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Distributed Receiver-Oriented Adaptive Multichannel MAC for Underwater Sensor Networks

XIAONING FENG[1], ZHUO WANG[2], GUANGJIE HAN[3,4], (Member, IEEE), WENJIE QU[1], AND AKANG CHEN[1]

[1]College of Computer Science and Technology, Harbin Engineering University, Harbin 150001, China
[2]College of Shipbuilding Engineering, Harbin Engineering University, Harbin 150001, China
[3]Key Laboratory for Ubiquitous Network and Service Software of Liaoning province, School of Software, Dalian University of Technology, Dalian 116024, China
[4]Institute of Acoustics, Chinese Academy of Sciences, Beijing 100190, China

Corresponding author: Guangjie Han (hanguangjie@gmail.com)

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ABSTRACT As multichannel medium access control (MAC) protocol has higher network performance, it becomes an important issue in underwater sensor networks (UWSNs). The design of multichannel MAC faces many challenges caused by long-delay, low bandwidth and triple hidden terminal problems. We propose a Distributed Receiver-oriented Adaptive Multichannel MAC (DRAMAC) protocol for UWSNs in this paper. DRAMAC contains two key schemes: channel negotiation process based on cooperative correction (NPCC) and receiver-oriented dynamic channel negotiation strategy (DCNS). NPCC scheme can reduce the probability of collision by using the neighbors cooperation information. DCNS scheme can help select channel according to the packet length and the receivers network load condition. Thus we can improve the performance without any additional devices. The analysis and simulation results show that DRAMAC can achieve higher network throughput, lower end-to-end delay and has better adaptability in distributed environment.

INDEX TERMS Underwater sensor networks, multichannel, MAC, receiver-oriented.

I. INTRODUCTION

Since acoustic communication has been proved to be a practical method for long range wireless communication in underwater, UWSNs have gained tremendous attention [1], [2]. Researchers have become increasingly interested in underwater communications in the past three decades. Because of its applications in marine research, oceanography, marine commercial operations, the offshore oil industry and defense [3]. Underwater acoustic communications will play an important role in future. Network efficiency and reliability are prerequisites for these applications in UWSNs. [4], [5]. UWSNs have been extensively studied in recent years, especially in the area of underwater medium access control (MAC) [6]. Because MAC is an integral part for achieving the desired network performance in any network.

The terrestrial wireless networks utilize the radio channel. The acoustic channel is used by UWSNs. Thus posing new challenges to the design of MAC protocol [7]–[9]. The electromagnetic signal will quickly attenuate in the water. Only acoustic wave could propagate long distance in underwater environment in practices [10]. But acoustic communications have several disadvantages. First, the bandwidth is limited, which will have an impact on the design of the MAC protocol [11]. Second, the propagation speed of acoustic signals in water is about 1500m/s, which is five orders of magnitude lower than the radio propagation speed ($3 \times 10^8 m/s$). This causes higher propagation delay in underwater communication than in terrestrial communication. The large propagation delay may break or significantly degrade the performance of many existing protocols. Third, multipath spread is severe. It could be as long as few hundred symbols, which results in a significant frequency-selective signal distortion [23]. Fourth, Doppler spread shift, due to the dynamic nature of the water medium and motion of the nodes, is relatively high [23]. All these make underwater acoustic channel one of the most difficult media for information exchange [12]. Consequently, building UWSNs encounters grand challenges at almost every level of the protocol stacks,

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among which efficient MAC is one of the most fundamental issues.

The MAC protocols designed for terrestrial wireless networks can't directly adapted because of the long propagation delay. Many MAC protocols dedicated to UWSNs have been proposed in recent years to improve the network performance such as T-Lohi [13], DOTS [14], SF-MAC [15], Bic-MAC [16], CODTS [17], ST-MAC [18] and others [19]–[22]. However, all these researches focus on single channel network scenarios. Recent researches showed the development of underwater acoustic communications made it possible to utilize multiple acoustic channels in parallel. And multichannel MAC protocols can improve the network throughput and decrease channel access delay.

However, some critical issues should be noticed. MAC protocols for single channel networks such as T-Lohi, Bic-MAC and ST-MAC cannot be directly used in multichannel networks because of their low efficiency. MAC protocols based on multitransceiver will increase the cost because of the underwater transceiver is very expensive. The hidden terminal problems will also increase the probability of collision. The performance of the system will be greatly reduced if these problems are not well considered.

In order to reduce the cost of underwater system we chose single transceiver mode. The DRAMAC protocol we proposed can dynamically select channel according to packet length and the network load. It can also detect collision efficiently according to the neighbor nodes' cooperation. Both analytical and simulation results show that DRAMAC can achieve significantly better performance in network throughput, end-to-end delay and energy consumption.

The rest of this paper is arranged as follows. Section 2 briefly reviews some related works. In Section 3 we describe our MAC protocol in detail. We evaluate the scheme in Section 4. We give the conclusions of the paper in Section 5.

II. RELATED WORKS

In recent years, multichannel MAC protocols are well studied for UWSNs. All of these protocols have their own advantages and shortcomings. They have their own original intention and application scenarios when they are designed. The major challenges of these protocols are how to develop an efficient and practical method for channel negotiation. Most of the proposed multichannel MAC protocols can be divided into two categories: dedicated control channel protocol and split phase protocol.

Channels are divided into one control channel and several data channels in dedicated control channel approaches. The sender and receiver negotiate on the control channel to select the data channel for transmitting data. These protocols work as follows. The protocols use RTS/CTS mechanism to solve the single hidden terminal problem. The RTS message included the senders id, receivers id, available channel set and the packet length. The intended receiver selects one available data channel by some strategies after correctly receiving the RTS message. Then it responds a CTS message to inform the sender the selected data channel and turns to listen on this channel. The sender will send data packet on the selected data channel after receiving the CTS. CUMAC proposed in [23] is a paradigm in such approaches. CUMAC utilizes the neighbor negotiation for collision detection. And it also uses an additional hardware device tone for distributed collision notification. But channel negotiation requires too much communication cycles. Thus the increasing end-to-end delay reduces the overall performance. And the additional hardware increases the cost of the system. DMC-MAC proposed in [24] is another protocol. DMC-MAC utilizes the relative position information of the transmitting nodes to adaptively determine the best channel allocation (multichannel transmission). It can also decide the packet transmission scheduling that minimizes the collision free broadcasting duration.

For split phase approaches, time is divided into multiple beacon periods. And every beacon period is divided into alternate control and data phases respectively. Every node chooses one channel by some strategies from the available channel set for receiving data in the control phase. Then it broadcasts one control message to inform other nodes of their decisions. The sender and receiver transmit data in data phase. UMMAC proposed in [25] is one of these approaches. UMMAC is a split phase and reservation based multichannel MAC protocol. And it enables hosts to utilize multiple channels via a channel allocation and power control algorithm (CAPC). The CAPC algorithm aims at maximizing the networks capacity. Users can allocate their transmission power and channels in a distributed way. The efficiency is low when the nodes are distributed in multihop environment, because of UMMAC only considering one collision domain. To reduce collision probability, [26] proposes a Distributed Multiple-rendezvous Multichannel MAC protocol (MM-MAC) using the concept of cyclic quorum systems. MM-MAC enhances the network performance in a multihop UWSNs by reducing collision probability significantly. MM-MAC focuses on protocol performance of multihop and light-loaded network environment. Therefore, MM-MAC does not perform well in multinode environments. ROM-MAC proposed in [27] is another of these approaches. In this protocol, the negotiations and communications rely on the channels and the time of receivers. The waiting time of the network is reduced and the bandwidth utilization is improved by reducing the number of communication times. But the shortcoming of ROM-MAC is that it requires strict time synchronization.

In summary, the dedicated control channel protocol's channel negotiation is more efficient, but requires a dedicated control channel and has hidden terminal problem. The split phase protocol does not require a dedicated control channel. But the channel negotiation efficiency is low and requires strict time synchronization. With the analysis of the several existing multichannel MAC protocols for UWSNs, we focus on designing a multichannel MAC protocol to increase network performance in the distributed underwater environment.

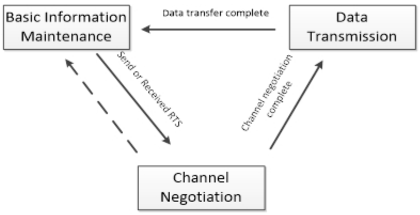

FIGURE 1. DRAMAC work phase diagram.

III. DRAMAC PROTOCOL DESIGN

According to the discussion in the second part, we found that the existing MAC protocols have lower efficiency in UWSNs. Therefore, in this part we will elaborate DRAMAC protocol we proposed. DRAMAC's core idea is trying to make full use of channel resources. Before describing DRAMAC in detail, we briefly describe the network model of this paper. The network model in this paper is as follows:

- All nodes have one control channel and several data channels. The control channel is used to exchange the control packet. The data channel is used for data transmission.
- Each node is equipped with a single transceiver. And can only listen to a single channel.
- The whole network does not require strict time synchronization.
- All nodes in the network are static or moving slowly. Each node knows its own position information.

In this section, we describe an overview of DRAMAC. Then we present the two key schemes of DRAMAC: NPCC and DCNS. Also we discuss why DRAMAC can solve the triple hidden terminal problem in detail.

A. DRAMAC OVERVIEW

DRAMAC is a multichannel MAC protocol based on handshaking. As shown in Fig. 1 DRAMAC contains three phases: there are basic information maintenance phase, channel negotiation phase and data transmission phase. In basic information maintenance phase, nodes automatically listen to the control channel when there is no sending and receiving task. Maintain the neighbor list, channel occupancy, network load index and other information for the subsequent channel negotiation. In channel negotiation phase, the channel is negotiated through the dynamic channel negotiation strategy. The negotiation phase includes RTS/WCTS/XCTS/CTS control packets exchange process. In data transmission phase, the sender and receiver carry on the data transmission and verification.

As shown in Fig. 2, node will initiate a channel negotiation process when it has data packets to send. First, the sender sends RTS when the control channel is idle. First, the sender sends RTS when the control channel is idle. The RTS contains receiver identification and packet length. After receiving the RTS, the receiver initiates the dynamic channel negotiation strategy (DCNS). Depending on the length of the packet and the network load conditions, dynamically select a simple handshake or the NPCC process. Then, the sender and the receiver are both switched to the negotiated data channel for transmission. After the data transmission is complete, the receiver will reply ACK, informing the sender that the data transmission is successful. Otherwise, the sender initiates the retransmission after the timeout. The idle node updates the basic information during channel negotiation.

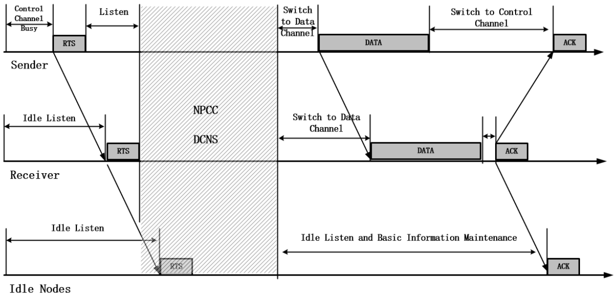

FIGURE 2. DRAMAC work process timing diagram.

The above is an overview of the DRAMAC. We can draw two key schemes of DRAMAC: NPCC and DCNS. Next, we describe these two key schemes in detail.

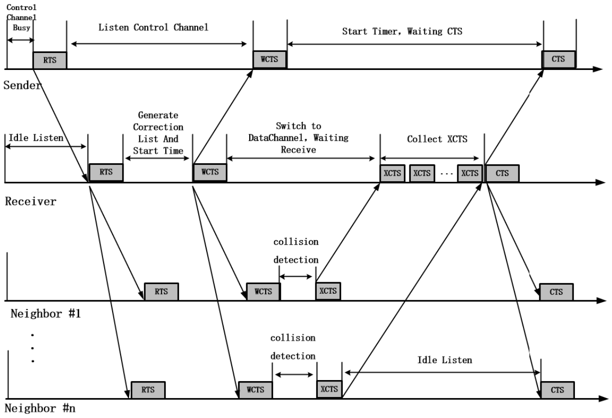

FIGURE 3. NPCC work process timing diagram.

B. CHANNEL NEGOTIATION PROCESS BASED ON COOPERATIVE CORRECTION (NPCC)

The core idea of NPCC is performing collision detection through cooperation among neighbor nodes. Neighbor nodes perform collision detection and give the proposed amendment. As shown in Fig. 3, the sender sends RTS to the receiver when the control channel is idle. The RTS message contains receiver identification and packet length. After receiving the RTS, the receiver generates correction list and start time. Then, the receiver broadcasts WCTS for collision detection. When the sender receives WCTS, it starts the timer and waits for CTS. If the sender receives a CTS before the timer expires, it will directly switch to the data channel in the CTS for data transmission. Otherwise, switch to the data channel in the CTS for data transmission. After the receiver broadcasts the

WCTS, it turns on the timer to wait for XCTS. If the receiver does not receive the XCTS before the timer expires, it will directly switch to the data channel in the WCTS for data reception. Otherwise, the receiver selects the most frequently occurring data channel from the received XCTS to reply the CTS. After the neighbor node receiving WCTS, first check whether they have permission to correction. Neighbor nodes will keep silent if has no correction permissions. Otherwise, the neighbor node will perform collision detection according to the local available channel list. If a collision is detected, the receiver will select a channel in the list of locally available channels according to the low channel priority policy. Then, send the XCTS at the time point specified in the WCTS. The above is NPCC's working process.

1) CORRECTION NODE FILTERING

In the above description of the NPCC, it is necessary to filter the correction nodes. Next, we will discuss why and how to filter.

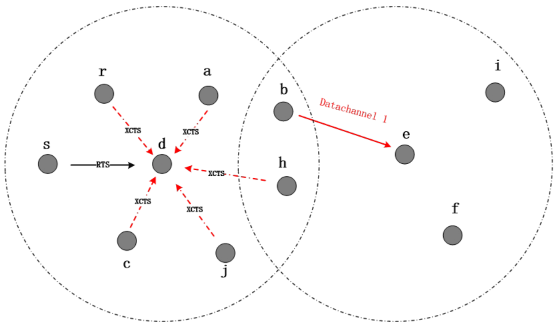

FIGURE 4. NPCC work process timing diagram.

As shown in Fig. 4, node 's' has data send request to 'd' so send RTS to 'd'. Node 'd' selects data channel 1 and broadcasts WCTS for collision detection. However, at this time nodes 'b' and 'e' are transmitting data on the data channel 1. Both nodes 'a', 'c', 'h', 'r' and 'j' all detect the occurrence of this collision. Then, all of them will send XCTS to notify node 'd' that a collision will occur. However, when there are many nodes sending XCTS, congestion will occur in the control channel, resulting in XCTS collision. In this paper, this problem is called redundant collision notification. Therefore, in order to solve this problem, this paper adopts the following measures:

- Correction node filtering.
- All correction nodes send corrective information (XCTS) at the same time point.
- A shorter XCTS frame format.

In order to facilitate the discussion of how to filter the nodes to avoid collision. We simplify this problem to two nodes send data to the same node in the same time, and discuss how to avoid collision. As shown in Fig. 5, node 'a' and 'c' send the data packet of the same length l to 'b' at the same time. The send delay t_s and the data send rate r have the following relations:

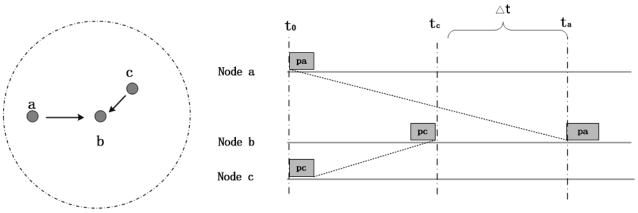

FIGURE 5. Collision avoidance example.

$$t_s = \frac{l}{r}, \tag{1}$$

The relationship between propagation delay t_p and distance D is:

$$t_p = \frac{D}{v}, \tag{2}$$

Where v represents the underwater acoustic speed, i.e., 1500 m / s. d_{ab} represents the distance between 'a' and 'b', d_{cb} represents the distance between 'c' and 'b', the space between them Δd is:

$$\Delta d = |d_{ab} - d_{cb}|, \tag{3}$$

With the formula (2), the node 'c' to send the packet to reach 'b' and complete receive time t_c is:

$$t_c = t_0 + 2t_s + \frac{d_{cb}}{v}, \tag{4}$$

The time for a packet sent by node 'a' to reach 'b' is:

$$t_a = t_0 + t_s + \frac{d_{ab}}{v}, \tag{5}$$

$$\Delta t = |t_c - t_a|, \tag{6}$$

The condition that no collision occurs is Δt larger than zero. Combine (1), (3), (4), (5) and (6) shows that:

$$\Delta d > \frac{v \times l}{r}, \tag{7}$$

In summary, the minimum distance d_{min} for which no collision can occur is calculated by equation (7).

In order to validate the correctness and feasibility of the above theoretical analysis, the actual minimum distance and the theoretical minimum distance are simulated in NS-3.

As shown in Fig. 6, there are two curves. The solid line represents the variation of the theoretical value of the minimum distance with the data transmission rate of the node when the packet length is 3 bytes, and the dotted line represents the simulation value. It can be seen from the figure that the theoretical value and the simulation value of the change characteristics are basically same and the value of the difference is very small, which illustrates the correctness of theoretical analysis. As shown in the figure, when the node data transmission rate is 1200bps, the simulation value of the minimum distance is 33 meters. Underwater propagation radius can be 1000-2000 meters. Therefore, we can select enough nodes for collision detection.

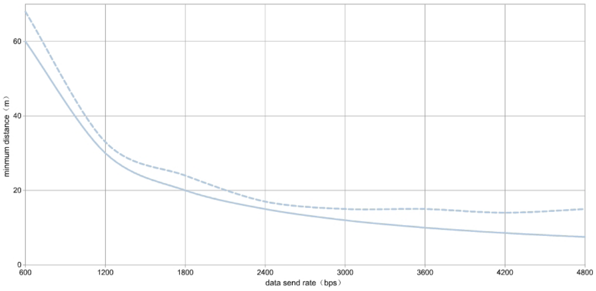

FIGURE 6. **Theoretical and simulation contrast diagram of minimum distance.**

2) MIXED COLLISION NOTIFICATION

In dense multihop UWSNs environment, multiple receivers simultaneously perform collision detection, there may be resulting in XCTS collision with each other. In this paper, this problem is called mixed collision notification.

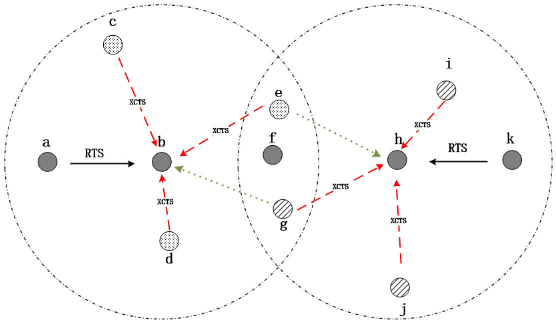

FIGURE 7. **Mixed collision notification example.**

As shown in Fig. 7, node 'a' has data send request to 'b' and send RTS. Node 'k' also has data send request to 'h' and send RTS. Then both nodes 'b' and 'h' initiate NPCC for collision detection. Then the nodes 'c', 'e' and 'd' reply XCTS to 'b', the nodes 'g', 'i' and 'j' reply XCTS to 'k'. Because nodes 'e' and 'g' are common neighbors of 'b' and 'h'. Therefore, the XCTS sent by the nodes 'e' and 'g' will produce error interference to the collision detection of the nodes 'b' and 'h'.

In this paper, the scheduling time is generated by arranging the time plan. Then the receiver broadcasts the WCTS containing the modification initiating time to avoid the mixed collision notification problem. In the neighbor nodes of the receiver, the last correction notification information start time T_{last} can be expressed as:

$$T_{last} = \max(T_{s1}, T_{s2}, T_{s3} \ldots T_{sn}), \tag{8}$$

where $T_{s1}, T_{s2}, T_{s3} \ldots T_{sn}$ respectively represent the start time of all XCTSs contained in the WCTS that the receiver listens. The relationship between the maximum propagation delay T_{max} and the maximum transmission radius R in the receiver hop range is as follows:

$$T_{\max} = \frac{R}{v}, \tag{9}$$

v represents the speed of underwater acoustic propagation, the XCTS initiation time T_s is generated by the following expression:

$$T_s = T_{last} + T_{\max} + T_{guard}, \tag{10}$$

where T_{guard} represents the guard time.

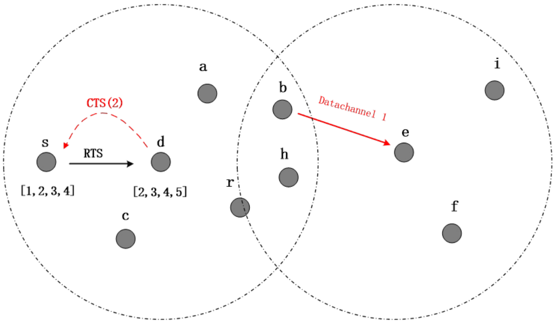

FIGURE 8. **Directly handshake process example.**

3) CONTRAST AND ANALYSIS

NPCC introduction is completed, next we will briefly describe the directly handshake process. Then, analyze and contrast them. As shown in Fig. 8, node 's' has data send request to 'd' and send RTS. RTS contains the available channel list of node 's'. After receiving the RTS, the node 'd' selects a data channel from the list of available channels of both parties, according to the strategy of low channel priority. And then directly reply to the CTS notification node 's'. This process is a directly handshake process.

The advantage of the direct handshake process is simple and easy to implement. When the network load is low, it has low delay and high efficiency. But the disadvantage is that with the increase of network load, the serious collision leads to more data retransmission to reduce the network performance.

The advantage of NPCC is the low collision rate due to the cooperation between neighbor nodes. When the network load is high, the lower collision rate leads to a higher data transmission success rate, making the network with higher throughput performance. But the disadvantage is that at low network load, it has higher end to end delay.

C. RECEIVER-ORIENTED DYNAMIC CHANNEL NEGOTIATION STRATEGY (DCNS)

DCNS is another key scheme of the DRAMAC proposed in this paper. The core idea of DCNS is to consider the packet length and network load synthetically. Combining the advantages of direct handshake process and NPCC. Dynamically select the best channel negotiation process, improve the network performance and adaptability in distributed environment.

1) NETWORK LOAD MAINTENANCE

The network load index is used to measure the busyness of the data channel within the one hop range of the node. The network load index is the ratio of the number of data channels in use and the sum of all data channels:

$$P(t) = \frac{C_{use}(t)}{C_{total}}, \tag{11}$$

where $P(t)$ represents the network load index at time t, $C_{use}(t)$ is the number of data channels in using at time t, C_{total} is a constant representing the sum of all data channels. The node updates the channel occupation list by automatically listing the control packets (RTS, CTS, WCTS, XCTS, ACK) transmitted on the control channel. And then the network load index is obtained by the formula (11).

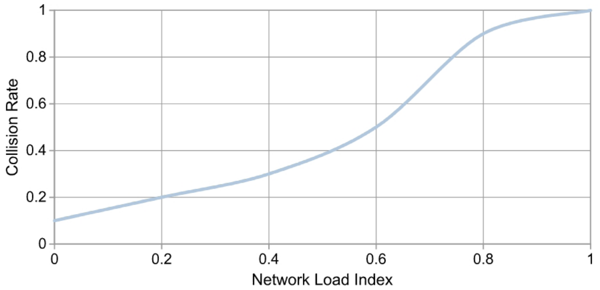

FIGURE 9. **The relationship between network load and collision rate.**

In this paper, the simulation results show that the collision rate of directly handshake process will fast increase when the network load is higher. As shown in Fig. 9, when the network load index is less than 0.6, the collision rate does not exceed 0.2 and relatively flat. When the network load index exceeds 0.6, the collision rate increases rapidly. When the network load index exceeds 0.9, the collision rate close to 100% and the network is almost unavailable. Based on this simulation experiment, the proposed DRAMAC takes 0.6 as the network load index threshold. When the network load index is lower than the threshold, it tends to adopt the direct handshake process, otherwise, NPCC will be adopted.

2) PACKET LENGTH SELECTION

UWSNs has long propagation delay and low data send rate. The cost of data retransmission is high when the data packet is long. As shown in Fig. 10, the delay rapidly increases as the packet length increases. The time from the send beginning to the receiving end is as follows:

$$t_{delay} = t_{send} + t_{pro} + t_{recv}, \tag{12}$$

t_{delay} is the total delay, t_{send} is the send delay, t_{pro} is the propagation delay, t_{recv} is the receiving delay. The send delay and the receive delay have the following relationship with the packet length:

$$t_{send} = t_{recv} = \frac{l}{r}, \tag{13}$$

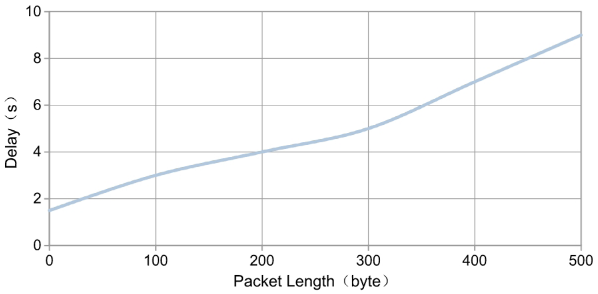

FIGURE 10. **The relationship between packet length and delay.**

Where l represents the packet length, and r represents the data sending rate. When the additional delay required for data retransmissions is greater than the amount of time it takes for a communication to travel. We believe that the cost of data retransmission cost is higher:

$$t_{delay} > 2t_{pro}, \tag{14}$$

According to the formula (12), (13), (14)

$$l > \frac{Rr}{2v}, \tag{15}$$

Where R represents the maximum transmission radius.

Based on the above analysis and discussion, this paper through the formula (15) calculated packet length threshold. DRAMAC tends to adopt the direct handshake process when the packet length lower than the threshold, otherwise NPCC tends to be adopted.

3) DYNAMIC CHANNEL NEGOTIATION

DRAMAC is a receiver-oriented MAC protocol. After receiving the RTS, the receiver dynamically adopts different strategies to negotiate the channel according to the packet length and the network load. As shown in Algorithm 1, After receiving the RTS, the receiver calculates the packet length threshold and the network load threshold. When the packet length and network load are both less than the threshold, it will use the direct handshake process. Otherwise, NPCC is used. Then, switch to the negotiated data channel for data receiving.

D. DATA TRANSMISSION PHASE

After the channel negotiation, both the sender and receiver will switch to the negotiated data channel for data transmission. After the receiver successfully receives the data and verifies no error, it will reply ACK notifies the sender. If the sender does not receive ACK within the specified time, it will resend RTS for data re-transmission.

E. HIDDEN TERMINAL PROBLEM ANALYSIS

The hidden terminal problem is a common problem in UWSNs. If we cannot effectively solve this problem, it will seriously influence the performance of the network. In DRAMAC, direct handshaking is used only for short packets and low network loading. Because when the packet is

Algorithm 1 Dynamic Channel Negotiation

```
Input: RTS, $P$, $L$
Output: $P_f$, $L_f$
procedure DynamicChannelNegotiation(RTS)
procedure ListenControlChannel(RTS)
if Receive RTS then
    Calculate network load threshold $P_f$ and packet length threshold $L_f$
    if $P < P_f$ && $L < L_f$ then
        Directly handshake
        Switch to datachannel
        Receive data
    else
        NPCC
        Switch to datachannel
        Receive data
    end if
else
    ListenControlChannel(RTS)
end if
end procedure
end procedure
```

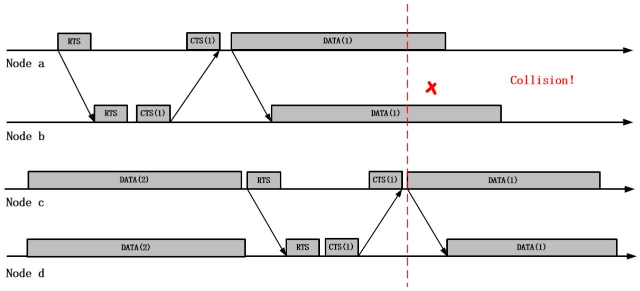

FIGURE 11. Multi-channel hidden terminal problem example.

shorter, the cost of retransmission after the collision is small. When the network load is low, the probability of collision is small. Therefore, we will only discuss how NPCC solves the hidden terminal problems.

Fig. 11 illustrates the multichannel hidden terminal problem. There are four nodes ‘a’, ‘b’, ‘c’ and ‘d’ in the figure. The nodes ‘c’ and ‘d’ are transmitting data on the data channel 2. Node ‘a’ and ‘b’ handshake on the control channel and select the data channel 1. Since nodes ‘c’ and ‘d’ are transmitting data at this time, the handshaking process for nodes ‘a’ and ‘b’ is not monitored. Next, the nodes ‘c’ and ‘d’ handshake the control channel again. Because the node ‘d’ does not know that the data channel 1 is already occupied, the data channel 1 is selected again. Then, a data collision occurs.

The problem of multichannel hidden terminals is due to the incomplete channel occupancy information. The NPCC in DRAMAC performs collision detection through cooperation among neighbor nodes. Relatively complete channel occupancy information can be obtained. So DRAMAC can effectively solve this problem.

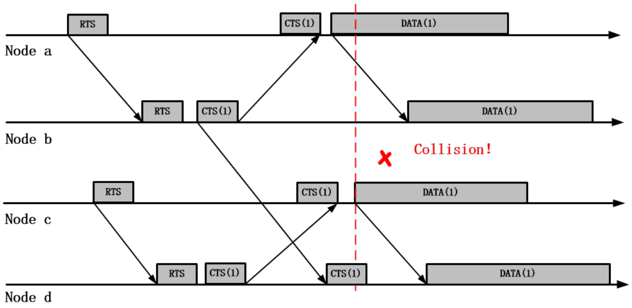

FIGURE 12. Long delay hidden terminal problem example.

Fig. 12 illustrates the long-delay hidden terminal problem. There are four nodes ‘a’, ‘b’, ‘c’ and ‘d’ in the figure. First nodes ‘a’ and ‘b’ handshake on the control channel, then nodes ‘c’ and ‘d’ also handshake on the control channel. Node ‘b’ first selects data channel 1 and replies CTS. Then the node ‘d’ performs data channel selection. Due to the longer propagation delay, the node ‘d’ after selecting the data channel 1 and sends the CTS, it receives the CTS sent by node ‘b’. Then, a data collision occurs.

The problem of long delay hidden terminals is due to the long propagation delay. So that the node cannot update the channel occupancy information in time. The NPCC in DRAMAC does not directly reply CTS after receiving the RTS request. But to wait for neighbor nodes for collision detection. Therefore, there is sufficient time to wait for the update of the channel occupation information. So DRAMAC can also effectively solve this problem.

IV. EVALUATION

In this section, we evaluate the performance of DRAMAC protocol we proposed and compare it with CUMAC and RTS/CTS-based MAC through NS3. For comparison purposes, we implemented CUMAC and RTS / CTS-Based MAC in NS-3. In this paper, we randomly deploy 50 underwater nodes in a $5000 \times 5000 \times 5000$(m) area and use the following parameters in simulation:

- The total channel count is 10.
- Bandwidth of each channel is 1 kbps.
- The propagation speed of the acoustic signal is 1500 m/s.
- The transmission range of every node is 1 km.
- The average data packet length is 300 bytes.
- The average transmitting power is 0.6 Watt.
- The average receiving power is 0.2 Watt.
- The idle listening power is 0.02 Watt.

For all three protocols, we measure the following three metrics:

- The average network throughput, which is defined as the number of successful data transmissions per unit time.
- End-to-end delay, which is defined as the time from packet being generated to being received completely.
- Energy consumption, which is measured as the consumed energy that sending one byte data.

A. THROUGHPUT

The average network throughput directly reflects the performance of the network. It is derived from the following formula:

$$\Lambda = \frac{\sum_{i=1}^{n} N(i) \times L_D}{T}, \tag{16}$$

where Λ is the average network throughput, n is the number of total nodes, T represents the duration time of the simulation,L_D is the average data packet length, $N(i)$ represents the number of data packets of the node 'i'.

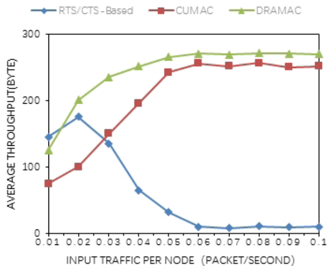

FIGURE 13. Network throughput: Packet length 500B.

Fig. 13 illustrates the trend of three protocols' throughput with the change of the input traffic. The input traffic is changed from 0.01 packets/s to 0.1 packets/s. The average packet size is 500 bytes. The throughput of RTS/CTS-based MAC decreases as the input traffic increases, because the collision rate of RTS/CTS-based MAC increases sharply with the increase of packet rate and network load. The throughput of DRAMAC and CUMAC does not decrease with the increase of input traffic. It is because they have the collision detection mechanism to ensure a lower collision rate, even when the network load is high. Overall, the throughput of DRAMAC is higher than CUMAC. Because when the network load is low, DRAMAC adopts the direct handshake procedure, the low-delay has brought higher throughput. When the network load is high, more efficient collision detection process makes the throughput of DRAMAC slightly higher than the CUMAC.

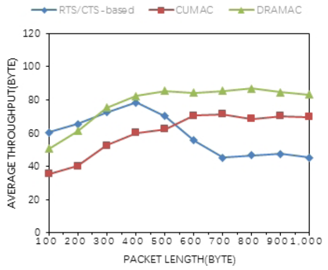

FIGURE 14. Network throughput: Input traffic 0.02 packet/s.

Fig. 14 illustrates the trend of throughput with the change of the packet length in these three MAC protocols. In this set of simulations, we change the packet length of every node from 100 to 1000 bytes. The picture shows that when the packet length is less than 500 bytes, the throughput of RTS/CTS-based MAC and DRAMAC is greater than CUMAC, when the packet length is greater than 500 bytes, then the throughput of DRAMAC and CUMAC is greater than RTS/CTS-based MAC gradually. Due to the DRAMAC dynamic selects different channel negotiation strategies based on the packet length, it will show a high throughput performance in different packet length. When the packet length is larger the throughput performance of RTS/CTS-based MAC will reduce due to the long-delay caused by the collision. When the packet length is short, the throughput performance of CUMAC is low due to the excessive number of communication cycles.

B. END-TO-END DELAY

As end-to-end delay is a critical performance indicator in the network, we compare the end-to-end delay in this sub-section. End-to-end delay is defined as the time from packet being generated to being received.

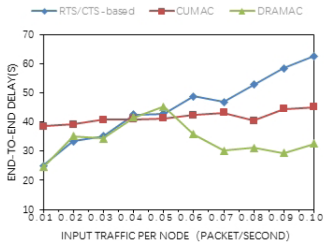

FIGURE 15. End-to-end delay: Packet length 100B.

Fig. 15 illustrates the trend of end-to-end delay with the change of the input traffic in these three MAC protocols. In this set of simulations, we change the input traffic of every node from 0.01 to 0.1 packets/s. From the picture, we can see the end-to-end delay of CUMAC is centered and has been very stable. When the input traffic is higher, the end-to-end delay of RTS/CTS-based MAC is relatively higher because of the collision. CUMAC always has lower end-to-end delay because when the input traffic is low, it can reduce the time delay by direct handshake process and when the input traffic is higher, it can reduce the time delay through reducing the number of communications.

C. ENERGY CONSUMPTION

The energy consumption is directly related to the lifetime of the network, we compare it in this sub-section. Energy consumption is measured as the consumed energy that sending one byte data. It is derived from the following formula:

$$E_{consume} = \frac{\sum_{i=1}^{n} e(i)}{P_{send} \times n \times L_D}, \tag{17}$$

where $E_{consume}$ is the energy consumption of sending one byte data, n represents the number of nodes, $e(i)$ represents the

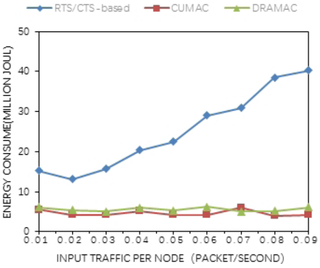

FIGURE 16. **Energy consumption.**

consumed energy of the node 'i' and P_{send} is the input traffic of nodes.

Fig. 16 illustrates the trend of three protocols energy consumption with the change of the input traffic. It can be seen from the figure that the energy consumption of RTS/CTS-Based MAC increases rapidly as the input traffic increases. This is due to the high collision rate. The energy consumption of CUMAC and DRAMAC is similar and far below of RTS/CTS-based MAC. This is because of that when the input traffic is higher, DRAMAC and CUMAC have a lower collision rate compared with RTS/CTS-based MAC.

V. CONCLUSIONS

In this paper, we propose a multichannel MAC protocol called DRAMAC. DRAMAC is based on single transceiver in long-delay UWSNs. DRAMAC is only equipped with a single transceiver on each node reducing the hardware cost. DRAMAC dynamically selects channel negotiation strategy according to packet length and the receivers network load condition. Using the neighborscooperation information can detect collision. Thus reducing the probability of collision. DRAMAC obtains a lower delay by using as few communication times as possible during channel negotiation phase. The simulation results show that DRAMAC can significantly improve the network throughput.

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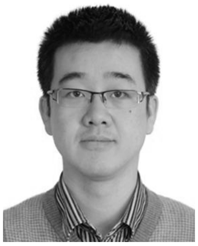

XIAONING FENG received the B.S. degree and the M.S. and Ph.D. degrees in computer science and technology from Harbin Engineering University. He is currently an Associate Professor with the Department of Computer Science and Technology, Harbin Engineering University. His research interests include underwater acoustic networks.

ZHUO WANG received the B.S. degree and the M.S. and Ph.D. degrees in computer science and technology from Harbin Engineering University. She is currently an Associate Professor with the College of Shipbuilding Engineering, Harbin Engineering University. Her research interests include autonomous underwater vehicle and underwater acoustic networks.

GUANGJIE HAN received the Ph.D. degree from Northeastern University, Shenyang, China, in 2004. From 2010 to 2011, he was a Visiting Research Scholar with Osaka University, Suita, Japan. He is currently a Professor with the Key Laboratory for Ubiquitous Network and Service Software of Liaoning province, School of Software, Dalian University of Technology, Dalian, China.

WENJIE QU received the B.S. degree from the College of Engineering, Qufu Normal University, in 2014 and the M.S. degree from the College of Computer Science and Technology from Harbin Engineering University in 2017. He is currently an Engineer with Baidu Co. Ltd. His research interests include underwater acoustic networks.

AKANG CHEN received the B.S. degree from the College of Science, Northeast Forestry University, China, in 2016. He is currently pursuing the master's degree with the College of Computer Science and Technology, Harbin Engineering University. His research interests include underwater acoustic networks.

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