ABMP: adaptive bitmap protocol within TDMA for mobile underwater sensor networks

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Abstract

Media access control (MAC) protocol design is one of hot topics in the research of underwater acoustic sensor networks (UWSN). The major challenge is the phenomenon of space-time uncertainty caused by the long delay in underwater signal propagation, where the occurrence of frame conflict is determined by not only two nodes' transmission time, but also by their locations. In this paper, the adaptive bitmap protocol-based(ABMP) within time division multiple access (TDMA) was proposed for UWSN, with specialized space-time uncertainty among mobile underwater nodes reducing channel idle time and improving energy efficiency and transmission efficiency. Finally, simulation experiments are conducted to present that the proposed protocol has better communication efficiency and energy efficiency, compared with other MAC protocols of Token-TDMA and T-lohi in terms of network traffic, end-to-end delay and energy efficiency.

Keywords: Underwater sensor networks, Adaptive bitmap protocol, Media access control, Time division multiple access

1 Introduction

Underwater sensor networks (UWSN) is the underwater extension of traditional terrestrial sensor network (WSN), which has important applications in a huge number of military and civilian areas, such as submarine detection, resource exploration, marine environmental monitoring and disaster warning, etc. Therefore, UWSN has been becoming one of the latest hot topics in recent years [1].

Compared with the conventional sensor network, most significant difference in UWSN is the communication method of acoustic signal as a carrier. Acoustic wave propagation characteristics in the sea has a huge difference from radio propagation in the air, which resulting in the unavailability of previous media access control (MAC) protocol in the UWSN.

1.1 CHARACTERISTICS OF UNDERWATER ACOUSTIC CHANNEL

Currently, there are numerous literatures on the propagation characteristics of the underwater acoustic channel study [2, 3], in general, the quality of underwater acoustic channel of communication is very poor, and its main characteristics are as follows:

(1) A large signal propagation delay. The average acoustic velocity in the sea is about 1,500 meters per second, which is several orders of magnitude lower than the propagation speed of the radio in the air, and acoustic wave propagation velocity changes with the environmental impacts of ambient temperature, salinity, pressure and other factors.

(2) Low communication bandwidth. In the common communication distance, bandwidth is only a few dozen kb per second.

(3) High error-code rate. The reasons include the great background noise in the sea, and more commonly existing Doppler effects and multi-path effects. In underwater network, sound waves reflect while going through the seabed, sea surface and layered interface etc., to form multi-path effects (or multi-purpose effects); furthermore, the mobile communication nodes will cause the Doppler effect.

The remainder of the paper is organized as follows: Section 2 describes the related research on underwater MAC, while Section 3 presents detailed design of the protocol. Then, Section 4 describes the simulation results and protocol analysis, and finally Section 5 provides the conclusions.

2 Related research on underwater MAC

Currently, the underwater MAC protocols can be divided into three categories: competition-based protocols, non-competition TDMA protocol and other protocols.

2.1 COMPETITION-BASED PROTOCOLS

John Heidemann, first proposed the features of space-time uncertainty in hydro-acoustic network [5]: because of the high underwater acoustic channel propagation

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delay, that whether the two nodes conflict or not, it is only depends on their transmission moment, but also on their geographic locations. And two targeted solutions were proposed: first, additional protection adding to the time slot Aloha protocol, secondly, T-lohi protocol [6] uses a competing channel with segment frame and uses back-off algorithm to avoid conflict.

Aloha-CA and Aloha-AN protocol [7] also uses the segment frame to compete channels, the main difference between them and T-lohi is that using virtual carrier sensing technology to avoid conflict without using back-off algorithm, the node maintains a neighbourhood state table, and on the basis of this table to adjust their transmission and reception. Aloha-CA split the data packet into shorter head and longer tail, and the head is used to compete for the channel, while Aloha-AN will not split the data packet using a separate channel segment frame to compete.

Slotted-FAMA protocol [8] is based on a handshake mechanism, which uses tome slots working mode, and expands the length of negotiation slots to overcome the effects of space-time uncertainty, all of the control frames are ensured to be received within one time slot. Expansion length of negotiation slots to avoid conflicts leads to increase the idle channels and decrease network traffic, and therefore, channel utilization of slotted-FAMA does not exceed by 10%, while [9] has improved this issue.

2.2 UNDERWATER TDMA

Token-based TDMA protocol was proposed for dynamic constituted with autonomous underwater vehicles (AUV) [10], since it is difficult for the mobile network nodes to divide into a fixed communication time slot, nodes use clustering approach to manage and use tokens to get the transmission right.

TABLE 1 Comparison of three underwater TDMA protocols

ST-MAC	ECS	UW-FLASHR
Centralized	Distributed	Distributed
Time slot	No time slot	Timeslot
Short frame	Long frame	Long frame
Pre-assigned	Pre-assigned	Dynamically assigned

The basic idea of ST-MAC protocol [11] is assuming that underwater link delay is an integer multiple times than frame time (if the frame time is small enough); by assigning different transmission negotiation slots to avoid conflict. ECS [12] improved the ST-MAC, which allocating transmission moment for the nodes, abolishing the former assumptions and designed as distributed algorithm. UW-FLASHR [13] divides the underwater parallel transmission mode is into three categories, and thus improves the efficiency of the conflict prediction. As for space-time uncertainty, better underwater solutions of these three TDMA protocols proposed are shown in the Table 1.

2.3 OTHER UNDERWATER PROTOCOLS

Using CDMA and FDMA technology faces many challenges in underwater sensor networks [14]. Wherein, TFO-MAC [15] is design for a single-hop network based on cluster multi-channel MAC protocol, while CDMA protocol based on tree topology was proposed in [16].

For AUV network a hybrid cluster protocol was proposed in [17], in which nodes in the same cluster using TDMA for communication, and between different clusters using CDMA to avoid interference. PLAN [18] is a hybrid protocol with CDMA and handshake mechanisms, by assigning different neighbours with CDMA orthogonal codes, multiple handshakes can be performed in parallel without conflict. A mixed protocol with Aloha and TDMA was presented in [19], the network switched based on load conditions: when the network load is light , using Aloha protocol of shorter delay, and when the network load is heavy, using TDMA protocol of non-conflict and heavy traffic.

2.4 RESEARCH TREND ON UNDERWATER MAC

As the underwater acoustic channel, communication environment is very harsh, and with characteristics of space-time uncertainty, underwater MAC protocol design generally has the following requirements to meet: high-energy efficiency (energy saving) [20], delays tolerance, robustness [22], reliability, flexibility (adaptation to the dynamic topology) [21]. To meet these requirements, the following means are mainly taken in current MAC protocol:

(1) Whenever possible, using a collision-avoidance scheme (e.g., TDMA) to save energy, in competition protocol, using short frame for competition or the reservation channel, instead of the manner of data packets direct competition, in order to ensure the transmission of data packets without conflict.

(2) For the characteristics of space-time uncertainty, use differences of different link delays to coordinate data transmission, and to improve the degree of parallelism in network transmission, and use clustering strategies and hierarchical topology management to deal with the dynamic changes of the network topology.

(3) Using a variety of techniques to improve transmission reliability. Such as CDMA and FDMA can solve hydro acoustic network problems of multipath effect and Doppler effect, using additional protection in the time slot scheduling to reduce the probability of conflict in this line, and to ensure synchronization of only lightweight and local clock.

MAC layer is located at a lower level location in network protocol stack, which is directly affected by the physical layer properties, continuous deepening and understanding on the study of underwater acoustic physical channel and acoustic communication will bring new ideas for the MAC protocol design.

2.5 CHALLENGES FOR UNDERWATER MAC PROTOCOL DESIGN

Media access control (MAC) protocol determines the using mode of radio channel, in which has a significant impact on the efficiency of communication network. Due to the special nature of the underwater acoustic communication, many difficulties and challenges [4] facing underwater MAC protocol design is included as follows:

(1) Space-time uncertainty: the larger underwater delay difference leads to nodes' conflict, in which it is simultaneously determined by transmission time and their locations. However, the traditional MAC protocol considered to avoid conflicts only through the coordination of transmission time, which cannot be applied to the underwater environment.

(2) Energy restriction: UWSN are energy-constrained networks, energy saving has always been one of the core issues facing the protocol design. Underwater communication protocol must be established on the basis of energy saving, then it can be considered to improve the communication efficiency.

(3) Topology changing frequently: in addition to the nodes fixed on the sea bed, other nodes suspending or floating in the sea will move with the ocean currents, so UWSN is a dynamic network with topology changing frequently, network protocol design must adapt to this change.

Existing underwater MAC protocol considers less for mobile nodes, in fact, most of the suspending and floating nodes cannot be completely fixed, they will move within local small range with the ocean currents, waves, winds and other environmental factors. In this case, the propagation delay of the link changes dynamically. Therefore, this paper presents a bitmap-based dynamic TDMA protocol for this dynamic underwater sensor networks.

Because of the space-time uncertainty, frame segments from different sites sending simultaneously arrive at different time without any conflict, nodes complete negotiations and channel reservation by taking advantage of this particular phenomenon, and reduce the communication delay from end to end by dynamically adjusting TDMA cycle length. Simulation results show that the proposed protocol has better communication efficiency and energy efficiency.

3 Detailed design of the proposed protocol

This section details the design of the protocol, including the basic idea of the protocol, workflow, and performance optimization, and performance is analysed theoretically.

3.1 THE PROPOSED PROTOCOL PROCESS

Hydro acoustic network characteristic of space-time uncertainty is shown in Figure 1, in Figure 1(a), the nodes A and C are sending a message to node B, A's transmission time is earlier than that of C, but the arrival time of A is later than that of C, this is due to the link delay of AB is much larger than that of BC, in which leading to "early sending and late arriving". In Figure 1(b), D and E simultaneously send messages to each other while they receive a message at the same time without conflict, this is because link delay between D and E is much greater than the time frame. This special phenomenon is unthinkable for traditional radio network with almost negligible link delay. We can take advantage of this particular phenomenon to perform a network protocol service in the hydro acoustic network, short frame collision probability is very low.

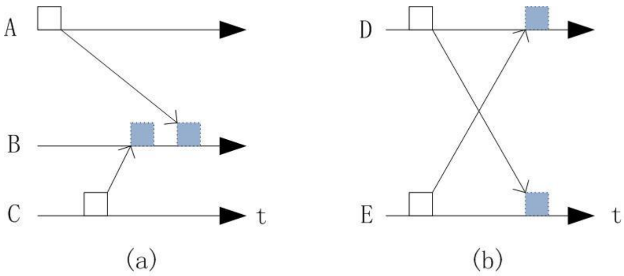

FIGURE 1 Example of space-time uncertainty

The basic process of the proposed ABMP within TDMA is shown in Figure 2. The protocol is composed of alternative negotiation time slot and TDMA transport period, and the transmission cycle is constituted of one or more negotiation slots, in which the length is dependent on the amount of data transmission required by the current nodes.

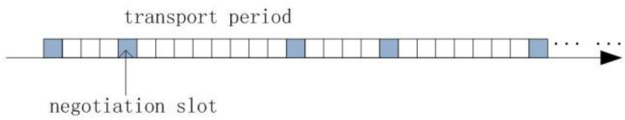

FIGURE 2 Protocol process of the proposed ABMP

Any frame should be transmitted at the beginning of the time slot, and guaranteed to be successfully received in the current time slot. Therefore, the length of the time slot is decided by the largest link propagation delay in the network, and the local nodes' movement under considerations. By definition, Dis(i, j) is the space distance between the two points i and j, Z (A) is the mobile node region of A, S(A) is set of neighbouring nodes of A, T_{slot} is the time slot length in data transport period. Assuming that underwater acoustic signal propagation speed is v, T_{data} is the time to send a data packet (i.e., the frame time of data packet), then T_{slot} can be calculated by Equation (1). This definition is applicable to any underwater sensor networks with one-dimensional, two-dimensional and three-dimensional mobile nodes.

$$L_{\max} = \max\{\max\{ Dis(i,j) \mid i \in Z(A), j \in Z(B), \forall B \in S(A)\} \mid \forall A \in UWSN\}$$

$$T_{slot} = \frac{L_{\max}}{v} + T_{data}. \tag{1}$$

The commonly known partial mobile nodes are shown in Figure 3, in which neighbouring nodes A and B floating in the sea are anchored to the sea bed, so that their movement range is a circle, this kind of mobile node with small movable range is called restricted nodes. It shows that in Figure 3 the longest communication distance between A and B is Dis(C, D), while maximum of the maximal communication distance among all links in the network determines the length of T_{slot}.

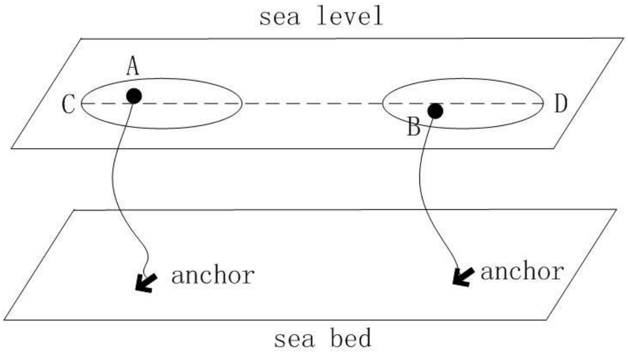

FIGURE 3 Calculation of the time slot length

During the time slot of consultation, each node which having data to transmit sends a short frame to reserve transmission order in the transport period. The short frame contains only three parameters: the source node ID, the destination node ID and a random number P, P is called the temporary priority, and which is calculated by the pseudo-random number generator as shown in Equation (2). The temporary priority is used to determine the node's transmission order in a data transport period.

$$P_{n+1} = aP_n + b(\bmod m). \tag{2}$$

Because of the existence of space-time uncertainty, nodes can receive the appointment short frame of other nodes with a great probability and without conflict; these nodes obtain the temporary priority of other nodes. In the data transfer phase, nodes can send data in the priority order of size, each node occupies the period of one slot time. Thus, the length of data transmission period is depended either on the number of nodes to be transmitted, or on the current network load.

Defined that T_{neg} is length of negotiation time slot, T_{short} is frame time required to send short frame of reservation ($T_{short} << T_{data}$), then T_{neg} is calculated by the following Equation (3).

$$T_{neg} = \frac{L_{\max}}{v} + T_{short}. \tag{3}$$

3.2 IMPROVEMENT AND OPTIMIZATION OF NEGOTIATION TIME SLOT

In the stage of negotiation time slot, short frame sent by nodes will conflict in the both scenarios below:

Scenario 1: two or more nodes have the same temporary priority. As the proposed protocol in Equation (2) generates random number using linear identical-residue generator, as long as the parameters of a, b, and m are set sufficiently large, the occurrence probability of this situation is almost zero and can be almost ignored. When this case happens, the node ID can be transmitted as a second level priority parameter.

Scenario 2: short frame of two or more nodes conflict at the place of the receiving node, the node cannot receive the conflict frame at this time and cannot obtain priority information related to the node, and which is unable to complete an appointment and consultation. As shown in Figure 4, nodes A and B send information to C, assuming that at the current time the link propagation delay of AC and BC is DAC and DBC, respectively, frame time of the short frame is T_{short}, the short frame conflict condition at this time is shown in Equation (4).

$$| D_{AC} - D_{BC} | < T_{short}, \tag{4}$$

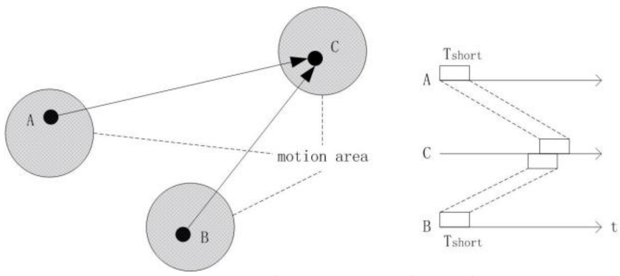

FIGURE 4 The conflict condition of short frame.

As the conflict of Scenario 2 occurs, the conflict nodes will lose the opportunity of channel reservation, and wait to resend short frame for negotiation in the next negotiation cycle. And the current transport period will waste one time slot, which is due to that other nodes without conflict are not unaware of this node's conflict, and will reserve one time slot for this node well in the current transport period according to its priority. The even worse situation is that, because in the ocean, the movement of the restricted mobile nodes has continuity and uncertainty, such a conflict state of short frame may continue for a long period.

Therefore, this subsection optimizes and improves the consultation slots to eliminate the conflict situation of the short frame. Before the beginning of the data transfer phase, nodes affected by conflict broadcast a warning message, then all nodes restart appointment. While reservation, the nodes with conflict run back-off algorithm to calculate their T_{wait} of back-off time, lastly before sending short frame the nodes prefer the awaiting time as T_{wait} shown in Equation (5). The re-appointment process is repeated until all the nodes in the network does not exist conflicts.

$$T_{wait}(i) = T_{short} \times random[0, \min(2^n, N_{\max})]. \tag{5}$$

Equation (5) is a calculating formula of back-off time, wherein T_{short} is the transmission frame time of a short frame, integer N_{max} is the upper limitation value of the contention window size, n is the number of participating in the negotiation.

Thus, the reservation negotiation slots is expanded into reservation period, the dynamic reservation period can eliminate continuous frames conflict caused by underwater nodes' movement, and it ensures the fairness of channel reservation, i.e., the transmission order of nodes depends only on their temporary priority, and is not affected by the conflict.

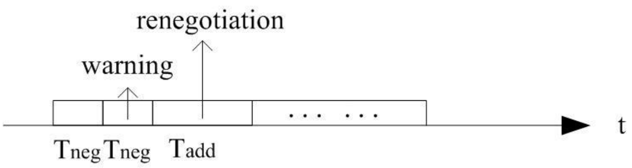

FIGURE 5 Negotiation period

Composition of negotiation cycle is shown in Figure 5, wherein Tadd denotes the length of negotiation slots when required renegotiation, its value is calculated by Equation (6).

$$T_{add} = \frac{L_{\max}}{v} + T_{short} \times N_{\max} . \quad (6)$$

3.3 NETWORK TRAFFIC ANALYSIS

Defined that T_n is the length of negotiation period, the length of the data packet is T_{data}, R is the ratio of T_{data} to T_{slot}, η is the channel utilization. Assuming that in the current data transfer phase, there are N nodes transmitting data, then η is calculated by Equation (7).

$$\eta = \frac{N \times T_{data}}{T_n + N \times T_{slot}} = \frac{1}{\frac{T_n}{N \times T_{data}} + \frac{1}{R}} . \quad (7)$$

The above Formula presents that the channel utilization is related with parameters of R and T_n in the protocol. η decreases with the increase of T_n, and increases with the increase of R. When conflicts of scenario 1 and scenario 2 of short frame do not occur, T_n is a constant value. However, when the conflict occurs, because of the randomness and irregularity of nodes movement in the underwater environment, it is more difficult to predict and change the value of T_n.

In short, under the conditions allowed by the network, the packet length is increased as much as possible (i.e., increasing T_{data} and R) to increase network traffic and achieve greater channel utilization.

4 Simulation results and analysis

This section describes the simulation results of the proposed protocol compared to other protocols of T-lohi and Token-TDMA. Where T-lohi is a representative of underwater competitive MAC protocol, while most of the existing non-competitive protocols cannot be applied in a dynamic network, then token-TDMA protocol is the representative of non-competitive protocols.

Simulation results mainly investigate the normalized throughput, normalized end-to-end delay, and energy efficiency under different conditions of traffic load with the three protocols. The number of nodes needed in transmission within a fixed period of time is on behalf of the network load conditions, the network traffic is represented with the amount of information (number of bits) transmitted per time unit, the unit of end-to-end propagation delay is the number of slots (T_{slot}), energy efficiency is the ratio of the energy consumed to transmit a packet to total energy the network consumption.

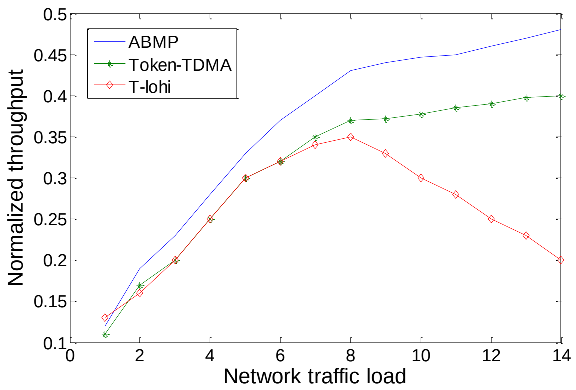

FIGURE 6 The network traffic when R = 0.5

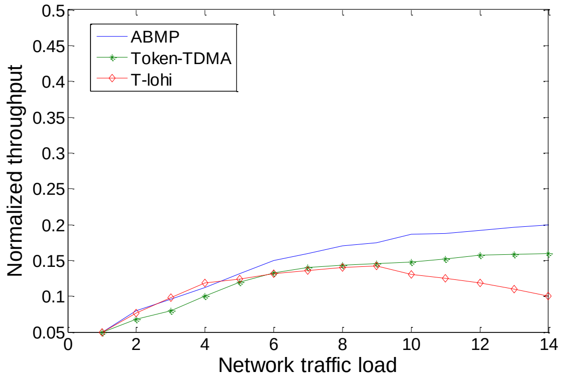

FIGURE 7 The network traffic when R = 0.2

Figures 6 and 7 show that normalized throughput as the function of network traffic load corresponding with different parameter values of R, the higher value of R, the larger network traffic, which verifies the flow analysis results in the above section. Results from Figure 6 and 7 present that the proposed protocol ABMP has the highest network traffic among the three MAC protocols. Under heavy load conditions, competitive-based protocols conflict more frequently, the performance of T-lohi protocol is the worst, traffic is minimum. For Token-

TDMA, when a node begins to transmit data till it has a token, so it must wait the first node in cluster head to assign a token, the waiting time increases the channel idle period, and reduces the channel utilization, so the flow is lower than protocols of ABMP.

Figure 8 shows the normalized end-to-end communication delay of the three protocols, when the network load is light, end-to-end delay of T-lohi is minimum, but it increases more greatly while the network load increases. Overall, protocol of ABMP has the smallest average end-to-end delay, due to the adaptation of dynamic transmission cycle strategy, avoiding the wait time of idle channel, when the network load grows, end-to-end delay only increase linearly.

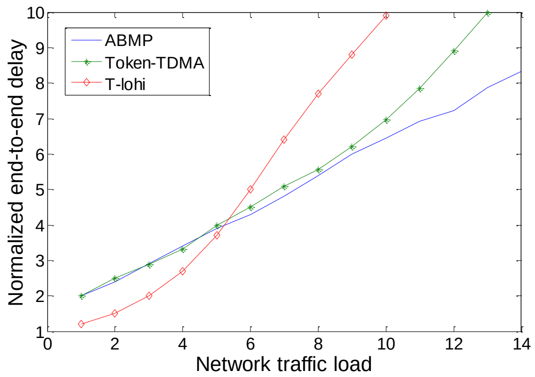

FIGURE 8 Normalized end-to-end delay

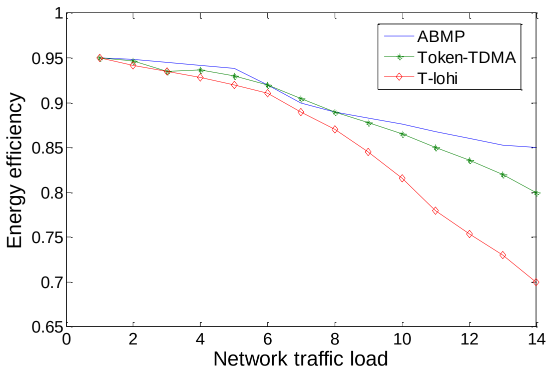

FIGURE 9 Energy efficiency

Figure 9 shows the energy efficiency of the three protocols, because the three protocols use short frame to compete or reserve channels, there does not exist conflicts in the data transfer phase, therefore which waste little energy, so its energy efficiency is higher and better than the other MAC protocols without using short frame reservation.

The proposed protocol of ABMP within TDMA has higher energy efficiency compared with these three protocols, which indicates that it uses fewer short frames; the efficiency of channel reservation is higher, because of using the characteristics of space-time uncertainty, short frames in the protocol of ABMP conflict less.

5 Conclusions

In this paper, we propose the ABMP TDMA protocol, which is for suitable underwater network with restricted mobile node. The protocol uses hydro-acoustic network feature of space-time uncertainty, the node is able to use only one time slot to complete the channel reservation and consultation together, thereby to increase the network traffic and reduce the end-to-end communication delay. In the data transfer phase, the length of time slot can ensure that data is not affected by node movement and conflict-free communication. In addition, the proposed protocol is distributed algorithm, which does not rely on the dispatch from centre node. Simulation results show that, compared with MAC protocol in conventional underwater mobile network, ABMP has a smaller end-to-end delay, the higher energy efficiency and the higher network traffic.

Overall, the study of underwater acoustic network is still in its infancy, the MAC protocol design will be further deepen and complete with gradual understanding improvement on characteristics of underwater acoustic channel. Underwater MAC protocol design shows the following trends: emphasis on cross-layer design, integrated optimization for data transmission through multiple protocol layers of physical layer, data link layer and network layer to further improve network performance; due to the real complex underwater acoustic communication environment, computer simulations and laboratory simulations on underwater acoustic communication experiment have limitations, so the researchers pay more attention to experimental research and verification in real underwater environment, however, for expensive acoustic network test equipment's and the high cost of experiments, it is difficult to spread widely, which is now one of the bottlenecks in underwater sensor network research to be overcome.

Acknowledgments

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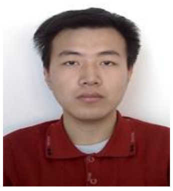

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