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A survey on energy efficient medium access control for acoustic wireless communication networks in underwater environments

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ABSTRACT

Underwater communication plays a crucial role in monitoring the aquatic environment on Earth. Due to their unique characteristics, underwater acoustic channels present unique challenges including lengthy signal transmission delays, limited data transfer bandwidth, variable signal quality, and fluctuating channel conditions. Furthermore, the reliance on battery power for most Underwater Wireless Acoustic Networks (UWAN) devices, coupled with the challenges associated with battery replacement or recharging, intensifies the challenges. Underwater acoustic communications are heavily constrained by available resources (e.g., very limited bandwidth, and limited energy storage). Consequently, the role of medium access control (MAC) protocol which distributes available resources among nodes is critical in maintaining a reliable underwater communication system. This study presents an extensive review of current research in MAC for UWAN. This study presents an extensive review of current research in MAC for UWAN. The paper explores the unique challenges and characteristics of UWAN, which are critical for the MAC protocol design. Subsequently, a diverse range of energy-efficient MAC techniques are categorized and reviewed. Potential future research avenues in energy-efficient MAC protocols are discussed, with a particular emphasis on the challenges to enable the broader implementation of the Green Internet of Underwater Things (GIoUT).

1. Introduction

The growing need for wireless underwater communication systems is recognized in various fields, including underwater sensing, environmental monitoring, underwater robotics, offshore exploration, disaster prevention, and navigation (Su et al., 2020a). Underwater environments present specific challenges for creating reliable and efficient communication links. Acoustic communication is the best approach to underwater data exchange. This is due to the limitations faced by Radio Frequency (RF) and optical communications in these conditions. RF signals are significantly attenuated and propagate only in very short range in underwater (Zhilin et al., 2023). On the other hand, optical communications are hindered by scattering and absorption, particularly in turbulent waters (Zhu et al., 2020). Despite being slower, acoustic signals are a more dependable means of transmitting data across extended distances under the ocean surface (Zenia et al., 2016). However, For Underwater Wireless Acoustic Networks (UWAN) to be effective and reliable, extensive research is required to address the significant challenges posed by harsh underwater conditions.

A major constraint to UWAN development is the severe energy constraints in underwater environments, in which most communication devices are powered by batteries that are difficult to recharge or replace on a regular interval (Barua et al., 2019).

In any communication system, MAC protocols regulate data transmission over a shared medium, underscoring their significant role in underwater communication systems. They help avoid collisions, ensure fair access, and when optimized, can significantly enhance system efficiency. In UWAN, the MAC protocol directly impacts the power consumption of communicating devices (Zhang et al., 2021) Additionally, the growing demand for real-time applications, such as military operations, human activity monitoring, and disaster alarms such as earthquakes and volcanoes, requires low-latency and reliable communication (Moghimi and Mohanna, 2021). Meeting these real-time requirements while managing power consumption is critical in underwater

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environments.

Given the slow propagation speed of acoustic signals and the long distances involved in underwater communication, limited bandwidth traditional MAC protocols designed for terrestrial wireless networks may not be directly applicable or efficient for UWAN. Therefore, understanding and optimizing MAC protocols specific to the underwater acoustic environment is of utmost importance (S and Dhongdi, 2022).

The main contributions of this paper are summarized as follows:

- A detailed review of MAC protocols for underwater acoustic networks is presented. Our focus is on identifying gaps and discussing underwater MAC protocols, particularly from an energy-efficiency perspective, since energy supply is a major limitation in underwater applications.
- Relevant underwater MAC challenges and constraints are presented, highlighting unique issues that distinguish them from terrestrial networks. The study identifies specific problems stemming from these challenges and underscores the inadequacies of current IoT and WSN terrestrial MAC protocols when implemented in underwater settings.
- Additionally, the survey identifies potential areas for future research aimed at enhancing the energy efficiency of MAC protocols for underwater applications.

We have organized the rest of this paper in the following manner. Section 2 examines existing surveys on MAC protocols for UWAN. It highlights gaps in energy efficiency, real-time communication, range transmission, and the broad classification of MAC protocols. In section 3, we highlight various challenges and problems of MAC protocols in UWAN, focusing on how they differ from terrestrial networks and highlighting the limitations of existing protocols in underwater settings. Subsequently, section 4 provides a comprehensive classification of energy-efficient MAC for UWAN protocols including, concept, range, suitability for real-time, energy achievement techniques, strengths, and limitations for each protocol. Followed by a discussion of future research opportunities and challenges for the development of green MAC for UWAN in section 5 and concludes this paper in section 6.

2. Related work

Several works have been conducted to explore MAC protocol design for underwater networks, each addressing different aspects of underwater communication and identifying their limitations in these unique environments. The identified gap of these studies is summarized in Table 1.

The earliest survey such as in (Pompili and Akyildiz, 2009) discusses the limitations of conventional terrestrial protocols in underwater environments and suggests hybrid MAC protocols and CDMA-based solutions as effective alternatives. However, it does not focus on energy MAC, without exploring aspects such as contention-free, contention-based, software-defined MAC techniques, MAC incorporating (Machine Learning) ML, or optical-acoustic MAC. Subsequent research (Chen et al., 2014) focused on various MAC protocols that were comprehensively compared based on diverse implementations. The authors highlighted the strengths and limitations of these protocols. However, this survey primarily does not focus on energy MAC, without exploring aspects such as cross-layer approaches, software-defined MAC techniques, MAC incorporating ML, or optical-acoustic MAC. The study in (Ansari et al., 2015) provides a detailed evaluation of existing MAC protocols in terms of throughput, delay, and energy consumption. However, there is a limitation similar to that in (Chen et al., 2014). Further advancements are introduced in (Jiang, 2017) which introduces a MAC reference model and examines cross-layer MAC protocols. Despite its comprehensive approach, the study does not prioritize energy efficiency or explore innovative MAC designs such as software-defined, MAC based on ML or optical-acoustic MAC. In (Li et al., 2019), the authors present an overview of high-reliability communication techniques, emphasizing acoustic and optical technologies but not focusing on energy-efficient MAC protocols. However, similar to the limitations observed in (Chen et al., 2014) and (Ansari et al., 2015). Authors in (Al Guqhaiman et al., 2020) present recent updates in MAC protocols for UWAN, focusing on both hardware and software aspects. A detailed analysis of the characteristics and limitations of each MAC protocol is provided, as well as an analysis of how different MAC protocol approaches affect channel transmission. Despite highlighting software-based approaches as a potential solution to UWAN challenges, the review does not elaborate on energy-efficient MAC strategies in underwater settings. Additionally, it does not address MAC protocols that incorporate ML and opto-acoustics. The survey in (Songzuo et al., 2021) examines full-duplex MAC protocols for underwater communication, comparing their performance in terms of throughput and energy consumption. However, it does not consider hybrid MAC, cross-layer MAC, software-defined approaches MAC-based ML, or optical-acoustic MAC. The study in (Alfouzan, 2021) presents an in-depth analysis of collision-free MAC protocols. However, its focus is limited to contention-free designs, excluding consideration of other methodologies within the broader MAC protocol framework. In (Khan et al., 2022) the authors classify existing energy-efficient MAC and routing protocols

Table 1
Summary of Existing Underwater MAC Protocol surveys.

Year	2009	2014	2015	2018	2019	2021	2021	2021	2022	2022	2024	2024
Relevant survey	Pompili and Akyildiz (2009)	Chen et al. (2014)	Ansari et al. (2015)	Jiang (2017)	Li et al. (2019)	Al Guqhaiman et al. (2020)	Songzuo et al. (2021)	Alfouzan (2021)	Khan et al. (2022)	Islam et al. (2022)	Zhu et al. (2024)	Our
Energy efficient	×	×	×	×	×	×	×	✓	✓	✓	×	✓
Real-time Analysis	×	×	×	×	×	×	×	×	×	×	×	✓
Contention free	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Contention based	×	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓
Hybrid	✓	✓	✓	✓	✓	✓	×	×	✓	✓	✓	✓
Cross-layer	✓	×	×	✓	×	✓	×	×	×	✓	×	✓
Software-defined	×	×	×	×	×	✓	×	×	×	✓	×	✓
MAC-based ML	×	×	×	×	×	×	×	×	×	×	×	✓
Optical-Acoustic MAC	×	×	×	×	×	×	×	×	×	×	×	✓

through a novel taxonomy but do not include discussions on cross-layer approaches, software-defined MAC, ML-enhanced designs, or optical-acoustic MAC. Recent research, in (Islam et al., 2022) focuses on energy-efficient methodologies across various layers, including physical, MAC and routing, as well as localization protocols. While it emphasizes energy conservation in underwater communication, MAC protocols are not the primary focus, and several advanced designs are not discussed such as MAC techniques based on ML or optical-acoustic. Recently, in (Zhu et al., 2024), a new classification of task-oriented MAC protocols for UWAN was introduced, emphasizing delay-aware and reliable communication strategies. Despite this contribution, the study does not explore energy-efficient MAC cross-layer or the integration of software-defined, ML-based, and optical-acoustic MAC.

According to Table 1 and the previous discussion, there is a substantial research gap in this area. Studies that systematically aggregate diverse mechanisms and classifications of energy-efficient MAC protocols for UWAN are lacking. The absence of such an extensive study is a notable gap in the existing literature. An encompassing survey of this nature would provide a comprehensive overview of the available solutions to address this significant aspect of underwater communication. To the best of our knowledge, our survey represents the first comprehensive analysis of energy-efficient MAC protocols in UWAN, incorporating a wide range of classifications from the existing literature. These include MAC protocols based on ML and Optical-Acoustic MAC, providing a detailed assessment of range, real-time suitability, energy achievement techniques, strengths, and limitations of each type.

3. Challenges, problem identification for designing MAC protocols in underwater acoustic networks

MAC protocols effectively manage shared medium access among sensor nodes. By reducing retransmissions and collisions, the MAC protocol ensures reliable and consistent data transmission. It also employs predefined rules to resolve conflicts among nodes during communication. This mechanism enhances energy efficiency, throughput, and fairness while minimizing communication delays. However, designing MAC protocols for underwater environments introduces unique challenges due to unique characteristics of underwater acoustic channels. The following subsections discusses these challenges in detail, explains problems that may arise, and highlights the limitations of conventional Internet of Things (IoT) and Wireless Sensors Networks (WSN) MAC protocols in underwater scenarios. Additionally, it identifies key factors that make them unsuitable for this application.

3.1. Challenges of designing MAC protocols in underwater acoustic networks

This subsection introduces the main challenges UWAN that present challenges for MAC protocols. The underwater acoustic environment presents distinct challenges for the design and implementation of MAC protocols that differ significantly from those encountered in terrestrial wireless networks. The following challenges by characteristics of acoustic waves underwater illustrate why conventional MAC protocols designed for terrestrial settings cannot be directly applied to UWAN.

3.1.1. Limited bandwidth

The underwater acoustic channel is significantly constrained by a narrower bandwidth than radio frequencies utilized in terrestrial networks. This limitation arises from factors such as high propagation delays, fluctuating channel conditions, and Doppler effects (Rani et al., 2017), (Hassan et al., 2023). Terrestrial MAC protocols, optimized for higher and more stable bandwidths, employ efficient collision detection and resolution mechanisms. In contrast, due to the restricted bandwidth of underwater channels, MAC protocols must incorporate bandwidth-efficient strategies, such as adaptive frequency allocation and scheduling techniques, to enhance data throughput without overloading the limited channel capacity (Kao et al., 2017). A challenge not typically encountered in terrestrial networks operating in higher and more stable frequency ranges.

3.1.2. Doppler shift

Doppler shifts are more prevalent in UWAN than terrestrial networks as acoustic signals travel slower. This is due to the relative motion between transmitters and receivers. Although doppler effects are generally minimal in terrestrial environments using RF communication, they cause significant frequency shifts in underwater channels (Lanbo et al., 2008), known as Doppler Spread or Doppler Diffusion (Sun et al., 2022). This phenomenon distorts signals and reduces data rates, negatively affecting the performance of MAC protocols. Understanding and mitigating the effects of Doppler dispersion is crucial in designing an effective MAC protocol for UWAN.

3.1.3. Acoustic noises

Compared with terrestrial networks, UWAN are more likely to encounter severe and unpredictable interference from noise, which can be categorized as human-made or ambient. Combined with ambient noise from natural sources, such as currents and marine life, human-made noise creates a highly dynamic environment (Roy and Sarma, 2017), (Zaheer et al., 2024). As a result of this variability, bit error rates are higher, and communications are frequently disrupted. In contrast, terrestrial noise is more stable and predictable, making it easier to manage (Ali et al., 2022). Underwater MAC protocols require advanced noise mitigation strategies, such as adaptive power control and dynamic channel selection (Wei et al., 2021).

3.1.4. Path loss

Underwater channels are more variable than terrestrial channels where UWAN suffers from severe path loss due to attenuation and geometric spreading (Afzal et al., 2020). Attenuation occurs as acoustic energy converts into heat, which increases with distance and frequency. Geometric spreading reduces signal strength as it propagates (Ahmed and Stojanovic, 2016). Thorp model estimates this path loss, incorporating factors such as distance and absorption coefficients (Afroz and Braun, 2020). Furthermore, underwater noise, such as turbulence, shipping noise, waves, and thermal energy, also degrades the signal in a different frequency (Tougaard et al., 2020). This results in a reduction in Signal to Noise Ratio (SNR) and overall communication quality (Acar and Adams, 2006). These strategies are less critical in terrestrial MAC designs.

3.1.5. High bit error rates

The underwater acoustic channel is highly susceptible to multipath propagation, reverberation, and signal absorption, leading to severe Inter-Symbol Interference (ISI) and high Bit Error Rates (BER) (Shovon and Shin, 2022). Multipath propagation causes multiple copies of the same signal to arrive at different times due to reflections off the seabed and water surface. This results in significant signal distortion and increased BER (Acar and Adams, 2006). Due to the slow propagation speed of acoustic waves, underwater environments are more prone to signal degradation than terrestrial ones. Terrestrial networks exhibit multipath propagation and fading, but they are less severe as electromagnetic waves travel faster and channel conditions are more stable (Al Guqhaiman et al., 2020). Advanced equalization techniques are needed to mitigate ISI in underwater networks. Underwater MAC protocols face unique challenges in managing BER and maintaining connectivity that are not faced in terrestrial networks where equalization is simpler.

3.1.6. Energy consumption

Energy efficiency is a crucial concern in UWAN due to the logistical difficulties of replacing or recharging batteries in remote and deep-sea environments (Jiang et al., 2016). In contrast to terrestrial networks, which may take advantage of accessible nodes, solar power, and other sources of renewable energy, underwater networks are unable to take advantage of such resources. This makes energy management even more challenging (Murad et al., 2015). Furthermore, underwater nodes require a significant amount of power for signal transmission due to the high levels of attenuation and absorption that occur in water (Un et al., 2021). Acoustic waves propagate at very slow speed compared to terrestrial radio waves, resulting in longer transmission times and higher energy consumption. As a result, energy-efficient MAC protocols in UWAN must employ advanced strategies such as adaptive transmission power control, sleep scheduling, and collision avoidance to prolong network lifetime and ensure reliable communication.

3.1.7. Propagation delays

In underwater environments, acoustic waves propagate at a much slower speed of approximately 1.5×10^3 m/s compared to terrestrial radio frequency (RF) signals, which travel at about 3×10^8 m/s. This difference results in propagation delays in UWAN that are about five orders of magnitude longer than those in terrestrial networks (Akyildiz et al., 2005), (Ali et al., 2021). Such high propagation delays are influenced by a combination of factors, including attenuation caused by signal reflection and refraction from the unpredictable seabed and water surface. Additionally, environmental factors such as temperature variations and water composition further contribute to the unpredictability of propagation delays, making signal transmission times highly variable (Afroz and Braun, 2020), (Alfouzan et al., 2018). This variability adversely affects accuracy and performance of UWAN, especially in applications such as sensor node localization and real-time data transmission to anchor nodes. (Al Guqhaiman et al., 2021), (Zaheer et al., 2023) Consequently, these delays pose a significant challenge in designing efficient MAC protocols, as they must account for extended and variable propagation times to establish reliable communication agreements and ensure effective data delivery in UWAN.

3.1.8. Node movement in three-dimensionality

Mobility in underwater networks such as Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs), is complex due to three-dimensional movement and unpredictable water currents, which cause nodes to drift unexpectedly (Schneider, 2013). Nodes in underwater networks experience frequent topology changes, which disrupt communication links, unlike in terrestrial networks (Dhongdi, 2022), (Caruso et al., 2008). Additionally, the lack of GPS availability underwater makes localization challenging, as precise positioning requires complex and energy-intensive methods such as acoustic localization, whereas terrestrial networks can easily utilize GPS for accurate node localization (González-García et al., 2020).Furthermore, 3D mobility aggravates hidden and exposed terminal problems, increases Doppler effects, and distorts signals (Awan et al., 2019). Vertical movements can result in sudden communication gaps and an increase in energy consumption (Lv et al., 2014). Terrestrial networks, on the other hand, experience fewer Doppler shifts and propagation delays (Ho et al., 2019). This makes mobility management in terrestrial MAC protocols significantly easier than in the dynamic underwater environment.

3.2. Problem identification and associated challenges for MAC protocol design underwater acoustic networks

Designing resource-sharing methods for UWAN requires a deep understanding unique characteristic of acoustic channel. With data transmission demanding far more energy than reception, minimizing retransmissions and avoiding collisions are essential to optimize energy efficiency and maintain network performance. These constraints present significant challenges for MAC protocol development, necessitating advanced strategies to overcome underwater environments' inherent complexities.

3.2.1. Hidden terminal problem

Hidden terminals occur when a network node cannot detect other nodes transmitting within its range of communication. As a result, there is a possibility of simultaneous transmissions and packet collisions at a shared destination (Multi-Channel, 2019). As illustrated in Fig. 1, node C can detect both nodes A and B, but A and B are unaware of each other. Consequently, if nodes B and A transmit data simultaneously, their packets collide at node A, causing transmission errors and network inefficiencies. This problem is particularly severe in underwater networks due to high propagation delays and limited node visibility, making it challenging to detect collisions and avoid data loss, which in turn increases power consumption. In contrast, terrestrial networks experience this issue to a lesser extent, as faster signal propagation and better visibility help mitigate collisions through more effective collision detection and avoidance mechanisms (Zhou et al., 2011).

3.2.2. Exposed terminal problem

An exposed terminal occurs when a node abstains from transmitting data because another node is communicating, even though its transmission would not interfere (Noh et al., 2014). This reduces network efficiency and underutilization of the communication channel (Zhu et al., 2014). As shown in Fig. 1(b), where node E remains idle because it detects a transmission between nodes B and C. While the transmission from node E would not disrupt communication between nodes B and C, it remains silent unnecessarily, resulting in decreased network throughput. The issue is less severe in terrestrial networks due to better visibility and faster signal propagation. Due to longer propagation delays and variable attenuation, UWAN faces a more severe interference problem. As a result, UWAN require more sophisticated MAC protocols than terrestrial networks.

3.2.3. Spatial-temporal uncertainty problem

Spatial-temporal uncertainty in UWAN arises due to sound propagation speed and varying distances between nodes (Yang et al., 2023). These factors lead to unpredictable transmission times, which can result in multiple signals arriving at the receiver simultaneously, causing data collisions (Hu et al., 2018). As illustrated in Fig. 1(c), nodes D, B, and F are located at different distances from node C, creating varying propagation delays. Consequently, transmissions initiated at different times may still converge at node C simultaneously, leading to collisions. Data loss is potentially caused by this spatial-temporal uncertainty, which

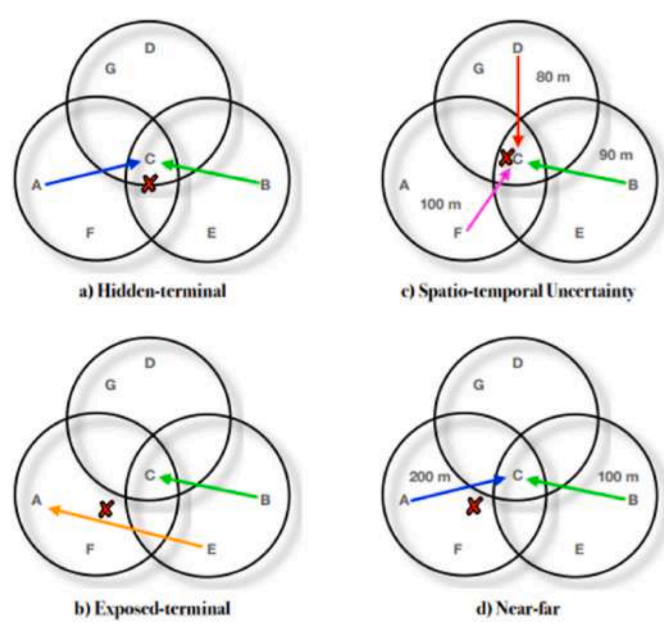

Fig. 1. Single channel collisions.

complicates network coordination and increases energy consumption. The longer propagation delays and the dynamic underwater environment make terrestrial solutions such as TDMA unsuitable for underwater networks (Xiong et al., 2016). By modifying these techniques, we can mitigate spatial-temporal uncertainty in underwater communication by estimating node distance and propagation delay.

3.2.4. Near and far problem

The near-far problem occurs when a destination node receives a much stronger signal from nearby nodes than signals from distant nodes (Zhou et al., 2019a). This is due to a difference in SNR, where a stronger signal from a nearby node may interfere with or even drown out a low signal from a distant node (Ullah et al., 2019). As illustrated in Fig. 1(d), when a nearby node transmits with high power, it creates interference at the destination, making it difficult to receive data from more distant nodes. Underwater communication range is reduced due to this issue. Terrestrial networks address the near-far problem through strategies such as power control, channel allocation, and spread spectrum techniques (Ali et al., 2020). Because of the unique characteristics of underwater environments, these methods cannot be directly applied. Consequently, specialized approaches must be developed to effectively address the near-far problem in underwater communication systems.

3.2.5. Synchronization problem

The synchronization problem encountered by UWAN is caused by the requirement for precise timing coordination between nodes, which is crucial for the reliability of distributed MAC protocols and applications (Guo and Liu, 2013). The propagation delay of acoustic and dynamic underwater environments, including changes in temperature, salinity, and node mobility, makes synchronization underwater challenging (Al-Habob et al., 2021). Terrestrial network synchronization algorithms are inadequate in this environment, necessitating specialized time-synchronization algorithms at the MAC protocol level (Do et al., 2016). As a result of insufficient time synchronization between the sensor nodes underwater, duty cycling cannot confirm the effective operation of the network. This leads to increased data loss and reduced network efficiency.

3.2.6. Centralization problem

The centralization problem in UWAN arises due to the inefficiencies of relying on a single node or coordinator for network management (Szymak, 2012). The high latency, low data rates, and long propagation delays of acoustic channels significantly restrict centralized control (Barr et al., 2011). This makes it difficult to maintain global network information and increases energy and time costs. Furthermore, centralized solutions lack scalability in dense networks and have limited coverage due to the restricted range of underwater modem (Conti et al., 2015). These challenges make it difficult to apply traditional terrestrial MAC protocols underwater.

3.3. Evaluation IoT and WSN MAC protocols for underwater

IoT is an essential component of modern communication with standard and research-based MAC protocols designed to manage network access efficiently, which are optimized for terrestrial environments, focusing on energy efficiency, collision avoidance, and reliable data transmission (Hasan et al., 2019), (Sotenga et al., 2020). However, underwater environments characteristics present significant challenges that terrestrial MAC protocols cannot adequately address. Consequently, there is a need to explore and develop specialized underwater MAC protocols to ensure reliable and efficient communication in such environments. This subsection examines the limitations of some common IoT and WSN MAC protocols in underwater settings, identifying the factors that make them unsuitable for this unique application.

Carrier Sense Multiple Access (CSMA) is a widely used MAC protocol designed to manage how multiple devices share a communication channel, primarily employed in terrestrial networks such as IEEE 802.11 (Wi-Fi) (Std, 1997). CSMA relies on devices listening to the channel before transmitting data, ensuring the channel is idle to prevent collisions. If the channel is busy, the device waits for a random backoff period before attempting to transmit again. This mechanism works effectively in environments with minimal propagation delays, and nodes can quickly sense the channel availability (Fang et al., 2010). While CSMA was integrated into underwater NATO standards such as JANUS (Potter et al., 2014) and PHORCY (Davies et al., 2022), it has high overhead, increased power consumption. Inefficient propagation delays lead to more collisions and a heightened risk of the hidden terminal problem, making underwater communication less effective.

To enhance energy efficiency in WSN and IoT devices, different MAC protocols were designed based on duty cycling, beacon signalling or adaptive preamble to minimize idle listening. For instant, IEEE 802.15.4 (used in ZigBee) (Cunha et al., 2007), Sensor (S-MAC) (Ye et al., 2004), Receiver Initiated (RI-MAC) (Sun et al., 2008) and (B-MAC) (Polastre et al., 2004),which are popular choices for terrestrial networks, focusing on low power consumption and organized sleep schedules. However, the unique challenges of underwater environments such as high propagation delays and significant signal attenuation limit the effectiveness of these protocols without considerable adaptation.

In addition, a hybrid MAC protocol RTH-MAC proposed in (Abdeli et al., 2013), combining TDMA and FDMA to prevent collision in WSN by using centralized scheduling of time slots and frequencies. However, limited acoustic bandwidth and slower propagation rates in underwater environments hinder its ability to maintain reliable in real-time communication. Moreover, a Traffic Adaptive Synchronization (TAS-MAC) protocol designed to enhance energy efficiency and reduce latency in WSN proposed in (Huang et al., 2013), dynamically allocating time slots based on current network traffic. However, in underwater environments, acoustic propagation disrupts synchronization, leading to reduced throughput, interference, and packet collisions. Two more energy-efficient designed for long range IoT communication are proposed, LoRaWAN (Allience, 2015) and Sigfox (Gomez et al., 2019), extending the range through chirp spread spectrum and ultra-narrowband modulation, respectively. While they are effective for terrestrial low-power, underwater use poses challenges due to severe signal attenuation and multipath propagation. These issues limit their range and compromise the power efficiency and data transmission benefits they provide, making them unsuitable for underwater environments without substantial modifications.

Furthermore, a Narrowband (NB-IoT) proposed in (Zayas and Merino, 2017), low-power MAC from the 3GPP framework, supports wide-area network connectivity with low data rates, making it efficient for terrestrial IoT applications. However, underwater conditions limit its effectiveness due to high latency and multipath propagation of acoustic signals, which disrupt timing, synchronization, and data transmission. These challenges result in packet loss and interference, undermining power-saving of NB-IoT benefits and scheduling accuracy in underwater environments.

Recent efforts in designing mission-critical MAC protocols for IoT and WSN have focused on supporting applications that require the rapid and reliable detection of critical events, such as fire outbreaks or emergency shutdowns in industrial IoT systems. Within strict deadlines, these applications require timely and dependable data delivery to the controller node. Failure to meet these delay constraints can result in system instability, financial losses, and even serious safety concerns. Therefore, mission-critical MAC protocols should be tailored to ensure low latency, high reliability, and energy efficiency.

A Work in (Farag et al., 2018) proposed Slot Stealing (SS-MAC) that prioritize critical transmissions by reallocating slots from non-critical data. In addition, MAC for mission critical application WSN was introduced in (Sakya and Sharma, 2019), adapts the duty cycle of nodes in real-time based on energy levels and traffic and prioritizes nodes with higher energy and more queued data for communication. Moreover, Energy-efficient and Fast (EF-MAC) (Poudel and Moh, 2020), has been proposed as an energy-efficient MAC protocol specifically for mission-critical WSN in Unmanned Aerial Vehicle (UAV). It utilizes a hybrid CSMA-TDMA mechanism to optimize energy consumption while minimizing transmission delay. It prioritizes transmissions based on factors such as contact duration, packet size, and residual energy to ensure timely and reliable data delivery. However, these all three mission critical MAC protocols rely on a structured approach where nodes establish contact with an access point before prioritizing critical data or specific nodes. Therefore, implementing these MAC protocols for mission critical applications underwater can lead to challenges due to delays and limited bandwidth. This can disrupt slot coordination and priority data management. These conditions make it difficult to maintain the real-time responsiveness needed for effective mission-critical applications in underwater environments.

4. Energy-efficient underwater acoustic wireless communication MAC protocols

Energy efficiency in the MAC layer is crucial for sustainable UWAN. Significant research has been conducted on offering energy-efficient MAC protocols and reviewing existing underwater protocols. Over the past decade, a few survey studies have aimed to classify, summarize, and analyze the range of MAC protocols presented in the underwater. These studies offer insights into the development and performance of MAC approaches tailored to the unique challenges of underwater environments. Fig. 2 illustrates an energy-efficient MAC protocol hierarchy examined in this article.

Authors in (Chen et al., 2014), classified them into three categories: contention-free, contention-based, and hybrid. Moreover, UWAN MAC protocol classification is done by (Jiang, 2017) in which they are categorized into traditional Radio Wireless Network (RWN)-based adaptations and novel designs. The former includes multiplexing such as TDMA, and non-multiplexing such as ALOHA approaches. The latter category introduces innovative solutions such as scheduling, reservation, and cross-layered designs to address challenges posed by long propagation delays in UWAN. An additional survey in (Al Guqhaiman et al., 2020) has categorized underwater MAC protocols into two main categories: software-based protocols and hardware-based protocols. A hardware-based protocol can be categorized into contention-free protocols, contention-based protocols, hybrid protocols, as well as cross-layer protocols. In contrast to this, software-based protocols such as Software-Defined Radio (SDR), Software-Defined Networking (SDN), and Network Function Virtualization (NFV) are based on software. More recently, energy-efficient MAC protocols in underwater communication were broadly categorized in (Khan et al., 2022) into three sections: frequency domain; full bandwidth; and hybrids combining elements of both frequency domain and random access approaches. Recently, scholars in (Islam et al., 2022) have categorized energy-Efficient MAC protocols underwater into three primary classifications: contention-free, contention-based, and a third category encompassing hybrid, cross-layer, and software-defined approaches. However, in this survey, we will categorize energy-efficient MAC for UWAN into seven major categories: contention-free protocols, contention-based, hybrid protocols which is a combination of (contention-free protocols, contention-based), cross-layer MAC protocols, software-defined MAC, MAC protocols based on ML and Optical-Acoustic MAC as it is shown in Fig. 2. This study seeks to highlight the most effective possible approaches for designing green MAC protocols by acoustic in underwater. In addition, it provides strategies and guidelines for addressing UWAN challenges by developing more robust solutions.

4.1. Contention free

The contention-free MAC protocol shares the resources available in a network among communication nodes, such as bandwidth, without any contention or competition in a network. These protocols ensure efficient allocation of resources among the communication nodes by allocating resources such as time (Time Division Multiple Access (TDMA)), frequency (FDMA), and code (Code Division Multiple Access (CDMA) to each communication node.

4.1.1. Frequency division multiple access

In FDMA wireless networks, sub-frequencies are assigned to each channel frequency, and then each sub-frequency is assigned to one of the node pairs for the transfer of the data (Jiang, 2017). The overall delay of FDMA can be increased since each node pair uses a unique frequency band to transmit packets (Khalil et al., 2012). Furthermore, The diffuse fading found in underwater environments is a significant factor in the low throughput of FDMA, which makes UWAN an ineffective method due to the narrow acoustic channel (Qin et al., 2016). Table 2 summarizes all energy-efficient underwater FDMA-MAC protocols and compares them.

Initial work has presented in (Cheon and Cho, 2011), introduces an

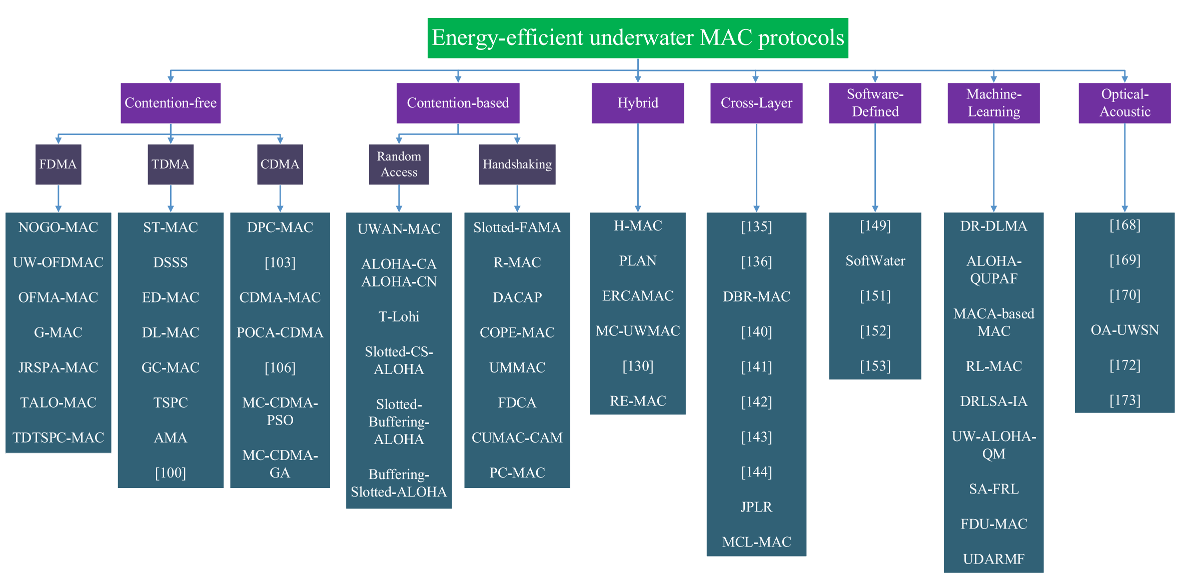

Fig. 2. Energy-efficient MAC protocol hierarchy examined in this article.

Table 2
Comparative analysis of energy efficient FDMA-MAC protocols in UWAN.

Protocol	Topology	Range	SYN	Real Time	Energy Achievement Techniques	Strengths	Limitations
NOGO-MAC (Cheon and Cho, 2011)	Centralized	Long	✓	✓	• Power control. • Frequency grouping. • Adaptive subchannel allocation	• Using grouping of frequency improved transmission speed and power consumption.	• Packets from nodes with similar distances to sink could collide.
UW-OFDMAC (Bouabdallah and Boutaba, 2011)	Distributed	V.short	✓	✓	• Dynamic power control. • Avoid collision by optimizing subcarrier and guard interval assignment. • Avoid control overhead.	• OFDMA parameters and power are distributed among all transmitters without centralized control.	• Complexity may increase with distributed OFDMA parameters.
OFDMA-MAC (Khalil et al., 2012)	Centralized	Short	✓	✓	• Energy-conscious mode (ECM) • Dynamic subcarrier allocation. • Power control.	• Consumes significantly less energy per bit than CDMA.	• Frequency and user diversity affect performance.
G-MAC (Su et al., 2018)	Mobile-Centralized	Medium	×	✓	• Dynamic optimizing subcarrier allocation • Power control. • Motion Prediction. • Avoid collision by minimizing Interference.	• G-MAC trajectory prediction method eliminates spatial-temporal uncertainty caused by node movement. • Enabling concurrent transmissions.	• Underwater channel conditions may render resource allocation ineffective during mission planning and it may not be suitable for dens network.
JRSPA-MAC (Su et al., 2020b)	Centralized	Medium	✓	✓	• Optimize joint relay selection. • Power allocation by practical swarm algorithm. • Avoid collision by minimizing interference	• Enhanced channel utilization through a parallel communication mechanism.	• efficiencies are negatively affected by frequent channel reservations.
TLAO-MAC (Su et al., 2021)	Distributed	Short	×	×	• Adaptive channel grouping algorithm. • Subcarrier and power allocation algorithm. • Avoid collision by channel busyness index.	• Adaptive channel grouping based on channel busyness helps achieve an unsaturated state. • Maximize throughput.	• Five types of control packets could cause network delays.
TDTSPC-MAC (Chen et al., 2023b)	Cluster Distributed	Short	✓	✓	• Power control. • Sleep mode. • Collision avoidance through synchronization. • Cluster strategy by reducing the need for long-range transmissions.	• Minimizing energy use while maintaining reliable data transmission. • Enhance throughput and delay.	• Require strict synchronization.

energy-efficient multi-access protocol called NOde Grouped OFDMA MAC (NOGO-MAC). Sensor nodes are grouped based on their distance from sink nodes. Different sensor groups operate at different frequencies protocol enhances communication efficiency. Optimizing power consumption through SNR-based power control and frequency allocation, assigning high frequencies to nearby nodes and low frequencies to long-range nodes. Additionally, adaptive subchannel allocation enhances data transmission rates. When bandwidths are between 15 and 35 kHz, this method reduces data transmission power by 7 dB. However, collisions are unclear due to the allocation of frequency bands to nodes with similarly distant sinks. Authors in (Bouabdallah and Boutaba, 2011) presented the UW-OFDMAC protocol based on (OFDMA) scheme, which involves determining optimal parameters such as transmit power, subcarrier spacing to avoid inter-symbol interference, and guard interval duration at the transmitter side to reduce retransmissions and save power. These parameters are distributed among all transmitters without relying on a centralized entity by using a unique algorithm that autonomously assigns power and OFDMA parameters. Even though this protocol consumes less energy and maximizes bandwidth efficiency, it may also increase the complexity of the system due to the distributed computation of OFDMA parameters. Subsequently, An adaptive OFDMA MAC protocol has been implemented in (Khalil et al., 2012), it offers three distinct modes of operation: random, equal opportunity, and energy conscious where subcarriers are allocated based on the residual energy of nodes. Nodes with lower energy levels are given priority in selecting subcarriers to minimize their energy consumption. It has flexibility that allows the protocol to be configured according to the specific operating requirements of the underwater network. Compared to CDMA technology, the proposed technique consumes considerably less energy per bit. However, its performance is affected by user diversity and frequency diversity. In (Su et al., 2018) a Glider-MAC (G-MAC) is proposed through dynamic subchannel allocation and power adjustment by Nash equilibrium. This is intended to optimize power of a network. Additionally, a motion prediction method based on the characteristics of an underwater glider is employed to reduce the negative impact of spatial uncertainty. Although G-MAC has proven to be effective in enhancing network goodput and conserving energy within a representative network scenario, resource allocation may be rendered ineffective due to highly dynamic underwater channel conditions in the mission-planning stage. More recent work in (Su et al., 2020b) has proposed an efficient data transmission method for MAC-based OFDMA, by optimizing relay selection and scheduling transmissions to minimize interference and avoid collisions, the protocol significantly reduces energy consumption. In addition, multiple nodes can communicate in parallel within a single communication cycle. This also enhances network throughput, average delay, and delivery rate. Despite this, channel reservations are relatively frequent for each node, which may negatively impact system efficiency. More recently work in (Su et al., 2021) proposed TLAO-MAC as a traffic load-aware solution for UWAN. Utilizing OFDMA addresses the specific operation requirements of distributed UWAN. by dynamically adjusting channel grouping based on traffic load, allocating subcarriers and transmission power according to minimum power requirements, and using optimized control packet exchanges to reduce collisions and retransmissions. Additionally, it continuously monitors channel utilization to prevent network saturation, which leads to minimizing the energy consumption in the distributed network and maximizing throughput. However, a resource negotiation phase with five types of control packets can cause a delay in network response time. Recently, Authors in (Chen et al., 2023a), provided an energy-efficient three-dimensional UWAN protocol named (TDTSPC-MAC), combining time synchronization, power management, clustering, sleep mode, and layering in a hierarchical and distributed clustering algorithm, this mechanism offers efficiency in energy, throughput, and delay. On the other hand, synchronization errors could lead to collisions during data transmission.

4.1.2. Time Division Multiple Access

The data transmission channel is segmented into time slots by TDMA to prevent collisions. This allows each node to only transmit data during the assigned time slot, reducing the likelihood of collisions with other nodes. Therefore, all network nodes must be time-synchronized. Moreover, a guard time separates each time slot, thereby further reducing the probability of collision. The propagation delays in underwater environments are also much longer and more variable than those in terrestrial networks, which is why it is necessary for an underwater scenario to have a longer guard period where propagation delays are much longer and more variable than those in terrestrial networks (Hong et al., 2008), (Islam et al., 2022). Table 3 summarizes energy-efficient underwater MAC based TDMA with comparison.

Spatial Temporal (ST-MAC) in (Hsu et al., 2009) was proposed at the first time in MAC based TDMA to solve spatial temporal uncertainty problem, the protocol minimizes power consumption by using spatial-temporal scheduling to coordinate transmissions and avoid collisions, employing TDMA-based time slot allocation to reduce idle listening and unnecessary active periods, and using conflict graph construction to prevent overlapping transmissions and maximize the throughput. However, despite these strengths, the protocol is not suitable for use in mobile networks. Work in (Chen et al., 2011), a Dynamic Slot Scheduling Strategy (DSSS) based TDMA proposed, prevents collision to reduce power and maximizes channel utilization by utilizing four strategies referred to as grouping, ordering, scheduling, and shifting transmission pairs. However, synchronization must be maintained strictly. In (Alfouzan et al., 2018), Efficient Depth-based MAC (ED-MAC) protocol considers energy efficiency, throughput, fairness, and collision avoidance while using TDMA-based distributed MAC underwater. As well as addressing spatial-temporal uncertainty and hidden terminal problems, ED-MAC arranges the transmission and reception of data packets on both the sender and receiver sides. Each node is periodically awake during the normal operational phase to transmit or receive data during media access. Based on scheduled periods. Power consumption

Table 3
Comparative analysis of energy efficient TDMA-MAC protocols in UWAN.

Protocol	Topology	Range	SYN	Real time	Energy Achievement Techniques	Strengths	Limitations
ST-MAC (Hsu et al., 2009)	Centralized	Short	✓	✓	• Avoid spatial-temporal problem scheduling by conflict graph construction. • Avoid collision by optimized slot allocation mechanism.	• Solve the problem of vertex colouring in a spatial-temporal conflict graph. • Maximize throughput.	• Not suited for mobile networks.
DSSS (Chen et al., 2011)	Centralized	Medium	✓	✓	• Avoid collision and interference by using dynamic slot scheduling.	• Increase transmission pairs without colliding to maximize channel utilization.	• Strict synchronization is required.
ED-MAC (Alfouzan et al., 2018)	Distributed	Short	✓	×	• Sleep mode. • Avoid collision by utilizing depth-based scheduling. • Reducing control overhead by distributed scheduling.	• Effectively optimizes energy consumption. • The protocol significantly mitigates idle listening and reduces unnecessary power usage. • The protocol addresses hidden node challenges and collision avoidance.	• High complexity, two-hop horizontal nodes are detected twice per cycle, reducing channel usage. • Collisions can cause timetable faults during the initial phases.
DL-MAC (Alfouzan et al., 2019a)	Distributed	Short	✓	×	• Sleep mode. • Minimize control message overhead by distributed clustering and layering. • Avoiding hidden and exposed terminal problems	• High reliability and flexibility while conserving energy effectively with low complexity.	• The scheduling mechanism's three-hop limit may exclude distant nodes from the transmission schedule, reducing network coordination.
GC-MAC (Alfouzan et al., 2019b)	Distributed	V.short	✓	×	• Sleep mode. • Avoid collision graph colouring techniques and conflict detection mechanisms.	• Can handle varying traffic rates and numbers of nodes by consuming less power, increasing throughput and packet delivery ratio.	• RPs must be located within the internal cube (e.g., using GPS).
TSPC (Chen et al., 2022)	Distributed	Short	✓	✓	• Power control. • Avoid collision using synchronization.	• TSPC provides energy efficiency and collision avoidance through dynamic power control and time synchronization. • Maximizing throughput and minimize latency.	• Limited for a particular scenario where it may not be suitable or effective in other scenarios.
AMA (Fan et al., 2023)	Cluster Mesh	Medium	✓	✓	• Dynamically power control.	• Incorporate a power and bandwidth joint optimization algorithm improve provide reliable data and energy transmission.	• Precise synchronization for second level cluster.
Wang et al. (2023a)	Centralized	V.short	✓	×	• Power optimization and relay selection.	• The strategic selection of relay nodes effectively distributes energy consumption across the network, thereby maximizing the overall network lifetime.	• Complex optimization processes.

can be minimized when nodes aren't transmitting or receiving packets. However, the complexity of the systems is high and there are double slots per cycle for detecting two-hop horizontal nodes, reducing the consumption of channels. Moreover, a collision could occur during the initial phase, leading to faults in some node timetables. Depth Layering (DL-MAC) protocol proposed in (Alfouzan et al., 2019a), improves reliability, flexibility, and energy conservation with low complexity, by addressing spatial-temporal uncertainty, hidden and exposed terminal problems, and near-far effects. Collision-free transmissions and receptions are achieved by scheduling communication in equal layers. There is less chance of collision between nodes located two layers apart. Nodes can also distribute scheduling information to neighbouring nodes to avoid collisions. Distributed scheduling requires only one-hop neighbouring data, simplifying the protocol. Moreover, the scheduling packet only reaches nodes within three hops of the immediate neighbourhood, potentially limiting its reach to faraway nodes. Moreover, Graph Colouring (GC-MAC) for UWAN introduced in (Alfouzan et al., 2019b), where duty cycle mechanism used within combination with a graph colouring approach to allocating a distinct timeslot or colour to each node within a two-hop neighbourhood. In addition, a conflict detection mechanism has been implemented to save power. In contrast to another reservation-based contention-free MAC protocol, GC improved throughput, energy consumption, Ratio of packets delivered and fairness index by varying the load offered. However, RPs must be located within the internal cube (e.g., by GPS). In (Chen et al., 2022), Time Synchronization and Power Control (TSPC) MAC implemented to limit communication range of the node. The TSPC protocol introduced a joint channel access scheme to synchronize time and power. Central nodes are deployed on an offshore seabed as synchronization references and maintain standard time across the network. This solution can effectively prevent communication collisions, maximize data rate, and reduce UWAN energy consumption with less synchronization error only in particular scenarios near to coast where the cable is used to communicate between central nodes and the ground station. More recently in (Fan et al., 2023) Adaptive Mobile Access (MA-MAC) is proposed for static and mobile UWAN. It eliminates traditional handshakes by utilizing long propagation delays for mobile node access, reducing energy consumption. Additionally, it dynamically optimizes power and bandwidth allocation based on distance, energy levels, and data priority in the network and maximizes throughput. However, AMA protocol may face challenges in maintaining precise synchronization. Recently, an energy-efficient multimode MAC is proposed in (Wang et al., 2023a) by dynamically switching between direct and relay-assisted transmission modes. It optimizes transmission power based on node distance and energy levels, balancing energy consumption across the network by selecting relay nodes strategically reduces power requirements and prevents premature energy depletion.

4.1.3. Code Division Multiple Access

A CDMA network allows multiple sensor nodes to be communicating simultaneously in a specific frequency band by spreading code assignments and controlling power, increasing network throughput, and making it more resistant to frequency fading. In order to maximize channel utilization and decrease packet retransmission requirements, this method enables destination nodes to identify and differentiate between signals transmitted concurrently by multiple sensor nodes (Bernard et al., 2022). An overview of energy-efficient underwater MAC based CDMA with comparisons is presented in Table 4.

A Distributed Power Control-based MAC (DPC-MAC) protocol proposed in (Wei et al., 2008), addresses the near-far problem in UWAN by dynamically adjusting transmission power and spread code length using a novel closed-loop distributed mechanism. This approach enhances energy efficiency and network throughput while optimizing communication performance. Additionally, it improves the traditional RTS-CTS handshake mechanism and leverages CDMA for channel access. Simulation results demonstrate superior energy efficiency and throughput compared to traditional MAC protocols. However, the protocol remains complex and lacks the inherent security features. Similarly, distributed CDMA-based UW-MAC protocol in (Pompili et al., 2009) proposed, effectively operating in both deep and shallow water environments. It

Table 4
Comparative analysis of energy efficient CDMA-MAC protocols in UWAN.

Protocol	Topology	Range	SYN	Real Time	Energy Achievement Techniques	Strengths	Limitations
DPC-MAC (Wei et al., 2008)	Distributed	Short	×	×	• Dynamic power adjustment during a closed loop.	• Using distributed power control and advanced handshake algorithms, the protocol can effectively manage energy consumption and optimize network performance.	• High level of complexity and not secure.
Pompili et al. (2009)	Distributed	Short	×	×	• Dynamic power adjustment during a closed loop distributed algorithm. • Optimize code length.	• It enhances security while conserving power.	• High level of complexity of dynamic adjustments.
CDMA-MAC (Kim et al., 2009)	Centralized-Tree	Short	×	×	• Power control. • sleeping mode.	• Saved energy and reduced latency by relaying receive packets immediately.	• Efficiency is impacted by the near-far problem.
POCA-CDMA (Chen et al., 2013)	Centralized	Short	×	×	Optimize code length.	• With shortened spreading sequences and simultaneous reception of data from multiple paths, the protocol increases data transmission efficiency and reduced delays.	• Near far problem, high complexity and scalability.
Du et al. (2015)	Distributed	Short	×	×	• Dynamic power control. • Optimize code length. • Avoid collision by eliminates the need for handshaking.	• Handshake removal reduces delay and energy consumption as well as increasing network throughput and delivery ratio in loaded networks.	• High complexity and not suitable for mobile nodes.
MC-CDMA-PSO (Nie et al., 2016)	Centralized	Short	×	×	• Dynamic power control by PSO. • Minimizing the near-far by considering SINR.	• Controlling power while considering underwater acoustic channel characteristics can mitigate the near-far effect.	• Not suitable for high density of nodes.
MC-CDMA-GA (Zhen et al., 2016)	Centralized	Short	×	×	• Dynamic power control by GA. • Selective subcarrier power distribution. • Minimizing the near-far by considering SINR.	• A genetic algorithm gets better BER performance and consume less power.	• latency and not suitable for larger networks.

employs a closed-loop distributed mechanism to optimize transmit power and code length, mitigating the near-far effect to save power and enhancing multi-user communication. By utilizing chaotic codes, the protocol provides robust security and equitable bandwidth distribution. Although UW-MAC achieves high throughput, low delay, and energy efficiency, its complexity poses a challenge for practical deployment. In (Kim et al., 2009) a novel MAC approach based on CDMA proposed, achieves power efficiency by employing a periodic sleeping mode and staggered wake-up schedule to minimize idle listening and reduce unnecessary energy consumption. Additionally, it dynamically controls transmission power to maintain constant received signal strength at parent nodes, ensuring efficient energy usage. By using orthogonal codes in a CDMA framework, the protocol allows simultaneous transmissions with minimal interference, reducing power wastage and optimizing overall network energy consumption. However, the efficiency could be impacted by the near-far problem. Authors in (Chen et al., 2013) introduced Path-Oriented Code Assignment (POCA) CDMA MAC, assigns specific spreading sequences to nodes along the same path and coordinates transmissions following a round-robin schedule, allowing the sink to receive data simultaneously from multiple paths. It reduces spread codes and minimizes packet collisions, thereby improving energy efficiency, increasing throughput, and decreasing end-to-end delay. However, there is a near-far problem with a high level of complexity. More recently work in (Du et al., 2015) has proposed the state-based MAC protocol for UWAN utilizes a hierarchical and distributed code assignment algorithm to minimize conflicts among spread codes. By maintaining neighbour tables with a state field and eliminating the need for RTS/CTS handshaking, the protocol improves channel utilization and prevents interference caused by concurrent transmissions to the same node. Power control mechanisms are implemented to reduce the near-far effect of CDMA systems. Extensive evaluations indicate that the protocol achieves outstanding throughput, delivery ratio, and resource utilization, demonstrating its high efficiency and effectiveness. However, this protocol is not suitable for mobile nodes because it is complexity. More recently, in (Nie et al., 2016) Multicarrier CDMA Particle Swarm Optimization (MC-CDMA-PSO) used power control to optimize power allocation, reduce energy consumption, and mitigate the near-far effect. PSO is employed due to its high computational efficiency, and simplicity. The protocol utilizes a fitness function at the receiver that balances power consumption and signal-to-interference-plus-noise (SINR), dynamically adjusting power levels based on node distances to maintain signal quality and minimize energy use, and overall performance are improved. However, it may not be suitable for mobile network. Similarity work has been proposed in (Zhen et al., 2016), Multicarrier CDMA Genetic Algorithms (MC-CDMA-GA) that combines the advantages of OFDM and CDMA, such as high spectrum utilization efficiency, strong anti-multipath interference ability, and multiple access capability. The proposed power allocation scheme aims to optimize energy consumption and (SINR) by GA that explores a vast solution space for optimal power allocation. Based on the numerical results, the proposed power allocation scheme is effective compared to conventional power allocation methods where it reduces energy consumption and increases bit-error-rate performance. It also outperforms a frequency-domain power adaptation scheme. However, high computational complexity could lead to latency and limited scalability in larger networks.

In summary, Contention-free MAC protocols in UWAN improve efficiency by distributing network resources including frequency, time, and code without competition. In FDMA, the frequency band is divided into fixed-size sub-bands, each allocated to a single signal. This approach facilitates collision-free and simultaneous transmissions, enabling a higher channel multiplexing rate and more efficient multiplexing channels. Additionally, it facilitates convenient branching of data and control frame transmissions. FDMA with orthogonal sub bands (OFDMA) further enhances spectral efficiency by allowing adjacent sub bands to overlap in an orthogonal manner. FDMA however requires synchronization between the receiver and transmitter frequencies, but not for the entire network. One limitation is the increased bandwidth consumption due to guard bands, which accommodate transmission uncertainties. Most of the FDMA-based MAC protocols in Table 2 are designed for short to medium communication ranges, except for NOGO-MAC, which supports long range communication. This is achieved by optimizing frequency allocation for each distance (grouping frequency), making the protocol suitable for extended ranges. Most FDMA-based MAC protocols incorporate power control mechanisms to minimize energy consumption and utilize subcarrier allocation strategies to prevent collisions across different topologies. Additionally, to these techniques, JRSPA-MAC protocol allocates subcarriers to nodes based on their residual energy levels in centralized multi-hop setting to extend network lifetime. Furthermore, TDTSPC-MAC protocol integrates a sleep mode to further reduce energy consumption and improve network lifetime. In contrast, G-MAC protocol enhances power efficiency for mobile networks by leveraging motion prediction, enabling mobile nodes to optimize power consumption during their movement underwater. Regarding real-time application suitability, most protocols effectively support real-time communication by assigning distinct frequencies to each node, allowing parallel transmissions, and reducing delays. However, TLAO-MAC may not be ideal for real-time scenarios due to the use of additional control packets, which can introduce transmission delays and compromise timely data delivery.

For TDMA, time is split into distinct slots, and each node is assigned a specific slot for signal transmission. Although TDMA allows multiple users to utilize a channel effectively, it requires accurate synchronization to ensure that each node transmits at the correct time. In addition, the number of carrier channels is limited. The TDMA protocol also includes guard times between slots as a means of avoiding signal overlap. These guard times are set based on the delay between signals. However, TDMA can present some challenges, including adjusting the timing between slots and managing the maximum signal propagation delay. As outlined in Table 3, TDMA-based MAC protocols employ diverse strategies to achieve energy efficiency between short and medium ranges only, protocols such as ED-MAC, DL-MAC, and GC-MAC operate within a distributed topology, while ST-MAC utilizes a centralized topology. These protocols optimize energy consumption without requiring strict synchronization by employing advanced scheduling mechanisms, and some, such as ED-MAC, DL-MAC and GC-MAC incorporate sleep modes for additional power savings. ED-MAC and DL-MAC also reduce control overhead through network segmentation using depth-based division for ED-MAC and layered structuring for DL-MAC to address spatial-temporal uncertainties and mitigate hidden and exposed terminal issues. In addition, GC-MAC, and ST-MAC only TDMA protocols apply graph colouring techniques to avoid collisions, with ST-MAC specifically designed to manage spatial-temporal conflicts effectively in underwater communication environments. On the other hand, protocols such as DSSS, TSPC, AMA, and (Wang et al., 2023a) rely on time-slot allocation with synchronization to prevent collisions. Certain protocols such as TSPC, AMA and (Wang et al., 2023a) incorporate additional strategies such as dynamic power control to further reduce energy. In addition protocol in (Wang et al., 2023a) distinguishes itself by using relay selection to efficiently distribute energy consumption across the network, thereby extending overall network. In terms of real-time suitability, only ST-MAC, DSSS, TPSC, and AMA are suitable for real-time applications as they avoid complex power management mechanisms that introduce additional processing delays. On the other hand, protocols such as ED-MAC, DL-MAC, and GC-MAC are less suitable for real-time applications due to their reliance on complicated processes, such as depth-based layering and graph colouring in distributed topologies. Unlike ST-MAC, which uses a simpler graphical construction in a centralized topology, these protocols face delays from their complex scheduling and coordination methods. Additionally, the protocol in (Wang et al., 2023a) employs a sophisticated power optimization process and relay selection, which could further contribute to delays, making it less ideal for real-time applications.

CDMA based MAC, spread spectrum techniques are employed to enable simultaneous data transmissions. A unique spreading code is assigned to each node, which facilitates concurrent communication as well as enhances the security of the transmissions. It is especially effective in mitigating multipath fading and resisting interference, which results in a high level of frequency utilization. However, the protocol requires the assignment of pseudo-random codes to every node, and it presents the issue of near-far problems, in which signals from nearby nodes may overpower those from further away, posing challenges in maintaining balanced communication.

Table 4 shows that all CDMA-based energy-efficient MAC protocols are limited to short-range communication, indicating that CDMA MAC protocols are generally not suitable for medium or long-range communication because of the limitations discussed previously. While most CDMA-based MAC protocols use power control to adjust transmission power, POCA-CDMA-MAC use another technique without power control. By optimizing the number of spreading codes required, protocols such as (Pompili et al., 2009), POCA-CDMA-MAC and (Du et al., 2015), the near-far effect is mitigated and energy consumption is reduced. By including SINR in optimization algorithms, MC-CDMA-PSO and MC-CDMA-GA protocols further minimize the near far effect and increasing energy efficiency. For real-time suitability, energy CDMA-based protocols listed in Table 4 are generally not suitable for real-time applications due to their inherent limitations. While these protocols attempt to mitigate the near-far effect, the complexity of their approaches, such as code length adjustments, can introduce latency, reducing their effectiveness in time-sensitive scenarios. Although protocols in (Pompili et al., 2009) and (Du et al., 2015) achieve lower delays than contention-based protocols such as ALOHA and CSMA, the additional computational overhead still presents challenges for real-time communication. Furthermore, while CDMA-MAC incorporates simple energy-saving techniques, its performance can be compromised by the near-far effect, further diminishing its suitability for real-time applications.

4.2. Contention based

This approach involves each node competing for the use of a common channel so that other nodes might not be able to use that channel. Depending on who decides who gets to use a channel, contention-based MAC protocols can be categorize as either random access protocols or protocols that require handshaking.

4.2.1. Random access

The core idea underlying random access MAC protocols is to permit nodes to send their data whenever they have information to transmit, all without the necessity for a central entity to manage or arrange their transmissions in a synchronized manner. Table 5 summarizes energy-efficient underwater Random-Access MAC protocols with comparisons.

Authors in (Park and Rodoplu, 2007) proposed a distributed, scalable, and energy-efficient MAC protocol UWAN-MAC. The protocol uses sleep mode that consumes less power than idle listening mode. To maintain synchronization, the protocol uses relative time stamps. However, it is not suitable for mobile nodes and low latency applications. Moreover, two ALOHA protocols proposed in (Chirdchoo et al., 2007) ALOHA-CA and ALOHA-AN adopt a distributed network architecture, Both protocols can significantly reduce collisions and boost the network capacity. ALOHA-CA is simpler and more scalable, while ALOHA -AN requires more resources but can provide better performance by using additional NTF packets to avoid collisions. More recently T-Lohi protocol proposed in (Syed et al., 2008), detect collisions and count contenders, T-Lohi uses a low-power wake-up receiver to significantly reduce energy consumption Additionally, T-Lohi utilizes a novel tone-based contention resolution mechanism that exploits space-time uncertainty and high latency. However, during every contention round, it is necessary for a node to remain idle and monitor the channel. More recently,Authors in (Khater et al., 2016) introduced Slotted-CS-ALOHA protocol aims to enhance ALOHA performance by conserving energy through dual-buffer usage. It consists of three stages: buffer evaluation, time slot and channel assessment, and packet transmission with ACK confirmation. While reducing energy consumption, improving throughput, and lowering dropped nodes, it encounters delay

Table 5
Comparative analysis of energy efficient random-access MAC protocols in UWAN.

Protocol	Topology	Range	SYN	Real Time	Energy Achievement Techniques	Strengths	Limitations
UWAN-MAC (Park and Rodoplu, 2007)	Distributed	V.Short	✓	×	• Sleep mode. • Minimize control overhead.	• Demonstrate the attainment of a locally synchronized schedule even when confronted with prolonged propagation delays.	• Not suitable for mobile and low latency applications.
ALOHA-CA ALOHA-AN Chirdchoo et al. (2007)	Distributed	Medium	×	×	• Avoid collision.	• a notable augmentation of network throughput while effectively mitigating collision issues.	• High levels of offered load present a challenging scenario, especially with ALOHA-AN.
T-Lohi (Syed et al., 2008)	Distributed	Short	×	×	• Sleep mode.	• Address the issue of uncertain data reservation in space-time through the utilization of concise wake-up tones.	• Mandate nodes to be inactive and monitor the channel during each contention round.
Slotted-CS- ALOHA (Khater et al., 2016)	Distributed	V.Short	×	×	• Slot status checking. • Buffering packets. • Sleep mode.	• Effectively decreases energy usage, particularly in densely populated networks.	• Delay issue arises due to utilization buffer before the ALOHA cycles.
Slotted-Buffering-ALOHA (Badawy et al., 2020)	Distributed	V.Short	×	×	• Slot status checking. • Buffering packets.	• It has energy efficiency, reduced delay, and improved throughput compared with Slotted-cs-ALOHA (Khater et al., 2016) due to optimal data transmission scheduling and intelligent buffer management.	• The cost arises due to its complexity.
Buffering-Slotted-ALOHA (Khater et al., 2021)	Cluster	V.short	×	×	• Slot status checking • Buffering packets. • Sleep mode.	• Performs particularly well in scenarios with high node density.	• Requires extra resources and infrastructure.

issues due to buffer inclusion before ALOHA cycles. Despite these benefits, the protocol struggles to effectively mitigate average delay because it comprises three stages, each with a buffer entry, it leads to extended time consumption. Similarly, in (Badawy et al., 2020), a novel approach called Slotted-Buffering-ALOHA protocol. By employing a buffering mechanism, this protocol enables the aggregation of multiple packets for retransmission on behalf of a node in the event of a missing ACK. Moreover, the use of carrier sensing verifies that the channel is clear of data, preventing collisions during communication and conserving power. Despite this protocol reduced data collision, energy consumption, average delay, and enhancing the throughput rate it needs more conditions to ensure that the collision does not occur, Therefore, the system may become more complex and may require more resources to implement, which may result in an increase in costs. Similarly, but in cluster approach, Buffering-Slotted-ALOHA protocol proposed in (Khater et al., 2021), utilizes an adapted buffer to retransmit data in case of missing ACK. The network is structured into closed clusters to minimize node movement. Each closed cluster comprises smaller clusters, reducing traffic and collisions to save power. Nodes within small clusters make transmission choices based on slot status for uw-sink or uw-main sink, enhancing efficiency spatially in a dens network. However, implementing this protocol requires additional resources and infrastructure due to the division of the network into closed clusters, each containing smaller clusters with specific node counts.

4.2.2. *Handshaking*

In communication protocols, handshake refers to a procedure in which the transmitting device must first establish control over the channel on which it intends to transmit the information before it may transmit data. The purpose of this preparatory step is to ensure that data will be transferred in a clear path that minimizes data collisions or interference (Lin and Chen, 2016). Fig. 3 presents a sequence diagram of a handshaking protocol involving a sender and a receiver. This diagram outlines the transmission sequence of Request to Send (RTS), Clear to Send (CTS), DATA, and Acknowledgment (ACK) packets. Additionally, it illustrates Network Allocation Vector (NAV) intervals, which are designated quiet times during which transmissions from other nodes are paused to prevent collisions. A comparison of energy-efficient underwater handshaking MAC protocols is presented in Table 6.

Slotted Floor Acquisition Multiple Access (Slotted FAMA) is presented in (Molins and Stojanovic, 2006) to solve the problem of hidden and exposed terminals. It achieves this by using a slotted TDMA approach, where time is divided into slots, and each node is assigned a specific slot for transmission. This approach ensures that only one node transmits at a time, enhancing power consumption by eliminating collisions. The protocol is designed to work in fully connected networks with small propagation delays and provides improved throughput and delay performance. However, it requires synchronization among nodes, and a fixed number of nodes, and may not be suitable for networks with high mobility or changing topology. In (Xie and Cui, 2007) Authors introduced an Reservation based (R-MAC), that ensures fairness through a contention-based approach combining

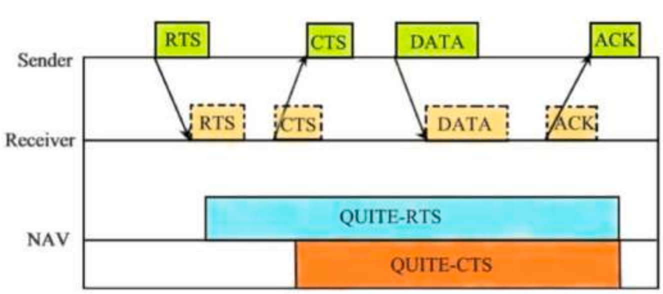

Fig. 3. Handshaking protocol sequence diagram.

random access and collision avoidance techniques. It also mitigates the exposed terminal issue associated with RTS/CTS-based protocols using scheduling algorithms at both the sender and receiver, which effectively mitigate the impact of high propagation delays and completely avoid collision to save power. However, implementing scheduling algorithms to completely prevent data packet collisions may require substantial resource consumption. More recently in (Peleato and Stojanovic, 2007), The Distance Aware Collision Avoidance protocol (DACAP) is introduced as a non-synchronized approach that optimizes hand-shake duration by tailoring it to different receivers, aims to save energy, prevent collisions by minimizing hand-shake duration and utilizing interference tolerance between closer nodes within the transmission range. However, it would not be appropriate to apply this method to a scenario in which many nodes are involved or topologies are highly dynamic. COPE-MAC in (Peng et al., 2010) uses parallel reservation and cyber carrier sensing techniques to reduce collision and save energy. By combining multiple data transmissions into a single handshake, parallel reservation optimizes channel usage and throughput. Cyber carrier sensing enables nodes to detect potential collisions in advance based on virtual channels mapped from physical channels. Compared to traditional handshake-based protocols, this mitigates propagation delays. Although it is better than FAMA and UWAN in term of energy consumption and eliminates the requirement for strict synchronization, parallel reservation techniques can increase latency, especially when multiple nodes compete for the same channel. Additionally, resource-constrained underwater acoustic systems might find it challenging to use cyber carrier sensing. In (Su and Jin, 2016) Underwater Multi-channel MAC (UMMA) has been proposed that uses a reservation-based handshake mechanism to minimize the energy wasted on retransmissions and avoid collisions. Additionally, the protocol utilizes a packet train scheme, which allows multiple packets to be transmitted within a single handshake, thus reducing control overhead. Furthermore, UMMAC utilizes a distributed power control algorithm, which enables nodes to dynamically adjust their transmission power based on real-time conditions. However, it could be reliant on a fixed slot length, which may not always be optimized for varying network topologies. This could lead to suboptimal performance in certain situations. More recently, a Full-Duplex Collision Avoidance MAC (FDCA) in (Li et al., 2016a) is proposed to efficiently utilize propagation delay in RTS/CTS-based protocols to improve network throughput. The protocol permits multiple packets concurrently in the underwater channel, reducing collisions in channel contention by imposing wait times on control packet transmissions which leads to saving energy. The simulation results presented confirm that the FDCA protocol outperforms the FDMAC protocol (Zhang et al., 2013) in terms of network throughput and energy. However, its power consumption is higher at low data rates compared to ALOHA when it comes to looking at low data rates. Similar to work (Su and Jin, 2016), the Cooperative Underwater Multi-Channel MAC (CUMAC-CAM) protocol proposed in (Rahman et al., 2019), aims to maximize the rate of successful transmission and overcome triple hidden terminal problems that reduce power. Delay mapping and channel allocation assessment are used to achieve this goal. Every node maintains a delay mapping database, which helps predict packet collisions. However, CUMAC requires additional memory allocation for maintaining the channel allocation matrix and delay map in addition to lacking a channel allocation assessment strategy to control packet transmission. Recently, Power Control handshake (PC-MAC) (Wang and Zhao, 2020), which uses a power control algorithm to adjust transmission power and a handshake mechanism to establish links between nodes, although this protocol significantly improved energy efficiency compared to DACAP in (Peleato and Stojanovic, 2007), it may not be suitable scenarios with a high density of nodes due to potential efficiency reduction caused by inherent latency from power control adjustments and handshake processes.

In summary of contention-based MAC underwater, random access protocols enable unscheduled data transmission in underwater

Table 6
Comparative analysis of energy efficient handshaking MAC protocols in UWAN.

Protocol	Topology	Range	SYN	Real Time	Energy Achievement Techniques	Strengths	Limitations
Slotted FAMA (Molins and Stojanovic, 2006)	Mobile	Medium	✓	×	• Avoid collision by slotted time.	• Reducing control packet lengths within time slots enhanced power efficiency.	• Require synchronization and may be not suitable with high mobility.
R-MAC (Xie and Cui, 2007)	Centralized	Short	×	×	• Schedules the transmissions of the control packet. • Burst-based acknowledgment. • Fairness and collision avoidance.	• Combining random access and collision avoidance techniques can completely avoid collisions.	• may require more computational resources.
DACAP (Peleato and Stojanovic, 2007)	Ad hoc	Medium	×	×	• Optimize handshake duration. • Reduces the overhead.	• DACAP reduces collisions by taking advantage of the fact that a receiver encounters less interference when two nodes are close together.	• Not suitable for scenarios involving many nodes or highly dynamic network topologies.
COPE-MAC (Peng et al., 2010)	Multi-hop	Short	×	×	• Parallel reservation reduces handshakes. • Cyber carrier sensing prevents collisions.	• Ideal for large networks with long inter-node distances.	• Due to parallel reservation techniques, latency increases. In addition, resource-constrained underwater acoustic systems might struggle with cyber carrier sensing.
UMMAC (Su and Jin, 2016)	Multi hop	Short	✓	×	• Power control • Reduces control overhead by employing a packet train scheme.	• Network performance is greatly improved by hosts negotiating channels and controlling power in a distributed manner.	• Fixed slot lengths may not always be optimized for varying network topologies. In some cases, this could result in suboptimal performance.
FDCA (Li et al., 2016a)	Multiple	Short	✓	×	• Avoid collision by concurrent handshakes in full-duplex communication.	• Wait times on control packets reduce channel contention and maximize throughput by using full-duplex modems.	• It tends to consume more power at low data rates compared to ALOHA.
CUMAC-CAM (Rahman et al., 2019)	Multi hop	V.short	×	×	• Minimizing collision by channel allocation matrix delay map.	• Mapped delay and channel allocation assessment maximize successful transmission rates and overcome triple-hidden terminals.	• requires additional memory and lacks a channel allocation assessment strategy.
PC-MAC (Wang and Zhao, 2020)	Mobile Ad hoc	Medium	×	×	• Power control.	• Power control reduces data transmission power after the handshake.	• May not be suitable for environments with a high density of nodes.

networks, increasing the flexibility and energy efficiency of the network. Because there is no scheduled access to these protocols, this may result in an increase in collisions and congestion on the network. In Table 5, most energy-efficient random access MAC protocols demonstrate effectiveness only over short ranges, except ALOHA-CA and ALOHA-AN, which support medium ranges of up to approximately 3 km. This indicate that random access MAC protocols are generally not suitable for long-range communication. One of the key power saving techniques employed by these protocols is the reduction of collisions, which occur due to random channel access. This is achieved through buffering mechanisms, where packets are queued until the channel becomes free. Protocols such as Slotted-CS-ALOHA, Slotted-Buffering-ALOHA, and Buffering-Slotted-ALOHA utilize this technique to avoid collisions. However, buffering mechanisms can introduce additional delays, making these protocols less suitable for real-time applications. Furthermore, while some protocols implement only sleep modes, such as T-Lohi, or attempt to minimize control overhead, such as UWAN-MAC, these strategies may still result in increased latency. Especially in distributed network topologies, where coordination is required for these techniques, this can increase delay of data transmission, further limiting their applicability for time-sensitive tasks.

Handshake protocols ensure a clear communication channel before data transmission, minimizing data collisions and interference. The energy handshake MAC protocols presented in Table 6 aim to reduce handshaking overhead through various strategies. One approach involves enabling parallel transmissions using techniques such as parallel reservation, multi-channel communication, or full-duplex systems. Protocols include Cope MAC, UMMAC, CUMAC-CAM, and FDCA leverage these methods to allow nodes to handshake without collisions. Alternatively, protocols such as Slotted-FAMA and DACAP focus on reducing control overhead. Slotted-FAMA achieves this through time-slotting techniques, while DACAP optimizes handshaking duration to improve efficiency. R-MAC, on the other hand, schedules control packet transmission in a centralized topology to streamline communication. Power control is utilized in only two protocols, UMMAC, where it is combined with other methods, and PC-MAC, where it operates independently to manage energy consumption. Although handshaking protocols offer many benefits, such as reducing collisions and improving communication reliability, they also present certain challenges, especially in dense network environments or long-range communication scenarios. Handshake-based MAC protocols are not suitable for long-range communication, as shown in Table 6. Communication channel availability is checked during handshaking, which can introduce delays. When timely data transmission is critical, delays become more pronounced. Therefore, previous handshaking MAC protocols are unsuitable for real-time applications.

4.3. Hybrid MAC protocol

A hybrid MAC protocol is defined as a combination of several different medium access protocols, including contention-based and contention-free protocols. It can be excellent for improving UWAN performance by utilizing the strengths and avoiding the weaknesses of each type of protocol. Table 7 summarizes all the research related to energy-efficient hybrid MAC and their comparison.

A Hybrid MAC (H-MAC) in (Kredo and Mohapatra, 2007) is one of the first energy-efficient MACs developed underwater where the communication frame is divided into scheduled and unscheduled

Table 7
Comparative analysis of energy efficient Hybrid-MAC protocols in UWAN.

Protocol	Topology	Range	Hybrid MAC Technique	SYN	Real Time	Energy Achievement Techniques	Strengths	Limitations
H-MAC (Kredo and Mohapatra, 2007)	Central	Medium	TDMA + Contention based	✓	×	• Eliminate packet collisions by scheduled slots.	• Achieve low power consumption while combining the benefits of a random-access protocol and contention-free protocols.	• It is possible that it may not work optimally in dense networks.
PLAN (Tan and Seah, 2007)	Distributed	Short	CDMA + Handshaking	×	×	• Reduce collision by assigning unique codes to different nodes.	• Reducing control packets and include timers to control access to the shared wireless channel led to minimizing power consumption.	• It may not be suitable for real-time monitoring, control systems or high ambient noise.
ERCAMAC (Zenia et al., 2015)	Cluster	Short	TDMA + Handshaking	✓	×	• Reducing direct transmissions and unnecessary communication between distant nodes by cluster approach.	• It has higher energy efficiency than CSMA/CA and M-FAMA because it uses sleeping mode.	• Large and mobile networks might not suit this solution.
MC-UWMAC (Bouabdallah et al., 2018)	Distributed	Short	TDMA + Handshaking	✓	×	• Reduce control overhead.	• Control and data packets can be transmitted simultaneously, improving network performance. As well as light loads, the protocol handles heavy loads.	• Quorum-based data channel allocation may not be optimal for highly dynamic traffic patterns networks.
Zhang et al. (2020)	Distributed	Short	TDMA + Handshaking	✓	×	• Reduce control overhead.	• Using a greedy algorithm to optimize the transmission schedules for both control and data packets reduces the number of collisions and retransmissions in the network.	• As a result of the TDMA-based handshaking method, the end-to-end delay is larger.
RE-MAC (Gazi et al., 2022a)	Centralized	V.Short	TDMA + Contention based	✓	✓	• Sleep mode.	• Handles different types of traffic, from delay-sensitive to less critical while saving energy.	• Restrict synchronization.

periods in order to combine the advantages of scheduled and random access protocols. In the scheduled segment, TDMA is utilized, whereas in the unscheduled segment, slots are allocated for random access. Combining these two techniques improves energy efficiency when nodes communicate without collisions and guarantee a certain data rate during scheduled frames. As well, nodes can adapt to dynamic underwater environments in the unscheduled portion. However, the H-MAC is not appropriate for dense or heavily loaded networks due to the high probability of collisions. Authors in (Tan and Seah, 2007) proposed a distributed CDMA-based MAC protocol PLAN designed to provide an efficient and effective way to coordinate access to the shared communication channel in half-duplex UWAN. CDMA is used as the underlying multiple access technique in PLAN to reduce multipath and Doppler effects that are inherent in underwater physical channels. Prior to data transmission, the protocol includes an RTS-CTS handshaking procedure, which minimizes energy consumption at sensor nodes while maintaining high throughput performance. Using handshaking, however, can introduce additional latency and overhead to the system. In addition, CDMA might not be suitable for high ambient noise in underwater acoustic environments. Authors in (Zenia et al., 2015) proposed ERCAMAC protocol which is an energy-efficient, reliable, cluster-based adaptive MAC protocol. It uses TDMA and burst-based CTS/ACK mechanisms to reduce energy waste and improve reliability. The protocol can adaptively change its sleeping and working periods based on traffic load, which reduces energy consumption and fairness problems. It also removes the exposed terminal problem of CSMA/CA. However, this solution may not be suitable for mobile and large networks. Authors in (Bouabdallah et al., 2018) introduced a multi-channel MAC protocol (MC-UWMAC) that uses TDMA and handshaking mechanisms to achieve a collision-free communication in UWAN. The protocol uses a single slotted control channel for handshaking, and the control channel is divided into a grid of slots. Due to its simultaneous use of all data channels, it achieves higher throughput than MM-MAC (Chao et al., 2012), as well as being energy-efficient because no additional control packets are exchanged. However, if the topology of a network is highly dynamic or changes frequently, quota-based allocation of data channels may not be optimal. More recently, authors in (Zhang et al., 2020) a collision-free hybrid MAC protocol based on pipeline parallel transmission for distributed multichannel that utilizes TDMA-based handshakes in dedicated control channels for multiple successful handshakes in a transmission cycle. Data packets are transmitted across multiple channels to ensure high network throughput. The protocol minimize power by using replication computation to reduce control overhead. Although, the proposed protocol is superior to the SFAMA (Molins and Stojanovic, 2006), ROPA (Ng et al., 2013), and DSCT (Zhang et al., 2019a) protocols in terms of throughput, packet delivery rate, and energy consumption. However, has a large average end-to-end delay due to the four pipeline stages in a transmission cycle. Recently, authors in (Gazi et al., 2022a) proposes an energy efficient hybrid RE-MAC for multimedia communication in underwater environment. The hybrid MAC protocol utilizes Transmission Opportunity (TXOP) to enable efficient multimedia streaming and employs a sleep mode for stations nodes, ensuring that nodes are active only when needed for communication. This minimizes the power consumption of nodes and makes this protocol energy efficient.

Overall, Hybrid MAC protocols represent a comprehensive solution for underwater communication, enhancing throughput and optimizing energy usage. They skilfully integrate different medium access strategies to leverage the advantages of each method, ensuring more efficient network performance. Most energy-efficient hybrid MAC protocols in Table 7 use a combination of TDMA and contention-based mechanisms to reduce collisions and control overhead, ultimately conserving power. However, an exception is the PLAN protocol, which employs CDMA to optimize code usage for energy savings. Most protocols aim to conserve power by employing hybrid techniques that help avoid collisions and reduce control overhead. In terms of real-time suitability, most protocols in Table 7 are not ideal for real-time applications due to challenges such as increased latency and the complexity of managing multiple access methods. Furthermore, these protocols are not well-suited for long-distance communication. On the other hand, RE-MAC shows potential for real-time applications, particularly in very short-range communication, where it can prioritize delay-sensitive traffic while conserving power using a sleep mode.

4.4. Cross layer MAC protocols

In these types of protocols, the physical layer, network layer, and MAC layer are all integrated as illustrated in Fig. 4, to benefit from several features. These features include enhanced flexibility, improved energy efficiency, higher reliability, higher bandwidth, and reduced end-to-end delays (Bhaskarwar and Pete, 2021). Research works on energy-efficient cross-layer MAC and their comparative analysis is summarized in Table 8.

Authors in (Sun et al., 2015) proposed VBF-improved cross-layer protocol for UWAN, optimizes energy efficiency and reliability by incorporating both location and residual energy of nodes to make forwarding decisions. It reduces unnecessary transmissions through hop-by-hop forwarding and balances energy consumption across the network. The protocol operates distributed without synchronization, making it scalable and energy efficient. However, inaccurate, or unreliable location information could lead to suboptimal routing decisions and reduces the network performance. By using a cross-layer vector--based forwarding approach. Similarly, An architecture for cross-layer UWAN

for monitoring marine environments is proposed in (Mythrehee and Julian, 2015). As part of this architecture, depth-based routing, holding time management, and opportunistic localization. It reduces unnecessary transmissions and conserves power through optimized routing. While this mechanism consumes less energy than VBF (Xie et al., 2006), it may introduces delays due to holding time management, which causes packets to be held before transmission, and depth-based routing, which slows down data forwarding by limiting it to specific nodes based on depth. Moreover, in (Li et al., 2016b), a Depth-based Routing MAC (DBR-MAC) was introduced, which combines depth-based routing with MAC layer control to improve data collection and energy efficiency. A depth-based backoff mechanism is used to reduce collisions and retransmissions by forwarding packets from deeper nodes to shallower ones. In addition to this, it is superior to M-FAMA (Han et al., 2013), DOTS (Noh et al., 2014), and S-FAMA (Molins and Stojanovic, 2006). However, DBR forwards packets based exclusively on the depth of nodes, which may result in suboptimal routing paths that are longer than necessary. Moreover, authors in (Prajapati and Trapasiya, 2016), proposed cross layer that calculates propagation loss and predicts the location of nodes at the physical layer. Additionally, it manages buffer space and transmission at the MAC layer, and at the network layer, it selects the next hop based on residual energy, mobility, and depth. By coordinating these layers, the protocol reduces energy consumption, increases transmission efficiency, and extends the life of the network. However, managing buffer space and selecting the next hop based on residual energy, mobility, and depth, may introduce delays. Authors in (Koseoglu et al., 2015) proposed a cross-layer optimization approach to minimize energy consumption by compensating for the physical layer disadvantages of distant nodes while accounting for the unique transmission properties of the underwater environment. ALOHA protocol is used as the MAC layer and an energy-optimal channel access rate is calculated analytically. This approach reduces energy consumption per bit and increases data transfer until the first node fails. As a result, the network lifetime is extended, and energy consumption is more homogeneous. However, due to ALOHA MAC that used, it may not be suitable to other MAC protocols or networks with different traffic patterns. A cross-layer protocol stack is presented in (Dhongdi et al., 2017), combines functionalities from the physical, MAC, and network layers to minimize power consumption. The key techniques include dynamic power management, where nodes adjust their transmission power based on distance, and Cluster-Head (CH) rotation, where the CH role is rotated among nodes based on their residual energy to evenly distribute energy usage. Additionally, sleep-wake cycles further reduce energy consumption, the protocol stack is designed with the assumption that the nodes are static, therefore mobility is not considered. Similarly in (Zhou et al., 2019b) present a cross-layer that maximizing network lifetime networks. It integrates energy-saving techniques across the physical, MAC, and network layers. The key strategies include a dynamic control based on node distance, TDMA scheduling to prevent collisions and reduce energy wastage, and an iterative algorithm that optimizes transmission rates and balances energy consumption across nodes. However, there is a possibility that it may not be suitable for mobile networks. More recently, work in (Rahmati et al., 2019) proposed CDMA-based cross-layer protocol aims to improve reliability and energy efficiency. It utilizes chaotic CDMA sequences to reduce interference during simultaneous transmissions and employs power control to adjust transmission power based on channel conditions. Additionally, the protocol includes a Hybrid ARQ to minimize retransmissions. Nevertheless, the proposed solution may not be scalable for large networks, and other topologies may affect performance. More recently, A centralized cross-layer protocol for Joint Power Control, Link scheduling, and Routing (JPLR) for mobile networks underwater has been introduced in (Yuan et al., 2023), optimizes power control on the physical layer, link scheduling on the MAC layer, and routing on the network layer simultaneously to achieve global optimization, with a particular focus on minimizing delay from end to end across the network while minimizing power. However, Efficiency may decrease in high-density networks due to increased interference, higher computational demands, longer queuing times, and bottlenecks in centralized scheduling. Building on (Rahmati et al., 2019), another cross-layer CDMA-based Multi-Channel (MC-CDMA) protocol for mobile UWAN was developed in (Guo et al., 2024), which combines the physical and MAC layers. This protocol saves energy by dynamically allocating communication resources based on node conditions. It also allows multiple nodes to communicate simultaneously without interference by using MC-CDMA while utilizing adaptive power control. However, a limitation arises from the fixed broadcast interval of the cluster node, leading to the absence of communication rounds during dynamic network changes.

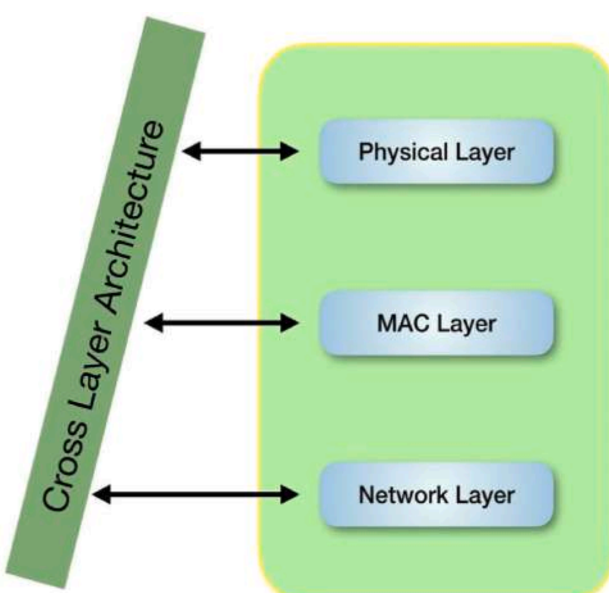

Fig. 4. Cross layer architecture.

Table 8
Comparative Analysis of Energy Cross layer MAC Protocols in UWAN.

Protocol	Topology	Range	Integrated layers	SYN	Real Time	Energy Achievement Techniques	•Strengths	•Limitations
Sun et al. (2015)	Distributed mobile	Short	MAC and Network	×	×	• Intelligent routing decisions based on location and energy metrics.	• Consider residual energy and data relay times when making data forwarding decisions led to optimized routing decisions to achieve more even energy consumption and reliable data transmission.	• Location information that is inaccurate or unreliable may reduce network performance.
Mythrehee and Julian (2015)	Multi-hop	Short	MAC and Network	×	×	• Depth-based routing. • Prevents duplicate packet transmissions.	• Localizing sensor nodes near the sea surface improves accuracy and reduces power consumption by using a game theoretic model.	• Holding time management and depth-based routing introduce delay.
DBR-MAC (Li et al., 2016b)	Mobile multi hop	Short	MAC and Network	✓	×	• Depth-based routing.	• Utilizing depth information increases the efficiency of load imbalance networks.	• DBR can result in longer paths, increasing delays.
Prajapati and Trapasiya (2016)	multi hop	Short	Physical, MAC and Network	×	×	• Power control. • Optimizes buffering and transmission at the MAC layer. • Selects next hop based on energy, mobility, and depth.	• Achieving temporal and spatial reuse that reduces collisions by accurately calculating neighbours' transmission schedules.	• Managing buffer space and selecting the next hop based on residual energy, mobility, and depth can introduce delays.
Koseoglu et al. (2015)	Distributed	Long	Physical and MAC	×	×	• Power control. • Channel access rate adjustment.	• Addressing the inherent disadvantage of distant nodes at the physical layer by maximizing their usage at the MAC layer leads to a more equitable distribution of energy consumption across nodes.	• Limited flexibility.
Dhongdi et al. (2017)	Clustered	V.short	Physical, MAC and Network	✓	×	• Dynamic power control. • Sleep mode. • Cluster-head rotation	• A protocol stack can optimize resource usage and explore the interaction between different layers by combining functionalities of layers.	• It may not be suitable for mobile network.
Zhou et al. (2019b)	Multi hop	Medium	Physical, MAC and Network	✓	×	• Dynamic power control. • Avoid collisions by assigning specific time slots. • Managing data flows and transmission rates.	• Iterative algorithms are mathematically and empirically supported, with simulation results showing their superiority.	• May not be suitable for mobile networks in underwater.
Rahmati et al. (2019)	Distributed	Short	Physical, and MAC	✓	✓	• Power control • Avoid collision by chaotic CDMA. • Minimize retransmission by Hybrid (ARQ).	• Using neighbouring node transmissions for error protection can significantly boost the throughput of a transmitting node operating in low-quality communication conditions.	• Performance may be affected by another topology or large networks.
JPLR (Yuan et al., 2023)	Mobile Centralized	Medium	Physical, MAC and Network	✓	✓	• Power control. • Adaptive slot duration. • Selecting energy-efficient relay nodes.	• Significantly reduces end-to-end delay through intelligent scheduling, power control, and routing. while offering strong scalability.	• High-density networks may lose efficiency.
MCL-MAC (Guo et al., 2024)	Mobile Centralized	Short	Physical and MAC	✓	✓	• Power control. • Optimize spreading code.	• Using Adaptive Node Clustering Algorithm (ANCA) improving communication efficiency.	• MCL-MAC is limited in its effectiveness due to the fixed broadcast interval of the cluster node.

In Table 8, several cross layer MAC protocols for UWAN are highlighted for their energy-saving strategies based on different approaches. Protocols such as those in (Sun et al., 2015), (Mythrehee and Julian, 2015) as well as DBR-MAC, are primarily achieved through advanced routing techniques. Additionally, other cross-layer protocols that integrate the network layer also focus on optimizing routing paths, ensuring efficient packet forwarding and minimizing energy consumption across the network. All Protocols that integrate physical with other layer, using power control. While those which integrating MAC layer with any other layers focused on minimizing collisions through techniques such as optimizing time slot allocation or implementing sleep modes including protocols such as (Dhongdi et al., 2017), JPLR and (Zhou et al., 2019b), where TDMA is employed to avoid collisions and enhance energy efficiency. On the other hand, protocols in (Prajapati and Trapasiya, 2016) and (Koseoglu et al., 2015) use contention-based MAC strategies, where power savings are achieved through mechanisms such as buffer optimization and channel access rate adjustments reducing overall energy consumption during transmissions. Additionally, two other cross-layer protocols, including (Rahmati et al., 2019) and MCL-MAC, employ CDMA to manage channel access efficiently and conserve power by reducing interference. Most protocols in Table 8 support short to medium range communication, with only the protocol in (Koseoglu et al., 2015) enabling long-range transmission. However, due to its reliance on ALOHA, this protocol is unsuitable for high-density networks, as the increased collision rates make it impractical for real-time applications. Additionally, protocols such as (Sun et al., 2015) (Mythrehee and Julian, 2015), and DBR-MAC, (Prajapati and Trapasiya, 2016) (Dhongdi et al., 2017), and (Zhou et al., 2019b) are also not ideal for real-time use due to delays introduced by routing techniques, holding time management, and depth-based cluster-head rotation, which contribute to communication latency. In contrast, protocols such as (Rahmati et al., 2019), JPLR and, MC-MAC show promise for real-time applications within their respective ranges, as their layer integration processes are less complex and more time efficient, making them better suited to timely communication in underwater networks.

4.5. Software defined MAC protocols

In traditional underwater acoustics communication systems, most components, such as filters, modulators, demodulators, and converters, are typically implemented in hardware. These analogy modules are highly optimized for specific applications, making them challenging to modify and reconfigure. However, by replacing many wireless transceiver functions with software implementations, conventional systems can become more flexible and reconfigurable. This shift offers several advantages, including cost reduction, increased resource utilization, and improved data link layer management (Luo et al., 2018). Software-based implementations enable easier modifications, adaptability to different scenarios, and the potential for optimization through software updates. Consequently, these advancements contribute to more efficient and effective underwater acoustics communication systems (Khaled et al., 2019). Table 9 summarizes all energy-efficient software defined MAC protocols underwater with comparison.

Authors in (Fan et al., 2016) investigated the issue of node mobility in UWAN and proposed a software-defined centralized network control approach employing existing Slotted FAMA and UW-ALOHA with centralized multi-hop topology. The proposed approach offers ease of management, high throughput, and packet delivery rates. The system reduces interference and the need for repeated control message exchanges by using dedicated control channel and it reduces energy consumption of the network. The system is flexible but exhibits scalability issues in larger bodies of water or open oceans. Moreover, the work in (Akyildiz et al., 2016) introduced an exceptionally versatile software-defined called Softwater, forwarding solution by segregating the control and data planes, enabling adaptive network control for a wide array of underwater applications. The system incorporates both single-hop and multi-hop approaches tailored to criticality of the applications and range requirements. The network controller keeps the global view of residual energy levels of all sensors and makes efficient decisions for routing paths. Consequently, it boasts the ability to optimize throughput and resilience while improving energy efficiency. Nonetheless, the system is not without drawbacks, involving trade-offs between reliability and latency, which depend on the number of network controllers. Moreover, work in (Dol et al., 2016) designed an efficient and compact software-defined modem using a multi-hop packet forwarding strategy. The modem effectively connects the physical layer to both the MAC and the network layer and employs ALOHA-MAC with Carrier Sensing (CS). The modulation schemes provided by software-defined design can be adjusted based on underwater conditions: simpler, low-power schemes are used in clear or short-range scenarios, while more complex schemes are applied in challenging environments to ensure reliable communication without excessive energy use. However, complexity could be found in a design and higher operational costs due to specialized equipment. More recently, work in (Ghannadrezaii et al., 2019), introduced a software-defined multi-hop relaying approach rooted in a hidden Markov process for channel state prediction using the probability distribution. MAC layer has been employed along with the beacon forwarding technique, to reduce network latency and energy consumption. In addition, selecting the optimal relay node with the best channel conditions by hidden Markov model also minimizes power. However, it does not adequately tackle the issues of constrained bandwidth and transmission rate, which come at the cost of long-range transmission. Recently study in (Luo et al., 2022), a software-defined multi-modal network was introduced for ocean monitoring, integrating the LoRaWAN-related MAC layer to achieve network fairness control. This hybrid system not only enhances speed and reduces latency but also leverages semi-centralized control to increase network flexibility and minimize overhead. Nonetheless, the static network deployment limits its mobility options which restricts its performance to various mobile applications.

Overall, MAC software-defined platforms are an excellent option for underwater communication systems because they offer enhanced

Table 9
Comparative analysis of software-defined MAC protocols in UWAN.

Protocol	Topology	Range	SYN	MAC Technique	Real Time	Energy Achievement Techniques	Strengths	Limitations
Fan et al. (2016)	Centralized	Short	✓	Slotted FAMA + UW-ALOHA	×	• Minimizes collision by using a dedicated control channel for control message exchanges.	• The Software-Defined paradigm separates control and data planes, enabling flexible, centralized control that simplifies network management and improves adaptability.	• Potential issues associated with the complexity and cost of deploying the system in larger bodies of water or open oceans.
Softwater (Akyildiz et al., 2016)	Centralized	Long	✓	OFDMA + TDMA + CDMA	✓	• Dynamic resource management based on current traffic demands. • Optimize routing paths.	• The proposed approach employs optimized control and data domains separately with AU assisted charging and SDN-enhanced fault recovery techniques.	• The impact of the number of controllers on reliability and the trade-offs between reliability and latencies need to be considered.
Dol et al. (2016)	Multi-hop	Medium	×	ALOHA + CS	×	• A flexible modulation scheme that can be dynamically adjusted to minimize power consumption.	• The modem is computationally efficient and compact in design for underwater applications.	• The modem cannot accommodate heavy duty protocol stacks due to energy consumption and increased wakeup times.
Ghannadrezaii et al. (2019)	Distributed	Medium	×	Contention based + Contention free	×	• Beacon signal usage. • Channel quality prediction by using hidden Markov model.	• The system incorporates beacon forwarding strategy that can reduce latency during routing.	• The system offers limited bandwidth and transmission rate which is a bottleneck for bulk information sharing.
Luo et al. (2022)	Semi-centralized	V.short	×	Slotted ALOHA	×	• Reduce overhead communication by balancing centralized and distributed control.	• Minimize latency of the network. • Semi centralized control enables the system to be robust and control efficient.	• The system has limited mobility which may not be feasible for robust monitoring applications.

flexibility, cost-efficiency, and adaptability. In addition to simplifying network management and resource utilization, they facilitate updates and reconfigurations. As a result of this shift from hardware-based systems, operational efficiency is greatly enhanced as well as responsiveness to technological changes.

Energy-efficient software-defined MAC protocols in Table 9 cover various MAC types, including contention-based, contention-free, and hybrid. However, these protocols achieved high performance especially in term of consuming energy by depending on flexibility of the modem due to its software-defined architecture. Protocols such as (Fan et al., 2016) and (Luo et al., 2022) focus on reducing control overhead, whereas protocol in (Ghannadrezaii et al., 2019) optimizes beacon signals. While most of these protocols are not suited to real-time applications because using contention based or hybrid, SoftWater stands out as it provides real-time capability by optimizing resource allocation and supporting long range communication. This is achieved through a hybrid approach that integrates contention-free MAC protocols such as OFDMA, TDMA, and CDMA.

4.6. MAC protocols based on ML

Machine Learning (ML) techniques, particularly Reinforcement Learning (RL), are increasingly being explored to solve complex decision-making problems in UWAN. These networks, characterized by dynamic environments and uncertain conditions, benefit significantly from the adaptive nature of RL (Chaudhary et al., 2022). In general, ML methods allow for the prediction and optimization of network parameters such as communication quality and energy consumption, using data-driven models (Niu et al., 2023). This results in energy-efficient solutions and improved network reliability. In RL, an agent interacts with its environment, learning to make optimal decisions based on feedback (rewards or penalties). Techniques such as Q-learning allow the agent to estimate the value of actions in specific states, helping it develop optimal policies for dynamic environments such as UWAN (Wang et al., 2023b). This leads to more efficient resource allocation and energy conservation. Deep Reinforcement Learning (DRL) extends RL by using deep neural networks to approximate value functions (Al-Fawa'reh et al., 2023), making it suitable for handling large or continuous state spaces that are typical in these environments. Although ML encompasses various techniques, most of the focus in UWAN is based on RL and its variants, such as DRL, because of their ability to adapt to changing conditions and optimize energy consumption. RL-based approaches can dynamically adjust transmission schedules and reduce idle time, ultimately leading to significant energy savings and improved network performance. However, the computational overhead and time required for RL to converge can challenge real-time applications. Once the learning phase is complete, RL allows for faster decision-making, making it a suitable tool for optimizing both energy efficiency and responsiveness. While general ML techniques are beneficial for predictive tasks such as communication channel quality estimation, most of the focus remains on RL due to its adaptive capabilities, which are crucial for managing the dynamic nature of underwater environments. Nevertheless, balancing the power efficiency benefits of RL with real-time responsiveness requires careful consideration. Fig. 5 illustrates how ML concepts are applied in UWAN. We have summarized all the significant papers contributing to power consumption reduction and provided a comparison between them in Table 10.

The authors in (Ye and Fu, 2019) presented a delayed-reward strategy using a DRL algorithm to counteract the throughput degradation caused by the long propagation delay in UWAN. Their method leverages DRL to determine an optimal channel access strategy, which not only maximizes network throughput but also improves power efficiency. By fully utilizing available time slots, including those arising from long propagation delays or those left unoccupied by other nodes, DRL minimizes idle listening and unnecessary retransmissions. This efficient use of resources helps reduce overall energy consumption, extending the

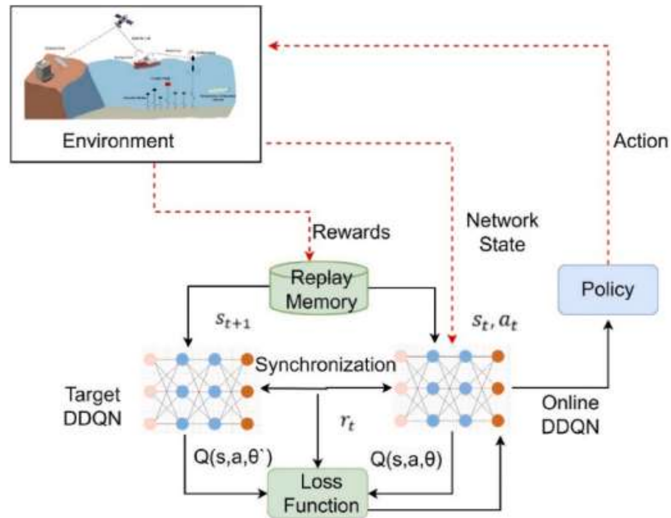

Fig. 5. MAC based on ML.

battery life of underwater sensor nodes while maintaining high network performance. The authors conducted a comparative evaluation of DR-DLMA against other models, such as FAMA and DOTS, within a heterogeneous environment. Experimental results demonstrated that DR-DLMA consistently outperformed both FAMA and DOTS. While the study suggests that energy consumption can be minimized by leveraging inactive nodes, it also notes that the DRL agent requires a significant duration to achieve a convergent state. Another work in (Alhassan and Mitchell, 2021), presented a DRL MAC protocol design that prioritizes transmission over shorter distances with more hops. The proposed approach modifies the two-stage Q-learning process to extract an implicit reward signal for a novel MAC protocol, using Packet Flow ALOHA with Q-learning (ALOHA-QUPAF). The authors employed a diagrammatic representation to map achievable channel utilization levels and then reformulated a Q-learning routine that leverages implicit feedback signal to negatively reinforce and isolate reception slots during the slot selection phase. They then averaged the packet flow rate to generate a distribution for belief states that control and consolidate the choice of transmission slot to achieve an overall network-wide packet flow. Such a configuration ensures power efficiency and maximizes transmission capacity. When benchmarked against a simulated pipeline monitoring chain network, the protocol outperformed both ALOHA-Q and framed ALOHA, registering impressive gains of 13% and 148%, respectively, across all simulation tests. Although the proposed protocol reduces power consumption, it adds extra cost to the nodes.

The work presented in (Cho et al., 2021) addressed energy conservation in MACA-based MAC protocols by proposing a reinforcement learning-based power control scheme. This approach minimizes data packet collisions while enhancing energy efficiency. Notably, it prevents collisions without prior knowledge of interferences, removing the need for additional signalling. The study also tackled the Long Inter-frame Reception Collision (LIRC) issue inherent in MACA-based protocols, using Q-learning to determine optimal transmission power. Results highlighted the resilience scheme to LIRC-induced collisions and its ability to conserve energy, crucial for underwater sensors. The authors in (Gazi et al., 2022b) introduced RL-MAC, a reinforcement learning-based MAC protocol for multimedia sensing in UWAN. This protocol uses Transmission Opportunity (TXOP) for relay nodes in multi-hop networks to optimize for relay and sensor node mobility, with Q-learning enhancing the contention mechanism during early multimedia transmission stages. RL-MAC assigns TXOP durations based on traffic needs and uses the Structural Similarity Index Measure (SSIM) to evaluate image quality, alongside compression methods to reduce image size. Power-Save Polling (PS-Poll) messages improve contention success,

Table 10
Comparative Analysis of Energy Efficient MAC based on Machine learning Protocols in UWAN.

Protocol	Range	Topology	SYN	MAC Technique	Real Time	Energy Achievement Techniques	Strengths	Limitations
DR-DLMA (Ye and Fu, 2019)	Short	Central	×	TDMA	✓	• Minimizing packet collisions.	• Full use of the available timeslots resulted from the long propagation delay or not used by other nodes in the network.	• Computation complexity during the exploration phase.
ALOHA-QUPAF (Alhassan and Mitchell, 2021)	Short	Multi-hop	×	ALOHA	×	• Minimizing packet collisions.	• Using shorter ranges to achieve higher capacity transmissions with minimal power consumption.	• Computation complexity during the exploration phase.
MACA-based MAC (Cho et al., 2021)	Short	Sink	×	Handshaking	×	• Minimizing packet collisions.	• It enables the sensor nodes to avoid collision without predefined information about the interfaces.	• Computation complexity during the exploration phase.
RL-MAC (Gazi et al., 2022b)	Short	Multi-hop	×	ALOHA	×	• Sleep mode. • Reduces ACK/ NACK packet exchange.	• Employ sleep mode to reduce the power consumption.	• Complexity increased by using data compression approach.
DRLSA-IA (Zhao et al., 2022)	Medium	Mesh	×	TDMA	✓	• Minimizing packet collisions.	• Using scheduling algorithm (TDIA) with DRL to increase network throughput and reduce the collision.	• Computation complexity during the exploration phase.
UW-ALOHA-QM (Park et al., 2020)	Short	Mobile	×	ALOHA	×	• Minimizing control packets exchanges.	• Using trial-and-error interaction to improve network resilience and adaptability.	• Computation complexity during the exploration phase.
SA-FRL (Zhang et al., 2022a)	Medium	Multi-hop	×	TDMA	×	• Selecting the best relay node.	• Using SA algorithm with RL to improve the performance of relay selection.	• Same as (Ye and Fu, 2019)
FDU-MAC (Zhang et al., 2022b)	Short	Centralized	✓	TDMA + Contention based	×	• Power control.	• Full-duplex transmission allows for simultaneous sending and receiving of data.	• Clock synchronization and algorithm complexity.
UDARMF (Zhang et al., 2021)	Medium	Distributed	×	TDMA	✓	• Power control.	• Demonstrated high network capacity, concurrency, and energy efficiency as compared to other baseline methods.	• It is not suitable for large scale networks.

though energy is consumed in image quality improvement and data compression. In (Zhao et al., 2022), a DRL-based algorithm combined with Time-Domain Interference Alignment (TDIA), called DRLSA-IA, was proposed to improve underwater node network throughput and reduce collisions. This approach optimizes power and energy conditions for nodes but does not account for the computational costs of deep reinforcement learning during the learning phase. The work in (Park et al., 2020) highlighted the increasing need for ocean exploration and mobile underwater vehicles, emphasizing the importance of adaptive solutions that reduce signalling and delays to conserve power. To tackle the mobility challenges in underwater channels, the authors introduced the UW-ALOHA-QM protocol, which leverages reinforcement learning (RL) to help nodes adapt to dynamic environments through trial-and-error, optimizing communication efficiency. This reduces energy consumption by minimizing unnecessary signalling and retransmissions, thus lowering power usage. Simulations showed UW-ALOHA-QM improved channel utilization by up to 300% compared to existing protocols, though the computational costs of RL were not addressed. This study has the same limitations in (Zhao et al., 2022).The authors in (Zhang et al., 2022a) developed a relay selection strategy for UWAN, addressing their dynamic nature and reducing the power consumption of the sensor nodes. Utilizing RL and a simulated annealing (SA) algorithm, they crafted a scheme that dynamically adjusts the RL exploration rate. A fast reinforcement learning (FRL) strategy with pre-training is introduced for practical implementation. Evaluations show the proposed SA-FRL approach converges faster than traditional RL approach, enhancing communication efficiency by selecting optimal relay nodes for high link quality which reduce power consumption and reduced delays. This study has the same limitations in (Zhao et al., 2022) and (Park et al., 2020). The work presented in (Zhang et al., 2022b) tackled challenges in UWAN by introducing a ML-based full-duplex MAC protocol, FDU-MAC, designed to optimize throughput and minimize delays. The protocol employs a contention-free approach for downlink transmissions, reducing collisions and saving power, while the uplink uses a hybrid scheme for efficiency. By accounting for transmission propagation time, FDU-MAC ensures fairer and more efficient resource utilization, leading to lower energy consumption. Simulations demonstrated superior performance in throughput, delay, and fairness compared to protocols such as TDMA, IBFD and VI-ALOHA. However, clock synchronization and algorithm complexity represent significant limitations. Recently Underwater Distributed and Adaptive Resource Management Framework (UDARMF) was proposed in (Zhang et al., 2021) to enhance communication in underwater networks by optimizing transmission parameters through deep multi-agent reinforcement learning. It addresses the challenges of limited energy, environmental constraints, and interference on the IoUT. UDARMF improves network capacity and energy efficiency by dynamically adjusting node parameters, resulting in a longer network lifespan. Despite its ability to adapt and provide efficient resource management, implementing deep learning algorithms underwater and maintaining robustness under dynamic conditions remains a challenge in large scale networks.

In Table 10, several MAC protocols leverage ML and its derivative, RL, to optimize power consumption and enhance network performance. Protocols that are based on contention-based or hybrid mechanisms are generally limited to short-range communication, whereas those based on TDMA have demonstrated the capability to support medium range communication. Protocols including DR-DLMA, ALOHA-QUPAF, MACA-based MAC, and DRLSA-IA utilize these intelligent mechanisms to minimize packet collisions. Meanwhile, protocols such as FDU-MAC and UDARMF employ ML for dynamic power control, adjusting transmission power based on environmental conditions. Additionally, RL-MAC and UW-ALOHA-QM reduce power consumption by minimizing control packet exchanges. Lastly, SA-FRL intelligently selects the optimal relay node.

Protocols that rely solely on contention-based mechanisms including, ALOHA-QUPAF, MACA-based MAC, RL-MAC, and UW-

ALOHA-QM or hybrid protocols such as FDU-MAC, may not be well-suited to real-time applications. These protocols can introduce significant delays due to their contention-based nature. Even though RL-MAC attempts to optimize multimedia transmission by compressing data, its reliance on random access mechanisms leads to higher collision rates, particularly in high dense network scenario. On the other hand, machine learning-based MAC protocols that incorporate TDMA techniques such as DR-DLMA, DRLSA-IA, and UDARMF are more suitable for real-time applications. These TDMA-based protocols provide more deterministic access to the communication medium, reducing collision and delay risk. However, SA-FRL, despite also using a TDMA structure, might not be ideal for real-time applications in multi-hop networks. The process of selecting the most efficient relay node in such topologies can introduce additional delays, making it less efficient for time-sensitive tasks.

4.7. Optical-acoustic MAC protocols

MAC protocols are difficult to implement in underwater networks due to various challenges including long propagation delays, low bandwidths, and high bit error rates. These challenges are further pronounced in heterogeneous networks consisting of both acoustic and optical nodes because of varying data transmission rates (Wang et al., 2017). Fig. 6 illustrated concept of using hybrid acoustic optical in underwater. Table 11 summarizes and compares all the works relating to energy-efficient optical-acoustic.

Some studies offer solutions to this problem by offering MAC protocols applicable to hybrid optical-acoustic underwater networks. For example, the work in (Tennenbaum et al., 2014) has evaluated the application of low-cost optical transmitter-receiver systems to improve the performance of UASN. To conserve energy for their Broadcast MAC, the approach leverages optical links to reduce the data transmitted over the acoustic network. Despite this, it does not provide a comprehensive performance evaluation or benchmarking of IR transmitters and receivers underwater. Authors in (Campagnaro et al., 2016) have proposed a Hybrid MAC protocol combining TDMA and CSMA, within a multimodal underwater network protocol stack implemented using the DESERT Underwater framework. This approach achieves higher throughput, enhanced robustness to mobility and various traffic types, and reduced service delay. By dynamically selecting the most energy-efficient physical layer (either acoustic or optical) depending on network demands and environmental conditions, the protocol saves power. However, it remains to be seen whether the proposed optical-acoustic approach can be implemented in practice. In (Wang et al., 2017), the authors propose a hybrid optical-acoustic network utilizing a MAC protocol that combines TDMA with CSMA/CA, leveraging spatial multiplexing to enhance data transmission efficiency. By employing resource-sharing mechanisms, they reduce the chance of packet collisions and minimize retransmissions, while also incorporating sleep modes to conserve energy. However, does not include a

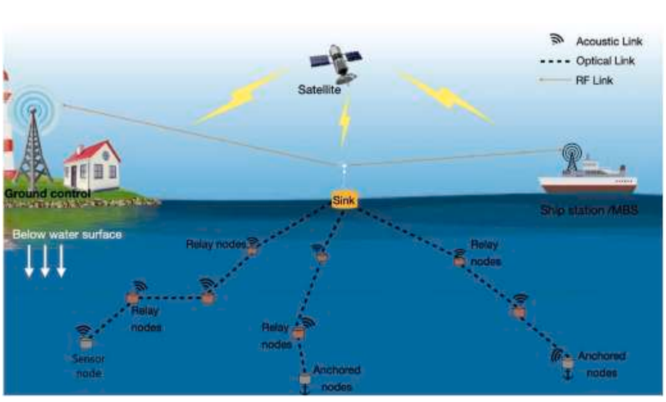

Fig. .6. Optical-acoustic hybrid network.

comparison of the solution against similar existing solutions. The work in (Chen and Xu, 2018) has proposed a MAC protocol for hybrid Optical-Acoustic Underwater Wireless Sensor Networks (OA-UWSN) which uses two-way handshaking to ensure reliable communications. It dynamically switches between acoustic and optical modes based on environmental conditions and distance, while also incorporating sleep mode to conserve power. The paper demonstrates through OMNET++ simulation software that the proposed MAC protocol enhances the channel utilization of the OA-UWSN by 24% more than the T-Lohi protocol. The energy consumption of the proposed MAC protocol in the OA-UWSN is significantly lower than that of a standalone acoustic communication network. The handshaking mechanism may, however, fail to function if there are poor channel conditions. The authors in (Celik et al., 2020) present a hybrid opto-acoustic network architecture for the IoUT. It achieves power savings through energy harvesting techniques, sleep modes, and dynamic power control managed by SDN and NFV. The proposed MAC protocol combines CDMA, Non-Orthogonal Multiple Access (NOMA), and wavelength-division multiplexing (WDM) for efficient resource allocation. The system integrates both optical and acoustic communication, using optical links for short-range, high-speed transfers and acoustic links for long-range, low-power communication, dynamically switching between them based on environmental conditions to optimize energy consumption and performance. However, deploying and maintaining the hybrid system with optical and acoustic modems, along with energy harvesting infrastructure, could be costly. More recently, the work in (Wang et al., 2021) has proposed a novel acoustic/optic hybrid MAC protocol based on TDMA. The protocol consists of one control channel and one or more data channels, with the control channel using acoustic waves for a highly connected link and the data channels using optical waves for high data-rate links. The protocol incorporates Maximum Waiting Time (MWT) and retransmission schemes to mitigate packet collision and loss of signal. Numerical results show that increasing the number of data channels effectively improves throughput and reduces average waiting time. The protocol demonstrates robustness under a certain degree of interference. However, as more data channels are added to a network, the cost of the network will also rise. These works provide a promising indication that hybrid optical-acoustic MAC protocols can offer better performance in terms of salient network parameters such as improved channel utilization, data rates, and energy consumption as compared to traditional MAC protocols.

In Table 11, all energy-efficient optical-acoustic MAC protocols for underwater communication utilize optical links for short-range, high-data-rate transmission, and acoustic links for long-range, low-data-rate communication to save power. Additionally, some protocols incorporate sleep modes, such as in (Wang et al., 2017) and (Chen and Xu, 2018). Furthermore, certain implementations, such as in (Celik et al., 2020) using software-defined architectures, integrate energy harvesting and power control mechanisms to enhance power savings. Optical communication typically has a very short range, while acoustic communication range in these protocols provides a short range, except (Campagnaro et al., 2016), which supports medium-range acoustic communication.

Regarding real-time suitability, some protocols can support real-time applications within their specific ranges only, while others cannot. For instance, protocol in OA-UWSN is not suitable for real-time communication due to its use of a handshaking mechanism, which increases delays. In addition, protocol in (Campagnaro et al., 2016), despite using optical links with TDMA, the reliance on CSMA for both control and image packet transmissions over acoustic channels introduces significant delays, particularly due to the low speed of underwater acoustic communication, making it unsuitable for real-time applications. In contrast (Wang et al., 2017), provides better real-time performance because it uses CSMA/CA only for acoustic control and lower-priority messages, while real-time data is transmitted through optical channels. Moreover, protocol in (Wang et al., 2021) could provide real time as it is TDMA based in centralized topology.

Table 11
Comparative analysis of energy-efficient optical-acoustic MAC protocols in UWAN.

Protocol	MAC Technique	Acoustic Range	Topology	SYN	Real Time	Energy Achievement Techniques	Strengths	Limitations
Tennenbaum et al. (2014)	Broadcast MAC	V.short	Cluster	✓	✓	• Utilizes optical links to reduce the amount of data transmitted over the acoustic network	• Cost effective implementation	• Lacks a comprehensive performance evaluation or benchmarking with existing underwater communication systems.
Campagnaro et al. (2016)	TDMA and CSMA	Medium	Mobile	×	×	• Selecting the most efficient communication method, either acoustic or optical.	• Offers higher throughput, lower service delay, and better quality of service compared to standalone acoustic or optical system.	• Practical implementation of the proposed optical acoustic remains unexplored.
Wang et al. (2017)	TDMA and CSMA/CA	Shorth	Centralized	×	✓	• Switching between optical and acoustic communication modes based on SNR and distance. • Sleep Mode	• TDMA and CSMA/CA improves data transmission efficiency	• Does not provide performance evaluation against similar existing solutions.
OA-UWSN (Chen and Xu, 2018)	Handshaking	V.short	Centralized	✓	×	• Switching between optical and acoustic communication modes based on distance. • Sleep Mode	• Enhances channel utilization by 24% more than the T-Lohi protocol with lower energy consumption compared to standalone acoustic	• Poor channel conditions can cause the handshaking mechanism to fail.
Celik et al. (2020)	CD-NOMA and NOMA with WDM	N/A	N/A	×	✓	• Switching between optical and acoustic communication modes based on distance. • Energy harvesting • power control.	• NFV enhances adaptability, and flexibility and offers demand-based network resource allocation.	• High cost and maintenance
Wang et al. (2021)	TDMA	V.short	Centralized	✓	✓	• Switching between optical and acoustic communication modes based on distance. • MWT and retransmission mechanisms mitigate packet collisions and losses	• Increased number of data channels (e.g., 2 and 4 channels) improves throughput and average waiting time.	• Increasing the number of data channels also increases network costs.

5. Future directions of energy-efficient MAC in underwater applications

The underwater environment poses unique challenges for MAC protocols in UWAN, such as signal attenuation, high delays, high BER, and dynamic channel conditions could impact energy efficiency, highlighting the need for underwater specific solutions. Future research could explore adaptive strategies and intelligent topology reconfiguration to accommodate node mobility and water dynamics. This would minimize energy waste from collisions, retransmissions, and unreliable links.

A novel hybrid MAC protocol Load Based Time Slotted Access (LBTSA) is introduced in (Zhang et al., 2019b), adjusting dynamically to network load. It integrates an energy-efficient distributed time synchronization algorithm (E^2DTS) to optimize power usage. While the study lacks comparative power consumption analysis, LBTSA advances MAC protocols by combining TDMA and CSMA, enhancing efficiency and adaptability in UWAN environments. This development marks a step forward in enhancing the efficiency and adaptability of MAC systems in UWAN.

Additionally, cross-layer approaches that integrate information from different network layers offer a way to optimize limited resources for terrestrial environment such as IoT and WSN, enhancing both energy efficiency and network performance. These approaches must consider the unique topology changes in underwater networks. Developing cross-layer protocols tailored to these underwater communication challenges presents a valuable research opportunity. A study in (Bayrakdar, 2020) has introduced a cost-effective ALOHA MAC protocol with priority-based access for a smart water pollution monitoring system, addressing the lack of efficient channel access prioritization in underwater networks. Similarly, work in (Cicioğlu and Çalhan, 2022) proposed an underwater simulation environment using a cross-layer design for the IoUT network, where critical data such as diver health and hazardous conditions are prioritized. These approaches can be applied to various underwater applications, offering a clear strategy for optimizing data transmission based on urgency. Furthermore, Multi-Input Multi-Output (MIMO) technology holds promise for increasing throughput and reducing latency in terrestrial networks. However, optimizing power efficiency of MIMO systems in underwater environments, where signal quality is affected by water turbulence and absorption, remains a critical area of research. Unlike terrestrial networks, underwater MIMO requires balancing power consumption with severe environmental conditions.

The future of non-orthogonal multiple access (NOMA) research must account for underwater communication challenges, such as severe attenuation over distance and complex power allocation. While NOMA shows promise in terrestrial networks, adapting it to UWAN will require careful consideration of underwater-specific parameters such as varying channel gain and user mobility. Hybrid NOMA-based MAC protocols in (Cheon and Cho, 2017), has introduced a NOMA protocol. This protocol enables simultaneous sharing of the same resource by leveraging differences in channel gain. Similar work in (Guo et al., 2023), proposed a hybrid NOMA-based MAC protocol (HN-MAC) that optimizes power consumption and coding rate simultaneously and achieves efficient concurrent communications. As a novel approach, NOMA could offer valuable insights for researchers aiming to enhance underwater communication by implementing NOMA effectively in UWAN demands.

In underwater communication, acoustic medium, combined with optical techniques, have been increasingly adopted to enhance reliability. This approach has been integrated into various MAC protocols, including TDMA, CSMA, and NOMA, with a focus on energy efficiency. This integration has prompted researchers to explore the combination of acoustic technology with other physical mediums, such as Magnetic Induction (MI), to develop new energy-efficient MAC protocols. This exploration aims to leverage the strengths of different mediums to further improve the performance and energy management of MAC in UWAN.

Recent advancement in UWAN suggests the integration of SDN to address the unique challenges of underwater communication. Flexibility of SDN is especially valuable in underwater networks, where the ability to adapt to extreme environmental changes is crucial for maintaining efficient communication. UWAN can benefit greatly from the adoption of SDN since it allows networks to dynamically adapt to the extreme and rapid changes that are typical of underwater channels. SDN based architectures system enhanced network configuration, enabling real-time optimization of the data link layer in response to rapidly changing underwater conditions. Furthermore, SDN provides a flexible framework for supporting various applications with strict QoS requirements, providing a versatile solution for various underwater communication requirements. SDN extends its application beyond traditional contention-free and contention-based MAC protocols to include optical-acoustic MAC and cross-layer architectures in underwater communication. This broader application of SDN is exemplified in research where authors in (Celik et al., 2020) have developed a concept for a software-defined hybrid opto-acoustic underwater network (SDUN). This network incorporates NFV to establish application specific cross-layer protocol suites. Such innovative use of SDN opens new research opportunities in the domain of MAC protocols for underwater communication. Researchers are now exploring a wider range of applications for SDN, aiming to further enhance the efficiency and adaptability of UWAN.

Unlike terrestrial networks, where ML applications are well-explored, underwater communication systems face additional challenges. ML-based protocols designed for underwater environments can learn to minimize energy consumption and collisions, considering unique underwater conditions such as changing salinity, pressure, and temperature. The continued development of ML approaches in UWAN presents an exciting opportunity to enhance energy efficiency without adding complexity to underwater nodes.

Integrating ML, particularly RL and DRL, into MAC protocols for UWAN shows great promise for improving energy efficiency. These methods can dynamically adjust transmission schedules and reduce power-consuming idle times by learning optimal communication strategies based on environmental factors. However, the challenge lies in making RL/DRL suitable for real-time communications. The iterative learning process, common in RL and DRL, can be computationally intensive, leading to longer convergence times and frequent policy updates that drain energy and affect real-time performance. During the learning phase, the computational demands can be too high for time-sensitive applications. Once RL has converged, it can make faster decisions, optimizing energy usage while being responsive enough for real-time tasks. A promising solution to address these issues is the use of teacher-student architectures (Abbasi et al., 2024), where a pre-trained model (teacher) guides a simpler, more efficient model (student). This approach can accelerate the learning process while maintaining power efficiency, enabling faster convergence, and reducing energy consumption. The development of MAC protocols underwater that combine ML-based optimization with low-latency, energy-efficient operation is essential for future advances in the field.

There is a noticeable lack of energy-efficient MAC protocols that support long-range communication, which is crucial for deep underwater exploration. Developing energy MAC protocols for such scenarios is essential to overcome energy consumption and signal attenuation over large distances. Additionally, proposed energy MAC protocols for real-time applications do not provide sufficient coverage for underwater environments, where delays can have critical consequences. Real-time applications, such as rescue operations, human activity monitoring, military applications, and natural disaster detection (e.g., earthquakes or volcanic eruptions), are highly sensitive to communication delays. These applications are categorized as mission-critical and require efficient resource allocation, yet underwater environments have significantly less bandwidth than terrestrial networks. Optimizing bandwidth in underwater environments through TDMA-based MAC protocols, combined with frequency grouping based on node distances, can significantly enhance communication reliability and energy consumption in real time within mission-critical applications. By allocating more resources both in terms of frequency and time exclusively to critical applications, this approach ensures QoS requirements are satisfied. Meanwhile, non-critical applications can be assigned fewer resources, thereby enhancing system efficiency without compromising high-priority tasks. As discussed in subsection 3.3, designing robust MAC mechanisms tailored for mission-critical applications in underwater environments is essential, as many solutions used in WSN and IoT for terrestrial applications are not directly applicable underwater, due to differences in environmental conditions and network constraints.

Underwater networks face significant challenges in balancing energy efficiency with real-time communication. Achieving this balance requires careful design, as real-time applications often demand low latency and high reliability, which increases energy consumption. To address this trade-off, adaptive MAC protocols are essential. With these protocols, energy efficiency and real-time performance can be maintained without compromising network functionality or critical mission objectives while minimizing latency.

The continued exploration and application of these techniques to underwater MAC protocols presents an exciting opportunity to further enhance underwater communication systems' efficiency, reliability, and adaptability.

6. Conclusion

The development of MAC protocols for UWAN encounters notable difficulties due to underwater harsh, complex, and dynamic environments. Moreover, controlling energy usage is critical representing a major barrier to the broad implementation of the IoUT. This survey outlines the unique challenges of MAC protocols for UWAN and highlights the limitations of applying terrestrial IoT and WSN protocols for underwater applications. The work provides detailed categorization and evaluation of a range of energy-efficient MAC techniques with comparisons in term of communication range, real time suitability and energy-efficiency techniques. An examination of some of the potential future avenues of research in energy-efficient MAC protocols is discussed. The paper serves not only as a comprehensive survey of the field but also as a strategic roadmap for researchers and academics.

CRediT authorship contribution statement

Walid K. Hasan: Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Iftekhar Ahmad:** Writing – review & editing, Supervision, Conceptualization. **Daryoush Habibi:** Writing – review & editing, Supervision, Conceptualization. **Quoc Viet Phung:** Writing – review & editing, Supervision, Conceptualization. **Mohammad Al-Fawa'reh:** Writing – original draft, Visualization, Investigation, Data curation. **Kazi Yasin Islam:** Writing – original draft, Investigation, Data curation. **Ruba Zaheer:** Writing – original draft, Investigation, Data curation. **Haitham Khaled:** Writing – review & editing, Writing – original draft, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

Abbasi, M., Shahraki, A., Prieto, J., Arrieta, A.G., Corchado, J.M., 2024. Unleashing the potential of knowledge Distillation for IoT traffic classification. IEEE Transactions on Machine Learning in Communications and Networking 2, 221–239.

Abdeli, D., Zelit, S., Moussaoui, S., 2013. RTH-MAC: a real time hybrid MAC protocol for WSN. In: 2013 11th International Symposium on Programming and Systems (ISPS). IEEE, pp. 153–162.

Acar, G., Adams, A., 2006. ACMENet: an underwater acoustic sensor network protocol for real-time environmental monitoring in coastal areas. IEE Proc. - Radar, Sonar Navig. 153 (4), 365–380.

Afroz, F., Braun, R., 2020. Energy-efficient MAC protocols for wireless sensor networks: a survey. Int. J. Sens. Netw. 32 (3), 150–173.

Afzal, M.S., Lim, Y., Lee, S., Yoon, H., Roh, Y., 2020. Optimization and characterization of a wideband multimode Tonpilz transducer for underwater acoustical arrays. Sensor Actuator Phys. 307, 112001.

Ahmed, R., Stojanovic, M., 2016. Joint power and rate control for packet coding over fading channels. IEEE J. Ocean. Eng. 42 (3), 697–710.

Akyildiz, I.F., Pompili, D., Melodia, T., 2005. Underwater acoustic sensor networks: research challenges. Ad Hoc Netw. 3 (3), 257–279.

Akyildiz, I.F., Wang, P., Lin, S.-C., 2016. SoftWater: software-defined networking for next-generation underwater communication systems. Ad Hoc Netw. 46, 1–11.

Al Guqhaiman, A., Akanbi, O., Aljaedi, A., Chow, C.E., 2020. A survey on MAC protocol approaches for underwater wireless sensor networks. IEEE Sensor. J. 21 (3), 3916–3932.

Al Guqhaiman, A., Akanbi, O., Aljaedi, A., Alharbi, A.R., Chow, C.E., 2021. DAMAC: a delay-aware MAC protocol for ad hoc underwater acoustic sensor networks. Sensors 21 (15), 5229.

Al-Habob, A.A., Dobre, O.A., Poor, H.V., 2021. Role assignment for spatially-correlated data aggregation using multi-sink Internet of Underwater Things. IEEE Transactions on Green Communications and Networking 5 (3), 1570–1579.

Al-Fawa'reh, M., Abu-Khalaf, J., Szewczyk, P., Kang, J.J., 2023. MalBoT-DRL: Malware botnet detection using deep reinforcement learning in IoT networks. IEEE Internet of Things, 11 (6), 9611–9629.

Alfouzan, F.A., 2021. Energy-efficient collision avoidance MAC protocols for underwater sensor networks: survey and challenges. J. Mar. Sci. Eng. 9 (7), 741.

Alfouzan, F., Shahrabi, A., Ghoreyshi, S.M., Boutaleb, T., 2018. An efficient scalable scheduling MAC protocol for underwater sensor networks. Sensors 18 (9), 2806.

Alfouzan, F.A., Shahrabi, A., Ghoreyshi, S.M., Boutaleb, T., 2019a. An energy-conserving collision-free MAC protocol for underwater sensor networks. IEEE Access 7, 27155–27171.

Alfouzan, F.A., Shahrabi, A., Ghoreyshi, S.M., Boutaleb, T., 2019b. A collision-free graph coloring MAC protocol for underwater sensor networks. IEEE Access 7, 39862–39878.

Alhassan, I.B., Mitchell, P.D., 2021. Packet flow based reinforcement learning MAC protocol for underwater acoustic sensor networks. Sensors 21 (7), 2284.

Ali, M.F., Jayakody, D.N.K., Chursin, Y.A., Affes, S., Dmitry, S., 2020. Recent advances and future directions on underwater wireless communications. Arch. Comput. Methods Eng. 27, 1379–1412.

Ali, U., Muhammad, W., Irshad, M.J., Manzoor, S., 2021. Multi-sensor fusion for underwater robot self-localization using PC/BC-DIM neural network. Sens. Rev. 41 (5), 449–457.

Ali, M.F., Jayakody, D.N.K., Li, Y., 2022. Recent trends in underwater visible light communication (UVLC) systems. IEEE Access 10, 22169–22225.

Allience, L., 2015. LoRaWAN Specification Version 1.0. 1.

Ansari, S., Gonzalez, J.P., Otero, P., Ansari, A., 2015. Analysis of MAC strategies for underwater applications. Wireless Pers. Commun. 85 (2), 359–376.

Awan, K.M., Shah, P.A., Iqbal, K., Gillani, S., Ahmad, W., Nam, Y., 2019. Underwater wireless sensor networks: a review of recent issues and challenges. Wireless Commun. Mobile Comput. 2019 (1), 6470359.

Badawy, M., Khater, E., Tolba, M., Ibrahim, D., El-Fishawy, N., 2020. A new technique for underwater acoustic wireless sensor network. In: 2020 15th International Conference on Computer Engineering and Systems (ICCES). IEEE, pp. 1–5.

Barr, S.J., Wang, J., Liu, B., 2011. An efficient method for constructing underwater sensor barriers. J. Commun. 6 (5), 370–383.

Barua, S., Rong, Y., Nordholm, S., Chen, P., 2019. Adaptive modulation for underwater acoustic OFDM communication. In: OCEANS 2019-Marseille. IEEE, pp. 1–5.

Bayrakdar, M.E., 2020. Cost effective smart system for water pollution control with underwater wireless sensor networks: a simulation study. Comput. Syst. Sci. Eng. 35 (4), 283–292.

Bernard, C., Bouvet, P.-J., Tomasi, B., 2022. Spread spectrum modulation with Grassmannian constellations for mobile multiple access underwater acoustic channels. Sensors 22 (21), 8518.

Bhaskarwar, R.V., Pete, D.J., 2021. Cross-layer design approaches in underwater wireless sensor networks: a survey. SN Computer Science 2, 1–26.

Bouabdallah, F., Boutaba, R., 2011. A distributed OFDMA medium access control for underwater acoustic sensors networks. In: 2011 IEEE International Conference on Communications (ICC). IEEE, pp. 1–5.

Bouabdallah, F., Boutaba, R., Mehaoua, A., 2018. Collision avoidance energy efficient multi-channel MAC protocol for underwater acoustic sensor networks. IEEE Trans. Mobile Comput. 18 (10), 2298–2314.

Campagnaro, F., Guerra, F., Casari, P., Diamant, R., Zorzi, M., 2016. Implementation of a multi-modal acoustic-optical underwater network protocol stack. In: OCEANS 2016-Shanghai. IEEE, pp. 1–6.

Caruso, A., Paparella, F., Vieira, L.F.M., Erol, M., Gerla, M., 2008. The meandering current mobility model and its impact on underwater mobile sensor networks. In: IEEE INFOCOM 2008-The 27th Conference on Computer Communications. IEEE, pp. 221–225.

Celik, A., Saeed, N., Shihada, B., Al-Naffouri, T.Y., Alouini, M.-S., 2020. A software-defined opto-acoustic network architecture for internet of underwater things. IEEE Commun. Mag. 58 (4), 88–94.

Chao, C.-M., Wang, Y.-Z., Lu, M.-W., 2012. Multiple-rendezvous multichannel MAC protocol design for underwater sensor networks. IEEE Transactions on Systems, Man, and Cybernetics: Systems 43 (1), 128–138.

Chaudhary, M., Goyal, N., Mushtaq, A., 2022. Internet of underwater things: challenges, routing protocols, and ML algorithms. Machine Learning Paradigm for Internet of Things Applications 247–263.

Chen, Z., Xu, L., 2018. A MAC protocol design for optical-acoustic hybrid underwater wireless sensor network. In: International Workshop on Millimeter-Wave Radar Technology and Application, pp. 274–279.

Chen, Y.-D., Lien, C.-Y., Chuang, S.-W., Shih, K.-P., 2011. DSSS: a TDMA-based MAC protocol with dynamic slot scheduling strategy for underwater acoustic sensor networks. In: OCEANS 2011 IEEE-Spain. IEEE, pp. 1–6.

Chen, H., Fan, G., Xie, L., Cui, J.-H., 2013. A hybrid path-oriented code assignment CDMA-based MAC protocol for underwater acoustic sensor networks. Sensors 13 (11), 15006–15025.

Chen, K., Ma, M., Cheng, E., Yuan, F., Su, W., 2014. A survey on MAC protocols for underwater wireless sensor networks. IEEE Communications Surveys & Tutorials 16 (3), 1433–1447.

Chen, Y., Jin, Z., Zeng, Q., Yang, Q., 2022. A collision-avoided MAC protocol with time synchronization and power control for underwater sensor networks. IEEE Sensor. J. 22 (19), 19073–19087.

Chen, Y., et al., 2023a. An energy-efficient MAC protocol for three-dimensional underwater acoustic sensor networks with time synchronization and power control. IEEE Access 11, 20842–20860.

Chen, Y., et al., 2023b. An energy-efficient MAC protocol for three-dimensional underwater acoustic sensor networks with time synchronization and power control. IEEE Access 11, 20842–20860.

Cheon, J., Cho, H.-S., 2011. A delay-tolerant OFDMA-based MAC protocol for underwater acoustic sensor networks. In: 2011 IEEE Symposium on Underwater Technology and Workshop on Scientific Use of Submarine Cables and Related Technologies. IEEE, pp. 1–4.

Cheon, J., Cho, H.-S., 2017. Power allocation scheme for non-orthogonal multiple access in underwater acoustic communications. Sensors 17 (11), 2465.

Chirdchoo, N., Soh, W.-S., Chua, K.C., 2007. Aloha-based MAC protocols with collision avoidance for underwater acoustic networks. In: IEEE INFOCOM 2007-26th IEEE International Conference on Computer Communications. IEEE, pp. 2271–2275.

Cho, J., Ahmed, F., Shitiri, E., Cho, H.-S., 2021. Power control for MACA-based underwater MAC protocol: a Q-learning approach. In: 2021 IEEE Region 10 Symposium (TENSYMP). IEEE, pp. 1–4.

Cicioğlu, M., Çalhan, A., 2022. Performance analysis of cross-layer design for internet of underwater things. IEEE Sensor. J. 22 (15), 15429–15434.

Conti, R., Meli, E., Ridolfi, A., Allotta, B., 2015. An innovative decentralized strategy for I-AUVs cooperative manipulation tasks. Robot. Autonom. Syst. 72, 261–276.

Cunha, A., Koubaa, A., Severino, R., Alves, M., 2007. Open-ZB: an open-source implementation of the IEEE 802.15. 4/ZigBee protocol stack on TinyOS. In: 2007 IEEE International Conference on Mobile Adhoc and Sensor Systems. IEEE, pp. 1–12.

Davies, J., Randall, P., Neasham, J., Sherlock, B., Hamilton, A., 2022. Phorcys Waveform architecture. In: 2022 Sixth Underwater Communications and Networking Conference (UComms). IEEE, pp. 1–4.

Dhongdi, S.C., 2022. Review of underwater mobile sensor network for ocean phenomena monitoring. J. Netw. Comput. Appl. 205, 103418.

Dhongdi, S.C., Nahar, P., Sethunathan, R., Gudino, L.J., Anupama, K., 2017. Cross-layer protocol stack development for three-dimensional underwater Acoustic Sensor Network. J. Netw. Comput. Appl. 92, 3–19.

Do, D.H., Nguyen, Q.K., Van Duc, N., 2016. A time synchronization method for OFDM-based underwater acoustic communication systems. In: 2016 International Conference on Advanced Technologies for Communications (ATC). IEEE, pp. 131–134.

Dol, H.S., Casari, P., Van Der Zwan, T., Otnes, R., 2016. Software-defined underwater acoustic modems: historical review and the NILUS approach. IEEE J. Ocean. Eng. 42 (3), 722–737.

Du, X., Peng, C., Liu, X., Liu, Y., 2015. Hierarchical code assignment algorithm and state-based CDMA protocol for UWSN. China Communications 12 (3), 50–61.

Fan, R., Wei, L., Du, P., Mc Goldrick, C., Gerla, M., 2016. A SDN-controlled underwater MAC and routing testbed. In: MILCOM 2016-2016 IEEE Military Communications Conference. IEEE, pp. 1071–1076.
Fan, R., Guo, J., Song, S., Gou, P., Cui, J., 2023. An adaptive mobile access MAC protocol for underwater sensor networks. In: Proceedings of the 17th International Conference on Underwater Networks & Systems, pp. 1–5.
Fang, D., Li, Y., Huang, H., Yin, L., 2010. A CSMA/CA-based MAC protocol for underwater acoustic networks. In: 2010 6th International Conference on Wireless Communications Networking and Mobile Computing (WiCOM). IEEE, pp. 1–4.
Farag, H., Gidlund, M., Österberg, P., 2018. A delay-bounded MAC protocol for mission- and time-critical applications in industrial wireless sensor networks. IEEE Sensor. J. 18 (6), 2607–2616.
Gazi, F., Ahmed, N., Misra, S., 2022a. RE-MAC: a hybrid MAC protocol for underwater multimedia communication system. IEEE Syst. J. 17 (1), 840–847.
Gazi, F., Ahmed, N., Misra, S., Wei, W., 2022b. Reinforcement learning-based MAC protocol for underwater multimedia sensor networks. ACM Trans. Sens. Netw. 18 (3), 1–25.
Ghannadrezaii, H., Bousquet, J.-F., Haque, I., 2019. Cross-layer design for software-defined underwater acoustic networking. In: OCEANS 2019-Marseille. IEEE, pp. 1–7.
Gomez, C., Veras, J.C., Vidal, R., Casals, L., Paradells, J., 2019. A sigfox energy consumption model. Sensors 19 (3), 681.
González-García, J., Gómez-Espinosa, A., Cuan-Urquizo, E., García-Valdovinos, L.G., Salgado-Jiménez, T., Escobedo Cabello, J.A., 2020. Autonomous underwater vehicles: localization, navigation, and communication for collaborative missions. Applied sciences 10 (4), 1256.
Guo, Y., Liu, Y., 2013. Time synchronization for mobile underwater sensor networks. J. Network. 8 (1), 116.
Guo, J., Song, S., Liu, J., Chen, H., Cui, J.-H., Han, G., 2023. A hybrid NOMA-based MAC protocol for underwater acoustic networks. IEEE/ACM Trans 32 (2), 1187–1200.
Guo, J., Song, S., Liu, J., Wan, L., Yu, Y., Han, G., 2024. An MC-CDMA-based MAC protocol for efficient concurrent communication in mobile underwater acoustic networks. IEEE Trans. Mobile Comput 23 (12), 12428–12443.
Han, S., Noh, Y., Lee, U., Gerla, M., 2013. M-FAMA: a multi-session MAC protocol for reliable underwater acoustic streams. In: 2013 Proceedings IEEE INFOCOM. IEEE, pp. 665–673.
Hasan, W.K., Ran, Y., Agbinya, J., Tian, G., 2019. A survey of energy efficient IoT network in cloud environment. In: 2019 Cybersecurity and Cyberforensics Conference (CCC). IEEE, pp. 13–21.
Hassan, S., Chen, P., Rong, Y., Chan, K.Y., 2023. Doppler shift compensation using an LSTM-based deep neural network in underwater acoustic communication systems. In: OCEANS 2023-Limerick. IEEE, pp. 1–7.
Ho, I.W.-H., Chau, S.C.-K., Magsino, E.R., Jia, K., 2019. Efficient 3D road map data exchange for intelligent vehicles in vehicular fog networks. IEEE Trans. Veh. Technol. 69 (3), 3151–3165.
Hong, L., Hong, F., Guo, Z.-W., Yang, X., 2008. A TDMA-based MAC protocol in underwater sensor networks. In: 2008 4th International Conference on Wireless Communications, Networking and Mobile Computing. IEEE, pp. 1–4.
Hsu, C.-C., Lai, K.-F., Chou, C.-F., Lin, K.-J., 2009. ST-MAC: spatial-temporal MAC scheduling for underwater sensor networks. In: IEEE INFOCOM 2009. IEEE, pp. 1827–1835.
Hu, K., Sun, Z., Luo, H., Zhou, W., Guo, Z., 2018. STVF: spatial-temporal variational filtering for localization in underwater acoustic sensor networks. Sensors 18 (7), 2078.
Huang, P., Liu, C.-J., Xiao, L., 2013. TAS-MAC: a traffic-adaptive synchronous MAC protocol for wireless sensor networks. In: 2013 IEEE International Conference on Sensing, Communications and Networking (SECON). IEEE, pp. 113–121.
Islam, K.Y., Ahmad, I., Habibi, D., Waqar, A., 2022. A survey on energy efficiency in underwater wireless communications. J. Netw. Comput. Appl. 198, 103295.
Jiang, S., 2017. State-of-the-art medium access control (MAC) protocols for underwater acoustic networks: a survey based on a MAC reference model. IEEE Communications Surveys & Tutorials 20 (1), 96–131.
Jiang, J., Han, G., Guo, H., Shu, L., Rodrigues, J.J.P.C., 2016. Geographic multipath routing based on geospatial division in duty-cycled underwater wireless sensor networks. J. Netw. Comput. Appl. 59, 4–13. https://doi.org/10.1016/j.jnca.2015.01.005.
Kao, C.-C., Lin, Y.-S., Wu, G.-D., Huang, C.-J., 2017. A comprehensive study on the internet of underwater things: applications, challenges, and channel models. Sensors 17 (7), 1477.
Khaled, H., Ahmad, I., Habibi, D., Phung, Q.V., 2019. An energy-aware cognitive radio-based communication approach for next generation wireless networks. In: 2019 IEEE 21st International Conference on High Performance Computing and Communications; IEEE 17th International Conference on Smart City; IEEE 5th International Conference on Data Science and Systems (HPCC/SmartCity/DSS). IEEE, pp. 1817–1824.
Khalil, I.M., Gadallah, Y., Hayajneh, M., Khreishah, A., 2012. An adaptive OFDMA-based MAC protocol for underwater acoustic wireless sensor networks. Sensors 12 (7), 8782–8805.
Khan, Z.U., et al., 2022. A comprehensive survey of energy-efficient MAC and routing protocols for underwater wireless sensor networks. Electronics 11 (19), 3015.
Khater, E.M., Ibrahim, D.M., Saidahmed, M.T.F., 2016. Contention-based mac protocol in uwsns: slotted_cs_aloha proposed protocol. In: 2016 11th International Conference on Computer Engineering & Systems (ICCES). IEEE, pp. 73–78.
Khater, E., El-Fishawy, N., Tolba, M., Ibrahim, D.M., Badawy, M., 2021. Buffering_Slotted_ALOHA protocol for underwater acoustic sensor networks based on the slot status. Wireless Network 27 (5), 3127–3145.
Kim, J.-P., Lee, J.-W., Jang, Y.-S., Son, K., Cho, H.-S., 2009. A CDMA-based MAC protocol in tree-topology for underwater acoustic sensor networks. In: 2009 International Conference on Advanced Information Networking and Applications Workshops. IEEE, pp. 1166–1171.
Koseoglu, M., Karasan, E., Chen, L., 2015. Cross-layer energy minimization for underwater ALOHA networks. IEEE Syst. J. 11 (2), 551–561.
Kredo, K.B., Mohapatra, P., 2007. A hybrid medium access control protocol for underwater wireless networks. In: Proceedings of the 2nd Workshop on Underwater Networks, pp. 33–40.
Lanbo, L., Shengli, Z., Jun-Hong, C., 2008. Prospects and problems of wireless communication for underwater sensor networks. Wireless Commun. Mobile Comput. 8 (8), 977–994.
Li, C., et al., 2016a. FDCA: a full-duplex collision avoidance MAC protocol for underwater acoustic networks. IEEE Sensor. J. 16 (11), 4638–4647.
Li, C., Xu, Y., Diao, B., Wang, Q., An, Z., 2016b. DBR-MAC: a depth-based routing aware MAC protocol for data collection in underwater acoustic sensor networks. IEEE Sensor. J. 16 (10), 3904–3913.
Li, S., Qu, W., Liu, C., Qiu, T., Zhao, Z., 2019. Survey on high reliability wireless communication for underwater sensor networks. J. Netw. Comput. Appl. 148, 102446.
Lin, W., Chen, K., 2016. MHM: a multiple handshaking MAC protocol for underwater acoustic sensor networks. Int. J. Distributed Sens. Netw. 12 (5), 9798075.
Luo, H., Wu, K., Ruby, R., Liang, Y., Guo, Z., Ni, L.M., 2018. Software-defined architectures and technologies for underwater wireless sensor networks: a survey. IEEE Communications Surveys & Tutorials 20 (4), 2855–2888.
Luo, H., Wang, X., Xu, Z., Liu, C., Pan, J.-S., 2022. A software-defined multi-modal wireless sensor network for ocean monitoring. Int. J. Distributed Sens. Netw. 18 (1), 15501477211068389.
Lv, C., Wang, S., Tan, M., Chen, L., 2014. UA-MAC: an underwater acoustic channel access method for dense mobile underwater sensor networks. Int. J. Distributed Sens. Netw. 10 (2), 374028.
Moghimi, M.K., Mohanna, F., 2021. Real-time underwater image enhancement: a systematic review. Journal of Real-Time Image Processing 18 (5), 1509–1525.
Molins, M., Stojanovic, M., 2006. Slotted FAMA: a MAC protocol for underwater acoustic networks. In: OCEANS 2006-Asia Pacific. IEEE, pp. 1–7.
Multi-Channel, M., 2019. Collision avoidance energy efficient Multi-Channel MAC protocol for UnderWater acoustic sensor networks. IEEE Trans. Mobile Comput. 18 (10).
Murad, M., Sheikh, A.A., Manzoor, M.A., Felemban, E., Qaisar, S., 2015. A survey on current underwater acoustic sensor network applications. International Journal of Computer Theory and Engineering 7 (1), 51.
Mythrehee, H., Julian, A., 2015. A cross layer UWSN architecture for marine environment monitoring. In: 2015 Global Conference on Communication Technologies (GCCT). IEEE, pp. 211–216.
Ng, H.-H., Soh, W.-S., Motani, M., 2013. An underwater acoustic MAC protocol using reverse opportunistic packet appending. Comput. Network. 57 (14), 2733–2751.
Nie, D., Feng, Y., Zhen, C., Zhang, J., Ning, G., 2016. Power control for underwater acoustic MC-CDMA communication networks using the improved PSO algorithm. In: OCEANS 2016-Shanghai. IEEE, pp. 1–4.
Niu, H., Li, X., Zhang, Y., Xu, J., 2023. Advances and applications of machine learning in underwater acoustics. Intelligent Marine Technology and Systems 1 (1), 8.
Noh, Y., et al., 2014. DOTS: a propagation delay-aware opportunistic MAC protocol for mobile underwater networks. IEEE Trans. Mobile Comput. 13 (4), 766–782.
Park, M.K., Rodoplu, V., 2007. UWAN-MAC: an energy-efficient MAC protocol for underwater acoustic wireless sensor networks. IEEE J. Ocean. Eng. 32 (3), 710–720.
Park, S.H., Mitchell, P.D., Grace, D., 2020. Reinforcement learning based MAC protocol (UW-ALOHA-QM) for mobile underwater acoustic sensor networks. IEEE Access 9, 5906–5919.
Peleato, B., Stojanovic, M., 2007. Distance aware collision avoidance protocol for ad-hoc underwater acoustic sensor networks. IEEE Commun. Lett. 11 (12), 1025–1027.
Peng, Z., Zhu, Y., Zhou, Z., Guo, Z., Cui, J.-H., 2010. COPE-MAC: a contention-based medium access control protocol with parallel reservation for underwater acoustic networks. In: OCEANS'10 IEEE SYDNEY. IEEE, pp. 1–10.
Polastre, J., Hill, J., Culler, D., 2004. Versatile low power media access for wireless sensor networks. In: Proceedings of the 2nd International Conference on Embedded Networked Sensor Systems, pp. 95–107.
Pompili, D., Akyildiz, I.F., 2009. Overview of networking protocols for underwater wireless communications. IEEE Commun. Mag. 47 (1), 97–102.
Pompili, D., Melodia, T., Akyildiz, I.F., 2009. A CDMA-based medium access control for underwater acoustic sensor networks. IEEE Trans. Wireless Commun. 8 (4), 1899–1909.
Potter, J., Alves, J., Green, D., Zappa, G., Nissen, I., McCoy, K., 2014. The JANUS underwater communications standard. In: 2014 Underwater Communications and Networking (UComms). IEEE, pp. 1–4.
Poudel, S., Moh, S., 2020. Energy-efficient and fast MAC protocol in UAV-aided wireless sensor networks for time-critical applications. Sensors 20 (9), 2635.
Prajapati, A., Trapasiya, S.D., 2016. Cross layer design approch for energy optimization in underwater acoustic sensor network. In: 2016 IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT). IEEE, pp. 1282–1286.
Qin, Z., et al., 2016. A joint duty cycle and network coding MAC protocol for underwater wireless sensor networks. In: 2016 25th International Conference on Computer Communication and Networks (ICCCN). IEEE, pp. 1–9.
Rahman, P., Karmaker, A., Alam, M.S., Hoque, M.A., Lambert, W.L., 2019. CUMAC-CAM: a channel allocation aware MAC protocol for addressing triple hidden terminal problems in multi-channel UWSNs. SN Appl. Sci. 1, 1–20.

Rahmati, M., Petroccia, R., Pompili, D., 2019. In-network collaboration for CDMA-based reliable underwater acoustic communications. IEEE J. Ocean. Eng. 44 (4), 881–894.
Rani, S., Ahmed, S.H., Malhotra, J., Talwar, R., 2017. Energy efficient chain based routing protocol for underwater wireless sensor networks. J. Netw. Comput. Appl. 92, 42–50. https://doi.org/10.1016/j.jnca.2017.01.011.
Roy, A., Sarma, N., 2017. Factors affecting MAC protocol performance in underwater wireless sensor networks. Int. J. Comput. Appl. 169 (5), 36–41.
S, A.S., Dhongdi, S.C., 2022. Review of underwater mobile sensor network for ocean phenomena monitoring. J. Netw. Comput. Appl. 205, 103418. https://doi.org/10.1016/j.jnca.2022.103418, 2022/09/01/.
Sakya, G., Sharma, V., 2019. ADMC-MAC: energy efficient adaptive MAC protocol for mission critical applications in WSN. Sustainable Computing: Informatics and Systems 23, 21–28.
Schneider, T.E., 2013. Advances in Integrating Autonomy with Acoustic Communications for Intelligent Networks of Marine Robots. Massachusetts Institute of Technology.
Shovon, I.I., Shin, S., 2022. Survey on multi-path routing protocols of underwater wireless sensor networks: advancement and applications. Electronics 11 (21), 3467.
Songzuo, L., Iqbal, B., Khan, I.U., Ahmed, N., Qiao, G., Zhou, F., 2021. Full duplex physical and MAC layer-based underwater wireless communication systems and protocols: opportunities, challenges, and future directions. J. Mar. Sci. Eng. 9 (5), 468.
Sotenga, P.Z., Djouani, K., Kurien, A.M., 2020. Media access control in large-scale Internet of Things: a review. IEEE Access 8, 55834–55859.
Std, I., 1997. 802.11, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications.
Su, Y., Jin, Z., 2016. UMMAC: a multi-channel MAC protocol for underwater acoustic networks. J. Commun. Network. 18 (1), 75–83.
Su, Y., Fan, R., Jin, Z., Fu, X., 2018. Design of an OFDMA-based MAC protocol for an underwater glider network with motion prediction. IEEE Access 6, 62655–62663.
Su, X., Ullah, I., Liu, X., Choi, D., 2020a. A review of underwater localization techniques, algorithms, and challenges. J. Sens. 2020 (1), 6403161.
Su, Y., Zhou, Z., Jin, Z., Yang, Q., 2020b. A joint relay selection and power allocation MAC protocol for underwater acoustic sensor network. IEEE Access 8, 65197–65210.
Su, Y., Liu, X., Han, G., Fu, X., 2021. A traffic load-aware ofdma-based mac protocol for distributed underwater acoustic sensor networks. IEEE Trans. Veh. Technol. 70 (10), 10501–10513.
Sun, Y., Gurewitz, O., Johnson, D.B., 2008. RI-MAC: a receiver-initiated asynchronous duty cycle MAC protocol for dynamic traffic loads in wireless sensor networks. In: Proceedings of the 6th ACM Conference on Embedded Network Sensor Systems, pp. 1–14.
Sun, N., Han, G., Wu, T., Jiang, J., Shu, L., 2015. A reliable and energy efficient VBF-improved cross-layer protocol for underwater acoustic sensor network. In: 2015 11th International Conference on Heterogeneous Networking for Quality, Reliability, Security and Robustness (QSHINE). IEEE, pp. 44–49.
Sun, D., Hong, X., Cui, H., 2022. A Kalman-based Doppler tracking algorithm for underwater acoustic spread spectrum communications. Appl. Acoust. 185, 108374.
Syed, A.A., Ye, W., Heidemann, J., 2008. T-Lohi: a new class of MAC protocols for underwater acoustic sensor networks. In: IEEE INFOCOM 2008-The 27th Conference on Computer Communications. IEEE, pp. 231–235.
Szymak, P., 2012. Comparison of centralized, dispersed and hybrid multiagent control systems of underwater vehicles team. Solid State Phenom. 180, 114–121.
Tan, H.-X., Seah, W.K., 2007. Distributed CDMA-based MAC protocol for underwater sensor networks. In: 32nd IEEE Conference on Local Computer Networks (LCN 2007). IEEE, pp. 26–36.
Tennenbaum, A., Dyakiw, M., Cui, J.-H., Peng, Z., 2014. Application of low cost optical communication systems to underwater acoustic networks. In: 2014 IEEE 11th International Conference on Mobile Ad Hoc and Sensor Systems. IEEE, pp. 755–758.
Tougaard, J., Hermannsen, L., Madsen, P.T., 2020. How loud is the underwater noise from operating offshore wind turbines? J. Acoust. Soc. Am. 148 (5), 2885–2893.
Ullah, I., Chen, J., Su, X., Esposito, C., Choi, C., 2019. Localization and detection of targets in underwater wireless sensor using distance and angle based algorithms. IEEE Access 7, 45693–45704.
Un, B.E., Yildiz, H.U., Tavli, B., 2021. Impact of critical node failures on lifetime of UWSNs with incomplete secure connectivity. In: 2021 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom). IEEE, pp. 1–6.
Wang, S., Zhao, D., 2020. A power control based handshake-competition MAC protocol for underwater acoustic networks. In: 2020 IEEE International Conference on Artificial Intelligence and Information Systems (ICAIIS). IEEE, pp. 665–669.
Wang, J., Shi, W., Xu, L., Zhou, L., Niu, Q., 2017a. Design of optical-acoustic hybrid underwater wireless sensor network. J. Netw. Comput. Appl. 92, 59–67.
Wang, J., Shi, W., Xu, L., Zhou, L., Niu, Q., liu, J., 2017b. Design of optical-acoustic hybrid underwater wireless sensor network. J. Netw. Comput. Appl. 92, 59–67. https://doi.org/10.1016/j.jnca.2017.02.014.
Wang, Y., et al., 2021. An acoustic/optic hybrid MAC protocol based on TDMA for underwater optical wireless networks. In: 2021 Asia Communications and Photonics Conference (ACP). IEEE, pp. 1–3.
Wang, R., Ma, R., Zhang, Y., Liu, G., Kang, W., 2023a. An energy-efficient multimode transmission scheme for underwater sensor network. IEEE Internet Things J. 10 (22), 19640–19654.
Wang, C., Shen, X., Wang, H., Zhang, H., Mei, H., 2023b. Reinforcement learning-based opportunistic routing protocol using depth information for energy-efficient underwater wireless sensor networks. IEEE Sensor. J. 23 (15), 17771–17783.
Wei, X., Zhao, L., Li, X., Zou, C., 2008. A distributed power control based MAC protocol for underwater acoustic sensor networks. In: 2008 4th IEEE International Conference on Circuits and Systems for Communications. IEEE, pp. 688–692.
Wei, X., Guo, H., Wang, X., Wang, X., Qiu, M., 2021. Reliable data collection techniques in underwater wireless sensor networks: a survey. IEEE Communications Surveys & Tutorials 24 (1), 404–431.
Xie, P., Cui, J.-H., 2007. R-MAC: an energy-efficient MAC protocol for underwater sensor networks. In: International Conference on Wireless Algorithms, Systems and Applications (WASA 2007). IEEE, pp. 187–198.
Xie, P., Cui, J.-H., Lao, L., 2006. VBF: vector-based forwarding protocol for underwater sensor networks. In: NETWORKING 2006. Networking Technologies, Services, and Protocols; Performance of Computer and Communication Networks; Mobile and Wireless Communications Systems: 5th International IFIP-TC6 Networking Conference, Coimbra, Portugal, May 15-19, 2006. Proceedings 5. Springer, pp. 1216–1221.
Xiong, S., Zhang, H., Zhu, X., Wang, J., Zhou, L., Zhu, M., 2016. Key technology and experimental research of underwater acoustic networks. In: 2016 IEEE/OES China Ocean Acoustics (COA). IEEE, pp. 1–5.
Yang, Q., Chen, Y., Dong, W., Li, T., Zhu, R., Huang, X., 2023. Cluster-based spatial–temporal MAC scheduling protocol for underwater sensor networks. IEEE Sensor. J. 23 (15), 17690–17702.
Ye, X., Fu, L., 2019. Deep reinforcement learning based MAC protocol for underwater acoustic networks. In: Proceedings of the 14th International Conference on Underwater Networks & Systems, pp. 1–5.
Ye, W., Heidemann, J., Estrin, D., 2004. Medium access control with coordinated adaptive sleeping for wireless sensor networks. IEEE/ACM Trans. Netw. 12 (3), 493–506.
Yuan, Y., Zhuo, X., Liu, M., Wei, Y., Qu, F., 2023. A centralized cross-layer protocol for joint power control, link scheduling, and routing in UWSNs. IEEE Internet Things J 11 (7), 12823–12833.
Zaheer, R., Ahmad, I., Habibi, D., Islam, K.Y., Phung, Q.V., 2023. A survey on artificial intelligence-based acoustic source identification. IEEE Access 11, 60078–60108.
Zaheer, R., Ahmad, I., Phung, Q.V., Habibi, D., 2024. Blind source separation and denoising of underwater acoustic signals. IEEE 12, 80208–80222.
Zayas, A.D., Merino, P., 2017. The 3GPP NB-IoT system architecture for the Internet of Things. In: 2017 IEEE International Conference on Communications Workshops (ICC Workshops). IEEE, pp. 277–282.
Zenia, N.Z., Kaiser, M., Ahmed, M., Mamun, S., Islam, M., 2015. An energy efficient and reliable cluster-based adaptive MAC protocol for UWSN. In: 2015 International Conference on Electrical Engineering and Information Communication Technology (ICEEICT). IEEE, pp. 1–7.
Zenia, N.Z., Aseeri, M., Ahmed, M.R., Chowdhury, Z.I., Shamim Kaiser, M., 2016. Energy-efficiency and reliability in MAC and routing protocols for underwater wireless sensor network: a survey. J. Netw. Comput. Appl. 71, 72–85. https://doi.org/10.1016/j.jnca.2016.06.005.
Zhang, J., Qiao, G., Wang, C., 2013. A Distance Aware Protocol for Underwater Acoustic Communication Networks.
Zhang, J., Lai, H., Xiong, Y., 2019a. Concurrent transmission based on distributed scheduling for underwater acoustic networks. Sensors 19 (8), 1871.
Zhang, Z., Shi, W., Niu, Q., Guo, Y., Wang, J., Luo, H., 2019b. A load-based hybrid MAC protocol for underwater wireless sensor networks. IEEE Access 7, 104542–104552.
Zhang, J., Hu, Z., Xiong, Y., Ning, G., 2020. A collision-free hybrid MAC protocol based on pipeline parallel transmission for distributed multi-channel underwater acoustic networks. Electronics 9 (4), 679.
Zhang, T., Gou, Y., Liu, J., Yang, T., Cui, J.-H., 2021a. UDARMF: an underwater distributed and adaptive resource management framework. IEEE Internet Things J. 9 (10), 7196–7210.
Zhang, W., Wang, X., Han, G., Peng, Y., Guizani, M., Sun, J., 2021b. A load-adaptive fair access protocol for MAC in underwater acoustic sensor networks. J. Netw. Comput. Appl. 173, 102867. https://doi.org/10.1016/j.jnca.2020.102867.
Zhang, Y., et al., 2022a. Reinforcement learning based relay selection for underwater acoustic cooperative networks. Rem. Sens. 14 (6), 1417.
Zhang, W., Li, J., Wan, Y., Yao, X., Li, M., 2022b. Machine learning-based performance-efficient MAC protocol for single hop underwater acoustic sensor networks. J. Grid Comput. 20 (4), 41.
Zhao, N., Yao, N., Gao, Z., Lu, Z., 2022. Deep reinforcement learning based time-domain interference alignment scheduling for underwater acoustic networks. J. Mar. Sci. Eng. 10 (7), 903.
Zhen, C., Feng, Y., Nie, D., Zhang, J., Ning, G., 2016. Transmission power allocation for underwater acoustic multicarrier-CDMA communication networks based on genetic algorithm. In: OCEANS 2016-Shanghai. IEEE, pp. 1–4.
Zhilin, I.V., Bushnaq, O.M., De Masi, G., Natalizio, E., Akyildiz, I.F., 2023. A universal multimode (acoustic, magnetic induction, optical, rf) software defined modem architecture for underwater communication. IEEE Trans. Wireless Commun. 22 (12), 9105–9116.
Zhou, Z., Peng, Z., Cui, J.-H., Jiang, Z., 2011. Handling triple hidden terminal problems for multichannel MAC in long-delay underwater sensor networks. IEEE Trans. Mobile Comput. 11 (1), 139–154.
Zhou, Y., Tong, F., Diamant, R., 2019a. A parallel decoding approach for mitigating near-far problems in underwater acoustic communications networks. In: Proc. Underwater Acoust. Conf. Exhibit, pp. 259–263.
Zhou, Y., Yang, H., Hu, Y.-H., Kung, S.-Y., 2019b. Cross-layer network lifetime maximization in underwater wireless sensor networks. IEEE Syst. J. 14 (1), 220–231.

Zhu, Y., Cui, J.-H., Peng, Z., Zhou, Z., 2014. Busy terminal problem and implications for MAC protocols in underwater acoustic networks. In: Proceedings of the 9th International Conference on Underwater Networks & Systems, pp. 1–8.
Zhu, S., Chen, X., Liu, X., Zhang, G., Tian, P., 2020. Recent progress in and perspectives of underwater wireless optical communication. Prog. Quant. Electron. 73, 100274.
Zhu, R., Boukerche, A., Li, D., Yang, Q., 2024. Delay-aware and reliable medium access control protocols for UWSNs: features, protocols, and classification. Comput. Network., 110631

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