A Survey on MAC Protocols for Underwater Wireless Sensor Networks

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***Abstract*—Underwater Wireless Sensor Networks (UWSNs) are expected to support a variety of civilian and military applications. In UWSNs, Medium Access Control (MAC) protocol has attracted strong attention due to its potentially large impact to the overall network performance. Unlike terrestrial networks, which mainly rely on radio waves for communications, UWSNs utilize acoustic waves, which pose a new research challenge in the design of MAC protocols. To present the development of MAC protocols in UWSNs, this paper surveys the current state-of-the-art MAC protocols for UWSNs. In the early development, the performance in terms of delay and throughput of the UWSNs has been the major concern of the MAC layer protocol design. Later, the design of energy-efficient MAC protocols becomes a new research focus because sensor nodes are generally powered by batteries which are less likely to be recharged. In this paper, we first describe the underwater acoustic environment and the challenges to the MAC protocols design in UWSNs. We then provide a comparative study of several types of MAC protocols according to current existing diverse implementations. Furthermore, open research issues will be summarized. Hopefully, this survey will inspire more active research in this area.**

***Index Terms*—MAC protocols, Underwater Wireless Sensor Networks, underwater acoustic environment, underwater communication.**

I. Introduction

In THE LAST couple of years, there has been a growing interest in the research and development of Underwater Wireless Sensor Networks (UWSNs). One important reason is that they can improve ocean exploration and fulfill the needs of a multitude of underwater applications [1-4]. UWSNs have emerged to be an ideal type of systems for efficiently exploring and observing the ocean. An UWSN consists of a variable number of sensors and vehicles that are deployed to perform collaborative monitoring tasks over a given area. To achieve this objective, sensors and vehicles self-organize in an autonomous network which can adapt to the characteristics of the ocean environment.

The features described below enable a broad range of applications of underwater acoustic sensor networks [5].

- Ocean sampling networks. Networks of sensors and vehicles can perform synoptic, cooperative adaptive sampling of the 3D coastal ocean environment.
- Environmental monitoring. UWSNs can perform chemical, biological and nuclear pollution monitoring.
- Undersea explorations. Underwater sensor networks can help detecting underwater oilfields or reservoirs, determine routes for laying undersea cables, and assist in exploration for valuable minerals.
- Disaster prevention. Sensor networks that measure seismic activity from remote locations can provide tsunami warnings to coastal areas, or investigate the effects of submarine earthquakes.
- Assisted navigation. Sensors can be used to identify hazards on the seabed, locate dangerous rocks or shoals in shallow waters, mooring positions, submerged wrecks, and to perform bathymetry profiling.
- Distributed tactical surveillance. AUVs and fixed underwater sensors can collaboratively monitor areas for surveillance, reconnaissance, targeting and intrusion detection systems.
- Mine reconnaissance. The simultaneous operations of multiple AUVs with acoustic and optical sensors can be used to perform rapid environmental assessment and detect mine-like objects.

To provide high throughput in an energy- efficient way, the design of an efficient Medium Access Control (MAC) protocol for UWSNs is of paramount importance because the MAC layer protocol coordinates nodesÕ access to the shared wireless medium. A MAC protocol allows the nodes in a network to share the common broadcast channel. The main task of a MAC protocol is to prevent simultaneous transmissions or resolve transmission collisions of data packets while providing energy efficiency, low channel access delays and fairness among the nodes in a network. A MAC layer protocol in UWSNs has much importance on the network utilization in the presence of a harsh underwater acoustic channel.

There has been a tremendous amount of research on the design and implementation of UWSNs [1-6]. However, those works study various aspects of UWSNs, for example medium access, network, transport, localization, synchronization protocols, and are not just for MAC protocols. There are a few surveys on MAC protocols in UWSNs [7, 8] that have been conducted to summarize the variations of designs and implementations. The survey in [7] has reviewed several early MAC protocols based on their medium access strategies and highlighted the issues inherited from physical layer, which should be considered in the design of MAC protocol. The work in [8] has analyzed some MAC protocols in UWSNs on the algorithm, advantages and disadvantages for each protocol.

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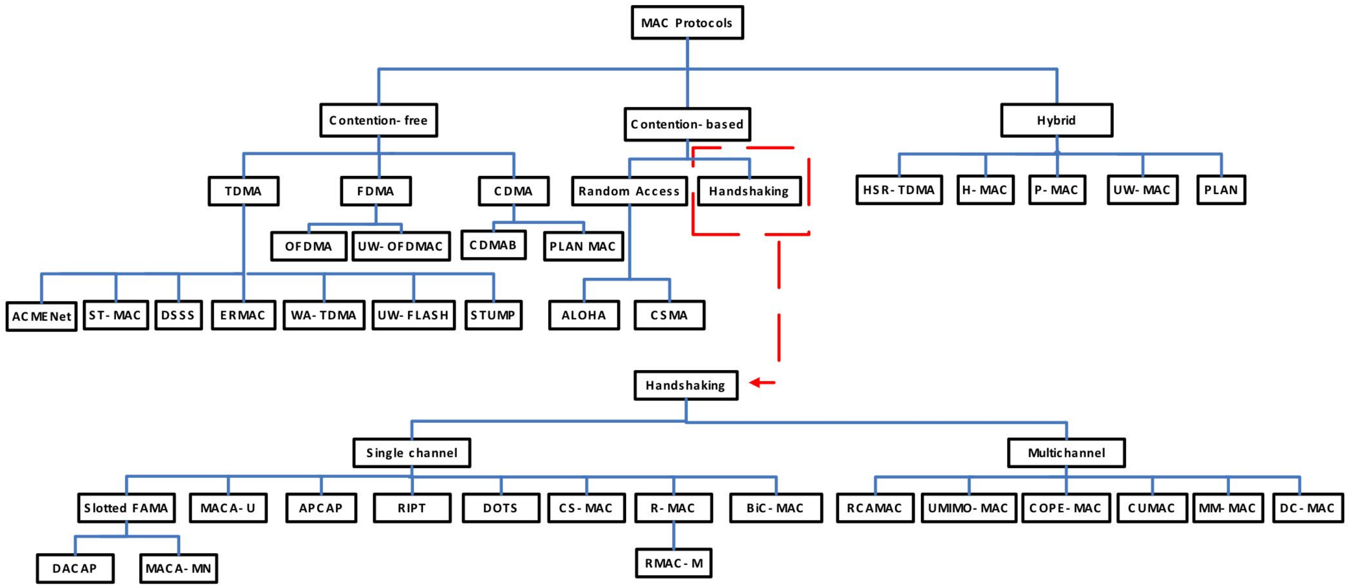

Fig. 1. The Classification of MAC Protocols for UWSNs.

Meanwhile, it has presented a MAC protocol that can be used in the UWSNs under the shallow water environment. On the other hand, this paper is different from the previous survey papers. It presents a comprehensive survey on the state-of-the-art MAC protocols for UWSNs since early 2005. It provides a more detailed classification on the basics of protocol together with the challenges to the design of MAC protocols. The MAC protocols in UWSNs are described with the following features or contributions.

- The influences of underwater acoustic environment and the challenges of design MAC Protocols in UWSNs will be addressed.
- The state-of-the-art MAC protocols and the classification of them based on the similarities and differences on the medium access approaches will be presented.
- A comprehensive and comparative investigation on some MAC protocols for UWSNs will be provided.
- Some open research issues will be summarized for further development.

The classification of MAC protocols for UWSNs in this paper is shown in Fig. 1. We start by introducing contention-free MAC protocols. According to different multiple access techniques, such as frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA), we classify and describe the contention-free MAC protocols. While contention-free MAC protocol is a simple paradigm, its direct adoption in underwater networks is not necessarily a good solution and the details are described in Section III. For the contention-based MAC protocols, we divided them into MAC protocols with random access and random MAC protocols with handshaking. Most of the efforts in the design of the MAC protocols for UWSNs have focused on the classification of handshaking MAC protocols, while we classify the MAC protocols according to the number of channels used for data transmission. Finally, hybrid MAC protocols will be introduced, which combine the advantages of the contention-free MAC and contention-based MAC protocols on demand.

The remainder of this article is structured as follows. In Section II, we describe the underwater acoustic environment and explore the challenges of the design of MAC protocols for the UWSNs. Next, in Section III, we describe the contention-free MAC protocols including FDMA-based, TDMA-based, and CDMA-based contention-free MAC schemes. We further describe the contention-Based MAC protocols in Section IV. In Section V, we describe the hybrid MAC protocols. Finally, we identify the open research issues with a conclusion in Section VI.

II. Challenges to the Design of MAC Protocols

A MAC layer protocol is critical to the UWSNs because it plays an important role to achieve the quality of service (QoS) in UWSNs. It is necessary to make a detailed study on different aspects of the design of MAC protocol to evaluate the performance of existing MAC protocols. In underwater acoustic environment, radio waves attenuate rapidly. Hence the signals can only travel over short distances. Optical signals are rapidly absorbed by water. Meanwhile the optical scattering caused by suspending particles and planktons is significant. So the optical signals cannot travel far in adverse conditions [2]. On the other hand, acoustic waves attenuate less and they are able to travel farther distances than radio waves and optical waves [9]. Consequently, unlike terrestrial networks that rely on radio waves for communication, UWSNs utilize acoustic waves to have information exchange. Therefore, in this section, we describe the underwater acoustic environment and identify the major challenges to the design of MAC protocols for UWSNs.

A. Features of the Underwater Acoustic Environments

The underwater acoustic environment poses more severe situation for MAC protocol design compared to MAC design for terrestrial networks [7, 10].

TABLE I
MAIN DIFFERENCES BETWEEN UNDERWATER ACOUSTIC NETWORKS AND TERRESTRIAL RADIO NETWORKS.

Underwater acoustics	Terrestrial radio
Nominal speed about 1.5×10^3m/s	Nominal speed about 3×10^8m/s
Low data rate and bandwidth	High data rate and bandwidth
Long and Variable prop delays	Short and Stable prop delays
Frequency-dependent noise	Typically white noise
Energy Consumption: TX > RX > Idle > Sleep	Energy Costs: TX $\approx$ RX $\approx$ Idle > Sleep
High Bit Error Rates	Low Bit Error Rates

1) **High and Variable Propagation Delay**: The propagation speed of sound in underwater is about 1500m/s [11]. Therefore, the propagation delay in underwater is five orders of magnitude higher than that of radio frequency (RF) terrestrial channels over air. The propagation delay in underwater is extremely variable that depends on temperature, salinity and depth of water. While propagation delay is negligible for short-range RF, it is a critical for underwater communications. It has profound implications on design of MAC protocols.

2) **Limited Bandwidth and Data Rate**: Due to high environmental noise at low medium frequencies, the available acoustic bandwidth depends on the transmission distance, which can be lower than 1 kHz or high-power absorption at high frequencies, which can be greater than 50 kHz [1]. Only a few kHz may be available at tens of kilometers, while tens of kHz will be available at a few kilometers. Typical acoustic modems work at the frequencies from merely a few Hz to tens of kHz. Hence, the data rate for underwater acoustic sensors can hardly exceed 100 kbps. Compared with the bandwidth in the order of several hundred MHz offered by RF radios, the very limited bandwidth of acoustic channels requires careful design of coding schemes and MAC protocols used in UWSNs.

3) **Noise**: Environment noises include man-made noise and ambient noise. Man-made noise mainly refers to machinery noise like pumps while natural noise refers to seismic and biological phenomena can cause ambient noise.

4) **Energy Consumption**: The acoustic transceivers under water have transmission powers in the order of magnitude higher than that of the terrestrial devices with a higher ratio of transmit to receive power, so the protocols which utilize the acoustic radio effectively become much more important in UWSNs [12]. Batteries are energy constrained and cannot be recharged easily.

5) **High Bit Error Rates**: The underwater channel is severely impaired, especially due to multi-path and fading. Multi-path propagation may be responsible for severe degradation of the acoustic communication signals because it generates Inter Symbol Interference (ISI). Higher value of ISI may result in higher bit error rates. Eventually temporary losses of connectivity, shadow zones, can be experienced in addition to the high bit error rates. “Shadow zone” is mainly caused by long paths and the frequency-dependent attenuation. It shows almost no acoustic signal existing in it. It would be a big challenge for a MAC protocol to provide certain reliability and maintain connectivity in such a harsh propagation conditions.

The main differences which have impacts on the design of MAC protocols are given in Table I. Due to these characteristics, the application of MAC protocols used for UWSNs will lead to inefficient results. Therefore, it is necessary to develop MAC protocols suitable for underwater acoustic communications taking all the characteristics into account.

B. Challenges to the Design of MAC Protocols for UWSNs

Conceiving a MAC protocol is a major challenge for the deployment of UWSNs. Ideally, an optimal underwater MAC protocol should provide higher network throughput, and lower energy consumption, taking into account of the harsh characteristics of the underwater acoustic environment. We describe the challenges which have to be addressed in the design of UWSNs MAC protocols in this section [7].

- **Network Topology and Deployment in UWSNs.** The performance of the MAC protocols for UWSNs is highly dependable on the deployment of underwater nodes which could be sparse or dense. Event readings of sparsely deployed nodes would be highly uncorrelated because the sensors nodes can monitor as well as communicate at long distance due to the availability of long range acoustic modems.
- **Synchronization.** Synchronization is a critical challenge in the design of MAC protocols because the MAC protocols such as the duty cycling approach work generally based on the time synchronization of the nodes. Without accurate synchronization, the duty cycling approach cannot ensure effective operation of sensor networks by handling time uncertainty between sensor nodes. This is due to the fact that the propagation delay is much higher and changes from time to time.
- **Hidden Node and Exposed Node Problem.** The problems of hidden nodes and exposed nodes arise more specifically in contention-based collision avoidance MAC protocols. A situation of a hidden node occurs when one node cannot sense one or more nodes that can interfere with its transmission. A situation of an exposed node occurs when a station delays transmission because of another overheard transmission that would not collide with it. In the first case, there will be collision and the nodes have to keep attempting for successful transmission.
- **High Delay Associated in Handshaking.** The conventional handshaking schemes can reduce the effect of hidden terminal and exposed terminal, which need time and energy to exchange control information. The exchange of control information takes the most of the communication time. It results in that the nodes have not much time for the payload delivery. The channel utilization rate is very low. The handshaking schemes have high propagation delay, which is a big challenge to the design of efficient protocols.

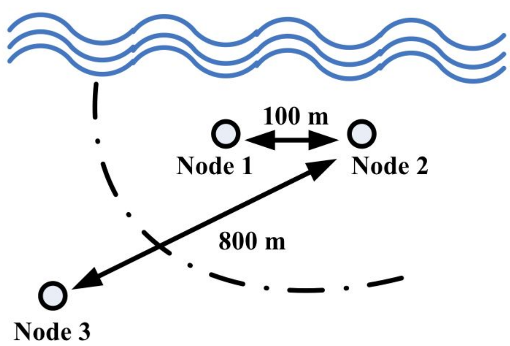

Fig. 2. Illustration of the "Near-Far" Problem.

- **Power Waste in Collision.** It is observed that a node consumes more power on transmission than on reception. The ratio of power required for reception to transmission is typically 1/125 [3]. Furthermore, the ratio becomes worse if collisions frequently appear due to the lack of an appropriate collision avoidance mechanism. So, the requirement of a MAC protocol should be able to avoid or minimize collisions.
- **Near-Far Effect.** The transmission power should be selected at the transmitter so that the signals transmitted from the transmitter to the intended receiver should be correctly received with the desired SNR which is neither lower nor higher than the required SNR. The near-far effect occurs when the signals received by a receiver from a sender near the receiver is stronger than the signals received from another sender located farther. There is an exemplified scenario illustrated in Fig.2 [21]. Nodes 1 and 3 are far away and therefore can transmit simultaneously without causing collisions. At node 2, the SNR level of the signals originated from node 1 is higher than that from node 3 due to the high level of noise produced by the signals coming from node 1. Therefore, although node 2 can receive both signals, it cannot decode the messages from node 3. The result is that node 1 is unintentionally screening the transmissions from node 3.
- **Centralized Networking.** Centralized solutions are not a suitable in UWSNs over an acoustic channel. In a centralized network scenario, the communication between nodes takes place through a central station. A major disadvantage of this configuration is the presence of a single failure point. Also, due to the limited range of a single modem, the network cannot cover large areas [6].

III. Contention-Free MAC Protocols

Contention-free MAC protocols have been considered for UWSNs in the earlier research studies. Therefore, in this section, we review the contention-free MAC protocols and their variations, which work based on three major multiple access techniques FDMA, TDMA, and CDMA.

A. Frequency Division Multiple Access (FDMA)

FDMA divides the available frequency band into sub bands and assigns each sub band to an individual user. The channel is used only by the user until it is released. The bandwidth of the total of the FDMA channels is smaller than the coherence bandwidth of original transmission channel [6]. Due to the limited bandwidth of underwater acoustic channels and the vulnerability of limited band systems to fading and multipath, the simple FDMA multiple access technique is not suitable for UWSNs.

A MAC layer protocol based on the FDMA technique can be found in [13], which tries to optimize the assignment of the available subcarriers among the neighboring nodes under an orthogonal FDMA MAC framework, with the objective of avoiding collisions and minimizing the overall energy consumption. The OFDMA is a special case of multicarrier modulation (MCM) in which multiple user symbols are transmitted simultaneously using different subcarriers with overlapping frequency bands that are mutually orthogonal. The OFDMA multiple access technique can effectively utilize the limited bandwidth and overcome multipath fading effects. To extend the work in [13], an adaptive OFDMA-based MAC protocol has been proposed in [14]. The protocol provides a more accurate underwater model to better capture the unique characteristics of acoustic waves in the water. Additionally, this work proposes, analyzes and compares three different modes of operation and involves extensive simulation experiments that evaluate a wider range of parameters. The results showed that the proposed protocol consumes considerably less energy while providing a considerably longer network lifetime by the CDMA-based technique. A new MAC layer protocol UnderWater Orthogonal Frequency Division Multiple Access Control (UW-OFDMAC) has been proposed in [15], where a transmitter-based OFDMA scheme integrates an original power and OFDMA parameters self-assignment algorithm to set the optimal transmission power, subcarrier spacing and guard interval duration. Each sensor can dynamically adapt the OFDMA parameters depending on the receiver location and its motion. As a result, the UW-OFDMAC scheme enables the most efficient use of the scarce acoustic spectrum and reduces packet retransmissions, which results in decreased energy consumption and increased network throughput. In particular, the UW-OFDMAC scheme has a good performance in shallow water communications, known to be heavily affected by multipath fading.

B. Time Division Multiple Access (TDMA)

Instead of dividing the frequency band, TDMA divides a time interval, called a frame, into time slots. Each time slot is assigned to an individual user. Time slots and overhead bits are combined into frames. Collisions of packets from adjacent time slots are prevented by adding guard times [6]. Therefore, TDMA is a better multiple access technique applied to UWSNs due to its simplicity and flexibility. Due to the large propagation delay and delay variance over the acoustic channels, guard time periods need be designed to separate different channels and minimize the probability of collisions in data transmissions, which can lead to lower channel utilizations [16]. Moreover, the variable delay makes it very difficult to implement a precise synchronization, with a common timing reference, which is required for the TDMA [5].

There are many TDMA-based MAC protocols proposed to overcome the shortcomings of the TDMA multiple access technique.

1) MAC protocols to improve channel utilization

A TDMA-based MAC protocol named as Acoustic Communication network for Monitoring of Environment (ACMENet) has been proposed in [17], which utilizes the acoustic propagation delay to avoid collisions. Sensor nodes in ACMENet are partitioned into two types as master nodes and slave nodes. The master nodes compute the propagation delays of the slave nodes and they should often be awakened to receive packets with certain intervals according to the slave nodes indices arranged at an ascending order of their propagation delays. Therefore, packet collisions can be avoided in ACMENet. However, the master nodes must be awakened many times in a duty cycle for each slave node, and thus the energy consumption is very high due to idle listening, especially in the case with low data load traffic [18]. In [19], a Spatial-Temporal MAC Scheduling protocol (ST-MAC) has been proposed. The ST-MAC is designed to overcome the spatial-temporal uncertainty in the TDMA-based MAC scheduling for energy saving and throughput improvement by constructing a spatial-temporal conflict graph (ST-CG). In [20], a novel Spatially Shared TDMA MAC (SST-MAC) protocol has been presented. This work introduces a quality measure taking into account both reliability and efficiency requirements of the network. The work in [21] has proposed a cellular MAC (C-MAC) protocol for UWSNs. The C-MAC uses different time scales for channel division which significantly alleviates the detrimental effect of long propagation delay on network throughput. The work in [22] has described an Underwater Distributed-TDMA (UD-TDMA) protocol and improves the utilization of the bandwidth, especially in high-density UWSNs.

In [23], a transmission scheduling for TDMA-based MAC protocol has been proposed, which takes the advantage of the long propagation delay of acoustic signals to facilitate concurrent transmissions and receptions of acoustic communications. A Priority Reservation MAC (PR-MAC) protocol has been developed in [24]. The PR-MAC protocol is energy efficient with the consideration of the long propagation delay and minimizing the conflicts and energy loss. In [25], a Dynamic Slot Scheduling Strategy (DSSS) MAC protocol has been proposed. The DSSS MAC protocol uses four heuristic strategies including grouping, ordering decision, scheduling, and shifting, to improve the channel utilization and to prevent the collisions. The DSSS MAC protocol can not only improve the channel utilization by increasing the transmission pairs without collisions to transmit in parallel, but also take the sink-to-node, node-to-node, and node-to-sink transmissions into account to increase the network applicability. The SYNChronization MAC (SYNC-MAC) protocol proposed in [26] guarantees real-time and energy efficiency, which is necessary for vehicle control system in difficult communication conditions. Meanwhile, it is useful to avoid data collisions in the half-duplex communications in the underwater networks.

2) MAC protocols to reduce delays

Efficiency Reservation MAC (ERMAC) protocol [27] makes only one sensor node in its transmission, while the other sensor nodes in their sleep mode so that the energy efficiency can be achieved. The ERMAC scheme groups sensor nodes according to their directions to the sink. Nodes belonging to the same group can transmit their packets in a pipelined and collision-free way. In [28], a new amendment-based TDMA time slot allocation mechanism (WA-TDMA) has been proposed, which can be applied to general multi-hop underwater applications. Slot allocation starts from the node which launched as the center outward to form the wave-like proliferation. The time slot allocation and amendment is continuously going without stopping. The scheme can shorten the initialization period of the network. With the help of amendment, the protocol can adjust the usage of the allocated time slots to improve the slots utilization and deal with slots reuse.

3) MAC protocols to improve synchronization

The work in [29] has presented an Underwater Wireless Acoustic Networks Medium Access Control (UWANMAC) protocol. Since the UWANMAC scheme strongly relies on the synchronization among the nodes' adaptive TDMA schedules, the network performance is much affected by the synchronization drift. The Underwater FLASHR (UW- FLASHR) protocol [30] is a TDMA-based MAC protocol which does not require tight clock synchronization, accurate propagation delay estimation or centralized control. As a TDMA-based protocol, UW-FLASHR operates over cycles of time, where each cycle has an experimental phase and an establishing phase. To send data, a node requests a new time slot by sending a data frame randomly in the experimental portion of each of several consecutive cycles. However, as each node contends to allocate a time slot by randomly choosing a transmitting time and checking to see whether such a transmission incurs any collisions, the UW-FLASHR scheme gradually constructs a loose transmission schedule in a distributed manner so that time gaps may exist between transmissions [23]. To solve the problems of strict synchronization and to provide long enough guard time of every time slot, [31] has presented a mechanism for nodes to adjust guard time according to the distance between the nodes of the transmission.

The staggered TDMA Underwater MAC Protocol (STUMP) [32] does not require tight node synchronization to achieve high channel utilization, allowing nodes to use simple or more energy efficient synchronization schemes. By the STUMP protocol, four possible conflicts and the propagation delay have made the scheduling to be constrained. Depending on the schedule constraints, several time slots may be scheduled for transmissions to prevent collisions [33].

C. Code Division Multiple Access (CDMA)

CDMA allows multiple users to operate simultaneously over the entire frequency band. Signals from different users are distinguished by means of pseudo-noise (PN) codes that are used for spreading the user messages [6]. The receiver can filter noise by the spreading-code to obtain the correct signal.

In [34], a CDMA-based MAC (CDMA-B) protocol for the underwater acoustic sensor networks has been proposed, which has a periodic sleeping mode jointly employed for the purpose of saving energy. CDMA technique is used to multiplex the transmission from the nodes at the same hierarchical level. Each node is allocated with different orthogonal codes. A hierarchical tree-topology is used with a staggered wakeup schedule across the multiple hierarchical levels. This protocol is a representative MAC protocol designed for a multi-hop network. There is another CDMA-based MAC protocol found in [35], which is named as Path Oriented Code Assignment CDMA-based MAC (POCA-CDMAMAC) protocol, has been proposed. By the POCA-CDMAMAC scheme, each node modulates its packets with a spreading sequence so that the sink can receive packets from multiple neighbors at the same time. Moreover, the nodes in the same path are assigned with the same spreading sequence and they transmit their packets in a round-robin way. The collision of packets can be reduced and the length of the spreading sequence codes will be shortened. There are also some CDMA-based hybrid protocols described in Section V.

D. Summary

In this section, we have reviewed the contention-free MAC protocols based on three major medium access techniques FDMA, TDMA, and CDMA, respectively. In the early development of underwater acoustic networks, FDMA medium access technique was predominant. The contention-free MAC protocols based on the FDMA technique have been developed to control the medium access. The most recent typical FDMA-based MAC protocol is the UW-OFDMAC scheme based on OFDMA technique. The FDMA based protocols and its improvements mainly face the design challenges of limited bandwidth.

To overcome the inherent inefficiency of the FDMA medium access, which has limited bandwidth and frequency selectivity on the acoustic channels, TDMA medium access technique becomes the major candidate for the underwater acoustic communications. Correspondingly, many contention-free MAC protocols based on TDMA multiple access technique have been developed to control the medium access and overcome the shortcomings of the TDMA medium access technique such as inaccurate synchronization and low channel utilization. We have classified the MAC protocols into three groups in our review. The TDMA-based protocols mainly face the design challenges of synchronization and high delay associated.

CDMA is the promising medium access technique without synchronization requirement. However, due to the inherent shortcomings on near-far problem by the CDMA technique, which is the major design challenge to the MAC protocols, the development of contention-free CDMA-based MAC protocol is few. A power control algorithm is used to reduce the output power level of each node such that it can deal with the near-far problem.

IV. Contention-Based MAC Protocols

Most of the efforts on the design of the MAC protocols for UWSNs have focused on the design of contention-based MAC protocols, which have the advantages to exploit the full bandwidth of the communication channel [1]. By the contention-based protocols, the nodes compete for a shared channel resulting in probabilistic coordination. The Contention-based protocols can be classified into random access and handshaking protocols.

A. Random Access

There are generally two approaches of random access in the classification of contention-based MAC protocols, which are ALOHA and Carrier Sense Multiple Access (CSMA) with their variances. By the random access approaches, a node simply starts its transmission whenever it has data ready for the delivery. When a data packet arrives at a receiver, if the receiver is not receiving any other packets and there is no other packet coming in the period, the receiver can receive this packet successfully. By the random access approaches, multiple nodes share the transmission medium randomly without any control. By the RCAMAC scheme, the entire bandwidth is shared by many stations which easily suffer various collisions.

1) ALOHA protocols

ALOHA is the simplest random access MAC protocol to be easily implemented without any effort to prevent collisions. The protocol works as follow. If a node has data ready to send, it will send the data at its will. If two nodes transmit packets at the same time, a collision occurs. In this case, a retransmission is required. Some variances based on the ALOHA have been proposed.

In [36], a study on Slotted ALOHA protocols for UWSNs has been presented. By the Slotted ALOHA, a node cannot send its packets at any time, but has to wait for the beginning of a timeslot. Thus, the chances of collisions will be reduced. Due to the long and varying propagation latency of the underwater acoustic channel, a study in [37-39] shows that the Slotted ALOHA protocol cannot get better performance than that of the ALOHA protocol in underwater acoustic networks. The work in [40] has proposed a solution to handle the performance degradation of the Slotted ALOHA protocol. It has shown that collision and reception in slow networks depend on both transmission time and the location of the receiver. The impact of space-time uncertainty to Slotted ALOHA performance has been improved in [38] with a modification that adds guard bands to the transmission slots. There is a tradeoff between the maximum propagation delay and the guard bands length. Based on the solution in [38], a propagation delay tolerant ALOHA (PDT- ALOHA) protocol has been proposed in [41].The PDT-ALOHA scheme has improved the performance of the Slotted ALOHA in terms of successful packet reception rate and the network throughput.

The further enhancements on the ALOHA scheme focus on the integration of the schemes to prevent collisions with the ALOHA protocol. In [42], two ALOHA-based protocols,

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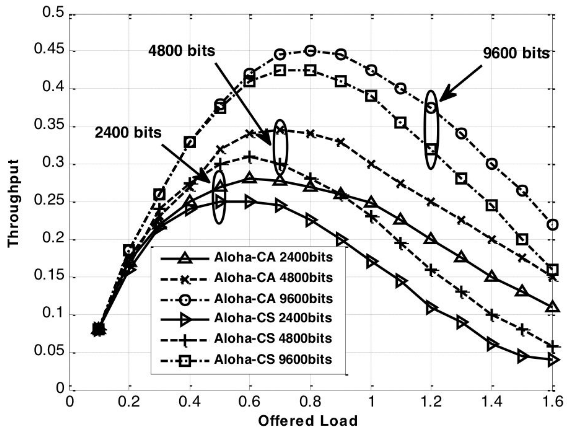

Fig. 3. Throughput of Aloha-CA Compared to Aloha-CS.

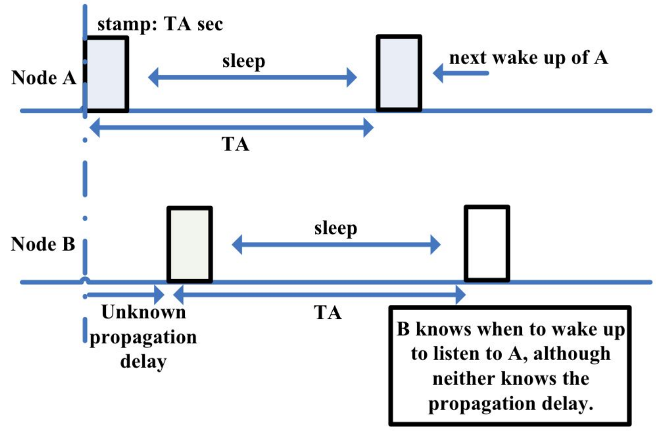

Fig. 4. Basic Idea of the UWAN-MAC Protocol.

one called ALOHA with carrier sense (ALOHA-CS) and the other, ALOHA with advance notification (ALOHA-AN), have been proposed. Each of the two protocols provides an essential increase of the network throughput in comparison with that of a pure ALOHA protocol. Both protocols have taken the advantage of the long propagation delay in underwater acoustic environments. There is no handshaking and no synchronization involved. The ALOHA-AN needs to collect and store more information, therefore it requires more resources than ALOHA -CA. However, the extra cost allows the ALOHA-AN to achieve much better throughput and the ability to support collision avoidance. The performance comparison in terms of throughput between ALOHA-CA and ALOHA-CS is shown in Fig. 3

Recently, a back-off tuning scheme for ALOHA has been proposed in [43]. This work uses the ALOHA scheme with the back-off technique for packets transmission to achieve a better throughput. The scheme is easy to be implemented and applicable to more complex protocols with a multi-channel. The work in [44] has proposed two enhanced Slotted ALOHA protocols to minimize the impact of propagation delay in UWSNs. They are respectively Synchronized Arrival Slotted ALOHA (SA-ALOHA) protocol and an Improved SA-ALOHA (ISA-ALOHA), which adjusts the size of time slot according to the range of delay estimation errors. The SA-ALOHA and ISA-ALOHA perform remarkably better than Slotted ALOHA for UWSNs. Furthermore, the ISA-ALOHA is more robust even when the estimation error of the propagation delay is large.

2) CSMA protocols

CSMA is a representative class of random access protocols, where all nodes have to sense the channel for a certain period of time before the channel access. The scarce resources of the channel can be utilized much better if users listen to the channel before transmitting a packet. Details and the variations of the CSMA scheme can be found in [16, 18, 40, 45, 46].

In [16], an Ordered CSMA for UWASNs has been proposed. Without the handshake mechanism and control packets, the Ordered CSMA, uses a round-robin scheduling and CSMA to avoid collisions. The Ordered CSMA scheme allows multiple carriers from multiple sources to propagate at the same time. Moreover, the time synchronization is not required in the Ordered CSMA. The protocol can greatly improve the channel utilization. However, the Ordered CSMA was originally designed for a single-hop network. When it is used in a multi-hop network, the performance will be degraded. Another CSMA-based MAC solution, termed as Propagation Delay Aware Protocol (PDAP), is proposed in [45]. The protocol aims at maximizing the bandwidth utilization to enable interleaved, yet reliable communications between different pairs of nodes. To improve the channel utilization, PDAP keeps track of the neighboring transmissions to avoid collisions and retransmissions [46].

In [18], a novel CSMA-based protocol with collision avoidance and low energy consumption has been proposed. This protocol works by using the differences of the propagation delay between pairs of incident nodes to avoid collisions.

In [47], the Underwater Wireless Acoustic Networks MAC (UWAN-MAC) protocol has been proposed. The UASN-MAC protocol is a distributed CSMA-based energy-efficient MAC protocol. The energy is the main performance metric rather than the bandwidth utilization. The algorithm is designed to achieve a locally synchronized schedule even in the presence of long propagation delays. The basic idea of the protocol is illustrated in Fig.4. Node A broadcasts a SYNC packet and turns into sleep mode. The shaded rectangle represents the SYNC packet in the transmission and TA is the transmission cycle period. When node B joins the network and listens to the SYNC packet, it decodes the length of the transmission cycle period from the packet. So node B knows when to wake up to listen to node A. However, in order to improve energy efficiency and operate at a low collision rates, each node requires a small duty cycle, which makes it difficult to achieve high throughput. In [48], an enhancement over the UWAN-MAC protocol is achieved by power control. By the power control, the network lifetime can be increased, especially, in underwater sensors networks as nodes battery cannot be recharged with solar energy. But the power control increases channel reuse and co-channel interference to the neighboring sensors, ultimately reducing the number of collisions.

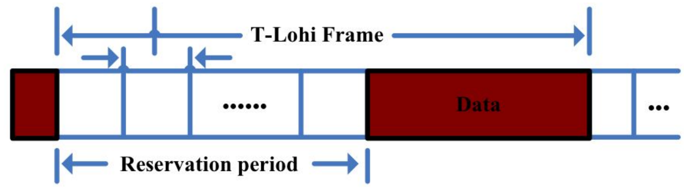

Fig. 5. The Tone-Lohi Protocol Frame.

In order to solve the problem of space-time uncertainty, a new class of CSMA-based MAC protocols, called Tone-Lohi (T-Lohi) has been proposed in [40]. By the T-Lohi, nodes contend to reserve the communication channel to send data. Fig 5 shows the process, where each frame consists of a reservation period (RP) followed by a data transfer. Each RP consists of a series of contention rounds (CRs) until one node successfully reserves the channel. Its reservation process is fully distributed, and it is rapid and energy-efficient by employing short tones and a low-power receiver. However, T-Lohi requires a node to be idle and listen to the channel in each contention round when competing for the channel. The listening period lasts at least the maximum single-trip propagation time plus the time to detect the contention tone, which results in a low channel utilization [49].

B. Handshaking

Another important type of the contention-based MAC protocol is the handshaking protocol, which is essentially a group of the reservation-based protocols. The basic idea of the handshaking or the reservation-based schemes is that a transmitter has to capture the channel before sending any data. We classify the handshaking MAC protocols into two categories as the MAC protocol with single channel and the MAC protocol with multiple channels.

1) MAC protocols with single channel

The MAC protocols with single channel utilize only one channel for data communication. The handshaking messages exchange for the channel capture will be performed before any payload transmission over only one channel.

The first group of the handshaking MAC protocols is a group of protocols with aims to achieve energy efficiency. The Slotted floor acquisition multiple accesses (Slotted FAMA) have been proposed in [50]. This protocol works based on the floor acquisition multiple accesses (FAMA) in [51] with time slot division. It combines both carrier sensing and a dialogue between the transmitter and the receiver prior to data transmission. There are some other works to improve the Slotted FAMA scheme. Like the Slotted FAMA, the Distance-Aware Collision Avoidance Protocol (DACAP) in [52] combines carrier sensing and an exchange of request to send/clear to send (RTS/CTS) control packets prior to data transmission, but it does not require the nodes to be synchronized to common time slots. DACAP is a collision avoidance protocol that is easily scalable to the changes in the number of nodes and the coverage area of the network. Additionally, it provides higher throughput than that of the Slotted FAMA scheme with similar power efficiency. To reduce the overhead associated with the Slotted FAMA scheme, another improvement that deals with both the energy efficiency and the delivery overhead has been proposed in [53]. The main idea of the protocol is to include a waiting period between the moment when a CTS frame is received and the moment the source node starts sending its data. An asynchronous MAC protocol, namely, MACA with packet train for Multiple Neighbors (MACA-MN) has been proposed in [54]. The MACA-MN utilizes a handshaking scheme in order to avoid collisions and alleviate the hidden terminal problem in multi-hop underwater networks. In addition, the MACA-MN goes one step further as the packet train is actually formed for multiple neighboring nodes simultaneously. However, due to the long duration of each handshake, the average waiting time can be very long before a node gains control of the channel for transmission [55].

The second group of the handshaking MAC protocols with single channel is a group of protocols with aim to alleviate the impact of long delays. There are normally two ways to handle the long delay impacts. One way is for the transmitting nodes to use the long delay period of control information exchange to complete some other work. The following solutions can be considered following this way. A modified four-way handshaking scheme, named Multiple Access Collision Avoidance for Underwater (MACA-U), has been proposed in [56]. By the MACA-U scheme, if a node which has transmitted a RTS frame receives another RTS frame from its neighbors, it can ignore the network allocation vector (NAV) setting to transmit its data frame in order to save time. But, collisions probability could be high by the MACA-U scheme. In [57], a MAC protocol called propagation-delay-tolerant collision avoidance protocol (PCAP) has been proposed. Besides the requirement of RTS and CTS frames, the protocol allows the transmitting node to perform other actions in the period waiting for the CTS frames returning. In [58], an adaptive propagation delay tolerant collision avoidance protocol (APCAP) is more comprehensively designed to accommodate the long propagation delay in the UASNs. It is flexible and adaptive to both of the offered traffic load and the availability of destination nodes.

Another way is to allow the source or destination nodes to manage a long delay period for the control information exchanged to accommodate more concurrent transmissions with aim to improve the overall performance. In [59], a Receiver initiated Packet Train (RIPT) protocol has been proposed, which also tries to reduce the impact of the long propagation delay by utilizing receiver-initiated reservations and coordinating packets from multiple neighboring nodes to arrive in a packet train at the receiver. Although this approach

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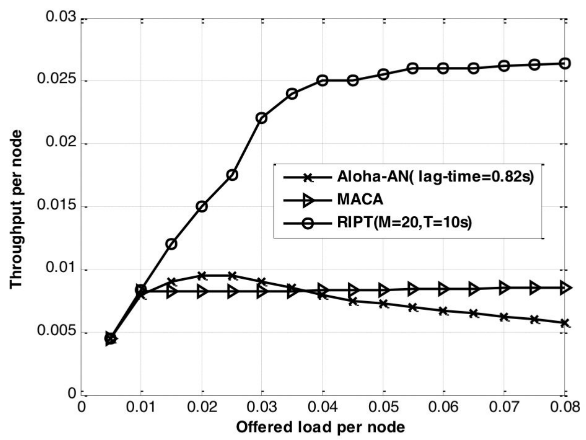

Fig. 6. Throughput Comparison.

can reduce the relative proportion of time on control signaling, the adoption of a receiver-initiated approach requires a complex traffic prediction algorithm. The throughput of RIPT, MACA, and Aloha-AN is shown in Fig.6. In [60], an adaptive distance aware scheduling protocol is proposed, which tries to overcome the long propagation delay in the UWSNs. The protocol uses a distance awareness scheduling model for UWSNs to improve the performance of the network in terms of data rate, throughput and the propagation delay over the underwater acoustic channels. A Delay-aware Opportunistic Transmission Scheduling (DOTS) protocol [61] uses passively obtained local information to increase the chances of concurrent transmissions while reducing the likelihood of collisions. It can alleviate the impacts of the long propagation latency and the severely limited bandwidth of acoustic communications. A Channel Stealing MAC (CS-MAC) protocol [62] has been proposed to improve the performance of the UWANs. The CS-MAC protocol effective makes use of the idle waiting time between the frame exchanges, and provides more transmission opportunities to improve the channel utilization.

The last group of the handshaking MAC protocols with single channel has the aim to achieve high channel utilization or fairness. A reservation-based MAC protocol (R-MAC) has been proposed in [63], which schedules the transmission of control packets and data packets at both the transmitter and the receiver nodes to avoid data packet collisions completely. By the R-MAC protocol, each node works in listen and sleep modes periodically. The durations for listen and sleep are the same for all nodes. And each node randomly selects its own schedule because no centralized scheduling and synchronization are required [64]. To extend the above reservation based R-MAC protocol, a Reservation-based MAC-Mobile (RMAC-M) [65] has been developed to support the mobile sensor nodes. It leverages the energy efficiency and fairness with ability to handle nodesÕ mobility. A Bidirectional-Concurrent MAC (BiC-MAC) has been proposed in [66], which is designed with a versatile MAC framework to support all three possible modes of bidirectional transmissions. In another attempt to improve the channel utilization, a reverse opportunistic packet appending (ROPA) has been proposed in [67]. It seeks to improve the channel utilization by reducing the proportion of time spent on control signaling. The transmitter can coordinate the packet appending so that those packets will arrive in a collision-free packet train.

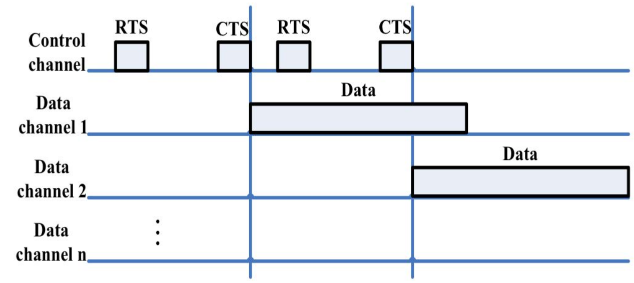

Fig. 7. Multiple Channels with Handshaking.

Recently, a spatially fair MAC protocol, named SF-MAC, has been proposed in [33] to solve the space uncertainty problem in UWSNs. SF-MAC protocol is a receiver-based protocol, by which the receiver captures the RTSs of all the contenders and determines the earliest transmitter by considering the potential transmission duration to achieve a fair transmission. Similar to the aforementioned protocol, a weight-based spatially fair MAC protocol (WSF-MAC) has been proposed in [68], which tries to overcome the issue of spatial unfairness. By the WSF-MAC scheme, the transmission of the underwater-reply packet will be postponed for a silence period of time at the receiver to capture the underwater-request packets of all the potential transmitting nodes.

2) MAC protocols with multiple channels

Different from single channel MAC protocols, multiple channel protocols utilize more than one channel for communication [69]. As shown in Fig.7, there are one common control channel and multiple data channels. The node with outgoing packets will sends a RTS message over the control channel. The RTS frame should include the sender/receiver identifier, the available channel set and the packet length. Some multiple channel MAC protocols are summarized below.

In [70], a Reservation Channel Acoustic Media Access Protocol (RCAMAC) based on RTS/CTS handshaking has been proposed. By the RCAMAC scheme, the entire bandwidth is divided into two channels. One is a control channel with less bandwidth. Another is the data channel with much more bandwidth. With taking both energy efficiency and throughput into consideration, a novel COntention based Parallel rEservation MAC (COPE-MAC) protocol has been proposed in [71], which introduces parallel transmission into the protocol design and makes concurrent transmission possible in the UWSNs, which augments the system throughput. On the other hand, it adopts a contention based reservation approach to avoid collisions and improve the system energy efficiency. Another Multiple channels MAC protocol, (MM-MAC), is proposed in [72-73], which aims to use a single modem to emulate multiple transceivers. Utilizing the cyclic quorum systems, nodes running MM-MAC are guaranteed to meet their intended receivers to solve the missing receiver problem. In [74], an Underwater Multiple Input Multiple Output MAC (UMIMO- MAC) protocol is proposed, which leverages MIMO capabilities to allow more flexible and high efficient utilization of the underwater acoustic channels. In particular, the UMIMO-MAC scheme is fully distributed and relies on lightweight message exchange. Moreover, the UMIMO-MAC scheme adapts its behavior to the condition of environmental noise, channel, and interference to maximize the network throughput or minimize the energy consumption, according to the QoS requirements of the traffic being transmitted.

In a single-transceiver multichannel long-delay underwater acoustic network, new hidden terminal problems, namely, multichannel hidden terminal and long-delay hidden terminal have been exposed. To handle the problems, a new MAC protocol, named Cooperative Underwater Multichannel MAC (CUMAC) has been proposed in [75]. CUMAC utilizes the cooperation of neighboring nodes for collision detections with a simple tone device designed for the distributed collision notification. In particular, this protocol considers a cost-effective network architecture where one and only one transceiver is required at each node. Tailored for a data-centric scenario, in [76], a Data-Centric MAC (DC-MAC) protocol has been proposed. The DC-MAC uses multi-channel strategy to eliminate the hidden terminal problem and uses dynamic collision-free polling strategy to offer efficient channel assignment. The combination of the two strategies as a single design helps to achieve high performance for the considered scenario.

C. Summary

In this section, we have reviewed the contention-based MAC protocols with the random access and the handshaking protocols. In the category of random access protocols, there are two main protocols of ALOHA and CSMA with their variations.

In practice, hidden nodes and exposed nodes will bring some challenges to random access protocols. By the ALOHA schemes, the transmitting nodes will not consider the channel state before their transmissions. It results in a high probability of collisions. Therefore, almost all the variations of ALOHA scheme work on avoiding collision. By the CSMA schemes, the transmitting nodes listen to the channel before the transmission of packets. The probability of collisions could be reduced while the scarce resources of the transmission channel can be much better utilized. However, due to the long propagation delay in the UWSNs, the CSMA schemes may lead to an exceedingly long vulnerable time period and the underwater carrier sense cost is very expensive. To prevent the collisions at the receiver side, it is also necessary to add a guard time between transmissions according to the maximum propagation delay in the network [5].

In the category of handshaking protocols, we classify the handshaking protocols according to the protocols with a single channel or the protocols with multiple channels. According to the ways to handle the design challenges, the handshaking protocols with a single channel can be classified into three categories, which are the protocols to achieve energy-efficiency, the protocols to alleviate the impact of long delays, and the protocols to achieve fairness or high channel utilization. Recently, parallel data transmission has attracted intense research attention because many MAC protocols in UWSNs emerged with multichannel supports. The bandwidth in UWSNs is limited, thus it is desirable to devise multichannel MAC protocols to handle the bursty traffic or provide multi-task support.

V. Hybrid MAC Protocols

The hybrid MAC protocols integrate different medium access techniques and different types of MAC protocols on demand or in a traffic-adaptive fashion to achieve better performance of the UWSNs. Recently, the design of the hybrid MAC protocols in UWSNs has become an attractive research topic. In the following, we present some typical hybrid MAC protocols as the examples to show the advantages and benefits of them.

1) HSR-TDMA: A hierarchical multiple channel MAC protocol has been proposed in [77] for clustered UWSNs, where the TDMA medium access technique is used for the intra-cluster communication and CDMA medium access technique is used for the inter-cluster communication. Clustering the sensor nodes can achieve the spatial reuse of channel resources to make the network availability significantly increased. However strict synchronization among all nodes is required. Evolved from the solution in [77], a Hybrid Spatial Reuse TDMA (HSR-TDMA) protocol has been proposed in [78], which enables the integration of CDMA medium access technique with the TDMA leading to a hybrid medium access technique. Different from the work in [77], the CDMA component is independent of locations of the nodes in the network. Furthermore, the HSR-TDMA scheme uses a mesh type protocol, which is usually less sensitive to the topology changes and allow robust solutions.

2) H-MAC: In order to take the advantages of both contention-free and random access MAC protocols, a hybrid MAC protocol has been presented in [12]. The proposed MAC protocol divides a time frame into two time slots, one of which is used by each node to transmit data by the contention-free scheme. Another one is used for random access by the nodes to adapt to variable traffic conditions. This H-MAC can yield the benefits from both contention-free and random access protocols with little power consumption due to its ability eliminating collisions and adaptive to the changes of traffic conditions.

3) P-MAC: In [79], a hybrid MAC protocol, named Preamble-MAC (P-MAC), has been proposed, which consists of a contention-free protocol and Slotted MACA. P-MAC overcomes the low precision of time synchronization. P-MAC works adaptively and dynamically according to the information of Virtual Distance Level (VDL), which is the estimated, accumulated information of channel status and variation obtained through periodically monitoring the underwater environment.

4) UW-MAC: A distributed CDMA-based energy-efficient (UW-MAC) protocol with ALOHA has been proposed in [80-82]. By this protocol, the signaling packets will be sent by the ALOHA scheme before the transmission of the payload by the CDMA medium access technique. The transmitter adjusts its pseudo-random sequences length and signal power to reduce

the multiple access interference (MAI) at the receiver. The UW-MAC protocol aims to guarantee high network throughput, low channel access delay, and low energy consumption.

5) PLAN: A distributed MAC protocol, named Protocol for Long-latency Access Networks (PLAN), has been proposed in [83]. The PLAN protocol utilizes the CDMA as the underlying medium access technique to minimize multipath and Doppler effects which are inherent in underwater physical channels. A MACA scheme is employed for each channel before actual data transmission. By this scheme, the CDMA spreading codes are distributed first by a contention-free algorithm and each node is assumed to get a unique spreading code among its one-hop neighbors.

To summarize, in this section we have presented a few hybrid MAC protocols as the examples to show the recent development on the research of design of MAC protocols for the UWSNs. The hybrid MAC protocols combine the strength of different medium access techniques and various MAC protocols while compensating their weakness to build more efficient MAC protocols. However, they may face the design challenge of communication overhead which is caused by the algorithm complexity. This advantage comes at the cost of the communication overhead and the protocol complexity caused by the complicated design and structure.

VI. Conclusions and Open Research Issues

In this paper, we have conducted a comprehensive survey of MAC protocols in UWSNs. Large numbers of mechanisms and protocols described in this survey reflect the importance of the research activities on the MAC protocol design for the UWSNs. This area of study is mostly challenging in the context of underwater acoustic environment.

A detailed comparison of different UWSNs MAC protocols with respect to topology, synchronization, advantages and disadvantages has been presented in Table II, in which the current state-of-the-art solutions of the MAC protocols in UWSNs can be found since early 2005. In the topology classification, we differentiate the protocols as centralized and distributed schemes. On the other hand, synchronization is required in most contention-free and hybrid protocols. As summarized in Table II, the improved contention-free protocols mainly handle the synchronization issue and try to reduce the delay with aim to improve the channel utilization. However, they still face the effect of near-far problem. Contention-free protocols use the advantage of the free distribution of the channel to improve the efficiency of the control packet transmission and to achieve fair access and energy efficiency, which can solve the space-time uncertainty and the issue of hidden node and exposed node problem to a certain extent. However, the high node density and high offered load will impact the achievements resulting in a challenge. Hybrid MAC protocols take use of the advantages of different types of protocols. For example, the UW-MAC in [82] sends the detection packets by the ALOHA approach, which combines the ALOHA and the CDMA schemes to highly improve the throughput of the networks.

The MAC protocols reviewed in this paper have provided an overall view on the current research progress on the development of the MAC protocols for the UWSNs. It seems that there is not a single protocol, which can be considered as a perfect solution to meet all the requirements from various applications. In order to promote further research on the design of the MAC protocols specifically tailored to UWSNs, we suggest the following open research issues which need to be addressed.

First, different applications impose various requirements on the MAC protocols. Although extensive research has been done on QoS provisioning, such as the work in [74], there is no ideal QoS-aware solution which would meet all the expectations of the underwater scenarios and can be flexible in time. Future research is required to design and develop adaptive MAC protocols to provide differentiated levels of QoS for various applications over underwater networks.

Second, most of the existing UWSNs MAC protocols have been designed based on the assumption that the nodes are mobile at a low rate or they donÕt move for a short period of time. Due to the ocean current, UWSNs nodes could move greatly and network topology will change. So the design of MAC protocols must take the reality of the situation into account to adapt to the topology changes.

Third, due to the robust ability to frequency selective fading caused by underwater multi-paths environments, CDMA is a promising multiple access technique for the UWSNs It is a challenging research work to design and develop CDMA-based MAC protocols to control the transmission power at all sensor nodes in order to counter the near-far effects. The design of CDMA-based MAC protocols is required because they are able to adaptively control the transmission power with features of high auto-correlation and low cross-correlation which can achieve the minimum interference among sensor nodes in the underwater networks.

Fourth, to further boost network throughput, handshaking MAC protocols with multiple channels are supposed to be the best candidate. Due to high and variable propagation delay in the underwater environments, the design and development of more intelligent and cost effective handshaking MAC protocols with multiple channels is expected. Furthermore, various cost- effective hybrid MAC protocols are expected to be autonomously flexible to various types of traffic of applications and different types of the topology of the UWSNs.

Lastly, there has been some research on MAC protocols for UWSNs applications, such as underwater acoustic localization technique. In the localization system of large-scale UWSNs, MAC protocols affect the localization coverage, speed and communication costs, while the localization results can also be used to improve the performance of MAC protocols. The future research is expected to analyze the performance of different MAC protocols and localization algorithms. Furthermore, the cross-layer design of MAC protocols and the issues of localization are worthy to investigate.

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TABLE II
COMPARISON OF DIFFERRNT UNDERWATER ACOUSTIC NETWORKS MAC PROTOCOLS.

		Protocol	Year	Topology	Synchronization	Advantage	Disadvantages
CONTENTION-FREE	FDMA	OFDMA [13,14]	2009	centralized	yes	Adopt an orthogonal FDMA MAC framework, eradicate the hidden terminal and the exposed terminal problem	Multiuser diversity and frequency diversity affect the performance
		UW-OFDMAC [15]	2011	distributed	yes	Adopt an orthogonal FDMA MAC framework, guarantee high bandwidth efficiency and low energy consumption	ISI and high PAPR affect the performance
	TDMA	ACMENet [17]	2006	centralized	yes	Utilize the acoustic propagation delay to avoid collisions	Energy consumption is high due to idle listening
		ST-MAC [19]	2009	multihop	yes	Construct a spatial-temporal conflict graph, solve the vertex- coloring problem	Not suit for mobile networks
		DSSS [25]	2011	centralized	yes	Improve the channel utilization by increasing the transmission pairs without collision to transmit in parallel	Strict synchronization is required
		ERMAC [27]	2008	centralized	yes	Efficiency Reservation which leads to energy efficiency	Not suit for multi-hop applications
		WA-TDMA [28]	2009	multihop	yes	Loosens the synchronization requirement, each node adopts periodic awake/sleep to reduce the energy waste	Slots allocation is important
		UW-FLASHR [30]	2008	distributed	yes	Not require tight clock synchronization or accurate propagation delay estimation	Time gap may exist between transmissions
		STUMP [32]	2009	both	yes	Not require tight node synchronization, using propagation delay estimates to schedule overlapping transmissions	Depending on the schedule constraints, several time slots may be scheduled
	CDMA	CDMA-B [34]	2009	multihop	yes	Adopt a periodic sleeping mode to the purpose of saving energy	Near-far problem affects the performance
		POCA-CDMAMAC [35]	2011	multihop	yes	Use a round-robin scheme to receive packets from multiple neighbors at the same time	First nodes of different paths send their packets periodically with the same periodic interval for simplicity
CONTENTION-BASED	Random Access	S-ALOHA [36]	2006	distributed	yes	Analyse the effectiveness of the Aloha and Slotted Aloha protocol	Not make systematic description
		ALOHA-CS(AN), [42]	2007	distributed	no	Capable of using the long propagation delays, provide a significant increase of network throughput	High offered load is challengeable
		UWAN-MAC[47]	2007	distributed	yes	Achieve a locally synchronized schedule even in the presence of long propagation delays	Due to require a small duty cycle, it is difficult to achieve high throughput
		T-Lohi[40]	2007	distributed	no	Solve the problem of space-time uncertain data reservation uses short wake-up tones	Require a node to be idle and listen to the channel in each contention round
	Handshaking	DACAP [52]	2007	distributed	no	Nodes obtain the distance information using the control packet roundtrip time, and use this information to improve the channel utilization	High propagation delay affects the throughput
		MACA-MN [54]	2008	multihop	no	Go one step further as the packet train is actually formed for multiple neighboring nodes simultaneously	Due to the long duration of each hand- shake, the average waiting time can be long
		RIPT [59]	2008	multihop	no	Utilize receiver-initiated reservations and coordinating packets from multiple neighboring nodes to arrive in a packet train at the receiver	Adoption of a receiver-initiated approach requires a complex traffic prediction algorithm
		R-MAC [63]	2007	multihop	no	Transmission of control and data packets is scheduled at both sender and receiver	There is no technique proposed when a new node joins or a node failure occurs
		UMIMO-MAC [74]	2011	multihop	no	Adaptively leverage the tradeoff between multiplexing and diversity gain	Need an extra device and each sensor node is equipped with M transceiver elements
		CUMAC [75]	2012	multihop	yes	Consider a cost-effective network architecture where one and only one transceiver is needed on each node	The critical hidden terminal problem is not completely eliminated
HYBRID		HSR-TDMA [77]	2010	multihop	yes	Mesh-type protocols are usually less sensitive to topology changes and allow robust solutions	Strict synchronization among all nodes is required
		H-MAC [11]	2007	centralized	yes	Yield the benefits from both contention-free and random access protocols with little power consumption	Not be optimal for dense and heavily loaded network
		P-MAC [79]	2010	centralized	yes	Work adaptively and dynamically according to the information of Virtual Distance Level	The extension of P-MAC with multi-channel and ad-hoc mechanism
		UW-MAC [80-82]	2007	distributed	yes	The transmitter adjusts pseudo-random sequences length and signal power to reduce multiple access interference	Require that all nodes know other nodesÕ multiple access interference
		PLAN [83]	2007	multihop	no	Utilize the CDMA as the underlying medium access technique to minimize multipath and Doppler effects	Suffer from the missing receiver problem

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