higher with more sensor nodes, the subfigure reveals a fluctuating trend in Goodput. Factors such as certain transmission ranges may prevent nodes from successfully acquiring the channel, resulting in fewer data packets being transmitted and a drop in Goodput. Additionally, the network topology could contribute to packet loss, further affecting Goodput performance.

Subfigure 15c shows the throughput, where a greater number of total bits are received per unit time in the network as the number of sensor nodes increases. This can be attributed to the higher presence of data and control packets in the network, resulting from a larger number of senders. Subfigure 15d shows the average E2ED. As competition among sensor nodes for channel access increases, the average E2ED also increases, as illustrated in the subfigure.

b: MAXIMUM NUMBER OF RETRANSMISSIONS

Secondly, we examine the effect of the maximum number of retransmissions, considering values of 3, 5, and 7 time slots. Due to the limited channel capacity of UWAC systems, the decision to retransmit data should be carefully considered. This is because excessive retransmissions can result in high network load, leading to poor packet success ratio and increased E2ED. These results will help us determine the optimal value of this parameter to achieve the desired performance in different network scenarios.

Subfigure 15e shows Goodput. As the receiver requests the sender to retransmit erroneous packets, the subfigure indicates an increase in Goodput with the maximum number of retransmissions allowed. This trend follows from the greater number of data bits successfully received in the GP-MRT scenario. Subfigure 15f shows the remaining energy percentage. The higher remaining energy at a greater maximum retransmission count can be attributed to fewer control packets needed to acquire the channel.

c: MAXIMUM NUMBER OF BACKOFF SLOTS

Thirdly, we examine the maximum number of backoff slots, considering values of 3, 5, and 7 time slots. To avoid repeated collisions among the same nodes upon detection of a collision, the sender is required to wait for a random period before it retries. This random period is referred to as backoff, and its duration is determined by the number of backoff slots. Very small backoff intervals can lead to a high probability of collisions, whereas long backoff durations may cause unnecessary overall packet delay. Therefore, simulations considering the variation of this parameter play a relevant role in designing the MAC protocol.

Subfigure 15g shows the average remaining energy percentage. When a node enters a backoff state, it transitions from its current state and resumes after completing the backoff period. The subfigure reflects that a higher number of backoff slots leads to greater EC, resulting in a lower remaining energy. Subfigure 15h shows the Average E2ED. As mentioned earlier, the subfigure follows the trend that a greater number of backoff slots results in a higher E2ED.

d: PACKET SIZE

Fourth, we examine the packet size, considering values of 50, 100, and 150 bytes. The efficiency of a MAC protocol depends on the packet size. By keeping the overhead bits per packet and round-trip delay relatively constant, the transmission efficiency can be optimized by dynamically

adjusting the packet length in response to the error rate in the channel.

Subfigure 15i shows the average energy percentage remaining. As the packet size increases, the remaining energy percentage tends to be slightly higher. This can be explained by the fact that larger packet sizes allow nodes to send more data per transmission, thus reducing the overhead associated with multiple smaller transmissions.

e: RESULTS SUMMARIZATION

Based on the obtained results, we can choose the best transmit range according to specific requirements, for example, certain applications are stringent on latency output, others are more concerned about the goodput to be high, and so on. This work could be further extended to a larger network, with clustering to study the SFAMA-MAC performance. More practical PHY layer models can be used to consider underwater-specific test cases. Additional attributes related to SFAMA can be varied to test performance.

B. ADAPTIVE ID-BASED SALSA STACK PROTOCOL

In the conventional SALSA protocols, sensor nodes are identified using static long MAC-IDs,⁴ which, while simple to implement, introduce significant communication overhead. Each packet must carry the full static identifier, increasing the header size and consequently reducing the effective payload per packet. This overhead not only limits the achievable throughput but also increases energy consumption and latency, particularly in resource-constrained wireless networks. In contrast, the proposed Adaptive ID-based SALSA stack protocol dynamically assigns shorter, context-aware identifiers, allowing devices to maintain unique identification while significantly reducing header size. By minimizing per-packet overhead, Adaptive ID-based SALSA enhances data throughput and energy efficiency, and reduces communication latency, making it more suitable for high-density dynamic network environments where minimizing communication cost is critical. In the following, we evaluate the numerical performance of the adaptive ID protocol and compare it with the static ID protocol as a baseline.

1) PERFORMANCE EVOLUTION

Figure 16 illustrates the performance of the Adaptive ID-based SALSA Stack Protocol as a function of the number of sensor nodes per network, based on our previously published results in [395]. The corresponding simulation settings are summarized in Table 13, consistent with those of the SALSA physical layer (i.e., JANUS). This is meant to demonstrate the impacts of the shorter ID on the network performance. We evaluate key performance metrics, including the ratio of average energy per packet for adaptive ID to that for static ID, the average energy per packet, and the numbers of transmitted and received packets, as functions of the total number of sensor nodes.

⁴MAC IDs are usually long and can reach up to 48 bits.

a: RATIO OF AVERAGE ENERGY PER PACKET

In Figure (16a), the adaptive ID-based transmission demonstrates superior energy efficiency compared to the static ID-based transmission, primarily due to its utilization of shorter node IDs, which reduces packet overhead. This efficiency becomes more pronounced as the network scales, i.e., more sensor nodes per network. For instance, with an election probability⁵ of 0.1, adaptive ID-based transmission achieves energy savings of 7% and 12% for networks comprising 200 and 2000 nodes, respectively. Increasing the election probability to 0.2 further enhances these savings to 9% and 13%, respectively. A higher election probability results in more clusters with fewer sensor nodes per cluster, which reduces the ID length and, consequently, decreases the average energy consumption per packet.

b: AVERAGE ENERGY PER PACKET

In Figure (16b), in terms of energy consumption, adaptive ID exhibits the lowest average energy usage per packet relative to static ID-based transmission, maintaining consistent performance in varying network sizes. By contrast, static ID's energy consumption increases with network size because of longer packets, leading to higher collision rates. For a network with 600 nodes, adaptive ID consumes 21.5 Joules per packet, whereas static ID consumes 23 Joules, respectively. This highlights the adaptive ID protocol's superior energy efficiency and scalability.

c: NUMBER OF TRANSMITTED AND RECEIVED PACKETS

In Figure (16c), adaptive ID significantly improves the successfully transmitted and received packets, i.e., high throughput and low latency. For example, in a network with 900 nodes, adaptive ID successfully processes 3 million packets, outperforming static ID, which handle 2.9 million packets, respectively. This translates into throughput improvements of 3.45% over the static ID transmission.

d: RESULTS SUMMARIZATION

Adaptive ID assignment improved communication latency and energy efficiency as compared to the static IDs. The results indicate that the Developed-SALSA protocol stack is suitable for latency- and energy-sensitive applications such as video surveillance and instant messaging systems.

C. ARCHITECTURE AND ALGORITHM OF D-SALSA PROTOCOL

The proposed D-SALSA stack protocols follow the same architecture of conventional SALSA, shown in Fig. 11, i.e., a four-layer structure—physical, MAC, network, and application—integrating JANUS/FRSS (PHY), GUAMANET (MAC/routing), and GUWAL (application). D-SALSA preserves this modular design while introducing targeted enhancements at the physical and MAC layers,

⁵Election probability is the probability that a node becomes a cluster head in a given round.

ensuring backward compatibility, extensibility, and improved overall performance without adding structural complexity.

Algorithm 1 Pseudo Code of D-SALSA Stack Protocols

```

Require: Set of sensor nodes  $N$ , transmission slots  $S$ , max retries  $R$ , initial IDs
Ensure: Efficient, adaptive, and layered data transmission
1: Initialization:
2: Assign initial node IDs
3: Initialize Application Layer: GUWAL module
4: Initialize Network Layer: Multi-Topology-Routing module
5: Initialize MAC Layer: SFAMA slots for transmission schedule
6: for each communication round  $t$  do
7:   if Transmitting Mode then
8:     Application Layer Operations:
9:     Collect and Aggregate data to reduce redundancy
10:    MAC Layer Operations:
11:    Apply ML to set SFAMA parameters
12:    Select an available SFAMA slot
13:    Physical Layer Operations:
14:    Apply SSFS/JANUS modulation
15:    Transmit/receive via LF/HF channels
16:    Apply ML to adjust transmission power and modulation scheme adaptively
17:    Adaptive ID Update: Adjusts the length of the node ID based on the number of active nodes
18:    Transmit packet to receiving node
19:    if collision occurs then
20:      Retry transmission up to  $R$  times
21:    end if
22:  end if
23:  if Receiving Mode then
24:    Physical Layer Operations:
25:    Apply SSFS/JANUS demodulation
26:    Receive via LF/HF channels
27:    if Destination ID matches my ID then
28:      Recover information from received packets
29:    else
30:      Network Layer Operations:
31:      Forward aggregated data to the destination using Multi-Topology-Routing
32:      Optionally apply ML-based routing for energy/delay optimization
33:    end if
34:  end if
35: end for
36: Termination:
37: Continue rounds until network lifetime expires or data collection completes

```

Algorithm 1 implements the D-SALSA stack protocol, preserving the original layered SALSA architecture while introducing adaptive and collision-aware mechanisms. In the Initialization phase, nodes are assigned initial IDs, and the Application, Network, and MAC layers are set up using the GUWAL, Multi-Topology-Routing, and SFAMA modules, respectively. Unlike traditional SALSA implementations that rely on ALOHA, this algorithm uses SFAMA at the MAC layer to schedule transmissions, reducing collisions and improving channel utilization. During each communication round, transmitting nodes collect and aggregate data at the Application Layer, select an SFAMA slot using ML-based optimization, and transmit packets over LF/HF

TABLE 14. A Concise Summary of the Differences Between the Conventional SALSA and D-SALSA Protocols.

Aspects	Conventional SALSA Stack Protocol	D-SALSA Stack Protocols
Physical Layer	Uses a significantly longer user ID (e.g., physical MAC address)	Significantly shorter user ID (e.g., node number)
MAC Layer	Uses ALOHA schemes	Uses SFAMA schemes
Merits	Offers low signal processing complexity and low implementation cost	Ensures superior performance, including low latency, high throughput, energy efficiency, and reliability
Challenges	Does not meet the requirements of modern applications, such as high speed and high reliability	Should be tested in real scenarios to ensure it performs well under real-world challenges
Applications	Small-scale scenarios, such as localized sensor networks, short-range communication systems, and confined environments in which simplicity and low power consumption are prioritized	Large-scale scenarios, including wide-area sensor networks, long-range communication systems, and complex distributed infrastructures requiring scalability, robustness, and efficient resource management

channels with adaptive power and modulation at the Physical Layer. Node IDs are dynamically updated according to the number of active nodes, reducing overhead bits, and enhancing scalability and load balancing. Receiving nodes demodulate incoming packets, recover data if the destination matches their ID, or forward aggregated data through Multi-Topology-Routing with optional ML-based routing optimization. Transmission collisions are handled with a retry mechanism up to a maximum count. The process continues until network lifetime expires or data collection completes, ensuring efficient, adaptive, and layered data transmission while maintaining SALSA's original architecture.

D. SUMMARY AND FUTURE WORKS

Table 14 provides a concise summary of the differences between the conventional SALSA and D-SALSA protocols. The SALSA stack protocol represents a robust and adaptive framework for UWAC, integrating key components such as JANUS and FRSS at the physical layer, GUAMANET for MAC and routing, and GUWAL at the application layer. The conventional SALSA protocol was enhanced through the D-SALSA stack, which replaces ALOHA-MAC with SFAMA-MAC and optimizes node ID lengths to reduce overhead, thereby improving energy efficiency and reducing end-to-end delay. The results of the performance evaluations demonstrate the effectiveness of these modifications, particularly in scenarios with varying node densities, retransmission limits, backoff slots, and packet sizes. The adaptive ID-based approach further enhances scalability and energy efficiency, making the protocol suitable for latency-sensitive applications. Although we have demonstrated the baseline performance of the novel SFAMA-based and Adaptive ID-based SALSA stack protocols, further in-depth investigation is required as part of the research agenda. In particular, integrating these protocols into a unified framework (i.e., a joint SFAMA and Adaptive ID SALSA stack protocol) represents a promising research direction.

Future work should explore the integration of machine learning techniques to further enhance the D-SALSA stack

protocol. For instance, machine learning could be used to optimize dynamic parameter adaptation, such as transmission duration and the number of slots in the SFAMA-based protocol, and ID length in the adaptive ID-based protocol under dynamic scenarios. Additionally, machine learning could help adapt modulation schemes and power allocation based on real-time environmental conditions. Moreover, the use of supercomputing and advanced signal processing could enable real-time network simulations and large-scale deployments, facilitating the development of next-generation underwater networks with improved reliability, efficiency, and adaptability. These advancements could position SALSA as a key enabler for future UIoT and autonomous marine systems.

In Section X, we investigate the integration of SFAMA-based and Adaptive ID-based SALSA stack protocols within heterogeneous acoustic-optical communication networks. Such integration can leverage the high bandwidth of optical links for short-range communication while relying on acoustic links for long-range connectivity.

X. HETEROGENEOUS NETWORKS FOR BIG MARINE DATA TRANSMISSION

Big Marine Data (BMD) and the IoUT are integral to the advancement of marine science, resource management, and environmental monitoring. BMD encompasses the vast volumes of data generated by various underwater sources, including sensors, hydrophones, cameras, and acoustic tags, offering critical insights into oceanographic parameters, marine life, and ecosystem health. This data is characterized by its volume, variety, value, and velocity, presenting significant opportunities for scientific discovery and improved resource management [79]. However, these opportunities are accompanied by substantial challenges, particularly in communication and data transmission. Furthermore, the large scale of BMD and the inherent constraints of underwater communication complicate efficient data processing, secure storage, and network-wide data transmission [79], [525], [526].

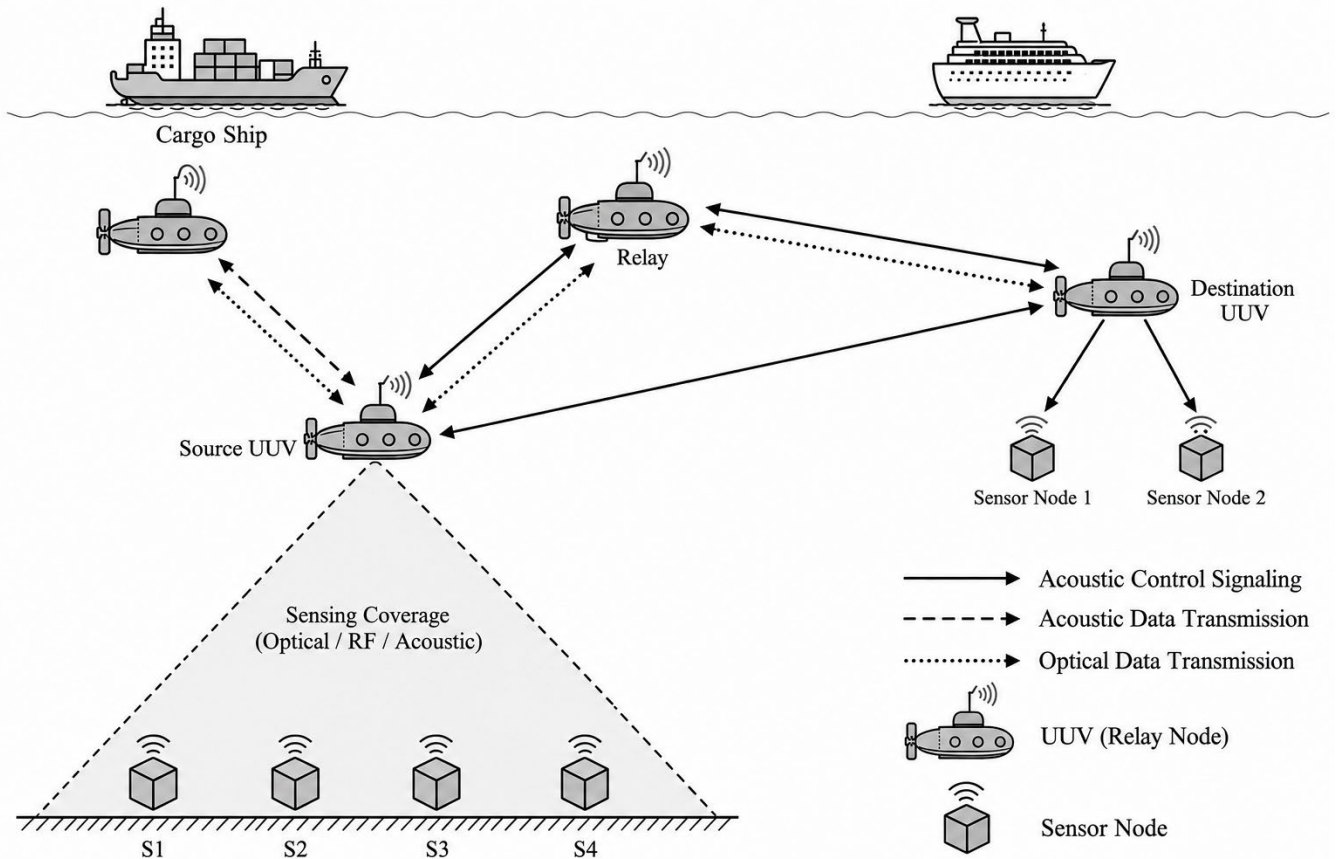


FIGURE 17. Proposed Two-tier Multi-RAT Cluster-based.

Traditional UWAC, while effective for long-range connectivity, is hindered by low bandwidth and high latency, restricting the data transfer rates necessary for the BMD applications. The limitations of single-technology communication systems in underwater environments necessitate the development of heterogeneous networks that integrate multiple communication technologies. Acoustic, optical, and radio frequency (RF) communication systems each offer distinct advantages and limitations, making their integration essential for underwater applications requiring high data rates. UWAC ensures long-range connectivity but suffers from low bandwidth, whereas OWC provides high bandwidth and low latency but is restricted to shorter distances due to water absorption and scattering [527], [528]. RF communication, while effective at the air-water interface and for short-range transmission, experiences significant attenuation in seawater. By integrating these diverse communication technologies, heterogeneous networks address the challenges posed by BMD and IoUT, enabling more efficient data transmission by selecting the most appropriate technology for each specific requirement. Additionally, heterogeneous networks optimize energy consumption (EC) and extend the lifespan of battery-powered underwater nodes, a crucial factor for sustained deep-sea monitoring and communication. The successful

integration of these communication technologies depends on well-structured network architectures, dual-mode modems, and adaptive networking strategies to facilitate seamless communication across underwater environments. A robust hybrid underwater communication system can be realized through a network architecture incorporating both acoustic and optical components. These networks typically feature optical base stations (OBSs) alongside acoustic access points (AAPs), with configurations tailored for either long-term monitoring through fixed infrastructural deployments or flexible, temporary setups via ad hoc deployments [529]. The seamless integration of acoustic and optical technologies is further enhanced through dual-mode modems, which allow underwater nodes to switch dynamically between communication modalities based on environmental conditions and operational requirements. In hybrid systems, acoustic signals often establish initial connectivity and aid in optical transceiver alignment [530]. Moreover, modern underwater communication systems leverage adaptive networking strategies to dynamically allocate resources and optimize communication mode selection. Software-defined underwater networks (SDUNs) provide a flexible, programmable framework for managing hybrid communication systems by continuously monitoring environmental parameters such as water clarity,

turbidity, and interference. Utilizing real-time data, SDUNs facilitate autonomous decision-making, allowing dynamic switching between acoustic and optical communication to ensure optimal performance [529].

A. ILLUSTRATIVE EXAMPLE OF AN UNDERWATER HETEROGENEOUS NETWORK: A TWO-TIER MULTI-RAT CLUSTER-BASED APPROACH

To clarify the advantages of integrating acoustic and optical communication systems in underwater scenarios, we present a two-tier cluster-based multi-RAT network, as shown in Fig. 17, which is a proposal for this integration. By two-tier, we mean separating data signals from signaling/control signals. The signaling/control information is transmitted using acoustic signals due to their long-range capabilities. The data signals that require high data-rate transmission are sent over the OWC signals. The integration of OWC and UWAC technologies in a multi-RAT system offers several significant advantages for IoUT. OWC’s high bandwidth enables rapid and efficient data transmission, supporting applications that require large data transfers or real-time processing, while its low-latency communication is particularly beneficial for time-sensitive tasks like remote vehicle operation and real-time monitoring. When combined with the long-range capabilities of UWAC, OWC ensures consistent connectivity across varying distances, making it suitable for diverse deployment scenarios. The multi-RAT approach also enhances network reliability by providing redundancy, allowing for dynamic switching between technologies based on environmental conditions, which improves overall network performance.

B. MANAGEMENT PROTOCOL

Figure 18 illustrates the proposed management protocol for enabling high-data-rate underwater communication between a source and a destination. In this scenario, the required data rate cannot be supported by acoustic communication alone, while the separation distance exceeds the feasible range of direct OWC, thereby necessitating relay-assisted transmission. To address these constraints, the SALSAs/D-SALSAs protocol stack is employed over the acoustic channel to provide adaptive control, discovery, and coordination among dual-band (acoustic and optical) Uncrewed Underwater Vehicles (UUVs).

Initially, the source node broadcasts a communication request using the SALSAs/D-SALSAs framework. This transmission is adaptively configured in terms of frequency band, transmission power, and modulation scheme to ensure reliable propagation over the required range. The request packet includes the source position, destination identifier, and quality-of-service requirements, particularly the target data rate. Upon reception, the destination evaluates the feasibility of establishing either a direct acoustic or OWC link. If neither option satisfies the communication requirements, a relay discovery procedure is initiated.

During the relay discovery phase, intermediate UUVs within the acoustic coverage region are identified using

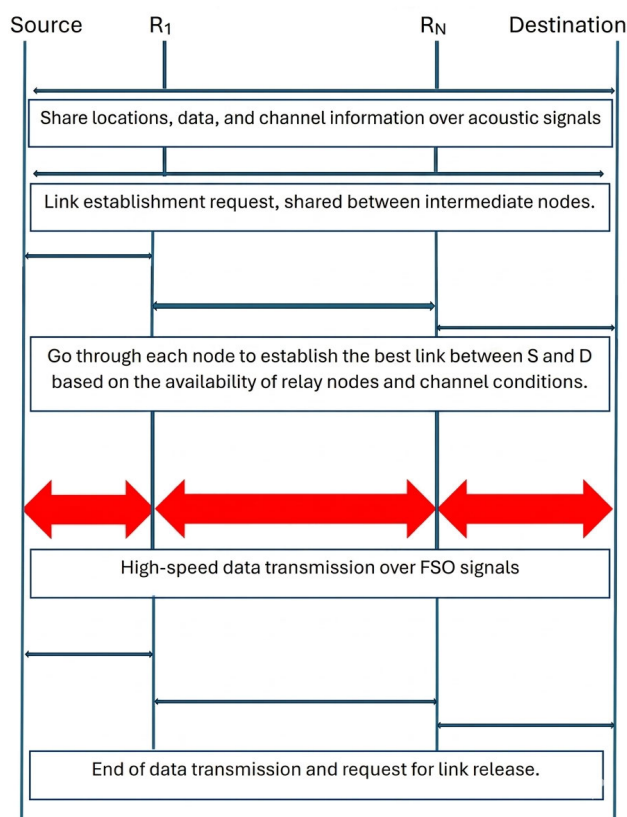


FIGURE 18. Two-tier multi-RAT cluster-based management protocol.

SALSAs/D-SALSAs-enabled signaling. Candidate relay nodes respond with relevant state information, including their spatial coordinates, residual energy, mobility characteristics, and estimated suitability for OWC link establishment. The SALSAs/D-SALSAs protocol dynamically adapts the discovery process by switching between long-range low-rate broadcast and short-range higher-rate exchanges, thereby ensuring efficient information gathering under varying channel conditions.

Based on the collected information, the source node selects an optimal set of relay nodes. The selection process accounts for both acoustic link reliability and the feasibility of forming line-of-sight OWC links between consecutive nodes. Following relay selection, OWC links are established between successive nodes, enabling high-data-rate transmission along the multi-hop optical path. Concurrently, the acoustic channel, governed by SALSAs/D-SALSAs, operates as a control plane to provide continuous link monitoring, adaptive reconfiguration, and signaling support. In the event of link degradation due to environmental dynamics or node mobility, SALSAs/D-SALSAs facilitates rapid relay reselection and route adaptation.

Upon completion of data transmission, the source node transmits a termination and resource release message via the acoustic channel to all participating relay nodes. This framework demonstrates the effectiveness of integrating adaptive acoustic control, via SALSAs/D-SALSAs, with high-capacity

OWC links to achieve reliable, long-range underwater communication.

Although both D-SALSA and SALSA can be used in this architecture, D-SALSA is preferred due to its merits, as discussed in Section IX.

C. MAIN CONCERNS IN FUTURE PROTOCOLS DESIGN TO ENABLE BMD AND HETEROGENEOUS NETWORKS

1) PHYSICAL LAYER

a: SIGNAL MODULATION AND CODING TECHNIQUES

The physical layer must support modulation and coding techniques optimized for each medium (acoustic, optical, RF), potentially requiring hardware changes to handle multiple schemes.

b: TRANSMISSION POWER CONTROL

The physical layer must include adaptive power control mechanisms, such as automatic gain control for RF and optical systems or power amplification for acoustic systems, to optimize transmission power for each medium.

c: CHANNEL SENSING AND INTERFERENCE MANAGEMENT

The physical layer should incorporate advanced interference management techniques, such as adaptive filtering, dynamic channel sensing, and interference cancellation, along with methods like frequency hopping or time-slotting to minimize collisions and interference in the RF and acoustic channels.

d: SIGNAL DETECTION AND CONVERSION

The physical layer must integrate multimodal transceiver hardware for acoustic transducers, optical detectors, and RF antennas. Additionally, signal conversion mechanisms between different transmission modes (acoustic to optical, RF to acoustic) should be supported.

2) MAC LAYER

a: DYNAMIC ADAPTATION TO MULTIPLE TECHNOLOGIES

The evolution of heterogeneous underwater networks necessitates significant advancements in MAC layer protocols to meet the diverse requirements of BMD transmission. The underwater environment is inherently dynamic, with channel variability caused by multipath fading, Doppler shifts, and variable propagation delays. Consequently, MAC protocols must integrate dynamic adaptation mechanisms to ensure robust and efficient communication under such conditions. Addressing the interplay among acoustic, optical, and RF communication technologies in heterogeneous networks is crucial. Incorporating real-time channel state monitoring into MAC designs enables adaptive switching between these technologies, optimizing performance for specific application needs.

b: ENERGY EFFICIENCY

Energy efficiency remains a critical challenge in underwater networks due to the limited power resources of nodes. Advanced MAC protocols must employ techniques such as

duty cycling, energy-aware scheduling, and collision avoidance to extend the operational lifetime of these nodes. Moreover, heterogeneous networks require protocols capable of balancing energy consumption (EC) across different communication modes. For instance, leveraging low-power optical communication for short-range, high-data-rate tasks can reduce reliance on energy-intensive acoustic transmissions.

c: CROSS-LAYER OPTIMIZATION

To ensure interoperability within heterogeneous networks, MAC protocols must support cross-layer optimization. Integrating physical-layer information, such as signal-to-noise ratio and node mobility, into the MAC layer can enhance scheduling and resource allocation. Furthermore, the introduction of cognitive MAC protocols, which leverage ML to predict channel conditions and dynamically adapt access strategies, offers promising avenues for improving network performance.

d: ADOPTING MACHINE LEARNING

ML can significantly enhance the MAC layer of heterogeneous underwater networks by enabling dynamic adaptation to varying channel conditions, improving traffic management, and optimizing resource allocation. ML algorithms can predict real-time channel state information, allowing for efficient switching between communication technologies (acoustic, optical, and RF) to optimize performance. Additionally, ML can classify and prioritize network traffic, reduce interference, and promote energy-efficient operations by analyzing patterns in network traffic and EC. These capabilities make ML an essential tool for addressing the challenges of diverse communication technologies in dynamic underwater environments, thus enabling more efficient and reliable MAC layer protocols in heterogeneous underwater networks.

3) ROUTING PROTOCOLS

The future routing protocols for underwater heterogeneous networks should carefully consider the following factors to effectively leverage the strengths of acoustic, optical, and RF systems, achieving optimal performance in terms of reliability, energy efficiency, and throughput.

a: DYNAMIC PATH SELECTION

- **Link Quality Assessment:** Protocols should continuously monitor the quality of each link type, considering factors like signal strength, noise levels, and propagation delays.
- **Adaptive Routing:** Based on real-time link quality assessments, the protocol can dynamically switch between acoustic, optical, and RF links to select the most suitable path for data transmission.
- **Multi-Hop Routing:** By combining different technologies in a multi-hop fashion, the network can leverage the strengths of each technology to achieve optimal performance.

b: ENERGY EFFICIENCY

- **Energy-Aware Routing:** Protocols should consider the EC of each technology and select routes that minimize energy expenditure.
- **Selective Activation:** Nodes can selectively activate different communication interfaces based on their energy levels and the current network state.
- **Power-Saving Modes:** When idle, nodes can enter low-power modes to conserve energy, periodically waking up to check for incoming messages or to transmit data.

c: ADOPTING ARTIFICIAL INTELLIGENCE (AI)

Artificial intelligence can significantly enhance routing strategies in multi-RAT underwater networks by enabling adaptive, energy-efficient, and intelligent path selection [383]. RL-based routing algorithms allow nodes to switch between acoustic, optical, and RF paths based on real-time environmental conditions, network topology, and energy constraints. AI-based multi-hop routing, such as Q-learning-based routing (QMCR and QELAR), ensures that sensor nodes autonomously choose optimal paths while balancing energy consumption and minimizing delays [360]. Additionally, AI enables cross-layer routing, where decisions are made by considering physical-layer factors (e.g., signal strength, modulation schemes) alongside network-layer parameters (e.g., congestion, link stability). Multi-Agent RL protocols allow multiple underwater nodes to collaborate, selecting optimal routes that enhance overall network reliability and performance. Furthermore, AI improves data transmission predictability by utilizing deep neural networks for traffic forecasting and intelligent decision-making, ensuring stable and efficient routing even in dynamic underwater environments.

d: RELIABILITY AND FAULT TOLERANCE

- **Redundancy:** By employing multiple communication paths and redundant links, the network can improve reliability and fault tolerance.
- **Error Correction:** Advanced error correction codes can be used to mitigate the effects of channel impairments, such as noise and interference.
- **Retransmission:** Retransmission mechanisms can be used to recover lost or corrupted packets.

e: DELAY AND THROUGHPUT

- **Priority-Based Scheduling:** Prioritizing critical data traffic can help ensure the delivery of important information.
- **Adaptive Modulation and Coding:** By adjusting modulation schemes and coding rates, the network can adapt to changing channel conditions and optimize data rate and reliability.

D. RESEARCH AGENDA FOR HETEROGENEOUS UNDERWATER NETWORK DESIGN

Based on the evidence reviewed in the previous section, we propose the following research agenda to guide efforts in heterogeneous underwater network designs:

1) DUAL-MODE/MULTI-MODE MODEM AND TRANSCEIVER DESIGN

Challenge Implementing devices capable of operating across multiple modalities (acoustic, optical, RF), considering severe energy constraints and form factor limitations of underwater nodes. In particular, optical transceivers require precise pointing, acquisition, and tracking (PAT), which increases complexity, cost, power consumption, and size.

Research Agenda

- Design and implement energy-aware, low-power multi-technology multi-mode gateways and nodes suitable for undersea applications;
- Develop sophisticated transceivers and signal processing techniques to mitigate modality-specific challenges (e.g., acoustic multipath and delay, optical alignment and absorption);
- Enable real-time reconfiguration of physical layer parameters (modulation, coding, power, beam shaping) using software-defined approaches to adapt to dynamic channel conditions;
- Investigate transceiver designs that reduce dependence on mechanical PAT mechanisms in optical systems;
- Conduct information-theoretic analysis of combining different transmission media to characterize achievable rate regions and optimize hybrid link strategies.

2) CROSS-LAYER HAND-OFF AND NETWORK SELECTION LOGIC

Challenge Deciding which technology or combination to use dynamically is complex due to the mix of characteristics and highly dynamic underwater conditions. Managing vertical handovers (VHO) is more challenging than in homogeneous environments. **Research Agenda**

- Develop fine-grained, intelligent network selection strategies based on traffic type, required data rate, security, mobility, LOS/NLOS conditions, and energy consumption;
- Design efficient VHO algorithms that minimize delay, data loss, and “ping-pong” effects, incorporating prediction of channel availability and blockage;
- Create cross-layer design methodologies integrating physical and data link layer metrics for hybrid systems;
- Investigate adaptive switching mechanisms for seamless transitions between modalities (acoustic, optical, RF, etc.) in response to operational demands or environmental changes.

3) HYBRID-LINK QUALITY OF SERVICE (QOS) ROUTING

Challenge Traditional routing is ill-suited for the characteristics of underwater networks, especially in hybrid contexts that involve links with drastically different bandwidth, delay, and reliability. **Research Agenda**

- Design distributed and fault-tolerant routing protocols for hybrid underwater networks that use the strengths of each communication mode and adapt to node failures and dynamic conditions;

- Develop routing strategies that factor in link quality, battery level, buffer status, alongside traditional metrics like hop count;
- Investigate new transport protocols tailored to hybrid underwater optical-acoustic networks (UOANs) for improved congestion and failure awareness;
- Research seamless data steering techniques in multi-transmitter systems to minimize delay and loss in heterogeneous underwater settings.

4) SECURITY

Challenge While technologies like optical communication offer inherent physical-layer security, integration of multiple modalities can introduce new attack vectors, making adaptation of terrestrial protocols to underwater contexts non-trivial.

Research Agenda

- Develop secure hybrid network architectures incorporating Software-Defined Networking (SDN) and cognitive elements to resist attacks (e.g., jamming, spoofing, wormholes);
- Explore the security implications of adapting terrestrial network management systems (e.g., OVSDB for SDN) to the underwater domain.

5) NETWORK MANAGEMENT AND RESOURCE ORCHESTRATION

Challenge Managing and controlling multimodal underwater networks is highly complex due to the lack of centralization and consistent backhaul. **Research Agenda**

- Use SDN to create a centralized control plane for underwater heterogeneous networks, enabling dynamic traffic management, resource allocation, and application-specific slicing;
- Apply Network Function Virtualization (NFV) to develop adaptable, application-specific protocol suites;
- Design Underwater Network Management Systems (U-NMS) to manage heterogeneity, synchronization, and multiple backhaul links in IoUT settings;
- Propose effective load-balancing strategies across available communication modalities.

6) APPLICATION OF MACHINE LEARNING AND AI

Challenge The underwater environment is complex and dynamic, making conventional modeling and control approaches inadequate. **Research Agenda**

- Apply ML and DL for channel modeling, joint signal detection, and network optimization tasks in hybrid underwater networks;
- Develop and curate datasets for training ML/DL models tailored to underwater communication features and dynamic behaviors.

Addressing the above challenges via theoretical modeling and experimental validation is critical for enabling robust, efficient, and scalable heterogeneous underwater networks.

XI. CONCLUSION

This paper highlights the pivotal role of UWSNs and addresses the unique challenges imposed by the underwater environment. Through a comprehensive review of network stack protocols—spanning the physical, MAC, and routing layers, and security threats—this study analyzes their underlying mechanisms, trade-offs, and limitations. This analysis further outlines key research gaps and establishes a forward-looking research agenda for advancing UWSN design and performance.

Special attention is given to the conventional SALSA stack protocol, which serves as the foundation for developing the proposed D-SALSA stack protocols, namely the SFAMA-Based SALSA and Adaptive ID-Based SALSA variants. These enhancements aim to improve channel access efficiency, reduce overhead, and enhance overall network performance. Nevertheless, the complexity of underwater communication environments has motivated us to propose a heterogeneous network architecture and adopt the D-SALSA stack protocol, as well as develop more generalized protocols capable of addressing diverse operational challenges.

Moreover, future research should focus on physical validation in real-world underwater environments to further evaluate and refine the proposed protocols and heterogeneous network architecture. This transition from simulation to practical experimentation is essential for developing robust and reliable underwater communication systems.

REFERENCES

- [1] A. Khan et al., "Routing protocols for underwater wireless sensor networks: Taxonomy, research challenges, routing strategies and future directions," *Sensors*, vol. 18, no. 5, p. 1619, May 2018.
- [2] A. G. Yisa, T. Dargahi, S. Belguith, and M. Hammoudeh, "Security challenges of Internet of Underwater Things: A systematic literature review," *Trans. Emerg. Telecommun. Technol.*, vol. 32, no. 3, p. 4203, Mar. 2021.
- [3] G. Yang, L. Dai, and Z. Wei, "Challenges, threats, security issues and new trends of underwater wireless sensor networks," *Sensors*, vol. 18, no. 11, p. 3907, Nov. 2018.
- [4] G. Yang, L. Dai, G. Si, S. Wang, and S. Wang, "Challenges and security issues in underwater wireless sensor networks," *Proc. Comput. Sci.*, vol. 147, pp. 210–216, Jan. 2019.
- [5] H. Kaushal and G. Kaddoum, "Underwater optical wireless communication," *IEEE Access*, vol. 4, pp. 1518–1547, 2016.
- [6] Z. Zeng, S. Fu, H. Zhang, Y. Dong, and J. Cheng, "A survey of underwater optical wireless communications," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 1, pp. 204–238, 1st Quart., 2016.
- [7] M. Jouhari, K. Ibrahim, H. Tembine, and J. Ben-Othman, "Underwater wireless sensor networks: A survey on enabling technologies, localization protocols, and Internet of Underwater Things," *IEEE Access*, vol. 7, pp. 96879–96899, 2019.
- [8] M. Tariq, M. S. Abd Latiff, M. Ayaz, and M. Z. Abbas, "Beacon-based routing protocols for underwater acoustic sensor networks," *Int. J. Commun. Syst.*, vol. 30, no. 18, p. 3375, Dec. 2017.
- [9] C. Baldone, G. E. Galioto, D. Croce, I. Tinnirello, and C. Petrioli, "Doppler estimation and correction for JANUS underwater communications," in *Proc. IEEE Global Commun. Conf.*, Taipei, Taiwan, Dec. 2020, pp. 1–6.
- [10] A. S. Ghazy, "Reliable high-speed short-range underwater wireless optical communication systems," Ph.D. dissertation, Dept. ECE, McMaster University, Hamilton, ON, Canada, Dec. 2021.
- [11] K. Chen, M. Ma, E. Cheng, F. Yuan, and W. Su, "A survey on MAC protocols for underwater wireless sensor networks," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 3, pp. 1433–1447, 3rd Quart., 2014.
- [12] S. Jiang, "State-of-the-art medium access control (MAC) protocols for underwater acoustic networks: A survey based on a MAC reference model," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 1, pp. 96–131, 1st Quart., 2018.

- [13] A. Boukerche and P. Sun, "Design of algorithms and protocols for underwater acoustic wireless sensor networks," *ACM Comput. Surv.*, vol. 53, no. 6, pp. 1–34, Nov. 2021.
- [14] A. Al Guqhaiman, O. Akanbi, A. Aljaedi, and C. E. Chow, "A survey on MAC protocol approaches for underwater wireless sensor networks," *IEEE Sensors J.*, vol. 21, no. 3, pp. 3916–3932, Feb. 2021.
- [15] F. A. Alfouzan, "Energy-efficient collision avoidance MAC protocols for underwater sensor networks: Survey and challenges," *J. Mar. Sci. Eng.*, vol. 9, no. 7, p. 741, Jul. 2021.
- [16] E. Kulla, K. Matsuo, and L. Barolli, "MAC layer protocols for underwater acoustic sensor networks: A survey," in *Proc. Int. Conf. Innov. Mob. Internet Serv. Ubiquitous Comput.*, 2022, pp. 211–220.
- [17] G. Han, J. Jiang, N. Bao, L. Wan, and M. Guizani, "Routing protocols for underwater wireless sensor networks," *IEEE Commun. Mag.*, vol. 53, no. 11, pp. 72–78, Nov. 2015.
- [18] P. V. Rao, N. M. K. Varma, and R. Sudhakar, "A systematic survey on software-defined networks, routing protocols and security infrastructure for underwater wireless sensor networks (UWSNs)," in *Proc. Emerg. Res. Data Eng. Syst. Comput. Commun.* Cham, Switzerland: Springer, 2020, pp. 551–559.
- [19] J. Luo, Y. Chen, M. Wu, and Y. Yang, "A survey of routing protocols for underwater wireless sensor networks," *IEEE Commun. Surveys Tuts.*, vol. 23, no. 1, pp. 137–160, 1st Quart., 2021.
- [20] S. Khisa and S. Moh, "Survey on recent advancements in energy-efficient routing protocols for underwater wireless sensor networks," *IEEE Access*, vol. 9, pp. 55045–55062, 2021.
- [21] J. Jiang, G. Han, and C. Lin, "A survey on opportunistic routing protocols in the Internet of Underwater Things," *Comput. Netw.*, vol. 225, Apr. 2023, Art. no. 109658.
- [22] L. Movva, C. Kurra, G. K. Rao, R. B. Battula, M. Sridhar, and P. Harish, "Underwater acoustic sensor networks: A survey on MAC and routing protocols," *Int. J. Comput. Technol. Appl.*, vol. 3, no. 3, 2012.
- [23] N. Li, J.-F. Martínez, J. Meneses Chaus, and M. Eckert, "A survey on underwater acoustic sensor network routing protocols," *Sensors*, vol. 16, no. 3, p. 414, Mar. 2016.
- [24] N. Z. Zenia, M. Aseeri, M. R. Ahmed, Z. I. Chowdhury, and M. S. Kaiser, "Energy-efficiency and reliability in MAC and routing protocols for underwater wireless sensor network: A survey," *J. Netw. Comput. Appl.*, vol. 71, pp. 72–85, Aug. 2016.
- [25] Z. U. Khan et al., "A comprehensive survey of energy-efficient MAC and routing protocols for underwater wireless sensor networks," *Electronics*, vol. 11, no. 19, p. 3015, 2022.
- [26] S. Climent, A. Sanchez, J. Capella, N. Meratnia, and J. Serrano, "Underwater acoustic wireless sensor networks: Advances and future trends in physical, MAC and routing layers," *Sensors*, vol. 14, no. 1, pp. 795–833, Jan. 2014.
- [27] S. S. Shahapur and R. Khanai, "Underwater sensor network at physical, data link and network layer—A survey," in *Proc. Int. Conf. Commun. Signal Process. (ICCSP)*, Apr. 2015, pp. 1449–1453.
- [28] M. Sharif-Yazd, M. R. Khosravi, and M. K. Moghimi, "A survey on underwater acoustic sensor networks: Perspectives on protocol design for signaling, MAC and routing," *J. Comput. Commun.*, vol. 5, no. 5, pp. 12–23, 2017.
- [29] R. V. Bhaskarwar and D. J. Pete, "Cross-layer design approaches in underwater wireless sensor networks: A survey," *Social Netw. Comput. Sci.*, vol. 2, no. 5, p. 362, Sep. 2021.
- [30] L. Songzuo, B. Iqbal, I. U. Khan, N. Ahmed, G. Qiao, and F. Zhou, "Full duplex physical and MAC layer-based underwater wireless communication systems and protocols: Opportunities, challenges, and future directions," *J. Mar. Sci. Eng.*, vol. 9, no. 5, p. 468, Apr. 2021.
- [31] E. M. Sozer, M. Stojanovic, and J. G. Proakis, "Underwater acoustic networks," *IEEE J. Ocean. Eng.*, vol. 25, no. 1, pp. 72–83, Jan. 2000.
- [32] A. K. Othman, A. E. Adams, and C. C. Tsimenidis, "Node discovery protocol and localization for distributed underwater acoustic networks," in *Proc. Adv. Int. Conf. Telecommun. Int. Conf. Internet Web Appl. Services (AICT-ICIW)*, Feb. 2006, p. 93.
- [33] R. Diamant, R. Francescon, and M. Zorzi, "Topology-efficient discovery: A topology discovery algorithm for underwater acoustic networks," *IEEE J. Ocean. Eng.*, vol. 43, no. 4, pp. 1200–1214, Oct. 2018.
- [34] Y. Liu, H. Wang, L. Cai, X. Shen, and R. Zhao, "Fundamentals and advancements of topology discovery in underwater acoustic sensor networks: A review," *IEEE Sensors J.*, vol. 21, no. 19, pp. 21159–21174, Oct. 2021.
- [35] J. Proakis, M. Stojanovic, and J. Rice, "Design of a communication network for shallow water acoustic modems," in *Proc. Oceans Commun. Conf.*, vol. 2, 1998, pp. 1150–1159.
- [36] A. Patil and M. Stojanovic, "A node discovery protocol for ad hoc underwater acoustic networks," *Wireless Commun. Mobile Comput.*, vol. 13, no. 3, pp. 277–295, Feb. 2013.
- [37] R. Zhao, Y. Liu, O. A. Dobre, H. Wang, and X. Shen, "An efficient topology discovery protocol with node ID assignment based on layered model for underwater acoustic networks," *Sensors*, vol. 20, no. 22, p. 6601, Nov. 2020.
- [38] R. Petroccia, "DIVE: A distributed ID assignment and topology discovery protocol for underwater acoustic networks," *Ad Hoc Netw.*, vol. 122, Nov. 2021, Art. no. 102610.
- [39] Y. Guo, X. Zhuo, L. Tang, W. Wu, Y. Wei, and F. Qu, "Neighbor discovery with directional transmission in integrated sensing and communication for underwater acoustic networks," in *Proc. IEEE/CIC Int. Conf. Commun. China (ICCC Workshops)*, Aug. 2023, pp. 1–6.
- [40] K. Pahlavan and A. H. Levesque, *Wireless Information Networks*, vol. 95. Hoboken, NJ, USA: Wiley, 1995.
- [41] M. He, F. Liu, Z. Miao, H. Zhou, and Q. Chen, "A mechanism of topology optimization for underwater acoustic sensor networks based on autonomous underwater vehicles," *Int. J. Distrib. Sensor Netw.*, vol. 13, no. 1, Jan. 2017, Art. no. 155014771668697.
- [42] Y. Song and P.-Y. Kong, "Optimizing design and performance of underwater acoustic sensor networks with 3D topology," *IEEE Trans. Mobile Comput.*, vol. 19, no. 7, pp. 1689–1701, Jul. 2020.
- [43] W. Lin, D. Chen, F. Tong, and Y. Zhou, "PSO based topology optimization for underwater acoustic sensor network," in *Proc. 17th Int. Conf. Underwater Netw. Syst.*, Nov. 2023, pp. 1–2.
- [44] L. Liu, Y. Liu, and N. Zhang, "A complex network approach to topology control problem in underwater acoustic sensor networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 25, no. 12, pp. 3046–3055, Dec. 2014.
- [45] R. Fan, Z. Jin, W. Yang, S. Yang, and Y. Su, "A time-varying acoustic channel-aware topology control mechanism for cooperative underwater sonar detection network," *Ad Hoc Netw.*, vol. 149, Oct. 2023, Art. no. 103228.
- [46] V. G. Menon, D. Midhunchakkaravarthy, A. Sujith, S. John, X. Li, and M. R. Khosravi, "Towards energy-efficient and delay-optimized opportunistic routing in underwater acoustic sensor networks for IoT platforms: An overview and new suggestions," *Comput. Intell. Neurosci.*, vol. 2022, Mar. 2022, Art. no. 7061617.
- [47] A. V. Sutagundar, B. S. Halakarnimath, L. B. Bhanjantri, and N. Nalini, "A novel approach of topology control in underwater sensor networks," in *Proc. IEEE 2nd Mysore Sub Sect. Int. Conf. (MysuruCon)*, Oct. 2022, pp. 1–5.
- [48] M. Choudhary and N. Goyal, "Dynamic topology control algorithm for node deployment in mobile underwater wireless sensor networks," *Currency Comput., Pract. Exper.*, vol. 34, no. 15, p. 6942, Jul. 2022.
- [49] A. Datta and M. Dasgupta, "Energy efficient topology control in underwater wireless sensor networks," *Comput. Electr. Eng.*, vol. 105, Jan. 2023, Art. no. 108485.
- [50] J. Jiang, S. Wang, G. Han, and H. Wang, "Reinforcement-learning-based adaptive neighbor discovery algorithm for directional transmission-enabled Internet of Underwater Things," *IEEE Internet Things J.*, vol. 10, no. 10, pp. 9038–9048, May 2023.
- [51] C. S. Nandyala, H.-W. Kim, and H.-S. Cho, "QTAR: A Q-learning-based topology-aware routing protocol for underwater wireless sensor networks," *Comput. Netw.*, vol. 222, Feb. 2023, Art. no. 109562.
- [52] R. A. Leathers, T. V. Downes, C. O. Davis, and C. D. Mobley, "Monte Carlo radiative transfer simulations for ocean optics: A practical guide," *Memorandum Rep. A*, vol. 1, Sep. 2004, Art. no. 426624.
- [53] R. C. Millard and G. Seaver, "An index of refraction algorithm for seawater over temperature, pressure, salinity, density, and wavelength," *Deep Sea Res. A. Oceanographic Res. Papers*, vol. 37, no. 12, pp. 1909–1926, Dec. 1990.
- [54] C. Gabriel, M.-A. Khalighi, S. Bourennane, P. Leon, and V. Rigaud, "Monte-Carlo-based channel characterization for underwater optical communication systems," *J. Opt. Commun. Netw.*, vol. 5, no. 1, pp. 1–12, Jan. 2013.
- [55] K. Bowden, "The mixing processes in a tidal estuary," *Int. J. Air Water Pollut.*, vol. 7, nos. 4–5, pp. 343–356, 1963.
- [56] N. Anous, M. Abdallah, M. Uysal, and K. Qaraqe, "Performance evaluation of LOS and NLOS vertical inhomogeneous links in underwater visible light communications," *IEEE Access*, vol. 6, pp. 22408–22420, 2018.

- [57] (2021). *Earth's Ocean is 95% Unexplored: So What?*. Accessed: Feb. 12, 2025. [Online]. Available: <https://oceanexplorer.noaa.gov/oceanos/explorations/10index/background/edu/media/sowhat.pdf>
- [58] T. C. Grenfell, "A theoretical model of the optical properties of sea ice in the visible and near infrared," *J. Geophys. Res., Oceans*, vol. 88, no. C14, pp. 9723–9735, Nov. 1983.
- [59] A. S. Ghazy, H. S. Khallaf, S. Hranilovic, and M.-A. Khalighi, "Under-sea ice diffusing optical communications," *IEEE Access*, vol. 9, pp. 1–21, 2021.
- [60] P. Qarabaqi and M. Stojanovic, "Statistical characterization and computationally efficient modeling of a class of underwater acoustic communication channels," *IEEE J. Ocean. Eng.*, vol. 38, no. 4, pp. 701–717, Oct. 2013.
- [61] M. Stojanovic and J. Preisig, "Underwater acoustic communication channels: Propagation models and statistical characterization," *IEEE Commun. Mag.*, vol. 47, no. 1, pp. 84–89, Jan. 2009.
- [62] P. Qarabaqi and M. Stojanovic, "Statistical modeling of a shallow water acoustic communication channel," in *Proc. Underwater Acoust. Meas. Conf.*, Nafplion, Greece, 2009, pp. 1341–1350.
- [63] L. M. Brekhovskikh and Y. P. Lysanov, *Fundamentals of Ocean Acoustics*. Cham, Switzerland: Springer, 2006.
- [64] M. Stojanovic, "Underwater acoustic communications: Design considerations on the physical layer," in *Proc. 5th Annu. Conf. Wireless Demand Netw. Syst. Services*, Jan. 2008, pp. 1–10.
- [65] F. De Rango, F. Veltri, and P. Fazio, "A multipath fading channel model for underwater shallow acoustic communications," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2012, pp. 3811–3815.
- [66] H. A. Naman and A. E. Abdelkareem, "Multipath geometry channel model in shallow water acoustic communication," *J. Mar. Sci. Appl.*, vol. 22, no. 2, pp. 359–369, Jun. 2023.
- [67] Y. Su, X. Liu, Z. Jin, and X. Fu, "Fast estimation of underwater acoustic multipath channel based on LFM signal," in *Proc. Global Oceans*, Oct. 2020, pp. 1–5.
- [68] B. Pranitha and L. Anjaneyulu, "Analysis of underwater acoustic communication system using equalization technique for ISI reduction," *Proc. Comput. Sci.*, vol. 167, pp. 1128–1138, Mar. 2020.
- [69] A. Lee-Leon, C. Yuen, and D. Herremans, "Underwater acoustic communication receiver using deep belief network," *IEEE Trans. Commun.*, vol. 69, no. 6, pp. 3698–3708, Jun. 2021.
- [70] J. H. Schmidt, I. Kochańska, and A. M. Schmidt, "Performance of the direct sequence spread spectrum underwater acoustic communication system with differential detection in strong multipath propagation conditions," *Arch. Acoust.*, pp. 129–140, Mar. 2024.
- [71] W. Pan, P. Liu, F. Chen, F. Ji, and J. Feng, "Doppler-shift estimation of flat underwater channel using data-aided least-square approach," *Int. J. Nav. Archit. Ocean Eng.*, vol. 7, no. 2, pp. 426–434, 2015.
- [72] D. V. Ha, V. D. Nguyen, and Q. K. Nguyen, "Modeling of Doppler power spectrum for underwater acoustic channels," *J. Commun. Netw.*, vol. 19, no. 3, pp. 270–281, 2017.
- [73] F. Qu, Z. Wang, L. Yang, and Z. Wu, "A journey toward modeling and resolving Doppler in underwater acoustic communications," *IEEE Commun. Mag.*, vol. 54, no. 2, pp. 49–55, Feb. 2016.
- [74] M. Stojanovic, "Low complexity OFDM detector for underwater acoustic channels," in *Proc. OCEANS*, 2006, pp. 1–6.
- [75] X. Zhang, X. Han, J. Yin, and X.-L. Sheng, "Study on Doppler effects estimate in underwater acoustic communication," in *Proc. Meet. Acoust.*, 2013, vol. 19, no. 1, Art. no. 070062.
- [76] Z. Xiao, H. Xiao, Y. Jingwei, and S. Xueli, "Study on Doppler effects estimate in underwater acoustic communication," *J. Acoust. Soc. Am.*, vol. 133, no. 5, p. 3463, 2013.
- [77] S. Anwar, C. Yuen, H. Sun, Y. L. Guan, and Z. Babar, "A novel receiver design of nonorthogonal FDM systems in underwater acoustics communication," *IEEE Syst. J.*, vol. 14, no. 3, pp. 3875–3884, Sep. 2020.
- [78] Y.-T. Hsieh, Z. Qi, and D. Pompili, "ML-based joint Doppler estimation and compensation in underwater acoustic communications," in *Proc. 16th Int. Conf. Underwater Netw. Syst.*, Nov. 2022, pp. 1–8.
- [79] M. Jahanbakht, W. Xiang, L. Hanzo, and M. Rahimi Azghadi, "Internet of Underwater Things and big marine data analytics—A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 23, no. 2, pp. 904–956, 2nd Quart., 2021.
- [80] V. D. Nguyen, H. L. N. Thi, Q. K. Nguyen, and T. H. Nguyen, "Low complexity non-uniform FFT for Doppler compensation in OFDM-based underwater acoustic communication systems," *IEEE Access*, vol. 10, pp. 82788–82798, 2022.
- [81] G. Yang et al., "Optimized Doppler estimation and symbol synchronization for mobile M-ary spread spectrum underwater acoustic communication," *J. Mar. Sci. Eng.*, vol. 9, no. 9, p. 1001, Sep. 2021.
- [82] J. M. Hovem, "Ray trace modeling of underwater sound propagation: Modeling and measurement methods for acoustic waves and for acoustic microdevices," in *Modeling and Measurement Methods for Acoustic Waves and for Acoustic Microdevices*. Rijeka, Croatia: InTech, 2013, p. 573.
- [83] W. Huang et al., "Collaborating ray tracing and AI model for AUV-assisted 3-D underwater sound-speed inversion," *IEEE J. Ocean. Eng.*, vol. 46, no. 4, pp. 1372–1390, Oct. 2021.
- [84] A. Ahmed and M. Younis, "Acoustic beam characterization and selection for optimized underwater communication," *Appl. Sci.*, vol. 9, no. 13, p. 2740, Jul. 2019.
- [85] P. M. Ameer and L. Jacob, "Localization using ray tracing for underwater acoustic sensor networks," *IEEE Commun. Lett.*, vol. 14, no. 10, pp. 930–932, Oct. 2010.
- [86] M. Ji et al., "A high-precision localization method for underwater targets incorporating direct path recognition and sound rays bending compensation," *Proc. Inst. Mech. Eng., M, J. Eng. Maritime Environ.*, vol. 239, no. 2, pp. 386–398, May 2025.
- [87] Y. Kang, X. Shen, Y. Yan, H. Wang, J. Chang, and C. Liu, "Sound ray correction method for deep-sea target localization in asynchronous underwater acoustic sensor networks," in *Proc. IEEE Int. Conf. Signal Process., Commun. Comput. (ICSPCC)*, Aug. 2021, pp. 1–5.
- [88] I. C. Ijeh, "Investigation of random channel effects on the performance of underwater wireless optical communication links," Ph.D. dissertation, Dept. Optics/Photonic, Ecole Centrale Marseille (ECM), Marseille, France, 2021.
- [89] M. Stojanovic, "Underwater acoustic communications," in *Proc. ElectroInt.*, 1995, pp. 435–440.
- [90] M. Stojanovic, "Recent advances in high-speed underwater acoustic communications," *IEEE J. Ocean. Eng.*, vol. 21, no. 2, pp. 125–136, Apr. 1996.
- [91] A. S. Ghazy, G. Kaddoum, and S. Satinder, "IRS-aided secure reliable underwater acoustic communications," *IEEE Trans. Veh. Technol.*, vol. 73, no. 11, pp. 16861–16875, Nov. 2024.
- [92] S. Li, Y. Wang, S. Wu, W. Niu, S. Yang, and S. Lan, "Multi-body modelling and analysis of the motion platform for underwater acoustic dynamic communication," *Appl. Math. Model.*, vol. 109, pp. 455–472, Sep. 2022.
- [93] G. Kalpana, V. Rajendran, and S. S. Murugan, "Study of de-noising techniques for SNR improvement for underwater acoustic communication," *J. Mar. Eng. Technol.*, vol. 13, no. 3, pp. 29–35, Dec. 2014.
- [94] A. Stefanov and M. Stojanovic, "Design and performance analysis of underwater acoustic networks," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 10, pp. 2012–2021, Dec. 2011.
- [95] Y. Y. Al-Aboosi and A. Z. Sha'ameri, "Improved signal de-noising in underwater acoustic noise using S-transform: A performance evaluation and comparison with the wavelet transform," *J. Ocean Eng. Sci.*, vol. 2, no. 3, pp. 172–185, Sep. 2017.
- [96] X. Feng, J. Wang, X. Kuai, M. Zhou, H. Sun, and J. Li, "Message passing-based impulsive noise mitigation and channel estimation for underwater acoustic OFDM communications," *IEEE Trans. Veh. Technol.*, vol. 71, no. 1, pp. 611–625, Jan. 2022.
- [97] Y. Li, B. Wang, G. Shao, S. Shao, and X. Pei, "Blind detection of underwater acoustic communication signals based on deep learning," *IEEE Access*, vol. 8, pp. 204114–204131, 2020.
- [98] X. Zhong, F. Ji, F. Chen, Q. Guan, and H. Yu, "A new acoustic channel interference model for 3-D underwater acoustic sensor networks and throughput analysis," *IEEE Internet Things J.*, vol. 7, no. 10, pp. 9930–9942, Oct. 2020.
- [99] L. Yan, X. Ma, X. Li, and J. Lu, "Shot interference detection and mitigation for underwater acoustic communication systems," *IEEE Trans. Commun.*, vol. 69, no. 5, pp. 3274–3285, May 2021.
- [100] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Trans. Inf. Theory*, vol. 46, no. 2, pp. 388–404, Feb. 2000.
- [101] B. A. Jebur, C. T. Healy, C. C. Tsimenidis, J. Neasham, and J. Chambers, "In-band full-duplex interference for underwater acoustic communication systems," in *Proc. OCEANS*, Jun. 2019, pp. 1–6.
- [102] Y. Lu, G. Qiao, C. Yang, Y. Zhao, G. Yang, and H. Li, "A real-time digital self interference cancellation method for in-band full-duplex underwater acoustic communication based on improved vss-lms algorithm," *Remote Sens.*, vol. 14, no. 12, p. 2924, Apr. 2022.

- [103] H. A. Naman and A. E. Abdelkareem, "Variable direction-based self-interference full-duplex channel model for underwater acoustic communication systems," *Int. J. Commun. Syst.*, vol. 35, no. 7, p. 5096, May 2022.
- [104] S. Tang, Y. Dong, and X. Zhang, "Impulse response modeling for underwater wireless optical communication links," *IEEE Trans. Commun.*, vol. 62, no. 1, pp. 226–234, Jan. 2014.
- [105] Y. Li, M. S. Leeson, and X. Li, "Impulse response modeling for underwater optical wireless channels," *Appl. Opt.*, vol. 57, no. 17, pp. 4815–4823, 2018.
- [106] R. Boluda-Ruiz, P. Rico-Pinazo, B. Castillo-Vázquez, A. García-Zambrana, and K. Qaraqe, "Impulse response modeling of underwater optical scattering channels for wireless communication," *IEEE Photon. J.*, vol. 12, no. 4, pp. 1–14, Aug. 2020.
- [107] B. Light, G. A. Maykut, and T. C. Grenfell, "A temperature-dependent, structural-optical model of first-year sea ice," *J. Geophys. Res., Oceans*, vol. 109, no. C6, pp. 4815–4823, Jun. 2004.
- [108] B. Hamre, J.-G. Winther, S. Gerland, J. J. Stannnes, and K. Stannnes, "Modeled and measured optical transmittance of snow-covered first-year sea ice in kongsfjorden, svalbard," *J. Geophys. Res., Oceans*, vol. 109, no. C10, pp. 1–14, Oct. 2004.
- [109] W. J. Wiscombe and S. G. Warren, "A model for the spectral albedo of snow. I: Pure snow," *J. Atmos. Sci.*, vol. 37, no. 12, pp. 2712–2733, Dec. 1980.
- [110] G. Schirripa Spagnolo, L. Cozzella, and F. Leccese, "Underwater optical wireless communications: Overview," *Sensors*, vol. 20, no. 8, p. 2261, 2020.
- [111] M. A. Khalighi, C. J. Gabriel, L. M. Pessoa, and B. Silva, "Underwater visible light communications, channel modeling and system design," in *Visible Light Communications: Theory and Applications*. Boca Raton, FL, USA: CRC Press, 2017, pp. 337–372.
- [112] C. Mobley, E. Boss, and C. Roesler, *Ocean Optics Web Book*, 2016. [Online]. Available: <https://www.oceanopticsbook.info>
- [113] I. C. Ijeh, M. A. Khalighi, and S. Hranilovic, "Parameter optimization for an underwater optical wireless vertical link subject to link misalignments," *IEEE J. Ocean. Eng.*, vol. 46, no. 4, pp. 1424–1437, Oct. 2021.
- [114] I. C. Ijeh, M. A. Khalighi, M. Elamassie, S. Hranilovic, and M. Uysal, "Outage probability analysis of a vertical underwater wireless optical link subject to oceanic turbulence and pointing errors," *J. Opt. Commun. Netw.*, vol. 14, no. 6, pp. 439–453, Jun. 2022.
- [115] C. Wang, H.-Y. Yu, and Y.-J. Zhu, "A long distance underwater visible light communication system with single photon avalanche diode," *IEEE Photon. J.*, vol. 8, no. 5, pp. 1–11, Oct. 2016.
- [116] Y. Ji, G. Wu, and Y. Zuo, "Performance analysis of SPAD-based underwater wireless optical communication systems," *Proc. Comput. Sci.*, vol. 131, pp. 1134–1141, May 2022.
- [117] I. C. Ijeh, O. Haddad, and M. Ali Khalighi, "Ergodic capacity of a vertical underwater wireless optical communication link subject to misalignment," in *Proc. 4th West Asian Symp. Opt. Millimeter-wave Wireless Commun. (WASOWC)*, May 2022, pp. 1–5.
- [118] R. Boluda-Ruiz, A. García-Zambrana, B. Castillo-Vázquez, and S. Hranilovic, "Impact of angular pointing error on BER performance of underwater optical wireless links," *Opt. Exp.*, vol. 28, no. 23, pp. 34606–34622, Nov. 2020.
- [119] F. Yang, M. Yi, and X. Yang, "ULMC-BSF: Underwater laser misalignment channel modeling based on beam spread function," *IEEE Internet Things J.*, vol. 11, no. 12, pp. 22590–22602, Jun. 2024.
- [120] J. Fu, K. Zhu, S. A. H. Mohsan, and Y. Li, "Channel model and signal-detection algorithm for the combined effects of turbulence and link misalignment in underwater optical massive MIMO systems," *J. Mar. Sci. Eng.*, vol. 11, no. 3, p. 547, Mar. 2023.
- [121] J. Qian et al., "Theoretical model and experiments of focused phased array for cross-medium communication in misaligned transmitter/receiver scenarios," *IEEE J. Ocean. Eng.*, vol. 48, no. 4, pp. 1348–1361, Oct. 2023.
- [122] A. A. Farid and S. Hranilovic, "Outage capacity optimization for free-space optical links with pointing errors," *J. Lightw. Technol.*, vol. 25, no. 7, pp. 1702–1710, Jul. 2007.
- [123] I. C. Ijeh, M. A. Khalighi, M. Elamassie, S. Hranilovic, and M. Uysal, "Bit-error-rate performance of an underwater wireless optical link under misalignment and turbulence effects," in *Proc. 13th Int. Symp. Commun. Syst., Netw. Digit. Signal Process. (CSNDSP)*, Jul. 2022, pp. 21–25.
- [124] R. Griffis and J. Howard, "Oceans and marine resources in a changing climate," *IEEE J. Ocean. Eng.*, 2013.
- [125] M. Elamassie and M. Uysal, "Vertical underwater visible light communication links: Channel modeling and performance analysis," *IEEE Trans. Wireless Commun.*, vol. 19, no. 10, pp. 6948–6959, Oct. 2020.
- [126] Z. Rahman, N. V. Tailor, S. M. Zafaruddin, and V. K. Chaubey, "Unified performance assessment of optical wireless communication over multi-layer underwater channels," *IEEE Photon. J.*, vol. 14, no. 5, pp. 1–14, Oct. 2022.
- [127] E. Zedini, H. M. Oubei, A. Kammoun, M. Hamdi, B. S. Ooi, and M.-S. Alouini, "Unified statistical channel model for turbulence-induced fading in underwater wireless optical communication systems," *IEEE Trans. Commun.*, vol. 67, no. 4, pp. 2893–2907, Apr. 2019.
- [128] M. V. Jamali et al., "Statistical studies of fading in underwater wireless optical channels in the presence of air bubble, temperature, and salinity random variations," *IEEE Trans. Commun.*, vol. 66, no. 10, pp. 4706–4723, Oct. 2018.
- [129] R. M. G. S. Karp, *Optical Communications*. Hoboken, NJ, USA: Wiley, pp. 249–519.
- [130] T. Hamza, M.-A. Khalighi, S. Bourennane, P. Léon, and J. Operbecke, "Investigation of solar noise impact on the performance of underwater wireless optical communication links," *Opt. Exp.*, vol. 24, no. 22, pp. 25832–25845, 2016.
- [131] I. C. Ijeh, "Optical wireless communication based smart ocean sensor networks for environmental monitoring," in *Proc. 2nd White Paper NEW-FOCUS COST Action*, 2023, pp. 39–42.
- [132] S. Nadarajah, X. N. Fernando, and R. Sedaghat, "Adaptive digital pre-distortion of laser diode nonlinearity for wireless applications," in *Proc. Can. Conf. Electr. Comput. Engineering. Toward Caring Humane Technol. (CCECE)*, vol. 1, Jun. 2003, pp. 159–162.
- [133] A. J. Rainal, "Laser clipping distortion in analog and digital channels," *J. Lightw. Technol.*, vol. 15, no. 10, pp. 1805–1807, Oct. 2016.
- [134] K. Hinton and T. Stephens, "Modeling high-speed optical transmission systems," *IEEE J. Sel. Areas Commun.*, vol. 11, no. 3, pp. 380–392, Apr. 1993.
- [135] H. M. Oubei et al., "4.8 Gbit/s 16-QAM-OFDM transmission based on compact 450-nm laser for underwater wireless optical communication," *Opt. Exp.*, vol. 23, no. 18, pp. 23302–23309, Sep. 2015.
- [136] R. T. Mithran, "Interaction of laser radiation with structures of the eye," *IEEE Trans. Educ.*, vol. 34, no. 3, pp. 250–259, Oct. 1997.
- [137] H. C. Van de Hulst, *Light Scattering by Small Particles*. Hoboken, NJ, USA: Wiley, 1957.
- [138] *Laser Products and Instruments*. Accessed: Aug. 7, 2020. [Online]. Available: <https://www.fda.gov/radiation-emitting-products/home-business-and-entertainment-products/laser-products-and-instruments>
- [139] S. Khoo et al., "Eyesafe optical link using a holographic diffuser," in *Proc. IEE Colloq. Opt. Wireless Commun.*, Apr. 1999, pp. 3-1–3-6.
- [140] J. W. Giles and I. N. Bankman, "Underwater optical communications systems. Part 2: Basic design considerations," in *Proc. IEEE Mil. Commun. Conf. (MILCOM)*, May 2005, pp. 1700–1705.
- [141] M. F. Ali, D. N. K. Jayakody, Y. A. Chursin, S. Affes, and S. Dmitry, "Recent advances and future directions on underwater wireless communications," *Arch. Comput. Methods Eng.*, vol. 27, no. 5, pp. 1379–1412, Nov. 2020.
- [142] J.-N. Decarpigny, B. Hamonic, and O. B. Wilson, "The design of low frequency underwater acoustic projectors: Present status and future trends," *IEEE J. Ocean. Eng.*, vol. 16, no. 1, pp. 107–122, Jun. 1999.
- [143] J. L. Butler and C. H. Sherman, *Transducers and Arrays for Underwater Sound*. Cham, Switzerland: Springer, 2016.
- [144] S. Hranilovic, *Wireless Optical Communication Systems*. Cham, Switzerland: Springer, 2005.
- [145] W. Wei, C. Zhang, W. Zhang, W. Jiang, C. Shu, and Q. Xiaorui, "LED-based underwater wireless optical communication for small mobile platforms: Experimental channel study in highly-turbid lake water," *IEEE Access*, vol. 8, pp. 169304–169313, 2020.
- [146] S. L. Peshkovsky and A. S. Peshkovsky, "Matching a transducer to water at cavitation: Acoustic horn design principles," *Ultrason. Sonochemistry*, vol. 14, no. 3, pp. 314–322, Mar. 2007.
- [147] V. T. Rathod, "A review of acoustic impedance matching techniques for piezoelectric sensors and transducers," *Sensors*, vol. 20, no. 14, p. 4051, Jul. 2020.
- [148] A. A. B. Raj et al., "A review—unguided optical communications: Developments, technology evolution, and challenges," *Electronics*, vol. 12, no. 8, p. 1922, Apr. 2023.

- [149] J. Yang and P. Ji, "Beam control of parametric array loudspeakers," in *Parametric Array Loudspeakers*. Cham, Switzerland: Springer, 2025, pp. 251–292.
- [150] F. A. Bozzi and S. M. Jesus, "Vector sensor steering-dependent performance in an underwater acoustic communication field experiment," *Sensors*, vol. 22, no. 21, p. 8332, Oct. 2022.
- [151] A. Derakhshandeh, P. A. Hoehner, and S. Pachnicke, "Underwater coherent optical wireless communications with electronic beam steering and turbulence compensation using adaptive optics and aperture averaging," *Photonics*, vol. 12, no. 3, p. 268, 2025.
- [152] V. V. Mai and H. Kim, "Non-mechanical beam steering and adaptive beam control using variable focus lenses for free-space optical communications," *J. Lightw. Technol.*, vol. 39, no. 24, pp. 7600–7608, Dec. 2021.
- [153] M. Liu, L. Zhang, W. Qu, L. Da, and T. Liu, "Advances in MEMS hydrophone technology," *IEEE Access*, vol. 13, pp. 79955–79976, 2025.
- [154] Y. Zhang, H. Yang, Z. Chen, F. Sun, and B. Mao, "Design and analysis of MEMS piezoelectric hydrophone based on signal-to-noise ratio," *IEEE Sensors J.*, vol. 25, no. 7, pp. 11314–11322, Apr. 2025.
- [155] M.-A. Khalighi, T. Hamza, S. Bourennane, P. Léon, and J. Opperbecke, "Underwater wireless optical communications using silicon photomultipliers," *IEEE Photon. J.*, vol. 9, no. 4, pp. 1–10, Aug. 2017.
- [156] T. Essalih, I. Chinazaekpere Ijeh, and M. A. Khalighi, "Influence of MPPC parameters on the performance of underwater optical links," in *Proc. 4th West Asian Symp. Opt. Millimeter-wave Wireless Commun. (WASOWC)*, May 2022, pp. 1–5.
- [157] T. Bretz et al., "Dynamic range measurement and calibration of SiPMs," *J. Instrum.*, vol. 11, no. 3, Mar. 2016, Art. no. P03009.
- [158] A. L. Egbewande, J.-F. Bousquet, and D. R. Barclay, "The effect of directional ambient noise on an underwater acoustic link in shallow environments," *IEEE J. Ocean. Eng.*, vol. 47, no. 4, pp. 1188–1202, Oct. 2022.
- [159] I. A. Tasadduq and M. Rashid, "Toward intelligent underwater acoustic systems: Systematic insights into channel estimation and modulation methods," *Electronics*, vol. 14, no. 15, p. 2953, Jul. 2025.
- [160] C. Fang, S. Li, Y. Wang, and K. Wang, "High-speed underwater optical wireless communication with advanced signal processing methods survey," *Photonics*, vol. 10, no. 7, p. 811, 2023.
- [161] H. Lu, W. Chen, and M. Jiang, "Deep learning aided misalignment-robust blind receiver for underwater optical communication," *IEEE Wireless Commun. Lett.*, vol. 10, no. 9, pp. 1984–1988, Sep. 2021.
- [162] S. R. Doha and A. Abdelhadi, "Deep learning in wireless communication receivers: A survey," *IEEE Access*, vol. 13, pp. 113586–113605, 2025.
- [163] X. Tu, Y. Wei, F. Qu, and A. Song, "Low computational complexity RLS-based decision-feedback equalization in underwater acoustic communications," *IEEE J. Ocean. Eng.*, vol. 49, no. 3, pp. 1067–1088, Jul. 2024.
- [164] H. Chen, W. Niu, Y. Zhao, J. Zhang, N. Chi, and Z. Li, "Adaptive deep-learning equalizer based on constellation partitioning scheme with reduced computational complexity in UVLC system," *Opt. Exp.*, vol. 29, no. 14, pp. 21773–21782, 2021.
- [165] K. S. Geethu and A. V. Babu, "A hybrid ARQ scheme combining erasure codes and selective retransmissions for reliable data transfer in underwater acoustic sensor networks," *EURASIP J. Wireless Commun. Netw.*, vol. 2017, no. 1, p. 32, Dec. 2017.
- [166] F. Mattoussi, M. A. Khalighi, and S. Bourennane, "Improving the performance of underwater wireless optical communication links by channel coding," *Appl. Opt.*, vol. 57, no. 9, pp. 2115–2120, 2018.
- [167] S. Barua, Y. Rong, S. Nordholm, and P. Chen, "Real-time adaptive modulation schemes for underwater acoustic OFDM communication," *Sensors*, vol. 22, no. 9, p. 3436, Apr. 2022.
- [168] Y. Lou, N. Ahmed, Y. Lou, and N. Ahmed, "Basic principles of underwater acoustic communication," in *Underwater Communications and Networks*. Berlin, Germany: Springer, 2022, pp. 3–33.
- [169] M. Stojanovic and L. Freitag, "Recent trends in underwater acoustic communications," *Mar. Technol. Soc. J.*, vol. 47, no. 5, pp. 45–50, Sep. 2013.
- [170] M. Chitre, S. Shahabudeen, L. Freitag, and M. Stojanovic, "Recent advances in underwater acoustic communications & networking," in *Proc. OCEANS*, Jul. 2008, pp. 1–10.
- [171] N. U. R. Junejo et al., "A survey on physical layer techniques and challenges in underwater communication systems," *J. Mar. Sci. Eng.*, vol. 11, no. 4, p. 885, Apr. 2023.
- [172] Z. Li, M. Chitre, and M. Stojanovic, "Underwater acoustic communications," *Nature Rev. Electr. Eng.*, vol. 47, pp. 1–13, Sep./Oct. 2024.
- [173] Z. Ghassemlooy, W. Popoola, and S. Rajbhandari, *Optical Wireless Communications: System and Channel Modelling With MATLAB*. Boca Raton, FL, USA: CRC Press, 2019.
- [174] M. A. Khalighi and M. Uysal, "Survey on free space optical communication: A communication theory perspective," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 4, pp. 2231–2258, 4th Quart., 2014.
- [175] Z. A. H. Qasem, H. A. Leftah, H. Sun, J. Qi, J. Wang, and H. Esmaili, "Deep learning-based code indexed modulation for autonomous underwater vehicles systems," *Veh. Commun.*, vol. 28, Apr. 2021, Art. no. 100314.
- [176] R. Jiang et al., "Deep learning-aided signal detection for two-stage index modulated universal filtered multi-carrier systems," *IEEE Trans. Cognit. Commun. Netw.*, vol. 8, no. 1, pp. 136–154, Mar. 2022.
- [177] Q. He, Z. Zeng, M. Liu, B. Zhu, B. Lin, and C. Chen, "AI-enabled efficient modulation classification in underwater OWC systems," *Opt. Rev.*, vol. 31, no. 6, pp. 688–693, Dec. 2024.
- [178] M. Shuai et al., "Machine learning for signal demodulation in underwater wireless optical communications," *China Commun.*, vol. 21, no. 5, pp. 297–313, May 2024.
- [179] J. Proakis and M. Salehi, *Digital Communications*. New York, NY, USA: McGraw-Hill, 2008.
- [180] M. Rowshan, M. Qiu, Y. Xie, X. Gu, and J. Yuan, "Channel coding toward 6G: Technical overview and outlook," *IEEE Open J. Commun. Soc.*, vol. 5, pp. 2585–2685, 2024.
- [181] S. Sabeer, M. D. Hassib, and Z. N. Jameel, "A review: Error correcting codes for efficient underwater optical communication MIMO system," in *Proc. Iraqi Int. Conf. Commun. Inf. Technol. (IICIT)*, Iraq, Sep. 2022, pp. 13–19.
- [182] W. C. Cox, J. A. Simpson, C. P. Domizioli, J. F. Muth, and B. L. Hughes, "An underwater optical communication system implementing Reed–Solomon channel coding," in *Proc. OCEANS*, Sep. 2008, pp. 1–6.
- [183] S. K. Mahapatra and S. K. Varshney, "Performance of the Reed–Solomon-coded underwater optical wireless communication system with orientation-based solar light noise," *J. Opt. Soc. Amer. A, Opt. Image Sci.*, vol. 39, no. 7, pp. 1236–1245, 2022.
- [184] X. Guo, B. Wang, Y. Zhu, Z. Fang, and Z. Han, "Hamming distance optimized underwater acoustic OTFS-IM systems," *Entropy*, vol. 25, no. 7, p. 972, Jun. 2023.
- [185] M. Rani and P. Singal, "An efficient IDMA-OFDM underwater wireless communication with Reed Solomon and Hamming code," *J. Opt.*, vol. 51, no. 2, pp. 456–466, Jun. 2022.
- [186] F.-Y. Wu, T. Tian, B.-X. Su, and Y.-C. Song, "Hadamard–Viterbi joint soft decoding for MFSK underwater acoustic communications," *Remote Sens.*, vol. 14, no. 23, p. 6038, 2022.
- [187] L. M. Wolff and S. Badri-Hoehner, "Convolutionally coded hopping pattern for MFSK modulation in underwater acoustic communication," *IEEE Access*, vol. 7, pp. 95569–95575, 2019.
- [188] M. Behgam, Y. R. Zheng, and Z. Liu, "Coding for short messages in multipath underwater acoustic communication channels," in *Proc. OCEANS MTS/IEEE Charleston*, Oct. 2018, pp. 1–5.
- [189] A. Elfikky et al., "Performance analysis of convolutional codes in dynamic underwater visible light communication systems," *Opt. Quantum Electron.*, vol. 56, no. 1, p. 55, Jan. 2024.
- [190] I. Karasalo, T. Öberg, B. Nilsson, and S. Ivansson, "A single-carrier turbo-coded system for underwater communications," *IEEE J. Ocean. Eng.*, vol. 38, no. 4, pp. 666–677, Oct. 2013.
- [191] I. Karasalo, "Time-domain modelling of turbo-coded underwater communication," in *Proc. OCEANS IEEE*, Jun. 2011, pp. 1–8.
- [192] Y. Yang and Y. Li, "Research and implementation of turbo coding technology in high-speed underwater acoustic OFDM communication," *J. Robot.*, vol. 2022, Mar. 2022, Art. no. 2576303.
- [193] N. Iruthayanathan, K. S. Vishvakshnan, V. Rajendran, and S. Mohankumar, "Performance analysis of turbo-coded mimo-ofdm system for underwater communication," *Comput. Electr. Eng.*, vol. 43, pp. 1–8, Apr. 2015.
- [194] M. M. Mansour and N. R. Shanbhag, "High-throughput LDPC decoders," *IEEE Trans. Very Large Scale Integr. (VLSI) Syst.*, vol. 11, no. 6, pp. 976–996, Dec. 2003.
- [195] J. Huang, S. Zhou, and P. Willett, "Nonbinary LDPC coding for multicarrier underwater acoustic communication," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 9, pp. 1684–1696, Dec. 2008.

- [196] S. K. Padala and J. D'Souza, "Performance of spatially coupled LDPC codes over underwater acoustic communication channel," in *Proc. Nat. Conf. Commun. (NCC)*, Feb. 2020, pp. 1–5.
- [197] J. Guo et al., "Performance analysis of LDPC-coded OFDM in underwater wireless optical communications," *Photonics*, vol. 10, no. 3, p. 330, Mar. 2023.
- [198] H. Jiang, N. He, X. Liao, W. Popoola, and S. Rajbhandari, "The ber performance of the ldpc-coded mppm over turbulence uwoc channels," *Photonics*, vol. 9, no. 5, p. 349, 2022.
- [199] R. Chen, W. Wu, Q. Zeng, and S. Liu, "Construction and application of polar codes in OFDM underwater acoustic communication," *Appl. Acoust.*, vol. 211, Aug. 2023, Art. no. 109473.
- [200] G. Qiao, S. Xing, and F. Zhou, "A multi-user detection scheme based on polar code construction in downlink underwater acoustic OFDM communication system," *IEEE Access*, vol. 7, pp. 65973–65981, 2019.
- [201] C.-C. Wu, N. He, H.-Y. Jiang, and L.-K. Deng, "Ber performance of the polar-coded underwater wireless optical communication," *Proc. SPIE*, vol. 11763, pp. 2084–2091, May 2021.
- [202] W. Li, H. Tang, S. Meng, W. Ni, and C. Yang, "Joint coding of polar code for laser-acoustic underwater communication," *Proc. SPIE*, vol. 13542, pp. 446–455, Jun. 2025.
- [203] S. Mani, T. M. Duman, and P. Hursky, "Adaptive coding-modulation for shallow-water uwa communications," *J. Acoust. Soc. Am.*, vol. 123, no. 5, p. 3749, 2008.
- [204] L. Wan et al., "Adaptive modulation and coding for underwater acoustic OFDM," *IEEE J. Ocean. Eng.*, vol. 40, no. 2, pp. 327–336, Apr. 2015.
- [205] W. Su, J. Lin, K. Chen, L. Xiao, and C. En, "Reinforcement learning-based adaptive modulation and coding for efficient underwater communications," *IEEE Access*, vol. 7, pp. 67539–67550, 2019.
- [206] L. Jing, C. Dong, C. He, W. Shi, and H. Yin, "Adaptive modulation and coding for underwater acoustic communications based on data-driven learning algorithm," *Remote Sens.*, vol. 14, no. 23, p. 5959, Nov. 2022.
- [207] NS-3 Consortium. (2025). *NS-3: A Discrete-Event Network Simulator for internet Systems*. Accessed: Feb. 11, 2025. [Online]. Available: <https://www.nsnam.org/>
- [208] X. Ji and F. Zhou, "Network protocol migration framework: A protocol migration framework for underwater network based on NS3," in *Proc. OES China Ocean Acoust. (COA)*, May 2024, pp. 1–5.
- [209] P. Mandal and S. De, "New reservation multiaccess protocols for underwater wireless ad hoc sensor networks," *IEEE J. Ocean. Eng.*, vol. 40, no. 2, pp. 277–291, Apr. 2015.
- [210] N. Z. Zenia, M. S. Kaiser, M. Mahmud, M. R. Ahmed, O. Kaiwartya, and J. Kamruzzaman, "REER-H: A reliable energy efficient routing protocol for maritime intelligent transportation systems," *IEEE Trans. Intell. Transp. Syst.*, vol. 24, no. 12, pp. 13654–13669, Dec. 2023.
- [211] R. Qadar, W. B. Qaim, B. Tan, and J. Nurmi, "Underwater optical communication module: An extension to the ns-3 network simulator," in *Proc. IEEE 96th Veh. Technol. Conf. (VTC-Fall)*, Sep. 2022, pp. 1–5.
- [212] B. Yan, L. Wang, Y. Su, Y. Tian, and B. Lu, "A novel routing metric for underwater optical wireless communication using ns-3," in *Proc. 7th Int. Conf. Big Data Comput. Commun. (BigCom)*, Aug. 2021, pp. 44–51.
- [213] L. Nkenyereye, L. Nkenyereye, and B. Ndiabanje, "Internet of Underwater Things: A survey on simulation tools and 5G-based underwater networks," *Electronics*, vol. 13, no. 3, p. 474, Jan. 2024.
- [214] K. Y. Islam, I. Ahmad, D. Habibi, M. I. A. Zahed, and J. Kamruzzaman, "Green underwater wireless communications using hybrid optical-acoustic technologies," *IEEE Access*, vol. 9, pp. 85109–85123, 2021.
- [215] L. Dai, R. Jiao, F. Adachi, H. V. Poor, and L. Hanzo, "Deep learning for wireless communications: An emerging interdisciplinary paradigm," *IEEE Wireless Commun.*, vol. 27, no. 4, pp. 133–139, Aug. 2020.
- [216] J. Mao, S. Chen, Y. Liu, J. Yu, and Y. Xu, "LT-MAC: A location-based TDMA MAC protocol for small-scale underwater sensor networks," in *Proc. IEEE Int. Conf. Cyber Technol. Autom., Control, Intell. Syst. (CYBER)*, Jun. 2015, pp. 1275–1280.
- [217] J. Mao, S. Chen, J. Yu, Y. Gu, R. Yu, and Y. Xu, "LTM-MAC: A location-based TDMA MAC protocol for mobile underwater networks," in *Proc. OCEANS*, Apr. 2016, pp. 1–5.
- [218] P. Anjangi and M. Chitre, "Experimental demonstration of super-TDMA: A MAC protocol exploiting large propagation delays in underwater acoustic networks," in *Proc. IEEE 3rd Underwater Commun. Netw. Conf. (UComms)*, Aug. 2016, pp. 1–5.
- [219] F. Alfouzan, A. Shahrabi, S. M. Ghoreyshi, and T. Boutaleb, "An energy-conserving depth-based layering MAC protocol for underwater sensor networks," in *Proc. IEEE 88th Veh. Technol. Conf. (VTC-Fall)*, Aug. 2018, pp. 1–6.
- [220] F. Alfouzan, A. Shahrabi, S. M. Ghoreyshi, and T. Boutaleb, "Efficient depth-based scheduling MAC protocol for underwater sensor networks," in *Proc. 9th Int. Conf. Ubiquitous Future Netw. (ICUFN)*, Jul. 2017, pp. 827–832.
- [221] F. Alfouzan, A. Shahrabi, S. M. Ghoreyshi, and T. Boutaleb, "Graph colouring MAC protocol for underwater sensor networks," in *Proc. IEEE 32nd Int. Conf. Adv. Inf. Netw. Appl. (AINA)*, May 2018, pp. 120–127.
- [222] X. Pan et al., "RAP-MAC: A robust and adaptive pipeline MAC protocol for underwater acoustic string networks," *Remote Sens.*, vol. 16, no. 12, p. 2195, Jun. 2024.
- [223] G. A. Shah, "A survey on medium access control in underwater acoustic sensor networks," in *Proc. Int. Conf. Adv. Inf. Netw. Appl. Workshops*, May 2009, pp. 1178–1183.
- [224] W. Lin, D. Li, J. Chen, T. Sun, and T. Wang, "A wave-like amendment-based time-division medium access slot allocation mechanism for underwater acoustic sensor networks," in *Proc. Int. Conf. Cyber-Enabled Distrib. Comput. Knowl. Discovery*, Oct. 2009, pp. 369–374.
- [225] K. Kredon II, P. Djukic, and P. Mohapatra, "STUMP: Exploiting position diversity in the staggered TDMA underwater MAC protocol," in *Proc. IEEE INFOCOM*, Apr. 2009, pp. 2961–2965.
- [226] Y. Noh et al., "DOTS: A propagation delay-aware opportunistic MAC protocol for mobile underwater networks," *IEEE Trans. Mobile Comput.*, vol. 13, no. 4, pp. 766–782, Apr. 2014.
- [227] Y. Ma, Z. Guo, Y. Feng, M. Jiang, and G. Feng, "C-MAC: A TDMA-based MAC protocol for underwater acoustic sensor networks," in *Proc. Int. Conf. Netw. Secur., Wireless Commun. Trusted Comput.*, Apr. 2009, pp. 728–731.
- [228] T. H. Nguyen, S.-Y. Shin, and S.-H. Park, "Efficiency reservation MAC protocol for underwater acoustic sensor networks," in *Proc. 4th Int. Conf. Networked Comput. Adv. Inf. Manage.*, Sep. 2008, pp. 365–370.
- [229] C.-C. Hsu, K.-F. Lai, C.-F. Chou, and K. C.-J. Lin, "ST-MAC: Spatial-temporal MAC scheduling for underwater sensor networks," in *Proc. IEEE INFOCOM*, Apr. 2009, pp. 1827–1835.
- [230] S.-Y. Shin, J.-I. Namgung, and S.-H. Park, "SBMAC: Smart blocking MAC mechanism for variable UW-ASN (underwater acoustic sensor network) environment," *Sensors*, vol. 10, no. 1, pp. 501–525, Jan. 2010.
- [231] F. Bouabdallah and R. Boutaba, "A distributed OFDMA medium access control for underwater acoustic sensors networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2011, pp. 1–5.
- [232] I. M. Khalil, Y. Gadallah, M. Hayajneh, and A. Khreishah, "An adaptive OFDMA-based MAC protocol for underwater acoustic wireless sensor networks," *Sensors*, vol. 12, no. 7, pp. 8782–8805, Jun. 2012.
- [233] G. Fan, H. Chen, L. Xie, and K. Wang, "An improved CDMA-based MAC protocol for underwater acoustic wireless sensor networks," in *Proc. 7th Int. Conf. Wireless Commun., Netw. Mobile Comput.*, Sep. 2011, pp. 1–4.
- [234] H.-X. Tan and W. K. G. Seah, "Distributed CDMA-based MAC protocol for underwater sensor networks," in *Proc. 32nd IEEE Conf. Local Comput. Netw. (LCN)*, Oct. 2007, pp. 26–36.
- [235] J.-P. Kim, J.-W. Lee, Y.-S. Jang, K. Son, and H.-S. Cho, "A CDMA-based MAC protocol in tree-topology for underwater acoustic sensor networks," in *Proc. Int. Conf. Adv. Inf. Netw. Appl. Workshops (WAINA)*, May 2009, pp. 1166–1171.
- [236] G. Açar and A. E. Adams, "ACMENet: An underwater acoustic sensor network protocol for real-time environmental monitoring in coastal areas," *IEEE Proc.-Radar, Sonar Navigat.*, vol. 153, no. 4, pp. 365–380, Aug. 2006.
- [237] A. A. Syed, W. Ye, J. Heidemann, and B. Krishnamachari, "Understanding spatio-temporal uncertainty in medium access with ALOHA protocols," in *Proc. 2nd Workshop Underwater Netw.*, 2007, pp. 41–48.
- [238] E. M. Khater, D. M. Ibrahim, and M. T. F. Saidahmed, "Contention-based MAC protocol in UWSNs: Slotted_CS_ALOHA proposed protocol," in *Proc. 11th Int. Conf. Comput. Eng. Syst. (ICCES)*, Dec. 2016, pp. 73–78.
- [239] N. Chirdchoo, W.-S. Soh, and K. C. Chua, "Aloha-based MAC protocols with collision avoidance for underwater acoustic networks," in *Proc. 26th IEEE Int. Conf. Comput. Commun. (IEEE INFOCOM)*, Apr. 2007, pp. 2271–2275.
- [240] S. Shahabudeen, M. Chitre, and M. Motani, "MAC protocols that exploit propagation delay in underwater networks," in *Proc. OCEANS MTS/IEEE KONA*, Sep. 2011, pp. 1–6.

- [241] S. Weber, A. Kini, and A. Petropulu, "A new approximation for slotted buffered Aloha," in *Proc. 42nd Annu. Conf. Inf. Sci. Syst.*, Mar. 2008, pp. 1143–1148.
- [242] K. Chen, E. Cheng, F. Yuan, W. Su, and M. Ma, "The influence of MAC protocol on a non-synchronous localization scheme in large-scale UWSNs," *IEEE Access*, vol. 6, pp. 16386–16394, 2018.
- [243] E. M. Khater and D. M. Ibrahim, "Proposed ST-Slotted-CS-ALOHA protocol for time saving and collision avoidance," *ISecure*, vol. 11, no. 3, pp. 1–6, 2019.
- [244] M. R. Aktar, "Performance evaluation of ALOHA-CS MAC protocol," *Glob. J. Comput. Sci. Technol.*, vol. 16, pp. 10–14, Jul. 2016.
- [245] S. De, P. Mandal, and S. S. Chakraborty, "On the characterization of Aloha in underwater wireless networks," *Math. Comput. Model.*, vol. 53, nos. 11–12, pp. 2093–2107, Jun. 2011.
- [246] E. P. M. C. Júnior, L. F. M. Vieira, and M. A. M. Vieira, "UW-SEEDEx: A pseudorandom-based MAC protocol for underwater acoustic networks," *IEEE Trans. Mobile Comput.*, vol. 21, no. 9, pp. 3402–3413, Sep. 2022.
- [247] L. Qian, S. Zhang, M. Liu, and Q. Zhang, "A MACA-based power control MAC protocol for underwater wireless sensor networks," in *Proc. IEEE/OES China Ocean Acoust. (COA)*, Jan. 2016, pp. 1–8.
- [248] X. Libin and C. Chunjie, "A short signal backoff MAC protocol based on game theory for underwater sensor networks," *IEEE Access*, vol. 10, pp. 125992–126000, 2022.
- [249] P. T. Kalaivaani and A. Rajeswari, "An analysis of H-MAC, HSMAC and H-MAC based AOMDV for wireless sensor networks to achieve energy efficiency using spatial correlation concept," in *Proc. 2nd Int. Conf. Electron. Commun. Syst. (ICECS)*, Feb. 2015, pp. 796–801.
- [250] Z. Chen, J. Wang, X. Wang, and L. Xu, "A MAC protocol design for optical-acoustic hybrid underwater wireless sensor network," in *Proc. 11th EAI Int. Conf. Mobile Multimedia Commun.*, Sep. 2018, pp. 1–8.
- [251] J. Wang, J. Shen, W. Shi, G. Qiao, S. Wu, and X. Wang, "A novel energy-efficient contention-based MAC protocol used for OA-UWSN," *Sensors*, vol. 19, no. 1, p. 183, Jan. 2019. [Online]. Available: <https://www.mdpi.com/1424-8220/19/1/183>
- [252] R. Li, J. Tu, and S. Yu, "Joint temporal and spatial reuse for underwater acoustic networks exploiting successive interference cancellation," *Ad Hoc Sens. Wireless Netw.*, vol. 44, no. 2, p. p83, 2019.
- [253] Y. Su, Z. Zhou, Z. Jin, and Q. Yang, "A joint relay selection and power allocation MAC protocol for underwater acoustic sensor network," *IEEE Access*, vol. 8, pp. 65197–65210, 2020.
- [254] Q. Liu, G. Qiao, S. Mazhar, S. Liu, and Y. Lou, "A full-duplex directional MAC framework for underwater acoustic sensor networks," *IEEE Sensors J.*, vol. 22, no. 14, pp. 14647–14661, Jul. 2022.
- [255] Y. Su, X. Liu, G. Han, and X. Fu, "A traffic load-aware OFDMA-based MAC protocol for distributed underwater acoustic sensor networks," *IEEE Trans. Veh. Technol.*, vol. 70, no. 10, pp. 10501–10513, Oct. 2021.
- [256] J. Guo, S. Song, J. Liu, H. Chen, B. Lin, and J.-H. Cui, "An efficient geo-routing-aware MAC protocol based on OFDM for underwater acoustic networks," *IEEE Internet Things J.*, vol. 10, no. 11, pp. 9809–9822, Jun. 2023.
- [257] Y. Wei and D. Wang, "Graph coloring-based multichannel MAC protocol in distributed underwater acoustic sensor networks," *Frontiers Mar. Sci.*, vol. 9, Jan. 2023, Art. no. 1005959.
- [258] H. A. Gaffar and P. V. Krishna, "Cooperative retransmission-based MAC method for underwater sensor networks," *Int. J. Adv. Intell. Paradigms*, vol. 26, no. 3, pp. 323–335, 2023.
- [259] S. Yang, X. Liu, and Y. Su, "A traffic-aware fair MAC protocol for layered data collection oriented underwater acoustic sensor networks," *Remote Sens.*, vol. 15, no. 6, p. 1501, Mar. 2023.
- [260] Y. Chen, Z. Jin, Q. Zeng, and Q. Yang, "A collision-avoided MAC protocol with time synchronization and power control for underwater sensor networks," *IEEE Sensors J.*, vol. 22, no. 19, pp. 19073–19087, Oct. 2022.
- [261] Y. Chen et al., "An energy-efficient MAC protocol for three-dimensional underwater acoustic sensor networks with time synchronization and power control," *IEEE Access*, vol. 11, pp. 20842–20860, 2023.
- [262] J. Guo, S. Song, J. Liu, H. Chen, J.-H. Cui, and G. Han, "A hybrid NOMA-based MAC protocol for underwater acoustic networks," *IEEE/ACM Trans. Netw.*, vol. 32, no. 2, pp. 1187–1200, Apr. 2024.
- [263] D.-M. Chiu and R. Jain, "Analysis of the increase and decrease algorithms for congestion avoidance in computer networks," *Comput. Netw. ISDN Syst.*, vol. 17, no. 1, pp. 1–14, Jun. 1989.
- [264] J.-I. Namgung, N.-Y. Yun, S.-H. Park, C.-H. Kim, J.-H. Jeon, and S.-J. Park, "Adaptive MAC protocol and acoustic modem for underwater sensor networks," in *Proc. ACM Int. Workshop Underwater Netw.*, 2009, pp. 20842–20860.
- [265] J.-I. Namgung, S.-Y. Shin, N.-Y. Yun, and S.-H. Park, "Adaptive GTS allocation scheme based on IEEE 802.15.4 for underwater acoustic sensor networks," in *Proc. IEEE/IFIP Int. Conf. Embedded Ubiquitous Comput.*, Dec. 2010, pp. 297–301.
- [266] F. Favaro, S. Azad, P. Casari, and M. Zorzi, "On the performance of unsynchronized distributed MAC protocols in deep water acoustic networks," in *Proc. 6th ACM Int. Workshop Underwater Netw.*, 2011, pp. 1–2.
- [267] C. L. Fullmer and J. J. Garcia-Luna-Aceves, "Floor acquisition multiple access (FAMA) for packet-radio networks," in *Proc. Conf. Appl., Technol., Archit., Protocols Comput. Commun.*, Oct. 1995, pp. 262–273.
- [268] M. Molins and M. Stojanovic, "Slotted FAMA: A MAC protocol for underwater acoustic networks," in *Proc. OCEANS Asia Pacific*, May 2006, pp. 1–7.
- [269] H.-P. Tan, W. K. G. Seah, and L. Doyle, "A multi-hop ARQ protocol for underwater acoustic networks," in *Proc. OCEANS-Eur.*, Jun. 2007, pp. 1–6.
- [270] S. Shahabudeen, M. Chitre, and M. Motani, "A multi-channel MAC protocol for AUV networks," in *Proc. OCEANS-Eur.*, Jun. 2007, pp. 1–6.
- [271] H.-H. Ng, W.-S. Soh, and M. Motani, "MACA-U: A media access protocol for underwater acoustic networks," in *Proc. IEEE Global Telecommun. Conf. (IEEE GLOBECOM)*, Jul. 2008, pp. 1–5.
- [272] J. Liu and J. Wang, "A MACA-based collision avoidance MAC protocol for underwater acoustic sensor network," in *Proc. IEEE/OES China Ocean Acoust. (COA)*, Jan. 2016, pp. 1–4.
- [273] A. A. Syed, W. Ye, and J. Heidemann, "T-Lohi: A new class of MAC protocols for underwater acoustic sensor networks," in *Proc. IEEE INFOCOM Conf. Comput. Commun.*, Aug. 2008, pp. 231–235.
- [274] A. A. Syed, W. Ye, and J. Heidemann, "Comparison and evaluation of the T-Lohi MAC for underwater acoustic sensor networks," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 9, pp. 1731–1743, Dec. 2008.
- [275] J. Zhang, X. Ma, G. Qiao, and C. Wang, "A full-duplex based protocol for underwater acoustic communication networks," in *Proc. OCEANS-San Diego*, Sep. 2013, pp. 1–6.
- [276] V. Rajendran, K. Obraczka, and J. J. Garcia-Luna-Aceves, "Energy-efficient collision-free medium access control for wireless sensor networks," in *Proc. Int. Conf. Embedded Netw. Sensor Syst.*, 2003, pp. 181–192.
- [277] P. Xie and J.-H. Cui, "R-MAC: An energy-efficient MAC protocol for underwater sensor networks," in *Proc. Int. Conf. Wireless Algorithms, Syst. Appl. (WASA)*, Aug. 2007, pp. 187–198.
- [278] N. Chirdchoo, W.-S. Soh, and K. C. Chua, "RIPT: A receiver-initiated reservation-based protocol for underwater acoustic networks," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 9, pp. 1744–1753, Dec. 2008.
- [279] L.-F. Qian, S.-L. Zhang, and M.-Q. Liu, "A slotted floor acquisition multiple access based MAC protocol for underwater acoustic networks with RTS competition," *Frontiers Inf. Technol. Electron. Eng.*, vol. 16, no. 3, pp. 217–226, Mar. 2015.
- [280] Y.-D. Chen, C.-Y. Lien, S.-W. Chuang, and K.-P. Shih, "DSSS: A TDMA-based MAC protocol with dynamic slot scheduling strategy for underwater acoustic sensor networks," in *Proc. OCEANS IEEE*, Jun. 2011, pp. 1–6.
- [281] F. A. Alfouzan, A. Shahrabi, S. M. Ghoreyshi, and T. Boutaleb, "A collision-free graph coloring MAC protocol for underwater sensor networks," *IEEE Access*, vol. 7, pp. 39862–39878, 2019.
- [282] M. A. Luque-Nieto, J. M. Moreno-Roldán, J. Poncela, and P. Otero, "Reliable transmissions in fair STDMA underwater sensor networks," in *Proc. 2nd Int. Conf. Comput. Sustain. Global Develop. (INDIACom)*, Mar. 2015, pp. 1285–1289.
- [283] H. Zhao, H. Chen, and L. Xie, "SSH-MAC: Service-aware and scheduling-based media access control protocol in underwater acoustic sensor network," *Remote Sens.*, vol. 16, no. 15, p. 2718, Jul. 2024.
- [284] W. Sun, X. Sun, B. Wang, J. Wang, H. Du, and J. Zhang, "MR-SFAMA-Q: A MAC protocol based on Q-learning for underwater acoustic sensor networks," *Dianmao Xuekan*, vol. 35, pp. 51–63, May 2024.
- [285] N. Z. Zenia, M. S. Kaiser, M. R. Ahmed, S. A. Mamun, and M. S. Islam, "An energy efficient and reliable cluster-based adaptive MAC protocol for UWSN," in *Proc. Int. Conf. Electr. Eng. Inf. Commun. Technol. (ICEICT)*, May 2015, pp. 1–7.
- [286] M. Gao, J. Li, W. Li, and Z. Deng, "A multi-channel MAC protocol for underwater acoustic networks," in *Proc. IEEE 20th Int. Workshop Comput. Aided Model. Design Commun. Links Netw. (CAMAD)*, Sep. 2015, pp. 293–298.
- [287] L. Wang, C. Lin, K. Chen, and Y. Zhang, "A learning-based ALOHA protocol for underwater acoustic sensor networks," in *Proc. 13th ACM Int. Conf. Underwater Netw. Syst.*, Dec. 2018, pp. 1–2.

- [288] S. Tomovic and I. Radusinovic, "DR-ALOHA-Q: A Q-Learning-based adaptive MAC protocol for underwater acoustic sensor networks," *Sensors*, vol. 23, no. 9, p. 4474, 2023.
- [289] S. H. Park, P. D. Mitchell, and D. Grace, "Reinforcement learning based MAC protocol (UW-ALOHA-QM) for mobile underwater acoustic sensor networks," *IEEE Access*, vol. 9, pp. 5906–5919, 2021.
- [290] F. Ahmed, J. Cho, E. Shitiri, and H.-S. Cho, "Reinforcement learning-based power control for MACA-based underwater MAC protocol," *IEEE Access*, vol. 10, pp. 71044–71053, 2022.
- [291] W. U. Rahman, Q. Gang, Z. Feng, Z. U. Khan, M. Aman, and M. Bilal, "A MACA-based energy-efficient MAC protocol using Q-learning technique for underwater acoustic sensor network," in *Proc. IEEE 11th Int. Conf. Comput. Sci. Netw. Technol. (ICCSNT)*, Oct. 2023, pp. 352–355.
- [292] D. Ekta, Y. Rajendra, and U. Nandini, "Securing underwater wireless communication networks," *Int. J. Adv. Res. Comput. Commun. Eng.*, vol. 5, no. 3, pp. 131–135, 2016.
- [293] H. Yan, Z. J. Shi, and J. H. Cui, "DBR: Depth-based routing for underwater sensor networks," in *Proc. IFIP-TC6 Netw.* Cham, Switzerland: Springer, 2008, pp. 72–86.
- [294] SensorsOne. (Nov. 15, 2021). *Underwater Pressure Sensors*. [Online]. Available: <https://www.sensorsone.com/underwater-pressure-sensors/>
- [295] L. Guangzhong and L. Zhibin, "Depth-based multi-hop routing protocol for underwater sensor network," in *Proc. IEEE 2nd Int. Conf. Ind. Mechatron. Autom.*, vol. 2, Wuhan, China, May 2010, pp. 268–270.
- [296] A. Wahid, S. Lee, H.-J. Jeong, and D. Kim, "EEDBR: Energy-efficient depth-based routing protocol for underwater wireless sensor networks," in *Proc. Int. Conf. Adv. Comput. Sci. Inf. Technol.*, 2011, pp. 223–234.
- [297] R. W. L. Coutinho, L. F. M. Vieira, and A. A. F. Loureiro, "DCR: Depth-controlled routing protocol for underwater sensor networks," in *Proc. IEEE Symp. Comput. Commun. (ISCC)*, Jul. 2013, pp. 000453–000458.
- [298] S. Mahmood et al., "Forwarding nodes constraint based DBR (CDBR) and EEDBR (CEEDBR) in underwater WSNs," *Proc. Comput. Sci.*, vol. 34, pp. 228–235, Jul. 2014.
- [299] H. Nasir et al., "CoDBR: Cooperative depth based routing for underwater wireless sensor networks," in *Proc. 9th Int. Conf. Broadband Wireless Comput., Commun. Appl.*, Nov. 2014, pp. 52–57.
- [300] H. Fahim et al., "Interference and bandwidth aware depth based routing protocols in underwater WSNs," in *Proc. 9th Int. Conf. Innov. Mobile Internet Services Ubiquitous Comput.*, Jul. 2015, pp. 78–85.
- [301] T. Liaqat, N. Javaid, S. M. Ali, M. Imran, and M. Alnuem, "Depth-based energy-balanced hybrid routing protocol for underwater WSNs," in *Proc. 18th Int. Conf. Netw.-Based Inf. Syst.*, Sep. 2015, pp. 20–25.
- [302] H. Yu, N. Yao, T. Wang, G. Li, Z. Gao, and G. Tan, "WDFAD-DBR: Weighting depth and forwarding area division DBR routing protocol for UASNs," *Ad Hoc Netw.*, vol. 37, pp. 256–282, Feb. 2016.
- [303] M. Khizar et al., "Enhanced energy efficient depth based routing protocol for underwater WSNs," in *Proc. 10th Int. Conf. Innov. Mobile Internet Services Ubiquitous Comput. (IMIS)*, Jul. 2016, pp. 70–77.
- [304] K. Pervaiz et al., "DEAC: Depth and energy aware cooperative routing protocol for underwater wireless sensor networks," in *Proc. 10th Int. Conf. Complex, Intell., Softw. Intensive Syst. (CISIS)*, Jul. 2016, pp. 150–158.
- [305] U. Shakeel, N. Jan, Khizar, U. Qasim, Z. A. Khan, and N. Javaid, "DRADS: Depth and reliability aware delay sensitive routing protocol for underwater WSNs," in *Proc. 10th Int. Conf. Innov. Mobile Internet Services Ubiquitous Comput. (IMIS)*, Jul. 2016, pp. 78–83.
- [306] B. Diao et al., "A reliable depth-based routing protocol with network coding for underwater sensor networks," in *Proc. IEEE 22nd Int. Conf. Parallel Distrib. Syst. (ICPADS)*, Dec. 2016, pp. 270–277.
- [307] T. Ahmed, M. Chaudhary, M. Kaleem, and S. Nazir, "Optimized depth-based routing protocol for underwater wireless sensor networks," in *Proc. Int. Conf. Open Source Syst. Technol. (ICOSST)*, Dec. 2016, pp. 147–150.
- [308] S. Gul, S. H. Jokhio, and I. A. Jokhio, "Light-weight depth-based routing for underwater wireless sensor network," in *Proc. Int. Conf. Advancements Comput. Sci. (ICACS)*, Feb. 2018, pp. 1–7.
- [309] S. N. Pari, M. Sathish, and K. Arumugam, "An energy-efficient and reliable depth-based routing protocol for underwater wireless sensor network (ER-DBR)," in *Proc. APSEM, ETAEERE*, 2018, pp. 451–463.
- [310] S. S. Rahim, S. Ahmed, F. Hadi, A. Khan, M. U. Akhtar, and L. Javed, "Depth-based adaptive and energy-aware (DAE) routing scheme for UWSNs," *EAI Endorsed Trans. Energy Web*, vol. 5, no. 17, p. e6, Apr. 2018.
- [311] J. Wang, H. Yu, Q. Guan, F. Ji, and F. Chen, "A power-controlled depth-based routing protocol for underwater wireless sensor networks," in *Proc. 13th ACM Int. Conf. Underwater Netw. Syst.*, Dec. 2018, pp. 1–2.
- [312] X. Liu, P. Liu, T. Long, Z. Lv, and R. Tang, "An efficient depth-based forwarding protocol for underwater wireless sensor networks," in *Proc. IEEE 3rd Int. Conf. Cloud Comput. Big Data Anal. (ICCCBDA)*, Apr. 2018, pp. 467–475.
- [313] M. Zhang and W. Cai, "Energy-efficient depth based probabilistic routing within 2-hop neighborhood for underwater sensor networks," *IEEE Sensors Lett.*, vol. 4, no. 6, pp. 1–4, Jun. 2020.
- [314] R. Mhemed, F. Comeau, W. Phillips, and N. Aslam, "EEDOR: An energy efficient depth-based opportunistic routing protocol for UWSNs," in *Proc. IEEE Can. Conf. Electr. Comput. Eng. (CCECE)*, Aug. 2020, pp. 1–6.
- [315] U. Farooq et al., "IDBR: Iot enabled depth base routing method for underwater wireless sensor network," *J. Sensors*, vol. 2021, no. 1, Jan. 2021, Art. no. 7777181.
- [316] Y. Cheng, L. Xie, and H. Chen, "FIDbOR: An intelligent depth-based opportunistic routing protocol for UASNs," in *Proc. IEEE Int. Conf. Signal Process., Commun. Comput. (ICSPCC)*, Nov. 2023, pp. 1–6.
- [317] E. Kulla, D. Elmazi, K. Matsuo, and L. Barolli, "Energy-aware depth-based routing protocol for underwater wireless sensor networks," in *Proc. Int. Conf. Network-Based Inf. Syst. (NBIS)*. Cham, Switzerland: Springer, 2023, pp. 371–382.
- [318] P. Xie, J.-H. Cui, and L. Lao, "VBF: Vector-based forwarding protocol for underwater sensor networks," in *Proc. IFIP-TC6 Netw.* Cham, Switzerland: Springer, 2006, pp. 1216–1221.
- [319] A. S. Ghazy, S. Hranilovic, and M.-A. Khalighi, "Angular MIMO for underwater wireless optical communications: Link modeling and tracking," *IEEE J. Ocean. Eng.*, vol. 46, no. 4, pp. 1391–1407, Oct. 2021.
- [320] A. S. Ghazy, S. Hranilovic, and M.-A. Khalighi, "Angular MIMO for underwater wireless optical communications: Channel modelling and capacity," in *Proc. 16th Can. Workshop Inf. Theory (CWIT)*, Jun. 2019, pp. 1–6.
- [321] A. Shaf, T. Ali, W. Farooq, U. Draz, and S. Yasin, "Comparison of DBR and L2-ABF routing protocols in underwater wireless sensor network," in *Proc. 15th Int. Bhurban Conf. Appl. Sci. Technol. (IBCAST)*, Jan. 2018, pp. 746–750.
- [322] H. Maulana, M. A. Prihandono, A. S. Elfa, R. Harwahyu, and R. F. Sari, "Analysis of VBF and DBR performance in environmental monitoring system using aquasim at NS-3," in *Proc. Int. Conf. Informatics, Multimedia, Cyber Inf. Syst. (ICIMCIS)*, Oct. 2019, pp. 17–22.
- [323] E. Kulla, D. Elmazi, and K. Matsuo, "Performance comparison of vector based forwarding and depth based routing in underwater wireless sensor networks," in *Proc. IEEE 9th Int. Conf. Big Data Comput. Service Appl. (BigDataService)*, Jul. 2023, pp. 53–57.
- [324] N. A. Somani and N. K. Chaubey, "Performance evaluation of VBF, DBR and modified CARP for underwater acoustic sensor network," in *Proc. Int. Conf. Comput. Sci., Commun. Secur. (ICCS)*. Cham, Switzerland: Springer, 2023, pp. 245–255.
- [325] L. Emokpae and M. Younis, "Reflection-enabled directional MAC protocol for underwater sensor networks," in *Proc. IFIP Wireless Days (WD)*, Oct. 2011, pp. 1–6.
- [326] J. Yang, Q. Hu, L. Xu, P. Xiao, J. Gao, and J. Zhang, "A deafness-free MAC protocol for underwater acoustic communication network with directional antennas," in *Proc. OES China Ocean Acoust. (COA)*, Jul. 2021, pp. 660–664.
- [327] J. Yang, S. Liu, Q. Liu, and G. Qiao, "UMDR: Multi-path routing protocol for underwater ad hoc networks with directional antenna," *J. Phys., Conf. Ser.*, vol. 960, Jan. 2018, Art. no. 012010.
- [328] T. Ali, L. T. Jung, and S. Ameer, "Flooding control by using angle based cone for UWSNs," in *Proc. Int. Symp. Telecommun. Technol.*, Nov. 2012, pp. 112–117.
- [329] Dreamstime. Accessed: Oct. 13, 2021. [Online]. Available: <https://www.dreamstime.com>
- [330] Gograph. Accessed: Oct. 13, 2021. [Online]. Available: <https://www.gograph.com>
- [331] (2021). *PNGtree*. Accessed: Oct. 13, 2021. [Online]. Available: <https://pngtree.com>
- [332] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in *Proc. 33rd Annu. Hawaii Int. Conf. Syst. Sci.*, 2000, p. 10.
- [333] W. B. Heinzelman, A. P. Chandrakasan, and H. Balakrishnan, "An application-specific protocol architecture for wireless microsensor networks," *IEEE Trans. Wireless Commun.*, vol. 1, no. 4, pp. 660–670, Oct. 2002.

- [334] S. Dong, X. Hong, and B. Ghosh, "An enhancing VBF protocol for AUVs: Integrating uncertainty management and energy efficiency," in *Proc. IEEE 44th Int. Conf. Distrib. Comput. Syst. (ICDCS)*, Jul. 2024, pp. 1476–1477.
- [335] S. Lee, Y. Bae, M. T. R. Khan, J. Seo, and D. Kim, "Avoiding spurious retransmission over flooding-based routing protocol for underwater sensor networks," *Wireless Commun. Mobile Comput.*, vol. 2020, Aug. 2020, Art. no. 8839541.
- [336] X. Xiao, C. Chi, H. Huang, J. Huang, and W. Wang, "An energy-efficient clustering routing protocol based on data aggregation for underwater acoustic sensor networks," in *Proc. Global Oceans*, Singapore, Oct. 2020, pp. 1–6.
- [337] C. Zhao, B. Feng, and Q. Zhang, "Mobile sink LEACH protocol for underwater acoustic sensor networks," in *Proc. 13th Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Oct. 2021, pp. 1–6.
- [338] T. R. Chenthil and P. Jesu Jayarin, "An energy-efficient distributed node clustering routing protocol with mobility pattern support for underwater wireless sensor networks," *Wireless Netw.*, vol. 28, no. 8, pp. 3367–3390, Nov. 2022.
- [339] A. Datta and M. Dasgupta, "Energy efficient layered cluster head rotation based routing protocol for underwater wireless sensor networks," *Wireless Pers. Commun.*, vol. 125, no. 3, pp. 2497–2514, Aug. 2022.
- [340] Y. Sun, M. Zheng, X. Han, S. Li, and J. Yin, "Adaptive clustering routing protocol for underwater sensor networks," *Ad Hoc Netw.*, vol. 136, Nov. 2022, Art. no. 102953.
- [341] Y. Zhao, G. Lu, S. Tan, X. Zhu, Z. Song, and Y. Chen, "A clustering guiding-network based routing protocol for underwater acoustic sensor networks," in *Proc. IEEE Int. Conf. Signal Process., Commun. Comput. (ICSPCC)*, Nov. 2023, pp. 1–5.
- [342] B. Ragavi, V. Baranidharan, and K. Ramash Kumar, "A novel hybridized cluster-based geographical opportunistic routing protocol for effective data routing in underwater wireless sensor networks," *J. Electr. Comput. Eng.*, vol. 2023, pp. 1–17, Nov. 2023.
- [343] S. Vahabi, A. Daneshvar, M. Eslaminejad, and S. E. Dashti, "CBDS2R: A cluster-based depth source selection routing for underwater wireless sensor network," *IEEE Trans. Signal Inf. Process. Netw.*, vol. 9, pp. 468–476, 2023.
- [344] D. Han, X. Du, X. Liu, and X. Tian, "Fuzzy C-means clustering and improved arithmetic optimization algorithm-based layering cooperative routing protocol for UASNs," *IEEE Sensors J.*, vol. 24, no. 15, pp. 24810–24824, Aug. 2024.
- [345] X. Chang and J. Wang, "UCNSR: Underwater wireless sensor networks clustered routing protocol based on core node set," *IEEE Sensors J.*, vol. 24, no. 23, pp. 39822–39834, Dec. 2024.
- [346] M. U. Khan, P. Otero, and M. Aamir, "An energy efficient clustering routing protocol based on arithmetic progression for underwater acoustic sensor networks," *IEEE Sensors J.*, vol. 24, no. 5, pp. 6964–6975, Mar. 2024.
- [347] R. Zhu, A. Boukerche, Y. Chen, and Q. Yang, "A reliable cluster-based opportunistic routing protocol for underwater wireless sensor networks," *Comput. Netw.*, vol. 251, Sep. 2024, Art. no. 110622.
- [348] T. Luo et al., "An innovative cluster routing method for performance enhancement in underwater acoustic sensor networks," *IEEE Internet Things J.*, vol. 11, no. 14, pp. 25337–25357, Jul. 2024.
- [349] Z. Jin, H. Li, Y. Wang, J. Liang, and S. Cheng, "Energy-balanced routing protocol with nonuniform clustering for underwater acoustic sensors networks," *IEEE Sensors J.*, vol. 24, no. 22, pp. 38082–38091, Nov. 2024.
- [350] R. S. Sutton and A. G. Barto, *Reinforcement Learning: An Introduction*. Cambridge, MA, USA: MIT Press, 2018.
- [351] Z. Jin, C. Duan, Q. Yang, and Y. Su, "Q-learning-based opportunistic routing with an on-site architecture in UASNs," *Ad Hoc Netw.*, vol. 119, Aug. 2021, Art. no. 102553.
- [352] C. Wang, X. Shen, H. Wang, H. Zhang, and H. Mei, "Reinforcement learning-based opportunistic routing protocol using depth information for energy-efficient underwater wireless sensor networks," *IEEE Sensors J.*, vol. 23, no. 15, pp. 17771–17783, Aug. 2023.
- [353] W. Bin, B. Kerong, H. Yixue, and Z. Mingjiu, "SQMCR: Stackelberg Q-learning-based multi-hop cooperative routing algorithm for underwater wireless sensor networks," *IEEE Access*, vol. 12, pp. 56179–56195, 2024.
- [354] M. S. Popli, R. P. Singh, N. K. Popli, and M. Mamun, "A federated learning framework for enhanced data security and cyber intrusion detection in distributed network of underwater drones," *IEEE Access*, vol. 13, pp. 12634–12646, 2025.
- [355] S. Song, B. Huangfu, J. Guo, J. Liu, J. Cui, and X. Shen, "A digital twin-based intelligent network architecture for underwater acoustic sensor networks," *IEEE Trans. Mobile Comput.*, vol. 24, no. 9, pp. 8196–8213, Sep. 2025.
- [356] Y. Zhou, T. Cao, and W. Xiang, "Anypath routing protocol design via Q-learning for underwater sensor networks," *IEEE Internet Things J.*, vol. 8, no. 10, pp. 8173–8190, May 2021.
- [357] Z. Fang, J. Wang, C. Jiang, B. Zhang, C. Qin, and Y. Ren, "QLACO: Q-learning aided ant colony routing protocol for underwater acoustic sensor networks," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, May 2020, pp. 1–6.
- [358] N. Krishnapriya and N. Kumareshan, "Improved ant colony routing protocol via Q-learning for underwater acoustic environment," in *Proc. 3rd Int. Conf. Inventive Res. Comput. Appl. (ICIRCA)*, Sep. 2021, pp. 370–375.
- [359] Z. A. Khan, O. A. Karim, S. Abbas, N. Javaid, Y. B. Zikria, and U. Tariq, "Q-learning based energy-efficient and void avoidance routing protocol for underwater acoustic sensor networks," *Comput. Netw.*, vol. 197, Oct. 2021, Art. no. 108309.
- [360] Y. Chen, K. Zheng, X. Fang, L. Wan, and X. Xu, "QMCR: A Q-learning-based multi-hop cooperative routing protocol for underwater acoustic sensor networks," *China Commun.*, vol. 18, no. 8, pp. 224–236, Aug. 2021.
- [361] Y. Zhang, Z. Zhang, L. Chen, and X. Wang, "Reinforcement learning-based opportunistic routing protocol for underwater acoustic sensor networks," *IEEE Trans. Veh. Technol.*, vol. 70, no. 3, pp. 2756–2770, Mar. 2021.
- [362] Z. Shen, H. Yin, L. Jing, Y. Liang, and J. Wang, "A cooperative routing protocol based on Q-learning for underwater optical-acoustic hybrid wireless sensor networks," *IEEE Sensors J.*, vol. 22, no. 1, pp. 1041–1050, Jan. 2022.
- [363] C. Han, C. Xu, S. Song, J. Liu, T. Yang, and J.-H. Cui, "QAAR: An application-adaptive routing protocol based on Q-learning in underwater sensor networks," in *Proc. IEEE/CIC Int. Conf. Commun. China (ICCC)*, China, Aug. 2022, pp. 162–167.
- [364] D. Han, X. Du, X. Liu, and X. Tian, "FCLR: Fuzzy control-based layering routing protocol for underwater acoustic networks," *IEEE Sensors J.*, vol. 22, no. 23, pp. 23590–23602, Dec. 2022.
- [365] S. Tu, X. Zhu, Y. Chen, and X. Xu, "A Q-learning and data priority-based routing protocol with dynamic computing cluster head for underwater acoustic sensor networks," in *Proc. IEEE Int. Conf. Signal Process., Commun. Comput. (ICSPCC)*, Oct. 2022, pp. 1–5.
- [366] R. Zhu, Q. Jiang, X. Huang, D. Li, and Q. Yang, "A reinforcement-learning-based opportunistic routing protocol for energy-efficient and void-avoided UASNs," *IEEE Sensors J.*, vol. 22, no. 13, pp. 13589–13601, Jul. 2022.
- [367] K. R. Shruthi and C. Kavitha, "Reinforcement learning-based approach for establishing energy-efficient routes in underwater sensor networks," in *Proc. IEEE Int. Conf. Electron., Comput. Commun. Technol. (CONECCT)*, Jul. 2022, pp. 1–6.
- [368] Z. Zhang and X. Du, "LRLRP: A layer and reinforcement learning based routing protocol for underwater acoustic networks," in *Proc. Int. Conf. Intell. Commun. Netw. (ICN)*, Nov. 2023, pp. 139–144.
- [369] Y. Yuan, M. Liu, X. Zhuo, Y. Wei, X. Tu, and F. Qu, "A Q-learning-based hierarchical routing protocol with unequal clustering for underwater acoustic sensor networks," *IEEE Sensors J.*, vol. 23, no. 6, pp. 6312–6325, Mar. 2023.
- [370] Y. Yuan, S. Song, C. Xu, J. Liu, and J.-H. Cui, "QPCR: A power controlled routing protocol based on Q-learning for energy-constrained underwater wireless sensor networks," in *Proc. IEEE/CIC Int. Conf. Commun. China (ICCC)*, China, Aug. 2023, pp. 1–6.
- [371] C. Wang, X. Shen, H. Wang, W. Xie, H. Mei, and H. Zhang, "Q learning-based routing protocol with accelerating convergence for underwater wireless sensor networks," *IEEE Sensors J.*, vol. 24, no. 7, pp. 11562–11573, Apr. 2024.
- [372] J. Yang, J. Wang, Y. Huang, Z. Peng, Z. Wu, and L. Du, "Q-learning-based routing protocol for underwater acoustic sensor networks," in *Proc. OES China Ocean Acoust. (COA)*, China, May 2024, pp. 1–6.
- [373] X. Liu and F. Zhou, "Q-learning-based energy-efficient routing protocol for underwater wireless sensor networks," in *Proc. OES China Ocean Acoust. (COA)*, China, May 2024, pp. 1–6.
- [374] Z. Zhang, Y. Li, J. Gao, and F. Ye, "Sink attraction Q-learning routing algorithm for UWSNs," in *Proc. IEEE/CIC Int. Conf. Commun. China (ICCC)*, China, Aug. 2024, pp. 1775–1780.

- [375] J. Gao, F. Ye, K. Zhang, and Z. Zhang, "A Q-learning-based load balancing routing protocol for underwater wireless sensor networks," in *Proc. IEEE 7th Int. Conf. Electron. Inf. Commun. Technol. (ICEICT)*, Jul. 2024, pp. 55–60.
- [376] J. Gao, J. Wang, J. Gu, and W. Shi, "Q-learning based routing optimization algorithm for underwater sensor networks," *IEEE Internet Things J.*, vol. 11, no. 22, pp. 36350–36357, Nov. 2024.
- [377] T. Xiong and R. Hou, "Reinforcement learning and vector-based clustering method to achieve energy balanced in underwater acoustic sensor networks," in *Proc. Int. Conf. Cloud Netw. Comput. (ICNC)*, May 2024, pp. 30–35.
- [378] S. Zhang, H. Chen, and L. Xie, "An adaptive SVM-based routing protocol for underwater acoustic sensor networks," in *Proc. OCEANS-Limerick*, Jun. 2023, pp. 1–7.
- [379] X. Li, X. Hu, R. Zhang, and L. Yang, "Routing protocol design for underwater optical wireless sensor networks: A multiagent reinforcement learning approach," *IEEE Internet Things J.*, vol. 7, no. 10, pp. 9805–9818, Oct. 2020.
- [380] C. Wang, X. Shen, H. Wang, W. Xie, H. Zhang, and H. Mei, "Multi-agent reinforcement learning-based routing protocol for underwater wireless sensor networks with value of information," *IEEE Sensors J.*, vol. 24, no. 5, pp. 7042–7054, Mar. 2024.
- [381] S. Liu, J. Wang, W. Shi, G. Han, S. Yan, and J. Li, "CLORP: Cross-layer opportunistic routing protocol for underwater sensor networks based on multiagent reinforcement learning," *IEEE Sensors J.*, vol. 24, no. 10, pp. 17243–17258, May 2024.
- [382] N. Hemavathy and P. Indumathi, "Deep learning-based hybrid dynamic biased track (DL-HDBT) routing for under water acoustic sensor networks," *J. Ambient Intell. Humanized Comput.*, vol. 12, no. 1, pp. 1211–1225, Jan. 2021.
- [383] X. Geng and B. Zhang, "Deep Q-network-based intelligent routing protocol for underwater acoustic sensor network," *IEEE Sensors J.*, vol. 23, no. 4, pp. 3936–3943, Feb. 2023.
- [384] Y. Su, R. Fan, X. Fu, and Z. Jin, "DQELR: An adaptive deep Q-network-based energy- and latency-aware routing protocol design for underwater acoustic sensor networks," *IEEE Access*, vol. 7, pp. 9091–9104, 2019.
- [385] S. Zhang, H. Chen, and L. Xie, "GNN-IR: An intelligent routing method based on graph neural network in the underwater acoustic sensor network," *IEEE Sensors J.*, vol. 24, no. 13, pp. 21566–21582, Jul. 2024.
- [386] Z. Peng, Z. Zhou, J.-H. Cui, and Z. J. Shi, "Aqua-Net: An underwater sensor network architecture: Design, implementation, and initial testing," in *Proc. OCEANS*, Oct. 2009, pp. 1–8.
- [387] S. N. Le, Z. Peng, J.-H. Cui, H. Zhou, and J. Liao, "SeaLinX: A multi-instance protocol stack architecture for underwater networking," in *Proc. 8th ACM Int. Conf. Underwater Netw. Syst.*, 2013, pp. 1–5.
- [388] Y. Sun and T. Melodia, "The internet underwater: An IP-compatible protocol stack for commercial undersea modems," in *Proc. 8th ACM Int. Conf. Underwater Netw. Syst.*, Jul. 2013, pp. 1–8.
- [389] K. Muppalla, N.-Y. Yun, S.-H. Park, and C. Kim, "Design of Internet of Underwater Things architecture and protocol stacks," in *Proc. Korea Inf. Process. Soc. Conf.*, 2013, pp. 486–488.
- [390] M. Chitre, R. Bhatnagar, and W.-S. Soh, "UnetStack: An agent-based software stack and simulator for underwater networks," in *Proc. Oceans*, Sep. 2014, pp. 1–10.
- [391] V. Di Valerio, F. L. Presti, C. Petrioli, L. Picari, and D. Spaccini, "A self-adaptive protocol stack for underwater wireless sensor networks," in *Proc. OCEANS*, Apr. 2016, pp. 1–8.
- [392] S. C. Dhongdi, P. Nahar, R. Sethunathan, L. J. Gudino, and K. R. Anupama, "Cross-layer protocol stack development for three-dimensional underwater acoustic sensor network," *J. Netw. Comput. Appl.*, vol. 92, pp. 3–19, Aug. 2017.
- [393] L. E. Emokpae, Z. Liu, G. F. Edelmann, and M. Younis, "A cross-stack QoS routing approach for underwater acoustic sensor networks," in *Proc. 4th Underwater Commun. Netw. Conf. (UComms)*, Aug. 2018, pp. 1–5.
- [394] D. Tronchin et al., "A secure cross-layer communication stack for underwater acoustic networks," in *Proc. OCEANS*, Sep. 2021, pp. 1–8.
- [395] A. S. Ghazy, G. Kaddoum, and S. Singh, "Low-latency low-energy adaptive clustering hierarchy protocols for underwater acoustic networks," *IEEE Access*, vol. 11, pp. 50578–50594, 2023.
- [396] H. Dol, "EDA-SALSA: Towards smart adaptive underwater acoustic networking," in *Proc. OCEANS*, Jun. 2019, pp. 1–6.
- [397] F. Campagnaro et al., "A simulation framework for smart adaptive long and short-range acoustic networks," in *Proc. OCEANS*, Sep. 2021, pp. 1–9.
- [398] H. Dol et al., "EDA-SALSA: Development of a self-reconfigurable protocol stack for robust underwater acoustic networking," in *Proc. OCEANS*, Jun. 2023, pp. 1–10.
- [399] R. Otnes, P. A. van Walree, H. Buen, and H. Song, "Underwater acoustic network simulation with lookup tables from physical-layer replay," *IEEE J. Ocean. Eng.*, vol. 40, no. 4, pp. 822–840, Oct. 2015.
- [400] H. Dol, K. Blom, and E. van der Spek, "Experiences with JANUS and efforts towards a common heavy-duty underwater communication stack," in *Proc. IEEE 3rd Underwater Commun. Netw. Conf. (UComms)*, Aug. 2016, pp. 1–5.
- [401] K. C. H. Blom, H. S. Dol, F. Berning, and P. A. Van Walree, "Development of a physical layer for adaptive underwater acoustic communications," in *Proc. 6th Underwater Commun. Netw. Conf. (UComms)*, Aug. 2022, pp. 1–5.
- [402] D. Green, J. Dellamorte, and J. Dellamorte, "Enhancing JANUS signaling," in *Proc. 5th Underwater Commun. Netw. Conf. (UComms)*, Aug. 2021, pp. 1–4.
- [403] R. Otnes, "An underwater first contact method using JANUS," in *Proc. 6th Underwater Commun. Netw. Conf. (UComms)*, Aug. 2022, pp. 1–5.
- [404] N. Adam, M. Ali, F. Naeem, A. S. Ghazy, and G. Kaddoum, "State-of-the-art survey schemes for the Internet of Underwater Things: A holistic survey," *IEEE Open J. Commun. Soc.*, vol. 5, pp. 6561–6592, 2024.
- [405] S. Jiang, "On securing underwater acoustic networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 1, pp. 729–752, 1st Quart., 2019.
- [406] W. Aman, S. Al-Kuwari, A. Kumar, M. M. Ur Rahman, and M. Muzammil, "Underwater and air-water wireless communication: State-of-the-art, channel characteristics, security, and open problems," 2022, *arXiv:2203.02667*.
- [407] H. Zhou, S. H. Huang, and W. Li, "Parametric acoustic array and its application in underwater acoustic engineering," *Sensors*, vol. 20, no. 7, p. 2148, Apr. 2020.
- [408] Y.-C. Yu, Z.-Z. Zeng, D.-S. Lu, D.-P. Su, and J.-Y. Wang, "Power minimization-based secure beamforming for MISO VLC having both perfect and imperfect CSI," *IEEE Signal Process. Lett.*, vol. 32, pp. 1830–1834, 2025.
- [409] S. Kisseleff, S. Chatzinotas, and B. Ottersten, "Reconfigurable intelligent surfaces in challenging environments: Underwater, underground, industrial and disaster," *IEEE Access*, vol. 9, pp. 150214–150233, 2021.
- [410] M. Di Renzo et al., "Smart radio environments empowered by reconfigurable intelligent surfaces: How it works, state of research, and the road ahead," *IEEE J. Sel. Areas Commun.*, vol. 38, no. 11, pp. 2450–2525, Nov. 2020.
- [411] J. Chen, Y.-C. Liang, Y. Pei, and H. Guo, "Intelligent reflecting surface: A programmable wireless environment for physical layer security," *IEEE Access*, vol. 7, pp. 82599–82612, 2019.
- [412] S. A. H. Mohsan, A. Mazinani, N. Q. H. Othman, and H. Amjad, "Towards the Internet of Underwater Things: A comprehensive survey," *Earth Sci. Informat.*, vol. 15, no. 2, pp. 735–764, Jun. 2022.
- [413] A. S. Ghazy, G. Kaddoum, C. Talhi, N. Iqbal, and A. H. Muqabel, "Reinforcement learning-assisted secure reliable underwater wireless acoustic communications," *IEEE Access*, vol. 13, pp. 180049–180068, 2025.
- [414] H. Kulhandjian, T. Melodia, and D. Koutsonikolas, "Securing underwater acoustic communications through analog network coding," in *Proc. 11th Annu. IEEE Int. Conf. Sens., Commun., Netw. (SECON)*, Jun. 2014, pp. 266–274.
- [415] Y. Ye, Z. Peng, and X. Hong, "Active jamming for eavesdropping prevention in underwater wireless networks," in *Proc. Int. Conf. Underwater Netw. Syst.*, 2019, pp. 1–5.
- [416] Y. Liu, L. Li, R. Fan, S. Ma, X. Liu, and Y. Su, "A physical layer security mechanism based on cooperative jamming in underwater acoustic sensor networks," in *Proc. IEEE/CIC Int. Conf. Commun. China (ICC Workshops)*, China, Jul. 2021, pp. 239–243.
- [417] Y. Su, L. Li, R. Fan, Y. Liu, and Z. Jin, "A secure transmission scheme with energy-efficient cooperative jamming for underwater acoustic sensor networks," *IEEE Sensors J.*, vol. 22, no. 21, pp. 21287–21298, Nov. 2022.
- [418] Y. Su, Y. Liu, R. Fan, L. Li, M. Han, and H. Zhang, "A secure relay selection scheme based on cooperative jamming for underwater acoustic sensor networks," *Comput. Netw.*, vol. 217, Nov. 2022, Art. no. 109307.
- [419] Y. Su, Y. Liu, R. Fan, L. Li, H. Fan, and S. Zhang, "A cooperative jamming scheme based on node authentication for underwater acoustic sensor networks," *J. Mar. Sci. Appl.*, vol. 21, no. 2, pp. 197–209, Jun. 2022.

- [420] Y. Huang, P. Xiao, S. Zhou, and Z. Shi, "A half-duplex self-protection jamming approach for improving secrecy of block transmissions in underwater acoustic channels," *IEEE Sensors J.*, vol. 16, no. 11, pp. 4100–4109, Jun. 2016.
- [421] L. Xiao, Q. Li, T. Chen, E. Cheng, and H. Dai, "Jamming games in underwater sensor networks with reinforcement learning," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2015, pp. 1–6.
- [422] L. Xiao, Donghua, Jiang, X. Wan, W. Su, and Y. Tang, "Anti-jamming underwater transmission with mobility and learning," *IEEE Commun. Lett.*, vol. 22, no. 3, pp. 542–545, Mar. 2018.
- [423] L. Xiao, D. Jiang, Y. Chen, W. Su, and Y. Tang, "Reinforcement-learning-based relay mobility and power allocation for underwater sensor networks against jamming," *IEEE J. Ocean. Eng.*, vol. 45, no. 3, pp. 1148–1156, Jul. 2020.
- [424] Y. Liu, C. Liu, Z. Zhao, and W. Qu, "Anti-interference transmission strategy for underwater acoustic communication based on deep reinforcement learning," in *Proc. IEEE 25th Int. Conf. Comput. Supported Cooperat. Work Design (CSCWD)*, May 2022, pp. 1167–1172.
- [425] C. Liu, Y. Zhang, G. Niu, L. Jia, L. Xiao, and J. Luan, "Towards reinforcement learning in UAV relay for anti-jamming maritime communications," *Digit. Commun. Netw.*, vol. 9, no. 6, pp. 1477–1485, Dec. 2023.
- [426] R. Diamant, P. Casari, and S. Tomasin, "Cooperative authentication in underwater acoustic sensor networks," *IEEE Trans. Wireless Commun.*, vol. 18, no. 2, pp. 954–968, Feb. 2019.
- [427] M. Khalid, R. Zhao, and N. Ahmed, "Physical layer authentication in line-of-sight underwater acoustic sensor networks," in *Proc. Global Oceans*, Singapore, Oct. 2020, pp. 1–5.
- [428] M. Khalid, R. Zhao, and X. Wang, "Node authentication in underwater acoustic sensor networks using time-reversal," in *Proc. Global Oceans*, Singapore, Oct. 2020, pp. 1–4.
- [429] R. Zhao, M. Khalid, O. A. Dobre, and X. Wang, "Physical layer node authentication in underwater acoustic sensor networks using time-reversal," *IEEE Sensors J.*, vol. 22, no. 4, pp. 3796–3809, Feb. 2022.
- [430] C. Liu, R. Zhao, T. Shi, and H. Wang, "Node authentication for underwater sensor networks based on time reversal and LinUCB," in *Proc. OCEANS-Limerick*, Jun. 2023, pp. 1–5.
- [431] W. Aman, M. M. U. Rahman, J. Qadir, H. Pervaiz, and Q. Ni, "Impersonation detection in line-of-sight underwater acoustic sensor networks," *IEEE Access*, vol. 6, pp. 44459–44472, 2018.
- [432] W. Aman, S. Al-Kuwari, and M. Qaraqe, "Location-based physical layer authentication in underwater acoustic communication networks," in *Proc. IEEE 97th Veh. Technol. Conf. (VTC-Spring)*, Jun. 2023, pp. 1–6.
- [433] W. Aman, S. Al-Kuwari, and M. Qaraqe, "A novel physical layer authentication mechanism for static and mobile 3D underwater acoustic communication networks," *Phys. Commun.*, vol. 66, Oct. 2024, Art. no. 102430.
- [434] P. Casari, F. Ardizzon, and S. Tomasin, "Physical layer authentication in underwater acoustic networks with mobile devices," in *Proc. 16th Int. Conf. Underwater Netw. Syst.*, 2022, pp. 1–8.
- [435] T. Shi, R. Zhao, X. Shen, and H. Wang, "Database-based physical layer authentication for dynamic underwater acoustic networks," in *Proc. OCEANS*, Jun. 2023, pp. 1–4.
- [436] L. Bragagnolo, F. Ardizzon, N. Laurenti, P. Casari, R. Diamant, and S. Tomasin, "Authentication of underwater acoustic transmissions via machine learning techniques," in *Proc. IEEE Int. Conf. Microw. Antennas, Commun. Electron. Syst. (COMCAS)*, Nov. 2021, pp. 255–260.
- [437] F. Ardizzon, R. Diamant, P. Casari, and S. Tomasin, "Machine learning-based distributed authentication of UWAN nodes with limited shared information," in *Proc. 6th Underwater Commun. Netw. Conf. (UComms)*, Aug. 2022, pp. 1–5.
- [438] F. Ardizzon, P. Casari, and S. Tomasin, "A RNN-based approach to physical layer authentication in underwater acoustic networks with mobile devices," *Comput. Netw.*, vol. 243, Apr. 2024, Art. no. 110311.
- [439] L. Xiao, G. Sheng, X. Wan, W. Su, and P. Cheng, "Learning-based PHY-layer authentication for underwater sensor networks," *IEEE Commun. Lett.*, vol. 23, no. 1, pp. 60–63, Jan. 2019.
- [440] R. Zhao, T. Shi, C. Liu, X. Shen, and O. A. Dobre, "Physical layer authentication without adversary training data in resource-constrained underwater acoustic networks," *IEEE Sensors J.*, vol. 23, no. 22, pp. 28270–28281, Nov. 2023.
- [441] P. van Walree, E. Sangfelt, and G. Leus, "Multicarrier spread spectrum for covert acoustic communications," in *Proc. OCEANS*, Sep. 2008, pp. 1–8.
- [442] A. Zhao, Y. Cheng, T. An, and J. Hui, "Covert underwater acoustic communication system using parametric array," *Mar. Technol. Soc. J.*, vol. 53, no. 1, pp. 20–26, Jan. 2019.
- [443] G. Leus, P. van Walree, J. Boschma, C. Fanciullacci, H. Gerritsen, and P. Tuzoni, "Covert underwater communications with multiband OFDM," in *Proc. OCEANS*, Sep. 2008, pp. 1–8.
- [444] J. Zhang, G. Gao, J. Zhang, and Y. Guo, "Secure and noise-resistant underwater wireless optical communication based on spectrum spread and encrypted OFDM modulation," *Opt. Exp.*, vol. 30, no. 10, pp. 17140–17155, 2022.
- [445] J. M. Hamamreh, H. M. Furqan, and H. Arslan, "Classifications and applications of physical layer security techniques for confidentiality: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 2, pp. 1773–1828, 2nd Quart., 2019.
- [446] M. Andersson, V. Rathi, R. Thobaben, J. Kliewer, and M. Skoglund, "Equivocation of eavesdropper using two edge type LDPC codes for the binary erasure wiretap channel," in *Proc. Conf. Rec. 44th Asilomar Conf. Signals, Syst. Comput.*, Nov. 2010, pp. 2045–2049.
- [447] Y. Cong, G. Yang, Z. Wei, and W. Zhou, "Security in underwater sensor network," in *Proc. Int. Conf. Commun. Mobile Comput.*, vol. 1, Apr. 2010, pp. 162–168.
- [448] M. C. Domingo, "Securing underwater wireless communication networks," *IEEE Wireless Commun.*, vol. 18, no. 1, pp. 22–28, Feb. 2011.
- [449] M. Xu, G. Liu, and J. Guan, "Towards a secure medium access control protocol for cluster-based underwater wireless sensor networks," *Int. J. Distrib. Sensor Netw.*, vol. 11, no. 5, May 2015, Art. no. 325474.
- [450] M. Ibragimov et al., "CCM-UW security modes for low-band underwater acoustic sensor networks," *Wireless Pers. Commun.*, vol. 89, no. 2, pp. 479–499, Jul. 2016.
- [451] M. Zuba, M. Fagan, J.-H. Cui, and Z. Shi, "A vulnerability study of geographic routing in underwater acoustic networks," in *Proc. IEEE Conf. Commun. Netw. Secur. (CNS)*, Oct. 2013, pp. 109–117.
- [452] C. Lal, R. Petroccia, M. Conti, and J. Alves, "Secure underwater acoustic networks: Current and future research directions," in *Proc. IEEE 3rd Underwater Commun. Netw. Conf. (UComms)*, Aug. 2016, pp. 1–5.
- [453] H. Rustad, "A lightweight protocol suite for underwater communication," in *Proc. Int. Conf. Adv. Inf. Netw. Appl. Workshops*, May 2009, pp. 1172–1177.
- [454] E. Barker, L. Chen, S. Keller, A. Roginsky, A. Vassilev, and R. Davis, "Recommendation for pair-wise key-establishment schemes using discrete logarithm cryptography," NIST, Cairo, Egypt, Tech. Rep., 2017.
- [455] C. Blundo, A. De Santis, A. Herzberg, S. Kutten, U. Vaccaro, and M. Yung, "Perfectly-secure key distribution for dynamic conferences," in *Proc. Annu. Int. Cryptol. Conf. Cham, Switzerland: Springer*, 1993, pp. 471–486.
- [456] M. Zuba, M. Fagan, Z. Shi, and J.-H. Cui, "A resilient pressure routing scheme for underwater acoustic networks," in *Proc. IEEE Global Commun. Conf.*, Dec. 2014, pp. 637–642.
- [457] S. Basagni, C. Petrioli, R. Petroccia, and D. Spaccini, "CARP: A channel-aware routing protocol for underwater acoustic wireless networks," *Ad Hoc Netw.*, vol. 34, pp. 92–104, Nov. 2015.
- [458] A. Caposese, G. De Cicco, and C. Petrioli, "R-CARP: A reputation based channel aware routing protocol for underwater acoustic sensor networks," in *Proc. 10th Int. Conf. Underwater Netw. Syst. (WUWNET)*, 2015, pp. 1–6.
- [459] K. Sharma and M. Ghose, "Cross layer security framework for wireless sensor networks," *Int. J. Secur. Appl.*, vol. 5, no. 1, pp. 39–52, 2011.
- [460] M. M. Farag, M. Azab, and B. Mokhtar, "Cross-layer security framework for smart grid: Physical security layer," in *Proc. IEEE PES Innov. Smart Grid Technol., Eur.*, Oct. 2014, pp. 1–7.
- [461] J. Wurm et al., "Introduction to cyber-physical system security: A cross-layer perspective," *IEEE Trans. Multi-Scale Comput. Syst.*, vol. 3, no. 3, pp. 215–227, Jul. 2017.
- [462] S. Basagni, C. Petrioli, R. Petroccia, and D. Spaccini, "Channel-aware routing for underwater wireless networks," in *Proc. Oceans Yeosu*, 2012, pp. 1–9, doi: 10.1109/OCEANS-Yeosu.2012.6263538.
- [463] P. A. Shelar, P. N. Mahalle, and G. Shinde, "Secure data transmission in underwater sensor network: Survey and discussion," in *Internet of Things, Smart Computing and Technology: A Roadmap Ahead*. Sandy Bay, TAS, Australia: Science and Engineering Research Support Society (SERSC), 2020, pp. 323–360.
- [464] K. Ashok and S. Gopikrishnan, "Statistical analysis of remote health monitoring based IoT security models & deployments from a pragmatic perspective," *IEEE Access*, vol. 11, pp. 2621–2651, 2023.

- [465] A. Alnajim, S. Habib, M. Islam, S. Thwin, and F. Alotaibi, "A comprehensive survey of cybersecurity threats, attacks, and effective countermeasures in industrial Internet of Things," *Technologies*, vol. 11, no. 6, p. 161, Nov. 2023.
- [466] B. Halak, "CIST: A threat modelling approach for hardware supply chain security," in *Hardware Supply Chain Security*. New York, NY, USA: IEEE, 2021, pp. 3–65.
- [467] M.-C. Lu, Q.-X. Huang, M.-Y. Chiu, Y.-C. Tsai, and H.-M. Sun, "PSPS: A step toward tamper resistance against physical computer intrusion," *Sensors*, vol. 22, no. 5, p. 1882, Feb. 2022.
- [468] S. Mavrouniotis and M. Ganley, "Hardware security modules," in *Secure Smart Embedded Devices, Platforms and Applications*. Cham, Switzerland: Springer, 2013, pp. 383–405.
- [469] D. Star. (2024). *SAM-1 Acoustic Modems*. Accessed: Dec. 2024. [Online]. Available: <https://www.desertstar.com/page/sam-1>
- [470] W. Lee, J.-H. Jeon, and S.-J. Park, "Micro-modem for short-range underwater communication systems," in *Proc. Oceans*, Sep. 2014, pp. 1–4.
- [471] T.-H. Won and S.-J. Park, "Design and implementation of an omnidirectional underwater acoustic micro-modem based on a low-power micro-controller unit," *Sensors*, vol. 12, no. 2, pp. 2309–2323, Feb. 2012.
- [472] H. Nam and S. An, "Low-power based coherent acoustic modem for emerging underwater acoustic sensor networks," *Wireless Pers. Commun.*, vol. 57, no. 2, pp. 291–309, Mar. 2011.
- [473] J.-H. Jeon, S.-H. Hwangbo, H. Peyvandi, and S.-J. Park, "Design and implementation of a bidirectional acoustic micro-modem for underwater communication systems," in *Proc. Oceans*, Oct. 2012, pp. 1–4.
- [474] M. S. Martins, J. Cabral, G. Lopes, and F. Ribeiro, "Underwater acoustic modem with streaming video capabilities," in *Proc. OCEANS*, May 2015, pp. 1–7.
- [475] J. Younce, A. Singer, T. Riedl, B. Landry, A. Bean, and T. Arikan, "Experimental results with HF underwater acoustic modem for high bandwidth applications," in *Proc. 49th Asilomar Conf. Signals, Syst. Comput.*, 2015, pp. 248–252.
- [476] S. Indriyanto and I. Y. M. Edward, "Ultrasonic underwater acoustic modem using frequency shift keying (FSK) modulation," in *Proc. 4th Int. Conf. Wireless Telematics (ICWT)*, Jul. 2018, pp. 1–4.
- [477] C. Renner, A. Gabrecht, B. Meyer, C. Osterloh, and E. Maehle, "Low-power low-cost acoustic underwater modem," in *Proc. Quant. Monitor. Underwater Environ., Results Int. Mar. Sci. Technol.*, 2016, pp. 59–65.
- [478] W. B. Abbas, N. Ahmed, C. Usama, and A. A. Syed, "Design and evaluation of a low-cost, DIY-inspired, underwater platform to promote experimental research in UWSN," *Ad Hoc Netw.*, vol. 34, pp. 239–251, Nov. 2015.
- [479] J. DelPreto, R. Katzschmann, R. MacCurdy, and D. Rus, "A compact acoustic communication module for remote control underwater," in *Proc. 10th Int. Conf. Underwater Netw. Syst.*, New York, NY, USA, 2015, pp. 1–7.
- [480] A. A. Sheikh, E. Felemban, and A. Ashraf, "Coralcon: An open source low-cost modem for underwater IoT applications," in *Proc. 13th IEEE Int. Conf. Intell. Comput. Commun. Process. (ICCP)*, Sep. 2017, pp. 503–508.
- [481] W. A. P. van Kleunen, N. A. Moseley, P. J. M. Havinga, and N. Meratnia, "Proteus II: Design and evaluation of an integrated power-efficient underwater sensor node," *Int. J. Distrib. Sensor Netw.*, vol. 2015, pp. 1–10, Jun. 2015.
- [482] A. Sánchez, S. Blanc, P. Yuste, A. Perles, and J. J. Serrano, "An ultra-low power and flexible acoustic modem design to develop energy-efficient underwater sensor networks," *Sensors*, vol. 12, no. 6, pp. 6837–6856, May 2012.
- [483] B. Benson et al., "Design of a low-cost underwater acoustic modem," *IEEE Embedded Syst. Lett.*, vol. 2, no. 3, pp. 58–61, Sep. 2010.
- [484] M. Y. I. Zia, P. Otero, and J. Poncela, "Design of a low-cost modem for short-range underwater acoustic communications," *Wireless Pers. Commun.*, vol. 101, no. 1, pp. 375–390, Jul. 2018.
- [485] Kongsberg. (2024). *CNODE Underwater Acoustic Modems*. Accessed: Dec. 2024. [Online]. Available: <https://www.km.kongsberg.com>
- [486] R. Zhao, H. Mei, X. Shen, W. Fang, and H. Wang, "Underwater acoustic network node design and anechoic pool network experimentation with five nodes," in *Proc. IEEE/OES China Ocean Acoust. (COA)*, China, Jan. 2016, pp. 1–5.
- [487] D. Torres, J. Friedman, T. Schmid, M. B. Srivastava, Y. Noh, and M. Gerla, "Software-defined underwater acoustic networking platform and its applications," *Ad Hoc Netw.*, vol. 34, pp. 252–264, Nov. 2015.
- [488] AppliCon. (2024). *Underwater Acoustic Seamodem*. Accessed: Dec. 2024. [Online]. Available: <http://www.applicon.it>
- [489] DiveNET. (2024). *Acoustic Modems*. Accessed: Dec. 2024. [Online]. Available: <https://www.divenetgps.com>
- [490] Sonardyne. (2024). *Modem 6 Underwater Acoustic Modems*. Accessed: Dec. 2024. [Online]. Available: <https://www.sonardyne.com>
- [491] B. Peng and H. Dong, "DSP based real-time single carrier underwater acoustic communications using frequency domain turbo equalization," *Phys. Commun.*, vol. 18, pp. 40–48, Mar. 2016.
- [492] Z. Shaolong, F. Dong, L. Xun, L. Yu, and H. Haining, "Modularized real-time communication modem design based on software defined radio of underwater acoustic network," in *Proc. Int. Conf. Commun., Electron. Autom. Eng.*, 2013, pp. 1197–1204.
- [493] A. S. Vershinin, "Experimental testing of hydroacoustic modem layout," in *Proc. 17th Int. Conf. Young Specialists Micro/Nanotechnologies Electron Devices (EDM)*, Jun. 2016, pp. 75–77.
- [494] AquaSeNT. (2024). *Underwater Acoustic Modems*. Accessed: Dec. 2024. [Online]. Available: <http://www.aquasent.com>
- [495] A. Bourré, S. Lmai, C. Laot, and S. Houcke, "A robust OFDM modem for underwater acoustic communications," in *Proc. MTS/IEEE OCEANS*, Jul. 2013, pp. 1–5.
- [496] M. Sadeghi, M. Elamassie, and M. Uysal, "Adaptive OFDM-based acoustic underwater transmission: System design and experimental verification," in *Proc. IEEE Int. Black Sea Conf. Commun. Netw. (Black-SeaCom)*, Jun. 2017, pp. 1–5.
- [497] M. Chitre, I. Topor, and T.-B. Koay, "The UNET-2 modem—An extensible tool for underwater networking research," in *Proc. OCEANS*, May 2012, pp. 1–7.
- [498] C. C. Naidu and E. S. Stalin, "Establishment of underwater wireless acoustic MODEM using C-OFDM," in *Proc. Int. Conf. Microelectron., Comput. Commun. (MicroCom)*, Jan. 2016, pp. 1–6.
- [499] L. Ma, G. Qiao, and S. Liu, "HEU OFDM-modem for underwater acoustic communication and networking," in *Proc. Int. Conf. Underwater Netw. Syst.*, 2014, pp. 1–5.
- [500] C. Wang, Q. Zhang, Z. Yan, J. Han, K. Lei, and L. Zhang, "Implementation of underwater acoustic modem based on the OMAP-L138 processor," in *Proc. IEEE Int. Conf. Signal Process., Commun. Comput. (ICSPCC)*, Aug. 2014, pp. 800–805.
- [501] H. Yan et al., "DSP based receiver implementation for OFDM acoustic modems," *Phys. Commun.*, vol. 5, no. 1, pp. 22–32, 2012.
- [502] Blueprint Subsea. (2024). *SeaTrac Underwater Acoustic Modems*. Accessed: Dec. 2024. [Online]. Available: <https://www.blueprintsubsea.com>
- [503] Tritech. (2024). *Micron Data Modem*. Accessed: Dec. 2024. [Online]. Available: <https://www.tritech.co.uk>
- [504] Oceania. (2024). *GPM 300 Underwater Acoustic Modem*. Accessed: Dec. 2024. [Online]. Available: <https://www2.13t.com/oceania>
- [505] LinkQuest. (2024). *Soundlink Underwater Acoustic Modems*. Accessed: Dec. 2024. [Online]. Available: <http://www.link-quest.com>
- [506] W. Lei, D. Wang, Y. Xie, B. Chen, X. Hu, and H. Chen, "Implementation of a high reliable chirp underwater acoustic modem," in *Proc. Oceans*, May 2012, pp. 1–5.
- [507] EvoLogics. (2024). *S2C Underwater Acoustic Modems*. Accessed: Dec. 2024. [Online]. Available: <https://www.evologics.de/>
- [508] Sercel. (2024). *Mats 3G Underwater Acoustic Modems*. Accessed: Dec. 2024. [Online]. Available: <http://www.sercel.com>
- [509] Aquatec. (2024). *Underwater Acoustic AQUA Modems*. Accessed: Dec. 2024. [Online]. Available: <http://www.aquatecgroup.com>
- [510] Subnero. (2024). *Software Defined Underwater Acoustic Modem*. Accessed: Dec. 2024. [Online]. Available: <https://subnero.com>
- [511] T. Marine. (2024). *Teledyne Benthos ATM-9XX Underwater Acoustic Modems*. Accessed: Dec. 2024. [Online]. Available: <http://www.teledynemarine.com>
- [512] L. Xu and S. Yan, "Design of underwater acoustic modems through high performance DSPs," in *Proc. Int. Conf. Underwater Netw. Syst. (WUWNET)*, 2014, pp. 1–2.
- [513] H. Zhang, S. Xiong, Z. Yue, and Z. Wang, "Sea trials of an underwater acoustic network in the East China Sea 2015," in *Proc. IEEE/OES China Ocean Acoust. (COA)*, Jan. 2016, pp. 1–5.
- [514] Q. Dong, Y. Wang, and X. Guan, "The design and implementation of an underwater multimode acoustic modem for autonomous underwater vehicles," in *Proc. 37th Chin. Control Conf. (CCC)*, Jul. 2018, pp. 4201–4205.
- [515] Develogic. (2024). *Hydro Acoustic Modem*. Accessed: Dec. 2024. [Online]. Available: <https://develogic.com/products/ham-uap-com/>

[516] G. Qiao, S. Liu, Z. Sun, and F. Zhou, "Full-duplex, multi-user and parameter reconfigurable underwater acoustic communication modem," in *Proc. OCEANS*, Sep. 2013, pp. 1–8.

[517] E. Demirors, G. Sklivanitis, G. E. Santagati, T. Melodia, and S. N. Batalama, "A high-rate software-defined underwater acoustic modem with real-time adaptation capabilities," *IEEE Access*, vol. 6, pp. 18602–18615, 2018.

[518] DSPComm. (2024). *Aquacomm Underwater Wireless Modems*. Accessed: Dec. 2024. [Online]. Available: <https://www.dspcomm.com>

[519] G. Cossu et al., "Sea-trial of optical Ethernet modems for underwater wireless communications," *J. Lightw. Technol.*, vol. 36, no. 23, pp. 5371–5380, Dec. 2018.

[520] I. V. Zhilin, O. M. Bushnaq, G. D. Masi, E. Natalizio, and I. F. Akyildiz, "A universal multimode (acoustic, magnetic induction, optical, RF) software defined modem architecture for underwater communication," *IEEE Trans. Wireless Commun.*, vol. 22, no. 12, pp. 9105–9116, Dec. 2023.

[521] I. B. Saksvik, V. Hassani, A. Pascoal, and A. Alcocer, "BlueLink: A bidirectional optical modem for high-speed underwater communication," in *Proc. IEEE Int. Workshop Metro. Sea Learn. Measure Sea Health Parameters (MetroSea)*, Oct. 2023, pp. 105–109.

[522] P. Góis et al., "Development and validation of blue ray, an optical modem for the MEDUSA class AUVs," in *Proc. IEEE 3rd Underwater Commun. Netw. Conf. (UComms)*, Aug. 2016, pp. 1–5.

[523] J. Potter, J. Alves, D. Green, G. Zappa, I. Nissen, and K. McCoy, "The JANUS underwater communications standard," in *Proc. Underwater Commun. Netw. (UComms)*, 2014, pp. 1–4.

[524] L. Freitag, M. Grund, S. Singh, J. Partan, P. Koski, and K. Ball, "The WHOI micro-modem: An acoustic communications and navigation system for multiple platforms," in *Proc. OCEANS MTS/IEEE*, Dec. 2018, pp. 1086–1092.

[525] Y. Li, Y. Zhang, W. Li, and T. Jiang, "Marine wireless big data: Efficient transmission, related applications, and challenges," *IEEE Wireless Commun.*, vol. 25, no. 1, pp. 19–25, Feb. 2018.

[526] F. S. Alqurashi, A. Trichili, N. Saeed, B. S. Ooi, and M.-S. Alouini, "Maritime communications: A survey on enabling technologies, opportunities, and challenges," *IEEE Internet Things J.*, vol. 10, no. 4, pp. 3525–3547, Feb. 2023.

[527] A. Vavoulas, H. G. Sandalidis, and D. Varoutas, "Underwater optical wireless networks: A k -connectivity analysis," *IEEE J. Ocean. Eng.*, vol. 39, no. 4, pp. 801–809, Oct. 2014.

[528] C. Christopoulou, H. G. Sandalidis, and N. Vaiopoulos, "Performance of an underwater optical wireless link with a randomly placed or moving receiver," *IEEE J. Ocean. Eng.*, vol. 46, no. 3, pp. 1068–1079, Jul. 2021.

[529] A. Celik, N. Saeed, B. Shihada, T. Y. Al-Naffouri, and M.-S. Alouini, "A software-defined opto-acoustic network architecture for Internet of Underwater Things," *IEEE Commun. Mag.*, vol. 58, no. 4, pp. 88–94, Apr. 2020.

[530] S. Han, Y. Noh, R. Liang, R. Chen, Y.-J. Cheng, and M. Gerla, "Evaluation of underwater optical-acoustic hybrid network," *China Commun.*, vol. 11, no. 5, pp. 49–59, May 2014.



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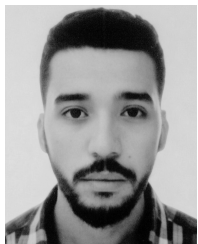
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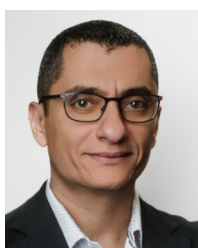
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