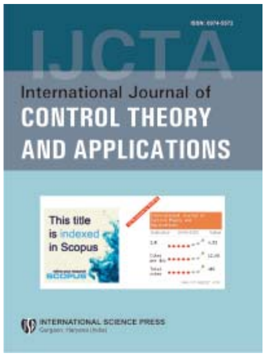

International Journal of Control Theory and Applications

ISSN : 0974–5572

Volume 9 • Number 42 • 2016

Future Trends and Challenges in MAC Layers of Underwater Acoustic Networks

Madhusudana Rao Kothari[a] and Mrinal Sarvagya[a]

[a]RITM, Visvesvaraya Technological University Rukmini Knowledge Park, Kattigenahalli, Yelahanka, Bangalore – 560064, India

E-mail: madhu77.kothari@gmail.com, mrinalsarvgya@gmail.com

Abstract: The Underwater Acoustic Sensor Networks (UASN) is a novel networking paradigm to expose wireless environment in the characteristics of mobile .The architecture of UASN is vulnerable to various issues such as large propagation delays, floating of sensor nodes limited link capacity multiple message recipients due to the reflection on sea ground and sea surface. In addition to these variables, UASNs nodes are powered by battery, the energy-limited nodes are highly difficult to deploy and recycle.MAC protocol plays a critical role in UASNs, determining the performance of UASN network, the research Institutions have continuously proposed the MAC protocols required for underwater acoustic environment and verified their performances using experiments with real time measured data and Simulations.

This survey aims to provide a comprehensive overview of the excellent researches in a decade on underwater Acoustic networks, focusing on the lower layers of the communication stack, and envisions future trends and challenges. It analyzes the current state-of-the-art on the physical, medium access control and Cross layers. It summarizes their security threads and surveys the currently proposed studies. This paper discusses the recent developments for the further advances in underwater networks research range from efficient, low-power algorithms and modulations to intelligent, energy-aware medium access control protocols.

Keyword: *Underwater acoustic sensor network, Energy Efficient, UASN Physical layer, UASN cross-layer design and UASN Medium access control protocol.*

1. INTRODUCTION

UASNs have emerged for efficiently exploring and observing the ocean and these consists of number of sensors and vehicles that are deployed to perform monitoring tasks collectively for a given area. The collaborative monitoring of tasks will be achieved by organising sensors and vehicles in an autonomous network which can adapt to the characteristics of the ocean environment. The applications of underwater acoustic sensor networks as described below [56].

1. **Ocean sampling networks :** Networks consisting of sensors and vehicles can perform synoptic, cooperative adaptive sampling of the 3D coastal ocean environment, Environmental monitoring. UASNs can perform chemical, biological and nuclear pollution monitoring.

2. **Explorations of undersea mines :** UASNs can help detecting underwater oilfields or reservoirs, determine routes for laying undersea cables and assist in exploration for valuable minerals.

3. **Prevention of Disasters :** Sensor networks that measure seismic activity from remote locations can provide tsunami warnings to coastal areas, or investigate the effects of submarine earthquakes.

4. **Navigation assistance :** Sensors can be used to identify hazards on the seabed, locate dangerous rocks or shoals in shallow waters, mooring positions, submerged wrecks, and to perform bathymetry profiling.

5. **Distributed tactical surveillance:** AUVs and fixed underwater sensors can collectively monitor areas for surveillance, reconnaissance, targeting and intrusion detection systems.

6. **Mine reconnaissance:** The simultaneous operations of multiple AUVs with acoustic and optical sensors can be used to perform rapid environmental assessment and detect mine-like objects.

The design of an efficient Medium Access Control (MAC) protocol for UASNs is needed to provide high throughput with energy- efficient way. It has paramount importance due to the MAC layer protocol coordinates access of the sensor nodes to the shared wireless medium. The nodes in a network will share the common broadcast channel using A MAC protocol. The main tasks of a MAC protocol are the prevention of simultaneous transmissions or resolving transmission collisions of data packets, while providing energy efficiency, low channel access delays and fairness among the nodes in a network. In presence of a harsh underwater acoustic channel, MAC layer protocol in UASNs has much importance on the network utilization.

There has been a tremendous amount of research on the design and implementation of UASNs [52-57] with various aspects, for example medium access, network, transport, localization, synchronization protocols, and are not just for MAC protocols. There are a few surveys on MAC protocols in UASNs [58, 59] that have been conducted to summarize the variations of designs and implementations. The survey in [58] has reviewed several early MAC protocols based on their medium access strategies and highlighted the issues inherited from physical layer, which should be considered in the design of MAC protocol. The work in [59] has analysed some MAC protocols in UASNs on the algorithm, advantages and disadvantages for each protocol.

Meanwhile, it has presented a MAC protocol that can be used in the UASNs under the shallow water environment. This paper presents a comprehensive survey on the state-of-the art MAC protocols for UASNs. It provides a more detailed classification on the basics of protocol together with the challenges to the design of MAC protocols. The MAC protocols in UASNs are described with the following features or contributions.

1. The influences of underwater acoustic environment and the challenges of design MAC Protocols in UASNs will be addressed.

2. The state-of-the-art MAC protocols and the classification of them based on the similarities and differences on the medium access approaches will be presented.

3. A comprehensive and comparative investigation on some MAC protocols for UASNs will be provided.

4. Some open research issues will be summarized for further development.

In Section II, the challenges to the design of MAC protocols were described. In Section III, we describe the contention free MAC protocols including FDMA-based, TDMA-based, and CDMA-based contention-free MAC schemes. Schedule based TDMA is explained in Section IV. Further to this, the contention-Based MAC protocols were described in Section V. The Hand shaking based protocol is explained in section VI. The hybrid MAC protocols were described in section VII. Cross Layer Protocols were detailed in section VIII. Finally, we identify the open research issues with a conclusion in Section IX.

2. CHALLENGES TO THE DESIGN OF MAC PROTOCOLS

USAN MAC layer protocol is critical due to its important role to achieve the quality of service (QoS) in UASNs. This makes a detailed study on different aspects of the design of MAC protocol to evaluate the performance of existing MAC protocols. The radio waves will travel over shorter distances due to the attenuation in underwater acoustic environment. Optical signals are not only rapidly absorbed by water but also usage is difficult due to the optical scattering caused by suspending particles and planktons are significant. So the optical signals cannot travel far in adverse conditions [53]. Because of acoustic waves have less attenuation they are able to travel farther distances than radio waves and optical waves [60]. Due to this UASNs utilize acoustic waves to have information exchange. This section describes the underwater acoustic environment and identifies the major challenges to the design of MAC protocols for UASNs.

2.1. Features of the Underwater Acoustic Medium

The properties of underwater acoustic medium go through the severe situation for MAC protocol design compared to MAC design for terrestrial networks [58, 61].

1. **High and Variable Propagation Delay:** The propagation speed of sound in underwater is about 1500m/s [62]. Due to this the propagation delay in underwater is five orders of magnitude higher than that of radio frequency (RF) terrestrial channels and varies extremely variable due to temperature, salinity and depth of water. These critical delay variations of underwater communications causes the implications on design of MAC protocols.

2. **Limited Bandwidth and Data Rate:** Because of high environmental noise at low medium frequencies lower than 1 kHz and be or high-power absorption at high frequencies greater than 50 kHz, the available acoustic bandwidth depends on the transmission distance [52]. Only tens of kHz will be available at a few kilometres, while few kHz may be available at tens of kilometres. Available acoustic modems work at the frequencies from merely a few Hz to tens of kHz and the data rate for underwater acoustic sensors can hardly exceed 100 kbps. The available limited bandwidth of acoustic channels comparing with Radio channel requires careful design of coding schemes and MAC protocols used in UASNs

3. **Noise:** UASN environment noises include man-made noise due to mainly machinery like pumps and ambient noise due to seismic and biological phenomena.

4. **Energy Consumption:** The acoustic transceivers under water have transmission powers in the order of magnitude higher than that of the terrestrial devices with a higher ratio of transmit to receive power, so the protocols which utilize the acoustic radio effectively become much more important in UASNs [63]. Batteries are energy constrained and cannot be recharged easily.

5. **High Bit Error Rates:** The underwater channel is severely impaired due to multi-path and fading. This Multi-path propagation causes Inter Symbol Interference (ISI) by degrading of the acoustic communication signals. Higher value of ISI may result in higher bit error rates there by temporary losses of connectivity, shadow zones, can be experienced. The Shadow zone that has no acoustic signal existing in it is mainly caused by long paths and the frequency-dependent attenuation. These parameters throw challenge at MAC protocol to provide reliable connection in such a harsh propagation conditions.

6. **Unstable network topology:** UASN nodes contain surface buoys, subsurface buoys and seabed buoys. The node location is severely changed by ocean currents and some nodes would exhaust and lose track addition limited and asymmetrical energy consumption, resulting in the unstable network topology in UASNs.

The main differences that impacts on the design of MAC protocols are given in Table I. the application of MAC protocols used for UASNs will lead to inefficient results due to these characteristics. It is necessary to develop MAC protocols suitable taking all the characteristics into account.

Table 1
Main differences between underwater acoustic networks and terrestrial radio networks

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

2.2. Challenges to the Design of MAC Protocols for UASNs

Selection of suitable MAC protocol is a major challenge for the deployment of UASNs. The required optimal underwater MAC protocol should provide higher network throughput, and lower energy consumption, taking into account of the harsh characteristics of the underwater acoustic environment. This section describes the challenges which have to be addressed in the design of UASNs MAC protocols [58].

1. **Network Topology and Deployment in UASNs:** The MAC protocol performance of UASNs is highly dependable on the deployment of underwater nodes which could be sparse or dense. Event readings of sparsely deployed nodes would be highly uncorrelated because the sensors nodes can monitor as well as communicate at long distance due to the availability of long range acoustic modems.
2. **Synchronization:** Synchronization is a critical challenge in the design of MAC protocols because the MAC protocols such as the duty cycling approach work generally based on the time synchronization of the nodes. Without accurate synchronization, the duty cycling approach cannot ensure effective operation of sensor networks by handling time uncertainty between sensor nodes. This is due to the fact that the propagation delay is much higher and changes from time to time.
3. **Hidden Node and Exposed Node Problem:** The problems of hidden nodes and exposed nodes arise more specifically in contention-based collision avoidance MAC protocols. A situation of a hidden node occurs when one node cannot sense one or more nodes that can interfere with its transmission. A situation of an exposed node occurs when a station delays transmission because of another overheard transmission that would not collide with it. In the first case, there will be collision and the nodes have to keep attempting for successful transmission.
4. **High Delay Associated in Handshaking:** The conventional handshaking schemes can reduce the effect of hidden terminal and exposed terminal, which need time and energy to exchange control information. The exchange of control information takes the most of the communication time. It results in that the nodes have not much time for the payload delivery. The channel utilization rate is very low. The handshaking schemes have high propagation delay, which is a big challenge to the design of efficient protocols.
5. **Power Waste in Collision:** It is observed that a node consumes more power on transmission than on reception. The ratio of power required for reception to transmission is typically 1/125 [54]. Furthermore, the ratio becomes worse if collisions frequently appear due to the lack of an appropriate collision avoidance mechanism. So, the requirement of a MAC protocol should be able to avoid or minimize collisions.

6. **Near-Far Effect:** The transmission power should be selected at the transmitter so that the signals transmitted from the transmitter to the intended receiver should be correctly received with the desired SNR which is neither lower nor higher than the required SNR. The near-far effect occurs when the signals received by a receiver from a sender near the receiver is stronger than the signals received from another sender located farther.

   There is an exemplified scenario illustrated in Fig.2 [64]. Nodes 1 and 3 are far away and therefore can transmit simultaneously without causing collisions. At node 2, the SNR level of the signals originated from node 1 is higher than that from node 3 due to the high level of noise produced by the signals coming from node 1. Therefore, although node 2 can receive both signals, it cannot decode the messages from node 3. The result is that node 1 is unintentionally screening the transmissions from node 3.

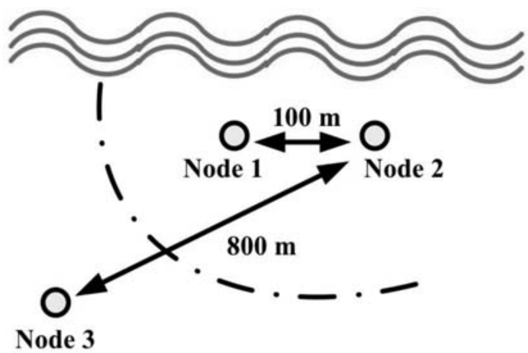

Figure 1: Illustration of the "Near-Far" Problem [86]

7. **Centralized Networking:** Communication in centralized network takes place between nodes through a central station .This makes it is not a suitable in UASNs over an acoustic channel due to single point of failure and the limited range of a single modem [57].

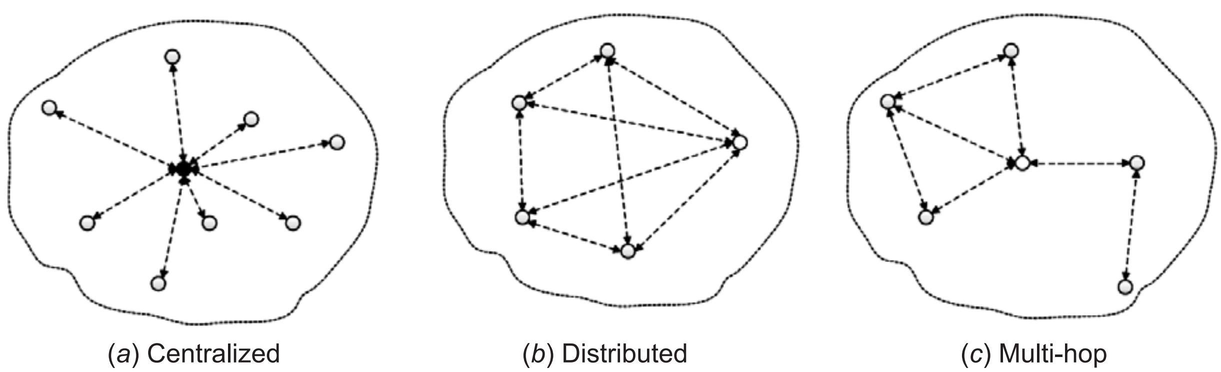

Figure 2: UASN topology structure diagram [87]

3. CLASSIFICATION OF MAC PROTOCOLS FOR UASNS

The classification of MAC protocols for UASNs in this paper is shown in Fig. 3. Introducing contention free MAC protocols and according to different multiple access techniques, such as frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA).The contention-based MAC protocols are divided random access , Reservation and random MAC protocols with handshaking. Most of the efforts in the design of the MAC protocols for UASNs have focused on the classification of handshaking MAC protocols, based on the number of channels used for data transmission. The hybrid MAC protocols will be introduced, which combine the advantages of the contention-free MAC and contention-based MAC protocols on demand. Finally, Cross layer protocols will bring more efficiency to MAC protocols.

3.1. Classification contention free based schemes

MAC protocols manage the transmission medium to avoid the collisions from unrequested signals in the medium. Because of the long propagation delays of underwater transmission the TDMA and CDMA based networks suffer from space uncertainty called space-time or spatio-temporal uncertainty [1].

Due to long propagation delays creates spatial unfairness [1] that causes nodes closer to the transmitter are able to gain access to the channel before nodes closer to the receiver.

The MAC Protocols will be contention-free and contention-based schemes. Contention free based scheme named Frequency Division Multiple Access (FDMA) by assigning the different frequency bands to all nodes, Time Division Multiple Access (TDMA) with different time slots to each node and Code Division Multiple Access (CDMA) by providing codes to different users in the network.

Contention-based MAC protocols will allocate random access to nodes with distributes transmissions with recovery mechanisms in case a collision occurs. Proposed classification protocols in Figure 3 are explained in the later part of this section, and their main properties are compared in Table 2. This table specifies the type of MAC protocol based TDMA , FDMA or CDMA or combination of these schemes.

3.2. Frequency-Division Multiple Access

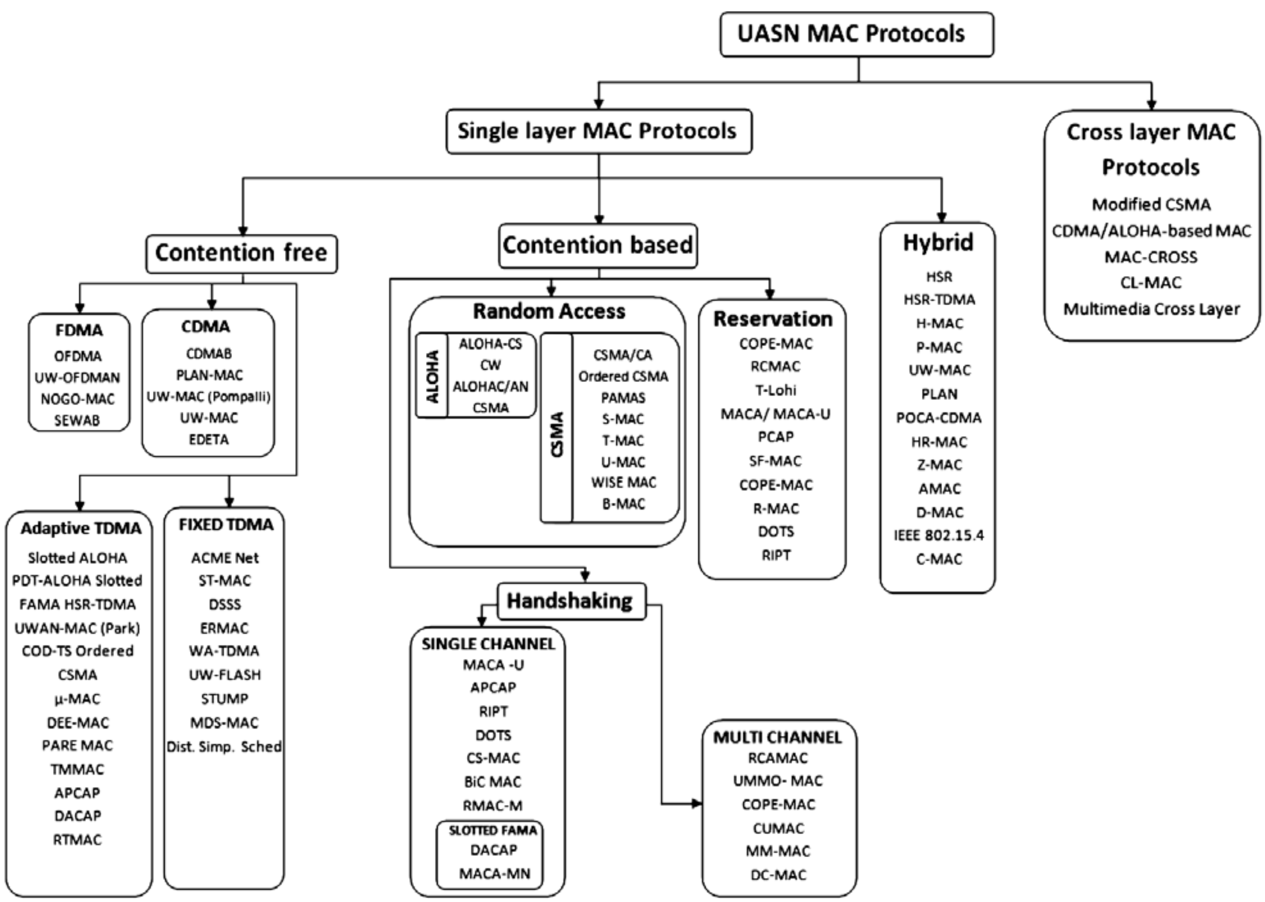

Figure 3: The Classification of MAC Protocols for UASNs [2][50][86][87]

Table 3
[50] Protocol classification and properties [86]

Category			*Protocol*	*Year*	*TDMA*		*CDMA*	*Random Access*	*Clustered*	*Routing*	*Handshaking*	*Requires*	
					Fixed	*Adaptive*						*Sync*	*Prop.Time*
FDMA-based			Saawab '98 and '99 (33)	1998	✓							✓	✓
CDMA-based			UWAN-MAC (Pom pih)(7)	2009			✓	✓					
			UW-MAC(8)	2010	✓		✓	✓	✓	✓		✓	✓
			EDETA(9)	2012	✓		✓		✓	✓		✓	✓
			HRMAC(156)	2013		✓	✓	✓	✓			✓	✓
Time based	Schedule based	Fixed TDMA	ST-MAC(12)	2009	✓							✓	✓
			STUMP-WR(13)	2010	✓					✓		✓	✓
			MDS-MAC(14)	2012	✓				✓	✓		✓	✓
			Distrib Simplified Sched(14)	2011	✓				✓	✓		✓	✓
		Adaptive TDMA	Slotted Aloha(17)	1975		✓		✓				✓	✓
			PDT-Aloha(18)	2011		✓		✓				✓	✓
			Slotted PAMA(19)	2007		✓		✓			✓	✓	✓
			HSR-TDMA(27)	2011		✓						✓	✓
			UWAN-MAC (Park)(28)	2007		✓		✓				✓	✓
			COD-TS(29)	2013		✓	✓	✓			✓	✓	
			Ordered CSMA(16)	2007	✓								✓
	Random based	Direct	Aloha/Aloha-CS[17]	1970				✓					
			CSMA[17]	1975				✓					
		Reservation	MACA/MACA-U[34]	2008				✓			✓		✓
			PCAP [35]	2007				✓			✓		
			SF-MAC[37]	2012				✓			✓		
			DACAP[37]	2007				✓			✓		
			FAMA[38]	1995				✓			✓		
			COPE-MAC[39]	2010				✓			✓		✓
			R-MAC[40]	2007				✓			✓		✓
			DOTS[41]	2010				✓			✓	✓	✓
			RIPT[42]	2008				✓			✓		✓
			T-Lohi[43]	2008				✓					

The different nodes in the FDMA scheme are a contention-free medium access that divides the available bandwidth into different frequency bands to transmit and receive at the same time while avoiding collisions. These frequency bands are planned to avoid collisions for each node is assigned with a receiving frequency when two or more nodes try to reach the same destination at the same time.

This scheme was used in the early phases of the Seaweb project [3]. For the communication between three clusters TDMA will be used and FDMA was used for inter-cluster communications. Because of the insufficient bandwidth, fading and multipath FDMA was considered to be unsuitable for underwater acoustic networks.

3.3. Code-Division Multiple Access

The use of CDMA in UASNs has been more useful due to its vulnerability of multi-path and Doppler effects [4]. In Direct Sequence (DS) CDMA systems, each node encodes its signal with a unique pseudorandom noise codeword (PN sequence) before transmitting. The transmitted signal is spread over a larger bandwidth as compared to the original non-spread bandwidth. This spread-spectrum technology that is being adopted by CDMA allows multiple nodes to transmit concurrently within the same time or frequency dimension, which are not achievable using TDMA or FDMA techniques. Hence, CDMA techniques are able to provide more capacity than other multiple access techniques due to their collision-free properties. The suseptablilty of CDMA to Doppler's effects and variable propagation delays, which are prevalent in UASNs. CDMA-based protocols aren't useful for USAN due to highly synchronized and effected for near far problem [5].

The binary codes will be used in CDMA to modulate the signal using a spread-spectrum technique. Different nodes will transmit using different codes in the CDMA network with low cross-correlation. Because of the anti-jamming feature of having difference in the codes from the other nodes sent in the same frequency band, the desired data will be received in the same network without collision. Unlike FDMA, this scheme will not undergo frequency selective fading it uses entire frequency band and due to transmission medium can be accessed at the same time by all users its is more advantageous than TDMA. The desired user payload will be reduced due to low cross-correlation implies long codes [6].

The available data rate per user (Vtx) depends on the code length (L) and the actual modem data rate (Vtxl):

$$\text{Vtx} = \text{Vtxl} / L \tag{1}$$

The code length (L) depends only on the number of different codes (N), as shown in below expression.

$$L = 4 \log_2 N - 1 \tag{2}$$

The proposed schemes using CDMA is as follows:

1. **CDMA and ALOHA:** As proposed by Pompili [7], the transmission power of the node will be calculated dynamically and spreads the code length for the efficient communication with the intended receiver. This spreading code is then sent using ALOHA without any sort of coding. The data packet is sent using the spreading code.

2. **Clustered based CDMA Networks:** This propose a cluster-based network [8] in which each cluster has its own CDMA spreading code assigned. Communication inside each cluster is executed by exchanging request-to-send (RTS) and clear-to-send (CTS) packets. The cluster heads communicate with the sink node using TDMA.

Each cluster uses its own CDMA spreading code [9] for intra-cluster communication. Transmissions inside the cluster are scheduled using TDMA. Instead of directly communicating to the sink node, cluster heads arrange themselves in a tree structure in order to send their collected data to the sink.

The hybrid reservation-based MAC protocol (HRMAC) [10] utilizes an adaptive TDMA along with CDMA spreading codes. Each node with data to transmit sends a notice packet with sender and destination IDs and data size to the cluster head. the cluster head computes a sending schedule with this information, and populates it. The nodes send their data packets in their assigned slots after receiving the transmission schedule. After this, the receivers of the data packets send a reply message back to the sender with the amount of data received. Due to non collision feature the CDMA codes are used for the notice and reply packets.

3.4. Time-Based Schemes

Protocols based on this scheme use the complete bandwidth for a certain amount of time. The multiple transmissions have to be distributed in time by scheduling and reserving the channel time prior to transmission or directly sending the data packet. Strategies to avoid collisions are as follows.

1. **Scheduled-based:** In this scheme the time interval or frame is divided between all nodes techniques are normally used:
    a) Each node in fixed TDMA is assigned a time period to transmit.
    b) Time periods of Adaptive TDMA are assigned on demand, either by dynamically assigning the slots by some coordinator or by allowing the nodes to contend for the slots.
2. **Random-based:** Selections of the transmission start and end times are arbitrary, and nodes directly compete for channel acquisition. This group of protocols can also be sub-divided into:
    a) Protocols in direct mode will send data directly without performing any channel reservation.
    b) Protocols in Reservation mode will reserve the channel using control packets before node transmits the actual data packet.

4. SCHEDULED-BASED SCHEMES

In the schedule-based protocols, each node is assigned a time period in which it is able to transmit. This technique requires synchronization between all nodes, which can be done using a synchronization algorithm [10]. In addition, in order to guarantee a contention-free communication, it might be necessary to include guard times. The duration of these guard times depends on the maximum propagation delay and the synchronization accuracy, which degrade the network performance.

There are basically two types of schedule-based protocols, fixed TDMA and adaptive TDMA. In fixed TDMA, each of these time periods is assigned to a node, and the node is only able to transmit during this time.

Given the large propagation delays in the underwater medium, it is possible that packets from two different nodes arrive successfully, even if the packets were transmitted at the same time [11]. Based on this, different approaches have been proposed that try to schedule the TDMA-based transmissions in such a way that they can overlap without conflicting at the intended receivers.

The proposed [12] spatial-temporal MAC (ST-MAC), which formulates the TDMA-based scheduling problem as a vertex-coloring problem. The algorithm constructs a spatial-temporal conflict graph describing the conflict delays among transmission links. Further to that, an optimal solution is proposed based on a mixed integer linear programming model, and a new approach is proposed to solve the vertex-colouring problem. The staggered TDMA underwater MAC protocol (STUMP) is a similar approach introduced in [13]. A set of TDMA scheduling constraints is derived, and the authors propose centralized and distributed algorithms in order to solve the scheduling problem. First it will determine the order of transmissions between the conflicting nodes. Once the order is fixed, the scheduling constraints become a system of difference equations, which is solved using the Bellman–Ford algorithm. In a subsequent work [84], the authors further improve their proposal by adding routing capabilities.

A recent alternative proposed in [14], is multi-dimensional scaling MAC (MDS-MAC). This protocol integrates time-synchronization, localization and communication scheduling for small underwater clusters. The operation of the protocol is divided into coordination and communication phases, which are repeated periodically. During the coordination phase, nodes perform range measurements in order to calculate the propagation delay between them and to achieve relative localization and time synchronization. At the beginning of the communication phase, the cluster head broadcasts the communication schedule and routing information. Afterwards, during the remainder of this communication period, all nodes within the network follow this schedule.

A clustering scheduling approach is described in [15]. Spatial-temporal communication scheduling is performed within clusters by the cluster head. The cluster heads forward the length of the complete schedule to a central scheduler, which assigns time to the different clusters. By allowing the cluster heads to schedule within the cluster, the central scheduler does not need to know the positions of all nodes within the network to guarantee a collision-free schedule. This reduces the otherwise very significant overhead of spatial-temporal communication scheduling.

Ordered CSMA [16] schedules transmissions through ordering. Every node in the transmission chain waits until it has detected the carrier of the preceding node in the schedule. After detecting the carrier, the node is allowed to transmit its data. By ordering the transmissions in such a way, collision-free transmissions are guaranteed.

On the other hand, adaptive TDMA protocols allow nodes to adaptively assign time periods on demand. This assignment can be done through contention and handshaking processes or by learning the transmission schedules of the neighbouring nodes.

In slotted aloha, as in pure aloha, nodes contend for the channel [17]. However, in slotted aloha, the transmission is deferred to the beginning of each time slot. Hence, each node is obliged to schedule the beginning of its transmissions at the beginning of each time slot. Nevertheless, because slots are not assigned as in pure TDMA, collisions may also occur if different nodes select the same slot to transmit. However, given the space uncertainty of the underwater acoustic medium, the performance of this protocol is degraded to that of pure aloha. In [18], the authors try to cope with this problem by adding extra guard time in the time slots, achieving 17%–100% better throughput results than the original slotted aloha in an underwater medium.

There is strict time synchronization is required TDMA based schemes. Collisions idle listening and over hearing are avoided due to scheduling. TDMA also solves the hidden terminal problem without extra message overhead because neighbouring nodes transmit at different time slots. Some of these schemes are explained.

1. **μ-MAC:** High sleep ratios are obtained while preserving the message latency and reliability at the acceptable level. In this, the contention period is used to organize a network and to initialize transmission sub-channels. The contention-free period is used to transfer data between nodes. The drawback in this protocol is the contention period incurs large overhead, and has to take place frequently. Furthermore, the knowledge of the traffic pattern has to be available [19].
2. **DEE-MAC :** In this protocol, energy consumption is reduced by forcing the idle listening nodes to sleep using synchronization performed at the cluster head. Each cluster is dynamically formed based on the remaining power as all nodes. DEE-MAC operations consist of rounds. Every round includes a cluster formation phase and a transmission phase.

   In the cluster formation phase, the node decides whether to become the cluster head based on its remaining power. The transmission phase comprises of a number of sessions and each session consists of a contention period and a data transmission period [20].
3. **PARE MAC:** This TDMA based MAC protocol is designed to save energy by limiting the impact of idle listening and traffic overhearing. Here a distributed scheduling solution is adopted to assign specific radio resources to each sensor node for reception and spreads the information of the assigned Reception Schedules to neighbouring nodes. The protocol decreases collisions and idle listening, but the control packet overhead is very large [21].

4. **TMMAC:** This is a TDMA based multi-channel MAC protocol for ad-hoc networks. TMMAC requires only a single half-duplex radio transceiver on each node. Here, the time is divided into fixed periods, which consists of an ATIM (Ad Hoc Traffic Indication Messages) window followed by a communication window. During the ATIM window, every node decides not only which channels to use, but also which time slots to use for data communication. In the communication window the time is divided into slots each of which is called a time slot. Each time slot has a duration required for a single data packet transmission or reception. This supports broadcast in an effective way and this is highly energy efficient [22].

5. **APCAP: ADAPTIVE PROPAGATION-DELAY COLLISION AVOIDANCE PROTOCOL:** The RTS/CTS scheme is used to reserve channel and send data. All nodes are synchronized. The use of these separate windows reduces the chance of the destination failing to transmit the CTS when the source requires it because it is unavailable, and also the likelihood of the destination not receiving the data packet because it is not ready for it [23].

6. **DACAP: DISTANCE AWARE COLLISION AVOIDANCE PROTOCOL:** This protocol uses the RTS/CTS scheme to reserve the channel and for transmitting data packets. The sender can compute this distance by measuring the RTS/CTS roundtrip time. Potential interferes are blocked as usual in RTS/CTS schemes [24].

7. **RTMAC:** This TDMA protocol has been carefully designed to overcome the high latency of the traditional TDMA design and also provides delay guarantee. This also conserves energy when the node is in isle state. RTMAC is suitable for real time applications like detection of radioactive radiation, earthquake which require that the sensed events (or packets) are delivered within a certain deadline [25].

The original floor acquisition multiple access (FAMA) requires long RTS and CTS packets in order to guarantee that the data packets will be transmitted collision-free [25]. However, in the underwater acoustic channel, where transmissions are expensive, excessively large control packets might be too energy expensive. In order to reduce these high energy costs, slotted FAMA uses time slots, in the same way as slotted aloha, to reduce the control packet size [26]. The slot length is equal to the maximum propagation delay plus the transmission time of a CTS packet, which assures that only control packets may collide and that the transmission of data packets is collision-free.

Another approach is the one proposed in [27], in which TDMA is used, but nodes are able to adaptively identify who can transmit at the same time without causing collision. In order to do so, nodes calculate a list of neighbours and share it by piggybacking it to their outgoing packets. Upon reception of a new list of neighbours, each node updates its connectivity matrix, and based on this, the node then decides whether or not it is able to safely transmit in the next slot.

A different proposal for low-duty-cycle underwater communication networks is given in [28]. This protocol sets up an adaptive TDMA schedule. Nodes first exchange SYNC packets within their transmission periods and learn their neighbours. Consequently, a node knows when it should wake up to hear a transmission and when there are no transmissions, so that it can remain in sleep mode.

Cluster-based on-demand time sharing (COD-TS) [29] proposes a different solution. Nodes are organized into clusters, and the cluster heads are the nodes in charge of assigning the slots for the next communication round. At the beginning of each round, the cluster head populates the schedule, and each node sends its request to transmit at the end of the communication round. In addition, cluster heads communicate among themselves in order to avoid collisions with neighbouring clusters.

5. CONTENTION BASED PROTOCOLS

MAC protocols for UASNs have been extensively studied to mitigate the limitations of underwater communication channels. Contention-based MAC protocol can achieve acceptable throughput and low latency with a low network load without requiring time synchronization. The contention based protocol divided into Random based, Handshaking based and Reservation based protocols.

5.1. Random based MAC protocols

The work in [65] has presented an Underwater Wireless Acoustic Networks Medium Access Control (UWANMAC) protocol. Since the UWANMAC scheme strongly relies on the synchronization among the nodes' adaptive TDMA schedules, the network performance is much affected by the synchronization drift. The Underwater FLASHR (UW- FLASHR) protocol [66] is a TDMA-based MAC protocol which does not require tight clock synchronization, accurate propagation delay estimation or centralized control.

As a TDMA-based protocol, UW-FLASHR operates over cycles of time, where each cycle has an experimental phase and an establishing phase. To send data, a node requests a new time slot by sending a data frame randomly in the experimental portion of each of several consecutive cycles. However, as each node contends to allocate a time slot by randomly choosing a transmitting time and checking to see whether such a transmission incurs any collisions, the UW-FLASHR scheme gradually constructs a loose transmission schedule in a distributed manner so that time gaps may exist between transmissions [23]. To solve the problems of strict synchronization and to provide long enough guard time of every time slot, [31] has presented a mechanism for nodes to adjust guard time according to the distance between the nodes of the transmission.

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

One called ALOHA with carrier sense (ALOHA-CS) and the other, ALOHA with advance notification (ALOHA-AN), have been proposed. Each of the two protocols provides an essential increase of the network throughput in comparison with that of a pure ALOHA protocol. Both protocols have taken the advantage of the long propagation delay in underwater acoustic environments.

There is no handshaking and no synchronization involved. The ALOHA-AN needs to collect and store more information, therefore it requires more resources than ALOHA -CA. However, the extra cost allows the ALOHA-AN to achieve much better throughput and the ability to support collision avoidance. The performance comparison in terms of throughput between ALOHA-CA and ALOHA-CS is shown in Fig. 4

Recently, a back-off tuning scheme for ALOHA has been proposed in [43]. This work uses the ALOHA scheme with the back-off technique for packets transmission to achieve a better throughput. The scheme is easy to be implemented and applicable to more complex protocols with a multi-channel.

The work in [44] has proposed two enhanced Slotted ALOHA protocols to minimize the impact of propagation delay in UASNs. They are respectively Synchronized Arrival Slotted ALOHA (SA-ALOHA) protocol and an Improved SA-ALOHA (ISA-ALOHA), which adjusts the size of time slot according to the range of delay estimation errors.

The SA-ALOHA and ISA-ALOHA perform remarkably better than Slotted ALOHA for UASNs. Furthermore, the ISA-ALOHA is more robust even when the estimation error of the propagation delay is large.

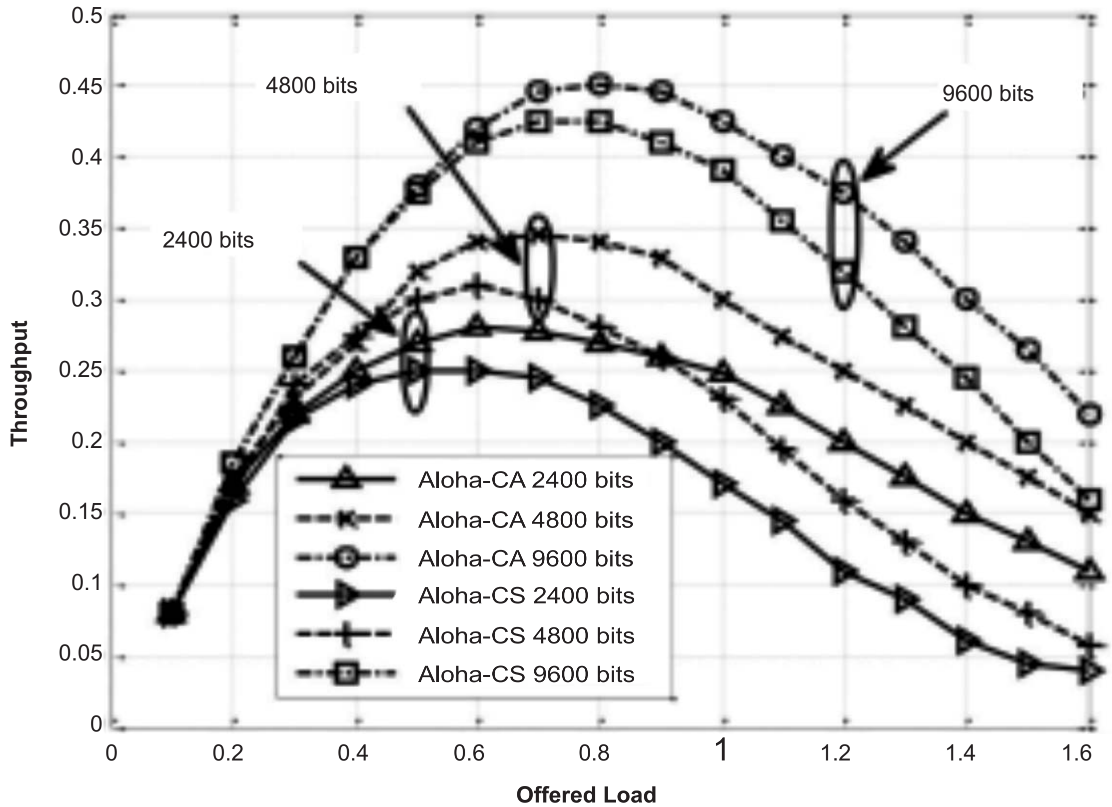

Figure 4: Throughput of Aloha-CA compared to Aloha-CS

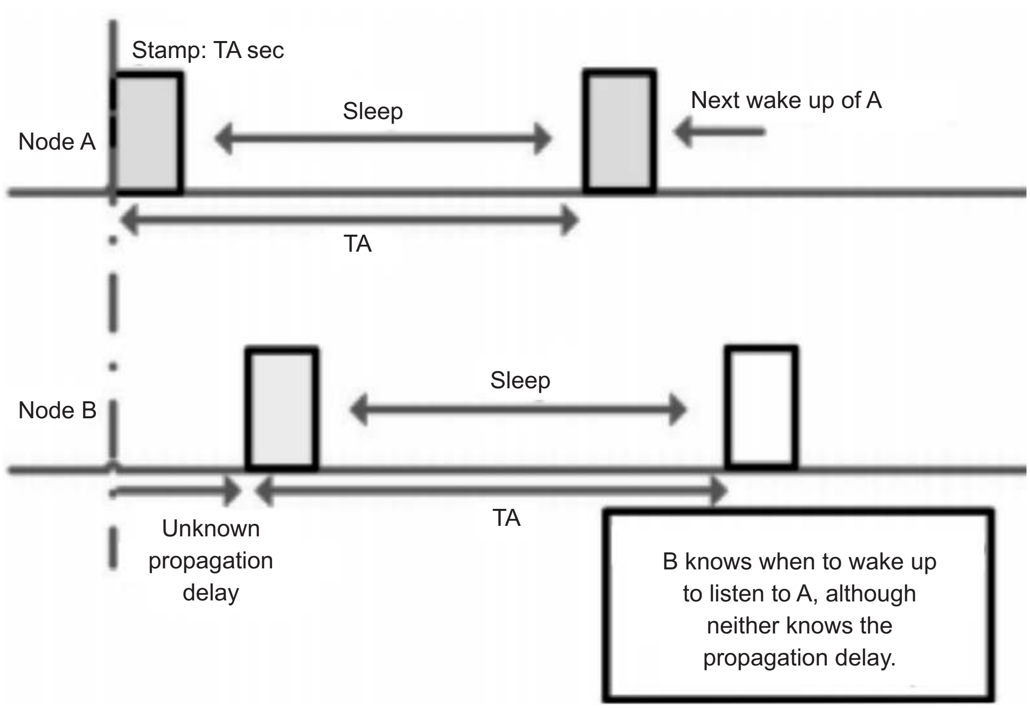

Figure 5: Basic idea of the UWAN-MAC Protocol [65]

ALOHA is the simplest random access MAC protocol to be easily implemented without any effort to prevent collisions.

The protocol works as follow. If a node has data ready to send, it will send the data at its will. If two nodes transmit packets at the same time, a collision occurs. In this case, a retransmission is required. Some variances based on the ALOHA have been proposed.

In [36], a study on Slotted ALOHA protocols for UASNs has been presented. By the Slotted ALOHA, a node cannot send its packets at any time, but has to wait for the beginning of a timeslot. Thus, the chances of collisions will be reduced.

Due to the long and varying propagation latency of the underwater acoustic channel, a study in [37-39] shows that the Slotted ALOHA protocol cannot get better performance than that of the ALOHA protocol in underwater acoustic networks. The work in [40] has proposed a solution to handle the performance degradation of the Slotted ALOHA protocol.

It has shown that collision and reception in slow networks depend on both transmission time and the location of the receiver. The impact of space-time uncertainty to Slotted ALOHA performance has been improved in [38] with a modification that adds guard bands to the transmission slots.

There is a tradeoff between the maximum propagation delay and the guard bands length. Based on the solution in [38], a propagation delay tolerant ALOHA (PDT- ALOHA) protocol has been proposed in [41]. The PDT-ALOHA scheme has improved the performance of the Slotted ALOHA in terms of successful packet reception rate and the network throughput. The further enhancements on the ALOHA scheme focus on the integration of the schemes to prevent collisions with the ALOHA protocol. In [42], two ALOHA-based protocols, one called ALOHA with carrier sense (ALOHA-CS) and the other, ALOHA with advance notification (ALOHA-AN), have been proposed. Each of the two protocols provides an essential increase of the network throughput in comparison with that of a pure ALOHA protocol. Both protocols have taken the advantage of the long propagation delay in underwater acoustic environments. There is no handshaking and no synchronization involved. The ALOHA-AN needs to collect and store more information, therefore it requires more resources than ALOHA -CA. However, the extra cost allows the ALOHA-AN to achieve much better throughput and the ability to support collision avoidance.

Recently, a back-off tuning scheme for ALOHA has been proposed in [43]. This work uses the ALOHA scheme with the back-off technique for packets transmission to achieve a better throughput. The scheme is easy to be implemented and applicable to more complex protocols with a multi-channel.

The work in [44] has proposed two enhanced Slotted ALOHA protocols to minimize the impact of propagation delay in UASNs. They are respectively Synchronized Arrival Slotted ALOHA (SA-ALOHA) protocol and an Improved SA-ALOHA (ISA-ALOHA), which adjusts the size of time slot according to the range of delay estimation errors. The SA-ALOHA and ISA-ALOHA perform remarkably better than Slotted ALOHA for UASNs. Furthermore, the ISA-ALOHA is more robust even when the estimation error of propagation delay is too large.

This set of protocols avoids the pre-allocation of resources by allowing nodes to compete with each other and obtain medium access on demand. These protocols usually rely on random access to distribute transmissions. They also normally include some recovery mechanisms in case a collision occurs. Protocols under this category can be subdivided into direct access, handshake access and contention access.

Direct Access Protocols under this category do not perform any kind of handshake for channel reservation. However, they can perform carrier sensing prior to transmission in order to avoid disrupting ongoing transmissions, deferring it until the channel is free.

Aloha [30] is the simplest method to access the medium. It simply sends a packet whenever there is data to send, without performing any type of channel assessment or retransmission. In its variant, called aloha with carrier sensing (aloha-CS), prior to transmission, each node performs a clear channel assessment (CCA) in order to avoid disrupting any ongoing transmission. If the channel is sensed to be free, the sending node transmits its packet. However, if an ongoing transmission is sensed, the node waits until the channel is free and then sends the packet.

Different studies have been conducted in order to understand the performance of aloha in an underwater medium. In [31], the authors develop an analytic model to study the performance of contention-based protocols by modeling different versions of aloha in an array network. Although the authors make several simplifications, different conclusions are drawn. Arrays longer than five hops are probably not going to perform well when using the simple aloha protocol. However, using p-persistent aloha without dropping packets increases the network throughput at the cost of increasing the delay.

Another study based on the aloha protocol is presented in [32], in which two different variants of aloha are proposed. Aloha with collision avoidance (aloha-CA) tries to avoid collisions by overhearing the transmitted packets and knowing the propagation delays between all node pairs. The other proposed modification is aloha with advanced notification (aloha-AN), which consists of sending a short data packet prior to the actual data transmission with information on the sender and the intended receiver.

CSMA [30] is another well-known protocol under this category. Similar to aloha-CS, this protocol uses carrier sensing. However, unlike aloha-CS, after waiting for the channel to be free, a node does not immediately send its packet. Instead, it performs random back-offs to mitigate the probability of collisions. This variant is called non-persistent CSMA. In another variant, called p-persistent CSMA, a node transmits with a probability of p when the channel is sensed to be free. Note that 1-persistent CSMA is equivalent to aloha-CS.

Reservation Access This technique consists of reserving the channel prior to the transmission of the actual data packet. In order to do so, usually, short control packets are sent before transmission. By reserving the channel, the frequency of the collisions of data packets is minimized, and the additional traffic introduced by the control packets is compensated for.

In the handshake-based alternative, whenever a transmitter wants to send a data packet, it first sends a control packet informing the other nodes that it has data to send. Upon reception of this control packet by the intended receiver, it replies if the channel is not being used. After receiving this reply packet, the transmitter can start the transmission of the data packet.

However, this reservation mechanism cannot guarantee collision freeness, because of the well-known hidden and exposed node problems. Many authors have proposed different solutions to cope with this problem.

Multiple access collision avoidance (MACA) [33] is the first approach of a handshake algorithm proposed to reserve the channel. The sender first sends an RTS control packet in order to start the channel reservation. This packet contains the length of the data packet, so that other nodes know how long they should wait until they can initiate their own transmissions. Afterwards, the receiver replies with a CTS packet. When the transmitter receives the CTS, it starts the transmission of the actual data packet.

However, this algorithm does not entirely solve the exposed terminal problem, especially in channels with long propagation delays, such as the underwater channel. MACA for underwater (MACA-U) [34] adapts MACA to the long propagation delays of the underwater medium by modifying some of the state transition rules of the original protocol.

Another protocol to solve the handshaking problems in the underwater medium is the propagation-delay-tolerant collision avoidance protocol (PCAP) [35]. This protocol splits the transmission of a CTS packet, so that it arrives at the transmitter after twice the maximum propagation delay. While waiting for the CTS packet, the transmitter and its neighbours can perform different actions, such as transmitting data packets or starting the handshaking process for another transmission.

Spatially fair MAC (SF-MAC) [36] also tries to avoid collisions by deferring the CTS packet transmission for a predefined amount of time. During this time, the receiver analyses all RTS packets that are sent to it and determines, based on an estimate, which node was the first to send the RTS packet and the node to which the CTS packet should be addressed. Another random access with reservation protocol is the distance-aware collision avoidance protocol

(DACAP) proposed in [37]. This protocol tries to avoid data and RTS packet collisions by deferring the data transmission for t seconds after sending the RTS. This waiting time has to be chosen based on a trade-off between throughput and collision probability. Moreover, it also introduces a short warning packet sent by the receiver if it overhears an RTS after sending a CTS.

Another approach is given by the original FAMA protocol [38], which completely prevents data packet collisions, provided that the RTS and CTS frames are sufficiently long. The length of an RTS packet should be greater than the maximum channel propagation delay, and the length of the CTS packet has to be greater than the length of an RTS plus one maximum round-trip time.

In order to introduce some energy savings, Molins et al. propose in [26] the slotted FAMA protocol described by reserving different transmissions in one multiple reservation packet broadcast to all neighbors and trying to arrange data transmission with several nodes, contention-based parallel reservation MAC (COPE-MAC) [39] improves channel utilization. Moreover, neighboring nodes can, by overhearing, learn about future scheduled transmissions and adapt their own channel utilization to avoid collisions.

The reservation-based MAC (R-MAC) protocol is proposed in [40] and is designed for long-term monitoring applications. Nodes alternate between sleep and listen modes periodically and randomly select their schedule. The protocol requires all nodes to know the propagation delay to all of their neighbors and their listen and sleep periods. Afterwards, the protocol reserves the channel in an RTS/CTS fashion, but gives higher priority to the CTS packets.

Another protocol that exploits spatio-temporal uncertainty is delay-aware opportunistic transmission scheduling (DOTS) [41], which exploits temporal and spatial reuse by learning the propagation delay to neighboring nodes and their scheduled transmissions. In order to achieve this, nodes must be synchronized and continually overhear the channel. The protocol is based on a MACA-like random access protocol with RTS and CTS packets. By promiscuously overhearing, a node using DOTS can locally calculate the transmission and reception schedules of its neighbors and schedule on its own to avoid collisions.

Receiver-initiated packet train (RIPT) [42] is different from the previous protocols, as it employs a receiver-initiated four-way handshake mechanism. Instead of the sender, the node that initiates the handshaking process is the receiver, which informs its neighbors that it is available to receive. After that, the neighboring nodes inform the receiver about the size of their transmissions, and with that information and the previously known propagation delay, the receiver can calculate and broadcast a transmission order. Finally, senders follow this transmission order, and the data arrives at the receiver in a sequence of packets.

Tone-Lohi (T-Lohi) [43] implements this technique. It automatically adapts the contention time to the number of contending nodes. The nodes send a short packet, called tone prior, to the actual data packet to count the number of terminals contending for the channel. If a node does not receive any other tones, it starts the transmission. If it receives more tones, it adapts its back-off time, depending on the number of tones received.

5.2. Handshaking

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

Some Contention based protocols relaxed on time synchronization are detailed below.

1. **PAMAS:** POWER AWARE MULTI-ACCESS SIGNALING:The nodes which are not transmitting or receiving are turned "off" in order to conserve energy. This uses two channels for data and control packets. The main disadvantage of this protocol is that it uses two radios at sensor node. This increases the cost, size and design complexity. This also leads to excessive power consumption due to switching between sleep and wake up states.
2. **S-MAC: SENSOR-MAC:** This protocol is based on adaptive listening concept. Instead of listening to the medium constantly, the control protocol sensor node periodically goes to the fixed listen/ sleep cycles to reduce the energy consumption. The time frame is divided into smaller parts: One for listening session, other for sleeping session. The advantage is that the idle listening is reduced. But there is high latency for multi-hop networks, the probability of collision increases, and therefore the efficiency decreases.
3. **T-MAC: TIME-MAC:** This is an improvement to S-MAC to reduce energy consumption on idle listening. An adaptive duty cycle is introduced: all messages are transmitted in variable length bursts and the lengths of bursts are dynamically determined. In the time frame, the active period ends if there is no activity for a time period of Ta. (Ta is the minimum listening time in the time-frame). The major defect in T-MAC is the early sleeping problem.
4. **U-MAC:** This provides three main improvements on the SMAC protocol (various duty-cycles, utilization based tuning of duty-cycle, selective sleeping after transmission). All the nodes are assigned with various duty-cycles. The nodes have to exchange their schedules and synchronize clock with neighbors within a fixed period. Selective sleeping after transmission avoids unnecessary energy wastage. After a node finishes a transmission, it checks if there is its scheduled sleep time, and forces a sleep if it is. It does not introduce additional delays, since traffic is not expected to this node.
5. **WISEMAC:** Wise MAC protocol uses non-persistent CSMA (np-CSMA) with preamble sampling to decrease idle listening. Here all the nodes in a network sample the medium with a common period but with different offset schedule times. Initially the preamble is equal to the sampling period.
6. **B-MAC: BERKELEY MEDIA ACCESS CONTROL:** This is a CSMA based MAC protocol for WSNs. In this there is Clear Channel Assessment (CCA) for effective collision avoidance. Here samples of the media are taken to estimate the noise floor. B–MAC also utilizes a preamble sampling technique called Low Power Listening (LPL) to minimize the idle listening problem. The use of ACK frames for reliability purposes and throughput improvement is also included.
7. **Traffic Adaptive Medium Access Protocol (TRAMA):** Energy is saved by ensuring collision free transmission and by switching the nodes to low power idle state when they are not transmitting or receiving. This protocol is more efficient and has higher throughput than S-MAC. The main disadvantages are high latency and higher delays. TRAMA is mainly suitable for delay sensitive applications.

6. HAND SHAKING BASED MAC PROTOCOLS

In Hand shaking Protocols, the nodes transmit only after negotiating with other nodes. These MAC Protocols are divided into Single channel and Multichannel based Protocols.

6.1. MAC protocols with single channel

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

The first group of the handshaking MAC protocols is a group of protocols with aims to achieve energy efficiency. The Slotted floor acquisition multiple accesses (Slotted FAMA) have been proposed in [50]. This protocol works based on the floor acquisition multiple accesses (FAMA) in [51] with time slot division. It combines both carrier sensing and a dialogue between the transmitter and the receiver prior to data transmission. There are some other works to improve the Slotted FAMA scheme.

Like the Slotted FAMA, the Distance-Aware Collision Avoidance Protocol (DACAP) in [52] combines carrier sensing and an exchange of request to send/clear to send (RTS/CTS) control packets prior to data transmission, but it does not require the nodes to be synchronized to common time slots. DACAP is a collision avoidance protocol that is easily scalable to the changes in the number of nodes and the coverage area of the network. Additionally, it provides higher throughput than that of the Slotted FAMA scheme with similar power efficiency. To reduce the overhead associated with the Slotted FAMA scheme, another improvement that deals with both the energy efficiency and the delivery overhead has been proposed in [53].

The main idea of the protocol is to include a waiting period between the moment when a CTS frame is received and the moment the source node starts sending its data. An asynchronous MAC protocol, namely, MACA with packet train for Multiple Neighbors (MACA-MN) has been proposed in [54]. The MACA-MN utilizes a handshaking scheme in order to avoid collisions and alleviate the hidden terminal problem in multi-hop underwater networks. In addition, the MACA-MN goes one step further as the packet train is actually formed for multiple neighboring nodes simultaneously. However, due to the long duration of each handshake, the average waiting time can be very long before a node gains control of the channel for transmission [55].

The second group of the handshaking MAC protocols with single channel is a group of protocols with aim to alleviate the impact of long delays. There are normally two ways to handle the long delay impacts. One way is for the transmitting nodes to use the long delay period of control information exchange to complete some other work. The following solutions can be considered following this way.

A modified four-way handshaking scheme, named Multiple Access Collision Avoidance for Underwater (MACA-U), has been proposed in [56]. By the MACA-U scheme, if a node which has transmitted a RTS frame receives another RTS frame from its neighbors, it can ignore the network allocation vector (NAV) setting to transmit its data frame in order to save time. But, collisions probability could be high by the MACA-U scheme.

In [57], a MAC protocol called propagation-delay-tolerant collision avoidance protocol (PCAP) has been proposed. Besides the requirement of RTS and CTS frames, the protocol allows the transmitting node to perform other actions in the period waiting for the CTS frames returning. In [58], an adaptive propagation delay tolerant collision avoidance protocol (APCAP) is more comprehensively designed to accommodate the long propagation delay in the UASNs. It is flexible and adaptive to both of the offered traffic load and the availability of destination nodes.

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

Although this approach can reduce the relative proportion of time on control signalling, the adoption of a receiver-initiated approach requires a complex traffic prediction algorithm. The throughput of RIPT, MACA, and Aloha-AN is shown in Fig.6. In [60], an adaptive distance aware scheduling protocol is proposed, which tries to overcome the long propagation delay in the UASNs.

The protocol uses a distance awareness scheduling model for UASNs to improve the performance of the network in terms of data rate, throughput and the propagation delay over the underwater acoustic channels. A Delay-aware Opportunistic Transmission Scheduling (DOTS) protocol [61] uses passively obtained local information to increase the chances of concurrent transmissions while reducing the likelihood of collisions.

It can alleviate the impacts of the long propagation latency and the severely limited bandwidth of acoustic communications. A Channel Stealing MAC (CS-MAC) protocol [62] has been proposed to improve the performance of the UWANs. The CS-MAC protocol effective makes use of the idle waiting time between the frame exchanges, and provides more transmission opportunities to improve the channel utilization.

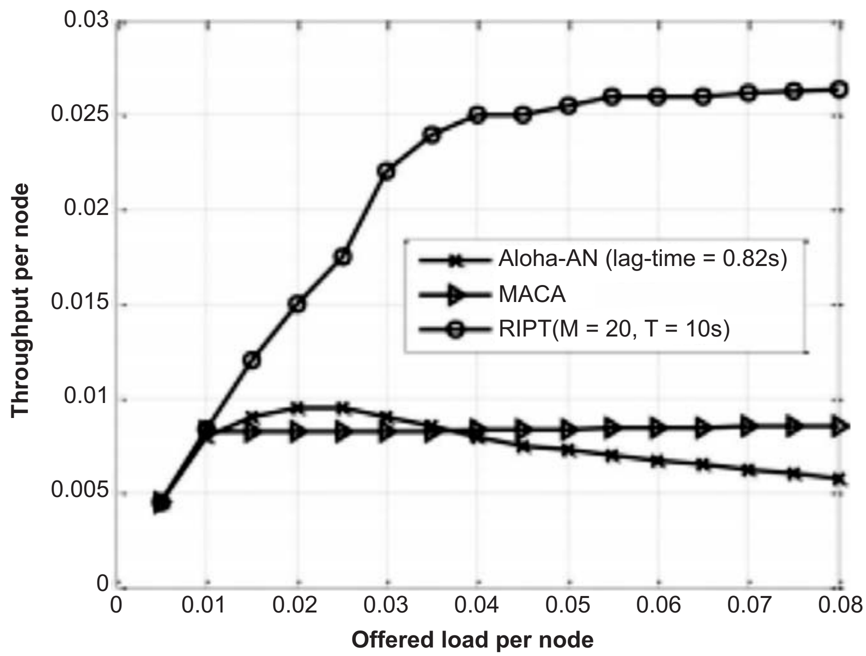

Figure 6: Throughput Comparison [88]

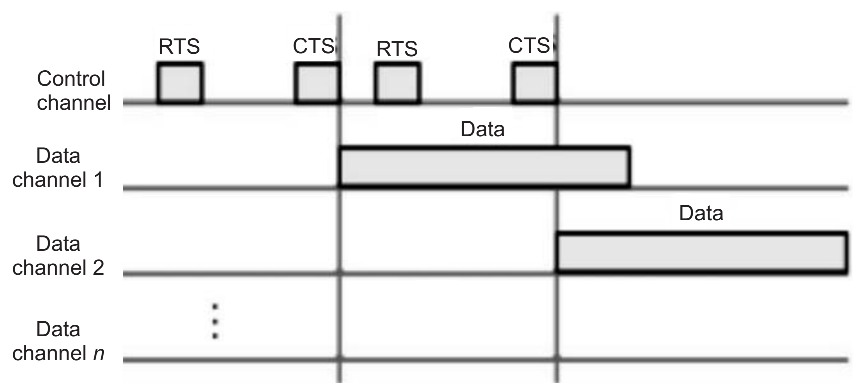

Figure 7: Multiple channel with hand shaking [88]

The last group of the handshaking MAC protocols with single channel has the aim to achieve high channel utilization or fairness. A reservation-based MAC protocol (R-MAC) has been proposed in [63], which schedules the transmission of control packets and data packets at both the transmitter and the receiver nodes to avoid data packet collisions completely.

By the R-MAC protocol, each node works in listen and sleep modes periodically. The durations for listen and sleep are the same for all nodes. And each node randomly selects its own schedule because no centralized scheduling and synchronization are required [64]. To extend the above reservation based R-MAC protocol, a Reservation-based MAC-Mobile (RMAC-M) [65] has been developed to support the mobile sensor nodes. It leverages the energy efficiency and fairness with ability to handle nodes' mobility.

A Bidirectional Concurrent MAC (BiC-MAC) has been proposed in [66], which is designed with a versatile MAC framework to support all three possible modes of bidirectional transmissions. In another attempt to improve the channel utilization, a reverse opportunistic packet appending (ROPA) has been proposed in [67]. It seeks to improve the channel utilization by reducing the proportion of time spent on control signalling. The transmitter can coordinate the packet appending so that those packets will arrive in a collision-free packet train.

Recently, a spatially fair MAC protocol, named SF-MAC, has been proposed in [67] to solve the space uncertainty problem in UASNs. SF-MAC protocol is a receiver-based protocol, by which the receiver captures the RTSs of all the contenders and determines the earliest transmitter by considering the potential transmission duration to achieve a fair transmission.

Similar to the aforementioned protocol, a weight-based spatially fair MAC protocol (WSF-MAC) has been proposed in [68], which tries to overcome the issue of spatial unfairness. By the WSF-MAC scheme, the transmission of the underwater-reply packet will be postponed for a silence period of time at the receiver to capture the underwater-request packets of all the potential transmitting nodes.

6.2. MAC protocols with multiple channels

Different from single channel MAC protocols, multiple channel protocols utilize more than one channel for communication [69]. As shown in Fig.7, there are one common control channel and multiple data channels. The node with outgoing packets will sends a RTS message over the control channel.

The RTS frame should include the sender/receiver identifier, the available channel set and the packet length. Some multiple channel MAC protocols are summarized below. In [70], a Reservation Channel Acoustic Media Access Protocol (RCAMAC) based on RTS/CTS handshaking has been proposed. By the RCAMAC scheme, the entire bandwidth is divided into two channels. One is a control channel with less bandwidth.

Another is the data channel with much more bandwidth. With taking both energy efficiency and throughput into consideration, a novel COntention based Parallel rEservation MAC (COPE-MAC) protocol has been proposed in [71], which introduces parallel transmission into the protocol design and makes concurrent transmission possible in the UASNs, which augments the system throughput.

On the other hand, it adopts a contention based reservation approach to avoid collisions and improve the system energy efficiency. Another Multiple channels MAC protocol, (MM-MAC), is proposed in [72-73], which aims to use a single modem to emulate multiple transceivers. Utilizing the cyclic quorum systems, nodes running MM-MAC are guaranteed to meet their intended receivers to solve the missing receiver problem. In [74], an Underwater Multiple Input Multiple Output MAC (UMIMO- MAC) protocol is proposed, which leverages MIMO capabilities to allow more flexible and high efficient utilization of the underwater acoustic channels.

In particular, the UMIMO-MAC scheme is fully distributed and relies on lightweight message exchange. Moreover, the UMIMO-MAC scheme adapts its behaviour to the condition of environmental noise, channel, and interference to maximize the network throughput or minimize the energy consumption, according to the QoS requirements of the traffic being transmitted.

In a single-transceiver multichannel long-delay underwater acoustic network, new hidden terminal problems, namely, multichannel hidden terminal and long-delay hidden terminal have been exposed. To handle the problems, a new MAC protocol, named Cooperative Underwater Multichannel MAC (CUMAC) has been proposed in [75]. CUMAC utilizes the cooperation of neighbouring nodes for collision detections with a simple tone device designed for the distributed collision notification. In particular, this protocol considers a cost-effective network architecture where one and only one transceiver is required at each node.

Tailored for a data-centric scenario, in [76], a Data-Centric MAC (DC-MAC) protocol has been proposed. The DC-MAC uses multi-channel strategy to eliminate the hidden terminal problem and uses dynamic collision free polling strategy to offer efficient channel assignment. The combination of the two strategies as a single design helps to achieve high performance for the considered scenario.

7. HYBRID PROTOCOLS

These are based on the advantages of both contention based and TDMA protocols. Here the access channel is divided into two parts: The control packets are sent through random access channel. The data is sent through the scheduled access channel. In these hybrid protocols, the control packet overhead is large and energy waste in transition between two operation modes is high.

Moreover, in these protocols high latency is introduced due to transition between the two mechanisms. There are several protocols in this category:

1. **Z-MAC:** Owner slot concept is used here. A node has a guaranteed access to its owner slot (TDMA style) and contention-based access to other slots (CSMA style). Hence, collisions are reduced and energy consumption is reduced. Z-MAC has two components:

   First is Neighbour discovery and slot assignment, in which a TDMA group will be formed and a node is given a slot. Second component is Local framing and synchronization that has the time frame is decided here [20].

2. **AMAC :** In this the nodes are alert for a long time and inactive most of the time until something is detected. The main feature of AMAC is that the nodes are informed in advance when they will receive the packets. The node remains active when it sends or receives and remains in sleep mode the rest of the time. This is designed for long-term surveillance and monitoring applications. This is collision-free, non-overhearing and has less idle listening transmission services [44].

3. **D-MAC: DATA GATHERING MAC:** This is a schedule based MAC protocol designed and optimized for tree based data gathering in wireless sensor network. This is designed to achieve low latency while maintaining the energy efficiency. In D-MAC protocol the time is divided in small slots and runs CSMA with ACK within each slot to transmit/receive one packet. This protocol also includes an overflow mechanism to handle the problem when each single source node has low traffic rate but the aggregate rate at intermediate node is larger than the basic duty cycle [45].

4. **IEEE 802.15.4:** It is proposed for low-rate Wireless Personal Area Networks (WPAN). It has a super-frame structure, in which a TDMA-based period is used for guaranteed access, and a contention-based period is used for non-guaranteed access. All nodes can enter the sleep state in an inactive period. There is a coordinator operating to maintain the Synchronization of time-frames. There is no special design for energy conservation except a typical duty cycle controlling scheme [46].

5. **CONVERGENT MAC (CMAC):** When there is no packet to transmit, this protocol uses unsynchronized sleep scheduling while transmitting packets, this first uses aggressive RTS to unicast packets to potential forwarders which wake up first and detect the traffic using double channel check. After the sender transmits the packets to a node with acceptable routing metric, then CMAC converges from unicast forwarding to unicast to avoid the overhead of unicast.

6. **HSR-TDMA:** A hierarchical multiple channel MAC protocol has been proposed in [77] for clustered UASNs, where the TDMA medium access technique is used for the intra cluster communication and CDMA medium access technique is used for the inter-cluster communication. Clustering the sensor nodes can achieve the spatial reuse of channel resources to make the network availability significantly increased.

   However strict synchronization among all nodes is required. Evolved from the solution in [77], a Hybrid Spatial Reuse TDMA (HSR-TDMA) protocol has been proposed in [78], which enables the integration of CDMA medium access technique with the TDMA leading to a hybrid medium access technique.

Different from the work in [77], the CDMA component is independent of locations of the nodes in the network. Furthermore, the HSR-TDMA scheme uses a mesh type protocol, which is usually less sensitive to the topology changes and allow robust solutions.

7. **H-MAC:** In order to take the advantages of both contention-free and random access MAC protocols, a hybrid MAC protocol has been presented in [85]. The proposed MAC protocol divides a time frame into two time slots, one of which is used by each node to transmit data by the contention free scheme. Another one is used for random access by the nodes to adapt to variable traffic conditions. This H-MAC can yield the benefits from both contention-free and random access protocols with little power consumption due to its ability eliminating collisions and adaptive to the changes of traffic conditions.
8. **P-MAC:** In [79], a hybrid MAC protocol, named Preamble-MAC (P-MAC), has been proposed, which consists of a contention-free protocol and Slotted MACA. P-MAC overcomes the low precision of time synchronization. PMAC works adaptively and dynamically according to the information of Virtual Distance Level (VDL), which is the estimated, accumulated information of channel status and variation obtained through periodically monitoring the underwater environment.
9. **UW-MAC:** A distributed CDMA-based energy-efficient (UW-MAC) protocol with ALOHA has been proposed in [80-82]. By this protocol, the signaling packets will be sent by the ALOHA scheme before the transmission of the payload by the CDMA medium access technique. The transmitter adjusts its pseudo-random sequences length and signal power to reduce the multiple access interference (MAI) at the receiver. The UW-MAC protocol aims to guarantee high network throughput, low channel access delay, and low energy consumption.
10. **PLAN:** A distributed MAC protocol, named Protocol for Long-latency Access Networks (PLAN), has been proposed in [83]. The PLAN protocol utilizes the CDMA as the underlying medium access technique to minimize multipath and Doppler effects which are inherent in underwater physical channels. A MACA scheme is employed for each channel before actual data transmission. By this scheme, the CDMA spreading codes are distributed first by a contention-free algorithm and each node is assumed to get a unique spreading code among its one-hop neighbors.

8. CROSS LAYER PROTOCOLS

The cross layer is a novel method to improve energy efficiency. The cross layer design uses forward error correction (FEC) coding and determines the awake/sleep periods for narrowband wireless sensor networks. The traditional Network layer and Transport layer are removed, thus simplifying the protocol stack. Some traditional function of the two layers is merged into the top and the bottom layers.

1. **MAC-CROSS:** This protocol has improved its energy efficiency by making use of interaction between MAC layer and routing layer. In the MAC-CROSS algorithm, routing information at the network layer is utilized for the MAC layer so that it can maximize sleep duration of each node [47].
2. **CLMAC PROTOCOL :** This protocol operates like the B-MAC protocol but it includes routing distance in the preamble field of the B-MAC. Without big routing table, it enables nodes to reduce control traffic routing overhead [48].
3. **MULTIMEDIA CROSS-LAYER PROTOCOL:** For better underwater applications such as multimedia coastal and tactical surveillance, undersea explorations, picture and video acquisition and disaster prevention, differentiated-service support to delay-sensitive and delay tolerant data traffic as well as to loss-sensitive and loss tolerant. Traffic is provided in this protocol. This allows multiple devices to efficiently and fairly share the bandwidth-limited high-delay underwater acoustic medium [49].

9. CONCLUSION AND FUTURE SCOPE

The MAC protocols reviewed in this paper have provided an overall view on the current research progress on the development of the MAC protocols for the UASNs. It seems that there is not a single protocol, which can be considered as a perfect solution to meet all the requirements from various applications.

Large numbers of mechanisms and protocols described in this survey is current state-of-the-art solutions that captured from the recent developments .This survey will reflect the importance of the research activities on the MAC protocol design for the UASNs. This area of study is mostly challenging in the context of underwater acoustic environment.

The recent contention-free protocols improvised for better synchronisation and delay reduction with aim to improve the channel utilization. The effect of near-far problem is still persists. Contention-free protocols use the advantage of the free distribution of the channel to improve the efficiency of the control packet transmission and to achieve fair access and energy efficiency, which can solve the space-time uncertainty and the issue of hidden node and exposed node problem to a certain extent.

However, the high node density and high offered load will impact the achievements resulting in a challenge. Hybrid MAC protocols take use of the advantages of different types of protocols.

For further research and the promotion on the design of the MAC protocols for UASNs, we suggest the following open research issues which need to be addressed.

First, The large amount of available MAC protocol developed is for the scenarios where the sensors have to correlate data and nodes that can adapt to the varying traffic scenarios. However, in the USAN application for monitoring changing network topology, the network node likely focus on maximizing long system lifetime, low latency for data transfer and higher QoS. Future research is required to design and develop adaptive MAC protocols to provide optimised levels to achieve QoS for various applications over underwater networks.

Second, Due to the ocean current, UASNs network topology will change because of the movement of nodes due to ocean current. Future designed MAC protocols should sustain to these conditions.

Third, further research is required to design CDMA-based MAC protocols to control the transmission power adaptively with features of high auto-correlation and low cross-correlation to achieve the minimum interference among sensor nodes in the underwater networks.

Fourth, handshaking MAC protocols with multiple channels are supposed to be the best for boosting network throughput. the design and development of more intelligent and cost effective handshaking MAC protocols with multiple channels in high and variable propagation delay underwater environments is required. In addition to this various cost- effective hybrid MAC protocols are required to be autonomously flexible to various types of traffic of applications and different types of the topology of the UASNs.

Fifth, Research is required in improvisation of the localization system of large-scale UASNs. The MAC protocols should be designed for the localization coverage, speed and communication costs .Also for the performance improvisation of MAC protocols the localization results can be used. The through research is needed to analyse the performance of different MAC protocols and localization algorithms.

Sixth., future scope demand for high quality data transfer with self powered systems provides maximum benefit for the end-user. Such energy efficient scalability adds the new parameter design of the present protocol architecture.

Seventh, it is important to develop secure communication for UASNs. Without these security measures, the application of WSNs will be limited.

Eight, the importance of mobility is sensor network focus on energy constraints. In many applications cluster node moves in various patterns. So a cluster based MAC and Network layer, need to handle the mobility pattern by making self-configuring process for more energy conserving. We still think there is a chance for improvement of above architecture areas.

Lastly, various protocols with FEC and energy efficient improvement were discussed for the improvement and enhancement of new cross-layer architecture design will enable to support the future demand needs. More attention is required in several areas of interest like cross-layer design consideration of clustering with sleep scheduling, sensor localization and hybrid routing to maximize energy efficiency of USAN nodes. For the future demand of UASNs, the present architecture needs to optimize for network performance and hardware sensor nodes. So that future trends of the wireless sensor networks goal can be "anytime" and "anywhere" communication network that minimize the gap between the device and users.

Conflicts of Interest: The authors declare no conflict of interest.

REFERENCES

[1] Syed, A.A.; Ye, W.; Heidemann, J.; Krishnamachari, B. Understanding Spatio-Temporal Uncertainty in Medium Access with ALOHA Protocols. In Proceedings of the Second Workshop on Underwater Networks (WuWNet '07), Montreal, Quebec, Canada, September 2007

[2] Salvador Climent; Antonio Sanchez; Juan Vicente Capella; Nirvana Meratnia and Juan Jose Serrano. Underwater Acoustic Wireless Sensor Networks: Advances and Future Trends in Physical, MAC and Routing Layers. Sensors 2014, 14, 795-833; doi:10.3390/s140100795

[3] Rice, J.; Creber, B.; Fletcher, C.; Baxley, P.; Rogers, K.; McDonald, K.; Rees, D.; Wolf, M.; Merriam, S.; Mehio, R.; et al. Evolution of Seaweb Underwater Acoustic Networking. In Proceedings of the OCEANS 2000 MTS/IEEE Conference and Exhibition, Providence, RI, USA, September 2000; Volume 3, pp. 2007–2017.

[4] W. Cheng, A. Y. Teymorian, L. Ma, X. Cheng, X. Lu, and Z. Lu, "Underwater localization in sparse 3D acoustic sensor networks," in Proc.IEEE INFOCOM, Apr. 2008, pp. 236–240.

[5] P. Xie and J. H. Cui, "R-MAC: An Energy-Efficient MAC Protocol for Underwater Sensor Networks", In Proc. Of the IEEE WASA'07, 2007

[6] Stojanovic, M.; Freitag, L. Multichannel detection for wideband underwater acoustic CDMA communications. IEEE J. Ocean. Eng. 2006, 31, 685–695

[7] Pompili, D.; Melodia, T.; Akyildiz, I.F. A CDMA-based medium access control for underwateracoustic sensor networks. IEEE Trans. Wirel. Commun. 2009, 8, 1899–1509

[8] Watfa, M.K.; Selman, S.; Denkilkian, H. UW-MAC: An underwater sensor network MAC protocol. Int. J. Commun. Syst. 2010, 23, 485–506

[9] Climent, S.; Capella, J.; Meratnia, N.; Serrano, J. Underwater sensor networks: A new energy efficient and robust architecture. Sensors 2012, 12, 704–731.

[10] Syed, A.A.; Heidemann, J. Time Synchronization for High Latency Acoustic Networks. In Proceedings of the 25th IEEE International Conference on Computer Communications, Barcelona, Spain, April 2006; pp. 1–12

[11] Syed, A.A.; Ye, W.; Heidemann, J.; Krishnamachari, B. Understanding Spatio-Temporal Uncertainty in Medium Access with ALOHA Protocols. In Proceedings of the Second Workshop on Underwater Networks (WuWNet '07), Montreal, Quebec, Canada, September 2007

[12] Hsu, C.C.; Lai, K.F.; Chou, C.F.; Lin, K.C.J. ST-MAC: Spatial-Temporal MAC Scheduling for Underwater Sensor Networks. In Proceedings of the IEEE 28th Conference on Computer Communications, Rio de Janeiro, Brasil, April 2009; pp. 1827–1835.

[13] Kredo, K., II; Djukic, P.; Mohapatra, P. STUMP: Exploiting Position Diversity in the Staggered TDMA Underwater MAC Protocol. In Proceedings of the 28th IEEE Conference on Computer Communications, Rio de Janeiro, Brasil, April 2009; pp. 2961–2965.

[14] Van Kleunen, W.; Meratnia, N.; Havinga, P.J. MDS-MAC: A Scheduled MAC for Localization, Time-Synchronisation and Communication in Underwater Acoustic Networks. In Proceedings of the IEEE 15th International Conference on Computational Science and Engineering, Nicosia, Cyprus, December 2012; pp. 666–672.

[15] Van Kleunen, W.; Meratnia, N.; Havinga, P. MAC Scheduling in Large-Scale Underwater Acoustic Networks. In Proceedings of the International Conference on Wireless Information Networks and Systems (WINSYS 2011), Sevilla, Spain, July 2011.

[16] Chen, Y.J.; Wang, H.L. Ordered CSMA: A Collision-Free MAC Protocol for Underwater Acoustic Networks. In Proceedings of the IEEE Oceans 2007, Vancouver, BC, Canada, October 2007.

[17] Tanenbaum, A.S.; Wetherall, D.J. Computer Networks; Prentice Hall: Boston, MA, USA, 2010.

[18] Ahn, J.; Syed, A.; Krishnamachari, B.; Heidemann, J. Design and analysis of a propagation delay tolerant ALOHA protocol for underwater networks. Ad. Hoc. Netw. 2011, 9, 752–766.

[19] Suh Changsu,Ko Young-Bae, Son DongMin.An Energy Efficient Cross-Layer MAC Protocol for Wireless Sensor Networks[C]//Proc.of the 8th Asia Pacific Web conference, Harbin, 2006:410-419.

[20] Dario Pompili, Member, IEEE, and Ian F. Akyildiz, Fellow, IEEE"A Multimedia Cross-Layer Protocol for Underwater Acoustic Sensor Networks"

[21] LIU Yunhuai, NI Lionel M. A New MAC Protocol Design for Long-term Applications in Wireless Sensor Networks[C]// Proc. of Parallel and Distributed Systems, Hsinchu, 5-7 Dec 2007, 1:1-8

[22] Jingbin Zhang, Gang Zhou, Chengdu Huang , Sang H. Son, John A. Stankovic. "TMMAC: Energy Efficient MultiChannel MAC Protocol for Ad Hoc Networks"

[23] I.F. Akyildiz et al., "Wireless sensor networks: a survey", Computer Networks, Vol. 38, pp. 393-422, March 2002.

[24] R. Min, et al., "Low Power Wireless Sensor Networks", in the Proceedings of International Conference on VLSI Design, Bangalore, India, January 2001.

[25] Fullmer, C.L.; Garcia-Luna-Aceves, J.J. Floor acquisition multiple access (FAMA) for packet-radio networks. SIGCOMM Comput. Commun. Rev. 1995, 25, 262–273.

[26] Molins, M.; Stojanovic, M. Slotted FAMA: A MAC Protocol for Underwater Acoustic Networks.In Proceedings of the OCEANS 2007, Singapore, May 2007; pp. 1–7.

[27] Diamant, R.; Lampe, L. Spatial reuse time-division multiple access for broadcast ad hoc underwater acoustic communication networks. IEEE J. Ocean. Eng. 2011, 36, 172–185.

[28] Park, M.K.; Rodoplu, V. UWAN-MAC: An energy-efficient mac protocol for underwater acoustic wireless sensor networks. IEEE J. Ocean. Eng. 2007, 32, 710–720.

[29] Zhu, Y.; Jiang, Z.; Peng, Z.; Zuba, M.; Cui, J.; Chen, H. Toward Practical MAC Design for Underwater Acoustic Networks. In Proceedings of the IEEE INFOCOM, Turin, Italy, April 2013.

[30] Tanenbaum, A.S.; Wetherall, D.J. Computer Networks; Prentice Hall: Boston, MA, USA, 2010.

[31] Xiao, Y.; Zhang, Y.; Gibson, J.; Xie, G.; Chen, H. Performance analysis of ALOHA and p-persistent ALOHA for multi-hop underwater acoustic sensor networks. Clust. Comput. 2011, 14, 65–80.

[32] Chirdchoo, N.; Soh, W.; Chua, K. Aloha-Based MAC Protocols with Collision Avoidance for Underwater Acoustic Networks. In Proceedings of the 26th IEEE International Conference on Computer Communications, Anchorage, AK, USA, May 2007; pp. 2271–2275.

[33] Karn, P. MACA—A New Channel Access Method for Packet Radio. In Proceedings of the ARRL/CRRL Amateur Radio 9th Computer Networking Conference, London, UK, September 1990; pp. 134–140.

[34] Ng, H.H.; Soh, W.S.; Motani, M. MACA-U: A Media Access Protocol for Underwater Acoustic Networks. In Proceedings of the 2008 IEEE Global Telecommunications Conference, New Orleans, LO, USA, December 2008; pp. 1–5.

[35] Guo, X. A Propagation-Delay-Tolerant Collision Avoidance Protocol for Underwater Acoustic Sensor Networks. In Proceedings of the OCEANS 2006, Singapore, May 2007; pp. 1–6.

[36] Liao, W.H.; Huang, C.C. SF-MAC: A Spatially Fair MAC Protocol for Underwater Acoustic Sensor Networks. IEEE Sens. J. 2012, 12, 1686–1694.

[37] Peleato, B.; Stojanovic, M. Distance aware collision avoidance protocol for ad-hoc underwater acoustic sensor networks. IEEE Commun. Lett. 2007, 11, 1025–1027.

[38] Fullmer, C.L.; Garcia-Luna-Aceves, J.J. Floor acquisition multiple access (FAMA) for packet-radio networks. SIGCOMM Comput. Commun. Rev. 1995, 25, 262–273.

[39] Peng, Z.; Zhou, Z.; Guo, Z.; Cui, J.H. COPE-MAC: A Contention-Based Medium Access Control Protocol with Parallel Reservation for Underwater Acoustic Networks. In Proceedings of the IEEE OCEANS 2010, Sydney, Australia, May 2010.

[40] Xie, P.; Cui, J.H. R-MAC: An Energy-Efficient MAC Protocol for Underwater Sensor Networks. In Proceedings of the IEEE International Conference on Wireless Algorithms, Systems and Applications, WASA 2007, Chicago, IL, USA, August 2007; pp. 187–198.

[41] Noh, Y.; Wang, P.; Lee, U.; Torres, D.; Gerla, M. DOTS: A Propagation Delay-Aware Opportunistic MAC Protocol for Underwater Sensor Networks. In Proceedings of the 18th IEEE International Conference on Network Protocols, Kyoto, Japan, October 2010; pp. 183–192.

[42] Chirdchoo, N.; Soh, W.S.; Chua, K. RIPT: A Receiver-Initiated Reservation-Based Protocol for Underwater Acoustic Networks. IEEE J. Sel. Areas Commun. 2008, 26, 1744–1753.

[43] Syed, A.; Ye, W.; Heidemann, J. T-Lohi: A New Class of MAC Protocols for Underwater Acoustic Sensor Networks. In Proceedings of the 27th IEEE Conference on Computer Communications, Phoenix, AZ, USA, April 2008; pp. 231–235.

[44] G. Xiaoxing, R. Frater, and J. Ryan. "An adaptive propagation-delaytolerant MAC protocol for underwater acoustic sensor networks". In Proceedings of MTS/IEEE OCEANS 2007, Aberdeen, Scotland, June 18– 21 2007.

[45] W. R. Heinzelman, et al., "Energy-Scalable algorithms and protocols for Wireless Sensor Networks", in the Proceedings of the International Conference on Acoustics, Speech, and Signal Processing (ICASSP '00), Istanbul, Turkey, June 2000.

[46] B. Peleato and M. Stojanovic. "Distance aware collision avoidance protocol for adhoc underwater acoustic sensor networks. Communications Letters", IEEE, 11(12):1025–1027, December 2007.

[47] G. Lu, B. Krishnamachari, C. Raghavendra: An Adaptive Energy Efficient and Low Latency MAC for Data Gathering in Wireless Sensor Networks, Proceedings of 18thth International Parallel and Distributed Processing Symposium (April 2004).

[48] ChoJaejoon,KimSungho,NamHeungwoo, et al. An Energy-Efficient Mechanism using CLMAC Protocol for Wireless Sensor Networks[C]//Proc. Of the third International Conference on Networking and Services (ICNS'07), Athens, 2007:3-3.

[49] B. Karp and H. T. Kung. GPSR: Greedy Perimeter Stateless Routing for Wireless Networks. In IEEE MobiCom, August 2000.

[50] Underwater Acoustic Wireless Sensor Networks: Advances and Future Trends in Physical, MAC and Routing Layers , Salvador Climent ; Antonio Sanchez , Juan Vicente Capella , Nirvana Meratnia and Juan Jose Serrano ,Sensors 2014, 14, 795-833; doi:10.3390/s140100795.

[51] Underwater Acoustic Sensor Networks: A Survey on MAC and Routing Protocols , Lakshmi Movva, Chaithanya Kurra, Koteswara Rao G, Ramesh Babu Battula,Miriyala Sridhar,Paruchuri Harish;IJCTA,2012.

[52] P. Casari, and M. Zorzi, "Protocol Design Issues in Underwater Acoustic Networks," Computer Communications, Vol. 34, No.17, Nov. 2011, pp. 2013-2025.

[53] L. Liu, S. Zhou, and J-H. Cui, "Prospects and Problems of Wireless Communication for Underwater Sensor Networks," Wireless Communications and Mobile Computing, Vol. 8, No. 8, Oct. 2008, pp. 977-994.

[54] J. Partan, J. Kurose, and B. N. Levine, "A Survey of Practical Issues in Underwater Networks," Proceedings of WUWNet'06, Sept.2006, pp. 17-24.

[55] E. M. Sozer, J. A. Rice, and M.Stojanovic, "Shallow Water Acoustic Networks," IEEE CommunicationsMagazines, Vol.39, No.11, Nov. 2001, pp.114-119.

[56] I. F. Akyildiz, D. Pompili, and T. Melodia, "Underwater Acoustic Sensor Networks: Research Challenges," Ad Hoc Networks, Vol.3, No.3, May. 2005, pp.257-279.

[57] E. M. Sozer, M. Stojanovic, and J .G. Proakis, "Underwater Acoustic Networks," IEEE Journal of Oceanic Engineering, Vol.25, No.1, Jan. 2000, pp.72-83.

[58] G. A. Shah, "A Survey on Medium Access Control in Underwater Acoustic Sensor Networks," Proceeding of WAINA '09, May 2009, pp.1178-1183.

[59] F. Yunus, S. H. S Ariffin, and Y. Zahedi, "A Survey of Existing Medium Access Control (MAC) for Underwater Wireless Sensor Networks (UASN)," Proceedings of Mathematical/Analytical Modeling and Computer Simulation (AMS), May 2010, pp.544-549.

[60] M. Erol-Kantarci, H. T. Mouftah, and S. Oktug, "A Survey of Architectures and Localization Techniques for Underwater Acoustic Sensor Networks," IEEE Communications Surveys & Tutorials, Vol.13, No.3, March 2011, pp.487-502.

[61] I. F. Akyildiz, D. Pompili, and T. Melodia, "Challenges for Efficient Communication in Underwater Acoustic Sensor Networks," ACM SIGBED Review, Vol.1, No.2, July 2004, pp.3-8

[62] G. E. Burrowes, and J. Y. Khan, "Investigation of A Short-range Underwater Acoustic Communication Channel for MAC Protocol Design," Proceedings of Signal Processing and Communication Systems (ICSPCS), Dec. 2010, pp.1-8.

[63] K. B. Kredo II and P. Mohapatra, "A Hybrid Medium Access Control Protocol for Underwater Wireless Networks," Proceedings of MobiCom'07, Sept. 2007, pp.33-40.

[64] Y. Ma, Z. Guo, Y. Feng, M. Jiang and G. Feng, "C-MAC: A TDMAbased MAC Protocol for Underwater Acoustic Sensor Networks," Proceedings of NSWCTC'09, April 2009, pp.728-731.

[65] P. Casari, F. E. Lapiccirella, and M. Zorzi, "A Detailed Simulation Study of the UWAN-MAC Protocol for Underwater Acoustic Networks," Proceedings of Oceans '07, Sept. 29 2007, pp.1-6

[66] J. Yackoski and C. Shen, "UW-FLASHR: Achieving High Channel Utilization in A Time-based Acoustic MAC Protocol," Proceedings of WUWNet '08, Sept. 2008, pp. 59-66

[67] W-H. Liao and C-C. Huang, "SF-MAC: A Spatially Fair MAC Protocol for Underwater Acoustic Sensor Networks," IEEE Sensors Journal, Vol.12, No.6, June 2012, pp.1686-1694.

[68] F. Dou, Z. Jin, Y. Su, and J. Liu, "WSF-MAC: A Weight-based Spatially Fair MAC Protocol for Underwater Sensor Networks," Proceedings of Consumer Electronics, Communications and Networks (CECNet), April 2012, pp.3708-3711.

[69] Z. Zhou, Z. Peng, J.-H. Cui, and Z. Shi, "Analyzing Multi-Channel MAC Protocols for Underwater Acoustic Sensor Networks," Technical Report UbiNet-TR08-02, Univ. of Connecticut, Dept. of Computer Science and Engineering, Aug. 2008.

[70] L. Tracy, and S. Roy, "A Reservation MAC for Ad-Hoc Underwater Acoustic Sensor Networks," Proceedings of MobiCom'08, Sept. 2008, pp 95-98.

[71] 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," Proceedings of Oceans'10, May 2010, pp.1-10.

[72] C.-M. Chao and Y.-Z. Wang, "A Multiple Rendezvous Multichannel MAC Protocol for Underwater Sensor Networks," Proceedings of Wireless Communications and Networking Conference (WCNC), April 2010, pp.1-6.

[73] C.-M. Chao, Y.-Z. Wang, and M.-W. Lu, "Multiple-Rendezvous Multichannel MAC Protocol Design for Underwater Sensor Networks,"IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems, Vol. 43, No. 1, Jan. 2013, pp.128-138.

[74] L.-C. Kuo, and T. Melodia, "Distributed Medium Access Control Strategies for MIMO Underwater Acoustic Networking," IEEE Transactions on Wireless Communications, Vol.10, No.8, Aug. 2011, pp.2523-2533.

[75] 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 Transactions on Mobile Computing, Vol.11, No.1, Jan. 2012, pp.139-154.

[76] M. Yang, M. Gao, C.H. Foh, J. Cai, and P. Chatzimisios, "DC-MAC: A Data-centric Multi-hop MAC Protocol for Underwater Acoustic Sensor Networks," Proceedings of Computers and Communications (ISCC), June 2011, pp.491-496.

[77] R. Diamant and L. Lampe, "A Hybrid Spatial Reuse MAC Protocol for Ad-hoc Underwater Acoustic Communication Networks," Proceedings of Communications Workshops, May 2010, pp.1-5.

[78] R. Diamant, and L. Lampe, "Spatial Reuse Time-Division Multiple Access for Broadcast Ad Hoc Underwater Acoustic Communication Networks," IEEE Journal of Oceanic Engineering, Vol.36, No.2, Apr.2011, pp.172-185.

[79] 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," Proceedings of UUASN'10, Dec. 2010.

[80] D. Pompili, T. Melodia, and I. Akyildiz, "A CDMA-based Medium Access Control for Underwater Acoustic Sensor Networks," IEEE Transactions on Wireless Communication Vol. 8, No. 4, April 2009, pp. 1899-1909.

[81] D. Pompili, T. Melodia, and I. Akyildiz, "A Distributed CDMA Medium Access Control for Underwater Acoustic Sensor Network," Proceedings of Mediterranean Ad Hoc Networking Workshop, 2007.

[82] D. Pompili, and I. Akyildiz, "Overview of Networking Protocols for Underwater Wireless Communications," IEEE Communications Magazine, Vol.47, No.1, January 2009, pp.97-102.

[83] H.-X. Tan and W.K.G. Seah, "Distributed CDMA-Based MAC Protocol for Underwater Sensor Networks," Proceedings of IEEE 32nd Conf. Local Computer Networks, 2007, pp. 26-36.3

[84] Kredo, K., II; Mohapatra, P. Distributed Scheduling and Routing in Underwater Wireless Networks. In Proceedings of the IEEE Global Telecommunications Conference GLOBECOM 2010, Miami, FL, USA, December 2010; pp. 1–6

[85] K. B. Kredo II and P. Mohapatra, "A Hybrid Medium Access Control Protocol for Underwater Wireless Networks," Proceedings of MobiCom'07, Sept. 2007, pp.33-40.

[86] Keyu Chen, Maode Ma, En Cheng, Fei Yuan, and Wei Su; " A Survey on MAC Protocols for Underwater" , IEEE COMMUNICATIONS SURVEYS & TUTORIALS, VOL. 16, NO. 3, THIRD QUARTER 2014.

[87] Feng Xiao, Qipei Liu, Mingyu Song, Jiansheng Tang; "A Survey on recent researches of MAC protocols in UASNs"", Proceedings of the 22nd International Congress on Acoustics, ICA2016-235,Sept.2016.

[88] Kayu Chen, Maode Ma, En Cheng, Fei Yuan and WeiSu ""A survey on MAC Protocols for Underwater Wireless Sensor Netwoks" IEEE Communications Surveys & Tutorials ,Volume: 16, Issue: 3, Third Quarter, 2014.