State-of-the-Art Medium Access Control (MAC) Protocols for Underwater Acoustic Networks: A Survey Based on a MAC Reference Model

Shengming Jiang, *Senior Member, IEEE*

***Abstract*—Similar to radio-frequency-based wireless networks (RWNs) used in terrestrial environments, the medium access control (MAC) protocol is a key element for underwater acoustic networks (UWANs). However, due to peculiar features of underwater acoustic channels such as long propagation delay, very small channel capacity, low channel reliability, and high dynamics of channel quality, not only MAC protocols but also MAC design strategies originally developed for RWNs cannot work well in UWANs. A large number of UWAN MAC protocols have been investigated in the literature, and most of them have not been reviewed in the available surveys. To allow the reader to have an overview on the state-of-the-art UWAN MAC protocols, this paper reviews these proposals with an enhanced MAC reference model. This model decomposes an MAC protocol into a couple of components that make up a common structure for various MAC protocols so that they can be more easily understood. The major remaining issues and possible research directions are also discussed.**

***Index Terms*—Medium access control (MAC), underwater acoustic network (UWAN), MAC reference model and radio wireless network (RWN).**

I. INTRODUCTION

HUMAN underwater activities in oceans are growing fast in recent years and a huge number of sensors, actuators and various types of vehicles have been deployed underwater. Underwater things equipped with communication functions are able to construct the Internet of Underwater Thing (IoUT) [1]. Thus, underwater wireless networking has been becoming a hot research topic for more than one decade. Similar to radio-frequency based wireless networks (RWNs) used in terrestrial environments, the medium access control (MAC) protocol is one of the most important parts for underwater wireless networks. Since radio signal cannot propagate well in underwater environments, currently acoustic communication is widely used [2]. However, due to peculiar features of underwater acoustic channels such as slow signal propagation speed (about 1.5 km/s in seawater), very small channel capacity, low channel quality and high dynamics of channel quality, MAC protocol design for underwater acoustic networks (UWANs) faces many new challenges [3]–[5]. Especially, the long propagation delay is a key factor that makes the MAC design strategy widely adopted by RWNs unsuitable for UWANs.

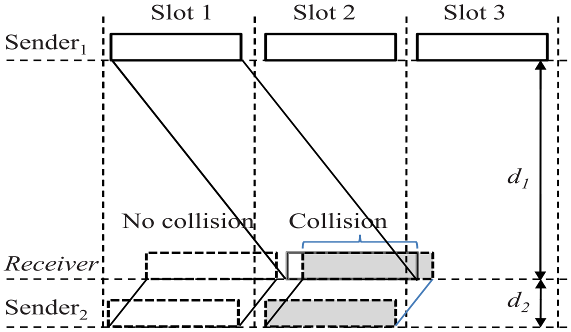


Fig. 1. Example of spatio-temporal uncertainty: Sender$_1$ transmits in Slot 1. If Sender$_2$ also transmits in Slot 1, two transmissions will arrive at the receiver without collision. However, if Sender$_2$ transmits in Slot 2, collision will happen.

The objective of a MAC protocol is to allow multiple users to share fairly a common medium efficiently, and is achieved if and only if the reception is successful. The major event leading to reception failure is collision at the receiver, and how to avoid such collision is the main task of each MAC protocol. Ideally, to avoid effectively collision, the receiver should make a MAC decision because only it can know exactly whether a new transmission should be allowed for collision-free reception (called receiver-centric MAC protocol). However, it is the sender rather than the receiver who triggers all transmissions. Thus, coordination between senders and receivers is necessary to make MAC decisions at the cost of more protocol overhead.

In RWNs, the signal travels almost at light speed (300,000 km/s), and the following assumptions are reasonably held: the signal propagation delay between nodes or the difference in such delays can be negligible. In this case, how to avoid collision at a receiver can be handled by controlling transmission times at different senders (called sender-centric MAC protocol). Such strategy can much simplify MAC protocol design, which however may not make sense with long propagation delays. In this case, a collision-free transmission does not always lead to a collision-free reception, while

---

Manuscript received June 1, 2017; revised September 18, 2017; accepted October 23, 2017. Date of publication November 1, 2017; date of current version February 26, 2018. This work was supported by the National Natural Science Foundation of China for the project "Basic theory of open network architecture for the marine Internet" under Grant 61472237.

The author is with the Marine Internet Laboratory, College of Information Engineering, Shanghai Maritime University, Shanghai 201306, China (e-mail: smjiang@shmtu.edu.cn).

Digital Object Identifier 10.1109/COMST.2017.2768802

concurrent transmissions may result in a collision-free reception, due to non-negligible differences in propagation delays between nodes as illustrated in Fig. 1. This phenomena is called spatio-temporal uncertainty in [6].

Many UWAN MAC proposals have been published in the literature, and most of them have not been reviewed in the available surveys such as [5] and [7]–[10]. To allow the reader to have an overview on the state-of-the-art UWAN MAC protocols, this paper reviews these proposals using an enhanced MAC reference model mainly with the following contributions.

- More than 130 UWAN MAC proposals are reviewed using an enhanced MAC reference model, with highlighting protocol validation methods, dependence on time synchronization and target network topologies, which affect the complexity, feasibility and validity of protocols. The major remaining issues and possible research directions for UWAN MAC protocols are also discussed.
- To facilitate the reader to understand various UWAN MAC proposals by grasping the major characteristics, the MAC reference model originally proposed in [11] is enhanced. It tries to capture a common structure for various MAC protocols by decomposing a protocol into three components. The key component is a set of well-developed and easily understood MAC mechanisms, whose combination is actually the kernel of almost each MAC protocol. This model can also be used as a description structure for new UWAN MAC proposals.

The remainder of this paper is organized as follows. Section II provides an overview of UWAN MAC protocols, followed by an introduction to typical RWN MAC protocols and the MAC reference model in Sections III and IV, respectively. Sections V–X review UWAN MAC proposals based on this model. A comprehensive discussion on the major problems remaining and topics necessary for further investigation is given in Section XI. The paper is concluded in Section XII.

II. OVERVIEW OF UWAN MAC PROTOCOLS

This section briefly discusses the major characteristics of underwater acoustic communications, challenging issues of UWAN MAC protocol design and a classification for the surveyed UWAN MAC protocols.

A. Characteristics of Underwater Acoustic Channels

Typically, the following features characterize underwater acoustic channels.

1) Long & Variable Propagation Delay: Acoustic wave propagation speed in seawater is approximately five order of magnitude slower than light speed. It is further affected by the temperature, salinity and depth [12], which lead to dynamics of propagation speeds. Long and variable propagation delay further causes the following problems beside the spatio-temporal uncertainty mentioned earlier. Doppler effect becomes more severe in mobile UWANs because its magnitude is proportional to the ratio of the transmitter-receiver relative speed and the signal propagation speed. This effect causes considerable frequency shifting and motion-induced distortion [13], which contributes to dynamics of channel quality.

2) Small & Crowded Channel: Only a limited bandwidth of maximal kHzs is feasible for underwater acoustic communication. It is also shared by underwater localization and navigation. The effective bandwidth is affected by frequency-dependable signal-heat conversion and the spreading loss of the expansion of transmitted energy over a large surface. Both increase with signal propagation distances, which further limits the channel capacity for long range transmission [2], [13]. Acoustic channel data rates for short ranges (roughly less than 1 km) can have more than 100 kbit/s. For medium ranges (roughly less than 10 km), a maximum rate is about 50 kbit/s, and a maximum rate of 10 kbit/s is achievable around 20 km.

3) Vulnerable & Changing Channel: Multi-path propagation causes a signal from a source may arrive at the receiver in different paths with phase shift [14]. It is caused by acoustic signal reflected from surfaces, seabed and floating objects etc. These out-of-phase simultaneously arriving signals may cause severe inter-symbol interference (ISI), with which a signal for one symbol may interfere with those for subsequent symbols. Different from an RF receiver, in which the ISI may involve only a few symbols, due to the long propagation delay, the ISI in a single-carrier UWAN may span tens or even hundreds of symbol intervals [13], which makes it more difficult to resolve ISI for demodulation [15].

Another factor impacting underwater channel quality is plentiful underwater noises, which typically includes ocean ambient noise and self-noise of vessels [16]–[19]. They affect acoustic communication at different frequencies roughly as follows: turbulence noise for communication frequencies less than 10 Hz, shipping noise for frequencies between 10 and 100 Hz, wave and other surface motion caused by wind and rain for 100 $Hz \sim 100\ kHz$, and thermal noise for frequencies over 100 kHz [19].

Underwater acoustic channel quality may also change in very short time scale [20]. A measurement of a 3000m-long link in a 100m-deep water column captures oscillations of the average signal-noise ratio of a channel equalizer as follows [21]: about $9 \sim 5.7$ dB within about 0.5 minute, and about $9 \sim 3.5$ dB within less than 1.5 minutes. As discussed in [2], channel coherence time can be in an order of 40 ms. This experiment also shows large bit error rate (BER) oscillations in short time intervals. For example, BER drops from 0.11 (with one equalizer) and 0.06 (with four equalizers) to 8.1×10^{-4} within about 2 s, and both show periodic increase.

B. Challenges for UWAN MAC Design

Due to the above-mentioned characteristics of underwater acoustic channels, MAC protocols for UWANs face the following challenges.

1) Medium Utilization: It reflects how efficiently a medium can be used to transmit user data. With very small channel capacity, high medium utilization is especially important but difficult issue with long propagation delay. It is because spatio-temporal uncertainty makes sender-centric MAC unable to avoid collision at the receiver, resulting in bandwidth waste. Receiver-centric MAC protocols need receiver-sender cooperation often requiring message exchange, which is undesirable with long propagation delay.

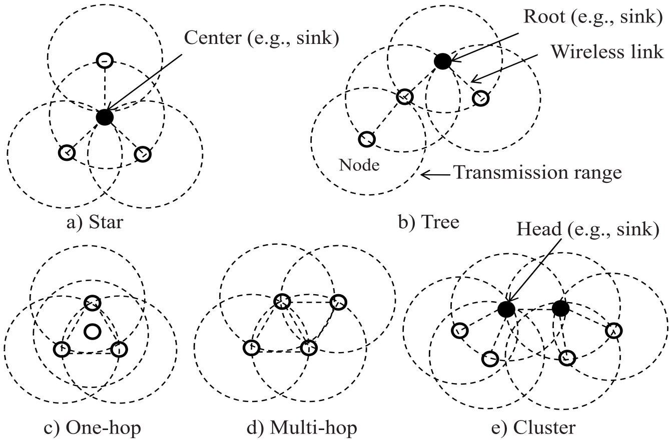
2) Energy Efficiency: Due to excessive attenuation, underwater acoustic communication generally requires transmission and reception powers much larger than that of terrestrial radio communication for the same ranges. Tens of Watts are typically required for transmission, depending on transmission distances, while from tens of mWatts up to a few Watts for reception, depending on the type of processing [22]. In battery-powered UWANs, it is very difficult and costly to recharge and re-deploy underwater nodes, and minimizing transmission and reception activities is effective to save energy. However, some MAC operations need message exchange, while transmission power has to be large enough for acceptable data rates in noisy acoustic channel over long distance.

3) Fairness: When propagation delays or differences in propagation delays between different nodes are negligible, location-dependent unfairness can be ignored so that a simple fairness police such as first-in-first-out can work well. With non-negligible differences in propagation delays, an earlier departure may arrive at a node later than its followers, resulting in earlier sent packets may not be served earlier accordingly. Particularly, MAC protocols sensing channel status are favorable to nodes near the signal source, making them to have more access opportunities [23].

4) Quality of Service (QoS): The MAC protocol is a key factor for QoS provisioning to satisfy application requirements in terms of medium access delay and effective throughput. The former is the time that data has to wait before being successfully transmitted, and the latter is the amount of data successfully received per time unit. However, long propagation delays compress the room available for medium access delays, and the limited channel capacity almost cannot allow using large protocol overheads for resource reservation.

5) Mobility Support: A mobile UWAN should also consider Doppler effect on communication quality and terminal mobility effect on time synchronization and localization in selecting MAC design strategy. Particularly for an autonomous underwater vehicle (AUV), the impact of its own noise on communication quality is an issue necessarily to be addressed, while its narrow space limits the application of acoustic arrays for better communication quality.

6) Protocol Validation Method: Besides mathematical analysis suitable for simple scenario, computer simulation has been extensively used since field trial is very expensive for UWANs. How well a simulation package can properly simulate the peculiar features of underwater acoustic channels and high dynamics of UWANs affects the credibility of simulation results, and more research is needed to develop a package to well simulate these features. Prototyping in laboratory is also used for validation, and can check protocol complexity, but such test environment may be still far away from the reality. However, validation through field trial is expensive and even dangerous.



a) Star
b) Tree
c) One-hop
d) Multi-hop
e) Cluster

Fig. 2. Typical network topologies adopted by UWAN MAC protocols.

C. Important Features of UWAN MAC Protocols

The following features affect the complexity and feasibility of a UWAN MAC protocol.

1) Dependence on Time Synchronization: Time synchronization (SYN) enables all nodes in a system to have the same timing reference for communication and networking. Since the RF-based Global Position System (GPS) cannot work well underwater to provide a common timing reference, SYN in UWANs is usually realized through message exchange. Due to long and variable propagation delays in UWANs, it is very difficult to realize a precise SYN [5], [24]. Relatively precise SYN can be achieved if the propagation delay is predictable and static for a short period of time [17]. However, channel state may also change in very short time scale [20], and such changes increase with propagation delay.

2) Network Topologies: It affects the complexity of a MAC protocol. Fig. 2 depicts typical topologies adopted by the surveyed MAC protocols, which can be classified as follows.

a) Centralized topology: There is a central node to coordinate communication especially between itself and other nodes within the communication range. This node may also function as a data sink, bridge or gateway to interface with other networks like a base station and an access point. However, the central node is a one-point failure of the whole network. Such topology may be further divided into:

- Star: The central node is in the mutual range with every node as illustrated in Fig. 2(a), and can coordinate MAC operation. This topology can simplify MAC protocol design and support QoS with small network coverage.
- Tree: It is a hierarchical structure of star topologies as illustrated in Fig. 2(b), and can cover a large area. A special case is that multiple strings are linked to the root. A parent node is a one-point failure of its sub-tree.

b) Distributed topology: Different from the centralized topology, there is no central node, and nodes communicate each other directly. It can also be further divided into:

- One-hop: The distance between any nodes is one hop so that they can hear each other as illustrated in Fig. 2(c). There is neither hidden nor exposed terminals but with very small network coverage.

- Multi-hop: Distances between some nodes are larger than one hop as illustrated in Fig. 2(d), and some nodes need to relay data destined to remote nodes. It can cover larger areas, while end-to-end network performance degrades with the number of hops in the path.

c) Cluster topology: It combines centralized and distributed topologies through grouping nodes as illustrated in Fig. 2(e). Each group called cluster may be either a star or a tree topology. The cluster heads coordinate communication between cluster members, and form a multi-hop network to cover large areas.

D. Category of Surveyed UWAN MAC Protocols

Many UWAN MAC protocols have been proposed to tackle the problems caused by long propagation delay, whereas there are also some proposals try to leverage such delay as an opportunity because it can provide larger available space-time volume than smaller delay [25]. Very small acoustic channel capacity and highly dynamic communication environments require more bandwidth-efficient and adaptive MAC protocols. These requirements make MAC protocols based on frequent message exchanges undesirable. Therefore, there are many MAC proposals exploit communication technologies such as multiplexing to allow concurrent transmissions at the same frequency. Cross-layer design [26], [27] is used to improve channel utilization with sophisticated MAC protocols.

The surveyed UWAN MAC protocols can be roughly divided into two categories: typical RWN protocol-based and newly designed as illustrated in Fig. 3. It is relatively straightforward to modify RWN MAC protocols by making them suitable to peculiar features of UWANs, while deliberate efforts are necessarily made to tackle the UWAN problems. The first category can be further split into the multiplexing (e.g., TDMA) and non-multiplexing based (e.g., ALOHA), which will be discussed in Sections V and VI, respectively. The second category include scheduling, reservation and cross-layered design. Scheduling (Section VII), which requires the sender to decide locally the transmission time, aims to overcome the impact of handshaking in the case of long propagation delay. Similarly, reservation (Section VIII), with which the transmission decision is not made by the sender itself, tries to handle more efficiently the problems caused by long propagation delays, such as the hidden/exposed terminal problems. Cross-layer designed protocols (Section IX) can address the related issues more comprehensively, e.g., channel utilization. There are also several schemes mainly focusing on design or implementation of RWN MAC protocols in UWANs without modification (Section X).

III. TYPICAL RWN MAC PROTOCOLS WITHOUT MULTIPLEXING

This section introduces some well-established RWN MAC protocols that have been widely used to design UWAN MAC protocols. They will be used as examples in describing the MAC reference model and help understanding the UWAN MAC protocols based on them, as to be discussed later.

A. ALOHA

It is the simplest MAC protocol, with which, a node transmits a data frame anytime at its will. The receiver needs to acknowledge the sender of each successful reception. If the sender cannot receive the acknowledgment within a particular time interval, it will retransmit the same frame after a random waiting time (called backoff) subject to a maximum number of retransmissions. With slotted ALOHA (S-ALOHA), the time is divided into fixed and equally sized slots, and a new attempt is only allowed at the beginning of a slot to prevent a new transmission from colliding with an ongoing transmission, which may frequently happen with ALOHA.

B. Carrier Sensing Multiple Access (CSMA)

A node senses carriers first before any transmission. If a carrier is sensed, the node does not transmit. When no carrier is sensed, how to act yields several variants of CSMA such as CSMA with collision detection (CSMA/CD) and CSMA with collision avoidance (CSMA/CA). With CSMA/CD, the node transmits immediately and at same time keeps listening to the medium to detect collision. This protocol is used for early Ethernet, but cannot be used in wireless networks due to difficulty in implementing “listening-while-talking” operation. With CSMA/CA, a node defers its transmission for a random backoff time, and transmits only when the medium is still sensed idle at the end of the backoff time. CSMA/CA is used by several well-known MAC protocols for RWNs such as IEEE 802.11 and IEEE 802.15.4 as well as the European standard for LANs: High Performance Radio LAN (HIPERLAN). However, CSMA may cause the hidden and exposed terminal problems as follows:

- Hidden terminals: When two nodes are too far away to sense each other’s transmission activity, they may transmit simultaneously, causing collision at nodes located between them.
- Exposed terminals: When the receiver of an on-going transmission of a sender is out of the interference range of another sender, which actually can transmit without harm. However, such transmission is not allowed by carrier sensing if the two senders can hear each other.

1) IEEE 802.11: It consists of two functions: Distributed Coordination Function (DCF) and Point Coordination Function (PCF). DCF follows CSMA/CA, jointly using a rotation backoff contention window (CW). A node failing in the first round of competition does not need to generate a new CW in the second round. Instead, the remaining time of the first round CW is used as the backoff time. Different Inter-Frame Spaces (IFSs), namely, Short IFS (SIFS), PCF IFS (PIFS) and DCF IFS (DIFS), are used to handle uncertainty caused by propagation delays, and enable priority for different MAC operations with SIFS<PIFS<DIFS.

On the top of CSMA/CA, the following optional RTS/CTS handshake protocol is used to handle the hidden terminal problem.

- A node needs to send a short frame Request-to-Send (RTS) to the intended receiver before data transmission,

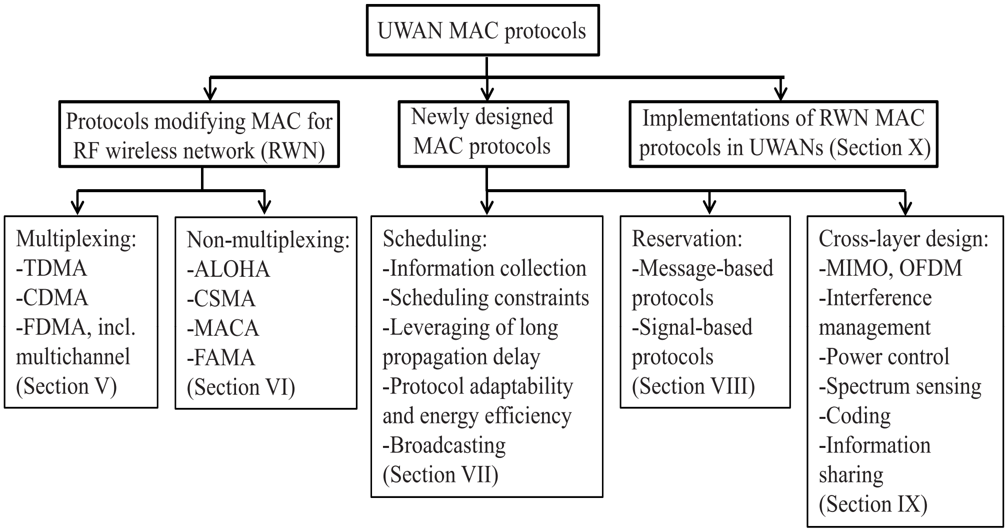


Fig. 3. Categories of surveyed UWAN MAC protocols.

which carries the information on the planned transmission length in time.

- Upon receiving an RTS, the node replies a short frame Clear-to-Send (CTS) to the RTS sender if it is ready to receive. This CTS carries the information on the planned reception length in time.
- Upon receiving the CTS, the sender starts data transmission. Any nodes overhearing an RTS and/or a CTS keep silent during the time period indicated by the RTS and the CTS.

The receiver acknowledges the sender of each successfully received data frame.

PCF requires an access point (AP) to control medium sharing by using a polling scheme. DCF and PCF can coexist simultaneously by using a super-frame structure as illustrated in Fig. 4, which is divided into two segments: one for PCF and the other for DCF.

2) IEEE 802.15.4: It is designed for low data rate wireless personal area networks (PANs) [28], using a superframe consisting of an active portion and an inactive portion. The coordinator interacts with its PAN during the active portion and sleeps during the inactive portion. A simple action portion is composed of a contention access period (CAP) using CSMA/CA. Another type of action portion comprises a CAP and a contention free period (CFP), which is divided into guaranteed time slots (GTSs) to be allocated by the coordinator. Both unslotted and slotted CSMA/CAs are defined. With the slotted CSMA/CA, carrier sensing is conducted only at the beginning of a slot.

3) HIPERLAN: Compared to IEEE 802.11, it uses an additional jamming signal for a high-priority node to eliminate competitors as follows [29]:

- Every node needs to keep sensing the medium. Once the medium becomes idle, it enters the sensing period.
- Each node keeps sensing the medium till the end of this sensing period. If a carrier is sensed, the node leaves the competition.
- If no carrier is sensed during the whole sensing period, the node sends a random-length signal to jam other nodes.

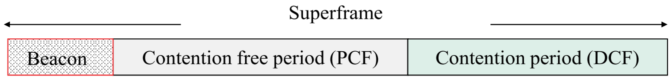


Fig. 4. Superframe structure for the co-existing of PCF and DCF modes.

- At the end of the jamming period, if a carrier is sensed, the node leaves the competition; otherwise, it conducts a random backoff like the DCF of IEEE 802.11.

The lengths of the sensing and jamming periods depend on a node's priority.

C. Multiple Access Collision Avoidance (MACA)

Both RTS and CTS contain some information such as transmission time, and the protocol operates as follows [30]:

- A node sends an RTS without carrier sensing.
- The receiver returns a CTS if it is ready to receive.
- A node overhearing an RTS defers long enough so that the RTS sender can receive the returning CTS.
- Once receiving the CTS, the receiver can start its transmission.
- A node overhearing a CTS stops transmission to avoid colliding with the returning data transmission.
- A node overhearing an RTS but not a CTS can start its transmission without harm.

Note that the RTS of IEEE 802.11 can be transmitted only after a node wins competition via CSMA/CA. MACA makes better sense i) when hidden terminals exist because a lack of carrier does not mean that it is good to transmit, and ii) when exposed terminals exist because a carrier does not always mean a harmful transmission.

D. Floor Acquisition Multiple Access (FAMA)

It aims to eliminate the hidden terminal problem by guaranteeing that a node having acquired the medium control will not suffer from data collision during its transmission and retransmission, operating as follows:

- The node listens to the medium before an RTS transmission. Only when the medium is clear, the node can send

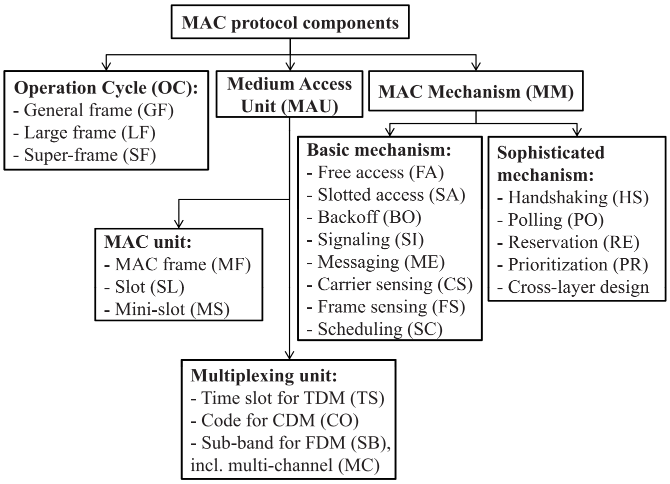


Fig. 5. A reference model for MAC protocols.

it. This excludes any RTS transmission during a packet's arrival.

- The sent CTS lasts long enough to jam any hidden sender that does not hear the acknowledged RTS by setting it as long as one round-trip propagation delay plus one RTS transmission time.

The major difference between MACA and FAMA is that FAMA uses carrier sensing while MACA does not before sending an RTS.

IV. A REFERENCE MODEL FOR MAC PROTOCOLS

As illustrated in Fig. 5, a MAC protocol can be divided into three components: operation cycle (OC), medium access unit (MAU) and MAC mechanism (MM). The relationship between them is illustrated in Fig. 6. At the beginning of one OC, a node runs some MMs such as carrier sensing, and then accesses the medium with certain MAUs like time slots. The adopted MMs, their running sequence, the content of messages exchanged and the number of MAUs available per OC make up the MAC protocol procedure, which vary with the particular protocol design.

A. Operation Cycle

A MAC operation cycle (OC) is a repeated time epoch with either a fixed format or a random interval, which depends on transmission length. During each OC, nodes will follow the same procedure to access the medium. Typical OCs include general frames, large frames and superframes as described below.

- General frame (GF): It mainly consists of transmission time of frames and the other time used to run MAC mechanisms for obtaining medium access as illustrated in Fig. 6. For example, for ALOHA, the GF consists of the transmission times of a data frame and the corresponding ACK, and the GF for CSMA/CA is the sum of running time of CSMA/CA and ALOHA's GF.
- Large frame (LF): The time interval is divided into small units (e.g., time slots), each of which is allocated to one node for medium access following the same access scheme, such as the Time Division Multiple Access (TDMA) based protocols used by Global System for Mobile Communications (GSM) ([31, Sec. 3.2.2]).
- Super-frame (SF): The time interval is divided into several segments, each of which adopts different access schemes, e.g., random access or coordination-based access. For example, the SF of the IEEE 802.11 MAC protocol consists of two segments: one running DCF and the other running PCF, as illustrated in Fig. 4.

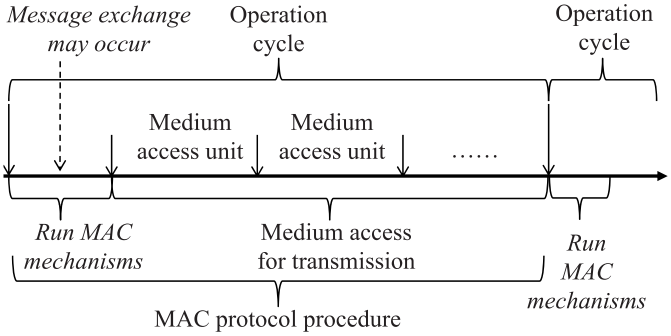


Fig. 6. Relationship between the MAC protocol components.

B. Medium Access Units

A medium access unit is the basic unit for a node to share the medium, and can be defined by either a MAC protocol (called MAC unit) at the data link layer or a multiplexing scheme at the physical layer (called multiplexing unit).

1) MAC Unit: It typically includes MAC frames, slots and mini-slots. Here "time slot" is used to refer to a multiplexing unit.

a) MAC frame (MF): It is a data block corresponding to a MAC transmission with or without a pre-defined delimitation. Without a delimitation, its boundary can be sensed by transmission activity detection. It is also called "MAC protocol unit" in the literature, and mainly consists of addresses and a payload. The exact format depends on particular MAC protocols such as IEEE 802.11.

b) Slot (SL): It is a fixed-sized unit that a node can occupy for once transmission. To reduce collision, each node can start transmission only at the beginning of a slot, e.g., slotted-ALOHA (Section III-A).

c) Mini-slot (MS): Similar to the slot, it is a per-node unit but with a smaller size and usually used to transmit control messages, e.g., reservation requests in the Packet Reservation Multiple Access (PRMA) protocol [32]. It is usually accessed through random schemes without SYN.

2) Multiplexing Unit: A multiplexing scheme at the physical layer can transmit multiple signals over a common medium through dividing a medium into multiple sub-channels each for one signal, and aggregating signals into one for transmission. Typical schemes include Time/Code/Frequency Division Multiplexing (TDM/CDM/FDM). The corresponding multiple access schemes include Time/Code/Frequency Division Multiple Access (TDMA/CDMA/FDMA). Usually, a centralized or cluster topology is suitable for these MAC protocols because the central node can control request collection, medium access allocation and result notification. Their multiplexing medium access units are discussed below.

a) Time slot (TS) for TDM: The time is divided into TSs each to be assigned to one signal. The TDMA-based MAC protocol mainly allocates TSs to requesting nodes and informs them of the allocation results. Precise SYN is required to establish a common timing reference for every node to locate the TSs allocated to it. A guard-time has to be inserted between adjacent TSs to guarantee collision-free reception. The size of the guard-time depends on propagation delay [33], and in the worst-case, the maximum propagation delay (D_m) has to be considered. A time margin, which also increases with propagation delays, is also needed between consecutive TSs to handle the shift in the clocks used by different nodes.

b) Code (CO) for CDM: CDM uses spread spectrum (SS) technique to allow multiple signals to share a whole frequency spectrum with concurrent transmissions. SS is further divided into frequency-hopping SS (FHSS) and direct-sequence SS (DSSS). With FHSS-CDMA, at a time point, each node occupies a different sub-band and hops to another at the next time point following a hopping sequence, which is different for each node. With DSSS-CDMA, each node is assigned a unique spreading code to multiply its signal for spreading over the whole spectrum for simultaneous transmission. A spreading code can be either an orthogonal code or a pseudo-noise. The codes assigned to different users are orthogonal to each other with the former, while uncorrelated to each other with the latter. The spread signals can be decoded with orthogonal codes if the orthogonality of the codes holds for the received signal, and with pseudo-noise if the received signal from each node is at the same level. Thus, power control is used to avoid the near-far effect, with which strong signals cause weak signals to fail in decoding. In a multiuser system, SYN can be used for optimum multiuser detection [34], [35].

The large bandwidth of FHSS and DSSS is robust to frequency-selective fading, resilient to Doppler effect, and can compensate for the multipath effect by using Rake filters [36]. DSSS-CDMA with multi-carrier transmissions may also offer higher spectral efficiency than with single-carrier [3]. With the major CDMA used in practice, spreading codes are not transmitted in parallel with the data so that it can tolerate unsynchronized nodes caused by different propagation delays in UWANs.

c) Sub-band (SB) for FDM: FDM divides a frequency band into multiple fixed-sized sub-bands each to be occupied by one signal. With FDMA, each node is assigned a different sub-band for interference-free concurrent transmissions and collision-free reception without SYN but with receiver-transmitter frequency synchronization. A guard-band between adjacent sub-bands is used to tolerate transmission uncertainty. However, small bandwidth channels are more vulnerable to frequency-selective fading and multi-path propagation effect [5], [24], [37]. In mobile UWANs, non-negligible Doppler effect may cause a large frequency shift and bandwidth spread at receivers [13]. With orthogonal FDMA (OFDMA), adjacent sub-bands overlap in a mutually orthogonal mode to improve spectral efficiency.

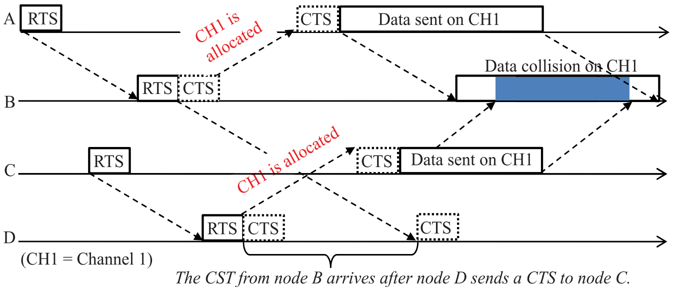


Fig. 7. Triple hidden-terminal problems in UWANs: The CTS sent by node B to node A arrives later at node D, which actually has also allocated to node C the same data channel as allocated by node B to node A. Both nodes A and C use the same data channel for transmission, resulting in collision at node B.

d) Multichannel (MC): Similar to FDMA, a MC scheme also divides a physical channel into multiple sub-channels, and how to synchronize a sender-receiver pair to the same sub-channel is an important issue. A dedicated control channel (DCC) is often used to transmit control messages only and prevent collision with data transmission but at the cost of bandwidth waste. The DCC may also become the performance bottleneck if it cannot satisfy request submission, leading to data channels (DCHs) under-utilized.

With a single transceiver, a so-called triple hidden-terminal problem may arise [38]. In this case, a node can work either on the DCC or a DCH but not on both simultaneously. Thus, a node communicating in a DCH cannot learn about the channel assignment undergoing in the DCC. Consequently, this node may select a DCH already allocated to another node for new transmission, causing collision. Similarly, in the case of a long propagation delay, a CTS assigning a DCH may arrive at a node just after this node sent out another CTS assigning the same DCH to other nodes as illustrated in Fig. 7.

C. MAC Mechanisms

When no multiplexing scheme is used on the physical layer, some MAC mechanisms have been used by a MAC protocol for collision avoidance. A MAC mechanism is an action taken by a node to obtain medium access opportunity, and can be divided into basic mechanisms, their combinations and cross-layer design. An acknowledgement scheme for the logical link control is often used jointly with a MAC protocol, stipulating that the receiver has to send an acknowledgement on every successful reception to the sender.

1) Basic Mechanisms: A set of basic MAC mechanisms extensively adopted by many MAC protocols are discussed below.

a) Free access (FA): It includes random access and probabilistic access. With the former, a node can access the medium at its will without using any other mechanisms, e.g., ALOHA (Section III-A). With the latter, a node accesses a medium with probability ω and does not with probability $1-\omega$ [39]. This scheme is very simple, robust and applicable to any network topologies but with low medium utilization due to frequent collisions.

TABLE I
CHARACTERISTICS OF MULTIPLEXING ACCESS SCHEMES AND MAC MECHANISMS

Scheme / mechanism	Basic operation condition	Main strength	Main weakness
Multiplexing based access schemes			
TDMA	Time synchronization (SYN)	Relatively simple	Bandwidth waste due to guard-time proportional to propagation delay
CDMA	Orthogonal/uncorrelated codes, SYN is often used in multiuser system	Collision-free simultaneous transmission (data/control frame transmission with MC). High bandwidth utilization & communication security with CDMA	Complex implementation, affected by nonorthogonality / near-far effect
FDMA	Sender-receiver frequency synchronization		Bandwidth waste due to guard-band. Control channel is bottleneck for MC
Multi-channel (MC)			
MAC mechanisms			
Free access (FA)		Very simple & robust	Frequent collision
Slotted access (SA)	Time synchronization (SYN)	Less collision than free access	The same as TDMA
Backoff (BO)		Useful for collision avoidance/prioritization	Bandwidth waste due to backoff time
Signaling (SI)		Invulnerable to channel quality	No much information available
Carrier sensing (CS)		Simple & robust	Hidden & exposed terminal problems
Messaging (ME)	Channel quality should satisfy decoding of received signal for successful reception of message	Availability of explicit information. ME provides as much information as necessary	Vulnerable to channel quality, susceptive to propagation delay. More protocol overhead for ME
Frame sensing (FS)			
Handshaking (HS)		Efficient for collision avoidance at the receiver. QoS support with PO and RE	
Polling (PO)*			
Reservation (RE)			
Scheduling (SC)	SYN for TDMA-based scheme	Able to leverage long propagation delay for more simultaneous transmissions	Affected by availability/accuracy of information for scheduling calculation
Cross-layer design	Depending on schemes jointly used in MAC protocol design	Improving performance, bandwidth utilization & energy efficiency	Complex protocol with issues on implementation & inter-operability

*Suitable for star-topology

b) Slotted access (SA): It divides the time into slots, stipulating that any new medium access is allowed only at the beginning of each slot, e.g., slotted ALOHA (Section III-A). It can prevent an ongoing transmission from being interfered by a new attempt. For implementation, a network-level SYN is needed to make all nodes to have an identical time reference. Similar to TDMA, to avoid collision between consecutive slots, a guard-time has to be inserted between them. However, the beginning of each slot is just a synchronization point that invites multiple nodes to transmit simultaneously, leading to collision.

c) Backoff (BO): It enforces a node to wait a time period before accessing the medium, and a random backoff is adopted by CSMA/CA in IEEE 802.11 (Section III-B1). Furthermore, assigning shorter backoff time to higher priority nodes can prioritize medium access. It may waste bandwidth if backoff period is too long while no other competitors present.

d) Signaling (SI): A node deliberately sends a short signal to either block ongoing transmissions (e.g., CSMA/CD) or jam competitors, e.g., HIPERLAN (Section III-B3). The receiver does not need to decode the received signal so that its operation is invulnerable to channel quality but without much information available. It can be applicable to any topologies, and can prioritize nodes in medium access by using different signaling lengths.

e) Messaging (ME): Similar to signaling, a node deliberately sends nodes messages carrying explicit information such as the length of transmission or reception indicated by RTS/CTS adopted by MACA and FAMA (Sections III-C and III-D). It is much more informative than signaling if the received signal is successfully decoded. A piggyback scheme allows data frames to carry information incidentally to reduce protocol overhead.

f) Carrier sensing (CS): It judges whether a medium is busy according to the received signal without decoding to prevent a new transmission attempt from colliding with an ongoing transmission, e.g., CSMA (Section III-B). It can be applied to any topologies, but may cause the hidden and exposed terminal problems as mentioned in Section III-B. Its efficiency is also affected by the propagation delay of the received signal.

g) Frame sensing (FS): A node obtains explicit information from the received frame[1] by decoding the received signal [40], e.g., the reception of RTS/CTS with MACA and FAMA (Sections III-C and III-D). It is much more informative than CS and applicable to any topologies. However, it is susceptive to propagation delay and channel quality. When ME is used, usually FS will be used too, thus only ME if is highlighted for the reviewed protocols for conciseness.

h) Scheduling (SC): A node calculates its transmission time to assure collision-free reception and its sleep/wakeup times for energy saving. An optimal scheduling decision relies on the availability and accuracy of the required information. When a global time is used for scheduling, such as TDMA-based protocols, SYN is required. Note that, scheduling in RWNs is typically used to differentiate transmission orders for QoS support rather than collision avoidance, such as traffic scheduling in IEEE 802.11e [41].

2) Sophisticated Mechanisms: They typically include combinations of basic mechanisms and cross-layered design ones.

a) Handshaking (HS): It is a combination of messaging and frame sensing, and the receiver must reply the sender. It allows nodes to exchange explicit information following a predefined procedure. The typical one is RTS/CTS used by MACA and FAMA (Sections III-C and III-D).

---

[1] Some reviewed MAC protocols call the MAC protocol unit as "packet", while others call it as "frame". Actually, "frame" is conventionally used as the data link layer protocol unit while "packet" as the network layer protocol unit. This paper tries to follow this convention as much as possible.

TABLE II
TYPICAL RWN MAC PROTOCOLS WITHOUT MULTIPLEXING DESCRIBED FOLLOWING THE MAC REFERENCE MODEL

MAC protocol	OC	MAU	Basic MAC mechanisms							
			FA	SA	SI	CS	ME	FS	SC	BO
ALOHA	GF	MF	✓							
S-ALOHA	GF	SL		✓						
CSMA	GF	MF				✓				
CSMA/CA	GF	MF				✓				✓
MACA	GF	MF	✓				✓	✓		✓
FAMA	GF	MF	✓			✓	✓	✓		✓
802.11 DCF	GF	MF				✓	✓	✓		✓
802.11 PCF	SF	MF				✓	✓	✓		✓
802.15.4	SF	MF,SL				✓	✓	✓		✓
HIPERLAN	GF	MF			✓	✓	✓	✓		✓

Abbreviations are described in Fig. 5.

b) Polling (PO): It also combines messaging and frame sensing for a central node to poll potential senders, and only a polled node can transmit. It is mainly suitable for a star topology and can efficiently support QoS. To avoid idle nodes from being polled, the central node needs the information on transmission requests of the potential senders. This can be achieved by allowing each node to submit its request in advance via random access such as ALOHA.

c) Reservation (RE): A node has to submit a request for data transmission. Different from scheduling, the decision here is not made by the requesting node itself. When the decision is made by the receiver, it is a receiver-centric MAC protocol. It can reduce message exchange overhead and medium access delay for large and periodic data transmission with QoS support. Requests can be submitted via random access like polling, which is a special RE. If request submission is scheduled, the protocol is categorized as scheduling.

d) Prioritization (PR): It tries to prioritize nodes in medium access by setting either a longer jamming time, e.g., HIPERLAN (Section III-B3), or a shorter backoff time for higher priority nodes, such as different IFSs used by IEEE 802.11 (Section III-B1).

3) Cross-Layer Design: It tries to exploit functions and/or information available on the physical layer, the network layer or the transport layer to improve MAC performance and reduce the consumption of bandwidth and energy. Typical physical-layer schemes adopted by UWAN MAC protocols include Multi-Input Multi-Out (MIMO), Orthogonal Frequency Division Multiplexing (OFDM) and power control, and more details will be discussed in Section IX.

D. Application of the MAC Reference Model

The MAC reference model can be used to help understanding a MAC protocol following the basic operation conditions and the major characteristics of each MAC mechanism adopted in its design, which are summarized in Table I. New MAC protocols can also use this model for protocol description. Table II summarizes the typical RWN MAC protocols following this model as described in Section III.

In the following sections, we will first list the components of the MAC reference model for each reviewed UWAN MAC protocol in the corresponding tables to provide an overview. To save space, all the components of the model are described with their abbreviations described in Fig. 5. When some components of the model are not explicitly described by a reviewed protocol, the following settings may be inferred: general frame for operation cycle, and MAC frame or slot for medium access unit. Stationary & distributed topology might be a default setting for topologies. These unspecified settings will not be listed in the table.

V. UWAN MAC BASED ON MULTIPLEXING

Here we review some UWAN MAC protocols based on TDMA, CDMA and FDMA as well as multi-channel. Table II summarizes them following the MAC reference model depicted in Fig. 5 with a comparison in terms of SYN requirement, validation methods, network topologies and major characteristics. A summary is given at the end of the section.

A. TDMA

There are many TDMA-based MAC protocols that jointly using other MAC mechanisms such as scheduling and reservation, which will be discussed separately in Sections VII and VIII, respectively. The proposals discussed here mainly address setting and allocation of time slots as well as protocol adaptability to dynamic underwater environments.

For time slot allocation, the WA-TDMA (Wave-like Amendment-based TDMA) [42] starts allocation from the central node to outward nodes in a form of wave-like proliferation to shorten network initialization time. To assure different nodes to use different time slots, nodes are allowed to modify existing allocations during the amendment process. That is, a node closer to the central node has higher priority to modify existing time slot allocation for nodes farther away from the central node. With the LT-MAC (Location-based TDMA MAC) [44] for a stationary meshed UWAN, each node circulates the transmission permission according to a pre-determined sequence to shorten waiting time. Time slot assignment depends on the positions of related nodes. Slot length is decided dynamically according to traffic loads of the local node and its neighbors. A large protocol overheard is generated to spread information on position and traffic loads. It is enhanced to support AUVs, called LTM-MAC, by adding carrier sensing to be used by a stationary node to detect AUV's transmission activities [45]. For all these protocols, the accuracy of the required information affects protocol performance.

To cover large areas, the channel reuse approach of mobile cellular networks is adopted by the C-MAC (Cellular MAC) [43] for time slot allocation. It organizes seven time slots into a frame to cover a cluster consisting of seven hexagonal cells with one surrounded by the six. One cell is allocated a time slot to avoid inter-cell collision. The time slot allocated to a cell is shared by the nodes therein under coordination of the sink according to nodes' positions to it. Message exchanging to share position information is needed. Such fixed time slot allocation per cell wastes bandwidth if traffic loads are different in each cell.

TABLE III
UWAN MAC PROTOCOLS BASED ON MULTIPLEXING SCHEMES OF THE PHYSICAL LAYER

Protocol name / Reference	MAC Ref. Model (Fig. 5)			Comparison (SYN=Time Synchronization, VM=Validation Method)			
	OC	MAU	Mechanism	SYN	VM†	Topology‡	Main characteristics
TDMA (MAU = TS)							
WA-TDMA[42]		TS	RE	✓	S	**Star**	Node's positions used to improve performance, affected by information accuracy
C-MAC[43]	LF	TS	RE	✓	S	Cluster	Large coverage but inefficient for uneven traffic distributions
LT-MAC[44]		TS	ME	✓	S	One-hop	Adaptive settings for allocation & lengths of time slots, large overhead, depending on required information
LTM-MAC[45]		TS	ME,CS	✓	S	*One-hop*	
[46]		TS	PR	✓	S		Time-slot sharing without an explicit realization method
SBMAC[47]		TS	RE,SC	✓	S	Star	High-level adaptability with large protocol overheads
[48]	SF	TS	FS		S	Star	Adaptive settings of slot length & guard time, affected by the accuracy of the measured distances
CDMA (MAU = CO)							
[49]		CO	HS			Tree	Easy node joining/leaving network, large probing cost/delay
[50]		CO	SC		S	Tree	Code reusing without an explicit assignment process
POCA[51]		CO	HS		S	Tree	Shorter code length with less simultaneous transmissions
[52]		CO	CS,BO,HS		S	Star	Joint-use of CSMA/CA without clear description on operation
PLAN[53]		CO	HS		S	Multi-hop	Support code reuse with large code assignment delay
[54]		CO	ME		S	Multi-hop	Simple & fast with possible code assignment failure
UW-MAC[55]		CO	FA,ME		S	*Cluster*	Optimized code length & power setting with frame header collision affecting performance
DPC MAC[56]		CO	HS,CS		S	Multi-hop	More accurate power control with handshaking overhead
FDMA (MAU = SB)							
[57]		SB,SL	SC,SA,ME,CS	✓	S	Cluster	Improving bandwidth utilization with low scalability
UW-OFDMAC[58]		SB	FA,ME		S	*Tree*	Improving adaptability with a dedicated control channel
NOGO-MAC[59]		SB	FS		S	Star	Adaptability to propagation characteristics, affected by accuracy of distance measurement
McNOGO-MAC[60]		SB	FS		S	Cluster	
Multi-channel (Multichannel itself is not listed in "Mechanism" for conciseness)							
MC-ALOHA[61]			FA		A,S	One-hop	Insensitive to propagation delays with poorer performance
MC-RTS/CTS[61]			HS		A,S	One-hop	Enhancing MC-ALOHA, susceptive to propagation delay
CUMAC[62]			HS,CS		S	Multi-hop	Improving bandwidth utilization, affected by the accuracy of location information
DC-MAC[63]			FA,RE		S	Multi-hop	
HCFMA[64]			RE,BO		S	One-hop	Reducing handshake overhead with complex design
RCAMAC[65]			RE	✓	S	**Star**	Improving bandwidth utilization with triple hidden-terminals
[66]			HS				Leverage of frequency-selective features without validation
UMMAC[67]		SL	RE,BO	✓	S	Multi-hop	More parallel transmissions with complex design
MM-MAC[68]	SF	MS,SL	HS	✓	S	Multi-hop	Logical multi-channel used to avoid collision between control and data frames with performance bottleneck
DMM-MAC[69]	SF	MS,SL	HS	✓	S	Multi-hop	

†VM: A=Analysis, S=Simulation. ‡The italic font indicates mobility support, and the bold font requires 1-hop setting.

To adapt MAC to long propagation delay for high throughput, the protocol discussed in [48] uses a defer time instead of a fixed time-slot such that the sink can receive data frames one by one without gaps between them. This time is a time interval between when a node receives a superframe and when it begins to send a frame. It also uses a lightweight SYN scheme to reduce energy consumption through determining an optimal length of the guard time as a function of frame lengths and the covariance of underwater propagation delay. Its performance relies on the accurate information on the distances between the sink and the other nodes. Network reliability and protocol efficiency are further taken into account to improve protocol adaptability by the spatially-shared TDMA MAC [46]. It aims to allow nodes to share time slots for simultaneous transmissions according to their priorities for high throughput, using a quality measure (e.g., average message propagation time). How to share time-slots without collision is not addressed adequately.

The above protocols enable protocol adaptability through dynamically changing parameter settings. Differently, the SBMAC (Smart Blocking MAC) [47] dynamically determines transmission and retransmission policies according to environment variables to reduce the number of transmissions. It proposes an adaptive method to determine TDMA transmission period, normal / block data transmission and ACK schemes. The master node uses the following information to calculate the policy and broadcasts it to all nodes: distance, acoustic frequency, channel quality and the number of nodes in the network as well as traffic load, which causes a large protocol overhead.

B. CDMA

Several proposals try to take advantages of the features of CDMA mentioned in Section IV-B2b, mainly addressing the following issues: spreading code assignment, power control and energy efficiency.

We first look at proposals for tree-topology UWANs. Reference [49] adopts a probe process for code assignment and power control. The sink node initiates a discovery probe through a dedicated channel. The probe includes a set of CDMA codes randomly selected from the entire code set and the transmission power information. Each receiver replies the probe by sending another probe, which additionally carries the signal strength of the received probe and its selected code sets that are different from those included in any received probe.

A probe will be resent if it is not replied within a certain time. This process can allow each node to select a code set different from each other, and exchanged information can be used for power control. It can also allow nodes to be added in or removed from the network dynamically. The probing delay and broadcast storm for probing are two major issues in large UWANs, and the proposal was not validated.

With the proposal in [50], the transmissions from the nodes located at the same hierarchical level are multiplexed with different orthogonal codes to allow simultaneous transmissions. The staggered wake-up scheduling algorithm with periodic sleeping proposed in [70] is applied across multiple levels from the bottom to top for energy saving. This assignment can allow the nodes located in different levels with certain distance to reuse the same codes. How different codes are assigned to each node in the network is not clear. Similarly, the POCA (Path-Oriented Code Assignment) [51] requires each 1-hop neighbor of the sink to spread each frame with a different code for simultaneous transmission by assigning different codes to different paths. Such assignment can reduce code length because the number of paths is usually less than that of nodes in a network. Nodes in the same path may not transmit simultaneously. A MAC protocol jointly using CSMA/CA and CDMA is discussed in [52] for a star-topology, aiming to allow simultaneous transmissions without using RTS/CTS to avoid long handshaking delay. However, the description on its MAC operation is not clear.

For multi-hop UWANs, the PLAN (Protocol for Long-latency Access Networks) [53] adopts the distributed code assignment scheme [71] to prevent a node from using the same code within its two-hop neighborhood. It jointly uses a collated RTS/CTS scheme for code assignment. It collates multiple RTS frames from different sources to the same destination so that only a CTS is sent for accumulated RTS frames to reduce protocol overhead. The delay for code assignment becomes long in large UWANs due to handshaking. A simple and fast hierarchical code assignment algorithm without handshaking is discussed in [54]. It adopts a divisive probability function to avoid conflict between spread codes with high probability but without orthogonality guarantee. Different nodes may use the same code simultaneously. The MAC transmission decision is made according to the state of neighboring nodes, and each node has to maintain neighbor state information through control frames.

For cluster UWANs, the UW-MAC [55] adopts a closed-loop distributed scheme to set the optimal transmit power and code length to minimize the near-far effect without handshaking. It is a hybrid of ALOHA and CDMA, i.e., ALOHA is used to transmit the header of a frame while its payload is transmitted via CDMA. Frames from different nodes are allowed to be transmitted simultaneously. A node randomly broadcasts a short header using a common chaotic code, which is followed by data transmission using an optimal transmit power and code length set by a self-assignment algorithm. The header carries the information on the intended next hop and the parameters used to generate the spreading code for the transmission of the up-coming data frame. If the header is successfully decoded by the chosen next hop, the receiver locally generates the spreading code used to decode the up-coming data frame [24]. However, the collision of header transmission affects the decoding of the payload.

To overcome the near-far effect with efficient power control, the DPC (Distributed Power Control) [56] assigns each node a common code to transmit control frames and a unique code to transmit data frames. Once a node has data to transmit, it first broadcasts a control frame containing power control information. Upon receiving it, the receiver estimates the transmission power suitable for the data transmission, and informs the sender by returning a control frame. Since the interference only affects the reception quality, a receiver-centric interference constraint along with a code assignment scheme is further studied in [72]. With this scheme, each receiver determines its transmission power subject to the minimum signal to interference and noise ratio such that additional interference is allowed to support additional communication links in each receiver's vicinity.

C. FDMA

Actually, there are few MAC proposals that simply only use FDMA, while several MAC proposals adopt OFDMA. The main issues addressed for OFDMA include sub-channel allocation, adaptability and energy efficiency.

The MAC protocol proposed in [57] and [73] is based on OFDMA for a cluster network, with cluster heads connected to a surface node. A node can reserve a sub-channel for use until relinquishing it. A negotiation process between nodes using CSMA determines a sub-channel for each node pair, and time is further slotted to reduce collision. It is not suitable for large UWANs, in which, long propagation delay and more collisions caused by a large number of nodes affect the performance of the CSMA and slotted access schemes.

The UW-OFDMAC [58] aims to adaptively set OFDMA parameters at the transmitter in mobile UWANs according to the receiver location and motion effect. Each user is assigned a dedicated sub-channel to avoid multi-user interference, and a sub-channel is further divided into multiple orthogonal subcarriers. When a new transmission starts, a node randomly accesses the medium, using the common OFDMA parameters to transmit a notification frame, which contains the parameters for up-coming data transmission. Immediately after this transmission, the node transmits the data frame on the channel using the declared parameters. Once a transmission fails, the sender increases the transmission power to improve success probability. The dedicated sub-channel is wasted if the associated nodes have no frames to transmit.

To improve energy efficiency, the NOGO-MAC (Node Grouped OFDMA MAC) [59] groups nodes in a star UWAN according to their distances to the sink because propagation loss depends on distances at high frequency more than at low frequency. The closer to the sink, the higher frequency is used to reduce the overall transmission power consumption for a required signal-to-noise ratio (SNR) level. To improve data transmission rate, the sink allocates orthogonal sub-channels to nodes according to the information collected from the transmission of other nodes. It is enhanced for a cluster network in [60], called McNOGO-MAC, by using two different frequency channels for uplink and downlink, respectively. These channels are scheduled alternately on the time axis so that they can cross each other between contiguous clusters to avoid inter-cluster interference. For both, the accuracy of the measured distances between the sink and nodes affects their performance.

D. Multichannel-Based MAC Protocols

These protocols mainly address the following issues: sender-receiver synchronization, the hidden terminal problem and the optimization of bandwidth utilization.

1) Sender-Receiver Synchronization: Two schemes using a dedicated control channel (DCC): one with ALOHA (MC-ALOHA) and the other with RTS/CTS (MC-RTS/CTS), are analyzed in [61]. With the former, the sender simply sends a control frame over the DCC to inform the receiver of the selected data channel (DCH) for up-coming transmission, and then transmits data immediately over the DCH. With the latter, the sender does not send data until an RTS/CTS handshaking with the receiver has completed for DCH selection. The results show that RTS/CTS often outperforms ALOHA, while RTS/CTS is more vulnerable than ALOHA to dynamic network conditions.

2) Hidden Terminal Problem: To handle the triple hidden-terminal problem depicted in Fig. 7, the CUMAC (Cooperative Underwater Multichannel MAC) [62] adds a beacon in the RTS/CTS handshaking. The beacon carries the information on the DCH selected for the incoming RTS, and the RTS receiver broadcasts it via a control channel (CCH) to seek cooperation from its neighbors for collision detection. It is possible for multiple neighbors to send responses simultaneously to congest the CCH. Thus, when a neighbor detects a collision, it sends a tone pulse sequence (i.e., signaling) at a specific time. This sequence is calculated based on the location information such that it can arrive at the intended receiver on the expected detection point. Differently, the DC-MAC (Data Centric multi-hop MAC) [63] divides nodes into different collision domains, which have adequate space separation to avoid transmission interference. Then, a receiver-initiated handshake with precise time-space determination is used to enable multiple collision-free data transmissions. The performance of both protocols is affected by the accuracy of location information.

The HCFMA (Hybrid Collision-Free Medium Access) protocol [64] combines multichannel, reservation, handshaking and the juggling-like stop-and-wait (JSW) [74] reliable transmission schemes. With JSW, a node relays a received frame immediately to its intended receiver. This relay retains the receiver of the relayed frame, which is a potential hidden terminal of the original sender, to keep silent during this period. It also acts as an ACK to its original sender to reduce handshaking overhead. A polling-like handshaking tires to offer time-bounded collision-free channel assignment.

RTS/CTS frames are usually transmitted at the maximum power while data frames at low power. However, some nodes out of RTS/CTS interference range may still transmit, leading to collision at the receiver located within the RTS/CTS transmission range, which is often called Large Interference Range Collision (LIRC) problem in the literature. To solve this problem, the MAC proposal in [66] suggests that a sub-channel with lower frequency is allocated to transmit control frames, while another one with higher frequency to transmit data frames. This is because both the transmission rate and distance in underwater acoustic channels are frequency-selective, with lower frequency propagating longer at lower rates. This setting tries to allow control frames to be transmitted farther with large power while data frames at higher rates. However, it is not validated for addressing the triple hidden-terminal problem.

3) Optimization of Bandwidth Utilization: To maximize bandwidth utilization by avoiding collision between RTS/CTS and data frame transmissions in a centralized UWAN connected to a gateway, the RCAMAC (Reservation Channel Acoustic Media Access Control) [65] divides a channel into a small DCC and a large DCH. The DCC is used by nodes to submit reservation requests through RTS/CTS handshaking. The gateway monitors the DCC for incoming RTSs and allocates contiguous blocks for incoming data frames. After receiving all scheduled frames, the gateway first sends out ACKs, and then CTSs to the nodes that are scheduled for the next cycle. SYN is expectedly available by including time stamps in control frames sent over the DCC.

To enable more parallel transmissions without much negotiation overhead for channel allocation, the UMMAC (Underwater Multi-channel MAC Protocol) [67] divides the channel into multiple sub-channels via phase splitting so that only one transceiver is needed per node. In this case, a node can only listen, transmit or receive on a specific channel at one time. Optimal transmission power is calculated to maximize the channel capacity based on the collected channel state information (CSI). The time is also slotted to reduce collision, and backoff and reservation schemes are jointly used. The slot length is set to the sum of the maximum propagation delay (D_m), the transmission time of a control frame and the guard time between slots, similar to S-FAMA. Such setting tries to assure that the control frames can reach the farthest node. A transmitter-receiver pair has to back off for some time to exchange control messages on a predetermined sub-channel, and then hops to the negotiated sub-channel for data transmission.

The MM-MAC (Multiple rendezvous Multichannel MAC) [68], [75] is not a real multichannel MAC because it does not physically divide the channel. Actually, the channel is structured into superframes each divided into control and data periods. The control period is slotted, and each slot consists of two mini-slots. Control frames are sent at the beginning of a mini-slot. The length of the mini-slot is equal to the frame transmission time plus the maximal propagation delay, similar to the hybrid MAC [76]. It adopts a cyclic quorum system to handle the sender-receiver synchronization to the same time slot and time slot allocation such that multiple transmission pairs can concurrently handshake over a control slot. To increase channel utilization, the length of a data period is set such that a node can transmit several frames. At the end of each data period, a mini-slot is reserved to transmit an ACK frame. It is enhanced in [69] to support bursty traffic transmission by allowing a node to dynamically adjust its duty cycle, called DMM-MAC (Dynamic MM-MAC). However, the control period is a performance bottleneck, similar to a DCC.

E. Summary

The main advantages of UWAN MAC protocols based on multiplexing schemes include i) simplifying MAC protocol design because they may avoid collisions, and ii) FDMA and CDMA can provide collision-free simultaneous transmissions / receptions without handshaking. However, many protocols ignore potential difficulties in providing basic operation conditions to run the proposed MAC. For example, several CDMA code assignment schemes do not discuss how to assure practically adequate orthogonality of the theoretically orthogonal codes assigned for nodes with different large time offsets. This issue arises because signals may propagate through different paths, resulting in long and variable delays [56]. For TDMA and slot-based MAC protocols, how to tradeoff well between minimizing collision and maximizing channel utilization in guard time setting is an important issue. For MAC protocols relying on precise SYN (e.g., TDMA) and message exchanging (e.g., handshaking) will suffer the same problems as encountered by other protocols to be discussed collectively in Section XI.

For multichannel-based MAC protocols to prevent collision between data and control message transmissions, they suffer the same problem as FDMA-based protocols for low bandwidth utilization due to guard-band. This issue has not been considered by some protocols. The use of a DCC may further worsen such situation with the triple hidden terminal problem even in one-hop UWANs, although it can simplify sender-receiver synchronization. This motivates research on non-DCC based protocols such as those proposed for RWNs [77], which however is not investigated for UWANs.

VI. UWAN MAC BASED ON RWN PROTOCOLS WITHOUT MULTIPLEXING

Table IV lists UWAN MAC proposals based on the RWN MAC protocols listed in Table II mainly with the following modifications:

- Making protocol settings aware of propagation delays and node's location. Typical settings include contention window (CW), guard-times and inter-frame-space (IFS).
- Enabling concurrent handshaking and transmitting even during the original waiting period.
- Centralising access control instead of the distributed ones, or using slotted access to replace free access.
- Jointly using ARQ and backoff to improve performance.

A. ALOHA and S-ALOHA

A random backoff is added to ALOHA (ALOHA-RB) in [78] to reduce collision, which requires a node to randomly back off before transmission when a packet arrives. Two backoff schemes, namely binary exponential and Poisson, along with a probabilistic access based on an analysis on the back-off schemes, are implemented by the UW-ALOHA (underwater ALOHA) [79]. It shows that collision probability is around 0.4 for most traffic arrival rates. Similarly, the adaptive CW [80] tries to reduce collision by increasing the CW randomness as follows: the entire CW (i.e., M) is divided into n segments: $(0, \frac{M}{n})$, $(0, \frac{2M}{n}) \cdots (0, [1-\frac{1}{n}]M)$ and $(0, M)$. When a collision happens, the node selects the next range to generate randomly a CW setting. Both backoff and adaptive CW may cause unnecessary waiting, resulting in long access delays.

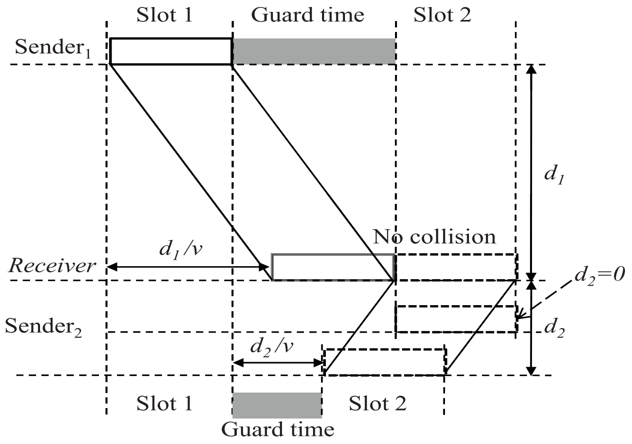


Fig. 8. Guard time setting: senders 1 and 2 transmit at slots 1 and 2, respectively. To avoid collision at the receiver, the guard time should be set to $(d_1 - d_2)/v$. The worst case is that d_1 is equal to the maximum distance while $d_2 = 0$.

To reduce collision caused by transmissions from different senders to the same receiver with different distances between them, the S-ALOHA with guard band [6] suggests adding a guard-time to each slot, which is set equal to $\beta \times D_m$, where β is the fraction of the maximum propagation delay (D_m). When $\beta = 1$ for the maximum guard-time, it can guarantee collision-free transmissions in different slots as illustrated in Fig. 8. The analysis in [102], which names this protocol as PDT-ALOHA (Propagation Delay Tolerant ALOHA), shows that its throughput can reach $17 \sim 100\%$ higher than that of the conventional S-ALOHA for a star UWAN. However, the guard-time may cause bandwidth waste proportional to the propagation delay.

A probabilistic access scheme is also jointly used with S-ALOHA in the LiSS (Lightweight Stochastic Scheduling) proposal [81] to reduce collision without handshaking. Each node is assigned a transmission probability, which is adjusted at a given time based on its local network topology. A heuristic objective function to assign transmission probability is studied. Similarly, a probabilistic scheme for both transmission and reception is adopted by the DTMAC (Delay Tolerant MAC Protocol) [82], which allows a node to transmit with probability p or receive with probability $1-p$ in any of m slots. The success condition for the receiver to receive the transmitted frame against p and m is formulated. Both backoff and probabilistic access schemes may cause unnecessarily waiting, resulting in longer access delay.

Another probabilistic access to time slots is used to leverage long propagation delays by enabling more concurrent

TABLE IV
UWAN MAC BASED ON TYPICAL RWN PROTOCOLS WITHOUT MULTIPLEXING

Protocol name / Reference	MAC Ref. Model (Fig. 5)			Comparison (SYN=Time Synchronization, VM=Validation Method)			
	OC	MAU	Mechanism	SYN	VM†	Topology‡	Major characteristics
ALOHA and Slotted ALOHA							
ALOHA-RB[78]			CS,BO		S	Star	Less collisions than ALOHA probably with longer access delays
UW-ALOHA[79]			FA,BO		A,P	**Star**	
[80]			FA,BO		S		Less collision with possible large access delays
[6]		SL	SA	✓	S	Star	Less collision with bandwidth waste in large UWANs
LiSS[81]		SL	FA,SA	✓	A,S	Multi-hop	Reducing collision probably with increased access delays
DTMAC[82]		SL	FA,SA	✓	A,S	Multi-hop	
DAP-MAC[83]		SL	SA,ME	✓	S	*Multi-hop*	Leverage of long propagation delays (LPD) using more information
TARS[84]		SL	FA,SA	✓	S	*Multi-hop*	
CSMA and CSMA/CA							
ALOHA-CS[85]			CS,BO		S	Multi-hop	Less collision, affected by propagation delays
CSMA-ALOHA[86]			CS,BO		S	Multi-hop	More access opportunities with more collisions
CS-MAC[87]		SL	FA,SA,HS,CS	✓	S	Multi-hop	Reducing hidden-terminals with increased access delays
P-MAC[88]	SF	TS	RE,SC	✓	P	Cluster	Adaptive time-slot allocation without explicit description
MACA (FAMA)							
PCAP[89]			FA,HS		S	One-hop	Leverage of LPD for better performance with large access delays even at low traffic loads. Reduced collision with APCAP
APCAP[90]			FA,HS,BO		S	One-hop	
MACA-MCP[91]			CS,HS,BO	✓	S	*Multi-hop*	High bandwidth utilization with large protocol complexity
MACA-U[92]			HS,BO		S	Multi-hop	Increasing successful handshaking/data reception, may waste opportunity for new transmission
DACAP[93]			FA,HS,BO		S	Multi-hop	Leverage of near-far effect for protocol adaptability, affected by the accuracy of distance information
MACA-MN[94]			FA,HS,BO		S	Multi-hop	More transmissions per handshake using accurate information
POMAC[95]			FA,HS		A	Multi-hop	Reducing end-to-end delay with difficult implementation
FI-MACA[96]			HS,FS		S		Aiming to reduce RTS/CTS related collision, affected by long propagation delays
MACA-PC[97]			HS		S	Multi-hop	
FAMA-CF[98]			PO		A,T	Star	Avoiding RTS/CTS collision using specific modulation
S-FAMA[99]		SL	HS	✓	A,S	Multi-hop	Reduce collision between RTS/CTS and data transmission with guard-time proportional to the maximum propagation delay, leading to low bandwidth utilization
[100]		SL	HS	✓	A	*Multi-hop*	
HTCC[101]		SL	CS,BO,RE	✓	S	Multi-hop	

†VM: A=Analysis, P=Prototyping, S=Simulation, T=Field test. ‡The italic font indicates mobility support, and the bold font requires 1-hop setting.

transmissions in the DAP-MAC (Delay-Aware Probability-based MAC) [83]. The access probability is determined dynamically at run-time by using a utility-optimization framework, which allocates the channel to senders proportionally to their packet sending success capabilities. The TARS (Traffic-Adaptive Receiver-Synchronized) [84] from the same authors further suggests adjusting the frame transmission time in a slot according to sender-receiver distances to align frame receptions for collision reduction. Both protocols are evaluated by a test-bed study in [103], which shows that they can achieve remarkable performance in terms of packet delivery ratio and of end-to-end delay in comparison with S-ALOHA due to considerable shortening of the slot duration. This improvement comes at cost of more information to be collected, such as ACKs and sender-receiver distances. Their performance depends on the availability and accuracy of such information.

B. CSMA and CSMA/CA

The ALOHA with carrier sensing (ALOHA-CS) [85] actually is a variant of CSMA using a new backoff window to adapt the protocol to variable propagation delays. The window size ranges between twice and five times the maximum propagation delay (D_m). Data is transmitted once the channel is sensed idle, and backs off a random time for a new attempt for unsuccessful transmission. If consecutive transmission occurs, the maximum backoff time is set up to $5D_m$. Similarly, CSMA-ALOHA [86] adopts a random sensing duration shorter than the time required for the signal to propagate over the sensing range to improve medium access opportunity, but may also cause more collisions at the receiver. That is, when the channel is sensed busy, the node keeps sensing until the ongoing transmission is completed. Then it senses the channel again for a short random time, and starts a transmission if the channel is sensed idle. The performance of both protocols largely depends on propagation delays between nodes, especially when D_m is considered.

To tackle the hidden terminal problem, the CS-MAC (Channel Stealing MAC) [87] modifies IEEE 802.11 by requiring the receiver of an RTS to postpone the transmission of the CTS for a duration equal to twice the difference between D_m and the sender-receiver propagation delay. Similarly, the sender also defers the same amount of time for data transmission. To reduce collision, the time interval between when an RTS is sent and when the expected CTS is received is slotted. Such postponed transmission increases medium access delays.

The P-MAC (Preamble-MAC) [88] modifies IEEE 802.15.4 to improve its adaptability in a cluster UWAN with a virtual distance level adaptive GTS allocation scheme. This scheme is based on the status and variation of underwater channels estimated through monitoring channel environments, such as propagation delay. Unfortunately, the allocation scheme has not been explicitly described.

C. MACA & FAMA

The following reviews typical modifications to enhance MACA, which mainly aim to leverage long propagation delays and improve efficiency and success of handshaking for high throughput. Note that, although several proposals claim themselves as modifications of FAMA, they are variants of MACA because they do not sense carrier before sending RTSs. Thus, they are also discussed here in Section VI-C4.

1) Leveraging of Long Propagation Delays: The PCAP (Propagation-delay-tolerant Collision Avoidance Protocol) [89] suggests that a CTS transmission is deferred such that it can reach the RTS sender after $2D_m$ since the RTS was sent out. This deferred time aims to allow the RTS sender or its neighbors to take other actions during this period, such as transmitting data or handshaking for the next transmission. Similarly, with the APCAP (Adaptive Propagation-delay-tolerant Collision-Avoidance Protocol) [90], the RTS receiver also postpones the CTS transmission, and the CTS receiver delays data transmission, so that both RTS and CTS can have enough time to reach their destination nodes without collision. It also allows the source node to continue data transmission while waiting for the expected ACK. Such arrangement cannot be always effective because it depends on traffic loads, while a long access delay is inevitable even with low traffic load.

Due to the near-far effect, at a receiver, a frame coming from a far-away node may not corrupt a frame from a much closer node if they are transmitted with the same power. Similarly, a large reception power over a short distance allows handshaking between nodes with shorter distances to take place without worrying about the interference from a remote transmission. Thus, the DACAP (Distance Aware Collision Avoidance Protocol) [93], [104] tries to leverage such effect by exploiting the difference in distances between nodes to set handshaking lengths to avoid collisions instead of using waiting times proportional to the maximum inter-node distance. It avoids collision due to transmission from nodes closer than certain distance, and the idle period length is set according to the actual inter-node distance. The accuracy of the information on distances affects the performance.

2) Improving Handshaking Efficiency: A packet train consisting of multiple transmitted frames is adopted by the MACA-MCP (MACA-like Multi-channel MAC protocol) [91] to improve throughput in a small AUV network, different from the original MACA that transmits only one frame per handshaking. An ACK is sent at the end of the train to acknowledge all received successfully frames, and the lost frames are retransmitted. It also uses handshaking and carrier sensing. Multiple transceivers operating at different frequencies for different ranges are used simultaneously. Train length should be adaptive to the propagation delay between nodes, and avoiding collision to a packet train becomes more important because a collided train causes more loss than a collided frame. Thus, further improvement is necessary for the expected performance.

Since handshaking may take long time in UWANs, the MACA-MN [94] suggests that an RTS sent by a node can simultaneously require for data transmissions to multiple neighbors instead of only one originally allowed by MACA. A node receiving an RTS and ready for reception will feedback a CTS. Then, CTS collision happens when multiple neighbors reply simultaneously. Such a collision is expectedly avoided by using the information on the inter-node propagation delay provided by the sender. That is, after a node calculates and learns that an immediate transmission of a CTS will cause collision with a CTS sent earlier by another node, it defers its CTS transmission to the next earliest possible time. The effectiveness of such opportunistic transmission depends on traffic distributions and the accuracy of the information used for collision-free CTS transmission.

The OPMAC (On-demand Pipelined MAC) [95] aims to set an end-to-end pipeline between a source-destination pair to support time-critical applications. Different from MACA, the CTS corresponding to the RTS from the source node is served as both the positive response to the RTS and the RTS of the CTS sender to one of its neighbors toward to the destination of the packet, and so on, until reaching the destination. Besides, it also uses a piggyback acknowledgement to send ACKs to the previous hop of the data packet when it is sent to the next hop. Such CTS transmission requires routing information, and may collide with other transmissions without proper scheduling.

3) Improving Handshaking Success: In the case of long propagation delays, a node may receive frames not destined to it in handshaking or data reception. To handle such situation, the MACA-U [92] proposes the following modification: whenever a node overhears a foreign RTS or CTS, it does not go to silent state as done by the original MACA. Instead, the sender of an RTS keeps waiting for the expected CTS until it overhears a foreign CTS, and the CTS sender keeps waiting for the expected data by disregarding any incoming RTS and CTS. This modification can increase the successful probability of handshaking or data reception. However, such persistent waiting may end up with nothing, missing opportunity for initiating new transmission.

To avoid collision for RTS/CTS transmission due to spatio-temporal uncertainty, the FI-MACA (Fixed Interval MACA) [96] jointly uses a frame sensing scheme with the original MACA. That is, after sending an RTS, the sender listens to the channel for a fixed period in order to wait for the returning CTS. Similarly, for an RTS receiver, it also listens to the channel for a fixed period before sending the CTS upon receiving an RTS. If any other RTS frames arrive during this listening period, the handshaking is considered unsuccessful. To tackle the LIRC problem mentioned in Section V-D2, the MACA-PC (MACA based Power Control) [97] suggests that the sender still transmits a signal at the maximum transmit power to notify other nodes periodically of its data transmission plan to avoid collision. This can be realized by dividing a long data transmission into segments so that the above signal transmissions can be inserted in between. Both protocols still suffer from long propagation delays, which may cause information obsolete.

4) FAMA: The FAMA-CF (FAMA - Collision Free) [98] jointly uses a polling scheme in a star UWAN to archive high throughput. Its major difference from MACA is to provide collision-free transmission of RTS/CTS through the single access robust (SAR) modulation, which is typically used for synchronization of transmission parameters between users.

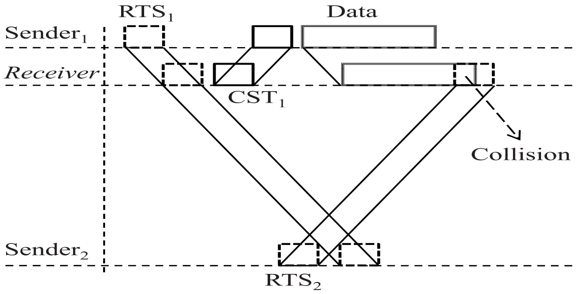


Fig. 9. Collision between RTS and data frames [99]: send$_1$ first submits RTS$_1$, and the receiver returns CTS$_1$. However, sender$_2$ submits RTS$_2$ before the arrival of the CTS$_1$. Then, RTS$_2$ collides with the data frame from sender$_1$ at the receiver.

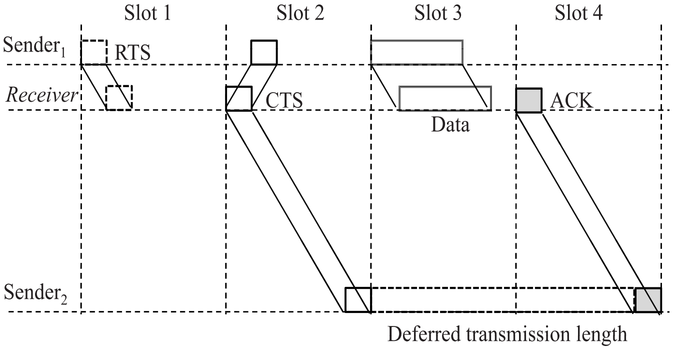


Fig. 10. Principle of S-FAMA [99]: sender$_2$ defers its transmission according to the information carried by the CTS.

The central node inquires each node about data ready for transmission by sending a Request-for-RTS frame, and a receiving node replies by sending an RTS. The central node confirms one of the replying nodes by sending a CTS to it. Experimental results in a real UWAN shows that the maximum efficiency of channel use can be achieved by using FAMA-CF.

With a long propagation delay, the transmission of RTS/CTS frames may collide with an ongoing data transmission as illustrated in Fig. 9. The S-FAMA (Slotted FAMA) [99] suggests that a frame transmission is allowed only at the beginning of a slot, and the slot length is set to D_m plus the transmission time of a CTS or RTS frame to prevent data frame collision, as illustrated in Fig. 10. Such slot length setting is adjusted in [100] by further considering the fluctuation of round-trip time (RTT) due to its effect on the performance. That is, the slot length is set to $RTT/2 + Guard\ time$, where RTT is predicted by the Bayesian dynamic linear algorithm. S-FAMA is enhanced by the HTCC (Handshake Triggered Chained-Concurrent) [101] to support multi-directional concurrent handshaking with different nodes. However, SYN is needed to run the above protocols.

D. Summary

UWAN MAC protocols based on typical RWN protocols can make better use of existing results to minimize development cost and maximize inter-operability with existing networks. Many modifications take into account long propagation delays by setting relevant parameters to be aware of the delay for collision avoidance. To this end, simply using guard time or guard bands may significantly reduce bandwidth utilization. Thus, several methods to leverage long propagation delay are investigated, such as parallel handshaking, packet train and transmission during the original waiting period. However, this endeavor is not sufficient because more precise transmission plan is necessary for better leverage of large space-time volume offered by long propagation delays. This can be realized through scheduling as to be discussed in Section VII. However, these protocols are sender-centric, and it is difficult for them to resolve the problems caused by spatio-temporal uncertainty.

VII. SCHEDULING-BASED UWAN MAC PROTOCOLS

These protocols are listed in Table V, mainly addressing information collection, scheduling constrain calculation, leveraging of long propagation delays, protocol adaptability and energy efficiency as well as broadcasting.

A. Information Collection

Information can be carried by either specific frames (e.g., RTS/CTS) or piggybacked by data frames. The ALOHA-CA (ALOHA with Collision Avoidance) [105] requires each node to overhear every frame to extract useful information about its sender and receiver. It also assumes that each node has the knowledge of propagation delays between all node pairs. The node uses the above information to calculate the busy duration caused by this frame at every other node to avoid collision. It is simple without extra protocol overhead but provides limited information for collision avoidance. The ALOHA-AN (ALOHA with Advance Notification) [105] enhances ALOHA-CA by requiring a source node to transmit a small notification carrying the information prior to data transmission with a small lag between the transmissions of the notification and the data frame. A node overhearing the notification learns when the associated data frame will arrive. A node may extract multiple notifications to have more information with extra protocol overhead. These two passive collection methods may not provide the information useful to calculate schedules for collision avoidance, e.g., propagation delays between nodes.

More useful information can be obtained with the CSMA-based PDAP (Propagation Delay Aware Protocol) [106], which jointly uses RTS/CTS handshaking to estimate distances between senders and receivers according to the channel propagation delay. This delay is calculated based on the time stamps and the network allocation vectors carried by RTS/CTS frames. All nodes are synchronized and transmissions are scheduled to reduce collision. Compared to the above passive collection, more protocol overheads yield, and the protocol performance is affected by propagation delays.

B. Scheduling Constrains

Scheduling constrains regulate a scheduler to make scheduling decisions, and how to determine them is an important issue. Some schemes investigated for UWANs are summarized below.

TABLE V
SCHEDULING-BASED UWAN MAC PROTOCOLS (SCHEDULING ITSELF IS NOT LISTED IN "MECHANISM" FOR CONCISENESS)

Protocol name / Reference	MAC Ref. Model (Fig. 5)			Comparison (SYN=Time Synchronization, VM=Validation Method)			
	OC	MAU	Mechanism	SYN	VM†	Topology‡	Major characteristics
Information collection							
ALOHA-AN[105]			FA,ME		S	One-hop	Simple with no extra overhead and less information collected
ALOHA-CA[105]			FA,FS		S	One-hop	More information collected with extra protocol overhead (PO)
PDAP[106]			CS,HS	✓	S	Multi-hop	More information with large PO, susceptive to propagation delay (PD)
Scheduling constrains							
ST-MAC[107]		TS	ME	✓	S	Tree	Theoretically analysed collision elimination and fairness, complex implementation for computation and information collection
ISTLS[108]		TS		✓	S	Tree	
ETFBS[109]	GF		ME		S	One-hop	More collision-free concurrent transmissions with large computation load
CMS-MAC[110]		TS		✓	S	Multi-hop	
Leverage of long propagation delay							
BiC-MAC[111]			HS		S	Multi-hop	Improving bandwidth utilization with collision to other nodes
Twin-TDMA[112]		TS		✓	A	Star	Improving time-slot utilization for small UWANs
Twin-ALOHA[112]		TS	SA	✓	A	One-hop	Improving time-slot utilization for smaller UWANs. Twin-ALOHA is for sporadic communication
TSR[113]			HS		S	One-hop	
STUMP[20]	LF	TS	ME	✓	S	Tree	Allow collision-free concurrent communication with large cost for information collection
UD-TDMA[114]		TS		✓	S	Multi-hop	
Super-TDMA[115]		TS	ME	✓	S,T	Multi-hop	Managing interference for more simultaneous transmissions with more information to be used/collected
DOTS[116]			HS	✓	S,P	*Multi-hop*	More collision-free concurrent transmissions, susceptive to PD
FDCA[117]			HS	✓	S	*Multi-hop*	Assuming full-duplex underwater acoustic communication
Protocol adaptability & energy efficiency							
Ordered CSMA[118]			CS		S	One-hop	Using relative PD instead of maximal PD for stable and small networks
UW-FLASHR[119]	SF	SL	FA,HS	✓	S	One-hop	Using uneven time slots adaptively, affected by the number of nodes
SA-ALOHA[120]		SL		✓	S	Star	Reducing reception collision via aligning frame arrival at receiver, requiring node position information
ISA-ALOHA[120]		SL		✓	S	Star	
DTSM[121]		SL,MS	SA,HS,BO	✓	S	Multi-hop	Optimizing bandwidth allocation, susceptive to propagation delay
UAN-MAC[122]	LF		FA,FS		S	Multi-hop	Improving energy efficiency, affected by synchronization accuracy
Broadcast							
[123]	SF	TS		✓	S	Multi-hop	Robust broadcast, relying on topology information
[124]			FS		S	Cluster	Able to cover large areas with large protocol overhead to group nodes for each reference/anchor node
B-MAC[125]				✓	S	Cluster	
[126]		TS		✓	A	Multi-hop	Spatial reuse with protocol overhead for node arrangement

†VM: A=Analysis, P=Prototyping, S=Simulation, T=Field test. ‡The italic font indicates mobility support.

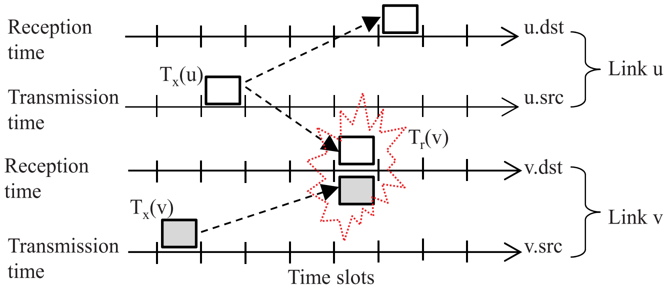


Fig. 11. Conflict relationship in ST-CG [107]: *u.src* and *u.dst* indicate the sender and receiver of link u, $T_x(u)$ and $T_x(v)$ are transmission times over u and v, and $T_r(v)$ for reception time over v, respectively. The difference in propagation delays causes collision due to spatio-temporal uncertainty.

1) Spatio-Temporal Conflict Graph (ST-CG): An ST-CG is a conflict graph, in which, a vertex indicates a transmission link, and the edge between two vertices represents the conflict relationship between the two transmission links, with extra information on the edge to describe spatial uncertainty. It is constructed according to the routing topology, mutual interference and propagation delay. The ST-MAC (Spatial-Temporal MAC) [107], [127], as illustrated in Fig. 11, formulates a TDMA-based scheduling problem as a NP-complete vertex coloring problem of ST-CG. This problem is solved by a heuristic algorithm called TOTA (Traffic based One-step Trial Approach) in polynomial time by considering both traffic loads and routing information. In [108], a slotted ST-CG link-scheduling algorithm additionally considers link transmission delays to eliminate collision and guarantee fairness. A link scheduler, which jointly uses the ISTLS (Interference-aware Spatio-Temporal Link Scheduling) and the SDLO (Smallest-Degree-Last Ordering) algorithms [128], assigns each transmission link a number of time slots such that a scheduled transmission will not cause a collision at both the sender and the receiver. However, the collection of the required information complicates the implementation.

2) Conflict Control: The ETFBS (Earliest Transmission First with Best Start) [109] is a heuristic scheduler aiming to set a conflict-free constraint through computing transmission start times to avoid collision at the receivers and allow more concurrent transmissions. The scheduling problem is formulated into an MILP (Mixed Integer Linear Programming) model to optimize throughput. Similarly, to find conflict-free scheduling and approximate the minimum frame in finite iteration, a correlation matrix is used to describe the conflict relationship between TDMA links in [110]. Then, a heuristic scheme CMS-MAC (Conflict Matrix Solution for underwater MAC) is further studied to control access according to link priorities. This model is optimized in [129] by a comprehensive and concise method, with which, a conflict matrix is generated according to time slot positions. The correlation and conflict matrixes are used by the link-scheduling algorithm to provide conflict-free communication with random scheduling orders.

C. Leveraging of Long Propagation Delay

Long propagation delays are exploited to enable more collision-free concurrent transmissions in the following scenarios:

- Sender-receiver pair: A sender and the intended receiver transmit to each other simultaneously.
- Multiple senders to a receiver: Multiple senders transmit to the same receiver simultaneously.
- Multiple concurrent transmissions: Simultaneous transmissions are allowed between any nodes.

1) Sender-Receiver Pair: The BiC-MAC (Bidirectional-Concurrent MAC) [111], [130] allows a pair of nodes to transmit to each other simultaneously per successful handshaking and even exchange multiple rounds of bidirectional transmissions during a burst. A throughput analysis for a 1-hop UWAN is approximated with a time-slotted BiC-MAC in [131] because the slot mechanism loses its effect when inter-nodal propagation delay is longer than the frame transmission time.

Similarly, the Twin-TDMA [112] allows a pair of nodes to exchange bursts of data frames simultaneously in each time slot, while nodes in-pair can also transmit to other nodes simultaneously instead of the original one node transmission. Particularly for sporadic communication, Twin-ALOHA allows both nodes in a pair to choose the same random slot for transmission. For both, SYN is required, and nodes are assumed to know the activities of each other for scheduling. The same design can also be found in the TSR (Time and Spatial Reuse) [113], [132] for an 1-hop UWAN with static or slowly moving nodes and moderate message transmission. When a two-way communication is required, it allows both nodes to simultaneously exchange messages.

2) Multiple Senders to a Receiver: The STUMP (Staggered TDMA Underwater MAC protocol) [20] uses propagation delay estimate to make scheduling decisions in order to prevent reception conflict, and allow communication overlapping to decrease channel idle time. The scheduler has to ensure frames to arrive at the intended receiver during different times with the following principal schedule constraint: the arrival time of time slots from different nodes to the receiver plus their slot durations should not overlap at the receiver. To this end, each neighbor of a potential receiver should have the information on the schedules of its neighbors' transmissions to the same receiver, resulting in large protocol overheads. The size of time slots can be fixed or dynamically adjusted, and a node can transmit in contiguous time slots within a frame.

3) Multiple Concurrent Transmissions: The UD-TDMA (Underwater Distributed TDMA scheduling for UASN) [114] uses a distributed maximal independent set algorithm to determine the maximum number of nodes that can transmit without collision during the same time slot. To this end, each node has to exchange related information with its 2-hop neighbors, which leads to a large protocol overhead. Energy consumption is reduced by allowing nodes to remain active only during the time slots allocated to itself and the nodes within its communication range. The Super-TDMA [115] is designed for specifically structured networks such as grid [133] and linear topologies [134]. It uses transmission schedules to allow simultaneous transmissions while concentrating interferences at unintended nodes as much as possible. To this end, the frame transmission time and time slot length are set comparable to propagation delays among the nodes. The proper operation requires information on location and transmission schedules of the related nodes. A field test for a linear network consisting of three nodes with 783 m, 807 m and 1574 m distances apart from each other [135] is conducted in Singapore water. With a time slot length and the frame duration of 514 ms and 368 ms, respectively, synchronization accuracy achieved is 181 μs, and the normalized throughput is 0.95.

Similarly, the DOTS (Delay-aware Opportunistic Transmission Scheduling) [116], [136] also allows nodes to overhear neighboring transmissions to obtain information to build a delay map database to support concurrent transmissions even in the presence of exposed terminals. This database is updated for every overheard MAC frame, and used by a sender to estimate collision situation at the intended receivers. Intelligent scheduling schemes are used to increase chances of concurrent transmissions and reduce collision. A network level SYN is implemented by using the SYN scheme proposed in [17], while RTS/CTS is also adopted to handle the hidden-terminal problem, which makes the performance susceptive to propagation delays. In a similar protocol FDCA (Full-Duplex Collision Avoidance) with full-duplex underwater acoustic modems [117], a node tries to build up a map for propagation delays to its neighbors of up to 2-hop, and learn its neighborsąŕ transmission and reception schedules through overhearing. Then, a collision free map can be built to support concurrent handshake processes.

D. Protocol Adaptability and Energy Efficiency

Several scheduling algorithms try to adaptively change protocol settings instead of default ones in order to improve protocol adaptability and energy efficiency. Typical settings include guard time, waiting time and transmission time.

The ordered CSMA [118] uses a round-robin scheme to make each node to have collision-free transmission in a fixed order. To this end, a network coordinator is selected to compute the relative position of each node, work out a transmission order, and broadcast it to every node. This is performed according to the signal strength and arrival angle of the beacon broadcast by each node. After obtaining a transmission order, a node can transmit immediately at the end of an ongoing transmission of another node in order, instead of waiting for the maximum propagation delay. Thus, every node has to sense constantly the carrier to listen to the ongoing transmissions of other nodes. When a node overhears the end of the last transmission of other nodes, which means that the carrier has passed over its position, it starts transmission so that the transmissions can arrive at the same node sequentially following the previously passed ones without collision. However, for dynamic networks with either dynamic traffic loads or mobility, the network initialization needs to be performed frequently, resulting in a large protocol overhead.

The UW-FLASHR (UnderWater-FLASHR) [119], an extension of its RF version [137], schedules transmissions to avoid collision by using uneven time slots and per-node enforced guard time. The operation cycle is divided into a small experimental portion and a much larger established portion. During the first portion, control frames and requests are transmitted to acquire new transmission time slots to be used by nodes in the established portion, which is similar to the RTS/CTS handshaking of IEEE 802.11 mentioned earlier. The major differences are listed below. Here, the requests and responses are transmitted randomly, which may cause collisions so that a handshaking may go through multiple rounds, and requests can be piggybacked in data frames. During the second portion, nodes can transmit only in the acquired time slots, each of which may start at an arbitrary point with an arbitrary length (i.e., uneven time slot), and possibly overlapping with the time slots of other nodes is allowed. Coarse SYN is achieved via the information piggybacked in transmitted frames. The protocol performance largely depends on the efficiency of the experimental portion, during which collision increases as the number of active nodes.

Based on an analytical observation that differences in propagation delays increase the probability of frame collisions at the central receiver, SA-ALOHA (Synchronized Arrival Slotted-Aloha) and ISA-ALOHA (Improved SA-ALOHA) are studied in [120]. SA-ALOHA aims to align the arrival time of each frame at the receiver so that they can arrive in the corresponding slots without collision. This is realized by adjusting the frame transmission time according to the propagation delay between the sender and the central receiver. Since errors of propagation delay estimate may affect the performance, ISA-ALOHA tries to adjust slot sizes according to the range of delay estimation error. Both schemes relay on the position information of nodes to calculate propagation delay for arrival alignment, which however is not easy in UWANs.

The DTSM (Distributed Traffic-based Scheduling MAC) [121] is based on an analytical model to optimize bandwidth allocation in multi-hop UWANs. It suggests that scheduling is carried out according to frame ages, with older ones to be scheduled earlier, similar to the differentiated queuing service (DQS) proposed in [138] and [139]. To let a node know the ages of frames in other nodes, a RTS/CTS handshake is used to determine ages in a distributed manner. It also allows a node to transmit multiple frames per successful RTS/CTS handshake to improve bandwidth utilization, similar to the packet train mentioned earlier. A slotted-access scheme is adopted to avoid data collision, and each slot is further divided into mini-slots for RTS/CTS exchange along with carrier sensing. The combination of the above schemes makes the protocol performance very susceptive to propagation delays.

To reduce energy consumption, with the UAN-MAC (Underwater wireless Acoustic Networks - MAC) [122], [140] for delay-tolerant applications, each node announces its scheduled transmission cycle before going to sleep so that its neighbors can know when to wake up to listen. When a node sleeps, its transceiver circuit is turned off to save energy. For the transmission during wake-up, the initial transmission time can be selected randomly within the first cycle, and the same transmission slot is used in the consecutive cycles. As illustrated in Fig. 12, a node broadcasts a SYNC frame at the beginning of its cycle to realize a local synchronization with its neighbors. Once a node overhears this SYNC, it learns the length of the transmission cycle of the sender so that it can always go to sleep and wake up at the correct time in the next cycle for reception. When a new node joins the network, it needs to listen to the channel in order to receive a SYNC frame for local synchronization. A separate simulation study conducted in [141] shows that network performance drops fast as synchronization drift increases because UAN-MAC strongly relies on the synchronization between nodes' schedules.

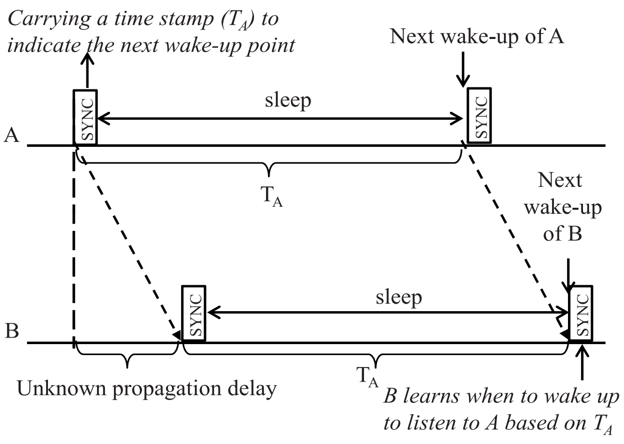


Fig. 12. Basic idea of UAN-MAC [122]: node A broadcasts a SYNC announcing its transmission cycle T_A, and goes to sleep. When new node B joins, it listens until receiving A's SYNC, from which B can learn T_A and transmission cycle period. Then B also goes to sleep from when it decodes out the SYNC for the duration of T_A.

E. Broadcasting

Broadcasting here refers to one-way transmission from one sender to multiple listeners or blind nodes for localization and SYN, and multiple senders may appear in a cluster UWAN. All listeners can receive the broadcast messages without collision.

In a sparse UWAN, the spatial-reuse TDMA scheduling algorithm [123], [142] combines topology-transparent and topology-dependent scheduling schemes. The former ensures that topology information mismatch does not cause too many collisions, while the latter tries to exploit spatial reuse when reliable topology information is available. A flow control scheme is further used to guarantee the delivery of broadcast packets with high periodic broadcast traffic load. It assumes the availability of network topology at each node to tackle topology changes.

In the case of multiple reference nodes, the MAC protocol discussed in [124] allows each reference node to broadcast periodically a beacon message to the sensors on the floor in order to realize a GPS-style localization and SYN (i.e., a reference node acts like a satellite). This is realized by stipulating that a node's transmission can only follow its neighbors' ones through detecting transmission activities like the ordered CSMA discussed earlier. Similarly, the B-MAC (Broadcasting packet scheduling MAC) [125] aims to schedule transmissions from different anchors such that they can be received by all nodes in its range without collision to minimize the duration of localization task. It formulates collision-free packet transmission and shows that the optimization problem is NP-hard. Then, an algorithm is proposed to obtain the optimum solution. For both, it is necessary to group properly the nodes corresponding to each reference / anchor node, which may cause a large protocol overhead for dynamic UWANs.

The MAC protocol in [126] is designed for broadcasting of measurement signals in a networked underwater sensor system. The sensors are arranged into non-overlapping triangles with each sensor transmitting only to its 1-hop neighbors to minimize interference to other communications. A TDMA scheduling scheme is formulated to leverage spatial reuse by allowing nodes with two or more hops away from each other to share the same time slot. Node arrangement for spatial reuse yields protocol overhead.

F. Summary

In RWNs, scheduling is mainly used to provide QoS, while in UWANs, it typically tries to arrange collision-free receptions and node's activities (e.g., sleeping / waking-up) for energy efficiency. Its most abstractive feature is the ability to leverage long prorogation delays to improve bandwidth utilization through enabling more concurrent transmissions with less collision at the receiver. However, its efficiency largely depends on the availability and accuracy of the information used to compute schedules, such as prorogation delay and even the schedules of other nodes. The amount of such information and the method used to collect it determine the complexity of a scheduler and the protocol overhead. However, long propagation delays may cause exchanged information obsolete, and transmission error may worsen such situation. To obtain more up-to-date information, frequent specific message exchange is necessary but at the cost of more protocol overhead. Although a piggyback scheme can reduce such overhead, it cannot guarantee sufficient information to be available timely for a node to make correct decisions. What information to be used and the impact of information collection should be considered in protocol performance evaluation. For (time) slot-based scheduling schemes [143], they also need to handle similar problems faced by TDMA-based protocols mentioned earlier, and inaccurate SYN may affect the efficiency of the computed schedules.

VIII. RESERVATION-BASED UWAN MAC PROTOCOLS

Reservation is more efficient to eliminate reception collision, and many protocols are investigated as listed in Table VI. A reservation protocol may use either message or signal to reserve medium access opportunities. Network topologies affect protocol complexity for reservation because negotiation is necessary between nodes. In the following, the protocols are reviewed according to topologies, and some polling-based proposals are also discussed together.

A. Message-Based Protocols for Centralized (Cluster) Topologies

In this case, reservation is usually carried out in a client-server mode, i.e., a node submits a request to the central node (e.g., a sink), which then makes a decision on the request. A superframe structure is often adopted, and how to divide it and how to submit requests vary for different protocols.

1) Star and Tree: In the TDMA-based ACMENet for a tree-topology UWAN to monitor coastal environments [144], a master node, which may also become a slave node in the presence of the primary master, collects data from its slave nodes. The master node computes transmission schedules based on the propagation delays between itself and each slave node, and then broadcasts them to the nodes. The schedule reception time at a slave node is a reference time point, from which the schedule specifies the time that the slave node has to wait before its transmission. To avoid collision at the master node, the schedule computation takes into account the transmission time of the data frames to be sent by each slave node, and makes data frames from slave nodes to arrive at the master node in an ascending order of the propagation delays between them. To this end, the master node needs the information on the global node locations in the network, which is a large overhead especially for mobile UWANs.

Similarly, the ERMAC (Efficiency Reservation MAC) for a star UWAN [145] allows the sink to group nodes according to their locations and directions relative to it. Then the transmission of each group is arranged such that the unscheduled groups sleep to reduce energy consumption. The reservation requests are submitted during a contention period, which is further divided into mini-slots. The sink computes transmission schedules and broadcasts them to the requesting nodes. Data transmission starts from nodes closer to the sink to those outward.

Also for a star UWAN, with the Twin-DTDMA (Dynamic Twin-TDMA) [112], a node sends its reservation request during a contention portion with a free access scheme and a uniform backoff window. The central node tries to arrange simultaneous transmissions in the same assigned time slot. Similarly, with the DSSS (Dynamic Slot Scheduling Strategy) MAC [146], a node has also to negotiate with the sink or its neighbors during an initial phase before data transmission, which is arranged during a time-slotted communication phase. The time-slot size is set to the propagation delay between two neighboring nodes to support node-to-node communication instead of direct transmission to the sink in order to reduce energy consumption. It tries to improve further time-slot utilization by increasing collision-free transmission pairs in parallel through grouping time-slots according to their interference relationships. More information such as relative position between nodes is needed.

Similarly, with the PR-MAC (Priority Reservation MAC) [147], a node reserves time slots for data transmission during a slot reservation period, and time slots are allocated according to channel conditions and power levels of nodes. To reduce energy consumption, a node wakes up only during its reserved time slot, and a potential receiver wakes up only during the data transmission time-slots scheduled for its neighbors. An additional random access period using CSMA and backoff is added to exchange basic information such as a node's identity, increasing the protocol overhead. Similarly, with the CF-MAC (Collision-Free MAC) [148], the data collector (e.g., an AUV) wakes up a requesting node

TABLE VI
RESERVATION (POLLING)-BASED PROTOCOLS (RESERVATION ITSELF IS NOT LISTED IN "MECHANISM" FOR CONCISENESS)

Protocol name / Reference	MAC Ref. Model (Fig. 5)			Comparison (SYN=Time Synchronization, VM=Validation Method)			
	OC	MAU	Mechanism	SYN	VM†	Topology	Major characteristics
Message-based protocols for centralized (cluster) topologies							
ACMENet[144]		TS		✓	T	Tree	Improving bandwidth utilization (BU) with large protocol overhead to collect information on each node's location
ERMAC[145]	SF	MS,SL	FA	✓	A	Star	
Twin-DTDMA[112]	SF	TS	FA,BO	✓	A	Star	More simultaneous transmissions with reservation overhead
DSSS MAC[146]	SF	TS	FA,SA	✓	S	Star	Improving BU and energy efficiency using more information
PR-MAC[147]	SF	TS	FA,CS,BO	✓	P,S	Star	Improving energy efficiency (EE) with more protocol overhead
CF-MAC[148]			PO (only)		A,S	Star	Simple with possible bandwidth waste
COD-TS[149]	SF	MS,SL	PO	✓	A,S	Cluster	Adaptive to changing traffic loads (CTL) with large access delays
[150]					S	Cluster	Improving protocol adaptability without explicit description
Message-based protocols for distributed topologies: Hidden/exposed terminals							
RIPT[151]			PO,HS		S	Multi-hop	Improving BU with more messages exchanged. More protocol overhead for ROPA.
ROPA[152]			HS,BO		S	Multi-hop	
DSH-MAC[153]			PO		S	Multi-hop	Improving BU with senders's message collision
Message-based protocols for distributed topologies: Bandwidth utilization							
R-MAC[154]			FA	✓	S	Multi-hop	Improving energy efficiency and fairness through avoiding data collision, but collision for control messages may still happen frequently.
RMAC-M[155]			SA		S	Cluster	
NR-MAC[156]			FA	✓	S	Multi-hop	
COPE-MAC[157]			HS,FA		S	Multi-hop	Improving BU & EE with collisions due to control messages
Message-based protocols for distributed topologies: Protocol adaptability							
Hybrid[76]	SF	TS,SL	FA,SA	✓	A,S	One-hop	Adaptive to CTL with large buffer for collision avoidance
UPMAC[158]			FA,HS	✓	A,S	Multi-hop	Adaptive to CTL with large protocol overhead for control
D-MAC[159]	SF		FA				Adaptive to CTL, affected by long propagation delays
Message-based protocols for distributed topologies: Fairness							
SF-MAC[23]			BO		S	Multi-hop	Improving fairness with possible impact on overall performance caused by delayed actions
WSF-MAC[160]			BO	✓	S	Multi-hop	
Signal-based protocols							
ST-Lohi[161]	GF	SL	FA,SI,CS,BO,ME	✓	S	Multi-hop	Less collision and protocol overhead due to reservation, but collided receptions may still happen.
UT-Lohi[161]	GF		FA,SI,CS,BO		S	Multi-hop	

†VM: A=Analysis, P=Prototyping, S=Simulation, T=Field test; CTL=Changing Traffic Load

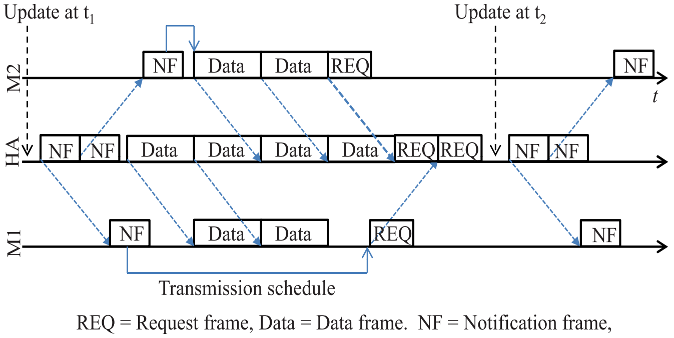


Fig. 13. COD-TS [149]: a communication round (CR) between t_1 and t_2 for single hop controlled by HA. An NF sent by HA informs M2 to send data frames, and M1 and M2 to submit their requests. HA also sends data to M1. The next schedule update is sent in the next CR starting from t_2.

through polling, and assigns it a temporarily reserved channel for transmission. After data transmission is completed, the collector acknowledges the sender. Bandwidth will be wasted if the polled node has no traffic to send.

2) Cluster: The COD-TS (Cluster-based On-Demand Time Sharing) [149], [162] adopts a distributed clustering algorithm proposed in [163]. As illustrated in Fig. 13, the time is split into communication rounds each consisting of data/control frames exchanged between two successive schedule updates from the cluster head. The size of a communication round can be adaptive to traffic loads. The cluster head arranges collision-free transmissions for both data and requests for each 1-hop member by sending notification frames in a polling style, from which, a member can know when to send requests and data frames. A node can send data only when it has been polled with successful request submission, resulting in large access delays. It is extended for multi-hop networks through organizing the cluster heads into an ad hoc network with scheduling. A cluster head has to know the up-to-date schedule of the cluster members within two hops through exchanging schedules.

The self-adaptive MAC protocol in [150] tries to improve protocol adaptability to dynamic environments for a cluster UWAN. Basically, a cluster head creates a profile for each member node based on signal strengths and distances, and arranges transmission schedule accordingly, which is then broadcast to all member nodes for transmission arrangement. However, schedule computation is not discussed adequately.

B. Message-Based Protocols for Distributed Topologies

Without central units used to coordinate reservation, several protocols are designed to eliminate hidden/exposed terminals, and improve bandwidth utilization and protocol adaptability as well as fairness.

1) Hidden and Exposed Terminals: The RIPT (Receiver Initiated Packet Train) [151] is a receiver-centric protocol, jointly using a handshake-based reservation and the packet train scheme mentioned earlier. To improve bandwidth utilization, the receiver initiates reservation and arranges packets from different neighboring nodes to arrive in a packet train within each round of handshaking through polling. To this end, every node has to know the propagation delays between itself and its neighbors so that their transmissions can be arranged to avoid collision at the receiver. This protocol can also solve the hidden/exposed terminal problems.

To exploit spatio-temporal uncertainty, the ROPA (Reverse Opportunistic Packet Appending) in [152] allows receivers (called appenders) to transmit too per successful handshaking. After completing transmission, the sender switches immediately to receiving the incoming data from appenders with the following handshaking. An RTS is broadcast to poll potential appenders having data to send, and each appender sends a request to the sender, who will arrange the transmission and notify the appenders. Appenders' requests may collide when multiple appenders follow up the polling, which is solved by a collision-free schedule computed by the sender to allow each appender to know when to transmit its request. To this end, every node needs to sense the control frames containing necessary information, which is also used to alleviate the hidden-terminal problem.

Similarly, the DSH-MAC (Decoupled and Suppressed Handshaking) [153] also allows the receiver to poll potential senders to transmission with a traffic prediction scheme to avoid the hidden and exposed terminals. The senders need to broadcast their transmission intentions, which the receivers do not need to reply to. The above two messages are decoupled from each other, which is different from the conventional handshake protocol. Reception collision between the above messages may occur, which degrades the protocol performance.

2) Bandwidth Utilization: To avoid data collision for energy efficiency and fairness, the R-MAC (Reservation-based MAC) [154] requires each node to detect the propagation delay to its neighbors and randomly select its listen/sleep schedule. The schedule is broadcast to its neighbors so that they can wake up and sleep accordingly to minimize energy consumption. A node randomly broadcasts a control frame for neighbor discovery, and sends a request to reserve slots for transmission when it has data to transmit. If the receiver is ready for reception, it sends an ACK, which also notifies its neighbors about the reserved period, during which they should keep silent, and only the granted node can transmit. Data frames are transmitted and acknowledged in a burst to reduce overhead. An enhanced R-MAC for a stationary cluster UWAN, RMAC-M [155] uses a mobile node to communicate dynamically with the cluster header, It slots the period of the original contention-based access portion to reduce collision. Another enhancement NR-MAC [156] is studied to overcome a problem similar to the exposed terminal problem by using an additional control message.

The COPE-MAC (Contention based Parallel Reservation MAC) [157] jointly uses parallel reservation and cyber carrier sensing (CCS) to enable concurrent transmission. With the reservation, handshaking processes happen in parallel between multiple senders and receivers to reserve transmission time. With CCS, every node keeps track of its neighborhood activity based on the information obtained from the handshaking process, inferring collision status with computation rather than physical detection. Similar to R-MAC, a node also broadcasts randomly a request to its neighbors for i) neighbor discovery, ii) arranging transmission with multiple nodes and iii) reserving the channel for multiple transmissions to the same neighbor at different times. Each node is supposed to have a virtual channel, via which the propagation delay to its neighbors can be determined in order to map its neighbor's time to its local time. Collision may happen frequently when a large number of control messages are transmitted.

3) Protocol Adaptability: To adapt MAC protocols to changing traffic loads for energy efficiency in a meshed-UWAN, the hybrid MAC protocol [76] adopts a superframe consisting of two portions: scheduled and unscheduled. The first portion uses reservation to provide collision-free access with TDMA to guarantee a data rate to each granted node. A node can hold an assigned time slot for a long time for both data transmission and state information distribution. The second portion is slotted, and the slots can be used by different nodes with random access to support changing traffic loads. To avoid collision, slot length is set to the transmission length plus the maximum propagation delay. All nodes have to listen to the channel and maintain slot synchronization with their neighbors. Such a long slot (around several seconds) is expected to minimize the effect of clock drift and synchronization inaccuracy, but will make nodes to remain idle for long time so that a large buffer is needed to avoid frame dropping.

Similarly, the UPMAC (Underwater Practical MAC protocol) [158] provides two access modes for high and low traffic loads, and allows nodes to switch between them according to traffic loads. ALOHA is used in the low load mode for arbitrary data transmission. A reservation scheme in the high load mode is used to reduce collision with schedules established by a receiver-initiated 3-way handshake and a piggyback scheme. A receiver first broadcasts an initial packet to its neighbors, which then response it immediately once receiving it. Finally, the receiver broadcasts an announcement frame containing the schedule. The process, which may generate a large overhead for control message exchanging, is also used to estimate propagation delays between nodes.

The superframe of the D-MAC (Dual MAC) [159] also consists of two parts: one for short message exchanging at a low bit rate through contention access, and the other for large volume data transmission at an optimal bit rate between intended nodes via a connection established through RTS/CTS handshaking. This process may cause collision to ongoing data receptions, and its efficiency is affected by long propagation delays.

4) Fairness: To handle spatial unfairness, with which earlier requesting nodes are severed later due to different distances, the SF-MAC (Spatially Fair MAC) [23] adopts a receiver-based protocol without assuming the availability of distance information. It tries to guarantee the node submitting an RTS earliest to transmit data first. To this end, the receiver captures the RTS frames from the contenders to determine the earliest transmitter by considering the potential transmission duration. To reduce collision, upon receiving an RTS, the receiver postpones sending the CTS, evaluates the RTS received during the RTS contention period, and discards those whose estimated transmission time is earlier than the arrival time of the first received RTS. For the remaining RTSs, the receiver considers its potential transmission time to determine which RTS is most likely to be sent earliest, and sends a CTS to the sender of this RTS. However, if the earliest node is far away from the receiver, nodes close to the receiver suffer from long waiting time, which degrades network performance. A similar scheme with postponed responses is also adopted by the WSF-MAC (Weight-based Spatially fair MAC) [160]. Some heuristic algorithms to find a fair time slot planning with maximum throughput and optimal frame lengths for transmission reliability are also investigated in [164].

C. Signal-Based Reservation

To reduce collision and protocol overhead caused by message-based reservation, the T-Lohi (Tone-Lohi) [161], [165] exploits proactive tone to reserve the channel and carrier sensing to verify the reservation result. A node wishing to transmit data first sends a short tone, and then listens to the channel for the duration of a contention round (CR). If the node does not overhear any other tones at the end of the CR, the reservation is considered successful, and it can transmit; otherwise it backs off and tries again in a later CR. Both synchronized T-Lohi (ST-Lohi) and unsynchronized T-Lohi (UT-Lohi) have been studied. As illustrated in Fig. 14(a), ST-Lohi aims to synchronize each CR by distributing the reference time so that every node can know the boundaries of each frame and its reservation period. Thus, each node can decide when to send a reservation tone (which can be sent only at the beginning of each CR) and when to send its data to avoid collision after it wins the contention. With UT-Lohi illustrated in Fig. 14(b), carrier sensing is used to detect activities of nodes, and a reservation tone can be sent at any time. Only if the channel is sensed idle after a predefined time interval, the node thinks that it wins the reservation. A low-power wake-up tone receiver is used to activate a node once it detects a tone to reduce energy consumption. However, since no explicit information is available to arrange collision-free reception, collisions may still happen at receivers.

A contender counting is also used to improve fairness and stability under heavy traffic loads. A Markovian analysis conducted in [25] quantifies the bound of convergence time for MAC protocols using an exact contender counting. It shows that such counting can make contention to converge quickly with an asymptotic limit of 3.6 CRs on average, which is independent of network density. This result explains the load-stability of T-Lohi.

D. Summary

With scheduling, the transmission decision is made by the sender locally to reduce collided transmissions from different senders. However, collision may still happen at receivers if no accurate information on the reception plan of the receiver is available to make scheduling decision, and reservation-based MAC protocols can solve this problem. This kind of protocol is more suitable for a centralized topology, in which the central unit can arrange collision-free transmissions with less information exchanged between nodes. If the center unit is also the receiver, the MAC protocol is receiver-centric. In distributed topologies, reservation operation is more complex.

A message-based reservation is more informative than a signal-based one, but vulnerable to channel quality and collision because both may lead to reception failure of requests and control messages. Short signal tone based reservation can alleviate this problem, but can only provide inexplicit reservation without the information on the duration and owner of a reservation. The delay between when a node submits a request and when it is notified of the result for both types of reservations is a large overhead for short message transmission in long-delay UWANs.

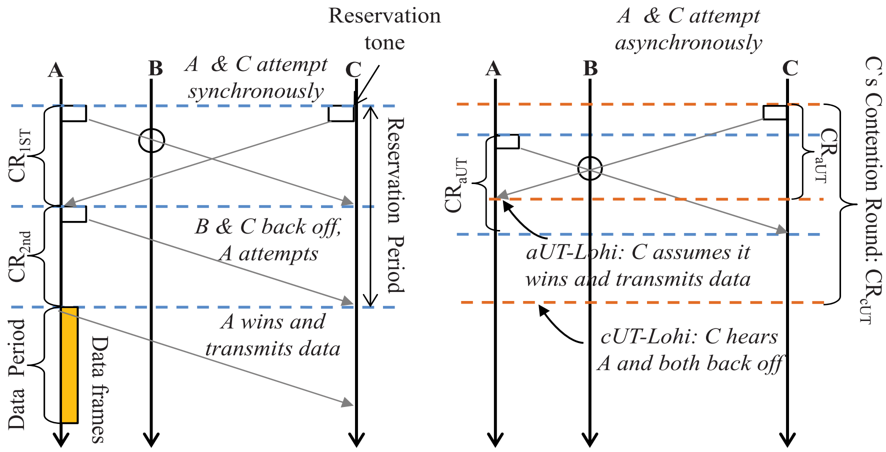
IX. CROSS-LAYER DESIGNED UWAN MAC PROTOCOLS

The cross-layer designed MAC protocols listed in Table VII jointly uses the following techniques and schemes in MAC protocol design, most of which are implemented at the physical layer:

- MIMO: It uses antenna arrays at transmitters and receivers to allow multiple nodes to transmit at the same frequency simultaneously without causing reception failure. It can significantly improve channel capacity through exploiting propagation spatial diversity without using additional power and bandwidth. Particularly in UWANs, MIMO can further exploit rich scattering and multipath fading for high spectral efficiency [114], [166].
- OFDM: A channel is divided into multiple sub-channels with a mutually orthogonal overlapping of adjacent subbands to improve spectral efficiency. Data symbols modulated over these sub-channels are transmitted in parallel, with all the information-bearing waveforms of the subchannels being orthogonal without causing inter-channel interference [167].
- Interference management: It exploits interference patterns to improve the success of signal decoding.
- Power control: It takes advantage of the capture effect to improve spatial reuse efficiency by adjusting transmit power. With the capture effect, stronger signal can be decoded in the presence of low interference signals.
- Spectrum sensing: It exploits cognitive communication techniques to detect holes of the spectrum allocated to the primary user for opportunistic communication.
- Coding: It uses encoding and decoding schemes to improve decoding efficiency (e.g., collided frame recover) or channel utilization (e.g., network coding [168]).
- Information sharing: It uses the information available on the physical layer, the network layer and the transport layer to improve protocol performance.

A. MIMO

The UMIMO-MAC [24], [169], [190] jointly uses MIMO, CDMA and an RTS/CTS like handshake protocol to improve the network capacity and adaptability to channel conditions and application requirements. The handshake protocol is used to negotiate and regulate channel access among competing nodes, and control frames are transmitted with CDMA using



a) ST-Lohi b) UT-Lohi

Fig. 14. Synchronous T-Lohi versus asynchronous T-Lohi [161]. a) During 1^{st} contention round (CR), nodes A and C contend simultaneously by sending reservation tones (RT) but fail. Node B overhears node A's tone first. During 2^{nd} CR, only node A sends an RT while the other nodes back off, and it wins. b) Nodes A and C each sends an RT, and then senses the channel for a duration. At the end of this duration, both nodes A and C receive the tones from each other, and back off to contend again later. If no other tones are received by node C at the end of this period, it wins.

TABLE VII
CROSS-LAYER DESIGNED UWAN MAC (CROSS-LAYERED SCHEMES ARE NOT LISTED IN "MECHANISM" FOR CONCISENESS)

Protocol name /	MAC Ref. Model (Fig. 5)			Comparison (SYN=Time Synchronization, VM=Validation Method)			
Reference	OC	MAU	Mechanism	SYN	VM†	Topology‡	Major characteristics
MIMO							
UMIMO-MAC[169]		CO	HS		S	Multi-hop	Efficient and robust with large implementation complexity
CT-MAC[170]		TS	ME,PR	✓	S	Star	More concurrent transmissions, relying on channel state information
OFDM							
MC-CDMA[171]		CO	MC	✓	S,P	Star	Robust against multi-path and frequency selective fading, affected by orthogonality of spread codes and sub-channel overlapping
TFO-MAC[172]	SF	TS	RE	✓	S	Cluster	Less affected by long propagation delays (PDs) but by SYN accuracy
[173]			FS,BO		S	Star	Adaptive to channel quality, affected by spatio-temporal uncertainty
Interference management							
[174]	SF	TS	FA	✓	S		Interference model used for MAC operation with parameters to be set
NF-STDMA[175]		TS	SC,ME	✓	S	Star	Able to decode collided frames with protocol overhead (PO)
DAS[176]			HS		A	One-hop	Leveraging long PDs for more transmissions for a specific network
Coding							
FDA/AFDA[177]			FA		S	Star	Recovering collided frames following certain collision pattern
LO-MAC[178]	SF	MS,SL	FA,SC		S	Star	Adaptive to channel quality following channel state information
NCDC-MAC[179]		TS	RE,FA	✓	S	Tree	Network coding used to improve throughput with request collision
Power control							
UPC-MAC[180]		SL	SA,ME	✓	S	Multi-hop	More spatial reuse with protocol overhead for global optimization
TLPC[181]			HS		S		Less control/data frame collision with less spatial reuse possibility
SMARP[182]			ME,FS	✓	S		Improving fairness with protocol overhead for broadcast and SYN
Spectrum sensing							
RISM[183]			HS,MC		S		Cognitive spectrum allocation with bottleneck caused by CCC
DCC-MAC[184]			HS,MC		S		No CCC bottleneck of RISM with S/R synchronization overhead
[185]					A		Less spectrum sensing time, relying on distance information
Information sharing							
[186]			CS,BO,HS		S	**Star**	Routing information used to support priority with [186] and DBR-MAC, collision-free transmissions with STUMP-WR. All are affected by the accuracy of the used information.
STUMP-WR[187]	SF	TS	SC	✓	S	Multi-hop	
DBR-MAC[188]			HS,SC,BO	✓	S	Tree	
[189]		SL	SC,ME,FS	✓	S	Multi-hop	Fair sharing with PO for computation and information collection

†VM: A=Analysis, P=Prototyping, S=Simulation. ‡The bold font means one-hop setting. CCC=Common Control Channel, S/R=Sender/Receiver

a common spreading code. These frames contain the information on spreading code assignment, power control and the number of frames to be sent as well as the MIMO transmission models selected by the transmitter. The model affects the tradeoff between multiplexing gain and diversity gain that can be offered by MIMO because higher multiplexing gain comes at the cost of sacrificing diversity gain, and vice versa.

The CT-MAC (Coordinated Transmission MAC) [170] is investigated for a MIMO uplink-based UWAN, in which all underwater nodes transmit to a surface base station. It exploits MIMO to enable MAC-level simultaneous transmissions to combat long propagation delays, similar to the logical MIMO proposed for cellular networks in [191] and [192]. To this end, CT-MAC tries to select active nodes to transmit simultaneously, and ensure i) their transmissions to arrive at the

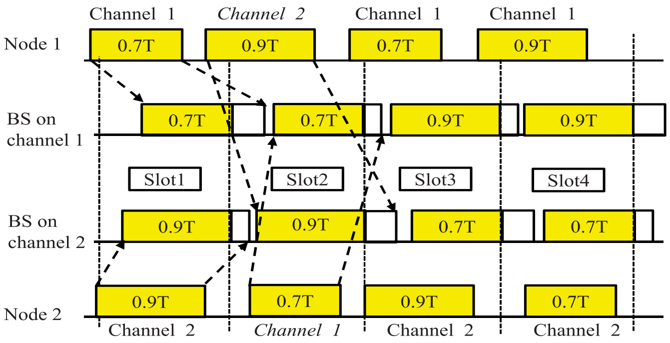


Fig. 15. Principle of TFO-MAC [172]: channels 1 and 2 are associated with base stations 1 and 2 with data rate R. Nodes 1 and 2 requesting a service with a data rate 0.8R, and multi-path delays for nodes 1 and 2 are 0.3T and 0.1T, respectively (T is slot length). With a fixed channel assignment (CA), the maximal data rate for node 1 is 0.7R (i.e., $1 - 0.3$), and 0.9R for node 2. Node 1 cannot be satisfied while node 2 is over-provisioned. With dynamic CA, nodes 1 and 2 use channels 1 and 2 alternatively so that both can be satisfied on average.

base station at the same time, and ii) the number of the selected nodes approaching to $\frac{Mr}{Mt}$, where M_r is the number of hydrophones available at the base station, and M_t the number of transducers equipped at each node. The major issue is how for the base station to obtain CSI and the number of active nodes quickly.

B. OFDM

To improve resistance to frequency-selective fading and multipath fading, the MC-CDMA (Multi-Carrier CDMA) [171] combines OFDM and CDMA to overcome the low transmission efficiency of the conventional single-carrier CDMA proposed in [193]. Each node is preassigned a spread code, and the entire channel bandwidth is divided into multiple sub-channels, over which data symbols are modulated for the OFDM parallel transmission. The protocol performance is affected by the orthogonality of both spread codes and sub-channel overlap in the case of long and variable propagation delays.

The TFO-MAC (TDM with FDM over OFDM MAC) [172] aims to adjust adaptively the sharing of the up-link channel in a cellular-like UWAN, where the nodes transmit to the base station covering them. The available bandwidth is divided into multiple sub-channels, and OFDM is used in every sub-channel for data transmission. Each sub-channel is further divided into equal-length time slots, which are organized into a superframe. A large available bandwidth especially for short-range communication can be fully used to overcome the relatively small bandwidth provided by the OFDM modems currently available for UWANs. To alleviate the impact of large guard time caused by long propagation delay (during which nodes cannot transmit) on network throughput, nodes dynamically switch to different channels under the coordination of the base station (Fig. 15), which conducts a joint optimization of the channel assignment, transmission mode and transmit power. The accuracy of SYN between the base station and its covered nodes affects the performance.

The modified CSMA/CA protocol [173] sits on an adaptive OFDM sub-layer, which can adjust the modulation level and/or transmit power to maximize the system throughput over time-varying channels. It makes use of the physical layer information available at a receiver to distinguish the causes for decoding failure: either a bad channel or a collision. Then, the sender retransmits in the former case and backs off in the latter case. It also adopts frame sensing instead of carry sensing originally used by CSMA to provide information for the sender to adjust ARQ/backoff operations and data rates to maximize the throughput. The protocol performance will be affected by spatio-temporal uncertainty.

C. Interference Management

The typical schemes include interference alignment, interference cancellation and interference modeling.

The queue-aware distributed MAC protocol proposed in [174] tries to capture the statistical behavior of time-varying acoustic channels through historic observations. For each time slot, a node either transmits a frame with a probability ω or stays silent with probability $1 - \omega$ by queuing the incoming frames in the buffer. As a result, the interference at a receiver is coupled with ω setting. An interference model is proposed to allow a node to optimize transmission decisions based on the signal measurement conducted by each receiver with an algorithm to search a globally optimal ω. However, to run properly the model, the values of several parameters have to be set, such as transmitter-receiver distances, medium absorption coefficients and transmission anomaly for acoustic intensity degradation caused by multiple path propagation, refraction, diffraction and scattering.

The NF-STDMA (Near-Far Spatial Reuse TDMA) [175] applies interference cancellation technique (ICT) to decode the jammed frames caused by the near-far effect. If a receiver has a multiple frame reception capability, it can directly decode the frame from the jammer with strong signals, while applying ICT to decode the jammed frame with weak signals. It leverages such effect to design a scheduling algorithm for a star-topology UWAN to allow multiple nodes to transmit in the same time slot. To this end, the central node calculates a collision-free schedule based on the topology information, and broadcasts it to every node in the network, which causes protocol overhead.

An interference channel can achieve significant spectral benefit through using interference alignment (IA) technique, which arranges signals from different senders to arrive at the same node at different times to avoid collision. This scheme can leverage the slow propagation speed of underwater acoustic waves to schedule more concurrent transmissions for different transmitter-receiver pairs. An IA-based DAS (Distance-Alignment Structure) scheme for a 1-hop UWAN is studied for up to four transmitter-receiver pairs in [176], [194], and [195]. Based on this structure, a delay-aware adaptive MAC protocol using RTS/CTS is also investigated to allow a node to automatically switch between access modes according to interference distances. This research results are extended to a 2-hop UWAN in [196]. This method can be applied only to some specifically structured UWANs.

D. Power Control

The UPC-MAC (Underwater Power Control MAC) [180], [197] jointly uses power control with a slotted-access scheme to handle the relatively low spreading loss of acoustic signals to maximize spatial reuse possibility for more concurrent transmissions. The optimal transmit power is set according to the proposed game-theory calculation based on the information carried by messages exchanged between the sender and receiver. It also allows senders to adjust their data transmission rates by considering the features of a real OFDM acoustic communication system according to the channel information. To achieve the overall performance optimization, sufficient information on all sender-receiver channels is necessary for a globally optimal power setting, which may lead to a large protocol overhead. Similarly, with the TLPC (Two-Level Power Control) [181], a node transmits with two levels of power to handle the LIRC problem mentioned in Section V-D2. Control frames such as RTS/CTS/ACK are transmitted at a low power, while data frames at the maximum power, to avoid collision between them. Such kind of power setting may reduce spatial reuse possibility.

A fixed power-level setting may cause unfairness problems, with which some nodes with higher power can have more successful opportunities. The SMARP (Stochastic MAC Protocol with Randomized Power Control) [182] adds randomness to power selection with a power control algorithm based on an underwater acoustic path loss model. Every node regularly broadcasts a hello message at the maximum transmit power for neighbor discovery and distance measurement. With SYN, the distance between a pair of nodes can be calculated according to the propagation delay between the frame sending time carried in the hello message and the frame receiving time.

E. Spectrum Sensing

In a cognitive network (CN), a secondary acoustic user (i.e., unlicensed users) tries to use spectrum holes in the absence of the primary acoustic user (i.e., licensed users). Particularly in underwater acoustic CNs, the primary users refer to marine mammals or other man-made acoustic users [198], and several MAC protocols are investigated. The RISM (Receiver-Initiated Spectrum Management) [183], [199] is a receiver-initiated handshake multichannel scheme jointly using spectrum sensing. An intended receiver first polls the senders via a control frame to collect local sensing results from its neighbors. Then, the receiver selects frequencies with an optimal transmission power, and assigns them to its neighboring senders based on a spectrum-sharing scheme. A traffic prediction based polling mechanism is also proposed to decide when a receiver should receive from its neighbors. However, all these control frames are transmitted on a common control channel (CCC), which may become a bottleneck. The authors further proposes a DCC-MAC (Dynamic Control Channel MAC) in [184], which allows nodes to adjust the bandwidth of the control channel dynamically according to traffic loads. That is, whenever a node finds that the CCC is congested, it can select a proper data channel to be used as a control channel temporarily. In this case, how to synchronize quickly a sender-receiver pair to the selected data channel has to be addressed.

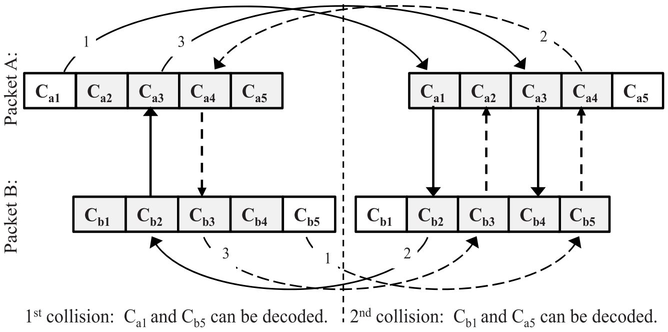


Fig. 16. Principle of Zigzag decoding [200]: frames A and B collide (left side), but chunks C_{a1} of frame A and C_{b5} of frame B are clear and used to decode collided chunks in the retransmitted frames (right side), i.e., C_{a1} is used to decode C_{b2}, C_{b5} to C_{a4}. The remaining blocks are calculated one-by-one following the lines: i) the solid lines from C_{a1} : C_{b2}, C_{a3} and C_{b4}, and ii) the dashed lines from C_{b5}: C_{a4}, C_{b3} and C_{a2}.

An optimal spectrum sensing scheme is studied in [185] to avoid sensing all channels in order to find an idle one with the minimum delay while obtaining the maximum SNR. It is based on the fact that, to obtain a larger SNR, a long distance acoustic communication can carry out at a low frequency, while a short-distance one at a high frequency. This protocol allows a second user to sense the channel at a high idle probability first in the best frequency range according to its transmission distances. The probability calculation is also formulated.

F. Coding

As discussed in [39], a collided frame can be recovered if collision follow certain pattern. The FDA (Flipped Diversity ALOHA) [177], renamed as AFDA (Asynchronous FDA) in [201], exploits this feature by using a superframe consisting of the original frame and its flipped replica, which are transmitted back-to-back. It jointly uses a special diversity transmission scheme and the Zigzag decoding scheme originally used to combat hidden terminals (HTs) [200]. Usually once a collision due to HTs happens, the source node will trigger retransmission with a random backoff, resulting in a second collision because the backoff delay is typically much smaller than the transmission time of a frame in UWANs. Instead of dropping collided frames, Zigzag tries to exploit pattern difference between two collisions to recover collided frames through iterative decoding as illustrated in Fig. 16. So the efficiency depends on collision pattern.

To reduce transmission delays, the LO-MAC (Latency-Optimized and energy-efficient) [178], an extension from the asynchronous schedule-based MAC (ASMAC) for RWNs [202], combines scheduling and random access schemes with variable-size frames for a star-topology UWAN, which uses an AUV as a mobile agent to collect data from sensor nodes. It allows a node to sleep during the off-phase to save energy, and jointly uses convolution coding (CC) and inter-leaver because CC can support adaptive coding according to underwater channel status in terms of flexible code lengths, soft decoding and short decoding delay. A receiver can adaptively adjust the puncture rate based on channel status to ensure a satisfied BER for reception. Channel state information is necessary and how to get it is not explicitly addressed.

The NCDC-MAC (Duty Cycle and Network Coding MAC) [179] jointly uses a network coding [168] and a duty cycle scheme to improve network throughput and energy efficiency in a tree-topology UWAN. The sensor nodes are grouped into levels around the sink, and the level information is carried by the MAC protocol header. The packets from the same-level nodes are coded with network coding. When a node wants to send data, it wakes up and sends an announce packet (NF) to the relay node to demand a transmission allocation. The relay node selects a requesting node with the maximal utility in terms of the ratio of its own traffic load and its relayed traffic load, aiming to provide more opportunities to highly loaded nodes. The performance is affected by NF collision.

G. Information Sharing

The distance-aware scheduling protocol in [186] uses inter-frame spaces (IFSs) to differentiate channel access priority according to users' locations. It sets IFSs according to propagation delays between senders and receivers, with a node closer to its receiver waiting less time. A routing table is used by a node to estimate the distance and propagation delay between itself and its neighbors. Similarly, the STUMP-WR (STUMP with Routing) [187] enhances STUMP (See Section VII-C2) by combing a routing protocol into the scheduling algorithm to select and schedule links for collision-free transmission. Also the Depth-Based Routing (DBR) protocol [203], which determines the next hop on the fly, is jointly used by the DBR-MAC (DBR Aware MAC) [188] to design a depth-aware RTS/CTS handshake protocol. A scheduling and backoff schemes are also proposed to give priority to the nodes linking the surface sink. The performance of the above three protocols is affected by the accuracy and validity of the routing information.

To provide fair bandwidth sharing in a multi-hop UWAN, where flows may compete medium sharing, several constrains are used to regulate a node's transmission activity. For example, a node cannot transmit to a node if i) it is receiving from another node due to the half-duplex constrain, and ii) it is in the interference range of other transmissions. The MAC protocol proposed in [189] aims to interact with a max-min fair rate allocation scheme on the network layer. This scheme first allocates the bandwidth equally to all contending nodes. If a node is constrained elsewhere, its bandwidth is distributed among others. It provides the entitled rates of single-hop sub-flows, and schedules contention-free transmissions of each sub-flow accordingly. The transmission time is slotted, and a node listens to the medium to get rate information, and exchanges the information with its neighbors. Lots of computation and information for such fair sharing are required

H. Summary

Cross-layer designed MAC protocols are used to address several issues related to the peculiar features of UWANs. Both MIMO and OFDM are used to improve channel reliability and utilization, while MIMO is also used to enable MAC layer concurrent transmissions. Interference management improves spectrum utilization and protocol adaptability to dynamic environments. Encoding/decoding techniques further improve bandwidth utilization by recovering collided frames. Physical-layer information can be used to measure link quality and stability, while network layer information such as routing is also exploited to make better MAC decisions.

However, technique limitations for the practical implementation of cross-layer designed MAC protocols have not been adequately discussed. For example for MIMO, with a typical acoustic frequency around 10 kHz, the wavelength (λ) is 15 cm with the propagation speed of 1.5 km/s. It requires a hydrophone at least several centimeters because antenna sizes depend on λ ([204, p. 168]). This will lead a big antenna array, which is difficultly installed in a space-limit node such as AUVs. More discussion will be given in Section XI.

X. IMPLEMENTATION AND PERFORMANCE

This section reviews the implementation and performance of several MAC protocols used for UWANs reported in the literature.

A. Implementation Proposals

Table VIII lists MAC protocols prototyped and studied for UWANs, many of which are widely used in RWNs.

FDMA was applied in the Seaweb'98 system [205] with three interleaved FDMA sets, each of which has 40 multi-frequency-shift-keying (MFSK) tonals and 2 codewords. Seaweb uses a cluster structure, and all nodes in a cluster are assigned the same carrier set for reception. However, half the bandwidth is used for guard bands. Within a cluster, TDMA is used for intra-cluster bandwidth sharing. A field test based on a 300 bit/s modulation yields a net bit-rate of only 50 bit/s, resulting in inefficient bandwidth utilization. FDMA was abandoned in the subsequent Seaweb implementations [213].

An early implementation of a multichannel CSMA jointly using an ACK scheme for reliable transmission is investigated in [206], without taking into account peculiar features of UWANs. For each sub-channel, a timer and a flag are used for carrier sensing. Each sensing lasts a particular period. Upon timeout, if no carrier is detected, the flag is increased. If a carrier is detected during the period, clear the flag and restart the timer. A frame is transmitted via the sub-channel with the longest idle time. An early application of MACA in UWANs (MACAW) [207] also jointly uses an ACK scheme without any modifications to consider peculiar features of UWANs. Similarly, two ALOHA implementations in UWANs are discussed in [208]: one not using acknowledgement or retrial schemes, while the other using both. It shows that they perform well for a small UWAN with the latter being better.

With the Sync MAC [209], the surface gateway periodically broadcasts a SYNC message containing the frame length, which is used by nodes to synchronize with the gateway. A large frame is divided into three parts, and two of them are used for control, and one for nodes to transmit data to the

TABLE VIII
MAC IMPLEMENTATION PROPOSALS

Protocol name /	MAC Ref. Model (Fig. 5)			Comparison (SYN=Time Synchronization, VM=Validation Method)			
Reference	OC	MAU	Mechanism	SYN	VM†	Topology	Major characteristics
FDMA (Seaweb)[205]		SB,TS	HS	✓	T	Cluster	Simple and robust with low bandwidth utilization
CSMA[206]			CS	✓		Star	An implementation scheme without validation
MACAW [207]			HS,BO		S	Multi-hop	A simulation study of MACA in a UWAN
ALOHA[208]	GF	MF	FA,ME		P	Multi-hop	Simplicity but only suitable for small UWANs
Sync MAC[209]	LF	SL	ME,FA	✓	P	Cluster	A prototyped MAC without details nor test results
CB-TDMA[210]	LF	TS		✓	S,P	Cluster	A prototyped and tested MAC protocol with a testbed
Design framework[211]		TS	ME	✓	A		A design framework to enable protocol adaptability
SDCS[212]				Automatically select network protocols according to network conditions on real-time			

†VM: A=Analysis, P=Prototype, S=Simulation, T=Field test

cluster head in a contention method. However, the protocols is not explicitly described. It is prototyped with Cortex-M3 STM32F103xx family MCU and tested in a small water pool with no results reported.

A simulation and testbed implementation of a CB-TDMA (Cluster-Based TDMA MAC) protocol along with a SYN scheme are reported in [210], for a 3D UWAN, using the SUNSET simulation platform and Simple Acoustic Modems (SAMs). Nodes are distributed at suitable heights to cover the ocean column in a cylindrical shape. At each level, several nodes will be deployed to form a cluster, and one node is selected as the head, which relays data in the upward direction. In the vertical direction, time slots are assigned to each level for data transmission, and each level transmits data periodically.

The automated design framework in [211] aims to formulate the protocol optimization problem such that the exchange of control frames can be explicitly modeled via appropriate automation tools. It tries to model explicitly control frame exchange so that the designed tool can decide automatically whether and when a node should send a control frame to minimize average network energy consumption subject to per-node minimum throughput constraint. Furthermore, the SDCS (Software Defined Communication Stack) [212] is able to run different protocols at each layer of the network, using a policy engine to automatically select protocols adaptively according to the operational conditions. Particularly for MAC protocols, CSMA, T-Lohi and DACAP are used as candidates for real-time selection.

B. Performance Evaluaion

Several typical MAC protocols have been evaluated for UWANs, including AHOHA, CSMA, MACA, S-FAMA, T-Lohi and DACAP.

It is shown analytically that ALOHA has better robustness than S-ALOHA [214], [215]. The simulation study in [216] shows that the normalized throughput of ALOHA changes little for different depths. But in deep water, the throughput of nodes located near the surface is about half that in deeper water. In a string topology, it is shown analytically in [217] that saturation may occur in less than five hops and within three hops for the optimal load. Packets from upstream nodes have a very small opportunity to reach the gateway, and collision is the limiting factor to the performance. Similarly, for p-persistent ALOHA, without packet dropping, throughput can increase with traffic loads. But the latency increases significantly if nodes along the path defer transmission to avoid collisions at their downstream nodes [218]. A similar phenomenon is also observed for p-persistent S-ALOHA in [219]. Furthermore, the analytical and simulation studies in [220] show that, with a small number rather than an infinite number of active nodes usually adopted to analyze ALOHA, the maximum throughput of ALOHA approaches to 32.22% with buffering and 27.37% without buffering, which shows that ALOHA is more attractive than commonly understood.

In a large-scale UWAN, the simulation study in [221] shows that ALOHA and S-ALOHA perform better in sparse networks with very low traffic loads, while the handshake protocol is better in a dense network with higher traffic loads. However, the handshake protocol does not work so well for large transmission ranges, which does not affect ALOHA and S-ALOHA. The handshake protocol can perform better with large frames and yield higher throughput for bursty traffic. A slight modification to S-ALOHA in [215] also suggests using smaller slots to improve throughput. The simulation study in [222] also shows that ALOHA-CS [85] (See Section VI-B) consumes most energy with less delay, while FAMA consumes less but with largest delay per successful reception, and MACA is just in between them.

For MACA, closed-form expressions for mean service time and throughput against propagation delays, high detection and decoding errors are introduced in [223], which matches the results of the simulation configured with the preliminary sea trial settings. Several MACA-like protocols are further analyzed in [224], showing that optimal protocol parameter settings can improve performance significantly, e.g., both throughput and waiting time increase with batch sizes. A sea trial for a small UWAN also shows that the performance at sea was slightly worse than the results predicted by the analysis and simulation.

The analytical results in [225] show that S-FAMA can efficiently prevent hidden terminals at the cost of considerably reduced throughput especially with large coverage, and T-Lohi is better in terms of the resilience against congestion and energy-throughput tradeoff. The simulation study for a deep-water sparse network in [86] shows that CSMA-ALOHA (See Section VI-B) is the best while T-Lohi is better than DACAP in terms of network throughput. This is mainly due to that both DACAP and T-Lohi suffer significantly from the delay for handshaking and contender detection. For DACAP, even

TABLE IX
A STATISTICS OF THE REVIEWED UWAN MAC PROTOCOLS

MAC Table No.	Num	Network topology			Mob	Operation condition			Validation method	
		CT	CL	OH		SYN	CTL	EXC	S	P/T
III	29	10	4	5	3	11	26	16	27	
IV	25	4	1	2	4	11	15	14	20	3
V	26	6	2	7	2	18	14	7	22	2
VI	22	6	3	1		12	21	21	18	2
VII	21	9	1	1		11	14	8	19	2
VIII	8	1	3			5	5	2	2	4
Total	131	36	14	16	9	68	95	68	110	13
% (x/131)		50.4			6.9	51.9	72.5	51.9	84	9.9

CT=Centralized topology, CL=Cluster, OH=One-hop, P/T=Prototype/Field test, S=Simulation. Mob=Mobility support. CTL: Using Control Message, EXC: Exchanging Message

short RTS transmission may interfere with data transmission, and T-Lohi suffers from the hidden-terminal problem. The sea-trial results against traffic loads in [226] and [227] show that CSMA is the best in terms of throughput efficiency, which decreases quickly with DACAP. For packet latency, which is defined as the average time between data packet generation at sources and data packet reception at the sink, T-Lohi yields the lowest delay on average, while the delay with DACAP increases mush faster than with CSMA.

The impact of packet sizes on the performance of CSMA and DACAP is also investigated in [228] through simulation for a tree topology with 100 nodes communicating over the pre-determined shortest path. The following phenomena, some of which are initially found in a single-hop network in [229], are observed. An improper setting can result in a high performance penalty, and performance on throughput, latency and energy consumption can be greatly improved by a proper setting. The best frame size depends on data generation and transmission rates as well as BER. DACAP shows the best performance with longer packets, while CSMA prefers short packets at low traffic loads. CSMA has lower waiting time but suffers more from re-transmissions, while DACAP suffers more from long waiting time and is more vulnerable to propagation delays.

XI. DISCUSSION

Table IX is a statistics on the reviewed MAC protocols listed in Tables III–VIII in terms of network topologies, operation conditions and protocol validation methods. This statistics shows some problems remaining and issues that require further studies.

A. Favorable Topologies

Many UWAN MAC protocols are proposed for the network topologies favorable for MAC operations, which include centralized (e.g., star or tree) or cluster topologies, each of which has a coordinator to facilitate MAC operations, and 1-hop topology eliminates hidden-terminals. Particularly for those based on multiplexing schemes (in the first row for Table III), most of them are designed for these topologies. Actually, many underwater applications are based on these topologies with underwater nodes forwarding data to surface stations, which can further form ad hoc networks or link satellites directly.

B. Operation Conditions

The operation conditions include time synchronization (SYN) and dependence on control messages (CTL) as well as message exchanging (EXC). The MAC mechanisms that require EXC include handshaking (HS) and reservation (RE) (except T-Lohi using signal). Those requires CTL includes messaging (ME) and frame sensing (FS) besides those using CTL.

Many reviewed protocols rely on SYN. The major SYN schemes adopted by UWAN MAC protocols include TSHL (Time Synchronization for High Latency) [17], MU-Sync [230] and Mobi-Sync [231]. Due to difficulties in realizing precise SYN underwater as mentioned in Section II-C1, these SYN schemes should have been tested adequately in real environments before being extensively used. Some SYN-based UWAN MAC protocols such as STUMP and [123] have considered possible SYN errors, but many protocols ignore such impact in performance evaluation. A similar problem also exists for underwater localization, which is another difficult issue to be handled [78] probably with localization errors. If a UWAN MAC protocol does not consider these impacts in its performance evaluation, it is only theoretically sound but may not be effective in reality.

Most of the reviewed protocols use control messages, while many further needs to exchange messages between nodes. Although most of them assume using short messages like RTS/CTS, as mentioned in [170], a long preamble sequence is often added for signal synchronization and channel estimation for physical transmission in underwater acoustic channels. For example, a preamble sequence may be about $0.49 \sim 1.5s$, depending on particular modems, while a 100-bit packet transmitted at 1 kbit/s [99] takes about only 0.1s. Thus, a short message from the data link layer is actually transmitted in much longer time. Furthermore, underwater acoustic channel quality may change in very short time scale [20], and more such changes may happen over long transmission period, especially when message exchanging is used because it takes more time. This feature affects successful reception and protocol efficiency. For energy-limited UWANs, energy consumption for short message transmission should also be taken into account because both transmission and reception consume lots of energy as mentioned earlier. However, these issues have not been considered adequately in many protocols in performance evaluation.

The majority of protocols are validated by computer simulation, while only several protocols are prototyped and/or tested in field or laboratory. A question is about their performance in real environments. As reported in [226] for CSMA, T-Lohi and DACAP, there is a significant gap between sea trial and simulation results with an inadequate acoustic channel model or without considering the overheads and delays caused by the specific hardware. To make simulation results more convincible, it is necessary to take into account acoustic channel characteristics, the accuracy of SYN and localization, potential overheads for physical transmission and information collection. A lightweight MAC protocol may suffer less from these problems, but it is still necessary to conduct a convincible validation.

C. Topics for Further Studies

Based on the above review, we think that the following topics need further studies to improve UWAN MAC design.

1) Leveraging of Long Propagation Delays: The most efficient way to combat long propagation delays is to exploit it as an opportunity by allowing more concurrent transmissions within the same contention domain that lead to successful receptions at the receivers [136]. However, as discussed in Section VII-C, most protocols are based on TDMA, which requires SYN and messages or message exchanging. These features may severely affect protocol performance, and it is necessary to study new methods to overcome these problems by jointly using the design strategies discussed below.

2) Receiver-Centric Protocols: As mentioned earlier, such a MAC protocol can avoid reception failure and the hidden/exposed terminal problems [232]. However, the majority of the reviewed UWAN MAC protocols are sender-centric with a few exceptions, such as DC-MAC [63], SF-MAC [23] and UPMAC [158]. This shows that most UWAN MAC proposals still follow the design strategy for RWNs, i.e., aiming to avoid transmission collision to realize collision-free reception. This does not make sense in UWANs as mentioned earlier, and receiver-centric MAC protocols still need further studies.

3) Lightweight Protocols: To avoid the problems caused by SYN, localization and the use of messages or message exchanging mentioned earlier, it is necessary to investigate lightweight MAC protocols that make better use of signaling and/or carrier sensing, such as T-Lohi [161] and CUMAC [62]. More efforts are also required to alleviate the impact of long propagation delays on such kind of protocol, and exploit receiver-centric MAC protocols for more successful collision-free receptions, particularly for reservation-based MAC protocols.

4) Systematical Cross-Layer Design: Such MAC protocols proposed so far are partially cross-layer designed. For example, they may either cross the physical layer or the network layer but not both simultaneously. Furthermore, they mainly focus on MAC function without jointly considering other network functions for overall performance improvement such as congestion control. A systematical design should consider all possible optimal options collectively to maximize performance gain.

5) Smart Protocols: To adapt a UWAN MAC protocol to highly dynamic underwater environments, it is necessary to enable a node to capture environmental characteristics with real-time prediction on possible changes, through exploiting learning techniques such as the reinforcement learning [233]. It is used to optimize the data link layer of UWANs for making better real-time decisions on access mode selection, scheduling policies and frame sizes. Thus, it is interesting to further exploit these techniques to improve a node's capability without increasing protocol complexity and overheads.

6) Mobility and QoS: As shown in Table IX, there are only several MAC protocols addressing terminal mobility. As application development, more mobile terminals will be used underwater. For example, a group of cooperating AUVs are much more efficient than an isolated AUV for underwater searching. However, mobility support in UWANs faces many challenges and more research is needed. Similarly, only a few protocols mentioned earlier address QoS issue such as OPMAC [95]. This issue is very important to enable UWANs to support underwater real-time applications. However, this issue is much more difficult than in RWNs due to long propagation delays and very limited capacity in UWANs as mentioned earlier, and becomes much harder in mobile UWANs.

XII. CONCLUSION

From the above reviews, we can find several interesting MAC strategies proposed to handle the peculiar features of UWANs, such as leveraging of long propagation delays, signal-based reservation, scheduling-based MAC and receiver-initiated protocols. However, none of them has been tested adequately in practice due to large difficulties and high cost of underwater field trial. In this case, computer simulation becomes a major validation method, and this situation is expected to last. To make simulation results more convincible, it is necessary to simulate adequately the characteristics of underwater acoustic channels to reflect the corresponding effect on channel capacity, time synchronization, localization and overheads for physical transmission as well as information collection. An important issue necessary for further study is the standardization of UWAN MAC protocols and cross-layer design framework. They are essential to guarantee inter-operability between devices provided by different manufacturers and useful to concentrate research efforts to certain UWAN MAC protocols.

REFERENCES

[1] M. C. Domingo, "An overview of the Internet of underwater things," *J. Netw. Comput. Appl.*, vol. 35, no. 6, pp. 1879–1890, Nov. 2012.

[2] J. Preisig, "Acoustic propagation considerations for underwater acoustic communications network development," in *Proc. ACM Int. Workshop Underwater Netw. (WUWNet)*, Los Angeles, CA, USA, Sep. 2006, pp. 1–5.

[3] I. F. Akyildiz, D. Pompili, and T. Melodia, "Challenges for efficient communication in underwater acoustic sensor networks," *ACM SIGBED Rev.*, vol. 1, no. 2, pp. 3–8, Jul. 2004.

[4] J. Partan, J. Kurose, and B. N. Levine, "A survey of practical issues in underwater networks," in *Proc. ACM Int. Workshop Underwater Netw. (WUWNet)*, Los Angeles, CA, USA, Sep. 2006, pp. 17–24.

[5] D. Pompili and I. F. Akyildiz, "Overview of networking protocols for underwater wireless communications," *IEEE Commun. Mag.*, vol. 47, no. 1, pp. 97–102, Jan. 2009.

[6] A. A. Syed, W. Ye, B. Krishnamachari, and J. Heidemann, "Understanding spatio-temporal uncertainty in medium access with ALOHA protocols," in *Proc. ACM Int. Workshop Underwater Netw. (WUWNet)*, Montreal, QC, Canada, Sep. 2007, pp. 41–48.

[7] H. Doukkali and L. Nuaymi, "Analysis of MAC protocols for underwater acoustic data networks," in *Proc. IEEE Veh. Technol. Conf. (VTC) Spring*, vol. 2. Stockholm, Sweden, May/Jun. 2005, pp. 1307–1311.

[8] F. Yunus, S. H. S. Ariffin, and Y. Zahedi, "A survey of existing medium access control (MAC) for underwater wireless sensor network (UWSN)," in *Proc. Math. Anal. Model. Comput. Simulat. (AMS)*, May 2010, pp. 544–549.

[9] A. D. Domenico, E. C. Strinati, and M.-G. D. Benedetto, "A survey on MAC strategies for cognitive radio networks," *IEEE Commun. Surveys Tuts.*, vol. 14, no. 1, pp. 21–44, 1st Quart., 2012.

[10] K. Y. Chen, M. D. Ma, E. Cheng, F. Yuan, and W. Su, "A survey on MAC protocols for underwater wireless sensor networks," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 3, pp. 1433–1447, 3rd Quart., 2014.

[11] S. M. Jiang, "A reference model for MAC protocols in underwater acoustic networks (extended abstract)," in *Proc. ACM Int. Conf. Underwater Netw. Syst. (WUWNet)*, Arlington, VA, USA, Oct. 2015, Art. no. 27.

[12] P. C. Etter, *Underwater Acoustic Modeling, Principles, Techniques and Applications*, 2nd ed. London, U.K.: E FN Spon, 1996.

[13] M. Stojanovic, "Underwater acoustic communications: Design considerations on the physical layer," in *Proc. Annu. Conf. Wireless Demand Netw. Syst. Services (WONS)*, Garmisch-Partenkirchen, Germany, Jan. 2008, pp. 1–10.

[14] J. A. Catipovic, "Performance limitations in underwater acoustic telemetry," *IEEE J. Ocean. Eng.*, vol. 15, no. 3, pp. 205–216, Jul. 1990.

[15] M. Lanzagorta, *Underwater Communications*. San Rafael, CA, USA: Morgan & Claypool, 2012.

[16] M. Stojanovic, "Underwater acoustic communication," in *Wiley Encyclopedia of Electrical and Electronics Engineering*. New York, NY, USA: Wiley, 1998, pp. 688–698.

[17] A. A. Syed, W. Ye, and J. Heidemann, "Time synchronization for high latency acoustic networks," in *Proc. IEEE INFOCOM*, Barcelona, Spain, Apr. 2006, pp. 1–12.

[18] D. Makhija, P. Kumaraswamy, and R. Roy, "Challenges and design of MAC protocol for underwater acoustic sensor networks," in *Proc. Model. Optim. Mobile Ad Hoc Wireless Netw.*, Boston, MA, USA, Apr. 2006, pp. 1–6.

[19] G. E. Burrowes and J. Y. Khan, "Investigation of a short-range underwater acoustic communication channel for MAC protocol design," in *Proc. Signal Process. Commun. Syst. (ICSPCS)*, Gold Coast, QLD, Australia, Dec. 2010, pp. 1–8.

[20] K. Kredo, II, P. Djukic, and P. Mohapatra, "STUMP: Exploiting position diversity in the staggered TDMA underwater MAC protocol," in *Proc. IEEE INFOCOM*, Rio de Janeiro, Brazil, Apr. 2009, pp. 2961–2965.

[21] B. Tomasi, G. Toso, P. Casari, and M. Zorzi, "Impact of time-varying underwater acoustic channels on the performance of routing protocols," *IEEE J. Ocean. Eng.*, vol. 38, no. 4, pp. 772–784, Oct. 2013.

[22] L. Freitag *et al.*, "The WHOI micro-modem: An acoustic communications and navigation system for multiple platforms," in *Proc. MTS/IEEE OCEANS*, vol. 2. Washington, DC, USA, Sep. 2005, pp. 1086–1092.

[23] W.-H. Liao and C.-C. Huang, "SF-MAC: A spatially fair MAC protocol for underwater acoustic sensor networks," *IEEE Sensors J.*, vol. 12, no. 6, pp. 1686–1694, Jun. 2012.

[24] T. Melodia, H. Kulhandjian, L.-C. Kuo, and E. Demirors, "Advances in underwater acoustic networking," in *Mobile Ad Hoc Networking: The Cutting Edge Directions*, S. Basagni, M. Conti, S. Giordano, and I. Stojmenovic, Eds. Hoboken, NJ, USA: Wiley, 2013, ch. 23, pp. 804–852.

[25] A. A. Syed and J. Heidemann, "Contention analysis of MAC protocols that count," in *Proc. ACM Int. Conf. Underwater Netw. Syst. (WUWNet)*, Woods Hole, MA, USA, Sep. 2010, pp. 1–8.

[26] V. Srivastava and M. Motani, "Cross-layer design: A survey and the road ahead," *IEEE Commun. Mag.*, vol. 43, no. 12, pp. 112–119, Dec. 2005.

[27] F. Foukalas, V. Gazis, and N. Alonistioti, "Cross-layer design proposals for wireless mobile networks: A survey and taxonomy," *IEEE Commun. Surveys Tuts.*, vol. 10, no. 1, pp. 70–85, 1st Quart., 2008.

[28] *Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs)*, IEEE Standard 802.15.4, 2006.

[29] *Radio Equipment and Systems (RES): High Performance Radio Local Area Network (HIPERLAN) Type 1; Functional Specification*, ETSI Standard ETS 350 652, Oct. 1996.

[30] P. Karn, "MACA—A new channel access method for packet radio," in *Proc. 9th Comput. Netw. Conf.*, London, ON, Canada, Sep. 1990, pp. 134–140.

[31] B. H. Walke, *Mobile Radio Networks: Networking, Protocols and Traffic Performance*, 2nd ed. New York, NY, USA: Wiley, 2002.

[32] D. J. Goodman, R. A. Valenzuela, K. T. Gayliard, and B. Ramamurthi, "Packet reservation multiple access for local wireless communications," *IEEE Trans. Commun.*, vol. 37, no. 8, pp. 885–890, Aug. 1989.

[33] J. G. Proakis, E. M. Sozer, J. A. Rice, and M. Stojanovic, "Shallow water acoustic networks," *IEEE Commun. Mag.*, vol. 39, no. 11, pp. 114–119, Nov. 2001.

[34] C. M. Chang and K.-C. Chen, "Multiuser synchronization," in *Proc. IEEE Symp. Pers. Indoor Mobile Radio Commun. (PIMRC)*, vol. 2. London, U.K., Aug. 2002, pp. 1090–1095.

[35] J. Kodithuwakku, N. Letzepis, R. McKilliam, and A. J. Grant, "Decoder-assisted timing synchronization in multiuser CDMA systems," *IEEE Trans. Commun.*, vol. 62, no. 6, pp. 2061–2071, Jun. 2014.

[36] L. Freitag, M. Stojanovic, S. Singh, and M. Johnson, "Analysis of channel effects on direct-sequence and frequency-hopped spread-spectrum acoustic communication," *IEEE J. Ocean. Eng.*, vol. 26, no. 4, pp. 586–593, Oct. 2001.

[37] E. M. Sozer, M. Stojanovic, and J. G. Proakis, "Underwater acoustic networks," *IEEE J. Ocean. Eng.*, vol. 25, no. 1, pp. 72–83, Jan. 2000.

[38] J. So and N. Vaidya, "Multi-channel MAC for ad hoc networks: Handling multi-channel hidden terminals using a single transceiver," in *Proc. Annu. ACM Int. Conf. Mobile Comput. Netw. (MobiCom)*, Tokyo, Japan, May 2004, pp. 222–233.

[39] Y. Yu and G. B. Giannakis, "High-throughput random access using successive interference cancellation in a tree algorithm," *IEEE Trans. Inf. Theory*, vol. 53, no. 12, pp. 4628–4639, Dec. 2007.

[40] C. L. Fullmer and J. J. Garcia-Luna-Aceves, "Solutions to hidden terminal problems in wireless networks," in *Proc. ACM SIGCOMM*, Cannes, France, Sep. 1997, pp. 39–49.

[41] *Amendment 8: Medium Access Control (MAC) Quality of Service Enhancements*, IEEE Standard 802.11e, 2005.

[42] W. Lin, D. Li, J. Chen, T. Sun, and T. Wang, "A wave-like amendment-based time-division medium access slot allocation mechanism for underwater acoustic sensor networks," in *Proc. CyberC*, Zhangijajie, China, Oct. 2009, pp. 369–374.

[43] Y. Ma, Z. Guo, Y. Feng, M. Jiang, and G. Feng, "C-MAC: A TDMA-based MAC protocol for underwater acoustic sensor networks," in *Proc. Int. Conf. Netw. Security Wireless Commun. Trusted Comput. (NSWCTC)*, vol. 1. Wuhan, China, Apr. 2009, pp. 728–731.

[44] J. Mao, S. Chen, Y. Liu, J. Yu, and Y. Xu, "LT-MAC: A location-based TDMA MAC protocol for small-scale underwater sensor networks," in *Proc. Annu. IEEE Int. Conf. Cyber Technol. Autom. Control Intell. Syst.*, Shenyang, China, Jun. 2015, pp. 1275–1280.

[45] J. Mao *et al.*, "LTM-MAC: A location-based TDMA MAC protocol for mobile underwater networks," in *Proc. MTS/IEEE OCEANS*, Shanghai, China, Apr. 2016, pp. 1–5.

[46] R. Diamant, M. Pinkhasevich, and I. Achrak, "A novel spatially shared TDMA protocol and quality measure for ad hoc underwater acoustic network," in *Proc. Int. Conf. Adv. Inf. Netw. Appl. Workshop (WAINA)*, Bradford, U.K., 2009, pp. 1160–1165.

[47] S. Y. Shin, J. I. Namgung, and S. H. Park, "SBMAC: Smart blocking MAC mechanism for variable UW-ASN (underwater acoustic sensor network) environment," *Sensors*, vol. 10, no. 1, pp. 501–525, Jan. 2010.

[48] L. Hong, F. Hong, Z.-W. Guo, and X. H. Yang, "A TDMA-based MAC protocol in underwater sensor networks," in *Proc. Int. Conf. Wireless Commun. Netw. Mobile Comput. (WiCOM)*, Dalian, China, Oct. 2008, pp. 1–4.

[49] G. G. Xie and J. A. Gibson, "A networking protocol for underwater acoustic networks," Dept. Comput. Sci., Naval Postgraduate School, Monterey, CA, USA, Tech. Rep. OMB 0704-0188, Dec. 2000.

[50] J.-P. Kim, J.-W. Lee, Y.-S. Jang, K. Son, and H.-S. Cho, "A CDMA-based MAC protocol in tree-topology for underwater acoustic sensor networks," in *Proc. Int. Conf. Adv. Inf. Netw. Appl. Workshops (WAINA)*, 2009, pp. 1166–1171.

[51] G. Y. Fan, H. F. Chen, L. Xie, and K. Wang, "An improved CDMA-based MAC protocol for underwater acoustic wireless sensor networks," in *Proc. Int. Conf. Wireless Commun. Netw. Mobile Comput. (WiCOM)*, Wuhan, China, Aug. 2011, pp. 1–4.

[52] H. Doukkali, S. Houcke, and L. Nuaymi, "A cross layer approach with CSMA/CA based protocol and CDMA transmission for underwater acoustic networks," in *Proc. IEEE Symp. Pers. Indoor Mobile Radio Commun. (PIMRC)*, Athens, Greece, Sep. 2007, pp. 1–5.

[53] H.-X. Tan and W. K. G. Seah, "Distributed CDMA-based MAC protocol for underwater sensor networks," in *Proc. IEEE Conf. Local Comput. Netw. (LCN)*, Dublin, Ireland, Oct. 2007, pp. 26–36.

[54] D. Xiujuan, P. Chunyan, L. Xiuxiu, and L. Yuchi, "Hierarchical code assignment algorithm and state-based CDMA protocol for UWSN," *China Commun.*, vol. 12, no. 3, pp. 50–61, Mar. 2015.

[55] D. Pompili, T. Melodia, and I. F. Akyildiz, "A CDMA-based medium access control for underwater acoustic sensor networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 4, pp. 1899–1909, Apr. 2009.

[56] X. Wei, L. Zhao, X. Li, and C. R. Zou, "A distributed power control based MAC protocol for underwater acoustic sensor networks," in *Proc. IEEE Int. Conf. Circuits Syst. Commun. (ICCSC)*, Shanghai, China, May 2008, pp. 688–692.

[57] M. Hayajneh, I. Khalil, and Y. Gadallah, "An OFDMA-based MAC protocol for under water acoustic wireless sensor networks," in *Proc. Int. Conf. Wireless Commun. Mobile Comput. (IWCMC)*, Leipzig, Germany, Jun. 2009, pp. 810–814.

[58] F. Bouabdallah and R. Boutaba, "A distributed OFDMA medium access control for underwater acoustic sensors networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Kyoto, Japan, Jun. 2011, pp. 1–5.

[59] J. Y. Cheon and H.-S. Cho, "A delay-tolerant OFDMA-based MAC protocol for underwater acoustic sensor networks," in *Proc. IEEE Symp. Underwater Technol. (UT) Workshop Sci. Use Submarine Cables Related Technol. (SSC)*, Tokyo, Japan, Apr. 2011, pp. 1–4.

[60] J. Y. Cheon, K. Son, S.-K. Lee, and H.-S. Cho, "Extended abstract: An extension of node-grouped OFDMA MAC into multi-clustered networks," in *Proc. ACM Int. Conf. Underwater Netw. Syst. (WUWNet)*, Los Angeles, CA, USA, Nov. 2012.

[61] Z. Zhou, Z. Peng, J.-H. Cui, and Z. J. Shi, "Analyzing multi-channel MAC protocols for underwater acoustic sensor networks," Dept. Comput. Sci. Eng., Univ. Connecticut, Mansfield, CT, USA, Tech. Rep. UbiNet-TR08-02, 2008.

[62] Z. Zhou, Z. Peng, J.-H. Cui, and Z. Jiang, "Handling triple hidden terminal problems for multichannel MAC in long-delay underwater sensor networks," *IEEE Trans. Mobile Comput.*, vol. 11, no. 1, pp. 139–154, Jan. 2012.

[63] M. Yang, M. S. Gao, C. H. Foh, J. F. Cai, and P. Chatzimisios, "DC-MAC: A data-centric multi-hop MAC protocol for underwater acoustic sensor networks," in *Proc. IEEE Int. Symp. Comput. Commun. (ISCC)*, Jul. 2011, pp. 491–496.

[64] M. Yang, M. S. Gao, C. H. Foh, and J. F. Cai, "Hybrid collision-free medium access (HCFMA) protocol for underwater acoustic networks: Design and performance evaluation," *IEEE J. Ocean. Eng.*, vol. 40, no. 2, pp. 292–302, Apr. 2015.

[65] L. Tracy and S. Roy, "Short paper: A reservation MAC for ad-hoc underwater acoustic sensor networks," in *Proc. ACM Int. Workshop Underwater Netw. (WUWNet)*, San Francisco, CA, USA, Sep. 2008, pp. 95–98.

[66] J. H. Cho and H.-S. Cho, "A multi-channel MAC protocol in underwater acoustic sensor networks," in *Proc. ACM Int. Conf. Underwater Netw. Syst. (WUWNet)*, Shanghai, China, Oct. 2016, Art. no. 25.

[67] Y. S. Su and Z. G. Jin, "UMMAC: A multi-channel MAC protocol for underwater acoustic networks," *J. Commun. Netw.*, vol. 18, no. 1, pp. 75–83, Feb. 2016.

[68] C.-M. Chao and Y.-Z. Wang, "A multiple rendezvous multichannel MAC protocol for underwater sensor networks," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Sydney, NSW, Australia, Apr. 2010, pp. 1–6.

[69] C.-M. Chao, M.-W. Lu, and Y.-C. Lin, "Energy-efficient multichannel MAC protocol design for bursty data traffic in underwater sensor networks," *IEEE J. Ocean. Eng.*, vol. 40, no. 2, pp. 269–276, Apr. 2015.

[70] G. Lu, B. Krishnamachari, and C. S. Raghavendra, "An adaptive energy-efficient and low-latency MAC for data gathering in wireless sensor networks," in *Proc. Int. Parallel Distrib. Process. Symp. (IPDPS)*, Santa Fe, NM, USA, Apr. 2004. p. 224.

[71] H.-X. Tan, W. K. G. Seah, and K.-M. Chan, "Distributed CDMA code assignment for wireless sensor networks," in *Proc. IEEE Radio Wireless Symp. (RWS)*, San Diego, CA, USA, Jan. 2006, pp. 139–142.

[72] H.-X. Tan, C. O'Sullivan, and W. K. G. Seah, "Interference management for medium access control in CDMA underwater acoustic sensor networks," in *Proc. IEEE Veh. Technol. Conf. (VTC) Spring*, Singapore, May 2008, pp. 2116–2120.

[73] I. M. Khalil, Y. Gadallah, and M. H. Khreishah, "An adaptive OFDMA-based MAC protocol for underwater acoustic wireless sensor networks," *Sensors*, vol. 12, no. 7, pp. 8782–8805, Jul. 2012.

[74] M. S. Gao and H. Jiang, "A JSW-based cooperative transmission scheme for underwater acoustic networks," in *Proc. ACM Int. Conf. Underwater Netw. Syst. (WUWNet)*, Los Angeles, CA, USA, Nov. 2012, Art. no. 22.

[75] C.-M. Chao, Y.-Z. Wang, and M.-W. Lu, "Multiple-rendezvous multichannel MAC protocol design for underwater sensor networks," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 43, no. 1, pp. 128–138, Jan. 2013.

[76] K. B. Kredo, II and P. Mohapatra, "A hybrid medium access control protocol for underwater wireless networks," in *Proc. ACM Int. Workshop Underwater Netw. (WUWNet)*, Montreal, QC, Canada, Sep. 2007, pp. 33–40.

[77] L. N. You, S. M. Jiang, and G. Wei, "A multi-channel MAC using no dedicated control channels for wireless mesh networks," in *Proc. Int. Conf. Wireless Commun. Signaling Process. (WCSP)*, Nanjing, China, Nov. 2009, pp. 2996–3000.

[78] N. Parrish, L. Tracy, S. Roy, P. Arabshahi, and W. L. J. Fox, "System design considerations for undersea networks: Link and multiple access protocols," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 9, pp. 1720–1730, Dec. 2008.

[79] Z. Peng, Z. Zhou, J.-H. Cui, and Z. J. J. Shi, "Aqua-net: An underwater sensor network architecture: Design, implementation, and initial testing," in *Proc. MTS/IEEE OCEANS*, Biloxi, MS, USA, Oct. 2009, pp. 1–8.

[80] N. M. Yao, Z. Peng, M. Zuba, and J.-H. Cui, "Improving aloha via backoff tuning in underwater sensor networks," in *Proc. Int. ICST Conf. Commun. Netw. China (CHINACOM)*, Harbin, China, Aug. 2011, pp. 1038–1043.

[81] D. Marinakis, K. Wu, N. Ye, and S. Whitesides, "Network optimization for lightweight stochastic scheduling in underwater sensor networks," *IEEE Trans. Wireless Commun.*, vol. 11, no. 8, pp. 2786–2795, Aug. 2012.

[82] C. Li *et al.*, "DTMAC: A delay tolerant MAC protocol for underwater wireless sensor networks," *IEEE Sensors J.*, vol. 16, no. 11, pp. 4137–4146, Jun. 2016.

[83] Y. Han and Y. S. Fei, "A delay-aware probability-based MAC protocol for underwater acoustic sensor networks," in *Proc. Int. Conf. Comput. Netw. Commun. (ICNC)*, Garden Grove, CA, USA, Feb. 2015, pp. 938–944.

[84] Y. Han and Y. S. Fei, "TARS: A traffic-adaptive receiver-synchronized MAC protocol for underwater sensor networks," in *Proc. IEEE Int. Symp. Model. Anal. Simulat. Comput. Telecommun. Syst. (MASCOTS)*, Atlanta, GA, USA, Oct. 2015, pp. 1–10.

[85] F. Guerra, P. Casari, and M. Zorzi, "World ocean simulation system (WOSS): A simulation tool for underwater networks with realistic propagation modeling," in *Proc. ACM Int. Workshop Underwater Netw. (WUWNet)*, Berkeley, CA, USA, Nov. 2009, Art. no. 4.

[86] F. Favaro, S. Azad, P. Casari, and M. Zorzi, "Extended abstract: On the performance of unsynchronized distributed MAC protocols in deep water acoustic networks," in *Proc. ACM Int. Workshop Underwater Netw. (WUWNet)*, Seattle, WA, USA, Dec. 2011, Art. no. 17.

[87] Y.-D. Chen, S.-S. Liu, C. M. Chang, and K.-P. Shih, "CS-MAC: A channel stealing MAC protocol for improving bandwidth utilization in underwater wireless acoustic networks," in *Proc. MTS/IEEE OCEANS*, Waikoloa, HI, USA, Sep. 2011, pp. 1–5.

[88] J.-I. Namgung, S.-Y. Shin, N.-Y. Yun, and S.-H. Park, "Adaptive GTS allocation scheme based on IEEE 802.15.4 for underwater acoustic sensor networks," in *Proc. IEEE/IFIP Int. Conf. Embedded Ubiquitous Comput. (EUC)*, Hong Kong, Dec. 2010, pp. 297–301.

[89] X. X. Guo, M. R. Frater, and M. J. Ryan, "A propagation-delay-tolerant collision avoidance protocol for underwater acoustic sensor networks," in *Proc. OCEANS Asia–Pac.*, Singapore, Sep. 2006, pp. 1–6.

[90] X. Guo, M. R. Frater, and M. J. Ryan, "Design of a propagation-delay-tolerant MAC protocol for underwater acoustic sensor networks," *IEEE J. Ocean. Eng.*, vol. 34, no. 2, pp. 170–180, Apr. 2009.

[91] S. Shahabudeen, M. Chitre, and M. Motani, "A multi-channel MAC protocol for AUV network," in *Proc. MTS/IEEE OCEANS*, Aberdeen, U.K., Jun. 2007, pp. 1–6.

[92] H.-H. Ng, W.-S. Soh, and M. Motani, "MACA-U: A media access protocol for underwater acoustic networks," in *Proc. IEEE Glob. Telecommun. Conf. (GLOBOCOM)*, New Orleans, LO, USA, Nov. 2008, pp. 323–336.

[93] B. Peleato and M. Stojanovic, "Distance aware collision avoidance protocol for ad-hoc underwater acoustic sensor networks," *IEEE Commun. Lett.*, vol. 11, no. 12, pp. 1025–1027, Dec. 2007.

[94] N. Chirdchoo, W.-S. Soh, and K. C. Chua, "MACA-MN: A MACA-based MAC protocol for underwater acoustic networks with packet train for multiple neighbors," in *Proc. IEEE Veh. Tech. Conf. (VTC Spring)*, Singapore, May 2008, pp. 46–50.

[95] F. Dou and Z. Peng, "On-demand pipelined MAC for multi-hop underwater wireless sensor networks," in *Proc. ACM Int. Conf. Underwater Netw. Syst. (WUWNet)*, Arlington, VA, USA, Oct. 2015, Art. no. 26.

[96] J. X. Liu and J. T. Wang, "A MACA-based collision avoidance MAC protocol for underwater acoustic sensor networks," in *Proc. IEEE/OES China Ocean Acoustics (COA)*, Harbin, China, Jan. 2016, pp. 1–4.

[97] L. F. Qian, S. L. Zhang, M. Q. Liu, and Q. F. Zhang, "A MACA-based power control MAC protocol for underwater wireless sensor networks," in *Proc. IEEE/OES China Ocean Acoustics (COA)*, Harbin, China, Jan. 2016, pp. 1–8.

[98] A. Kebkal, K. Kebkal, and M. Komar, "Data-link protocol for underwater acoustic networks," in *Proc. MTS/IEEE OCEANS*, vol. 2. Brest, France, Jun. 2005, pp. 1174–1180.

[99] M. Molins and M. Stojanovic, "Slotted FAMA: A MAC protocol for underwater acoustic networks," in *Proc. MTS/IEEE OCEANS*, Singapore, Sep. 2006, pp. 1–7.

[100] Y. K. Chen, F. Ji, Q. S. Guan, F. J. Chen, and H. Yu, "A new MAC based on RTT prediction for underwater acoustic networks," in *Proc. ACM Int. Conf. Underwater Netw. Syst. (WUWNet)*, Shanghai, China, Oct. 2016, Art. no. 26.

[101] D. F. Zhao, G. Y. Lun, and M. S. Liang, "Handshake triggered chained-concurrent MAC protocol for underwater sensor networks," in *Proc. ACM Int. Conf. Underwater Netw. Syst. (WUWNet)*, Shanghai, China, Oct. 2016, Art. no. 23.

[102] J. Ahn and B. Krishnamachari, "Performance of a propagation delay tolerant ALOHA protocol for underwater wireless networks," in *Proc. Distrib. Comput. Sensor Syst. (DCOSS)*, vol. 5067. Santorini, Greece, Jun. 2008, pp. 1–16.

[103] Y. M. Aval *et al.*, "Testbed-based performance evaluation of handshake-free MAC protocols for underwater acoustic sensor networks," in *Proc. MTS/IEEE OCEANS*, Monterey, CA, USA, Sep. 2016, pp. 1–7.

[104] B. Peleato and M. Stojanovic, "A MAC protocol for ad-hoc underwater acoustic sensor networks," in *Proc. ACM Int. Workshop Underwater Netw. (WUWNet)*, Los Angeles, CA, USA, Sep. 2006, pp. 113–115.

[105] N. Chirdchoo, W.-S. Soh, and K. C. Chua, "Aloha-based MAC protocols with collision avoidance for underwater acoustic networks," in *Proc. IEEE INFOCOM*, Barcelona, Spain, May 2007, pp. 2271–2275.

[106] C. Petrioli, R. Petroccia, and M. Stojanovic, "A comparative performance evaluation of MAC protocols for underwater sensor networks," in *Proc. MTS/IEEE OCEANS*, Quebec City, QC, Canada, Sep. 2008, pp. 1–10.

[107] C.-C. Hsu, K. Lai, C.-F. Chou, and K. C.-J. Lin, "ST-MAC: Spatial-temporal MAC scheduling for underwater sensor networks," in *Proc. IEEE INFOCOM*, Rio de Janeiro, Brazil, Apr. 2009, pp. 1827–1835.

[108] J. Ma and W. Lou, "Interference-aware spatio-temporal link scheduling for long delay underwater sensor networks," in *Proc. Annu. Commun. Soc. Conf. Sensor Mesh Ad Hoc Commun. Netw. (SECON)*, Salt Lake City, UT, USA, Jun. 2011, pp. 431–439.

[109] Y. Guan, C.-C. Shen, and J. Yackoski, "MAC scheduling for high throughput underwater acoustic networks," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Cancún, Mexico, Mar. 2011, pp. 197–202.

[110] W. Bai, H. Wang, X. Shen, Z. Jiang, and R. Zhao, "An heuristic link scheduling model for underwater acoustic sensor networks," in *Proc. MTS/IEEE OCEANS*, Taipei, Taiwan, Apr. 2014, pp. 1–5.

[111] H.-H. Ng, W.-S. Soh, and M. Motani, "BiC-MAC: Bidirectional-concurrent MAC protocol with packet bursting for underwater acoustic networks," in *Proc. MTS/IEEE OCEANS*, Seattle, WA, USA, Sep. 2010, pp. 1–7.

[112] S. Shahabudeen, M. Chitre, and M. Motani, "MAC protocols that exploit propagation delay in underwater networks," in *Proc. MTS/IEEE OCEANS*, Waikoloa, HI, USA, Sep. 2011, pp. 1–6.

[113] R. Diamant, W. Shi, W.-S. Soh, and L. Lampe, "Joint time and spatial reuse handshake protocol for underwater acoustic communication networks," in *Proc. MTS/IEEE OCEANS*, Waikoloa, HI, USA, Sep. 2011, pp. 1–6.

[114] Z. Li *et al.*, "UD-TDMA: A distributed TDMA protocol for underwater acoustic sensor network," in *Proc. IEEE Int. Conf. Mobile Adhoc Sensor Syst. (MASS)*, Macau, China, Oct. 2009, pp. 918–923.

[115] P. Anjangi and M. Chitre, "Design and implementation of super-TDMA: A MAC protocol exploiting large propagation delays for underwater acoustic networks," in *Proc. ACM Int. Conf. Underwater Netw. Syst. (WUWNet)*, Arlington, VA, USA, Oct. 2015, Art. no. 1.

[116] Y. Noh, P. Wang, U. Lee, D. Torres, and M. Gerla, "DOTS: A propagation delay-aware opportunistic MAC protocol for underwater sensor networks," in *Proc. IEEE Int. Conf. Netw. Protocols (ICNP)*, Kyoto, Japan, Oct. 2010, pp. 183–192.

[117] C. Li *et al.*, "FDCA: A full-duplex collision avoidance MAC protocol for underwater acoustic networks," *IEEE Sensors J.*, vol. 16, no. 11, pp. 4638–4647, Jun. 2016.

[118] Y.-J. Chen and H.-L. Wang, "Ordered CSMA: A collision-free MAC protocol for underwater acoustic networks," in *Proc. MTS/IEEE OCEANS*, Vancouver, BC, Canada, Jun. 2007, pp. 1–6.

[119] J. Yackoski and C.-C. Shen, "UW-FLASHR: Achieving high channel utilization in a time-based acoustic MAC protocol," in *Proc. ACM Int. Workshop Underwater Netw. (WUWNet)*, San Francisco, CA, USA, Sep. 2008, pp. 59–66.

[120] Y. Zhou, K. Chen, J. H. He, and H. B. Guan, "Enhanced slotted aloha protocols for underwater sensor networks with large propagation delay," in *Proc. IEEE Veh. Tech. Conf. (VTC Spring)*, Yokohama, Japan, May 2011, pp. 1–5.

[121] Z. L. Liao, D. S. Li, and J. Chen, "Joint bandwidth optimization and media access control for multihop underwater acoustic sensor networks," *IEEE Sensors J.*, vol. 15, no. 8, pp. 4292–4304, Aug. 2015.

[122] V. Rodoplu and M. K. Park, "An energy-efficient MAC protocol for underwater wireless acoustic networks," in *Proc. MTS/IEEE OCEANS*, Washington, DC, USA, Sep. 2005, pp. 1198–1203.

[123] R. Diamant, G. N. Shirazi, and L. Lampe, "Robust spatial reuse scheduling in underwater acoustic communication networks," in *Proc. IEEE Veh. Tech. Conf. (VTC Fall)*, San Francisco, CA, USA, Sep. 2011, pp. 1–5.

[124] W. van Kleunen, N. Meratnia, and P. J. M. Havinga, "Short paper: Scheduled MAC in beacon overlay networks for underwater localization and time-synchronization," in *Proc. ACM Int. Workshop Underwater Netw. (WUWNet)*, Seattle, WA, USA, Dec. 2011, Art. no. 6.

[125] H. Ramezani and G. Leus, "Localization packet scheduling for underwater acoustic sensor networks," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 7, pp. 1345–1356, Jul. 2015.

[126] H. Chen, H. F. Chen, M. Deng, and L. Xie, "MAC protocol for measurement signal broadcasting in distributed ocean current estimation using underwater acoustic sensor networks," in *Proc. ACM Int. Conf. Underwater Netw. Syst. (WUWNet)*, Shanghai, China, Oct. 2016, Art. no. 27.

[127] C.-C. Hsu, M.-S. Kuo, C.-F. Chou, and K. C.-J. Lin, "The elimination of spatial-temporal uncertainty in underwater sensor networks," *IEEE/ACM Trans. Netw.*, vol. 21, no. 4, pp. 1229–1242, Aug. 2013.

[128] D. W. Matula and L. L. Beck, "Smallest-last ordering and clustering and graph coloring algorithms," *J. ACM*, vol. 30, no. 3, pp. 417–427, 1983.

[129] W. G. Bai, H. Y. Wang, X. H. Shen, and R. Q. Zhao, "Link scheduling method for underwater acoustic sensor networks based on correlation matrix," *IEEE Sensors J.*, vol. 16, no. 11, pp. 4015–4022, Jun. 2016.

[130] H.-H. Ng, W.-S. Soh, and M. Motani, "A bidirectional-concurrent MAC protocol with packet bursting for underwater acoustic networks," *IEEE J. Ocean. Eng.*, vol. 38, no. 3, pp. 547–565, Jul. 2013.

[131] H.-H. Ng, W.-S. Soh, and M. Motani, "Saturation throughput analysis of the slotted BiC-MAC protocol for underwater acoustic networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 7, pp. 3948–3960, Jul. 2015.

[132] R. Diamant, W. Shi, W.-S. Soh, and L. Lampe, "Joint time and spatial reuse handshake protocol for underwater acoustic communication networks," *IEEE J. Ocean. Eng.*, vol. 38, no. 3, pp. 470–483, Jul. 2013.

[133] S. Lmai, M. Chitre, C. Laot, and S. Houcke, "Throughput-maximizing transmission schedules for underwater acoustic multihop grid networks," *IEEE J. Ocean. Eng.*, vol. 40, no. 4, pp. 853–863, Oct. 2015.

[134] S. Lmai, M. Chitre, C. Laot, and S. Houcke, "Throughput-efficient super-TDMA MAC transmission schedules in ad hoc linear underwater acoustic networks," *IEEE J. Ocean. Eng.*, vol. 42, no. 1, pp. 156–174, Jan. 2017.

[135] P. Anjangi and M. Chitre, "Experimental demonstration of super-TDMA: A MAC protocol exploiting large propagation delays in underwater acoustic networks," in *Proc. IEEE Underwater Commun. Netw. Conf. (UComms)*, Lerici, Italy, Aug. 2016, pp. 1–5.

[136] Y. Noh *et al.*, "DOTS: A propagation delay-aware opportunistic MAC protocol for mobile underwater networks," *IEEE Trans. Mobile Comput.*, vol. 13, no. 4, pp. 766–782, Apr. 2014.

[137] J. Yackoski and C.-C. Shen, "Managing delay and jitter in mesh networks through path-aware distributed transmission scheduling," *ACM Mobile Comput. Commun. Rev.*, vol. 11, no. 2, pp. 49–50, Apr. 2007.

[138] S. M. Jiang, "Granular differentiated queueing services and cost model for end-to-end QoS: Principle," in *Proc. IEEE Int. Conf. Netw. (ICON)*, vol. 1. Singapore, Nov. 2004, pp. 369–374.

[139] S. M. Jiang, "Granular differentiated queueing services for QoS: Structure and cost model," *ACM SIGCOMM Comput. Commun. Rev. (CCR)*, vol. 35, no. 2, pp. 13–22, Apr. 2005.

[140] M. K. Park and V. Rodoplu, "UWAN-MAC: An energy-efficient MAC protocol for underwater acoustic wireless sensor networks," *IEEE J. Ocean. Eng.*, vol. 32, no. 2, pp. 710–720, Jul. 2007.

[141] P. Casari, F. E. Lapiccirella, and M. Zorzi, "A detailed simulation study of the UWAN-MAC protocol for underwater acoustic networks," in *Proc. MTS/IEEE OCEANS*, Vancouver, BC, Canada, Sep. 2007, pp. 1–6.

[142] R. Diamant, G. N. Shirazi, and L. Lampe, "Robust spatial reuse scheduling in underwater acoustic communication networks," *IEEE J. Ocean. Eng.*, vol. 39, no. 1, pp. 32–46, Jan. 2014.

[143] K. Kredo, II and P. Mohapatra, "Scheduling granularity in underwater acoustic networks," in *Proc. ACM Int. Workshop Underwater Netw. (WUWNet)*, Seattle, WA, USA, Dec. 2011, Art. no. 7.

[144] G. Açar and A. E. Adams, "ACMENet: An underwater acoustic sensor network protocol for real-time environmental monitoring in coastal areas," *IEE Proc. Radar Sonar Navig.*, vol. 153, no. 4, pp. 365–380, Aug. 2006.

[145] T. H. Nguyen, S.-Y. Shin, and S.-H. Park, "Efficiency reservation MAC protocol for underwater acoustic sensor networks," in *Proc. IEEE NCM*, Gyeongju, South Korea, Sep. 2008, pp. 365–370.

[146] Y.-D. Chen, C.-Y. Lien, S.-W. Chuang, and K.-P. Shih, "DSSS: A TDMA-based MAC protocol with dynamic slot scheduling strategy for underwater acoustic sensor networks," in *Proc. MTS/IEEE OCEANS*, Santander, Spain, Jun. 2011, pp. 1–6.

[147] H.-J. Cho *et al.*, "Contention free MAC protocol based on priority in underwater acoustic communication," in *Proc. MTS/IEEE OCEANS*, Santander, Spain, Jun. 2011, pp. 1–7.

[148] J. R. Zhang, G. Qiao, B. Kuang, and C. Wang, "Conflict-free MAC protocol for regional underwater observation networks," in *Proc. China Nat. Doctoral Acad. Forum Inf. Commun. Technol.*, Beijing, China, Aug. 2013, pp. 1–7.

[149] Y. B. Zhu *et al.*, "Toward practical MAC design for underwater acoustic networks," in *Proc. IEEE INFOCOM*, Turin, Italy, Apr. 2013, pp. 683–691.

[150] P. Hegde, M. Meghashree, S. S. Bhat, and L. K. Kumar, "A self adaptive MAC layer and routing layer framework for delay-tolerent underwater wireless sensor networks," in *Proc. IEEE Int. Adv. Comput. Conf. (IACC)*, Bengaluru, India, Jun. 2015, pp. 440–443.

[151] N. Chirdchoo, W.-S. Soh, and K. C. Chua, "RIPT: A receiver-initiated reservation-based protocol for underwater acoustic networks," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 9, pp. 1744–1753, Dec. 2008.

[152] H.-H. Ng, W.-S. Soh, and M. Motani, "ROPA: A MAC protocol for underwater acoustic networks with reverse opportunistic packet appending," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Sydney, NSW, Australia, Apr. 2010, pp. 1–6.

[153] T. S. Hu and Y. S. Fei, "DSH-MAC: Medium access control based on decoupled and suppressed handshaking for long-delay underwater acoustic sensor networks," in *Proc. IEEE Conf. Local Comput. Netw. (LCN)*, Sydney, NSW, Australia, Oct. 2013, pp. 523–531.

[154] P. Xie and J.-H. Cui, "R-MAC: An energy-efficient MAC protocol for underwater sensor networks," in *Proc. Int. Conf. Wireless Algorithms Syst. Appl. (WASA)*, Chicago, IL, USA, Aug. 2007, pp. 187–198.

[155] S. A. Samad, S. K. Shenoy, G. S. Kumar, and P. R. S. Pillai, "RMAC-M: Extending the R-MAC protocol for an energy efficient, delay tolerant underwater acoustic sensor network application with a mobile data mule node," in *Proc. SYMPOL*, Kochi, India, Nov. 2011, pp. 217–223.

[156] M. Q. Liu, W. K. Huang, L. F. Qian, and S. L. Zhang, "An improved R-MAC based MAC protocol for underwater acoustic networks," in *Proc. IEEE Int. Conf. Signal Process. Commun. Comput. (ICSPCC)*, Hong Kong, Aug. 2016, pp. 1–6.

[157] Z. Peng, Y. Zhu, Z. Zhou, Z. Guo, and J.-H. Cui, "COPE-MAC: A contention-based medium access control protocol with parallel reservation for underwater acoustic networks," in *Proc. MTS/IEEE OCEANS*, Sydney, NSW, Australia, May 2010, pp. 1–10.

[158] M. Zhu *et al.*, "UPMAC: A localized load-adaptive MAC protocol for underwater acoustic networks," *IEEE Sensors J.*, vol. 16, no. 11, pp. 4110–4118, Jun. 2016.

[159] O. Kebkal, M. Komar, and K. Kebkal, "D-MAC: Hybrid media access control for underwater acoustic sensor networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Capetown, South Africa, May 2010, pp. 1–5.

[160] F. Dou, Z. Jin, Y. Su, and J. Liu, "WSF-MAC: A weight-based spatially fair MAC protocol for underwater sensor networks," in *Proc. Cons. Electron. Commun. Netw. (CECNet)*, Yichang, China, Apr. 2012, pp. 3708–3711.

[161] A. A. Syed, W. Ye, and J. Heidemann, "T-Lohi: A new class of MAC protocols for underwater acoustic sensor networks," in *Proc. IEEE INFOCOM*, Phoenix, AZ, USA, Apr. 2008, pp. 789–797.

[162] Y. B. Zhu, Z. Peng, J.-H. Cui, and H. Chen, "Toward practical MAC design for underwater acoustic networks," *IEEE Trans. Mobile Comput.*, vol. 14, no. 4, pp. 872–886, Apr. 2015.

[163] S. Bandyopadhyay and E. J. Coyle, "An energy efficient hierarchical clustering algorithm for wireless sensor networks," in *Proc. IEEE INFOCOM*, San Francisco, CA, USA, Apr. 2003, pp. 1713–1723.

[164] M. A. Luque-Nieto, J. M. Moreno-Roldan, J. Poncela, and P. Otero, "Reliable transmissions in fair STDMA underwater sensor networks," in *Proc. Int. Conf. Comput. Sustain. Glob. Develop. (INDIACom)*, New Delhi, India, Mar. 2015, pp. 1285–1289.

[165] A. A. Syed, W. Ye, and J. Heidemann, "Comparison and evaluation of the T-Lohi MAC for underwater acoustic sensor networks," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 9, pp. 1731–1743, Dec. 2008.

[166] D. B. Kilfoyle, J. C. Preisig, and A. B. Baggeroer, "Spatial modulation experiments in the underwater acoustic channel," *IEEE J. Ocean. Eng.*, vol. 30, no. 2, pp. 406–415, Apr. 2005.

[167] L. Cimini, "Analysis and simulation of a digital mobile channel using orthogonal frequency division multiplexing," *IEEE Trans. Commun.*, vol. 33, no. 7, pp. 665–675, Jul. 1985.

[168] R. Bassoli, H. Marques, J. Rodriguez, K. W. Shum, and R. Tafazolli, "Network coding theory: A survey," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 4, pp. 1950–1978, 4th Quart., 2013.

[169] L. C. Kou and T. Melodia, "Medium access control for underwater acoustic sensor networks with MIMO links," in *Proc. ACM Int. Conf. Model. Anal. Simulat. Wireless Mobile Syst.*, Tenerife, Spain, Oct. 2009, pp. 204–211.

[170] Y. Luo, L. Pu, Z. Peng, Z. Zhou, and J.-H. Cui, "CT-MAC: A MAC protocol for underwater MIMO based network uplink communications," in *Proc. ACM Int. Conf. Underwater Netw. Syst. (WUWNet)*, Los Angeles, CA, USA, Nov. 2012, Art. no. 23.

[171] J. M. Yan, R. Xu, D. Q. Wang, H. B. Chen, and X. Hu, "Study on MC-CDMA for underwater acoustic networks," in *Proc. Int. Conf. Comput. Sci. Softw. Eng.*, vol. 3. Hubei, China, Dec. 2008, pp. 614–617.

[172] Z. Zhou, S. Le, and J. H. Cui, "An OFDM based MAC protocol for underwater acoustic networks," in *Proc. ACM Int. Conf. Underwater Netw. Syst. (WUWNet)*, Woods Hole, MA, USA, Sep. 2010.

[173] Y. L. Yin, S. Roy, and P. Arabshahi, "A modified CSMA/CA protocol for OFDM underwater networks: Cross layer design," in *Proc. ACM Int. Conf. Underwater Netw. Syst. (WUWNet)*, Arlington, VA, USA, Oct. 2015, pp. 1–8.

[174] Z. Y. Guan, T. Melodia, and D. F. Yuan, "Stochastic channel access for underwater acoustic networks with spatial and temporal interference uncertainty," in *Proc. ACM Int. Conf. Underwater Netw. Syst. (WUWNet)*, Los Angeles, CA, USA, Nov. 2012, Art. no. 8.

[175] R. Diamant, P. Casari, and M. Zorzi, "A TDMA-based MAC protocol exploiting the near-far effect in underwater acoustic networks," in *Proc. MTS/IEEE OCEANS*, Shanghai, China, Apr. 2016, pp. 1–5.

[176] S. C. Jiang, F. Liu, and S. M. Jiang, "Distance-alignment based adaptive MAC protocol for underwater acoustic networks," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Doha, Qatar, Apr. 2016, pp. 1–6.

[177] L. Zheng and L. Cai, "Flipped diversity ALOHA in wireless networks with long and varying delay," in *Proc. IEEE Glob. Telecommun. Conf. (GLOBOCOM)*, Kathmandu, Nepal, Dec. 2011, pp. 1–5.

[178] Q. C. Ren and X. Z. Cheng, "Latency-optimized and energy-efficient MAC protocol for underwater acoustic sensor networks: A cross-layer approach," *EURASIP J. Wireless Commun. Netw.*, vol. 2010, no. 1, Apr. 2010, Art. no. 323151.

[179] Z. Q. Qin *et al.*, "A joint duty cycle and network coding MAC protocol for underwater wireless sensor networks," in *Proc. IEEE Conf. Comput. Commun. Netw. (ICCCN)*, Paris, France, Aug. 2016, pp. 1–9.

[180] Y. Su, Y. Zhu, H. Mo, J.-H. Cui, and Z. Jin, "UPC-MAC: A power control MAC protocol for underwater sensor networks," in *Proc. Int. Conf. Wireless Algorithms Syst. Appl. (WASA)*, Zhangjiajie, China, Aug. 2013, pp. 377–390.

[181] Y.-D. Chen, C.-Y. Lien, Y.-S. Fang, and K.-P. Shih, "TLPC: A two-level power control MAC protocol for collision avoidance in underwater acoustic networks," in *Proc. MTS/IEEE OCEANS*, Bergen, Norway, Jun. 2013, pp. 1–6.

[182] Y. Han, Y. S. Fei, and A. Ding, "SMARP: A stochastic MAC protocol with randomized power control for underwater sensor networks," in *Proc. Annu. Commun. Soc. Conf. Sensor Mesh Ad Hoc Commun. Netw. (SECON)*, London, U.K., Jun. 2016, pp. 1–9.

[183] Y. Luo, L. Pu, Z. Peng, Y. Zhu, and J.-H. Cui, "RISM: An efficient spectrum management system for underwater cognitive acoustic networks," in *Proc. Annu. Commun. Soc. Conf. Sensor Mesh Ad Hoc Commun. Netw. (SECON)*, Singapore, Jun./Jul. 2014, pp. 414–422.

[184] Y. Luo, L. Pu, Z. Peng, and J.-H. Cui, "Dynamic control channel MAC for underwater cognitive acoustic networks," in *Proc. IEEE INFOCOM*, San Francisco, CA, USA, Apr. 2016, pp. 1–9.

[185] X. Zhang, Q. X. Zhu, and J. Q. Wang, "Efficient MAC-layer spectrum sensing scheme over underwater cognitive acoustic networks," in *Proc. ACM Int. Conf. Underwater Netw. Syst. (WUWNet)*, Shanghai, China, Oct. 2016, Art. no. 36.

[186] O. O. Aldawibi, B. S. Sharif, and C. C. Tsimenidis, "Distance awareness scheduling for single-hop underwater ad-hoc network," in *Proc. MTS/IEEE OCEANS*, Bremen, Germany, May 2009, pp. 1–6.

[187] K. Kredo, II, and P. Mohapatra, "Distributed scheduling and routing in underwater wireless networks," in *Proc. IEEE Glob. Telecommun. Conf. (GLOBOCOM)*, Miami, FL, USA, Dec. 2010, pp. 1–6.

[188] C. Li, Y. J. Xu, B. Y. Diao, Q. Wang, and Z. L. An, "DBR-MAC: A depth-based routing aware MAC protocol for data collection in underwater acoustic sensor networks," *IEEE Sensors J.*, vol. 16, no. 10, pp. 3904–3913, May 2016.

[189] X. Su, S. Chan, and M. Bandai, "A cross-layer MAC protocol for underwater acoustic sensor networks," *IEEE Sensors J.*, vol. 16, no. 11, pp. 4083–4090, Jun. 2016.

[190] L.-C. Kuo and T. Melodia, "Distributed medium access control strategies for MIMO underwater acoustic networking," *IEEE Trans. Wireless Commun.*, vol. 10, no. 8, pp. 2523–2533, Aug. 2011.

[191] S. M. Jiang, "A logical MIMO MAC approach for uplink access control in centralized wireless networks," in *Proc. IEEE Int. Conf. Commun. Syst. (ICCS)*, Guangzhou, China, Nov. 2008, pp. 1130–1134.

[192] S. M. Jiang, *Future Wireless and Optical Networks: Networking Modes and Cross-Layer Design*. London, U.K.: Springer, 2012.

[193] S. Hara and R. Prasad, "Overview of multicarrier CDMA," *IEEE Commun. Mag.*, vol. 35, no. 12, pp. 126–133, Dec. 1997.

[194] S. C. Jiang, F. Liu, S. M. Jiang, and X. Geng, "A feasible distance aligned structure for underwater acoustic X networks with two receivers," *IEICE Trans. Fundam. Electron. Commun. Comput. Sci.*, vol. E100-A, no. 1, pp. 332–334, Jan. 2017.

[195] F. Liu, S. C. Jiang, S. M. Jiang, and C. G. Li, "DoF achieving propagation delay aligned structure for K X 2 X channels," *IEEE Commun. Lett.*, vol. 21, no. 4, pp. 897–900, Apr. 2017.

[196] Z. J. Bao, F. Liu, S. M. Jiang, and S. C. Jiang, "DoF-achieving distance-aligned structure for layered underwater acoustic 2x3x3 X networks," in *Proc. ACM Int. Conf. Underwater Netw. Syst. (WUWNet)*, Shanghai, China, Oct. 2016, Art. no. 39.

[197] Y. Su, Y. Zhu, H. Mo, J.-H. Cui, and Z. Jin, "A joint power control and rate adaptation MAC protocol for underwater sensor networks," *Ad Hoc Netw.*, vol. 26, pp. 36–49, Mar. 2015.

[198] Y. Luo, L. Pu, M. Zuba, Z. Peng, and J.-H. Cui, "Challenges and opportunities of underwater cognitive acoustic networks," *IEEE Trans. Emerg. Topics Comput.*, vol. 2, no. 2, pp. 198–211, Jun. 2014.

[199] Y. Luo *et al.*, "Receiver-initiated spectrum management for underwater cognitive acoustic network," *IEEE Trans. Mobile Comput.*, vol. 16, no. 1, pp. 198–212, Jan. 2017.

[200] S. Gollakota and D. Katabi, "Zigzag decoding: Combating hidden terminals in wireless networks," in *Proc. ACM SIGCOMM*, New York, NY, USA, Aug. 2008, pp. 159–170.

[201] L. Zheng and L. Cai, "AFDA: Asynchronous flipped diversity ALOHA for emerging wireless networks with long and heterogeneous delay," *IEEE Trans. Emerg. Topics Comput.*, vol. 3, no. 1, pp. 64–73, Mar. 2015.

[202] Q. Ren and Q. Liang, "Asynchronous energy-efficient MAC protocols for wireless sensor networks," in *Proc. IEEE Mil. Commun. Conf. (MILCOM)*, Atlantic City, NJ, USA, Oct. 2005, pp. 1850–1856.

[203] H. Yan, Z. J. Shi, and J.-H. Cui, "DBR: Depth-based routing for underwater sensor networks," in *Proc. IFIP Netw. Conf.*, Singapore, May 2008, pp. 72–86.

[204] B. Sklar, *Digital Communications: Fundamentals and Applications*, 2nd ed. Upper Saddle River, NJ, USA: Prentice-Hall, 2002.

[205] J. Rice *et al.*, "Evolution of seaweb underwater acoustic networking," in *Proc. MTS/IEEE OCEANS*, vol. 3. Providence, RI, USA, Sep. 2000, pp. 2007–2017.

[206] J.-K. Yeo, Y.-K. Lim, and H.-H. Lee, "Modified MAC (media access control) protocol design for the acoustic-based underwater digital data communication," in *Proc. IEEE Int. Symp. Ind. Electron.*, vol. 1. Busan, South Korea, Jun. 2001, pp. 364–368.

[207] K. Y. Foo, P. R. Atkins, T. Collins, C. Morley, and J. Davies, "A routing and channel-access approach for an ad hoc underwater acoustic network," in *Proc. MTS/IEEE OCEANS*, vol. 2. Kobo, Japan, Nov. 2004, pp. 789–795.

[208] S. Shahabudeen and M. A. Chitre, "Design of networking protocols for shallow water peer-to-peer acoustic networks," in *Proc. MTS/IEEE OCEANS*, vol. 1. Brest, France, Jun. 2005, pp. 628–633.

[209] N.-Y. Yun *et al.*, "Sync MAC protocol to control underwater vehicle based on underwater acoustic communication," in *Proc. Embedded Ubiquitous Comput. (EUC)*, Melbourne, VIC, Australia, Oct. 2011, pp. 452–456.

[210] S. C. Dhongdi, K. R. Anupama, R. Agrawal, and L. J. Gudino, "Simulation and testbed implementation of TDMA MAC on underwater acoustic sensor network," in *Proc. Nat. Conf. Commun. (NCC)*, Mumbai, India, Mar. 2015, pp. 1–6.

[211] V. Rodoplu, A. A. Gohari, and W. Tang, "Towards automated design of MAC protocols for underwater wireless networks," in *Proc. ACM Int. Workshop Underwater Netw. (WUWNet)*, San Francisco, CA, USA, Sep. 2008, pp. 67–74.

[212] V. D. Valerio, F. L. Presti, C. Petrioli, L. Picari, and D. Spaccini, "A self-adaptive protocol stack for underwater wireless sensor networks," in *Proc. MTS/IEEE OCEANS*, Shanghai, China, Apr. 2016, pp. 1–8.

[213] J. Gibson, A. Larraza, J. Rice, K. Smith, and G. Xie, "On the impacts and benefits of implementing full-duplex communications links in an underwater acoustic network," in *Proc. Int. Mine Symp.*, Monterey, CA, USA, Oct. 2002, pp. 204–213.

[214] L. F. M. Vieira, J. Kong, U. Lee, and M. Gerla, "Analysis of ALOHA protocols for underwater acoustic sensor networks," in *Proc. ACM Int. Workshop Underwater Netw. (WUWNet)*, Los Angeles, CA, USA, Sep. 2006.

[215] S. De, P. Mandal, and S. S. Chakraborty, "On the characterization of ALOHA in underwater wireless networks," *Math. Comput. Model.*, vol. 53, nos. 11–12, pp. 2093–2107, Jun. 2011.

[216] R. Y. Su, R. Venkatesan, and C. Li, "Acoustic propagation properties of underwater communication channels and their influence on the medium access control protocols," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Ottawa, ON, Canada, Jun. 2012, pp. 5015–5019.

[217] J. H. Gibson, G. G. Xie, Y. Xiao, and H. Chen, "Analyzing the performance of multi-hop underwater acoustic sensor networks," in *Proc. OCEANS Europe*, Aberdeen, U.K., Jun. 2007, pp. 1–6.

[218] Y. Xiao, Y. P. Zhang, J. H. Gibson, and G. G. Xie, "Performance analysis of p-persistent ALOHA for multi-hop underwater acoustic sensor networks," in *Proc. Int. Conf. Embedded Softw. Syst. (ICESS)*, Zhejiang, China, May 2009, pp. 305–311.

[219] Y. P. Zhang, "Performance of p-persistent slotted ALOHA for underwater sensor networks," in *Proc. Int. Conf. Comput. Netw. Commun. (ICNC)*, Honolulu, HI, USA, Feb. 2014, pp. 583–587.

[220] J. Paul, T. A. Wheatley, and C. R. Benson, "Effect of buffering on the throughput of ALOHA," in *Proc. MTS/IEEE OCEANS*, Monterey, CA, USA, Sep. 2016, pp. 1–6.

[221] P. Xie and J.-H. Cui, "Exploring random access and handshaking techniques in large-scale underwater wireless acoustic sensor networks," in *Proc. MTS/IEEE OCEANS*, Boston, MA, USA, Sep. 2006, pp. 1–6.

[222] S. Climent, A. Sanchez, J. V. Capella, and J. J. Serrano, "Simulating MAC protocols under real underwater sensor networks assumptions," in *Proc. ACM Int. Conf. Underwater Netw. Syst. (WUWNet)*, Los Angeles, CA, USA, Nov. 2012, p. 34.

[223] S. Shahabudeen and M. Motani, "Short paper: Performance analysis of a MACA based protocol for adhoc underwater networks," in *Proc. ACM Int. Workshop Underwater Netw. (WUWNet)*, Berkeley, CA, USA, Nov. 2009, p. 8.

[224] S. Shahabudeen, M. Motani, and M. Chitre, "Analysis of a high-performance MAC protocol for underwater acoustic networks," *IEEE J. Ocean. Eng.*, vol. 39, no. 1, pp. 74–89, Jan. 2014.

[225] P. Casari, B. Tomasi, and M. Zorzi, "A comparison between the Tone–Lohi and slotted FAMA MAC protocols for underwater networks," in *Proc. MTS/IEEE OCEANS*, Quebec City, QC, Canada, Sep. 2008, pp. 381–384.

[226] C. Petrioli, R. Petroccia, and J. Potter, "Performance evaluation of underwater MAC protocols: From simulation to at-sea testing," in *Proc. MTS/IEEE OCEANS*, Santander, Spain, Jun. 2011, pp. 1–10.

[227] R. Petroccia, C. Petrioli, and J. Potter, "Performance evaluation of underwater medium access control protocols: At-sea experiments," *IEEE J. Ocean. Eng.*, to be published.

[228] S. Basagni, C. Petrioli, R. Petroccia, and M. Stojanovic, "Choosing the packet size in multi-hop underwater networks," in *Proc. MTS/IEEE OCEANS*, Sydney, NSW, Australia, May 2010, pp. 1–9.

[229] M. Stojanovic, "Optimization of a data link protocol for an underwater acoustic channel," in *Proc. MTS/IEEE OCEANS*, Brest, France, Sep. 2005, pp. 68–73.

[230] N. Chirdchoo, W.-S. Soh, and K. C. Chua, "MU-sync: A time synchronization protocol for underwater mobile networks," in *Proc. ACM Int. Workshop Underwater Netw. (WUWNet)*, San Francisco, CA, USA, Sep. 2008, pp. 35–42.

[231] J. Liu *et al.*, "Mobi-sync: Efficient time synchronization for mobile underwater sensor networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 24, no. 2, pp. 406–416, Feb. 2013.

[232] S. M. Jiang, J. Q. Rao, D. J. He, X. H. Ling, and C. C. Ko, "A simple distributed PRMA for MANETs," *IEEE Trans. Veh. Technol.*, vol. 51, no. 2, pp. 293–305, Mar. 2002.

[233] V. D. Valerio, C. Petrioli, L. Pescosolido, and M. V. D. Shaar, "A reinforcement learning-based data-link protocol for underwater acoustic communications," in *Proc. ACM Int. Conf. Underwater Netw. Syst. (WUWNet)*, Arlington, VA, USA, Oct. 2015, Art. no. 2.

Shengming Jiang (A'96–M'00–SM'07) received the bachelor's degree from Shanghai Maritime Institute, China, in 1988, the master's degree from the University of Paris VI, France, in 1992, and the doctoral degree from the University of Versailles Saint-Quentin-En-Yvelines, France, in 1995, all in computer science. He is a Professor and the Dean of the College of Information Engineering, Shanghai Maritime University. From 1988 to 1990, he was an Assistant Engineer with Nanjing Petrol Transportation Company, China. He was a Research Associate with the Department of Electrical and Electronic Engineering and the Computer Science Department, Hong Kong University of Science and Technology, from 1995 to 1997. He was a Technical Staff Member with the Centre for Wireless Communications, National University of Singapore, from 1997 to 2000, and a Senior Member of Technical Staff as well as the acting Leader of the Network Strategic Group from 2001 to 2003. He was an Associate Lead Scientist and the Leader of the End-to-End QoS Laboratory, Institute for Infocomm Research, Singapore, from 2003 to 2004. He was a Principal Lecturer with the Faculty of Advanced Technology, University of Glamorgan (currently, the University of South Wales), U.K., from 2007 to 2009. He was a Professor with the School of Electronic and Information Engineering, South China University of Technology from 2004 to 2013.

His research interests include networking issues in both wired and wireless networks as well as mobile computing with over 25 years of international Research and Development experiences in France, Hong Kong, Singapore, U.K., and China, respectively. He is currently leading in the research of marine Internet. He has published over 140 papers on related areas, some of which were published in prestigious international journals and conferences, such as the IEEE/ACM TRANSACTIONS ON NETWORKING, the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, the IEEE TRANSACTIONS ON COMMUNICATIONS, the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, ACM SIGCOMM *Computer Communication Review*, and IEEE INFOCOM.