CHAPTER 1

MEDIUM ACCESS CONTROL LAYER FOR UNDERWATER SENSOR NETWORKS[*]

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There are increasing interests in underwater sensor networks (USNs). Different from terrestrial radio-based sensor networks, communication in underwater sensor networks relies on acoustic signals. Acoustic signals have a propagation speed that is around five orders of magnitude slower than radio signals. Meanwhile, featured by the bandwidth limitations, high transmit energy cost, complex multi-path effects, and high bit-error rates; medium access control (MAC) with an acoustic medium in USNs becomes a complex and challenging problem. In this chapter, we will discuss various MAC protocols which are designed for short range acoustic underwater sensor networks, energy-efficient reliable MAC protocol, and slotted FAMA MAC protocol and low-power acoustic modem for dense underwater sensor networks.

1. Introduction

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The earth is water planet. Over two-thirds of the surface of the earth is covered by the ocean [21]. Long time ago, the ocean is mystery to Human being and thus attracted lots of interests to learn about it. Even in nowadays research, the aqueous environment (including oceans, rivers, lakes, ponds and reservoirs, etc.) is also a critical research area for many scientists and different applications, such as scientific exploration, commercial exploitation and attack protection [21].

Usually, underwater environment monitoring is the common way to learn the ocean. Through monitoring underwater environmental variables, such as water temperature, pressure, conductivity, turbidity and certain pollutants [22], people have achieved more and more understanding of the ocean. The application of underwater sensor networks has also attracted more and more interests .

The traditional way to monitor ocean bottom or column is to connect underwater sensors by cables [20], and this approach seriously limits the flexibility and applicable of existing wired underwater surveillance systems. The stability of the system could be threatened by many situations. For instance, wires might be cut-off by intruders, which would make monitored data fail to be transported. Also, a power outage might render the system unusable. Finally, such deployment might be unsuitable for some real time monitoring applications. For example, in the application of seismic monitoring, the cables connecting sensors or instruments are likely broken due to the rupture of the earth's crust.

To solve the above problem and broaden the underwater surveillance applications, underwater acoustic sensor networks (UASN) is proposed [20], which relies on the transmission of underwater sensory data through wireless acoustic connections that improve failure resilience otherwise present in their wired counterparts. UASNs can support lots of potential applications, such as monitoring environmental factors (such as seismic events detection in underwater environment, weather condition forecast, etc.) coordinating marine/submarine equipments (such as navigating ships) [1]. An important example is in the offshore oil industry, UASN enables wireless communication between submarine controlled vehicles as well as some elements which are above the surface of the sea. The viability of wireless acoustic transmission lowers the cost in installing an oil platform [1] and as well as improves failure resilience compared with traditional underwater sensor networks.

A UASN is constituted by a number of sensors and underwater vehicles, which are deployed in a specific underwater area to perform collaborative monitoring tasks. Sensor nodes and vehicles communicate with each other through acoustic signals [1]. They are required to be capable of self-configuration, which means that they must be able to coordinate to do actions based on exchanging self configurations like location and movement information and then to relay monitored data to an above ocean surface station [1].

Underwater sensor networks are different from terrestrial sensor networks in many aspects, including physical, technological and economic differences. However, research on application specific protocols of UASNs is still in its early stage. Due to the great difference between the acoustic communication and the terrestrial radio propagation environments, it is hard to say if the experiences for designing the radio signal protocols can be reprocessed in a way so that it can be applicable for underwater acoustic communications [1].

In this chapter, we investigate the features (e.g., more costly equipment, higher mobility, and different energy regimes) of underwater networks, especially related MAC protocols. Although there have been some work on the development of MAC and routing protocols, the fundamental networking primitive, that is broadcast, has not been fully explored yet. Broadcast is the basic and essential way for varieties of vital networking functions, like neighbor discovery, route establishment, and data transmissions [1]. Broadcast is also with a higher probability of correct delivery than directly routing to destination in some specific applications like tsunami detection [1]. Meanwhile, reliable broadcast is required in some network applications such as network reprogramming of nodes [1]. However, for the higher costs for acoustic modems, the broadcast among underwater acoustic sensors is still unreliable [1]. Thus, the unique properties of the underwater acoustic channel should be furnished to design novel protocols with reliable broadcast that are different from radio networks.

The rest of the chapter is organized as follows. In Section 2, we present the basic practical issues in UASNs. Then, we discuss various challenges of MAC protocol design for UASNs in Section 3. We will study different MAC and routing protocols in UASNs in Sections 4 and 5, respectively.

2. UASN Communication Architecture

2.1. *Two Types of Architecture*

In [20], two types of architecture are discussed: static two-dimensional UASNs for ocean bottom monitoring, and static three-dimensional UASNs for ocean column monitoring.

2.1.1. *Two-dimensional UASNs*

In two-dimensional architecture, sensor nodes are anchored to the bottom of the monitored underwater environment, such as an ocean, river, etc., [20]. The wireless acoustic links of UWSNs are established based on the interconnection between sensor nodes with one or more underwater sinks, which are also called UW-sinks functioning to relay data from the underwater sensors to the surface stations [20]. For this purpose, two acoustic transceivers are required on UW-sinks [20]. One is a vertical transceiver and the other is a horizontal transceiver [20]. The horizontal transceiver is used to communicate with the sensor nodes in terms of UW-sink to sensors communication and sensors to UW-sink communication, respectively. By comparison, the vertical transceiver of UW-sink relays data to a surface station. The surface station is capable to handle multiple parallel acoustic signals sent by the surrounding UW-sinks. In addition, a RF/satellite transmitter with long range is also deployed in the surface station to communicate with the onshore sink.

The connection between sensor and UW-sink can be established in two ways, direct link or multi-hop routing. By using direct link, sensors are able to send data directly to the selected UW-sink, while in multi-hop routing approach, the gathered data is forwarded by multiple intermediate nodes until it reaches the UW-sink [20].

2.1.2. *Three-dimensional UASNs*

In three-dimensional architecture, sensor nodes are deployed to be floating at different depths in the ocean for cooperative 3D environmental sampling. Meanwhile, each UW-sensor node is fixed to a surface buoy by a wire which can be adjusted for proper and suitable length, which is the depth of the sensor [20]. However, this architecture faces many challenges. First, sensors need to collaboratively regulate their depths to maximize the coverage of the whole network according to sensing ranges and communication coverage. Secondly, since there is no UW-sink deployed underwater, collected data should be correctly relayed to the surface station via multiple hops. Therefore, network devices should coordinate their depths so that for each sensor there should be at least one existing path for it to be connected with at least one surface station [20].

2.2. *Underwater Network Operating Regime*

Spatial coverage and node density are used to characterize underwater networks. Significant implicit factors related to the MAC layer and the network layer must be considered at design issues [1].

Two different scales of communications should be considered according to acoustic range of the nodes. For nodes that are in direct contact, the network works as a single hop network, which can be centralized or distributed control. Furthermore, for multiple-hop communication, the network is a larger communication network for data to reach destination. There is a situation that geographic coverage might be larger than the unpartitioned link-layer coverage of all nodes and then disruption-tolerant networking (DTN) routing techniques are required [1]. Due to the unique feature of acoustic signals, when lots of sensor nodes deployed in a small area, conflicts will be a serious problem for communication [1]. Secondly it will cost a lot for densely deployment in huge underwater environment, which makes DTNs an attractive solution [1]. In a UASN, both single hop and multi-hop clusters can be deployed to construct the whole network, in which DTN routing could be employed for infrequent communication [1].

Catipovic described the features of underwater acoustic channel in [2]. He also reviews the recent work implemented with another two media in underwater networks, i.e., long-wave radio and optical underwater networks. He also explains related technological limits for nodes and the further influence on the network topology etc.

2.2.1. *Physical Channel*

In underwater environment, acoustic signals are the main way used for communication. Neither radio signal nor optical signal is appropriate for the underwater communication. Ocean water is very salty water, which critically attenuates the radio waves [1]. There are also some applications of long-wave radio but only applicable for short-distance communication. Light signal is easily scattered and absorbed by water although some connections in absolutely clear water working with short range and high bandwidth may employ blue-green wavelengths [1]. In underwater environment, optical signal is also considered as an efficient communication media only for low-cost, short-range connections of order 1–2m [1]. The expectation of date rate for optical modems in extremely clear water is several Mbits/sec at ranges up to 100m [1]. Therefore, acoustic signal is the only appropriate way for communication for long range communication in underwater environment with common water clarity. The typical feature accompanied the acoustic communication is great propagation delay due to the slow spread speed of sound in water, which is approximately 1500 m/s, five orders of magnitude lower than the speed of light [1]. Compared to radio signal, acoustic signal has several other aspects of constraints, such as the correctness, bandwidth and channel dependency [1]. Firstly, there is a higher bit-error probability in acoustic communication because of its phase and amplitude fluctuations while forward error correction or error correction coding is required by radio channels [1]. Secondly, the bandwidth of acoustic communication is quite limited due to the strong attenuation, especially with increasing frequency [1]. Thirdly, acoustic communication can be disturbed by the environment, and the most common one is the multipath interference, which causes frequency-selectivity of the channel. Such frequency-dependent interference is always time-varying and might be caused by many different factors such as surface waves or vehicle motion [1]. However, the propagation delay of acoustic channels is always can be estimated and stable enough for configuring the network protocols [1].

2.2.2. *Technological Limitations*

The communication of underwater acoustic network is always half-duplex. The acoustic transducers can only do one thing of transmission and reception at the same time [1]. Because of the space constraint of the underwater environment, the network cannot provide far enough space for transducers in different frequency for establishing full-duplex connections [1]. Both autonomous underwater vehicles (AUVs) and compact stationary nodes follow the constraint. Meanwhile, the transducer size is proportional to wavelength and usually only higher center frequencies are available for small AUVs [1]. Furthermore, small AUVs can transmit data at high rates while cannot receive data at such high rates. There are mainly two aspects that contribute to the asymmetry, propulsion noise and mounting receiver of small AUVs [1]. The asymmetry in sending and receiving rates is also the main reason of the popularity of star topologies with base stations in current mobile underwater networks [1].

3. Challenges of MAC Protocol Design for UASNs

Because of the unique characteristics of acoustic channel and propagation, the design of acoustic communication sensor networks is a difficult problem. In this section, underwater acoustic communication channel and associated MAC layer challenges for underwater networking are summarized. The design challenges for UASNs are also discussed.

3.1. ***Underwater Communication Channels***

The spread of acoustic signal in underwater environment is about 1500m/sec, which is five orders of magnitude lower than the radio propagation speed. Only very limited bandwidth of underwater acoustic channels is available, which could be influenced by many factors, such as transmission range, frequency, etc. [21]

3.2. *The impact of Acoustic Propagation*

The challenge of underwater acoustic communication system is mainly caused by acoustic propagation in underwater environment. In [23] several aspects were discussed, such as speed of sound, channel latency, ambient noise, etc.

- *Acoustic signal propagation in seawater*: Spreading loss and absorption loss are critical feature of acoustic propagation [23]. When acoustic signal is sent out, the energy of the signal is fixed and expands when the signal is transmitted over large surface area [23]. Usually, sphere is used to describe the surface area, especially for short ranges [23] and the decay of the signal energy is at rate of R^{-2} where R is the distance from source [23]. Meanwhile, the surface and seabed form a natural boundary of the underwater environment, which also bound the range of acoustic communication [23]. Sometimes, when acoustic signals are sent out from a source, the signal cannot vertically spread [23]. Meanwhile, the spread of the signal, which should be spherical spreading, may change to cylindrical spreading. Such a situation may occur especially when the ranges are larger than the depth of the water [23]. Therefore the loss is the energy conversion during the propagation into heat, which is called absorption loss [23].
- *Waveguide propagation, multipath and shadow zones*: Acoustic signals can be refracted and reflected due to the environment. The refraction happens because the speed of sound varies spatially in the water column, while the reflection happens because of the bound formed by sea surface and bottom [23]. Both refractions and reflections could result in that the signal propagates in multiple paths to the destination, which could result in inter-symbol interference at the receiver [23]. Meanwhile, temporal

fluctuations have great relationship with the propagation environment variations and transmitting or receiving platforms [23].

- *Scattering Surface*: The moving sea surface can make the transmitted signal be scattered, which is a seriously challenging communication scenarios [23]. Rough sea surface provides various delays of surface bounce paths and reduces the space connection of scattered signals, which results in channel impulse response with high intensity [23].
- *Bubbles*: Breaking waves at the sea surface can produce bubbles, which greatly influent the propagation of high frequency acoustic signals both in open ocean and near shore regions [23]. Meanwhile, different layers of bubbles existing near the surface can cause a significant attenuation of surface scattered signals [23].
- *Environment noise*: Some natural sources, such as biological sources and rain, leading to environment noise in the ocean are breaking waves and bubbles. The common theme known for ambient noise is that for higher frequency, there will be a decrease of the power spectral density of the noise [23].

3.3. *Considerations for the Design of Underwater Protocols*

Lots of factors are able to hold great impact on the communication of underwater acoustic signals, such as transmission loss, noise, multipath, Doppler spread, varieties of propagation delays, as well as availability of rang and frequency dependent bandwidth [24]. The bandwidth available for long-range systems, such as over tens of kilometers is only a few kHz, while the bandwidth for short-range systems, such as operating over only several tens of meters is more than a hundred kHz [24].

The depth of water is a serious factor impacting UANs. The water no deeper than 100m is considered as shallow, which may with a larger bound for deeper oceans. There are many factors influent the underwater acoustic communication as follows:

- *Transmission loss*. Attenuation and geometric spreading are the main concern of transmission loss [24]. The attenuation mainly refers to the energy absorption or conversion into heat. Larger distance or higher frequency is corresponding to more serious attenuation [24].The geometric spreading can also spread the energy of acoustic signals because of the expansions of the wave fronts. Propagation distance could increase the geometric spreading, while frequency of the signal has nothing to do with it.

- *Noise including man-made noise and ambient noise*. Environment noise includes the man-made noise and natural noise. Man-made noises mainly refer to machinery noise like pumps, reduction gears and shipping activity [24]. Natural phenomenon like hydrodynamics, seismic and biological phenomena can cause ambient noise [24].
- *Multipath*. The propagation in multipath can severely degrade the acoustic signal. The link configuration such as horizontal channels characterization determines the geometry of multipath [24].
- *High delay and delay variance*. The speed of sound in underwater environment is five orders of magnitude lower than the radio signals. The throughput of the system can be reduced considerably by large propagation delay and its high variance.
- *Doppler spread*. The Doppler frequency spread can highly degrade digital communications and transmissions, which leads to the interference of many adjacent symbols at the receiver [18]. Some other situations are also greatly related to the Doppler spreading, such as simple frequency translation and a continuous spread of frequencies [24].
- *Bandwidth*. Bandwidth is very much limited in ranges of 0.1Km and 1000 Km of nearly 100 KHz and 1 KHz, respectively, leading fairly lower data rates than terrestrial wireless communications [13].
- *Attenuation*. The channel of underwater acoustic signal is quite impaired, resulting from absorption, multi-path, attenuation, and fading problems. Especially, there are

significant absorptive losses in underwater acoustic signals which greatly depend on frequency [13].

- *Shadow zones and channel characteristics.* The extreme characteristics of the underwater channel like salinity, density and temperature variations may cause high bit error and unconnected [13].

4. MAC protocols for underwater acoustic sensor networks

Medium access is an open problem in underwater acoustic networks [1]. In traditional radio networks, MAC protocols are a great attention in radio-based sensor networks and have been studied for at least10 years.

4.1. *Recent Work in Underwater MAC Protocols*

A variety of MAC protocols in underwater networks have been explored. Some MAC protocols like Aloha [14] are already been discussed in various research paper. In order to avoid collisions in the situation when two stations transmit concurrently, carrier sensing multiple access (CSMA) [15] and its mutants have been employed. Based on such protocols, stations are required to “listen” to the channel before transmitting packets and after it is sure there won’t be any collision they can continue to transmit. In fully connected and small propagation networks, CSMA is an efficient protocol. However, for the situation of both hidden and exposed terminal problems, it is insecure to employ protocols based on CSMA [1].

In [16], Karn a MAC protocol named MACA (Multiple Access Collision Avoidance) is proposed. In this protocol, any node planning to transmit a data will send a control packet first to the destination node, which is called RTS (Request To Send) [13]. Then the destination node replies the sender a CTS (Clear To Send) control packet, which also warns all its neighbors about its activity of sending packets. In [17], Bharghavan proposed a protocol called MACAW (MACA-Wireless), which modified some parts of the original MACA protocol. An adaptive back off algorithm is exploited in this protocol [17].And an ARQ technique is also added as a feature of this protocol, which resend packets with errors [17]. Fullmer and Garcia-Luna-Aceves [4] described the conditions to avoid collisions among data packets in a MACA. In [4], FAMA is exploited to prevent data packets from collisions with extending the time slots for the RTS and CTS. All these protocols need multi-way handshakes so propagation delays seriously reduce their efficiency. In order to make MACA, MACAW, and FAMA applicable for UANs, researchers have spent lots of efforts and made related adaptations to these protocols. In [13], Molins and Stojanovic proposed Slotted FAMA, which lessens the impact of propagation delays by introducing timeslots to FAMA. In [6], Kebkal *et al.* suggested to introduce ACK scheme in data transmission in order to reduce the impact of propagation delay on FAMA-and MACAW- based protocols as well as applying CDMA for RTS packets to avoid collisions. *Foo et al.* [7] provide more detailed proposition to extend CDMA to MACA with references to the radio-based MAC protocols.

There are also efforts, like current Seaweb implementations, trying to use combined TDMA/CDMA clusters, which is also described by Salv´a-Garau and Stojanovic [8]. This approach shortens the TDMA slot while increasing overheads and the interference probability among clusters. In [9], Doukkali and Nuaymi analyze several MAC protocols for underwater environment, including the TDMA-CDMA clusters [9].

Energy efficiency is a critical consideration not only in terrestrial sensor networks but also in underwater networks. Coordinated-sleeping MAC protocols such as S-MAC, are results of efforts to overcome energy constraints in terrestrial sensor networks [26]. Adopting these ideas as well as referencing some other MAC protocols both in underwater and terrestrial networks, Park and Rodoplu [11] proposed an energy efficient UWAN-MAC protocol for delay-tolerant underwater sensor networks. In the following discussion, we introduce some MAC protocols designed for underwater acoustic networks.

4.2. *Tone Lohi MAC protocol [12]*

In [12] Tone Lohi (T-Lohi), is discussed, which is a reservation based MAC protocol. T-Lohi MAC is proposed with mainly two ideas. One idea is to detect and count the number of contenders during the reservation and a traffic-adaptive back-off algorithm is proposed according to that number. As the duration for the occupication of the channel by contention packets is much less than the propagation delay, nodes are able to detect and count contenders as long as the duration of the occupication [12]. The other idea is employing a wake-up tone for the purpose of reserving the data transmission. Each node is equipped with a hardware wake-up tone detector on the acoustic modem, based on which nodes can spend minimal energy during listening to the tone. Substantial energy savings can be achieved by applying the wake-up tone during the reservation phase. The reservation protects the data transmission from collision and saves energy [12].

A reservation period is included in the T-Lohi protocol. The period includes multiple contention slots and is typically on the order of tenths of a second and after the period is a data transmission period. When a node tries to reserve the data transmission period, it will first transmit a tone during the reservation period. Other nodes will back off when they hear the tone.. And a node can finally occupy the data period to transmit data only if it successfully finished the transmission of the tone without hearing another tone during a contention slot [12]. T-Lohi protocol has mainly two variants: synchronized tone (ST) and unsynchronized tone (UT) Lohi protocols. For brevity we only describe the more efficient protocol, ST-Lohi [12].

In ST-Lohi [6], all stations are aligned to contention slots, i.e., a length of the maximum propagation delay and the tone length. Each station sends reservation tones at the beginning of these slots, if not restricted by back-off. During the rest of the contention slot after finishing the tone, the node will wait and listen to possible arrival tones. If no tones heard, it wins the reservation, and immediately sends its data, as shown in Fig. 1.

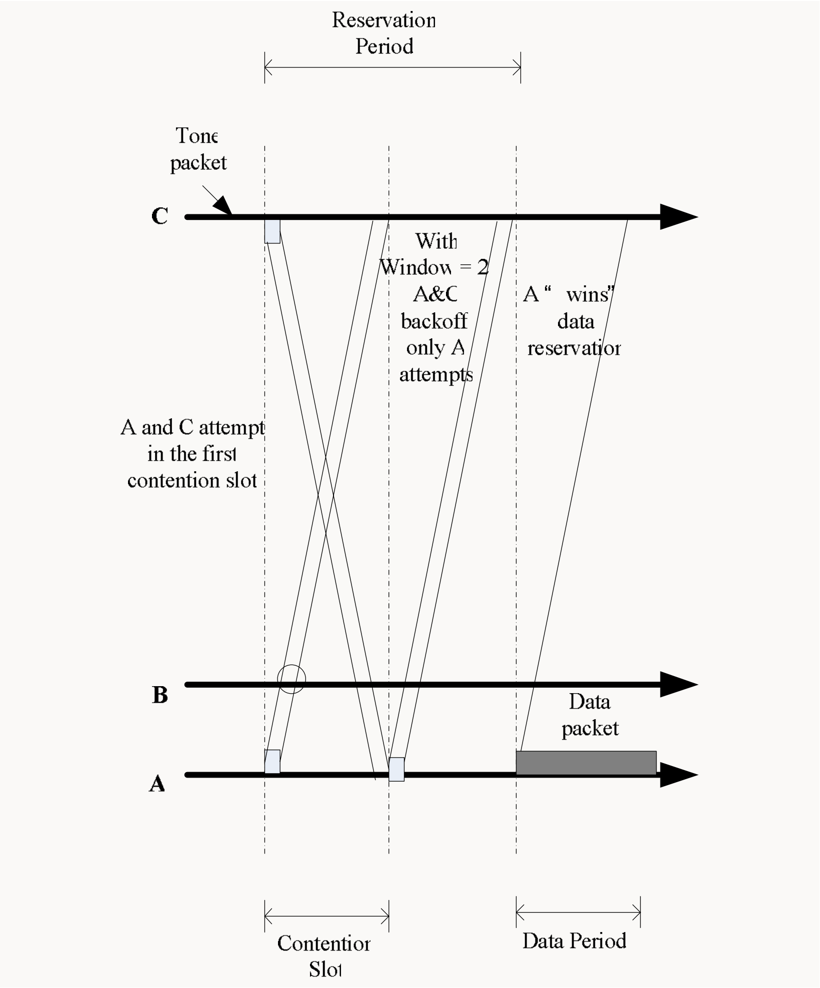

Fig. 1 ST-Lohi MAC [12]

If multiple nodes try to reserve the medium at the same time, they have to back-off and retry later. The back-off nodes will count the tones received in a given slot, that is, the number of contenders which is used as their back-off window size. After the data packet is finally transmitted, nodes with previous contention do so with smaller window compared to those nodes without contention. [12].

An interesting observation of medium access in acoustic medium with high latency is Space-time uncertainty [12]. Not only concurrent transmissions but also transmissions at different time and distances can cause collisions. To synchronize the transmission time is able to remove one dimension of uncertainty, and to wait for the maximum propagation delay can remove the other [12]. This uncertainty is due to the scheme of ST-Lohi, waiting for enough time (the maximum propagation time) in order to detect any possible collisions [12]. When there are no tones of contention, the node successfully "win" the reservation of the channel and its data can be transmitted in the next time slot. Usually, nodes are at different physical places in space, so even they might transmit in same time, their contention tones arrive at different time [12]. Nodes are allowed to count the number of contenders based on the space-time separation and the count is a basic consideration to intelligently select the back off for subsequent contention periods. Using the wake-up tone abstraction can achieve energy efficiency, which allows that nodes don't have to be fully active for the entire contention slot to transmit/ receive tones [12].

4.3. *Slotted FAMA*

As FAMA [4] protocol needs RTS and CTS packets, it would not be efficient in underwater acoustic networks. And data collisions are another problem in FAMA when violating these conditions, which is shown in Fig. 2. The problem can be solved if the new packets are forbidden to be sent while data is being transmitted. Nodes should be restricted to send any packet if it would collide with a current transmission. Slotted FAMA [13] apply a restriction on the time when packets are sent, which slots the time to eliminate the asynchronous nature of the protocols. All kinds of packets, including RTS, CTS, DATA or ACK, must be transmitted at the beginning of the slot. The way to choose the length of the slot length is to avoid all packet collisions. It seems that all nodes should know whether it will collide with an ongoing transmission if they send a packet at the beginning of the next time slot [13]. The way to accompany this is to set the time slot to be the total value of the maximum propagation delay τ and the transmission time of a CTS packet γ [13]. Such a choise of the time slot is to make sure that there is enough time for all the within range nodes to receive the RTS or CTS packet[13].

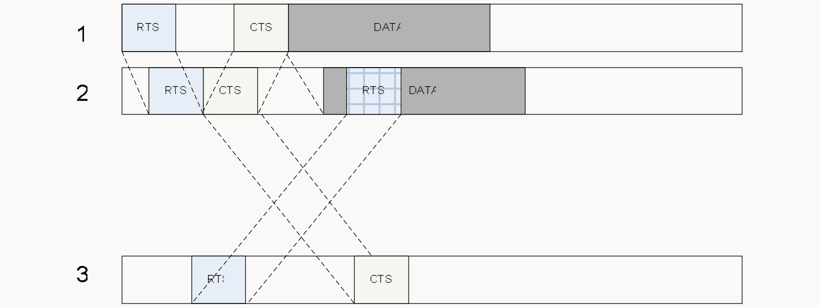

Fig. 2 RTS from C collides with data packet from A [13]

In Slotted FAMA [13], when a node needs to send a packet it first transmits an RTS packet and waits for the next slot, including the destination will receive the packet within the slot time. The destination node will then send a CTS packet at the beginning of the next slot [13]. All the terminals within the transitions range of the destination including the source node receive this CTS packet within the slot time. After receiving the CTS, the source knows that it has won the channel to send data, and it wait to send its data packet at the beginning of the next slot. After receiving the data packet, the receiver will also send ACK packet to confirm the successful transmission. Fig. 3 shows the whole process [13].

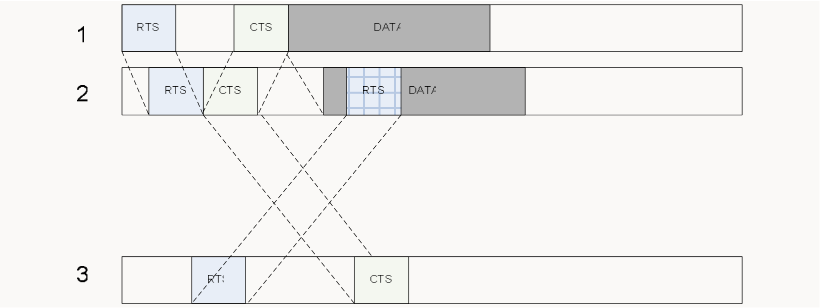

Fig. 3 A successful handshakes between terminals A and B in slotted FAMA [13]

Slotted FAMA [13] is mainly based on carrier sensing in which terminals are always listening to the channel. Terminals are keeping in Idle state when they don’t have packets to transmit or they cannot sense the carrier in the channel. When a node had packet to send and didn’t detect any carrier, then terminal sends an RTS and waits two slots for a CTS packet. During this time if no CTS received, the terminal assumed a collision existed and turned to Back off state for several slots, which is randomly decided. During the Backoff period if no carrier is sensed the terminal re-sends the RTS packet. And until the terminal successfully received CTS, it will begin transmitting the packet in the next time slot [13].

4.4. *An Energy Efficient MAC protocol for Underwater Wireless Acoustic Networks*

An energy-efficient distributed and scalable MAC protocol is presented in [5] which can work in spite of long, unknown propagation delays of acoustic medium in the underwater environment. This energy-efficient MAC protocol [5] can be used for underwater acoustic networks in which sensor nodes are quite energy-limited. Energy rather than bandwidth utilization is the main performance metric of such MAC protocols, which significantly differentiate the energy-efficient protocol from ALOHA, MACA, and MACAW protocols [5].

The basic idea of the energy-efficient protocol [5] is as shown in Fig. 4 below.

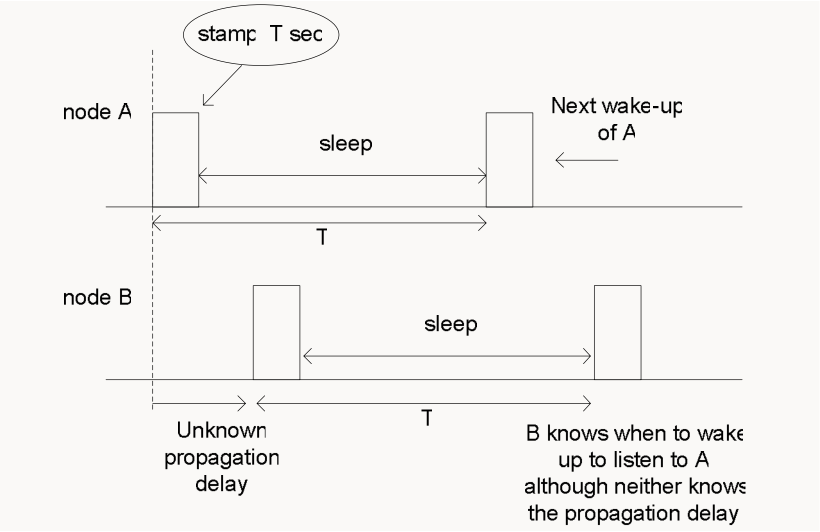

Fig. 4 Basic idea of MAC Protocol [5]

As a preamble, node A will send a beacon signal before its data transmission in any transmission cycle. The transmission cycle “T” of node A is announced. Whenever a new node (node B) tries to join the network it achieves frame synchronization by first listening to the channel for this preamble sequence [5].

Node B can achieve the value of transmission cycle period (T) through decoding the beacon message. This scheme stamping the transmission cycle explicitly enables node B to wake up exactly the correct time in the next cycle. As the propagation delay from one node to another normally remains the same, node B even has no need to know the value of the propagation delay [5]. This type of localized protocol can hold for any two nodes (A, B) [5]. Two types of collisions may occur in this protocol, which are and “” [5]. “Receive-receive collision” can occur when a node concurrently receives more than two data packets which overlap in duration. In such a situation both the two packets cannot be decoded correctly and related information is lost. “Transmit-receive collision” refers to when a node is transmitting data packet another packets from other nodes arrives at the node and collides with the node’s own transmission [5].

The topology control layer in [5] monitors the transmission of a node to track its neighbors and then determines when to wake up which node. The above scheme is used to predetermine the listen times and each node initially transmits a packet randomly and independently. In the protocol, once a transmission start time for a node is chosen, the node will send its data packet in the next cycle according to the schedule [5].

This protocol enhances existing protocol by choosing the duration of listen time. The duration is chosen as the sum of two values, SYNC packet duration and the maximum propagation delay between any two neighbors. Meanwhile, the choice of the length of duration induces trade off. If the duration is too long, it induces energy efficiency of the protocol while if it is too short it might lose some messages from the newcomers [5]. Also, in [5], guard time is adopted for both sides of its transmission durations.

4.5. *Modified MAC Protocol Design for the Underwater Acoustic Data Communication [19]*

There are some limitations to MAC protocol for UASNs including the acoustic transmission signal discussed before. The traffic data for an image transmission mainly requires the bit rate to be about 10-50 kbps. However, the physical layer of UASN, that is the acoustical transducers can support only 1-10 kbps bit rate. [19]. When multi-media data packets need to be transmitted in UASN, only one channel of acoustic medium is not capable enough to accomplish the transmissions. One way to extend the bit rate is to utilize multiple channels with different frequencies [19]. The protocol designed in [19] tries to balance the throughput and expected delay, both of which are mostly dependant on the transmission media and the transceiver [19].

There are many stations as well as many available acoustic channels in the underwater network. And each station can choose one of these channels to transmit data. In the following paragraphs, we study the collision free protocol designed in [19].

Fig. 5 shows carrier sensing transition algorithm, used when overflow which accumulate the idle time for each channels is occurred by the increasing flag [19]. If the carrier sensing is detected, the flags for the related channel is set to 0 and timer operates. The carrier sensing for the transmitting channel is detected as bit unit [19].

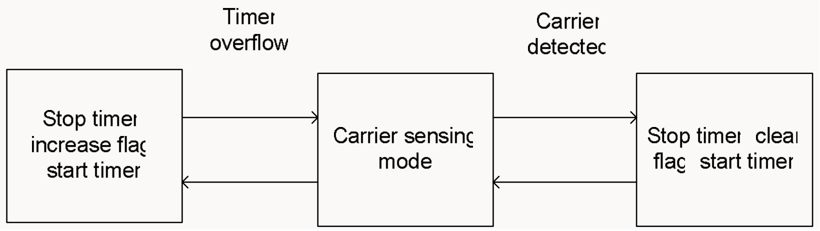

Fig. 5 The carrier sensing static diagram [19]

Fig. 6 describes the receiving state transition diagram. After receiving a frame, a station will first send ACK to related station. And then the station again turns to carrier sensing mode and processes the received frame. If the frame is with some error, , the station will send NAK signal to related stations and returned to carrier sensing mode as well as discarding the received frame.

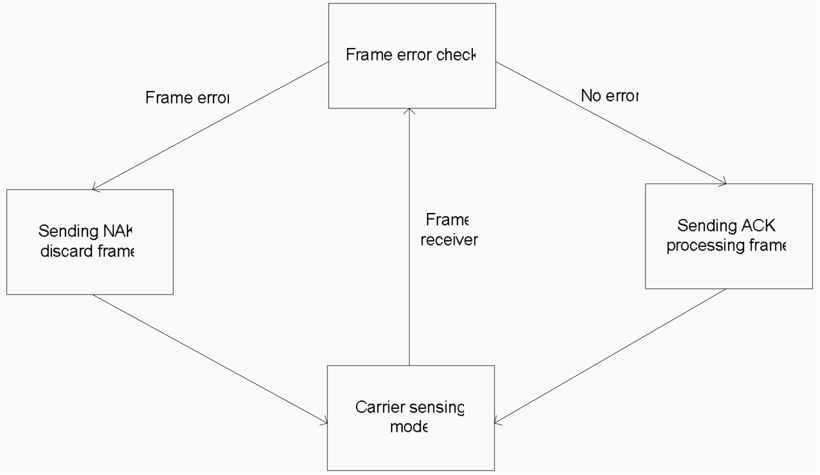

Fig. 6 The receiving state transition diagram [19]

The transmitting frame is built by requesting to frame transmit signal [19]. Fig. 7 shows transition procedure. In the transmitting frame one acoustical channel among them should be selected. In the first stage the candidate channel transmits the frame in its own station and to receive the frame in destination station is made to search. Fig. 8 shows the searching procedure and Fig. 9 shows the selecting procedure of candidate channels. The channel with the longest idle time is selected to transmit frame and after the transmission it returns to ACK receiving mode. In the case that no idle channel is found in the procedure, in order to search for candidate channels, carrier sensing is made [19].

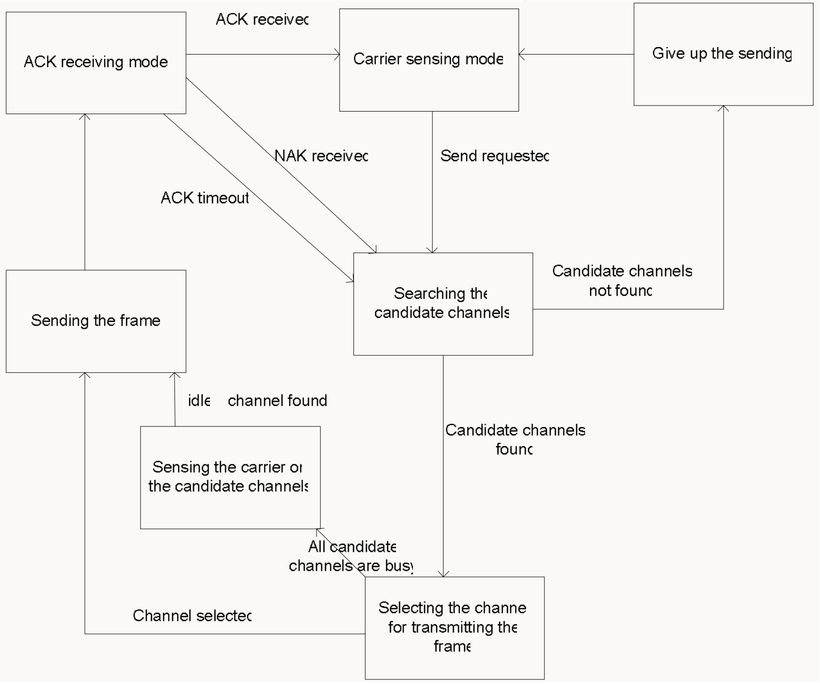

Fig. 7 The receiving sensing static diagram [19]

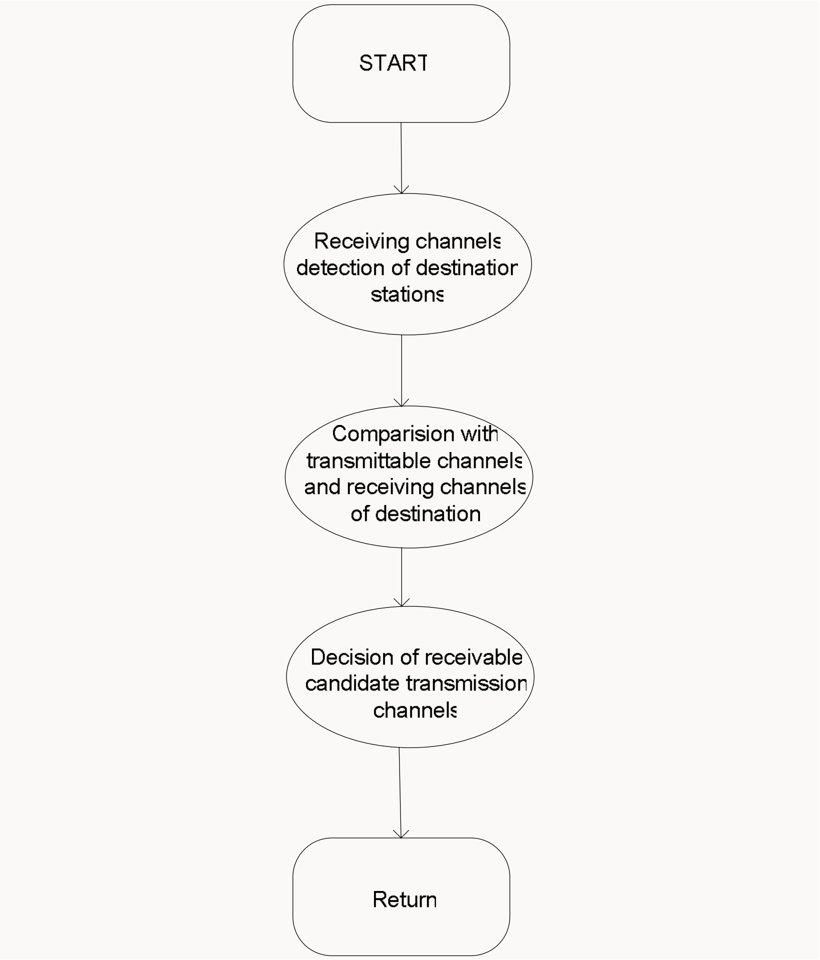

Fig. 8 The procedure for searching candidate channels

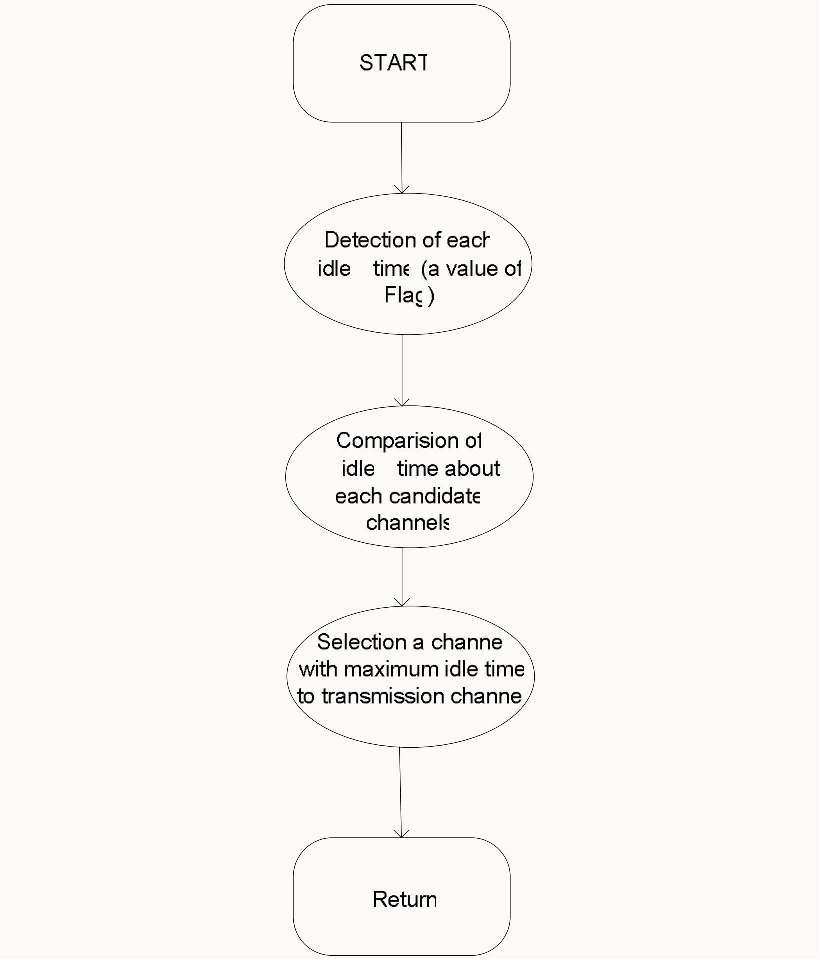

Fig. 9 The procedure for selecting the sending channel[19]

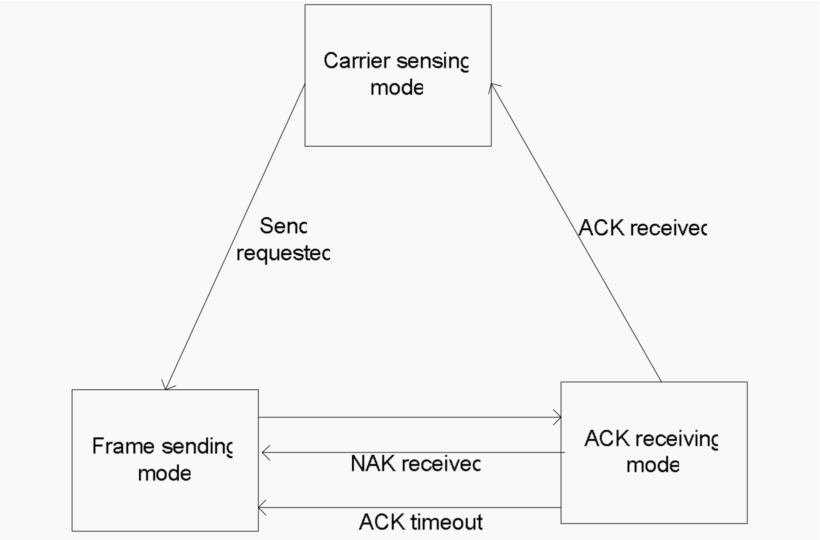

Fig. 10 The state transition diagram for receiving ACK [19]

Fig. 10 demonstrates the error control method, which includes the activity of stopping and waiting for ARQ. After finishing a frame transmission, the station turns back to ACK receive mode. If receiving NAK or not receiving ACK successfully, the station has to retransmitted the frame, just following the procedures previously explained [19].

5. Routing Protocols for Underwater Acoustic Sensor Network

5.1. *Three-Dimensional Routing Algorithms for Delay-insensitive and Delay-sensitive Applications in Underwater Sensor Networks*

In both [11] and [25], the features of underwater acoustic channel are discussed. Gathering data is an important consideration in a network, and that's also why routing protocols are so concerned by many researchers. In [25], cross-layer based network layer data gathering are discussed as well as the interactions between the routing and the unique feature of underwater acoustic medium. In addition, the distributed delay-insensitive routing algorithms and delay-sensitive routing algorithms are also presented in above papers. According to different application requirements and varying conditions of underwater acoustic channel, nodes can choose the next hop node for saving the energy consumption [11].

With the purpose of minimizing the energy consumption in the network, authors in [25], proposed two kinds of routing algorithms for delay-insensitive and delay-sensitive sensor network applications. Both algorithms allow sensor nodes to choose their next hop for an efficient path to save energy [25].

Compared to terrestrial sensor networks, underwater acoustic sensor networks are feathered with more challenges especially because of the more complex underwater environment and the larger delay of acoustic communication channels [25]. The most significant considerations of underwater acoustic sensor networks are summarized as follows [25]: 1) Compared to the radio based communication in terrestrial sensor network, the speed of acoustic signal in underwater environment is five orders of magnitude slower, which leads to much larger propagation delay for the communication in UASNs; 2) In underwater environment, acoustic signals have multipath and fading problems during the transmission, which severely make the underwater acoustic channel impaired; 3) Acoustic channel are always corresponded to high bit error rates as well as vulnerable connectivity, such as shadow zone ; 4) the bandwidth of acoustic medium is quite limited, which severely impacts the information transmission;5) Usually, after deployment in underwater environment, sensor nodes are not easy to recharge so that their battery power are quite limited; 6) Sensors may be eroded or foul in water, which makes the sensor nodes unable to work properly.

Delay-Insensitive Routing: In [25], delay-insensitive routing in 3D underwater environment is proposed for delay-insensitive applications. This routing algorithm is a distributed geographical routing solution. With the purpose of exploiting the channel efficiently as well as minimizing the energy consumption, the algorithm proposes the concept of packet train [25]. The idea of packet train is very similar with the idea in IEEE 802.11 [27-38]. Packet train is defined as juxtaposition of packets and it is a way of transmission that packets are transmitted back-to-back by a node and the node does not need to release the channel in a single atomic transmission. The ACK scheme is also included in the algorithm, which may need some packets to be retransmitted if ACKs are not correctly received in time. And in this algorithm, there are two kinds of retransmissions. One is to selectively request specific packets included in the next train to be retransmitted, and the other one is to cumulatively retransmit all packets that are included in the whole train.

From the energy saving point of view, the author designs the algorithm to allow nodes to select their next hop based on minimizing the energy cost [25]. When exploiting links, the algorithm tries to find those with low error rates in packets, that is, to find a way with maximum possibility that the receiver can correctly decode the data packet [25]. Meanwhile, the energy efficiency of the path is weighted by the retransmission number that is required during the communication, which objects to save energy [25].

The proposed strategy in [25] can achieve two objectives. Firstly, it can promote the efficiency of the channel which is achieved through the increment of the size of the transmitted train. Secondly, due to the short length of data packets, the error rate of transmissions is limited. The length of data packets greatly determines the error rate of the packets. The approach in this algorithm decouples the impact of the length of data packets and the choice of the train size [25]. Normally, when there is a need the size of the transmitted train can be increased which further increases the utilization of the channel [25].

Delay-Sensitive Routing: There are already many efforts spent on the development of the routing protocol in terrestrial sensor networks. For terrestrial ad-hoc and sensor networks, when designing routing protocols, researchers mainly follow a packet switching paradigm. In such paradigm, the routing functions separately work on each single packet and all the paths used during the routing is dynamically established [25]. UASNs are quite different from the terrestrial sensor network, which requires applicable routing protocols in the underwater environment. In UASNs, information or data packet is transmitted through acoustic medium, which is accompanied by large propagation delay and vulnerability in underwater environment. Meanwhile, compared to terrestrial networks, UASNs is relatively scare networks because it not as easy and convenient to deploy many sensor nodes as on the land [25]. Therefore, centralized planning of network topology is more applicable for UASNs, which can optimally utilize the resources in the network [25]. The design of routing protocol for UASNs can be achieved by devising some centralized protocols [25]. Because of the reasons discussed above, one technique could be considered for a delay-sensitive application in UASNs is virtual circuit routing technique. In such techniques, between each source and sink the multi-hop connections are established a priori and packets are also associated with a specific path [25]. The technique we discussed here, a centralized coordination is needed, which will limit the flexibility of the network architecture [25]. The strong point of the technique is with a centralized station the network can be exploited to achieve optimal performance at the network layer. For example, with the knowledge of global information, the central station is able to find a path according to needs, such as minimum delay paths for a time urgent packet or energy efficient paths just for saving the energy within the network, etc. In [25], authors concluded the problems related to the design of 3D routing protocol for delay-sensitive applications. The main optimization idea is to find two multi-hop data paths from each source to the station on the surface [25], which are called primary and backup data paths. Under such a scheme, if the primary path fails or some nodes on it cannot work normally, the backup path can offer protection for the communication [25].

6. Conclusion

In this chapter we have summarized practical issue of the differences between acoustic based underwater networks and terrestrial sensor networks which based on radio communication. The acoustic communication medium is one important factor that distinguishes the underwater sensor network from the terrestrial sensor networks. We first study the feature of the acoustic communication channel, especially its propagation character in underwater environment. Then we analyze the challenges of designing MAC protocol for underwater acoustic sensor networks (UASNs). After this analysis, we studied current achievements on MAC protocols for UASNs. Several MAC protocols for UASN were introduced, which includes ST-Lohi MAC protocol, a reservation based MAC protocol; as well as the Slotted FAMA which reduces the collisions among data packets and even doesn’t require the size of data packets. In Slotted FAMA a simple back off scheme is employed to achieve the avoidance of collisions. Power control is the main issue that is to be studied. Finally, some routing protocols are presented.

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