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Review of MAC Protocol of Underwater Acoustic Sensor Network

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Abstract

Medium access control (MAC) protocol has been widely reserached in underwater acoustic sensor network. This paper first analyzes the characteristics of underwater acoustic channels, and then presents the challenges of MAC protocol design under the condition of underwater acoustic channel propagation. Based on the analysis, the paper reviews the current research of three types of MAC protocols including of non-competition, competition, and intelligent algorithmsin with underwater acoustic transmission. This paper concludes the main features, core design ideas of different types of protocols. Finally, the comparison and analysis of various types of protocols are given, and future research trends are also presented.

Keywords

Underwater Sensor Network; MAC Protocol; Underwater Acoustic Communication.

1. Introduction

The underwater acoustic communication system was first applied in the underwater telephone system developed by the U.S. Naval Hydroacoustic Laboratory. After years of development, it was transformed from analog to digital system. The underwater acoustic transmission is quite different from the radio wave propagation used as the communication medium on land [1]. The propagation speed of acoustic waves in water is generally 1500m/s. The underwater acoustic channel has the characteristics of a long delay, low bandwidth, and serious multipath interference, which affects the quality of underwater acoustic communication, and let underwater acoustic communication in MAC protocol has huge challenges in design.

Underwater acoustic sensor networks (UASNs) is a kind of network that combines underwater communication technology, sensor technology, and network technology. In the underwater acoustic sensor network, the MAC protocol mainly solves the problem of reasonable sharing resources of underwater acoustic channels, especially when multi-node communication is carried out in a local area. The MAC protocol is required to coordinate the channel allocation between various nodes [2]. The MAC protocol determines the use of underwater channels, and its access control efficiency has a greater impact on the throughput of sensor networks. At present, researchers have developed a variety of MAC protocols for underwater acoustic sensor networks and applied them for different network structures and different purposes. The traditional MAC protocol design assumes that the nodes can obtain a continuous power supply. The network topology is relatively stable, and the fairness of the bandwidth used by the nodes and the improvement of throughput is the main considerations. In recent years, the MAC protocol of the sensor network is coordinated by many nodes to achieve its powerful functions, and taking energy efficiency, scalability, collision avoidance, channel utilization, delay, throughput, and fairness as main considerations.

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2. Challenges of MAC protocol in underwater acoustic sensor network

2.1 Features of Underwater Acoustic Communication Channel

The main features of the underwater acoustic communication channel include:

Long time delay: Under normal circumstances, the propagation speed of sound waves in water is 1500m/s, which is much lower than the propagation speed of electromagnetic waves in terrestrial wireless communication, resulting in long time delays in data transmission, which is a major challenge for underwater acoustic communication.

Path loss: The sound wave energy is converted into heat which produces energy absorption. Therefore, the transmision in underwater will be affected by path loss, particularly with the increase of distance and frequency.

Limited bandwidth: The bandwidth of the underwater acoustic communication channel is severely limited, with usually several hundred kHz.

Multi-path propagation: In the signal transmission process, the sound waves are affected by multiple factors. The scattering, refraction, and reflection of transmission cause the signal to reach the data receiver end through multiple paths, which causes different propagation delays.

Doppler effect: When the relative movement between the source and the sink occurs, the received signal frequency of the sink will be different from the transmitted signal frequency, resulting in additional distortion of the signal.

2.2 Challenges faced by protocol design

In the communication process, the MAC protocol manages and accesses the communication medium to avoid collision, It allocates channel resources for multiple nodes of underwater communication to achieve the purpose of making better use of channel resources. It affects the performance of the network.

Due to the complexity and variability of underwater acoustic channels, researchers faced many challenges when designing MAC protocols for underwater acoustic sensor networks. We conculde the challenges in Table 1.

Table 1. Challenges of MAC protocol design in UWN

Challenges	Description
Energy	When MAC protocol is applied, the node energy should be saved as much as possible
Scalability	To cope with the dynamic topology, the protocol should be scalable
Network efficiency	Fairness, throughput, and broadband utilization will affect network efficiency
Long delay	Long delay will cause packet congestion, collision, and loss

3. Overview of MAC Protocol of Underwater Acoustic Sensor Network

According to competitive relationship, the MAC protocols of underwater acoustic sensor networks can be divided into two categories. One is based on non-competitive MAC protocols, and the other is based on competition. In recent years, with the development of intelligent algorithms, researchers have also proposed MAC protocols based on intelligent algorithms.

3.1 Non-competitive MAC protocol

The non-competition-based MAC protocol allocates channel resources to each node , so that each node occupies the channel resources separately. The non- competitive scheme allocates frequency bands, time slots, or codes to different users. Under this scheme, the node does not get access to the channel through competition, so that the nodes transmit data without competition to avoid conllision [3]. According to their different access methods, they are divided into code division multiple access

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(CDMA) protocol, time division multiple Access (TDMA) protocols, and frequency division multiple access (FDMA) protocols.

3.1.1 CDMA protocol

The CDMA method uses different coding sequences to distinguish the transmission information of different users. The protocol for long-latency access networks MAC (PLAN-MAC) [4] protocol uses CDMA as the underlying multiple access technology and uses its robustness to frequency selective fading [5], the multipath and doppler effects in the underwater physical channel are minimized, through the three-way handshake mechanism, as shown in Figure 1 [4], the destination node D receives multiple request-to-send (RTS, request to send) data packets, and then to the source node (S_0 and S_1) send a clear-to-send (CTS, accept the request) data packet to reduce the number of control packets sent, thereby reducing the number of transmissions, achieving energy saving and improving transmission efficiency. This mechanism minimizes packet collisions and uses retransmissions to reduce the total end-to-end delay and energy consumption, so that it achieves high throughput performance and fairness between various data streams.

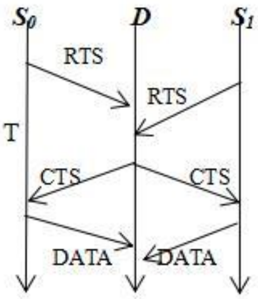

Figure 1. PLAN's three-way handshake mechanism

The path-oriented code assignment CDMA MAC (POCA-CDMA-MAC) protocol [6] overcomes the packet congestion, conflict, and loss caused by the leaky effect at the receiving end. It uses round-robin and CDMA technology to allow each node to use spreading sequence pairs. The data packet is reprocessed so that the receiver can receive data packets from multiple paths at the same time. This method shortens the transmission time, improves the channel efficiency, achieves a low packet loss rate, shortens the end-to-end network delay and higher throughput the amount.

3.1.2 TDMA protocol

TDMA divides user channels according to time slots, and different users transmit information according to specific time slots. For single-hop networks, Hong et al. [7] proposed a TDMA-based MAC protocol, in which superframes and delay time are used in the protocol to solve synchronization problems and node allocation channel problems, transmission time, and arrival time of data packets. As shown in Figure 2 [7], the receiver receives data packets one by one, and the data packets arrive accurately. T is the time to send data packets, L_i is the distance between node i and the receiver, s is the signal propagation speed, $2L_1+T$, $2L_1+2T$, $2L_1+3T$ are the arrival times of data packets at nodes 2, 3, and 4, respectively. There is no waiting time in this process, and the guard time is used to avoid collision after the node communication ends, to achieve the purpose of improving channel utilization.

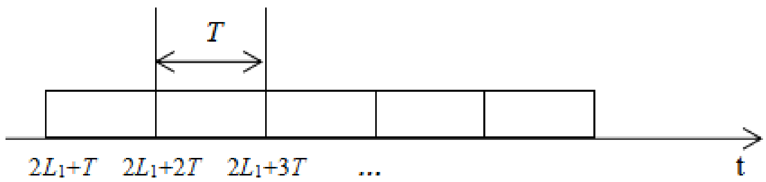

Figure 2. The arrival time of each transmission packet

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Morozs et al. [8] proposed the transmit delay allocation MAC (TDA-MAC) protocol. There is no need for clock synchronization between nodes. The gateway node measures all propagation delays and sends a transmission delay command packet to each node. As shown in Figure 3 [8], the propagation delay is accurately measured by sequentially exchanging data packets (*P*) between the gateway node and each sensor node, and then the propagation delay command TDI_i is sent to the first sensor node, which can effectively avoid data packets collision while reducing energy consumption. In particularly, when the data packet length is short and the number of nodes is less than 50, the protocol can produce better end-to-end data packets.

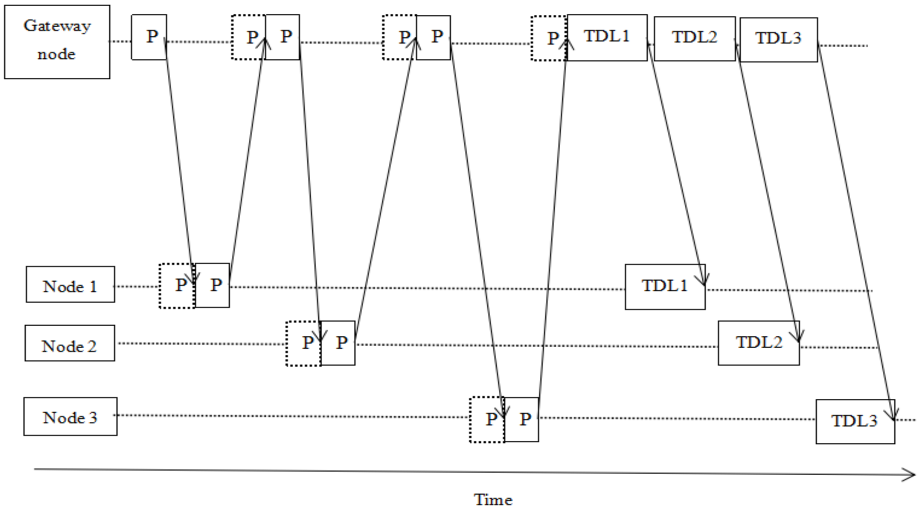

Figure 3. TDA-MAC establishment signaling process

3.1.3 FDMA protocol

FDMA divides the total bandwidth into different frequency channels, and different users transmit data information on different frequency channels. Due to the fading and multipath delay of underwater acoustic channels, the traditional FDMA protocol is not suitable for underwater acoustic sensor networks. According to current research, researchers generally apply orthogonal frequency division multiple access (OFDMA) to underwater acoustic sensor networks.

Using the multi-path characteristics of underwater acoustic channels, Hayajneh et al. [9] proposed an OFDMA-based MAC protocol, which makes full use of the limited bandwidth to complete the communication between nodes in the network, and avoids conflicts during data transmission, and it also minimizes the total network energy consumption. Khalil et al. [10] proposed a MAC protocol based on the [9]. This protocol can maintain fairness between nodes and minimize energy consumption under a more stringent channel model, and then extend the entire network`slife cycle. The OSPG-MAC protocol [11] let the nodes avoid collision easier during continuous sub-carrier allocation and data transmission according to the division of sub-channels. It maximizes the throughput on each sub-channel, and then the performance of the network has been improved.

3.2 Competitive MAC protocol

The competitive-based MAC protocol does not need to divide channels. Itallows collisions to occur and recovers the transmission from collisions. It allows nodes to compete with each other, and obtain media access on-demand to avoid pre-allocation of resources. It mainly includes random access protocol and collision avoidance protocol.

3.2.1 Random access protocol

The random access protocol means that when the user needs to send data, it will be sent immediately, and if there is a conflict, it will wait for retransmission. ALOHA protocol and carrier sense multiple access (CSMA) protocols are typical representatives of this type of protocol.

Pure ALOHA protocol will cause a lot of conflicts when multiple nodes send data at the same time, reducing throughput and channel utilization, so that it is not suitable for dense sensor networks.

The CSMA protocol is a widely used competition protocol in the network. In this protocol, each node will sense the channel before sending a signal. If the channel is busy, it will wait for a time with continuous sensingk. If the channel is free, the node will send data immediately. If a conflict is detected, the node will delay a random time slot and restart to send. [12] proposed an ordered CSMA protocol that combines round-robin scheduling and traditional CSMA. In the protocol, each station continuously detects the carrier and listens to all received frames. Then send immediately after the last station data frame is sent in a fixed order, instead of waiting for the maximum propagation delay. Compared with the traditional CSMA protocol, ordered CSMA improves the channel utilization.

3.2.2 Collision avoidance protocol

The collision avoidance protocol transmits data through channel reservation. If a collision is detected, the back-off algorithm is used. Currently, the slotted floor acquisition multiple access (SFAMA) protocols and multiple access with collision avoidance from wireless (MACAW) protocols are the mainprotocols. packet at the beginning of the next time slot. According to the feedback of the CTS, the source node sends the RTS control packet in the subsequent time slot.

At the beginning of the first time slot, the source node of SFAMA [13] sends an RTS control packet, and then the receiving node sends a CTS response packet at the beginning of the next time slot. According to the feedback of the CTS, the source node sends the RTS control packet in the subsequent time slot, and then the data packet is sent to the destination node. When the destination node finishes receiving it, it sends an ACK response packet to the source node. After the source node receives the ACK, the data packet transmission ends. The length of the time slot divided in the SFAMA protocol must ensure that all neighbor nodes can receive control data packets. Therefore, the time slot length and the handshake mechanism affect the throughput and end-to-end delay of the underwater acoustic sensor network.

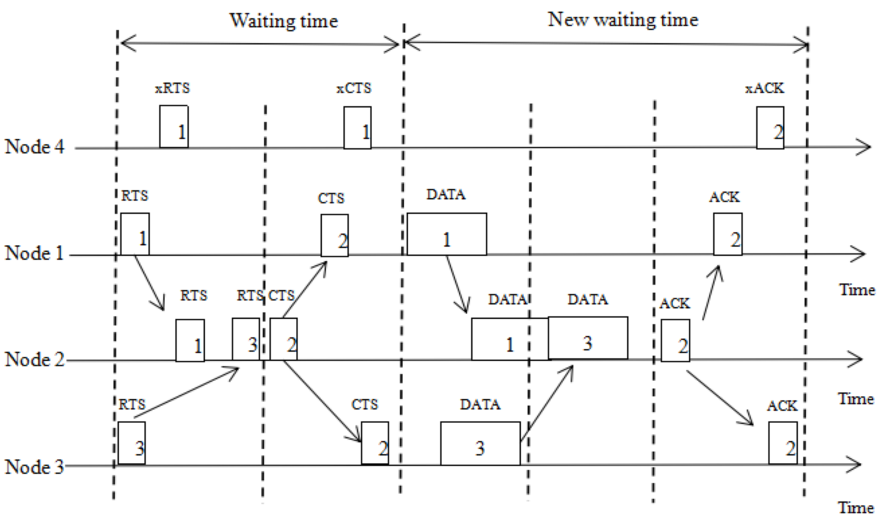

Figure 4. MR-SFAMA data transmission

Since the arrival time of a data packet isdetermined by the transmission distance, a data packet with a short transmission distance maybe arrives earlier, which leads to fairness issues. For this reason, Lin Wei et al. [14] proposed a new type of MAC protocol based on SFAMA, named SFAMA of multiple reception (MR-SFAMA) protocols. The protocol uses a new multi-receive handshake mechanism to improve throughput. As shown in Figure 4 [14], nodes 1, 3, 4 are the source nodes, node 2 is the destination node. When node 2 receives two RTS packets in the first time slot, it sends CTS to node 1 and node 3 in the next time slot, where the CTS includes the data packet transmission schedule of all senders (node 1 and node 3). According to the transmission schedule, node 1 sends a

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data packet in the next time slot, and node 3 must wait for a period of time before sending the data packet. After node 2 receives two data packets, it sends an ACK data packet in the next time slot. When node 1 and node 3 receive the ACK data packet, the data transmission is successful. When node 4 detects the xRTS packet sent by node 1, it must wait for the current time slot and the next time slot before sending data. MR-SFAMA protocol scheduling can ensure that the receiving node receives multiple data packets without data packet collisions. Compared with the traditional SFAMA protocol, it has a higher data transmission efficiency, as well as ensuring efficient throughput and fairness.

Due to the distance affect, the traditional MACA protocol cannot guarantee the fairness of communication. Therefore, the document [15] proposed the MACAW protocol, which is an improvement of the MACA protocol. Data confirmation frame ACK is added based on the traditional MACA. Reduce the energy consumption of the entire network, while ensuring fairness.

To solve the inefficiency of the traditional handshake protocol, [16] proposed the underwater MACAW protocol, where each node is the source node or the target node of the data exchange. As shown in Figure 5 [16], we take node B as the source node as an example. Before the node B is ready to transmit data to node A, it first sends an RTS control packet to A. To avoid mutual interference of messages from different nodes, RTS control data contains the sending duration of the source node. When receiving the RTS, the target node sends a response to the CTS control packet to notify its busy time to other nodes. Node D can listen to the RTS sent by node B, and node C can listen to the CTS sent by node A. Thereby node C and D delay their transmission. The research results show that the underwater MACAW protocol uses the long propagation delay of the underwater channel to improve network performance and channel utilization. Besides, packet transmission regard with thebusy time of neighboring nodes also solves the problems of hidden terminals and exposed terminals.

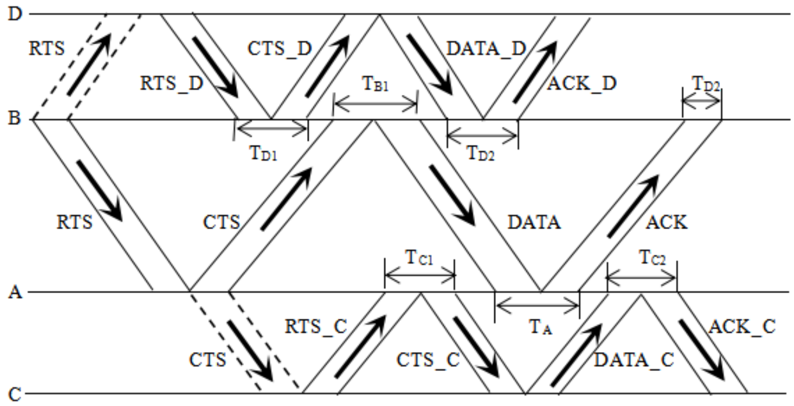

Figure 5. Underwater MACAW data exchange process

3.3 MAC protocol based on an intelligent algorithm

In recent years, intelligent algorithms have been introduced into the MAC protocol design of underwater acoustic communication. The agent nodes observe and learn about the surrounding environment and characteristics to improve network performance.

Ahmed Aliyu et al. [17] introduced the MAC protocol for underwater acoustic sensor networks, and proposed a MAC protocol based on fully cooperative multi-agent deep reinforcement learning. The protocol uses deep reinforcement learning (DRL) algorithms to share information between multiple agents, thereby realizing a self-organizing and adaptive network system to cope with long and variable propagation delays. Due to the complexity of the underwater environment, when one or more agents fail, the "smart node inheritance" is used at this time, and other nodes will take over some tasks of the failed node, thus making the entire network more robust.

Reference [18] proposed a MAC protocol for underwater acoustic networks, and proposed an asynchronous time environment model to consider underwater acoustic transmission characteristics

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to achieve the purpose of avoiding collisions. The DRL node can learn the communication environment and adjust its transmission strategy. When a DRL node coexists with a TDMA node or an Aloha node with time slots, the DRL node will learn to use the difference in propagation delay and occupy the available time slots of the network to achieve minimal collision in the UAN environment.

ALOHA-Q protocol of wireless sensor network in underwater acoustic communication areroposed based on reinforcement learning UW-ALOHA-Q protocol [19]. The improvement of the protocol includes three aspects. First, it can be realized in asynchronous communication. The different nodes learn the time slots for asynchronous transmission through reinforcement learning algorithms, and use idle time slots to transmit and avoid collisions. Second, The frame can contain multiple data packets, so that the total number of time slots can be reduced. Third, the agent node can find the optimal frame start time through learning so that the network can achieve rapid convergence.

4. Analysis and comparison of MAC Protocol for UASNs

This paper mainly focuses on three types of MAC protocols for underwater acoustic sensor networks. According to different design goals, we summarize different MAC protocols, as shown in Table 2. We hope the summary can help the future research on the MAC protocol design.

It can be seen from the table that improving network efficiency and reducing long delays are key issues in MAC protocol research, and protocol design based on intelligent algorithms will be one of the main research directions in the future.

Table 2. Performance comparison of different protocols

Protocols	Energy consumption	Channel utilization	Fairness	Throughput	Type
PLAN-MAC	Low	High	High	High	Non-competitive
POCA-CDMA-MAC	Low	Higher	General	High	
TDA-MAC	High	General	High	High	
MR-SFAMA	High	General	High	High	Competition
UMACAW	Higher	High	Higher	High	
DR-DLMA	High	High	High	High	Intelligence
DRL-MAC	High	High	High	High	
UW-ALOHA-Q	High	High	Higher	General	

5. Conclusion

This article reviews the MAC protocol research of underwater acoustic sensor network. Three types of protocols, that are non-competitive MAC protocol, competition-based MAC protocol, and intelligent algorithm-based MAC protocol are analyzed and conculded. Due to the complexity of the underwater environment, the design of the MAC protocol has gradually developed towards the direction of intelligent algorithms. Through the independent learning of nodes and the observation of the environment, the MAC protocol used by agent can adapt to the environment and then improve the channel utilization.

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