ISSN: 2414-1895 DOI: 10.6919/ICJE.202107_7(7).0068

Overview of the MAC Protocols for Underwater Acoustic Sensor Networks

Yanzhengfeng Wu

College of Information Engineering, Shanghai Maritime University, Shanghai 201306, China.

Abstract

In recent years, the ocean has become an indispensable part of the development of science and technology, economy and military. With the continuous improvement of the performance of underwater communication equipment, the communication requirements between underwater equipment as well as between underwater equipment and the land control center are constantly improving. The underwater communication technology is different from the land wireless communication channel characteristics and performance requirements, so such as long propagation delay, limited channel capacity, MAC (Medium Access Control) protocol designed for land wireless communication cannot be directly applied to underwater communication. For this reason, the corresponding underwater acoustic MAC protocol is proposed according to the requirements of different scenes of underwater communication. The paper reviews proposed MAC protocols across the range of underwater network transmissions for easier understanding. It also discusses the major problems and possible research directions in underwater communications.

Keywords

Underwater Acoustic Sensor Network (UWASN); Media Access Control (MAC) Protocol; Multi-hop; Single-hop.

1. Introduction

With the development of science and technology and the research on a high-quality wireless communication network, China had planned to achieve a 4G coverage rate of more than 98% in administrative villages in the year 2020, which shows the rapid development of land communication, while the research on marine communication is just beginning. With the development of VLSI technology and the emergence of composite digital signal processors, the underwater communication system had been constantly optimized. Human beings have gradually focused on developing marine resources, detecting the marine environment and studying marine organisms in recent years. Many underwater communication devices are deployed in the unreachable underwater world to carry out underwater operations on behalf of humans. Among them, the installation and maintenance cost of cable is high, and the fixed activity range limits the application of wired communication in an underwater environment. Underwater wireless network technology has thus become a hot research topic in the past decade. Similar to land-based wireless communication, MAC protocol is also a crucial part of underwater acoustic communication. However, the difference between the underwater communication environment and the land communication environment is that the radio signals used in the land communication are seriously attenuated in the water. The acoustic communication mode is widely used in underwater communication at present [1]. As an essential part of the communication protocol, MAC protocol ensures that all nodes can reasonably and effectively use the limited bandwidth transmission resources to obtain the highest network throughput, which has become the essential work of UWAN network protocol research.

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2. Underwater Acoustic Network

The underwater acoustic network is composed of a large number of nodes deployed in the ocean. The nodes in fixed or mobile conditions collect or process information and transmit it to processing centers on the water or land surface to break the communication barrier between land and underwater so as to extend the range of land communication. Acoustic wave transmission is not the only way of underwater communication. Due to severe attenuation of electrical signals in the water and high requirements for equipment, light wave is also affected by scattering and attenuation [28], and the acoustic wave is the only means capable of long-distance communication. Sound travels in water as a pressure wave [28], and can travel longer distances using lower frequencies.

2.1 Characteristics of the Underwater Acoustic Channel

The underwater acoustic channel is considered one of the most extraordinary and complex communication media. Due to the particularity of underwater channels, the following channel characteristics should be taken into consideration when designing underwater communication protocols:

1) Large propagation delay. The propagation velocity is dynamic due to the temperature, salinity and pressure of seawater. The underwater acoustic signal travels at a low speed of about 1500m/s, five orders of magnitude slower than the terrestrial radio signal[29]. The delay caused by underwater transmission can lead to signal distortion, and the mobile transmission caused by wave flow and tide can produce an extreme Doppler effect. This phenomenon needs to be taken into account when designing communication systems.

2) Narrow available bandwidth. The available channel bandwidth for acoustics is limited, about 5kHz. The bandwidth of the acoustic channel depends on the transmission distance. Within a certain distance, the bandwidth and power of the acoustic channel depend on the signal-to-noise ratio (SNR), sound path loss parameters, and environmental noise of the target node. At great distances, bandwidth is severely limited. For example, only 1kHz of bandwidth is available at 100km. The narrow bandwidth of the underwater acoustic channel means that efficient bandwidth modulation is required when the bandwidth exceeding 1b /s/Hz is achieved on the channel [2]. When the distance between the source node and the destination node is too long, the multi-hop network structure can be considered to transmit at a higher bit rate to reduce the delayed loss and the total power consumption.

3) Time-varying multi-path and spatially variable channels. The speed of sound changes with the location and depth of the nodes. The multi-path effect exists when sound travels underwater. Multi-path in the ocean is the refraction of sound signals in the water or reflected off the surface, bottom and any object in the water. Signals from the source node take different paths to the destination node. The target node will observe multiple signal arrivals and receive multiple delayed signal components. Horizontal channels may have very long multi-path propagation, and acoustic signals will degrade seriously when the propagation distance is too long. Time-varying multi-path channels affect signal processing and it also determines signal throughput and communication system performance. Underwater links are greatly affected by the spatial variability of underwater acoustic channels, which can change which are the channel's physical characteristics.

4) Complicated channel noise. The noise of the underwater acoustic channel includes the ambient noise and the noise of a specific scene. There is always environmental noise in the quiet deep sea. The environmental noise comes from waves, rain, etc. Most of the environmental noise can be considered as continuous and regular Gaussian noise. Site-specific noise only happens in certain situations, such as animal calls and ship movements. Underwater noise is the main factor that determines available bandwidth, propagation range and signal-to-noise ratio.

2.2 Problems and Challenges of Underwater MAC Protocol Design

Considering the above characteristics of the underwater acoustic channel, the following factors must be taken into consideration when designing underwater MAC protocol:

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1) Synchronization. The Doppler shift and expansion caused by node movement, frequency attenuation, multi-path and low sound velocity require phase and delay synchronization [2] in the underwater network to avoid the sending failure of the source node due to the conflict at the target node.

2) Energy consumption. Underwater sensor nodes are usually battery-powered, so energy consumption must be considered when designing underwater communication protocols. This is especially important for fixed nodes installed on the seabed where replacing the batteries or redeploying the nodes is costly. Maintaining the overall life of the network is a crucial factor, so it is essential to design an efficient media access protocol to save energy.

3) Node dynamics. When a node in the underwater network runs out of energy or a new node joins the network, the network structure will change. When designing the MAC protocol, it is necessary to consider the network expansibility to adapt to the new network topology.

4) Fairness. Long delays in acoustic propagation under water can cause nodes that send requests earlier to fail to send them first. Moreover, the source node that is closer to the target node has a greater probability of obtaining the channel first and may always be occupied by the closer node, while the node that is farther away from the target node has less chance to occupy the channel. In a large-scale network, if all nodes are saturated and need to send data frequently, some nodes may never have a chance to occupy the channel. MAC protocol should consider the fairness of the node to use the channel and ensure that all the nodes in the network have the chance to use the channel.

5) Service requirement of reliability. Many underwater applications require reliable service assurance. If there is a packet collision or loss, it needs to be buffered and retransmitted until it is acknowledged.

3. MAC Protocol Based on Transmission Range

Underwater nodes often have limited batteries. Energy consumption and energy efficiency is a significant concern in the design of underwater networks. In theoretical research, when the distance between the source node and target node is too long, if the single-hop transmission is adopted to make the target node receive the signal, the source node must increase the transmitting power. This method will increase the node's energy consumption, and if the intermediate node is used to reach the target node through multi-hop transmission, the transmitting power can be reduced. The MAC protocol should also be designed with end-to-end throughput in mind, because the maximum delay increases as the number of hops increases.

3.1 Single-hop network

The single-hop network generally refers to the network structure in which the source node transmits directly to the sink node.

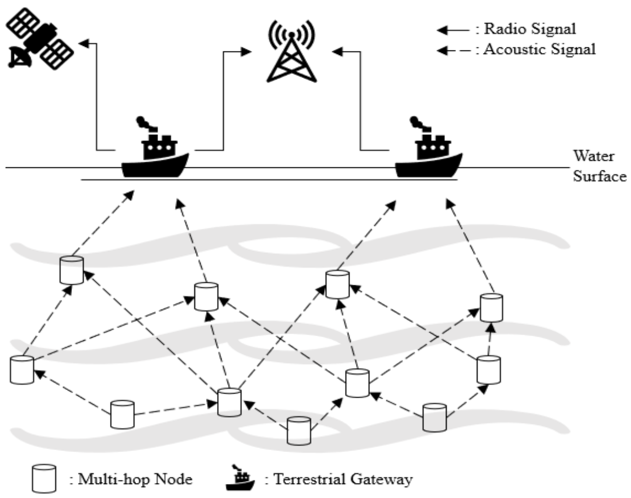

Fig. 1 An example of an underwater multi-hop acoustic network

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3.2 Multi-hop network

Unlike the single-hop network transmission mode, each node in the multi-hop network can act as an AP. The source node transmits data to the sink/gateway node through multi-hop, and the communication range of each node is small. Data flow in underwater acoustic networks often has specific flow patterns. Traffic generated by all nodes typically flows to the gateway, so the load provided within a particular single neighbor is inversely proportional to the number of hops that the neighborhood has away from the gateway, which increases the vulnerability of data traffic to congestion as it approaches the gateway.

4. Design of Multi-hop MAC protocol

4.1 Network model

Multi-Hop (MH) can save energy, while blindly increasing the number of hops without limit is ineffective [3]. When designing a multi-hop network simultaneously, we should consider the problem of interference in the simultaneous transmission of nodes. Here, we propose an underwater multi-hop transmission network model, in which each source node occupies a unique segment for transmission, and the length of each segment is T_d, and then divide it into several small-time slots for transmission, and each time slot has a length of T_s, as shown in Fig. 2. Assume that the state of transmission from node u to node v in time slot t can be defined as:

$$X_{(u,v)}(t) = \begin{cases} 1, (u,v) \ is \ occupied \\ 0, \ otherwise \end{cases} \tag{1}$$

The propagation delay between node u and node v is:

$$D(u,v) = \frac{d(u,v)}{T_s c} \tag{2}$$

Where c is the sound propagation speed and $d(u,v) = \|x_u - x_v\|$ is the distance between node u and node v.

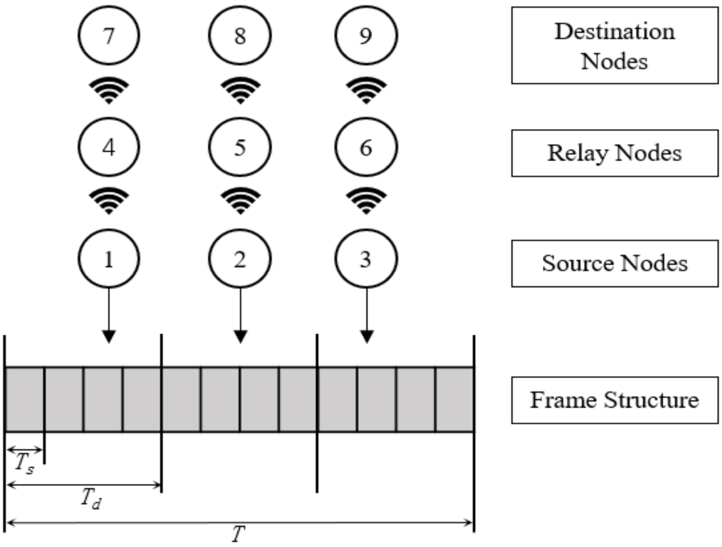

Fig. 2 Network model

4.2 Underwater path loss

We assume the underwater path loss between the underwater source node and the underwater target node:

$$H(d,\theta) = AS(d,\theta)e^{-\alpha d} \tag{3}$$

Where A is the transmission anomaly coefficient, α is the absorption coefficient and $S(d,\theta)$ is the energy diffusion coefficient, and D is the distance between the source node and the target node. The Angle between the direction of the transmitting signal and the horizontal plane is θ. $S(d,\theta)$ is defined as:

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$$\begin{cases} d^{-2}, \ \ if \ d\cos\theta \le K \\ d^{-2}(d\cos\theta / K)^{\log 10(d\cos\theta/K)/2}, \ \ if \ K < d\cos\theta \le 10K \\ d^{-1}K^{-1}\cos\theta\sqrt{0.1}, \ \ if \ d\cos\theta > 10K \end{cases} \tag{4}$$

4.3 Physical interference model

As shown in Fig. 4, in a network centered on u, there are two kinds of ranges on distance: transmission range R_d and the interference range R_i [4]. Each node has its transmission range and interference range, determined by the transmission power. The transmission range is the maximum distance between the target node u and the source node z, at which the received data can be correctly decoded by the target node u. The interference range is the maximum distance between another node w and the target node u. Node w is within the interference range of node u, and node w and node u can hear each other's transmission. The data sent by node w cannot be demodulated at node u, so node w interferes with the transmission between node v and node u [5]. Since the successful reception of the physical layer depends on the signal-to-noise ratio of the target node, the transmission range R_d and the interference range R_i. It can be expressed as:

$$\frac{P_{(z,u)}(t)H(R_d,\theta_d)}{N_s} = \gamma_{phy} \tag{6}$$

$$\frac{P_{(v,u)}(t)H(R_s,\theta_s)}{N_s+P_{(w,x)}(t)H(R_i,\theta_i)} = \gamma_{phy} \tag{7}$$

Where $P(w,x)$ is the transmitted power of w. The above equation is the implicit expression of the transmission range R_d and the interference range R_i.

In literature [6,7], the protocol interference model is further subdivided into three kinds of interference models: the ideal protocol model, the sender interference model, and the sender-receiver interference model.

In order to make sure that the data transmitted from the node z to u in time slot t and the one transmitted from the node w to z in time slot $t+[D(z,u)-D(w,x)]$ or $t+[D(z,u)-D(w,x)]-1$, from causing physical interference due to simultaneous transmission, and considering that the threshold value of node u cannot be exceeded, as shown in Fig. 3, if the SINR of two simultaneous signals exceeds the threshold value, there will be a conflict. In order to prevent the conflict, the following constraints should be required:

$$2X_{(z,u)}(t) + X_{(w,x)}(t+[D(z,u)-D(w,x)]) + X_{(w,x)}(t+[D(z,u)-D(w,x)]-1) \le 2, \tag{8}$$

4.4 Multi-hop mac protocols for UWAN

Therefore, when designing the MAC protocol of underwater multi-hop networks, the network topology is one aspect that needs to be paid attention to.OPMAC (On-Demand Pipelined MAC) protocol, its basic idea is to establish a pipeline, so that data can be transferred from the source node to the target node through multiple hops in the shortest time (reducing the process of reinitializing the handshake for the next hop). The CTS packet broadcast by the relay node contains the response to the previous-hop node and the request message for the next hop. This mechanism significantly reduces the time for the message to arrive. CTS configured by OPMAC requires advance routing information and may conflict with other transports. Based on distributed UWAN-MAC[12], COPESM-MAC [11] uses parallel execution reservation to reduce the control packet switching time. COPESM-MAC maps neighbor transfers to its schedule, transmitting packets in reserved slots. However, the protocol uses carrier listening technology and frequent monitoring and wake-up mechanism, which requires timely maintenance of the schedule to improve energy consumption and reduce the overall network use time.

In the underwater communication network, the long propagation delay makes the protocol using carrier listening more complicated, especially in the multi-hop network; the interaction of adjacent nodes complicates the problem.

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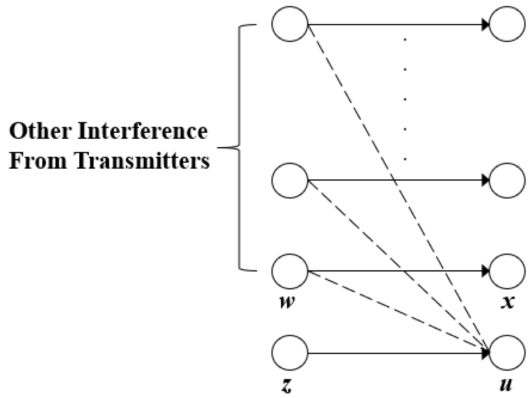

Fig. 3 Physical interference model

SFAMA-MM[13] protocol proposes a multi-receive mechanism that allows neighbor nodes to receive packets at the same time based on time slot FAMA. This protocol adds a new notification packet to avoid multi-hop network conflicts; that is, some source nodes use notification packets to inform their neighbors about the subsequent data transmission sequence. In the CTS packet sent by the target node, the sending sequence number is specified for each source node. Through simple calculation, the sending time of the target node can be known. Besides, the target node will send ACK in the next time slot after receiving the data. This protocol is suitable for dense networks, where when a node is idle and receives only one RTS, it waits to collect as many RTS control packets as possible in that slot.

[14-15] utilize long propagation delays to maximize throughput in multi-hop grid networks. In[14], The scheduling problem is transformed into a mixed-integer linear problem (MILP) to obtain the optimal scheduling law. In [15],the upper limit of network throughput is deduced to obtain the node transmission schedule in the network.

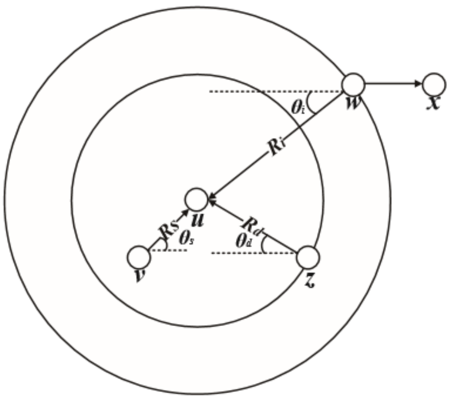

Fig. 4 Protocol interference model

The efficiency of handshaking-based protocols is adversely affected by long propagation delays. However, the protocol based on the reservation has limited scalability and relatively low robustness. The simplest of these protocols is that the ALOHA protocol or its enhancements may be more efficient. The protocol does not attempt to coordinate media access between different nodes, and the lack of coordination constraints reduces the complexity of the system and increases the probability of conflicts. With the increase of the number of nodes, the load of the whole network expands. Combining with the global time reference, the nodes in the network can only transmit data at the beginning of the time slot. The ALOHA-CA[16] protocol divides a packet into a header segment and a data segment. A random fallback is applied based on channel state information by listening for packets transmitted at every frame and knowing the propagation delay between all node pairs.

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ALOHA-AN[16] protocol can avoid conflicts by sending short notification packets (including information of source node and target node) before actual data transmission to make neighbor nodes temporarily delay data transmission. Both protocols reduce data conflicts and improve network throughput compared to the original ALOHA protocol; however, both protocols require nodes to maintain their tables to monitor neighboring nodes. The ALOHA-RB[17] protocol assumes that the expected number of rival nodes and the maximum propagation delay are known.

Based on the ALOHA protocol, a random retreat time is added to reduce conflicts. The retreat window CW is adjusted correctly, and the maximum throughput can be achieved regardless of the number of nodes. The percentage of transmitted power wasted in conflict is much smaller than pure ALOHA protocols. ALOHA-CS[18] is an ALOHA protocol with carrier listening technology that does not send any new packets as long as the current node hears that the modem is receiving a packet. It also has an escape window with a size between two and five times the maximum propagation delay. When the window is detected to be idle, data will be sent. If there is a conflict, it will enter the retreat time and wait for the subsequent transmission. If the first transmission is unsuccessful, the size of the retreat window will increase accordingly.

5. Design of Single-hop MAC protocol

What a single-hop network needs to consider is the conflict situation caused by the arrival of packets from different source nodes at the same time at the target node, and the occurrence of hidden and exposed terminals also needs to be considered in the design of multi-hop MAC protocol.

Hidden terminal: Two nodes that are far away from each other will transmit data to the same node, but neither of them is aware of the other' transmission, resulting in a conflict between the two at the target node. As shown in Fig. 5, node A needs to transmit to node B. Node A cannot detect the transmission status of any node within the dashed line when sensing the channel; that is, it cannot know the transmission of node C. Node A starts transmission, resulting in conflict at the target node B. The severe long-propagation delay hidden terminal problems in underwater communication, i.e., A multi-channel hidden terminal in multi-channel transmission. The multi-channel hidden terminal can be set up with special continuous monitoring channel hardware; the disadvantage is that the primary cost is increased. CuMAC [8] proposed a cooperative MAC protocol to effectively solve multiple covert terminals by using the cooperation of neighboring nodes for conflict detection. Besides, a tone device was also installed to solve the congestion of the control channel and further improve the system performance.

Exposure terminal: two nodes close to each other simultaneously listen to each other to transmit data, and one sender is outside the interference range of the transmitting receiver. As shown in Fig. 6, node A sends control information to node B, while node D transmits data to node C. In terms of chronological sequence, node D sends control information before node A . Node B enters the retreat period after hearing the reply control information of node C, and all node transmissions centered on node C will prevent the data transmission of node A, even though no interference exists.

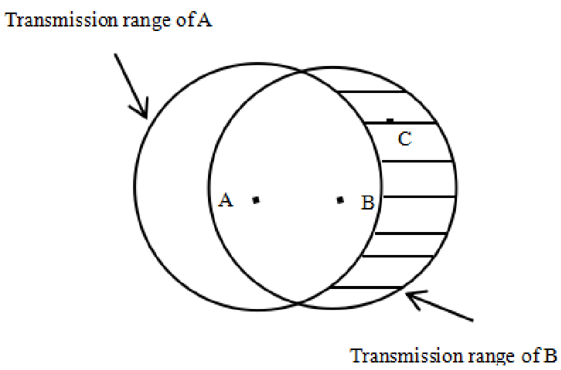

Fig. 5 Hidden terminal problem

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DOI: 10.6919/ICJE.202107_7(7).0068

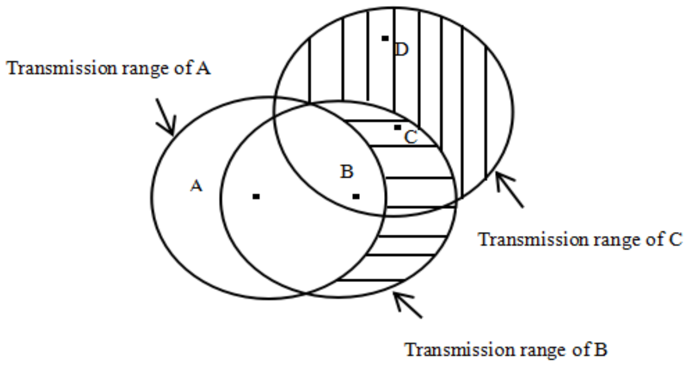

Fig. 6 Exposed terminal problem

In addition to solving the problem of hidden exposed terminals, the design of underwater MAC protocol also has challenges such as near and far effects and space-time uncertainty. In [9], the source node is one hop away from the target node, and the sending control packet is calculated according to the information of adjacent nodes, and the SNR and power requirements of the target node are met. The near-far effect is defined as that when the receiving power of the target node is not the same, the signal far from the target node cannot be received successfully. For example, Fig. 4 shows that the distance between node C and node A is longer than that between node B and node A. When node C sends a signal, the signal sent by node B is considered to be noise interfering with the signal reception of node C. There is spatial and temporal uncertainty in underwater communication. In terrestrial environments, the signal travels at a speed of 3×10^8 m/s, and the signal propagation delay between nodes or the difference between such delays is negligible. In this case, the collision at the target node can be avoided by controlling the transmission time of the different source nodes. However, this method is meaningless for underwater communication, as the conflict-free transmission does not mean conflict-free reception, and concurrent transmission may also lead to conflict-free reception due to the non-negligible difference in transmission delay between nodes.

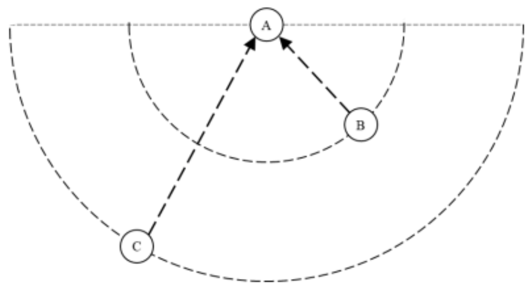

Fig. 7 Influence of near and far effect in underwater MAC protocol

ED-MAC [30] sorted the wake-up transmission schedule according to the node depth position. Each node in the network reserved a unique time slot for transmitting data, and nodes needed to maintain an information table to obtain the reserved time slot information of neighboring single-hop nodes. The protocol also divides each slot into smaller slots that are randomly selected to transmit data.

6. Reinforcement Learning in MAC Design

In the past decade, smart technologies have been widely applied in wireless communication networks. In the design of Media Access Protocol (MAC), nodes capture the network environment and interact with it through agents, learn to maximize throughput, minimize the occurrence of conflicts, and optimize network performance. Deep reinforcement Learning (DRL)[24] was first used in the calculation of terrestrial communication algorithm. Switching cost factor is incorporated into Hetnet algorithm proposed in [20] to balance the primary transmission rate and system overhead. DRL learns

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interference patterns from the secondary sender and selects an appropriate modulation and encoding scheme during actual transmission to enhance the primary transmission rate. In [20], DRL is used in the LTE-U network for channel selection and channel access. Although it also targets heterogeneous networks where the LTE-U base station coexists with WiFi AP, its predominant objective is to allow for the non-interference use of the WiFi channel in the downlink of the LTE base station. In both [21] and [22], handover management is implemented under dense networks based on DRL support from heterogeneous networks. In [23], a distributed execution model-free power allocation algorithm is proposed to achieve dynamic allocation of power in wireless networks. Each sender collects information regarding the channel status and quality of service (QoS) from its neighbors and makes corresponding adjustments to its transmitting power. Deep Q learning is used to solve multiple variations and delays in the information of the channel state. Machine to Machine (M2M) communication in a heterogeneous cellular network is discussed in [25]. Deep reinforcement learning with a recursive neural network should be applied when backoff configuration is also dynamic. DRL is used in [26] to design model-free MAC protocol for heterogeneous wireless networks, and carrier listening is introduced to improve its efficiency and flexibility and maximize the total throughput of all nodes in the network.

An underwater time-division media control access protocol is proposed in [27] based on Deep Reinforcement Learning (DRL). Source nodes are distributed around the sink node and start to transmit at a random time slot. It is put forward in [31] that the sending node learns the transmission scheduling strategy, with the time being divided into continuous time slots. At each time slot stage, it is decided whether to estimate Bit Error Probability (BEP), whether to send or how many packets have been sent and what kind of forward error correction coding should be used.

7. Conclusion

From the above review, it can be seen that current MAC protocols are designed to take into account the characteristics of underwater acoustic networks in specific situations, such as long propagation delays, space-time uncertainties, etc. It can be argued that there is no single universal MAC protocol for all underwater acoustic communications. In order to avoid transmission conflict, reduce multi-path phenomenon and Doppler diffusion, the underwater communication network needs to overcome network node position changes and coordinate the whole network. At present, the cost of underwater simulation experiments is high, and most papers are realized by computer simulation. Even if there are conditions for underwater experiments, there are some problems, such as significant disturbance of underwater environment factors and inaccurate experimental results, etc. Carrier Sense Multiple Access (CSMA) increases the protection time between transmissions and the propagation delay of the network to prevent its collision with the ongoing transmission. CSMA protocol has low efficiency in underwater networks. However, protocols that rely on handshakes also increase network propagation delay in transmission, waiting for control packets and confirmation, which leads to low channel utilization and higher collision probability caused by handshake delay. It is important to study the size of packets needed to maximize network efficiency when designing communication protocols in the future. Underwater network equipment has limited energy and should be reduced in the event of battery exhaustion to minimize damage to the overall network. In addition, most of the current MAC protocols only focus on the functions of the Mac layer and do not consider the overall design of network functions beyond the Mac layer. System design should focus on all possible best choices to maximize performance.

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