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Review

A survey on energy efficiency in underwater wireless communications

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ABSTRACT

Underwater wireless communication (UWC) networks have attracted substantial attention in recent years. UWC can facilitate critical emerging services including communications for: Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs), environmental monitoring, surveillance, navigation, and exploration. Most UWC devices are battery-powered, where recharging/swapping batteries is not straightforward. Since the reliability of a UWC network depends on limited energy storage, energy-efficient communication is critical for its operation. Whilst communication range and data rate in UWC have been popular research topics, until recently, this energy-efficiency aspect of UWC has not received the same level of attention. In this paper, we provide a comprehensive literature review on existing contributions in the area of energy-efficient UWC. At first, we provide a detailed overview of UWC network architectures and relevant challenges for UWC networks. Next, we discuss and compare the most commonly-used UWC physical layer technologies, reviewing the existing physical layer power-saving techniques proposed in the literature. Then, we review various energy-saving techniques in the upper layers, including Medium Access Control (MAC) protocols, routing protocols, and localization techniques. Lastly, we provide a detailed discussion of alternative energy sources in UWC networks before highlighting future research directions in the field and challenges related to the widespread adoption of the Internet of Underwater Things (IoUT).

1. Introduction

Water bodies, such as rivers, seas, and oceans, cover almost three-quarters of the Earth's surface (Han et al., 2014). The exploration of these water bodies offers tremendous benefits across various application domains. The application domain of underwater wireless communication (UWC) can be broadly categorized into three groups: military, scientific, and industrial (Heidemann et al., 2012). Military applications involve diver-to-diver and/or diver-to-surface platform communications, border monitoring and control, underwater reconnaissance and surveillance, and submarine communications. The scientific endeavors that are enabled by UWC include studying water properties (e.g., temperature, pH, salinity, pressure and oxygen), aquatic lifeforms, and marine ecology. This also involves investigating tectonic plate movement, underwater volcanoes, and tsunami dynamics. Apart from these application domains, UWC is also widely used in industrial and commercial ventures for exploring oil and gas reservoirs, extraction of natural resources, monitoring underwater pipelines, and aquaculture (Gkikopouli et al., 2012; Saeed et al., 2019a). This long list of applications demonstrates the diverse range of fields in which UWC is beneficial.

Recent technological advancements in the field of underwater wireless communication networks (UWCN) have given rise to the phenomenon of the Internet of Underwater Things (IoUT) (Khalil et al., 2020). The IoUT is a lucrative domain for science, commerce, and the military. Consequently, it has attracted significant attention from both business and research communities (Saeed et al., 2019c). The subsea hardware equipment and installation market alone is estimated to grow into a US$100 million industry by 2025, according to an estimate made by Rystad Energy (Furuholmen et al., 2013). Additionally, according to a recent market report (Reportlinker, 2020), the global UWC market is forecast to grow into a US$2.3 billion industry by the year 2026, with a compound annual growth rate (CAGR) of 8.99%.

However, for the IoUT to be practical and functional, further research and development efforts are required in order to overcome severe communication challenges imposed by harsh underwater conditions. Amongst its many challenges, the major impediment to the growth of the IoUT is the severely energy-constrained nature of underwater environments.

Most underwater communication devices are battery-powered, where these batteries cannot be easily recharged or replaced frequently

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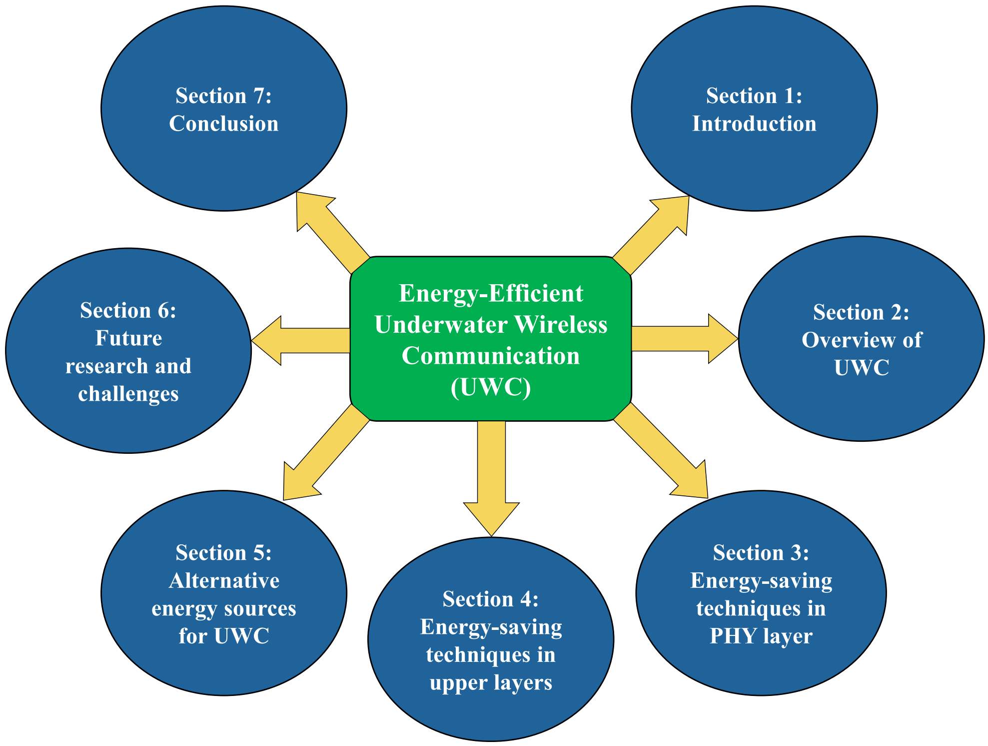


Fig. 1. Overview of this paper.

due to harsh underwater conditions and the expense of such operations. Therefore UWC design considerations must take into account the power consumption of underwater nodes so that network lifetime can be extended to a practicable duration. As Akyildiz and Vuran (2010) have highlighted in their work, the grand challenge in the large-scale adoption of UWCNs is overcoming limitations posed by energy consumption in underwater equipment. Improving overall network power consumption not only prolongs network lifetime but also saves huge operational costs for relevant stakeholders.

The other major challenge in UWC relates to the inherent physical properties of water. Conventional radio frequency (RF) technologies, which are widely used in the conventional over-the-air (OTA) medium, are impractical for data transmission underwater. The underwater medium does not possess the same physical (PHY) layer wave propagation characteristics as the OTA medium, causing RF to experience severe attenuation underwater. Therefore, establishing stable and reliable RF wireless communications in these environments becomes extremely difficult (Gussen et al., 2016).

To overcome this issue, alternative PHY layer technologies have been developed over the last few decades. Currently, the predominant PHY layer UWC technique is underwater acoustic communication (UAC). The use of underwater acoustics can be traced back a few hundred years; however, UAC has experienced rapid growth and accelerated technological development since World War II (Bjørnø, 2017). Besides UAC, other alternative PHY layer techniques such as underwater optical communication (UOC) and underwater magnetic induction communication (UMIC), have also gained in popularity due to their unique characteristics.

Each of these PHY layer technologies has its own merits and drawbacks (Mostafa et al., 2018). For instance, UAC offers a larger communication range at the cost of poor data rate and high power consumption along with multipath and Doppler spread issues (Gkikopouli et al., 2012). Conversely, UOC and UMIC can transmit data at higher speeds with lower power consumption but they suffer from shorter transmission ranges compared to UAC (Pranitha and Anjaneyulu, 2016; Kisseleff et al., 2018). Therefore, future robust, reliable, and energy-efficient UWC systems are likely to adopt multiple PHY layer technologies in a multimodal (Campagnaro et al., 2017) manner in order to deliver a more reliable and durable system.

In recent years, a flurry of research has been undertaken discussing the advances in the field of UWC, identifying fundamental issues, and proposing solutions to overcome various challenges for the next generation of UWC networks leading to the IoUT (Ali et al., 2019a; Li et al., 2019a; Fattah et al., 2020; Boukerche and Sun, 2020). A recently published editorial (Song et al., 2019) has explored the current state-of-the-art in the UAC domain within the PHY layer and network layer stacks, before addressing implementation issues and opportunities for further research toward low cost, widely-adopted, and readily available UAC technologies. Besides UAC, UMIC is also a promising PHY layer technology for future UWC, as discussed in Jouhari et al. (2019), creating new horizons toward enabling the capability of wireless power transfer (WPT) in UWCNs; hence, promising longer network lifetimes. More recently, work in Jahanbakht et al. (2021) has explored the relationship between IoUT and Big Marine Data (BMD) analytics, starting with underwater sensors and leading to machine learning (ML) solutions and future research directions in the field.

Although these recent review works include some discussion regarding energy consumption issues in UWC, almost none of these articles have addressed this aspect from a pure energy-efficiency point of view. Additionally, most of the review articles that can be found in the literature deal with a specific layer of the protocol stack. For instance, a number of surveys on underwater medium access control (MAC) protocols (link layer) have been published in Chen et al. (2014), Zenia et al. (2016), Jiang (2017) and Al Guqhaiman et al. (2020). Additionally, various survey works on underwater routing protocols (network layer) have been conducted in Ayaz et al. (2011), Khalid et al. (2017), Khan et al. (2018), Islam and Lee (2019b) and Khan et al. (2020), Luo et al. (2021); and works on underwater localization techniques (application layer) have been reviewed in Erol-Kantarci et al. (2011), Fengzhong et al. (2016a), Luo et al. (2018a), and Islam and Park (2020). These reviews only discuss energy consumption in addition to the other various challenges within a single layer of the protocol stack.

Table 1
Relevant surveys and their contributions, scopes, and limitations.

Survey	Year	Main contribution	Scope	Limitation
Jouhari et al. (2019)	2019	Provides a comprehensive survey on existing works related to two common PHY layer UWC techniques: UAC and UMIC.	Covers research on two enabling technologies for UWC: UAC and UMIC, their channel propagation characteristics, challenges, and proposals to overcome these challenges.	Energy-efficiency is not the core focus of this work.
Ali et al. (2019a)	2019	Provides a comprehensive overview of latest research projects and emerging topics in UWC with a comparative analysis of UAC, UOC, underwater electromagnetic communication (UEMC).	Highlights related issues of each enabling UWC technology with future prospects and provides recommendations for next generation enabling technologies in UWC.	Similar to Jouhari et al. (2019), energy-efficiency is not the focus of this survey.
Li et al. (2019a)	2019	Provides an in-depth review on UAC, UOC, underwater routing protocols, MAC protocols, multi-modal networks, and machine learning (ML)-based proposals in UWC.	Covers reliability aspects if UWC, highlighting the challenges to achieve reliability and offers recommendations to overcome them.	Similar to Jouhari et al. (2019) and Ali et al. (2019a), energy-efficiency is not the core focus of this work.
Fattah et al. (2020)	2020	Identifies the essential features of UWCN and provides a thematic taxonomy to classify existing literature on UWCN.	Discusses various aspects of UWCN such as: simulation platforms, network elements, enabling technologies, routing protocols, security, and applications.	Reviews works on energy-efficient underwater routing protocols (network layer) only; does not review energy-efficient techniques in other layers.
Boukerche and Sun (2020)	2020	Reviews and divides existing approaches in UAC into two categories: data gathering techniques and data forwarding techniques.	Categorizes research on node deployment and target detection algorithms into the data gathering category; and research on routing protocols, MAC protocols, and localization techniques into the data forwarding category.	Discussion is limited to UAC networks only; and similar to other surveys, energy-efficiency is not the primary focus of this paper.
This survey	2021	Provides a comprehensive survey of works that are primarily concerned about energy-efficiency in underwater wireless communications. Since underwater communication nodes are battery/power-constrained, energy-efficiency is a critical requirement for sustainable network lifetime and reliability. Consequently, the energy-efficiency aspect requires special attention.	Provides a comprehensive survey on energy-efficient techniques in UWC which is the main focus throughout the paper, whilst covering related research on energy-savings within various layers of the protocol stack, alternative energy sources, and future research directions for energy-efficient UWC.	

Based on the discussion above and Table 1, it can be observed that there is a lack of research compiling works on energy-saving techniques within individual layers of the protocol stack into one complete, comprehensive study to provide UWC system designers an overall, holistic perspective of energy consumption issues in UWC, along with the possible solutions available in the literature.

The major contributions of this work are as follows:

- Firstly, we provide a comprehensive review of the literature on green UWC and IoUT, including energy-saving techniques used in various layers of the protocol stack: physical, data link, network, and application layers. This review is intended to guide UWC network designers in forming improved green communication protocols and techniques, extending pathways toward green IoUT.
- For the physical layer, we provide a detailed comparison of the most-commonly used UWC physical layer technologies before discussing energy-efficient multi-modal UWC, power control, modulation, coding, and compressed sensing techniques proposed in the literature.
- For the upper layers, we provide a detailed discussion of energy-efficient MAC and routing protocols and localization techniques proposed in the literature.
- Further, we provide a detailed discussion of state-of-the art alternative energy sources to power the next-generation of UWCN and IoUT devices.
- Lastly, we discuss the possible future research directions for green IoUT and the challenges that these techniques need to overcome in order to develop green IoUT.

As illustrated in Fig. 1, we have organized the remainder of this paper as follows. In Section 2, we provide a detailed overview of UWCN architectures and the many challenges in UWC. Next, we discuss the energy-saving techniques applicable to the PHY layer of the UWC protocol stack in Section 3. This is followed by a detailed review in Section 4 of the energy-saving techniques in the upper layers of the protocol stack including energy-efficient MAC and routing protocols, and localization techniques. In Section 5, we study the most recent works on alternative energy sources and methods for powering UWCNs. We then explore future research opportunities and identify challenges for the development of green UWCNs in Section 6 before concluding this article in Section 7.

2. Overview of underwater wireless communication networks

This section provides an overview of UWCN in terms of its architecture, channel propagation models, and discusses the major communication challenges of UWCN.

2.1. Underwater wireless communication network architectures

A UWCN architecture is illustrated in Fig. 2, consisting of several communication nodes (CN) situated underwater and base stations (BS) located on the water surface. CNs can be classified in terms of their mobility as fixed, ballast, and floating nodes (Gkikopouli et al., 2012). As the name suggests, fixed nodes are attached to the bottom of the ocean beds and are responsible for collecting underwater data. Ballast nodes are comprised of remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs), which are generally mobile.

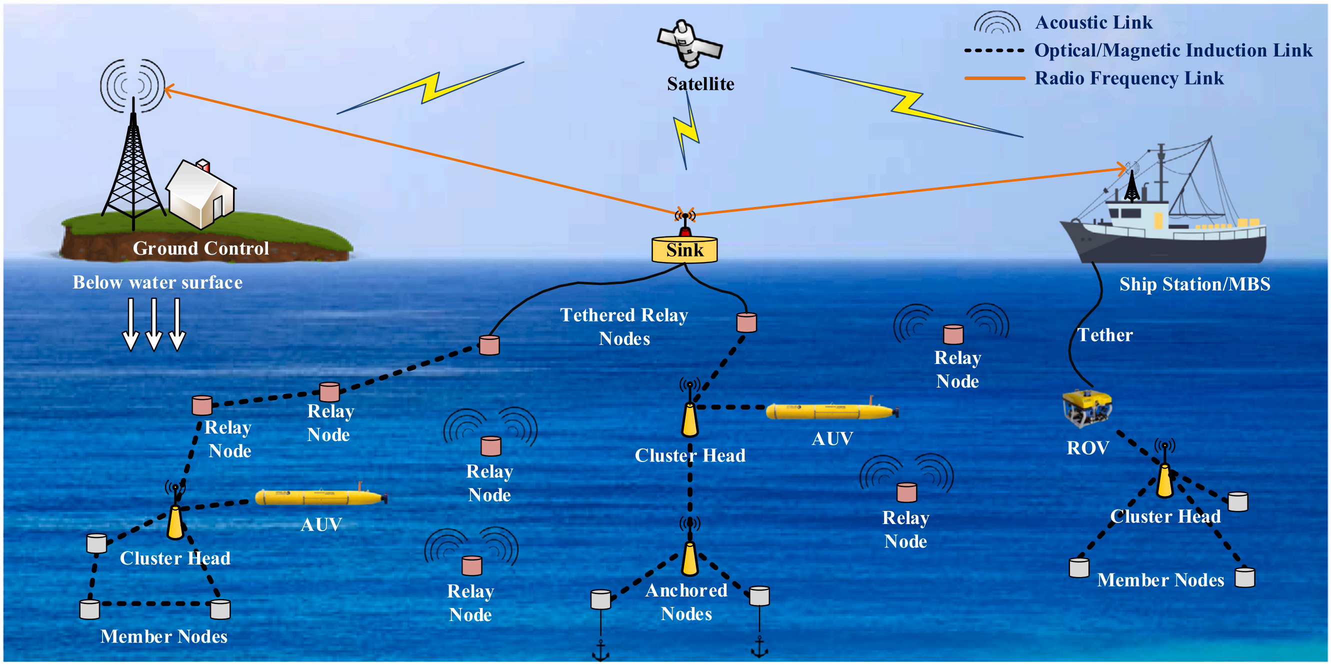


Fig. 2. Underwater wireless communication network scenario.

These vehicles collect data acquired by the anchored nodes and are often responsible for recharging nodes (Mostafa et al., 2018). Lastly, floating nodes are nodes with weights attached to them, making them either submerged in water or buoyant on the surface of the water as per requirement.

Some CNs can act as relay nodes (RN) to increase communication range when optical/magnetic induction links are used by cluster heads (CH) for collecting data from other nearby member nodes (MN) within a cluster. Data collected from CNs are aggregated in CHs and then forwarded to BSs or surface sinks (SS) or any ship station. The data from BS/SS is then forwarded to a ground control center using RF links, where the operator is located, and/or uploaded to satellites for redundancy.

The works in Akyildiz and Vuran (2010) and Gkikopouli et al. (2012) have discussed three UWCN architectures: static 2D, static 3D, and dynamic 3D AUV/ROV; however, as Akyildiz and Vuran (2010) have mentioned in their work, node deployment options are not limited to these three architectures only and the deployment strategy may vary depending on the specific underwater application. A brief description of the three architectures discussed in Akyildiz and Vuran (2010) and Gkikopouli et al. (2012) has been given below:

1. Static 2D — Used for two-dimensional ocean floor monitoring purposes. Here, CNs are all deployed at the same vertical distance from the water surface, where they communicate with horizontal communication links. Applications for these architectures include ocean floor monitoring for investigating environmental phenomena and plate tectonic activities. This architecture is illustrated in Fig. 3(a).
2. Static 3D — Used for three-dimensional ocean column monitoring purposes, where CNs can be deployed at various vertical distances from the water surface and they communicate with both horizontal and vertical wireless communication links. Applications for these 3D architectures include monitoring water pollution and oceanic biochemical processes, and military surveillance. This type of architecture is illustrated in Fig. 3(b).
3. Dynamic 3D AUV/ROV — Used for three-dimensional communication comprised of both static nodes and dynamic mobile/ballast nodes, such as AUVs and ROVs. This architecture finds its use in oceanography, environmental monitoring and other resource studies. Fig. 2 provides a good description of this UWCN architecture.

Each PHY layer wireless communication technology has a different channel response based on the chemical composition and physical condition of the water. For instance, properties such as water temperature, pressure, turbidity, and salinity have a large impact on acoustic communication. Contrastingly, other properties such as water acidity, chlorophyll and phytoplankton concentration, and water turbidity, all affect optical communication. Water salinity adversely affects electromagnetism-based PHY layer technologies such as RF and MI. Therefore, it is desirable for designers to consider the chemical composition of water to determine the best PHY layer technology to be used for communication.

Since UAC is the dominant PHY layer technology in UWC, it is also vital for network designers to consider various sound propagation models available in the literature. Using appropriate models can accurately capture sound propagation characteristics underwater. To this end, Morozs et al. (2020) have categorized the channel models found in the literature into three categories: binary range-based model, analytical transmission loss model, and specialized channel model. Binary range-based modeling is a simplistic approach that assumes binary connectivities among nodes with a fixed sound propagation speed of 1500 m/s. The analytical transmission loss model, otherwise known as the Urick model, takes a mathematical approach by expressing spreading loss as a function of the transmission distance between transceivers and absorption loss as a function of the transmission frequency (Urick, 1996). The third category consists of models based on beam/ray tracing techniques (Hovem, 2013), examples of which include BELLHOP (Porter, 2011) and World Ocean Simulation System (WOSS) (Guerra et al., 2009). Ray tracing calculates the trajectories of sound rays emanating from a source. When the speed of sound is not constant, as is the case in the underwater medium, the rays follow curved paths rather than straight lines; hence making this type of modeling particularly useful in underwater scenario.

To further assist network designers, we present a comparison of the four PHY layer UWC technologies based on their characteristics, highlighting their strengths and weaknesses in Table 2. Afterwards, we

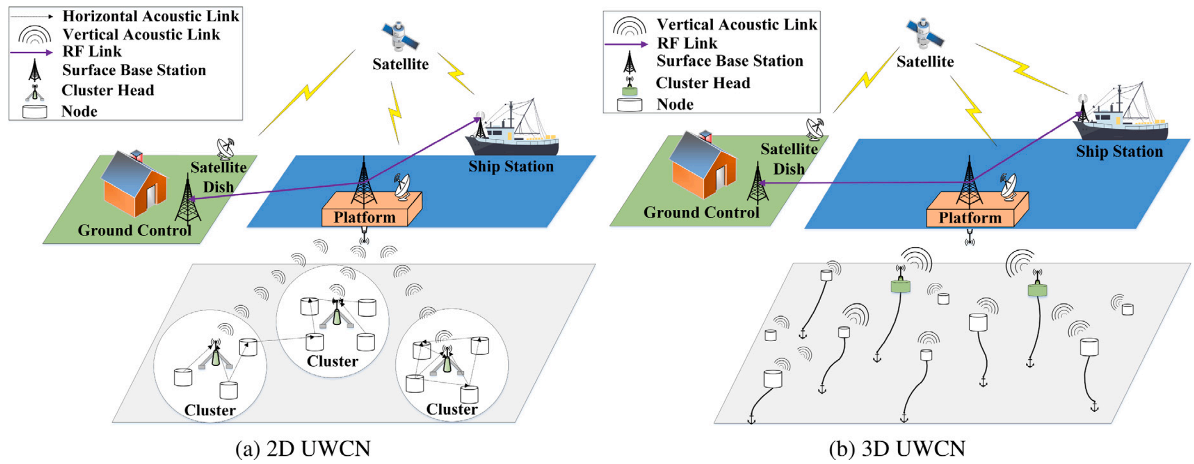


Fig. 3. Static 2D and 3D UWCN architectures.

provide a detailed discussion of each of these PHY layer technologies in Section 3, beginning with UAC, and followed by UOC, URFC and UMIC technologies, respectively.

2.2. Challenges in underwater wireless communication

Traditional underwater monitoring techniques involved deploying measurement instruments/nodes into water, using them to record data, retrieving them to the surface, and then extracting the collected data (Akyildiz and Vuran, 2010). However, these traditional techniques have several disadvantages.

Firstly, the data retrieval is not real-time, therefore time-critical data is often missed by the operator, which proved detrimental to operation. Secondly, the network cannot be easily reconfigured using control signals, as per requirement, which makes it inflexible in dynamic underwater environments. Thirdly, the data storage capacities of these instruments/nodes are extremely limited, and, therefore, it takes several iterations of the whole process to collect meaningful amount of data, which in turn increases costs of operation.

To overcome these challenges, it is optimal to strategically deploy wireless communication nodes to a target area of the water body, which offers real-time communications between underwater nodes and operators on the surface, enabling remote data collection and network re-configuration capabilities using control signals as per demand.

Although UWCNs have several benefits, they also have some drawbacks — attributed mostly to harsh underwater channel characteristics. The major issues in underwater networks are as follows:

- Power — As discussed previously, the battery power of underwater nodes is one of the largest constraints hindering the growth of the IoUT. Batteries in nodes cannot be easily recharged or replaced frequently due to harsh underwater conditions and the expense of these operations. Therefore design considerations of underwater networks must take into account the power consumption of underwater nodes to extend network lifetime to at least as long as the project duration.
- Propagation delay — Underwater RF propagation delay is at least five times greater than that in OTA medium. Due to severe attenuation, RF is almost never used for UWC. The dominant PHY layer technology currently used underwater is acoustics. However, the slow propagation speed of sound underwater introduces large propagation delay in data communication, resulting in multipath, intersymbol interference (ISI), and Doppler issues.
- Channel impairments — The underwater channel is highly dynamic due to water turbulence and node mobility. Additionally, underwater objects such as marine life, plantations, and contours can lead to multipath and fading issues for UAC. Moreover UOC demands unobstructed, perfect alignment of the transmitter–receiver pair so that data can be transmitted using light. Therefore, varying water currents and waves can easily impair optical links and cause signal degradation.
- Bit Error Rate (BER) — UWC suffers from high BER due to the highly dynamic environment resulting in temporary losses in connectivity between CNs. High BER requires intelligent receiver design with adaptive error correction features that can yield robust UWCNs against high channel uncertainties.
- Security (Jiang, 2018) — Data transmission within UAC networks can be easily eavesdropped, whereas UOC networks can be easily detected visually. Moreover, the energy-constrained nature of UWCNs and harsh channel characteristics pose severe restrictions on deploying canonical energy-hungry cryptographic techniques, such as encryption, in these networks. Since the military is one of the largest stakeholders in this domain, securing communication channels for transmission of mission-critical information is a major issue that needs to be addressed. UMIC is a promising PHY layer technology in this aspect because it is more difficult to intercept electromagnetic waves compared to sound and optics.

As per Akyildiz and Vuran (2010), the greatest challenge in the large-scale adaptation of UWCNs, and ultimately the IoUT, is energy. The motivation for this review has arisen due to this necessity of addressing the energy consumption implications of UWCNs, and assisting network designers with inspiration for conceiving and formulating solutions that lead to green UWCs.

3. Energy-saving techniques in the physical layer

In this section, we provide a detailed discussion of each PHY layer technologies currently used for UWC, and provide a comparative summary in Table 2. In addition to the discussion of each technology, we also review the state-of-the-art energy-saving proposals in the PHY layer of the protocol stack in the later part of this section. It should be noted here that the adoption of optics and magnetic induction technologies for UWC can also be considered as energy-saving techniques in the PHY layer when compared to traditional acoustics.

3.1. Underwater acoustic communication (UAC)

Underwater Acoustic Communication (UAC) is the most widely used PHY layer technology in UWCNs, facilitated by the modulation of acoustic sound waves generated from an acoustic transducer. The propagation speed of sound underwater (≈ 1500 m/s) is greater than that in air (≈ 343 m/s) (Muzzammil et al., 2020). The speed of sound is a proportional function of the water temperature, salinity, and depth.

Table 2
Comparison of existing PHY layer UWC technologies.

Features	PHY layer techniques			
	UAC (acoustic)	UOC (optical)	UMIC (magnetic induction)	URFC (radio frequency)
Energy efficiency	Exhibits low energy-efficiency (≈100 bits/Joule for several km) due to high energy consumption (Han et al., 2014)	Offers better energy-efficiency than acoustic communication (≈30,000 bits/Joule at 100 m) (Han et al., 2014)	Theoretical approximation shows UMIC may consume less power than acoustic and optical offering 0.4–2 Gbits/J at a transmission range of 180 m (Gulbahar and Akan, 2012)	More power-hungry than UAC and UMIC, transmitting at ≈9850 bits/Joule for 10 m range (Gulbahar and Akan, 2012)
Range	Offers long distance communication (in km) (Sozer et al., 2000; Stojanovic, 2006; Akyildiz et al., 2015)	Lower transmission range than acoustic (10–100 m) (Akyildiz et al., 2015)	Lower range than acoustic and optical, however use of magnetic waveguides techniques can increase range (10–100 m) (Akyildiz et al., 2015; Li et al., 2019b)	Suffers from high attenuation in conductive seawater (Akyildiz et al., 2015) and therefore has lower transmission range than optical and acoustic ($\leq$ 10 m) (Stojanovic, 2006)
Date rate	Low (in kb/s) (Akyildiz et al., 2015; Pompili and Akyildiz, 2009)	High (from Mb/s to Gb/s) (Zeng et al., 2016; Johnson et al., 2014; Khalighi et al., 2014)	High (in Mb/s) (Akyildiz et al., 2015)	High (in Mb/s) (Akyildiz et al., 2015)
Speed	Speed of sound underwater is ≈1500 m/s depending on water conditions such as depth, temperature, pH, and pressure (Gulbahar and Akan, 2012)	Optical beam travels at approximately the speed of light ($2.2–3\times10^8$ m/s) underwater (Gulbahar and Akan, 2012)	The propagation speed of EM waves is dependent on electric permittivity and magnetic permeability of the medium (Qureshi et al., 2016). For seawater, the frequency of the wave also needs to be taken into consideration (Qureshi et al., 2016).	Belonging to the EM spectrum, the propagation speed of RF waves is also dependent on electric permittivity and magnetic permeability of the medium and the frequency of the wave also needs to be taken into consideration to determine its speed in seawater (Qureshi et al., 2016)
Equipment cost	Expensive and heavy equipment required with larger antennae for greater ranges (Zeng et al., 2016; Wang et al., 2019) (antenna size 0.1 m)	Lower cost of equipment than acoustic (antenna size ≈0.1 m)	Small coils with antenna size of 0.15 m is sufficient for effective transmission (Wang et al., 2019)	Expensive equipment and larger antennae size required ≈0.5 m
Security	Unsecured communication (can be listened easily) (Akyildiz et al., 2015)	Unsecured communication (can be seen easily) (Akyildiz et al., 2015)	Offers more secured communication (Jouhari et al., 2019; Akyildiz et al., 2015) than acoustic and optical	Offers secured communication (Akyildiz et al., 2015)
Others	Suffers from large propagation delay (Zeng et al., 2016), multi-path and Doppler effects (Akyildiz et al., 2015); has adverse effects on aquatic lifeforms (Zeng et al., 2016)	No adverse effects on aquatic lifeforms (Zeng et al., 2016); affected by water turbidity and absorption (Akyildiz et al., 2015; Jaruwatanadilok, 2008); requires line of sight (LOS) communication (Zeng et al., 2016; Akyildiz et al., 2005)	Predictable and stable channel response (Akyildiz et al., 2015); not affected by multi-path and Doppler effects (Akyildiz et al., 2015); offers wireless power transfer capabilities (Yang et al., 2019); no known adverse effects on aquatic lifeforms (Sharma et al., 2016); affected by coil orientation and positioning (Muzzammil et al., 2020); affected by conductive seawater (Akyildiz et al., 2015)	Not affected by turbidity or turbulence (Che et al., 2010) unlike optical; no known adverse effects on aquatic lifeforms (Sharma et al., 2016); suffers from multi-path issues as acoustic (Akyildiz et al., 2015)

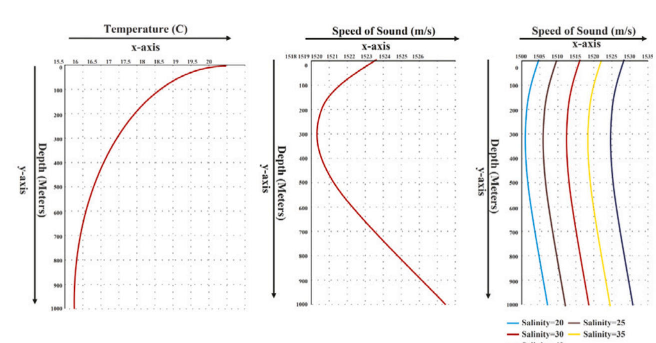
The underwater acoustic sound speed profile (SSP) for depths less than 1000 meters is given by (Gussen et al., 2016) and (Jensen et al., 2011)

$$c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.01T)(S - 35) + 0.016z, \quad (1)$$

where T is the water temperature (°Celsius), S denotes water salinity (parts per thousand (ppt)), and z is the depth of water (m).

This relationship is illustrated in Fig. 4, where it can be deduced that oceanic temperature decreases with increasing depth. Further, the speed of sound drops to a minimum until a certain depth threshold after which it starts to rise again. Additionally, it can be observed that the speed of sound is higher for greater saline concentration in water.

Although sound propagates faster in the water medium than the air medium, it is slower compared to the speed of light underwater (e.g. 2.25×10^8 m/s). A comparison of the propagation speeds of each can be found in Gulbahar and Akan (2012). Nevertheless, acoustic communication can be used extensively for UWC due to its long propagation



(a) Temperature versus depth (b) Sound speed versus depth (c) Salinity versus depth

Fig. 4. Relationship between the speed of sound, water temperature, salinity, and depth (Awan et al., 2019).

Table 3
Relationship between range, bandwidth, and data rate in UAC (Kaushal and Kaddoum, 2016).

Distance	Range (km)	Bandwidth (kHz)	Data rate (kbps)
Very Long	1000	< 1	≈ 0.6
Long	10–100	2–5	≈ 5
Medium	1–10	≈ 10	≈ 10
Short	0.1–1	20–50	≈ 30
Very Short	< 0.1	> 100	≈ 500

Table 4
Indicative extinction coefficients for various water types (Simpson et al., 2012).

Water Type	c (m^{-1})
Clear ocean	0.152
Coastal ocean	0.399
Harbour	2.195

ranges (up to several tens of kilometers) where RF communication is not possible (Muzzammil et al., 2020).

The range of UAC is heavily dependent on the carrier frequency of the wave and its bandwidth. Kaushal and Kaddoum (2016) have classified acoustic links as very short, short, medium, long, and very long based on transmission distance. Long-range UAC uses lower frequency carrier waves within the range of 30–300 Hz (Gkikopouli et al., 2012); however, the resulting bandwidth and data rate drops dramatically within this frequency range. In contrast, carrier frequencies up to 1 MHz can be utilized to yield a larger bandwidth and data rate, but then the signal suffers from severe absorption; therefore, the communication range diminishes dramatically to only a few meters (Pranitha and Anjaneyulu, 2016). Table 3 (Kaushal and Kaddoum, 2016) shows the relationship between the range and bandwidth as well as the data rate used in UAC.

Since useful bandwidth in UAC is low, the rate of data transmission for each channel utilization is also low. Additionally, due to the relatively lower speed of propagation, the round-trip time (RTT) of a signal between transmitter and receiver is higher, resulting in undesirable Doppler effects. Moreover, communication nodes underwater are highly mobile due to the inherent dynamic characteristics of the aquatic medium, which contributes further to the already existing Doppler effects. Furthermore, acoustic waves suffer from signal distortions and multipath fading, resulting in inter-symbol interference (ISI), which must be compensated for at the receiver end (Gussen et al., 2016; Pranitha and Anjaneyulu, 2016). In addition to these adverse effects, acoustic waves also pose a threat to underwater lifeforms, in particular whales and dolphins.

Due to these drawbacks of UAC, other PHY layer technologies have been investigated over the years. One viable alternative to UAC is underwater optical communication (UOC) which is addressed in the following subsection.

3.2. Underwater optical communication (UOC)

Underwater optical communication (UOC) uses electromagnetic (EM) waves in the visible light range for communication. The literature indicates that UOC suffers the least attenuation in the blue–green wavelength of 450-–550 nm of the EM spectrum (Hanson and Radic, 2008; Anguita et al., 2010; Alipour and Mir, 2018), which translates to extra high frequency (EHF) ranges of communication.

Compared to UAC and underwater radio frequency communication (URFC), UOC has certain advantages. UOC is more energy-efficient compared to UAC and URFC (Zeng et al., 2016), as we have presented in Table 2. Moreover, UOC transducers, generally containing low-cost light-emitting diodes (LEDs), laser diodes (LDs), and micro-LEDS (μ-LEDs), are more compact and less bulkier than UAC and URFC transducers, making them convenient and less expensive devices to deploy and maintain.

Besides the inherent energy-saving properties of UOC, a number of research works have been published recently where energy-efficient techniques in UOC are discussed. Zeng et al. (2016) suggest that compared to non-return-to-zero on–off keying (NRZ-OOK) modulation, the return-to-zero OOK (RZ-OOK) modulation scheme can yield greater energy efficiency in UOC. Further, pulse position modulation (PPM) scheme can save more power in UOC than OOK; however the former yields a lower bandwidth utilization rate and requires more complex hardware. More recently, the authors in Saeed et al. (2019c) have provided a comprehensive survey on the advances of UOC, its challenges and future prospects from a layer by layer standpoint. The authors discuss various energy-efficient routing and energy harvesting techniques related to UOC in their research.

Further energy-efficiency can be achieved in UOC by implementing dynamic adjustments to transmission power based on channel state information (CSI) because optical beam is affected by the murkiness of water. Turbid water requires higher transmission power than clear water. Smart optical transducers that can implement transmission power control (TPC) can yield better energy-efficiency in UOC. We have provided a more in-depth discussion on TPC and other energy-saving techniques in Section 3.6, some of which are also applicable for saving energy in UOC.

Apart from better energy-efficiency, Doppler effects in UOC as compared to UAC are negligible because the speed of light is 4–5 times greater than the speed of sound in fluids (Gussen et al., 2016). Additionally, because UOC operates at the speed of light, it offers higher data rates of up to gigabits per second (Gbps) (Fletcher et al., 2015; Sun et al., 2020).

Additionally, seawater behaves as a dielectric medium for frequencies greater than 250 GHz (Alipour and Mir, 2018). Since UOC transducers operate at higher frequencies, seawater behaves as a dielectric medium for UOC. This is advantageous when compared to RF because the water acts as a conductor for RF, restricting it to only low frequency communication. Since EM waves suffer from lower attenuation in dielectric media as opposed to conductive media, optical communication suffers lower attenuation than RF in water media, making optical mode a better option for communication compared to RF. Further, UOC operates within the unlicensed EM spectrum, making it a more economical option compared to RF which operates at the expensive, licensed spectrum.

Although UOC has a few advantages over other PHY layer technologies, it also has some drawbacks. One major drawback for UOC results from its dependence on water turbidity or murkiness. Optical communication is not plausible in highly turbid water because it results in a higher extinction/attenuation coefficient (c) that adversely affects the UOC signal-to-noise ratio (SNR). The attenuation coefficients for various water types are presented in Table 4. As mentioned above, propagation distance for UOC reduces considerably with increasing water turbidity because it affects SNR. This relationship is illustrated in Fig. 5.

The other major drawback for UOC is its requirement for line-of-sight (LOS) communication. In this manner, optical transmitters and receivers need to be perfectly aligned to establish and maintain a reliable communication link. Maintaining LOS in underwater environments is difficult because the environment is highly dynamic. Additionally, underwater vegetation and lifeforms can also interfere with LOS between optical transceivers. Although non line-of-sight (NLOS) communication can be performed, it increases BER and power consumption considerably (Sun et al., 2020).

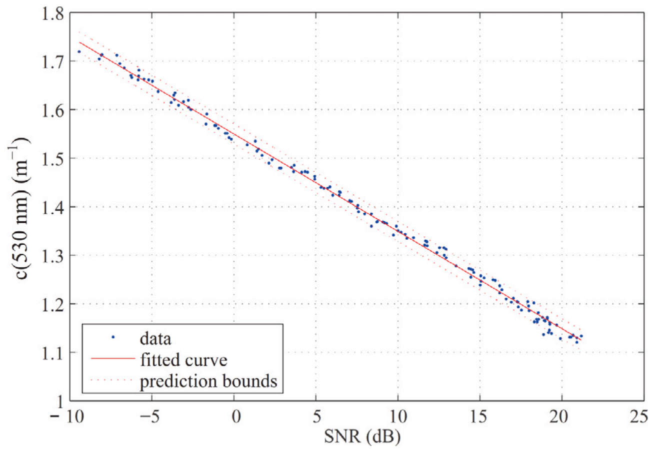


Fig. 5. Relationship between attenuation coefficient and SNR in UOC (Simpson et al., 2012)..

3.3. Underwater radio frequency communication (URFC)

URFC propagation characteristics are strikingly different from conventional OTA wireless communication characteristics. Underwater RF waves suffer from severe propagation loss, environmental noise, Doppler effect, and are extremely frequency-selective (Gussen et al., 2016). Although RF waves offer high data throughput over extremely short distances, this feature is of minor use.

The major obstacle to underwater RF communication is channel attenuation. Underwater RF channel attenuation is a proportional function of water permeability, conductivity, and frequency of radio waves, as shown in Eq. (2)

$$\alpha(f) = \sqrt{\pi\sigma\mu_0}\sqrt{f} = \kappa\sqrt{f}, \tag{2}$$

where f represents the radio carrier frequency, σ represents the water conductivity and μ_0 represents the permeability of the vacuum at approximately $4\pi \times 10^{-7}$.

While the permeability for both freshwater and seawater is approximately the same, conductivity is considerably different. This is because water conductivity is a function of water salinity and temperature, and due to its high salinity, seawater has greater conductivity. Seawater conductivity is measured to be 4.3 S/m as compared to the 0.001–0.01 S/m found in freshwater. Since URFC attenuation is a function of channel conductivity, RF waves suffer a higher attenuation in seawater than in freshwater. Therefore, higher frequency RF waves are not useful in seawater because of its high conductivity (Gussen et al., 2016).

Moreover, high-frequency RF waves contribute to larger attenuation. Therefore, only low-frequency RF waves are preferred in underwater RF communications. Accordingly, Extremely Low Frequency (ELF) and Very Low Frequency (VLF) waves in the range of 3 - 30 kHz are used for underwater communication within short ranges. Since bandwidth is extremely narrow, the transmission rate offered by these waves is remarkably low as well. However, ELF and VLF equipment are costly, cumbersome, and power-hungry, rendering them impractical for use in underwater environments (Pranitha and Anjaneyulu, 2016).

3.4. Underwater magnetic induction communication (UMIC)

Communication using magnetic induction (MI) is based on Faraday's law of electromagnetic induction. The law states that a conducting coil placed within a varying magnetic field induces a current in the coil. Since the opposite is also true, (a time-varying current passing through the coil induces a magnetic field), MI communication utilizes this idea to form a magnetic communication link between a transmitter and a receiver. Fig. 6 illustrates this idea.

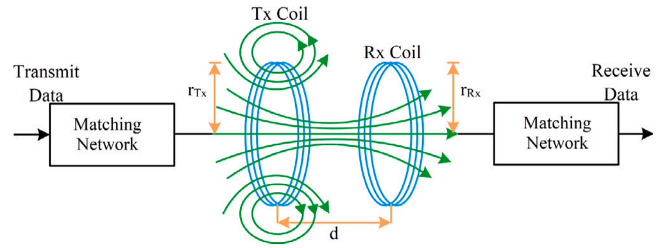


Fig. 6. MI communication technique (Muzzammil et al., 2020).

Accordingly, the transmitted magnetic flux density from the transmitter coil is given by (Muzzammil et al., 2020)

$$\mathbf{B} = \frac{\mu_0 \mu_r N I(t) A}{4\pi d^5 \hat{B}}, \tag{3}$$

where μ_0 denotes the magnetic permeability constant ($4\pi \times 10^{-7}$ H/m), μ_r denotes the relative permeability of the medium, N is the number of turns in the coil, $I(t)$ is the time-varying current in the coil, A denotes the coil area, and d represents the distance between the transmitter and the receiver coil.

A major advantage of MI communication is that μ_r for both air and water media is approximately the same; therefore, induced magnetic flux density remains the same in underwater medium as in air medium. Conversely, magnetic field strength decays at a cubic rate with the distance ($1/d^3$) between the transmitter and receiver, suffering rapid attenuation with increasing distance. However, techniques such as MI waveguides using relay coils, proposed in Sun and Akyildiz (2010), Masihpour and Agbinya (2010), Kisseleff et al. (2015), and Gulbahar and Akan (2017) can enhance the MI communication ranges to up to 100 m. Other challenges for underwater MI communication arise from magnetic coil orientation and alignment (Muzzammil et al., 2020) and seawater conductivity (Akyildiz et al., 2015). Nevertheless, MI offers several advantages in terms of power consumption, wireless power transfer, and high speed communication (Akyildiz et al., 2015; Yang et al., 2019; Sun et al., 2020).

3.5. Energy-saving techniques in underwater hardware

The choice of hardware used in UWC including transducers, analog electronic circuits, digital signal processors (DSPs), microcontrollers, modems, and batteries is one of the main factors affecting energy-efficiency. The hardware unit of an underwater node generally consists of the following modules: sensing, communication, power supply and energy management, and processing module (Viana et al., 2016).

Sensing modules are comprised of varied underwater sensors such as temperature, pressure, pH, and oxygen sensors, based on application requirements. Communication modules, as the name suggests, accommodate transducers, receivers and other devices necessary for communication. Power supply and energy management modules ensure proper supply and distribution of battery power amongst all other modules; and thus regulate energy consumption. Processing modules house the most vital components that coordinate the operation of all other modules, whilst facilitating signal processing, algorithm execution, data sampling, and data storage functions. The authors in Luo et al. (2017b) have published a comprehensive survey of various underwater hardware experimentation and simulation platforms, which can be useful to many network designers to learn about a range of UWC simulators that can be used to test designs before hardware implementation.

In the following subsections, we review some of the energy-saving techniques that have been implemented in underwater hardware components. In particular, we discuss energy-efficient underwater transducers proposed in the literature and then review related works on circuitry technologies for signal processing in both analogue and digital circuits. Next, we review some of the existing battery manufacturing technologies that save power in UWC.

3.5.1. Energy-saving techniques in underwater transducer manufacturing

Transducers are vital components in UWC that can convert one form of energy (mechanical, magnetic, optical, electrical) to other forms, and vice versa; and thus enable signal detection in underwater environments. For UWC, transducers can be categorized as projectors (transmitters) and hydrophones (receivers). The authors in Sherman and Butler (2007) have provided a comprehensive description of the working principles of various acousto-electric projector and hydrophone transducers including piezoelectric (Zhang et al., 2019), tonpilz (Afzal et al., 2020b), flextensional (Zheng et al., 2021), and flexural (Hu et al., 2021) transducers.

Besides acousto-electric transducers, Aliev et al. (2010) have investigated the properties of carbon nanotube (CNT) sheets as thermo-acoustic transducers, and have found that CNT transducers can yield 0.2% energy conversion efficiency in air. Their recent work on CNT as low-frequency thermo-acoustic transducers has demonstrated that short temperature pulses at 10 kW/pulse can yield over 10% and 60% energy conversion efficiency in air and water, respectively (Aliev et al., 2018).

Recently, the authors in Huang and Hossein-Zadeh (2018) have proposed an extremely low power-consuming and sensitive acousto-optical transducer using radiation pressure-assisted opto-mechanical micro-resonators. In their more recent work in Huang and Hossein-Zadeh (2020), the authors have shown that the opto-mechanical oscillators used in their proposed acousto-optical transducer can also isolate the intermediate frequency or baseband signal from the carrier signal; and thus eliminate the requirement for local RF oscillator and mixer, and achieve further simplicity in circuitry technology and higher energy-efficiency.

3.5.2. Energy-saving techniques in underwater circuitry technologies for signal processing

The choice of modems is also vital for reducing energy consumed by underwater node circuitry. Zia et al. (2021) have reviewed state-of-the-art commercial and research-based UAC modems, and have provided an evaluation of each in terms of operating range, data rate, modulation techniques, power consumption, and BER. Their analysis suggests that although commercial modems offer better data rate and operating range than research modems, commercial modems have a 2.2 times higher median transmit power compared to the latter. DSPs, microcontrollers, Field-Programmable Gate Arrays (FPGAs), and laptops are common platforms where these modems are implemented. The study also indicates that Frequency Shift Keying (FSK), Phase Shift Keying (PSK), Orthogonal Frequency Division Multiplexing (OFDM), and Spread Spectrum (SS) are common modulation techniques in both modem types. Recently the authors in Hussein et al. (2018) have proposed a novel fully generalized spatial modulation (FGSM) scheme that can offer higher energy-efficiency than other spatial modulation techniques.

The authors in Zia et al. (2018) have proposed a low-cost UAC modem prototype, where they have provided detailed description of their proposed hardware architecture which includes: a digital controller consisting of Raspberry Pi and RISC-based Atmega328P microcontrollers; an analog module consisting of an amplifier, a pre-amplifier and an FSK modem; and piezoelectric transducers. They have found that Class D amplifiers can offer lowest power consumption; however, these amplifiers are prone to electromagnetic interference effects and require impedance matching networks to reduce these effects.

The authors in Viana et al. (2016) have also provided a detailed description of various circuit components in underwater nodes including microcontrollers, memories, sensors, and batteries. The choice of microcontrollers has significant effects on power consumption of an entire node since microcontrollers can control the switching of the node between active, idle, and sleep modes – an operation called duty-cycling – that can save energy (Carrano et al., 2014).

Based on the works in Yang et al. (2009), Coutinho et al. (2018), and Dev et al. (2021), an energy consumption model for data communication can be given as the sum of: the energy required to transmit data (E_{tx}), the energy required to receive data (E_{rx}), the energy required to carry out signal processing by electronic circuits (E_{elec}), and the energy tax during node idle state (E_{idle}). The energy consumption ($E_{consumption}$) can then be expressed mathematically as

$$E_{consumption} = E_{tx} + E_{rx} + E_{elec} + E_{idle}. \tag{4}$$

Given a payload size of L bits, the total energy consumption to transmit and receive data packets based on data size can be given as

$$\begin{aligned} E_{total} &= LE_{tx} + LE_{rx} + LE_{elec} + E_{idle} \\ &= L(E_{tx} + E_{rx} + E_{elec}) + E_{idle}. \end{aligned} \tag{5}$$

Edelmann et al. (2005) have demonstrated the benefits of implementing time-reversal (TR) signal processing techniques in UAC. TR can offer better post-processing results at receivers that use adaptive channel equalization because TR communication sequences offer higher SNR, lower BER, and reduced multipath fading that promote energy-efficiency in UWC. More recently the authors in Esmaiel et al. (2020) have proposed a TR-based non-orthogonal multiple access (NOMA) scheme, TR-NOMA which exploits the TR technique to reduce signal fading at receiver and thus harvest energy which would not be possible otherwise due to high outage probability and sparse underwater channel conditions.

3.5.3. Energy-saving techniques in battery manufacturing

As discussed above, the power supply and energy management module is responsible for powering other modules in an underwater node. The power supply module houses batteries that supply power to other modules in an underwater node. Since underwater environment is extremely energy-constrained, these batteries must be manufactured to operate with as much energy-efficiency as possible. It is helpful to note that battery characteristics are dependent on ambient temperature, thermal conditions, and the rate of battery operation (Teeneti et al., 2021).

The literature indicates that the ambient temperature and operating temperature of sensors and batteries themselves have major impacts on battery lifetime (Chin et al., 2019). For instance, lithium-ion batteries tend to have a shorter lifetime with a decrease in temperature, and vice versa; although very high temperatures exceeding the operating temperature limits can have the opposite effect (Rodríguez García et al., 2021).

Rodríguez García et al. (2021) have also mentioned that the battery discharge time in a UMAC040130A003TA01 battery decreases from 60 min at 25 °C to 52 min at 0 °C under a constant discharge current of 3 mA. The variation in ambient temperature is more pronounced near the ocean surface, where the temperature can fluctuate between −2 °C to 35 °C. However, the ocean temperature remains at an average of 4 °C below 200 m depth, suggesting that sensor energy life will be less affected by temperature variation in deeper parts of the ocean than at the surface.

The authors in Pendergast et al. (2011) present an equation that relates heat generation in batteries with load current, open-circuit voltage, load voltage and the reversible entropy change in the battery cell. This equation shows that heat generation in batteries, and hence, the operating temperature increases with an increase in load, which can have detrimental effects on battery lifetime if the operating temperature limits are exceeded due to excessive load.

Besides temperature, other factors also affect underwater node battery lifetime such as the form factor, battery coating, and the chemical composition of the battery. The authors in Hyakudome et al. (2011) have recommended that underwater batteries need to be light and compact, resistant to water pressure, and sufficiently robust to endure low ambient water temperature, electrical noise, and mechanical disturbance. In this work, the authors have introduced a high-energy density lithium-ion battery to be used as secondary power source in underwater devices. Moreover, they have concluded that battery capacity can be increased by more than 1.3 times than that of conventional lithium-ion batteries by using nickel-based material for anode and cobalt-based material for cathode.

Besides lithium-ion batteries, a wide range of other battery types can also be found in the literature. Viana et al. (2016) have found that zinc-air batteries can offer the highest energy density (890 Wh/L) compared to batteries made of chemical compositions such as: carbon-zinc, nickel-metal-hydride, lithium-ion, lithium-polymer, nickel-cadmium, lithium-iron-phosphate, and alkaline batteries. However, zinc-air batteries are single-use, meaning they are non-rechargeable. Lithium-ion batteries – despite offering a lower energy density (250–670 Wh/L) than zinc-air batteries, and exhibiting thermal safety and reliability issues (Li et al., 2021a) – are rechargeable and support energy harvesting, and are therefore, promising battery technologies for underwater domain.

The authors in Chin et al. (2019) have proposed a smart battery management system, which incorporates a lithium-iron-phosphate battery. This battery management system performs accurate real-time state-of-charge (SOC) estimation and active cell-balancing, both of which are essential for longer battery lifetime. More recently, the authors in Weydahl et al. (2020) have discussed prospects of fuel cell-based power systems as key technologies that can outperform the capacities of conventional batteries powering AUVs.

Teeneti et al. (2021) have provided a comprehensive review of inductive wireless power transfer (IWPT) techniques for underwater applications, with a focus on battery technologies such as: SWE SeaSafe (Adams and White, 2013) (lithium-ion), Phoenix (lithium-ion) (Anon, 2013), and Fraunhofer (lithium-polymer) (Fuhr and Zimmermann, 2016), available for powering AUVs. The authors have identified and discussed the main challenges of underwater wireless charging operations before recommending the best practices for designing IWPT charging systems for AUVs. This work suggests that expensive underwater battery-swapping/contact-recharging operations can be replaced with low-cost wireless charging solutions.

3.6. Energy-efficient physical layer techniques

In this subsection, we present recent works on energy-efficient PHY layer techniques in UWCNs, including multi-modal systems, power control, modulation, coding, and compressive sensing techniques.

The recent work of Afzal et al. (2020a) has proposed a piezo-acoustic backscatter quadrature amplitude modulation (PAB-QAM) scheme that exploits the electro-mechanical coupling property of piezo-electric transducers to modulate their reflection coefficients. Compared to traditional acoustic modems that require energy-expensive carrier signals, PAB is a signal reflection-based ultra low-power approach that enables acoustic communication by mere reflection of existing acoustic signals in an environment. These types of techniques encouraging for re-thinking the design of existing acoustic, optical, and magnetic induction modems to save power.

Apart from standalone PHY layer technologies, the use of hybrid multi-modal techniques in UWC is a recently emerging frontier that offers power-saving in UWCNs, besides offering several other advantages in combining multiple PHY layer technologies together to complement each others' strengths and weaknesses. For instance, Han et al. (2014) have found that a hybrid multi-modal acoustic-optical communication mode outperforms a standalone acoustic mode in terms of energy consumption and throughput. The idea of this type of hybrid multi-modal communication technique has been more recently used in Celik et al. (2020), where the authors present an opto-acoustic software-defined underwater network (SDUN). They combine the SDUN with network function virtualization (NFV) to envision a flexible, scalable, agile, and programmable UWCN, which not only can save power but also offer other tremendous benefits to overcome the many challenges of UWCNs.

Besides these promising multi-modal techniques, many studies in the literature propose other energy-efficient PHY layer techniques, such as transmission power control (TPC), channel coding, modulation schemes, and compressed sensing (CS) techniques.

The authors in Zhou et al. (2011) have proposed a cross-layer multi-path power control transmission (MPT) scheme for time-critical applications that can save power while ensuring low end-to-end packet delay and packet error rate. This cross-layer approach integrates distributed, optimized power control with multi-path routing to deliver high energy-efficiency. Another similar work has been performed in Xu et al. (2012), proposing a novel Layered Multi-path Power Control (LMPC) technique that minimizes the total energy consumption of the subject network whilst offering acceptable packet error rate, data rate, and power available at each node. The above scheme allows the nodes that are not communicating in the tree-based multiple paths to switch into sleep mode, and thus save energy.

The feasibility of adaptive power control has been experimentally studied in Qarabaqi and Stojanovic (2011), where the transmitter of an UWCN dynamically adjusts its power based on the present channel state information perceived and fed back to the transmitter by the receiver. The authors derived analytical bounds to confirm the feasibility of achieving power savings of several dB using the adaptive power control method. More recently, a joint power and rate control for packet coding technique in underwater networks has been proposed in Ahmed and Stojanovic (2017), minimizing the average energy invested per successfully transmitted bit of information with maximal transmit power and maximal coding length as constraints. The above authors claim the adaptive power/rate control can save 5-–9 dB power compared to non-adaptive systems.

Another study on optimal power allocation with full-duplex energy-harvesting (EH) capability has been presented in Wang et al. (2020). The authors formulated an instantaneous sequential decision-making problem and solved it using reinforcement learning (RL). Although the objective of their scheme was to maximize the sum rate of the network, this work can inspire future works for using machine learning (ML) techniques on adaptive power control with the objective of minimizing energy consumption in EH-enabled UWCNs. EH-enabled networks can also take advantage of the concept of simultaneous wireless information and power transfer (SWIPT) as explored in Esmaiel et al. (2020), where the authors have proposed a time-reversed non-orthogonal multiple access (TR-NOMA) scheme to reduce the time–frequency dispersion in UAC channels, enabling the use of SWIPT and extend network lifetime.

Besides NOMA, there are other spectral and energy-efficient modulation techniques that have been proposed in the literature to pave the way toward multiple-in-multiple-out (MIMO) systems in UWCNs. Esmaiel and Jiang (2017) have proposed a time domain synchronization orthogonal frequency division multiplexing (TDS-OFDM) scheme that improves spectral efficiency (10.96%) and saves power (13.57%) in UAC networks compared to zero-padding OFDM (ZP-OFDM). More recently, the authors in Qasem et al. (2019) have proposed an Enhanced Fully Generalized Spatial Modulation (EFGSM) for energy-efficient and spectral-efficient UWC that delivers better energy savings compared to conventional spatial modulation, generalized spatial modulation, and FGSM schemes. A spread-spectrum fully generalized spatial modulation (SS-FGSM) has been proposed in Qasem et al. (2020). SS-FGSM can save power by exploiting the technique of transmitting the better part of information bits using spreading code and antenna indices, so that only a small number of bits are required to be transmitted physically.

In addition to modulation schemes, other techniques such as channel coding (Barreto et al., 2017) and compressed sensing (CS) (Qin et al., 2020; Jiang et al., 2020) techniques can deliver highly energy-efficient systems. The investigation in Barreto et al. (2017) has addressed the problem of energy-efficient communication in UAN through the use of an optimized mixed forward error correction (FEC) and fountain code (FC) scheme, comparing it with non-optimized schemes and no error-coding systems to determine that the proposed scheme delivers better energy-efficiency. Erdem et al. (2019) have proposed a joint optimization of CS, EH, and TPC to extend the lifetime of UWCNs.

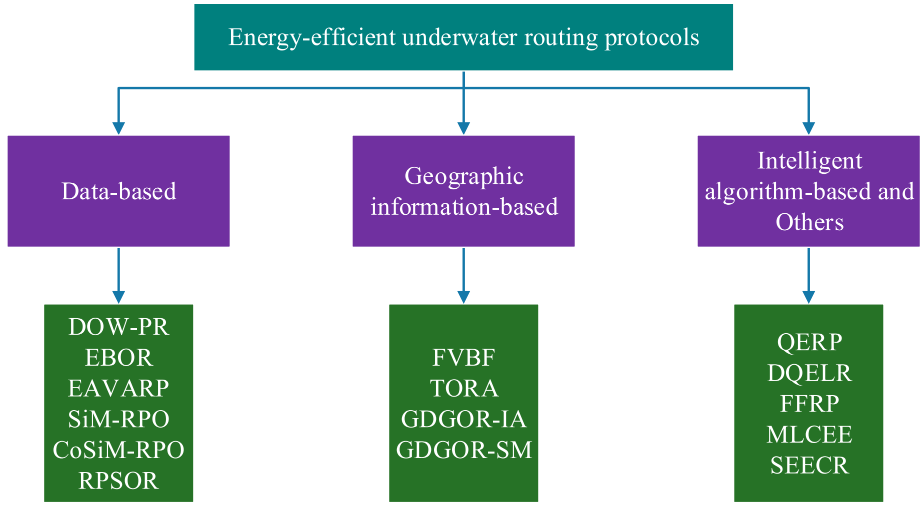


Fig. 7. Hierarchy of energy-efficient routing protocols discussed in this article.

Their study concluded that jointly optimizing these three techniques can extend the network lifetime to up to three times more than when none of these techniques are implemented.

All these proposed energy-efficient PHY layer techniques are indicative of the drive within current research trends toward green IoUT.

4. Energy-saving techniques in upper layers

In this section, we provide a detailed discussion of energy-saving mechanisms used in the upper layers of the protocol stack for UWC. At first, we discuss energy-efficient routing protocols. Then we discuss energy-efficient MAC protocols available in the literature. This is followed by an overview of energy-saving localization techniques used in UWC.

4.1. Energy-efficient underwater routing protocols

Effective routing protocols are vital components of efficient underwater communications that seek to achieve high packet delivery ratio (PDR), low end-to-end delay, low energy consumption, and longer network lifetime in underwater networks. In the last two decades, a flurry of research has been undertaken in the field of underwater routing protocols. This growing research trend has resulted in a rise in the number of review articles on underwater routing protocols (Han et al., 2015; Li et al., 2016a; Ahmed et al., 2017a,b; Khalid et al., 2017; Ismail and Mohamad, 2018; Khan et al., 2020; Luo et al., 2021). These review articles have attempted to categorize underwater routing protocols based on various features and techniques utilized for routing data effectively.

Han et al. (2015) have classified underwater routing protocols into energy-based, geographic information-based, and hybrid routing protocols. Li et al. (2016a) have divided all routing protocols into cross-layer and non cross-layer categories, sub-dividing the former into mobility-based, energy-efficient, time delay-based, and the latter into intelligent algorithm-based and traditional cross-layer routing protocols. Next, Ahmed et al. (2017b) have reviewed existing routing protocols and classified them based on data forwarding techniques such as flooding address based (FAB), flooding depth based (FDB), cluster source based (CSB), and path based (PB). The same authors have surveyed and classified routing protocols based on node mobility and categorized them under vector-based, depth-based, cluster-based, AUV-based, and path-based routing protocols in Ahmed et al. (2017a).

A more recent review article by Khalid et al. (2017) has discussed all localization-based and localization-free routing protocols in the literature. This was followed by a review on energy-efficient opportunistic underwater routing protocols by Ismail and Mohamad (2018), where the authors have classified opportunistic routing protocols into sender side-based, receiver side-based, and hybrid categories. Khan et al. (2020) have characterized the protocols based on their localization and cooperative techniques. Most recently, Luo et al. (2021) have offered a comprehensive review of both the legacy and state-of-the art underwater routing protocols by categorizing them into energy-based, data-based, and geographic information-based types.

In this work, we aim to provide a taxonomy of the work available on energy-efficient underwater routing protocols (see Fig. 7).

4.1.1. Data-based routing protocols

Data-based routing protocols route data according to the type of information that is required to be transmitted from the source to the destination. These protocols can be further sub-divided into two categories: direction aware and flood-based protocols. Direction-aware protocols are designed so that the transmitter selects its best possible next-hop neighbor to transmit data efficiently. Flood-based protocols, as the name suggests, are designed for the transmitting node to send data in a broadcast manner until the data reaches the receiving node. Although flood-based protocols require simple algorithms to be implemented, they are prone to wasting network resources such as energy. Therefore, in this article, we limit our discussion to energy-efficient, direction aware data based underwater routing protocols.

- DOW-PR: Wadud et al. (2018) have proposed DOlphin and Whale Pod Routing protocol (DOW-PR) in order to improve the performance of Weighting Depth and Forwarding Area Division Depth Based Routing (WDFAD-DBR) (Yu et al., 2016) which only considers the weighting sum of the difference in depth of two hops to select the Potential Forwarding Nodes (PFNs). DOW-PR can select the next PFNs from forwarding and suppressed zones simultaneously dividing the network into various transmission ranges and assigning different power levels to each. If an appropriate PFN is not available, DOW-PR selects a node from the suppressed region for broadcasting, thus ensuring reliability of data transfer. The optimal route discovery mechanism and transmission power adjustments in DOW-PR jointly save a significant amount of energy compared to DBR (Yan et al., 2008) for networks larger than 150 nodes. We illustrate the idea of depth-based routing in Fig. 8.

- EBOR: Based on the Dempster–Shafer theory, the evidence theory-based opportunistic routing (EBOR) protocol selects next optimal hop using residual energy and packet delivery probability as evidences (Jin et al., 2018). Accordingly, EBOR achieves high energy-efficiency and a longer network lifetime by optimizing the number of participating nodes in forwarding data, using a trust-based computation mechanism and evenly distributing residual energy amongst network nodes.
- EAVARP: Energy-aware and void-avoidable routing protocol (EAVARP) (Wang et al., 2018) is suitable for mobile 3D underwater sensor network architectures and does not require any node synchronization or localization mechanisms. The protocol works by dividing the routing into two phases: the first phase (layering) involves creating concentric coronas around sink nodes with sensor nodes being deployed on various coronas; the second phase (data collection) involves forwarding data packets using an opportunistic directional forwarding strategy (ODFS) that can bypass voids, re-transmissions, and flooding, and in addition to evenly distributing node residual energy.
- SiM-RPO/CoSiM-RPO: Similar to EAVARP, another energy-efficient protocol – sink mobility for reliable and persistence operation (SiM-RPO) – which is suitable for underwater networks with mobile sinks, has been proposed in Ali et al. (2019b). However, unlike EAVARP, SiM-RPO exploits mobile sinks to its advantage by dividing the network into four equal-sized regions with a mobile sink assigned to each region for data collection; thus avoiding the use of less reliable multi-hop techniques. CoSiM-RPO, the cooperative version of SiM-RPO, further enhances reliability at the cost of reduced energy-efficiency.
- RPSOR: A reliable, path-selective, opportunistic routing protocol (RPSOR) has been recently proposed in Ismail et al. (2020), using a priority function (PF) for the nodes to determine the best next hop. This PF takes into account: an advancement factor (ADV_f) – a depth-based parameter that helps select a lower-depth node for the next hop; a reliability index (REL_i) – an energy-based parameter that selects a higher residual energy node for the next hop; and a shortest path index (SP_i) in order to jointly determine the most reliable and energy-efficient route. Similar to DOW-PR, the performance of RPSOR has been compared against WDFAD-DBR, where RPSOR outperformed the latter in terms of energy tax, PDR, and end-to-end delay for dense networks.

4.1.2. Geographic information-based routing protocols

The underwater environment is highly dynamic with high node mobility, which makes energy-efficient routing by identifying the optimal next-hop neighbor nodes a tremendous challenge. However, geographic information-based protocols, as its name suggests, utilize the relative geographic positions of network nodes to determine the best possible routes for transmitting data to meet certain design objectives. Some of the popular energy-efficient geographic information-based underwater routing protocols that are available in the literature are described as follows.

- FVBF: In order to tackle the uncertain dynamic underwater environment, the authors of Bu et al. (2018) have proposed a fuzzy logic vector-based forwarding protocol (FVBF). Unlike VBF (Xie et al., 2006), FVBF utilizes a fuzzy logic-based inference engine that uses valid distance (the proximity of a node relative to the sink), node projection (the proximity of a node to the shortest path), and the residual energy of nodes in order to determine the fitness of a forwarder node, delivering a highly energy-efficient protocol with guaranteed reliability.
- TORA: The totally opportunistic routing algorithm (TORA) (Rahman et al., 2018) utilizes time-of-arrival (ToA) and trilateration techniques for recursive node localization. Moreover, it records node residual energy and then uses this node information for selecting the best candidate for forwarding data, most likely nodes closest to the sink. TORA saves energy because it only admits a limited forwarding node to its candidate matrix. The candidates that: carry the highest priority data, a higher residual node energy, and are located closer to the sink compared to other candidates, are preferred to be selected for opportunistically forwarding data towards the sink.

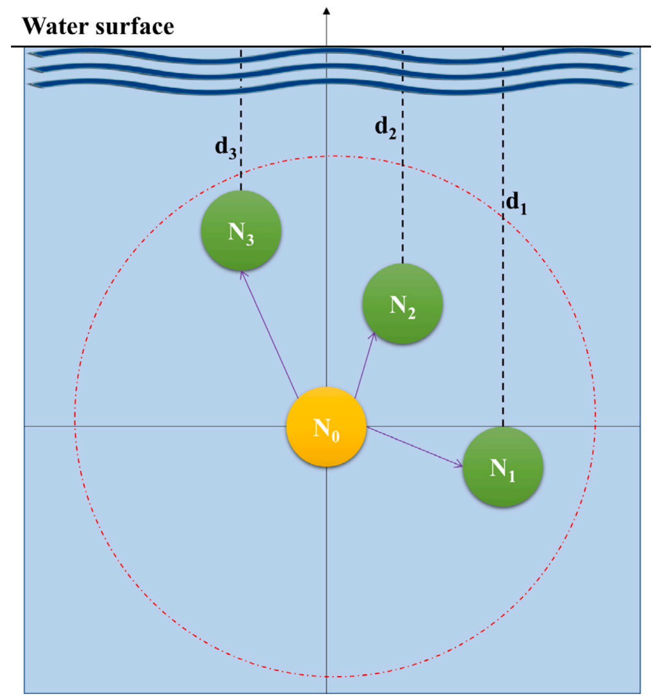


Fig. 8. Working principle of depth-based routing (DBR) (Yan et al., 2008) protocol. Node N_0 selects its next hop based on corresponding depth information (d_1, d_2, d_3) of its neighboring nodes (N_1, N_2, N_3). Nodes closer to water surface are selected for next hop.

- GDGOR-IA/GRMC-SM/GDGOR-SM: To tackle void nodes due to premature node energy depletion, Ahmed et al. (2018) have proposed three routing protocols: a geo-spatial division based geo-opportunistic routing scheme for interference avoidance (GDGOR-IA); a geographic routing for maximum coverage with sink mobility (GRMC-SM); and a geo-spatial division based geo-opportunistic routing scheme with sink mobility (GDGOR-SM). In GDGOR-IA, the topology is logically divided into smaller cubes that help avoid interference, and in turn, improve PDR. The logical cube technique also offers the opportunity to make local routing decisions that improve energy-efficiency. The GRMC-SM employs a mobile sink node that helps to reduce data traffic loads and recover from any void nodes. Moreover, since mobile sinks reduce transmission range, GRMC-SM can deliver a further reduction in energy consumption compared to the other two protocols.

4.1.3. Intelligent algorithm-based and other energy-efficient routing protocols

Similar to terrestrial networks, classical optimization-based and heuristic-based routing algorithms are becoming increasingly popular in the underwater domain. In addition, with rapidly rising interest in machine learning (ML) and artificial intelligence (AI), the next-generation routing protocols using these technologies are also being developed at an ever-increasing rate. For this study, we have reviewed some recently proposed energy-efficient intelligent algorithm-based underwater routing protocols in the literature. Additionally, we have

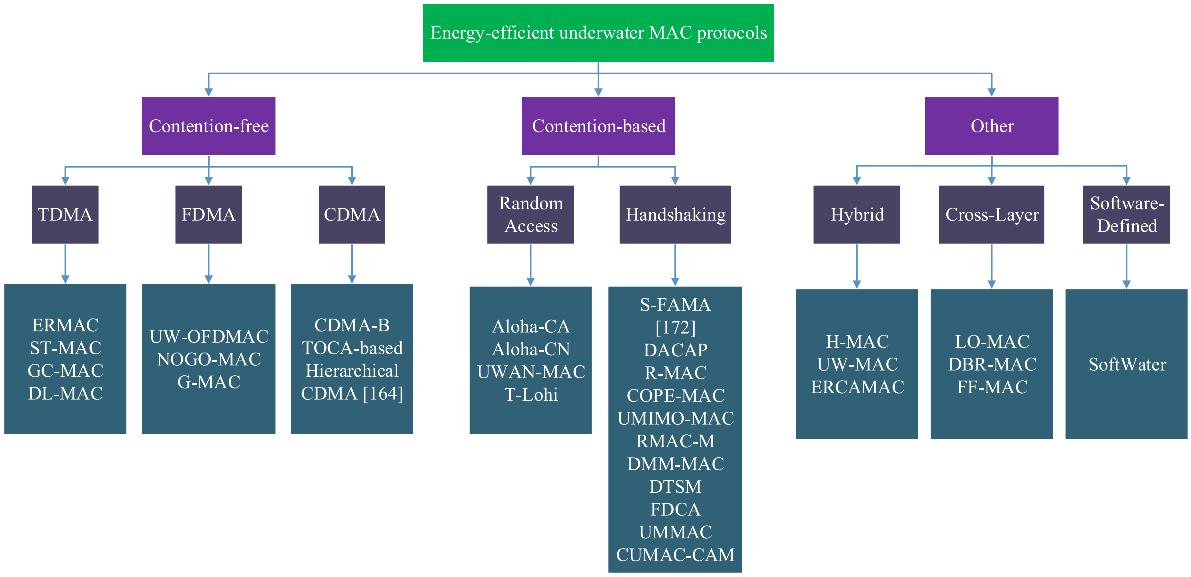


Fig. 9. Hierarchy of energy-efficient MAC protocols discussed in this article.

reviewed some state-of-the art energy-efficient routing protocols that utilize different techniques and performance objectives compared to traditional underwater routing protocols.

- QERP: A Quality of Service (QoS) aware evolutionary cluster based routing protocol (QERP) has been proposed in Faheem et al. (2017b). This intelligent algorithm-based routing protocol was proposed to subjugate the shortcomings of existing cluster-based routing techniques, especially in terms of link reliability and energy consumption. In this protocol, the network nodes are arranged in a hierarchical order into highly stable small clusters, allowing an even distribution of the traffic load and energy throughout the network and, hence, improving overall network lifetime as compared to DBR and VBF protocols. Moreover, in case of node failures, QERP protocol offers adaptive power adjustments along with routing table information to identify the next best hop neighbors; thus it maintains a low BER.
- DQELR: More recently, an adaptive Deep Q-Network based energy and latency-aware routing protocol (DQELR) has been proposed in Su et al. (2019). The algorithm in this protocol selects next optimal hop based on the maximum Q-value considering node energy and latency, delivering a 34%–36% improved network lifetime compared to its predecessor, the Q-learning-based adaptive routing protocol (QELAR) proposed in Hu and Fei (2010).
- FFRP: Apart from Q-networks, a dynamic firefly mating optimization scheme (FFRP) has been proposed more recently in Faheem et al. (2020). This routing scheme selects the most reliable routing path bypassing shadow zones and void holes. Similar to QERP, FFRP also balances the traffic load evenly, delivering better energy-efficiency with lower latency and local optimum issue avoidance as compared to LRP (Faheem et al., 2017a), MERP (Faheem et al., 2019), and QERP.
- MLCEE: A multi-layered clustering-based energy efficient routing protocol (MLCEE) has been proposed by Khan et al. (2019). Their protocol selects optimal routes based on Bayesian probability for residual energy, energy consumption rate, and link quality for each node after segregating the entire network into layers. This delivers improved network lifetime, energy-efficiency, and lower end-to-end delay as compared to other depth-based routing protocols such as DBR (Yan et al., 2008) and EEDBR (Wahid and Kim, 2012).
- SEECR: Due to the energy-constrained nature of the underwater environment, energy-costly security mechanisms are difficult to implement in underwater communication. To address this issue, a secure energy efficient and cooperative routing protocol (SEECR) has been proposed in Saeed et al. (2020) that uses multi-hop routing in a secured manner. SEECR delivers 23% energy tax improvement compared to the well-known AMCTD (Adaptive Mobility of Courier Nodes in Threshold-optimized DBR) (Jafri et al., 2013) protocol.

A summary of energy-efficient underwater routing protocols has been provided in Table 5.

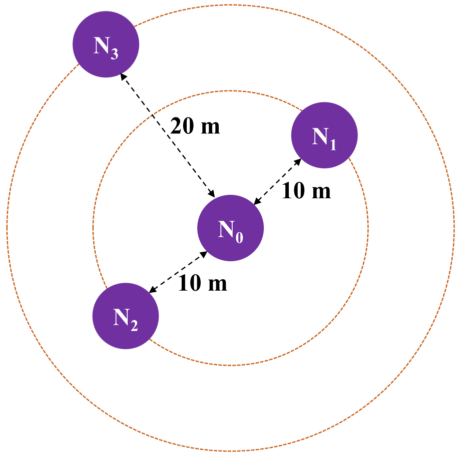
4.2. Energy-efficient underwater MAC protocols

Energy-efficiency in the MAC layer is a vital component of green UWC. A number of studies have been carried out in the literature that either propose novel energy-efficient MAC protocols for UWC or investigate existing MAC protocols and conduct performance evaluations. In the last decade, a few survey articles have been published seeking to compile and study the MAC protocols available in the literature on underwater communications. The authors in Chen et al. (2014) have surveyed the state-of-the-art underwater MAC protocols available until the first half of this decade. A brief survey of energy-efficient and reliable MAC protocols has similarly been conducted by the authors in Zenia et al. (2016). This was followed by a comprehensive study conducted by Jiang (2017) on the state-of-the-art MAC protocols based on a MAC reference model for better comprehension of the existing protocols. Most recently, another review of the most recently developed MAC protocols has been conducted in Al Guqhaiman et al. (2020), which also evaluated the performance of four different MAC protocols in terms of energy consumption, PDR, end-to-end delay, throughput, and number of collisions under various network loads.

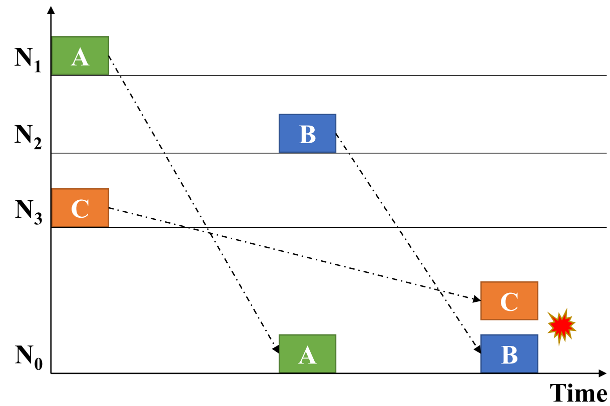
In our study, we have reviewed the literature extensively to identify and compile the energy-efficient MAC protocols available in the literature. We have categorized these energy-efficient MAC protocols into three broad classes: contention-free, contention-based, and any other MAC protocols that do not fit into the former two categories (see Fig. 9). This study seeks to highlight the best possible approaches for designing green UWC protocols and to offer ideas and guidance towards developing more robust solutions to overcome UWC challenges.

Table 5
Summary of energy-efficient underwater routing protocols.

Category	Protocol	Year	Advantages	Limitations
Data-based	DOW-PR (Wadud et al., 2018)	2018	Proposed two versions: dolphin and whale pods routing protocol, with the latter delivering lower energy tax compared to WDFAD-DBR (Yu et al., 2016) for any network size, and lower energy consumption as compared to DBR (Yan et al., 2008) for networks larger than 150 nodes. DOW-PR also increases PDR and minimizes end-to-end delay.	Some features such as transmission zones and hop-count techniques are computationally complex, making it unsuitable for resource-constrained underwater environments.
	EBOR (Jin et al., 2018)	2018	Offers better energy-efficiency than GEDAR (Coutinho et al., 2014), HH-VBF (Nicolaou et al., 2007), EECOR (Rahman et al., 2017), and VBF (Xie et al., 2006) protocols for large networks, while also improving PDR.	Energy consumption is higher in smaller networks with less number of nodes.
	EAVARP (Wang et al., 2018)	2018	Avoids re-transmission, flooding, and voids while improving energy consumption compared to APCRP (Al-Bzoor et al., 2015) and E-PULRP (Gopi et al., 2010).	The offered PDR is low compared to other related protocols for networks with less than 90 nodes.
	SiM-RPO CoSiM-RPO (Ali et al., 2019b)	2019	Proposed two protocols: SiM-RPO for reliable and resilient operation, and CoSiM-RPO — a cooperative version for efficient data exchange and lower data loss. The former ensures energy-efficiency whilst the latter reliable data delivery.	Operation requires the network to be divided into four regions with mobile sinks involved, which supports very specific network scenarios.
	RPSOR (Ismail et al., 2020)	2020	Offers better energy-efficiency and PDR compared to WDFAD-DBR.	The end-to-end delay of the proposed solution is higher than its benchmark in sparsely built networks.
Geographic information-based	FVBF (Bu et al., 2018)	2018	Delivers higher PDR with lower end-to-end delay and energy consumption as compared to VBF (Xie et al., 2006), power-efficient routing protocol (PER) (Huang et al., 2011), DBR (Yan et al., 2008), and LEVBF (Xiao et al., 2012).	Offered PDR is only low when the network size is small.
	TORA (Rahman et al., 2018)	2018	Offers better performance in terms of energy consumption, PDR, end-to-end delay, average hop count and propagation deviation factor compared to VBF, HH-VBF (Nicolaou et al., 2007), VAPR (Noh et al., 2012), and H2-DAB (Ayaz et al., 2012).	The mobility model used in this work is limited to 2D only when a 3D model would be more practical.
	GDGOR-IA, GRMC-SM (Ahmed et al., 2018)	2018	Improves energy-efficiency, PDR, end-to-end delay compared to RE-PBR (Khasawneh et al., 2018), EnOR (Coutinho et al., 2017), and other related protocols through void-hole recovery mechanisms.	Highly turbulent conditions may result in higher power consumption because the proposed technique relies on depth adjustments for void-recovery.
Intelligent algorithm-based and others	QERP (Faheem et al., 2017b)	2017	Reduces the overall network energy consumption, average end-to-end delay, and improves PDR. Delivers better network lifetime than DBR (Yan et al., 2008) and VBF (Xie et al., 2006) protocols.	The work limits performance comparison with traditional routing protocols and does not provide comparison against other intelligent-algorithm based routing protocols.
	DQELR (Su et al., 2019)	2019	Offers better energy-efficiency and network lifetime compared to QELAR (Hu and Fei, 2010) and VBF techniques.	Assumes the topology remains relatively stable for a short period of time, which may not be possible in turbulent ocean conditions.
	MLCEE (Khan et al., 2019)	2019	Offers better energy-efficiency, PDR, and end-to-end delay compared to DBR and EEDBR (Wahid and Kim, 2012).	Assumes nodes in the upper-most layer can reach the sink in single-hop which may not be possible during degraded link quality.
	FFRP (Faheem et al., 2020)	2020	Minimizes energy consumption, and increases PDR and throughput as compared to LRP (Faheem et al., 2017a), MERP (Faheem et al., 2019), and QERP (Faheem et al., 2017b).	No mobility model that can account for unreliable links has been considered in this study.
	SEECR (Saeed et al., 2020)	2020	Offers secured communication for sensitive networks such as military whilst reducing energy consumption and increasing throughput and end-to-end delay compared to AMCTD (Jafri et al., 2013).	The work does not compare its performance with other related secure and energy-efficient routing protocols.



(a) Sender node N_3 is twice as far from the receiver node N_0 as compared to sender nodes N_1 and N_2.



(b) Nodes N_1 and N_3 send data packets A and C, respectively, to node N_0 during the same time slot. Due to longer propagation delay experienced by packet C than A, there is no collision between these packets at N_0. Node N_2, however, sends packet B at a later time slot, but experiences collision with packet C at node N_0.

Fig. 10. The spatio-temporal uncertainty problem – an effect of long propagation delays in UWCNs – tackled in Hsu et al. (2009) and Alfouzan et al. (2019b).

4.2.1. Contention-free, energy-efficient underwater MAC protocols

Contention-free MAC protocols are protocols that allow the communication nodes in a network to share available resources, such as channel bandwidth, by allocating time (Time Division Multiple Access (TDMA)), communication frequency (Frequency Division Multiple Access (FDMA)), or code (Code Division Multiple Access (CDMA)) to the way resources are utilized by communication nodes. In terms of energy consumption, contention-free protocols are unsuitable for large-scale networks as they may allow multiple transmissions without exchanging any messages. However, there has been a considerable attempt in the literature to improve these protocols to save energy underwater. We have reviewed these works on contention-free, energy-efficient underwater MAC protocols and divided them into TDMA, FDMA, and CDMA types.

TDMA. In TDMA, the data transmission channel is segmented into time slots. A node in a network is only allowed to transmit data during its assigned time slot so that the timing does not collide with that of other nodes. This also implies that all nodes in the network require time-synchronization. Additionally, each time slot is separated to the next by a guard time that further reduces the probability of collision. However, in the underwater environment, the propagation delay is longer (approximately 1 s over 1.5 km) and more variable than terrestrial networks and, therefore, the guard times are required to be longer in the underwater scenario. Underwater TDMA MAC protocol designs, therefore, need to take these factors into consideration.

- Efficiency Reservation MAC (ERMAC) (Nguyen et al., 2008) exploits the propagation time delay underwater to determine the relative location of sensor nodes in a centralized topology. The sink in a cluster groups its member nodes as per their relative location and directions to schedule and manage data transmission reliably within that cluster. ERMAC also implements duty cycling where all other nodes except the transmitter is switched into sleep mode to conserve energy.
- Spatial–Temporal MAC (ST-MAC) (Hsu et al., 2009) attempts to overcome the spatio-temporal uncertainty in underwater transmission due to long propagation delays by formulating Spatial–Temporal Conflict Graph (ST-CG) — an NP-complete graph coloring problem solved by the proposed heuristic Traffic-based One-step Trial Approach (TOTA), which saves energy and also enhances network throughput. This approach has fostered many graph coloring-based, energy-efficient underwater MAC protocols, such as GC-MAC (Alfouzan et al., 2019a). The spatio-temporal uncertainty problem has been illustrated in Fig. 10.
- Similar to ST-MAC, another energy conserving, graph coloring MAC protocol (GC-MAC) has been proposed more recently in Alfouzan et al. (2019a). Since ST-MAC runs a centralized scheduling algorithm, it requires global information regarding the network nodes, making it costly due to high latency and low data transmission rates underwater. Compared to ST-MAC, GC-MAC can perform collision-free scheduling in a distributed manner without prior knowledge of global topology. Accordingly, it uses a graph coloring approach with a built-in duty cycle mechanism. This proposal assigns unique time-slots (referred to as 'color') to each node within every two-hop zone, allowing the nodes assigned the same color to transmit simultaneously in a collision-free manner. GC-MAC can also efficiently schedule inner and outer sensor nodes across the network.
- Depth-based layering MAC (DL-MAC) (Alfouzan et al., 2019b) offers energy-conserving and collision-free features in underwater communication. In addition to the spatial–temporal uncertainty, DL-MAC also tackles near-far effects and the hidden/exposed terminal issues in underwater networks. The proposed novel protocol utilizes the concepts of layering and distributed clustering algorithm to efficiently schedule packet exchange, eliminating chances of collisions, and hence improving energy-efficiency.

FDMA. In FDMA, the channel frequency is divided into sub-frequencies and each sub-frequency is assigned to a node pair for data transmission. Since each node pair utilizes a unique frequency band for packet transmission, FDMA techniques can exhibit an increase in overall delay (Al Guqhaiman et al., 2020). Additionally, the use of guard frequency bands to reduce interference results in decreased available bandwidth. Since the usable frequency band is severely restricted in the underwater domain, especially in UAC, many FDMA protocols use orthogonal FDMA (OFDMA) (Jiang, 2017), which allows concurrent collision-free transmissions between neighboring nodes within a small spectrum. Some of the most energy-efficient FDMA-based MAC protocols for UWCNs are described as follows.

- The UW-OFDMAC proposed in Bouabdallah and Boutaba (2011) is a transmitter-based scheme where each network node can dynamically adapt OFDMA parameters (transmit power, sub-carrier

spacing, and guard interval) optimally depending on the receiver movement and location. UW-OFDMAC is a fully distributed protocol, where the OFDMA parameters are optimized by each transmitter without having to rely on a centralized control. This guarantees low energy consumption and high bandwidth efficiency while offering interference and collision avoidance.
- A more recent OFDMA-based MAC protocol NOde Grouped OFDMA (NOGO-MAC) has been proposed in Cheon and Cho (2011), offering energy-efficiency by assigning member nodes in a UWCN a group depending on its distance from the sink. The groups closer to the sink use high-frequency bands and groups far away from the sink use low-frequency bands for data transmission. Using this technique, NOGO-MAC ensures all nodes can maintain their corresponding SNR above a certain minimum acceptable SNR threshold in addition to an improved data transmission rate by exploiting an adaptive sub-channel allocation method. Compared to non-grouping protocols, NOGO-MAC can save power to up to 7 dB within a changing bandwidth from 15 kHz to 35 kHz.
- Glider MAC (G-MAC) (Su et al., 2018) is another OFDMA-based MAC protocol for glider-based mobile underwater networks that offers simultaneous data transmissions by applying Nash equilibrium towards allocating transmission sub-channels depending on the required data rate, and adaptive power control depending on the channel condition.

CDMA. Unlike TDMA and FMDA, CDMA allows simultaneous data transmissions using the entire available bandwidth using spreading code assignment and appropriate power control mechanisms.

- A CDMA-based energy-efficient MAC protocol (CDMA-B) has been proposed in Kim et al. (2009), where the authors considered a tree-based hierarchical topology. The nodes located in the same level of the hierarchy were multiplexed using various orthogonal codes, and thus allowed to transmit data simultaneously. Additionally, a periodic wake-up and sleeping mode scheme used in the protocol enables energy-saving mechanisms. The authors analyze both single-code and multi-code CDMA to find the former technique outperforms the latter in terms of throughput and achievable data rate. However, both single-code and multi-code CDMA outperform a representative MAC protocol slotted-FAMA (S-FAMA) (Molins and Stojanovic, 2006) with respect to the aforementioned performance metrics.
- More recently, the authors in Du et al. (2015) have proposed a hierarchical, transmitter-oriented code assignment (TOCA) algorithm based on divisive probability function that efficiently minimizes conflicts between spread codes. Moreover, a state-based, handshake-avoidance CDMA protocol with power control mechanisms that improves energy-efficiency was also proposed by the authors.

4.2.2. Contention-based energy-efficient MAC protocols

Compared to the contention-free MAC protocols, contention-based protocols generally offer better energy efficiency for large scale networks along with high channel utilization since they allow resource sharing on-demand. Moreover contention-based protocols do not suffer from: narrow bandwidth problems in FDMA, synchronization problems in TDMA, and near-far problems in CDMA (Casari and Zorzi, 2011; Qian et al., 2016).

Contention-based MAC protocols can be sub-divided into random access and handshaking-based protocols. Random access protocols are more applicable for low data rate, sparse topologies where data packets are small in size. In contrast, handshaking-based protocols are more suitable for high data rate, dense networks with short-range transmission requirements, and larger packet sizes.

Random access. These protocols allow communication nodes to share the data transmission medium without much coordination. When data is ready for transmission from a node, the node simply transmits the data. This may result in high collision rate when the channel is busy with higher number of transmissions during a peak traffic period.

- The authors in Chirdchoo et al. (2007) have proposed two protocols — Aloha with collision avoidance (Aloha-CA), and Aloha with advance notification (Aloha-AN). Both of these protocols can improve network throughput and energy-efficiency by reducing the number of collisions. To avoid collision in Aloha-CA, each node determines the status of the channel and the busy duration caused by a specific frame by listening to every frame exchange over the channel. This technique is improved in Aloha-AN with the transmit node sending a notification to its neighbors prior to data transmission. A node listening to the notification learns when and where the associated data frame will arrive, thus avoiding collision and saving energy. However, Aloha-AN is not as scalable as Aloha-CA due to its resource-intensive nature.
- The Underwater Wireless Acoustic Networks MAC (UWAN-MAC) proposed in Park and Rodoplu (2007) is one of the earliest energy-efficient MAC protocols that differentiates from other random access protocols such as Aloha, MACA and MACAW by positioning energy efficiency as its main performance metric and not bandwidth utilization. This protocol utilizes the technique of relative time stamps (low duty cycles) both during data transmission, and for initiating communication with newcomers in the network, thus allowing nodes to operate in a synchronized manner, switching into sleep mode and saving energy while they are not transmitting/receiving data.
- Tone-Lohi (T-Lohi) (Syed et al., 2008) is another energy-efficient MAC protocol that operates based on a tone-based reservation system, where a sender node transmits a short tone and overhears the channel for the duration of a contention round. The channel is reserved for the transmitter if no other tones are overheard during that period. But in cases where there is another tone, the node backs off and tries again later.

Handshaking-based. Handshaking-based protocols rely on the establishment of a connection between the sender–receiver pair via control packet exchange prior to data transmission. This is done by exchanging the request-to-send (RTS) and clear-to-send (CTS) control packets prior to data transmission. If the control packets use the same channel as the data packets, the protocol is classified as single-channel handshaking-based protocol. When the control and data packets utilize separate channels, the protocol is classified as a multi-channel protocol.

Some legacy handshaking-based underwater MAC protocols that save energy are: slotted floor acquisition multiple access (S-FAMA) (Molins and Stojanovic, 2006), where the time-slotting mechanism avoids the use of long control packets and thus saves energy; the work in (Peleato and Stojanovic, 2006) and Distance Aware Collision Avoidance Protocol (DACAP) proposed in (Peleato and Stojanovic, 2007), where energy-efficiency is achieved in underwater networks by minimizing the duration of handshake mechanisms based on inter-node distances without the need for node synchronization; and reservation-based MAC (R-MAC) (Xie and Cui, 2007), where the nodes acquire their own listen/sleep schedule based on the propagation delays to its neighbors, and the schedule is broadcast to all neighbors to avoid collision and save energy.

- COntention based Parallel rEservation MAC (COPE-MAC) (Peng et al., 2010) introduces a joint parallel reservation and cyber carrier sensing technique in order to facilitate simultaneous transmissions. This protocol enjoys stable energy-efficiency in large-scale networks with high traffic loads when compared to UWAN-MAC and FAMA.

- UMIMO-MAC (Kuo and Melodia, 2011) is one of the earliest works on multiple-input-multiple-output (MIMO) techniques in underwater networks. This protocol dynamically adapts to varying channel conditions, such as environmental noise and interference, to deliver an optimal throughput-energy consumption trade-off, outperforming Aloha and UW-MAC (Pompili et al., 2009) in terms of network throughput, average delay and energy efficiency.
- A dynamic duty-cycled multiple-rendezvous multichannel MAC (DMM-MAC) (Chao et al., 2014) has been proposed to handle bursty traffic while saving energy. Accordingly, it delivers lower power consumption compared to its predecessor MM-MAC (Chao et al., 2012), in addition to S-FAMA (Molins and Stojanovic, 2006) and Reverse Opportunistic Packet Appending (ROPA) protocols (Ng et al., 2010).
- More recently, a Cooperative Underwater Multi-channel MAC protocol with Channel Allocation Matrix (CUMAC-CAM) has been proposed in Rahman et al. (2019). This work addresses the Triple Hidden Terminal (THT) problem while offering an efficient solution to collision detection and channel selection. CUMAC-CAM delivers better energy efficiency, throughput, end-to-end delay, and PDR when compared to its predecessor CUMAC (Zhou et al., 2011) protocol.

4.2.3. Other energy-efficient MAC protocols

Hybrid. As the name suggests, hybrid MAC protocols are a combination of both contention-free and contention-based MAC protocols, designed to extract the better features from both categories and discard poor characteristics.

- The work in Kredo and Mohapatra (2007) is one of the earliest works on energy-efficient hybrid MAC protocols. This protocol assumes a super-frame which is divided into two segments — a scheduled (contention-free) and an unscheduled (contention-based) portion. The scheduled segment utilizes TDMA, whilst the unscheduled portion operates using a random access slotted mechanism. The resulting hybrid strategy yields a lower, more stable latency, and better energy-efficiency for a variety of traffic arrival rates as compared to a standalone TDMA or random access protocol.
- Unlike the use of TDMA in Kredo and Mohapatra (2007), UW-MAC (Pompili et al., 2009) uses CDMA for transmitting the payload component of a packet with adaptive power control and code length to save energy. The header component of a packet is transmitted using an Aloha-like random access protocol, rendering UW-MAC a hybrid MAC protocol that guarantees low energy consumption, high network throughput, and low channel access delay.
- More recently, another hybrid energy efficient, reliable, cluster-based, and adaptive MAC protocol (ERCAMAC) has been proposed in Zenia et al. (2015). In this protocol, the intra-cluster collision-free communication is undertaken by utilizing a version of TDMA, with adaptive wake-up/sleep schedules for nodes, resulting in better energy-efficiency than CSMA/CA and M-FAMA (Han et al., 2013) protocols.

Cross-layer. Cross-layer MAC protocols are becoming more popular in recent times because their mechanisms offer more flexibility and help improve performance, bandwidth utilization, and more importantly, energy-efficiency. However, some cross-layer protocols may become too complex and prove difficult for practical implementation. Nevertheless, with the growing popularity of software-defined techniques, cross-layer MAC solutions are also experiencing tremendous development.

- The work in Ren and Cheng (2010) proposes a Latency-Optimized (LO-MAC) protocol that utilizes convolution coding and interleaving at the physical layer, and an energy-efficient asynchronous schedule-based MAC (ASMAC) (Qingchun Ren and Qilian Liang, 2005) protocol, which is a terrestrial MAC protocol, to undertake the scheduling operation in a star topology-based underwater network with AUVs.
- More recently, Depth-Based Routing MAC (DBR-MAC) (Li et al., 2016b) has been introduced to couple with the well-known DBR (Yan et al., 2008) routing protocol. DBR-MAC takes the node depth information, angle information, and one-hop neighboring node transmissions as inputs to schedule transmissions. The protocol yields better energy-efficiency as compared to M-FAMA (Han et al., 2013), S-FAMA (Molins and Stojanovic, 2006), and DOTS (Noh et al., 2014).
- Another recent cross-layer protocol that integrates the network and data link layer is Fitness Function-based MAC (FF-MAC) (Wahid et al., 2017). At the network layer, this protocol utilizes a fitness function comprised of node depth information, residual energy, and expected propagation delays in order to select the best possible forwarder node in the network. Then, at the link layer, a handshaking-based mechanism is undertaken in order to schedule packet transmissions and avoid collisions, resulting in an overall energy-efficient technique.

Software-defined. Most of the current underwater communication systems have traditionally been hardware-based. However, with the rising popularity of the software-defined networking (SDN) paradigm, there has been a significant attention towards developing next-generation underwater networks on the software-defined platform. This platform offers the potential to dramatically improve underwater network resource utilization, energy-efficiency, adaptability, and minimize operational costs. Based on these ideas, Akyildiz et al. (2016) have conceptualized SoftWater, an energy-efficient SDN architecture that offers a highly flexible operation by splitting the control and data planes, enabling highly effective network resource control and management across the physical, data link, and network layers through network function virtualization.

A summary of energy-efficient underwater MAC protocols has been provided in Table 6.

4.3. Energy-efficient underwater localization techniques

For underwater localization, there are two types of nodes: reference nodes and mobile nodes. Reference nodes are fixed and their position coordinates are known. In localization, the main aim is to find the position coordinates of mobile nodes (Zafari et al., 2019). Different techniques are used to determine these position coordinates. Localization accuracy, system complexity, and energy consumption are the key factors that need to be considered before deploying localization techniques (Su et al., 2020). For underwater nodes, energy consumption in localization is an important consideration.

As discussed above, underwater sensor nodes, as well as underwater miniaturized batteries, are expensive devices (Han et al., 2019). The energy consumption of underwater sensor nodes is high, where it is also difficult to replace their batteries, leading to a limited network lifetime (Zhang et al., 2020a). Keeping in mind the hardship of replacing batteries underwater and its overall cost, energy consumption becomes more important for underwater localization. In underwater localization, the cost of equipment can be crucial as well. A dive and rise (DNR)-assisted positioning algorithm has been proposed by authors in Zhang et al. (2018). The proposed solution has high localization accuracy and its communication loss is also low; however, this solution is not effective for large scale use due to high equipment cost.

Most localization algorithms fall under four categories. These categories, along with works in terms of energy consumption, are described in the following subsections.

Table 6
Summary of energy-efficient underwater MAC protocols.

Category	Protocol	Year	Topology	SYN	Comments
Contention-free energy-efficient underwater MAC protocols					
TDMA	ERMAC (Nguyen et al., 2008)	2008	Centralized	✓	Requires strict time synchronization of nodes through broadcasts made from sink node which may consume high energy in large-scale networks.
	ST-MAC (Hsu et al., 2009)	2009	Centralized	X	Concludes that ST-CG-based approaches outperform non-ST-CG-based schemes in terms of network throughput and energy-savings.
	GC-MAC (Alfouzan et al., 2019a)	2019	Distributed	X	Considers a fixed number of time-slots (colors) for each neighborhood which may cause low channel utilization.
	DL-MAC (Alfouzan et al., 2019b)	2019	Distributed	X	Since the scheduling phase precedes the operational phase, variations in traffic during the latter may cause horizontal or vertical collisions.
FDMA	UW-OFDMAC (Bouabdallah and Boutaba, 2011)	2011	Distributed	✓	Although guarantees high energy and bandwidth-efficiency, distributed computation of OFDMA parameters results in increased system complexity.
	NOGO-MAC (Cheon and Cho, 2011)	2011	Star	✓	Exploits UWC physical characteristics that low-frequency underwater acoustic waves travel further than high-frequency waves, and thus allocates frequencies based on the distance between a node and the sink.
	G-MAC (Su et al., 2018)	2018	Mobile	X	Highly dynamic underwater channel conditions may rapidly change during data transmissions, rendering the resource allocation performed during mission-planning stage ineffective.
CDMA	CDMA-B (Kim et al., 2009)	2009	Tree	X	The staggered wake-up/sleep pattern requires careful scheduling to ensure receiver nodes can listen to messages with long propagation delays.
	TOCA-based Hierarchical CDMA (Du et al., 2015)	2015	Multi-hop	X	Delivers better end-to-end delay, energy consumption, network throughput, and PDR compared to RMAC (Xie and Cui, 2007), S-FAMA (Molins and Stojanovic, 2006), and POCA-based CDMA MAC (Fan et al., 2011)
Contention-based energy-efficient underwater MAC protocols					
Random Access	Aloha-CA, Aloha-CN (Chirdchoo et al., 2007)	2007	Distributed	X	Due to its simplicity, Aloha-CA is more suitable for larger networks than the more resource-intensive yet better throughout-offering Aloha-CN.
	UWAN-MAC (Park and Rodoplu, 2007)	2007	Distributed	✓	One of the earliest works where energy-efficiency is the main performance metric. However, only static UWCNs has been considered without any node mobility that may cause varying propagation delay and hence adversely affect the proposed approach.
	T-Lohi (Syed et al., 2008)	2008	Multiple	X	The proposed ultra low-power wake-up receiver listening for wake-up tones with minimal power expenditure can dramatically improve energy-efficiency in UWC.
Handshaking	S-FAMA (Molins and Stojanovic, 2006)	2006	Mobile Ad-hoc	✓	The time-slotting feature reduces control packet lengths, and hence reduces energy consumption in UWC
	(Peleato and Stojanovic, 2006)	2006	Ad-hoc	X	Depending on the distance between transmitter and receiver nodes, the handshake length can be determined — shorter for closer nodes and longer for further nodes, reducing control overhead and the number of collisions; and thereby minimizing energy consumption.

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Table 6 (*continued*).

Category	Protocol	Year	Topology	SYN	Comments
	DACAP (Peleato and Stojanovic, 2007)	2007	Ad-hoc	X	Exploiting the idea that a receiver encounters lower interference when two nodes are closer than a certain transmission range, DACAP minimizes collisions and hence saves energy and maximizes throughput.
	R-MAC (Xie and Cui, 2007)	2007	Star	X	This reservation-based protocol implements scheduling algorithms with periodic listen/sleep slots, achieving high energy efficiency by eliminating collisions.
	COPE-MAC (Peng et al., 2010)	2010	Multi-hop	X	More suitable for larger networks with long inter-node distances, COPE-MAC yields better energy-efficiency compared to FAMA (Fullmer and Garcia-Luna-Aceves, 1995) and UWAN-MAC (Park and Rodoplu, 2007) by implementing smooth parallel reservation and cyber carrier sensing techniques.
	UMIMO-MAC (Kuo and Melodia, 2011)	2011	Multiple	X	A cross-layer protocol that uses two-way handshaking and joint optimization of transmit power and transmission mode according to channel conditions and application QoS requirements.
	DMM-MAC (Chao et al., 2014)	2015	Multiple	✓	Combines dynamic duty cycling scheme and the MM-MAC (Chao et al., 2012) protocol that handle channel negotiation and data transmission in each wake-up frame so that collisions can be reduced, hence improving energy efficiency.
	DTSM (Liao et al., 2015)	2015	Multi-hop	✓	DTSM's energy efficiency is unaffected even under high load because of the joint optimization of bandwidth and media access control.
	FDCA (Li et al., 2016c)	2016	Multiple	✓	Due to the proposed collision avoidance scheduling algorithm, FDCA can avoid most collisions and offer lower average energy consumption than FD-MAC (Zhang et al., 2013).
	UMMAC (Su and Jin, 2016)	2016	Multi-hop	✓	During increased load, the packet train scheme in UMMAC can reduce the number of required control packets. Moreover, a dynamic power control algorithm allows UMMAC to offer better energy efficiency compared to S-FAMA (Molins and Stojanovic, 2006) and MMAC (Chao et al., 2012).
	CUMAC-CAM (Rahman et al., 2019)	2019	Multi-hop	X	Each node maintains a channel allocation matrix (CAM) and delay map to assess the channel for making a collision-free transmission decision which requires extra memory allocation overhead on the nodes.
Other energy-efficient underwater MAC protocols					
Hybrid	H-MAC (Kredo and Mohapatra, 2007)	2007	Centralized	✓	Although the hybrid protocol (TDMA and unscheduled channel access combined) is useful in sparse networks, it may not be optimal for dense networks since the probability of higher number of collisions results in higher energy consumption compared to only TDMA-based protocols.
	UW-MAC (Pompili et al., 2009)	2010	Cluster	X	Guarantees high network throughput, low channel access delay, and low energy consumption by jointly optimizing transmit power and code length.
	ERCAMAC (Zenia et al., 2015)	2015	Cluster	✓	Depending on the traffic load, ERCAMAC allows nodes to adaptively adjust their on/off periods and thus saves energy.
Cross-Layer	LO-MAC (Ren and Cheng, 2010)	2010	Mobile	X	Implements a duty-cycling off-phase mode where nodes can sleep when not communicating, and hence save energy.
	DBR-MAC (Li et al., 2016b)	2016	Multi-hop	✓	Dependent on strict time synchronization among nodes and a known transmission and propagation time for each control packet. Additionally, assuming a fixed-length data packet restricts the protocol's applicability to networks with variable-length data packets.

(*continued on next page*)

Table 6 (*continued*).

Category	Protocol	Year	Topology	SYN	Comments
	FF-MAC (Wahid et al., 2017)	2017	Multi-hop	✓	Reduced number of packet collisions by implementing a managed transmission time and modified back-off algorithm, FF-MAC promises lower latency and energy consumption than Improved Vector Based Forwarding (I-VBF) (Sun et al., 2015).
Software-Defined	SoftWater (Akyildiz et al., 2016)	2016	Adaptive	✓	Conceptualizes highly flexible and adaptive software-defined networking-based UWCNs that save significant amount of energy by allowing the network operator to adjust network parameters based on channel conditions and network QoS requirements.

4.3.1. Time of arrival (TOA)

In the time of arrival (TOA) localization technique, the position coordinates of reference nodes or fixed nodes are already known. Further, signal propagation delay time is directly proportional to the distance between the reference node and the mobile node. The product of signal propagation time and the speed of signal propagation is then used to calculate the distance between the reference node and the mobile node (Carroll et al., 2010, 2011; Liu et al., 2015). For 2D positioning, TOA requires distance (between the reference node and mobile node) from at least 3 reference nodes to calculate position coordinates. As the position coordinates require distance, and distance is calculated from the signal propagation time, the TOA technique requires strict time synchronization. Considerably good accuracy can be achieved using the TOA technique, but time synchronization increases the energy consumption and overall complexity of the system. Factors such as node depth, water salinity, and temperature also affect the signal propagation in an underwater environment (Fengzhong et al., 2016b).

The authors in Zhang et al. (2020a) have proposed a movement prediction location (MPL) algorithm to address the challenges of high communication overhead, low location accuracy, and high energy consumption of sensor nodes in UAC networks. The MPL algorithm was based on a TOA strategy that minimizes energy consumption by reducing communication overhead. Similarly, the authors in Li et al. (2018) have proposed a node selection strategy where only a few nodes participate in localization and communication is limited to short-distance transmissions only to save power. In this manner, there is less influence of noise and energy consumption is also reduced due to less signal transmission.

To reduce strict time synchronization, roundtrip-TOA (RTOA) can be used. In this technique, the mobile node sends a signal to the reference node and then receives a signal from the reference node. From this roundtrip time (RTT) the distance between the two nodes is calculated. In this scenario only one node is required to compute time delay hence synchronization similar to TOA is not required. Hu et al. (2019) have proposed a RTOA localization algorithm where the use of prior knowledge of node mobility patterns reduces the time required for localization, which ultimately reduces energy consumption.

Authors in Yi et al. (2015) have proposed a model that uses the TOA technique with tracked synchronization (ToA-TS). In this technique, the reference nodes collect their location data from GPS and along with the time stamp, send it to mobile nodes, which save the message along with their submersible's local clock time.

4.3.2. Time difference of arrival (TDOA)

The time difference of arrival (TDOA) technique calculates the signal propagation time difference from multiple signal sources. Multiple hyperbolic curves intersect at the node where the position coordinates need to be determined (Poursheikhali and Zamiri-Jafarian, 2015; Zou and Wan, 2016; Ullah et al., 2019). TDOA uses relative time measurements taken from multiple reference nodes, in contrast to the TOA technique where absolute time measurements are required. Unlike TOA, where both transmitters and receivers are required to synchronize, only reference nodes are required to synchronize (Cong and Zhuang, 2002) in TDOA. However, in TDOA, the nodes require denser deployment (Fengzhong et al., 2016b).

Yan et al. (2019b) have proposed a TDOA technique based localization algorithm, where reducing the incorrect node position measurements minimizes network energy consumption. The localization process has two phases, where initially, a relationship is established between the position and propagation delay and later, an asynchronous algorithm estimates the position of the mobile node. Localization for AUVs using TDOA has been proposed by the authors in Yan et al. (2019a). An asynchronous localization algorithm was developed for localization of the AUV using reinforcement learning and the communication energy consumption was reduced consequently.

4.3.3. Angle of arrival (AOA)

In the angle of arrival (AOA) technique, the incident angle of the signal is measured (Yassin et al., 2016). There is an antenna array at the receiver, and when the signal is received the time difference in various elements of the antenna is exploited to measure the incident angle (Andersen and Pedersen, 2002; Su et al., 2020). Unlike other localization techniques that usually require at least three reference nodes to determine the position of the mobile node, AOA requires only two reference nodes. However, minor errors in the measurement of angles degrade the localization accuracy substantially. Moreover, ultrasound receivers and antenna arrays increase installation costs (Fengzhong et al., 2016b). Implementing AOA technique also requires complex hardware and careful calibration. Huang and Zheng (2018) have proposed a localization algorithm for UWCNs that uses the AOA technique. With only a few reference nodes, the overall energy consumption can be reduced and position can be determined using the Euclidian distance.

4.3.4. Received signal strength indication (RSSI)

The received signal strength indicator (RSSI) technique is one of the simplest techniques for underwater localization. Unlike the aforementioned techniques that require time synchronization and communication overheads resulting in increased energy consumption, RSSI does not require strict time synchronization (Islam and Park, 2020) and thus consumes less power. As a signal propagates through any medium, its energy is affected by the path loss (LN Nguyen and Shin, 2019; Su et al., 2020). The path loss factor exploits the relation between distance and signal energy. When a signal propagates from the transmitter towards the receiver, the signal attenuates with increasing distance. However, this relationship is more complex for UAC because acoustic waves propagate in curve trajectories that pose sound projection areas and sound dark areas underwater. Domingo (2008) have provided a detailed survey on ray-theory-based multipath Rayleigh underwater channel models; and more recently, Morozs et al. (2020) have categorized the existing underwater channel models into three categories: binary range-based model, analytical transmission loss model, and specialized channel model. These works can assist network designers with developing more accurate path loss models for underwater sound propagation which can then be used for underwater RSSI localization.

From RSSI values and path loss models, the distance between the transmitter and receiver can be determined in decibel milliwatts (dBm) (Qi, 2003; Kumar et al., 2009). Higher strength of the signal indicates close proximity of the transmitter and receiver pair. Although this technique is simple to implement, it is quite susceptible to noise and interference. However, unlike most other localization techniques, the RSSI technique does not require any clock synchronization; hence reducing system complexity and energy consumption.

Chang et al. (2019) have proposed an approach for underwater acoustic localization problems using the RSS-based convex relaxation technique in UWSNs. Their proposed solution improves the localization accuracy; however, considers a simplified model instead of a generalized model that limits its use. Additionally, an energy harvesting underwater optical wireless sensor networks (EH-UOWSNs) framework using RSS-based localization has been proposed by the authors in Saeed et al. (2019b). In their work, a model for the underwater optical communication channel characteristics was developed for measuring RSS of active nodes. More recently, to minimize energy consumption, a solution has been proposed in Islam and Lee (2019a), where only cluster heads performed a major part of localization on behalf of the whole cluster. A re-transmission control scheme was also proposed for controlling unnecessary transmission and reducing energy consumption.

5. Alternative energy sources for underwater wireless communication networks

Besides the considerable research efforts to reduce energy consumption of underwater equipment, significant attention is also being directed towards utilizing alternative sources of energy for underwater networks. There are two components to using alternative power sources: the first is the realization of renewable sources of energy underwater, and the second is harvesting that energy from these sources and converting it into electrical energy to power or recharge underwater equipment.

There are various renewable energy sources available in the underwater environment (Wang et al., 2012). Erdem and Gungor have summarized the research trends in underwater energy harvesting techniques in their work in Erdem and Gungor (2020). Based on their work, the types of energy that are possible to be harvested underwater include solar (using surface solar panels), mechanical, chemical, biomass, and acoustic energy.

Energy from water currents can be readily harvested using mechanical hydrokinetic turbines (Cario et al., 2017), which can harvest energy from water currents using special propeller blades; and piezo-ceramic cantilevers (Bhuyan et al., 2013) which can exploit the water-flow induced vibrations to convert the captured mechanical energy from water currents into electrical energy. Apart from ambient water currents, the underwater environment is also a natural source of acoustic energy which can be harvested using hydrophones.

Bereketli and Bilgen (2012) have proposed a new paradigm of harvesting acoustic energy sources in their work. They introduced the concept of a Remotely Powered Underwater Acoustic Sensor Network (RPUASN), where sensor nodes harvest and store energy supplied by an external acoustic source. Their analytical modeling showed that RPUASN allows the network nodes to replenish their energy for an indefinite period of time, given the energy supplied by the source is renewable in nature. The RPUASN architecture is comprised of four units with two modular functions: control, sensing, and data processing units perform sensing tasks, and the energy harvesting (EH) unit harvests energy from the external power source using an array of hydrophones. The external power (acoustic vibrations) registered by the piezoelectric components in the hydrophones are modeled as induced AC voltage which passes a DC rectifier circuit, a storage capacitor, and a voltage regulator circuit before the power is supplied to the load.

Another platform that utilizes EH capabilities for underwater networks is the SEANet G2 proposed in Demirors et al. (2016). The SEANet G2 is a software-defined underwater acoustic networking platform that offers high data rate communication, spectrum agility, and highly flexible distributed network monitoring. In addition, it also contains a power module with EH capability supporting wireless power transmission (WPT). This WPT architecture is similar to that of RPUASN with a diode rectifier circuit connected to a capacitor that converts the acoustic wave energy detected as AC power into DC power to be supplied to other components of the platform.

With the rise of EH capabilities, various new forms of WPT mechanisms are also being proposed. Apart from the acoustic energy transfer (AET) used in RPUASN and SEANet G2, there are various other forms of contactless energy transfer (CET) techniques available. Some of the most popular WPT techniques are capacitive coupling, electromagnetic (inductive) coupling, and optical coupling (Roes et al., 2012).

Unlike RPUASN and SEANet G2 which are based on AET (Roes et al., 2012), the authors in Cheng et al. (2014) have designed and analyzed a loosely coupled transformer (LCT) based on the inductive power transfer (IPT) technique, that can be used in air, freshwater, and seawater mediums. Experiments show that this IPT system exhibits similar power transmission efficiency across all three mediums at the operating frequency of 21 kHz. However, compared with that in freshwater and air, the transmission efficiency in seawater decreases by 2.5% at the operating frequency of 154.2 kHz. This finding and the work in Zhou et al. (2013) demonstrate that for IPT systems, the operating frequency plays a significant role in achieving a target optimal transmission efficiency.

Another AET-based EH technique has been presented by Guida et al. (2018), where they proposed a design of the first acoustically powered battery-less IoUT platform, capable of harvesting energy from distant ultrasonic sources sufficient enough to power both sensing and communication operations simultaneously. Their system is comprised of a set of supercapacitors that can be recharged at the rate of 1 W per 5 min within an operative distance of approximately 1 m — a longer range than offered by any inductive and magnetic power transfer technologies.

More recently, an optical coupling based EH technique has been proposed in de Oliveira Filho et al. (2020), exploiting the concept of simultaneous lightwave information and power transfer (SLIPT) toward building a self-powered IoUT. SLIPT was inspired by the concept of radio frequency (RF) simultaneous wireless information and power transfer (SWIPT). However, since RF encounters extreme attenuation in the water medium, an optics-based system such as SLIPT is a promising technology for simultaneous high-speed data and power transfer for next generation underwater networks.

A summary of alternative energy sources for UWC has been provided in Table 7.

6. Future research directions

With numerous communication challenges in the complex underwater environment, there exists tremendous potential for future research in the UWC domain. Considering the aspect of energy consumption, a huge amount of it is wasted in UWCNs due to low link reliability, high BER, channel impairment, and multiple re-transmission issues. Adaptive systems, such as on-the-fly power control mechanisms and smart topology reconfiguration techniques to tackle dynamic underwater conditions, can reduce energy consumption in UWCNs.

Recently proposed metaheuristic algorithms are promising new techniques for optimizing energy consumption in UWCNs. The authors in Zhang et al. (2020b) have used grey-wolf optimization (GWO) to develop an energy-efficient localization algorithm that also improves network location coverage and node location accuracy. Similarly, Gola and Gupta (2021) have proposed an energy-efficient and void-avoiding underwater routing protocol based on GWO. Some recently proposed

Table 7
Summary of alternative energy supply for underwater nodes. (RE = Renewable Energy, EH = Energy Harvesting, WPT = Wireless Power Transmission).

Article	Year	RE	EH	WPT technique	Major contributions
Wang et al. (2012)	2012	✓	✓	–	• One of the earliest works on alternative sources of energy underwater. • Addresses the challenges and offers solutions for re-charging unmanned underwater vehicles by harvesting ambient energy from solar, wind, ocean, and geothermal energy sources.
Bereketli and Bilgen (2012)	2012	X	✓	Acoustic	• Proposes a novel paradigm of remotely-powered underwater acoustic sensor networks (UASN) with energy-harvesting acoustic nodes. • Presents an analytical model for electrical power, range, directivity, and transmission frequency of external acoustic source, along with node power requirements in order to determine the number of remotely-powered UASN nodes required to cover a certain area of interest. • Finds that the harvested power drops below 1 mW when the acoustic power source goes beyond 1 km.
Demirors et al. (2016)	2015	X	✓	Acoustic	• Discusses a software-defined networking platform SEANet G2 containing an energy-harvesting unit capable of harvesting acoustic wave energy via Teledyne RESON TC4013 hydrophone. • The hydrophones can harvest power in the order of milliwatts from a 1 V_{p-p} sinusoidal source signal operating at 125 kHz.
Cheng et al. (2014)	2015	X	X	Inductive	• Investigates a high-power inductive power transfer (IPT) system for contactless charging in AUVs. • Designs a novel semi-closed enclosure for a loosely-coupled transformer (LCT) that can be deployed underwater and can effectively reduce magnetic flux leakage electromagnetic radiation. • Analyzes the power loss in three different media — air, freshwater, and seawater for various operating frequencies. • Establishes a relationship between the operating frequency of the transformer and transmission efficiency. The proposed IPT prototype can transfer 10 kW at 91% maximal transmission efficiency over a 25 mm air gap.
Guida et al. (2018)	2018	X	✓	Acoustic	• Proposes the first battery-less supercapacitor-based underwater node capable of recharging using ultrasonic waves. • The recharging distance for the proposed system has been found to be greater than existing inductive and capacitive power transfer schemes.
Erdem and Gungor (2020)	2019	✓	✓	–	• Analyzes three different EH techniques – hydrokinetic turbine-based, piezoelectric cantilever-based, and acoustic hyrdrophone-based – based on three different underwater renewable energy sources, and studies their impact on the lifetime of underwater nodes. • Findings suggest that turbine-based harvester can extend network lifetime beyond 2000 days, longer than other EH techniques.
de Oliveira Filho et al. (2020)	2020	✓	✓	Optical	• Provides an overview of various simultaneous lightwave information and power transfer (SLIPT) techniques in time, power, and space domains and addresses their major differences. • Conducts two experiments demonstrating the concept of SLIPT. • The first experiment successfully transmitted data at a rate of 500 kb/s through a 1.5 meter water tank, while a self-powered sensor measured water temperature fluctuations. • The second experiment demonstrated a 60-second long real-time video transmission after the capacitor of a device equipped with a low-power red laser and analog camera was fully charged.

metaheuristics such as Fitness-Averaged Rider Optimization Algorithm (FA-ROA) (Alazab et al., 2021) and a hybridized form of GWO and ROA called the Overtaker Assisted Wolf Update (OA-WU) (Dev et al., 2021) have been implemented in terrestrial IoT networks to optimize energy-efficiency with minimal computational costs. If applied to underwater networks, these algorithms are expected to yield similar performance. Similarly, green communication techniques for terrestrial networks proposed in Ahmed et al. (2015a), Ahmed et al. (2015b), Mowla et al. (2017a), Mowla et al. (2017b) and Mowla et al. (2019) can also inspire novel ideas toward similar energy-efficient techniques for underwater networks. Moreover, since demand for high-data-rate UWC systems is rising rapidly with the growing popularity of AUVs and ROVs, green data/content-caching techniques (Zahed et al., 2020; Aziz Zahed et al., 2020) can improve energy-efficiency of future UWCNs. Research on underwater information-centric architectures that can process data content efficiently is still in its early stages (Li et al., 2021b) and require further investigation for future cache-enabled IoUT.

Due to the inherent properties of acoustic/optical channels and with increased data traffic in underwater networks, security is becoming a considerable issue that requires attention. However, traditional security techniques such as encryption and cryptography are resource-intensive and consume huge amount of energy, and are therefore inapplicable in the underwater domain (Yisa et al., 2021). Therefore, energy-efficient security protocols need to be studied and developed for future UWCNs. The works in Jiang (2018), Yisa et al. (2021), Lal et al. (2017) and Yang et al. (2018) provide comprehensive reviews of the security threats, challenges, and proposed security mechanisms for UWC available in the literature.

Recent proposals for adopting software-defined networking (SDN) in UWC promise many advantages by enabling UWCNs to dynamically adjust according to extreme short-term channel variabilities in underwater conditions. SDN-based architectures open new horizons for autonomous and efficient IoUT network-wide management and configuration capabilities that can optimize PHY, data link, and network layer parameters in real-time to cope with rapidly-changing underwater conditions, whilst still supporting various applications demanding strict quality of service (QoS) requirements. For instance, the authors in Luo et al. (2017a) have proposed an hybrid adaptive routing scheme (HARS) that can adjust its routing strategy based on channel conditions and application-specific performance requirements. Demirors et al. (2015) proposed a high-data rate SDN-based UAC modem prototype which they later implemented in their more recent work in (Demirors et al., 2018). The authors have also developed a high-data rate UAC modem – SEANet G2 – that can achieve data rates of 522 kbit/s over short horizontal links for a BER as low as 10^{-3} (Demirors et al., 2016).

More recently, the authors in Ruby et al. (2021) have proposed an energy-aware routing scheme formulated as an optimization problem, that exploits SDN-enabled features including centralized routing, global network-wide awareness, and seamless route discovery; and thereby outperforms other routing protocols in terms of energy efficiency, network lifetime, latency, and fairness. The authors in Dol et al. (2017) have reviewed existing works on SDN-based underwater modems in both academia and industry. The authors also discuss the development of SDN-based NILUS SoftModem for the NILUS MK2 node that can perform real-time PHY and network layer protocol execution within a high-level programming framework. Later, the authors in Luo et al. (2018b) have provided a comprehensive review on software defined architectures and technologies available in the literature and offer discussions for future research on the next generation UWCNs such as cross-layer design, cognitive-oriented sensor networks, and AI-based designs. More recently, the authors in Wang et al. (2019) have reviewed SDN-based UAC networks, and have discussed the current SDN challenges such as optimal isolation of resources, load-balancing between single/multiple controllers, and design of architecture based on software processing.

Moreover, use of multi-modal equipment that incorporates hybrid opto-acoustic and/or magneto-acoustic technologies at the PHY layer can enhance system performance by complementing the strengths and weaknesses of these technologies. The literature suggests that hybrid multi-modal PHY layer technologies can reduce energy consumption while improving network throughput (Han et al., 2014; Islam et al., 2021). SDN-based architectures governing multi-modal UWCNs can intelligently and adaptively select the most suitable modem (acoustic, optical, or magnetic induction) based on channel conditions and QoS requirements of applications supported by the UWCN.

Besides SDN-based solutions, recent developments in AI and ML can be particularly effective in the design of efficient UWCNs. Authors in Pelekanakis et al. (2016) have proposed a decision tree-based adaptive modulation scheme, where an ML model was trained towards correlating modulation schemes with channel conditions for a target BER. After training, the model could select the best modulation scheme based on channel state information in order to deliver the maximal data rate. The work in Xi et al. (2017) highlights the potential underwater applications where ML techniques can improve machine vision capabilities and thus enhance sensor efficiency.

Considering the network layer, a Multi-modAl Reinforcement Learning-based RoutINg with soft QoS (MARLIN-Q) has been proposed in Basagni et al. (2019), which jointly selects the best forwarding relay and the best link from a choice of multi-modal (low-data rate, long range versus high-data rate short range) links for data transfer that either meets a reliability criteria or stringent QoS requirements of a UWCN under varying underwater conditions. Compared to a similar channel-aware protocol called CARP (Basagni et al., 2012) and a Q-learning based forwarding protocol QELAR (Hu and Fei, 2010), MARLIN-Q consumes the least energy due to its built-in strategy of selecting the best modem on a per-link basis. Similar to MARLIN-Q, another protocol called Channel-aware Reinforcement learning-based Multi-path Adaptive routing (CARMA) (Di Valerio et al., 2019) uses smart-switching between a fast, energy-efficient single-path and a more robust, but unfavorable multi-path routing driven by a distributed reinforcement learning algorithm. This smart-switching technique jointly minimizes route-long energy consumption and improves PDR. CARMA consumes the least energy per bit compared to CARP, QELAR, and EFlood. More recently, a discrete wavelet transform based deep learning model for real-time image compression in IoUT has been proposed in Krishnaraj et al. (2020), that can improve energy-efficiency by minimizing the quantity of data transmission through a UWCN. Within the data link layer, the authors in Ahmed and Cho (2021) have shown that their Q-learning based MAC-layer protocol, by smartly selecting back-off slots and scheduling packet transmission to avoid collisions, can offer better energy-efficiency, channel utilization, and lower latency compared to other related protocols.

Considering the PHY layer, the authors in Huang et al. (2020) have proposed an attention-aided k-nearest neighbor (A-kNN) algorithm that can perform adaptive modulation and coding (AMC) tasks without being affected by the characteristic underwater channel modeling uncertainties. Similar to the former work, Alamgir et al. (2020) have proposed a boosted regression tree-based link adaptation strategy that can adapt link transmission parameters with changing channel characteristics using data rate, SNR, and BER metrics. The authors in Yang et al. (2020) have discussed how ML techniques can be utilized for underwater target detection, classification, and localization. More recently, the work in Jahanbakht et al. (2021) have presented a comprehensive review of the works related to ML-based IoUT techniques and have introduced the concept of Big Marine Data (BMD) analytics that can improve decision-making capabilities of network controllers and hence improve network performance including energy-efficiency.

The recent emergence of cross-layer techniques carries the potential to deliver better energy-saving techniques in UWCNs. Existing works in the literature indicates that energy optimization can be carried out in multiple layers of the protocol stack, sometimes even simultaneously. The authors in Xu et al. (2012) have proposed energy optimization in the physical layer, the authors in Gopi et al. (2010) in the network layer, and the authors in Kuo and Melodia (2011) have implemented energy optimization as a cross-layer approach by jointly optimizing transmit power and appropriate transmission mode to save energy. Design of cross-layer MAC protocols in cooperation with power control, modulation, and coding mechanisms in the PHY layer can deliver efficient scheduling techniques that can reduce packet duplication, collision, and re-transmission, and thus reduce energy wastage. Moreover, adaptive power control techniques working across layers with MAC protocols in the link layer can improve data rate and offer efficient spatial re-utilization. In addition to that, MIMO transmission, intelligent coding, and cooperative communication in the PHY layer can work jointly with opportunistic routing protocols in the network layer to both save energy and enhance network throughput.

In recent years, the use of renewable energy sources, such as tidal waves and bio-fuel to power underwater equipment, has been rising rapidly. With the recent boom in WPT technologies, future UWCNs are expected to adopt energy harvesting techniques from renewable energy sources using WPT to power themselves indefinitely. SWIPT and SLIPT are promising techniques that are expected to enable underwater nodes to exchange of power and data at the same time in future UWCNs, paving the pathway toward a green, sustainable, self-powered IoUT.

7. Conclusion

Underwater wireless communication faces numerous challenges due to the harsh, complex, and dynamic nature of underwater environment. Among all these challenges, energy consumption is one of the most significant hurdles to overcome for widespread adoption of IoUT. In the last few decades, enormous research effort has been directed toward addressing this challenge of energy consumption in UWC. However, these research works have not been reviewed and collected in a comprehensive survey that can serve as a guide for network designers for designing a more energy-efficient underwater network. In our work, we have attempted to review some important research studies toward green underwater communications, and organized them in terms of layers of the network protocol stack.

First, we reviewed the progress of the relevant field in the PHY layer, and described and compared existing PHY layer UWC technologies in terms of their strengths and weaknesses. Moreover, we reviewed some of the latest works on PHY layer coding, modulation, and power control techniques. Next, we focused on the upper layers to review important research works on energy-efficient MAC protocols (link layer), routing protocols (network layer), and localization techniques (application layer). Added to that, we provided a comprehensive review of the state-of-the art works on renewable energy supply and energy harvesting techniques proposed for next generation UWCNs, followed by a detailed discussion on the possible future research directions in the domain of UWC. Lastly, we concluded the review by summarizing our work. It is our hope that this review will assist network designers with developing novel strategies and devising new schemes that tackle the fundamental problem of energy consumption in UWCNs, and thus foster pathways toward green IoUT.

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.

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