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RESEARCH ARTICLE

A Short Signal Backoff MAC Protocol Based on Game Theory for Underwater Sensor Networks

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ABSTRACT Underwater wireless sensor networks(UWSNs) have a long propagation delay; In order to avoid collision, the handshake mechanism is adopted in the design of media access control protocol. However, with the increase of propagation delay, The time of waiting for the feedback signal will increase continuously, resulting in the delay that too many channels are occupied by reservation. When the delay starts to be larger than the transmission time of the packet, the handshake protocol will lose its advantage in performance completely. However, the protocol that does not use the handshake mechanism has the loopholes of the confirmation mechanism or the excessive backoff after the number of nodes's increasing, which leads to the increase of conflicts. Therefore, this paper proposes a MAC protocol based on short signal game backoff. Based on counting the number of short signal messages in the reservation stage, The protocol adopts game theory to ensure that the sending node can send without conflict after winning the reservation channel competition with the best probability without using handshake mechanism. In addition, the remaining nodes are allowed to choose the backoff time in a more reasonable way, rather than the random backoff which reduces the efficiency infinitely. The simulation results show that the protocol can greatly improve the network performance.

INDEX TERMS Game theory, backoff algorithm, MAC protocol.

I. INTRODUCTION

Underwater Wireless Sensor Networks (UWSNs) [1], [2], as is shown in Figure 1 form self-organized networks by deploying sensor nodes with computing capacity, communication function and low energy consumption in the monitoring sea area. It has made great achievements in marine environment detections such as marine water quality monitoring, resource explorations and emergency predictions, which let it receiving more and more attention.

However, due to the particularities of underwater environment, such as low bandwidths, Doppler interferences,multipath interferences [3] and extremely low underwater sound velocity propagation(only about 1500m/s),the design of underwater protocols will face difficulties such as high bit error rate, long propagation delay and energy limiting.

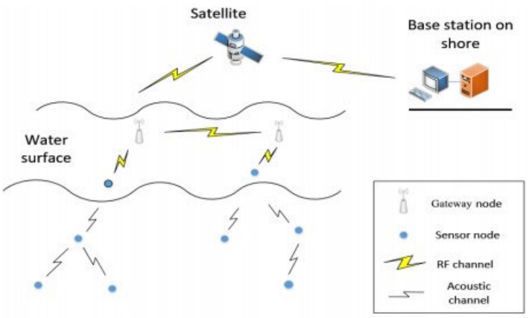

FIGURE 1. Frame schematic diagram of underwater acoustic network.

In addition, the propagation delay of wireless sensor networks is long, which makes the nodes unable to sense the channel states in time.In the traditional handshake based MAC protocol [4], only one node is allowed to send data after the handshake is successful. When multiple nodes shake

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hands at the same time, the backoff of multiple nodes will not only reduce the throughput, but also increase the delay in the process of waiting for the handshake with the deterioration of the underwater environment, even greater than the data transmission time, thus seriously affecting the performance of the MAC protocol.

Therefore, this paper proposes a multiple access protocol based on short signal game theory backoff algorithm (SSGTB). For the RTS control packet in the handshake system is actually a kind of signal sound, in order to avoid the problem that the performance of the handshake protocol will be greatly reduced, when the propagation time delay is much longer than the transmission time of the data packet, we let each node send a short wake-up signal sound to reserve the channel, and the transmission of each layer of data includes the reservation period and the transmission period. In the First competition period, the total number of nodes is counted first to decide to choose what kind of game.

Then, according to the game algorithm for node with best probability to choose to send or wait, eventually only one node successfully enters into the data transmission phase, after completion of the transmission, in the process of the next appointment channel, according to the previous round of the game, the node with minimum probability of wait will send in the new round of the channel competition with a higher probability. at the same time, according to the whole network's total number of nodes, the network dynamically adjusts the probability of the node which is requesting channels, to minimize multi-node access conflicts.

In this way, when the channel state is good and the nodes are sparse, in addition to counting the time required by the nodes, only one time slot is required to send successfully. If the number of nodes is increased and the time delay of the underwater channel is much longer than the transmission time of the data packet, the protocol efficiency can be greatly improved because there is no long-time confirmation reply of the handshake mechanism.

The rest of this paper is organized as follows: in Chapter 2, we will mainly introduce the current research on underwater MAC protocol. In Chapter 3, we will introduce the new SSGTB protocol in detail. Then, we will compare the results through simulation experiments in Chapter 4 to verify the superiority of the new SSGTB protocol over other multiple access protocols, and finally make a prospect and summary in Chapter 5.

II. RELATED WORK

Traditional MAC protocols are mainly divided into fixed multiple access protocol, random multiple access protocol and reserved multiple access protocol.

Among them, fixed allocation refers to the allocation of certain exclusive channel resources to users accessing the channel until the end of transmission. The fixed allocation multiple access protocols include FDMA [5], CDMA [6], TDMA [7] and SDMA [8]. FDMA divides the frequency band into several channels, and different users use different channels, which is not applicable to underwater channels with very low bandwidth. CDMA only uses different codewords to distinguish different users in the same frequency and time period. In the dual-use users of the same base station, there will be interference due to the same codewords. If different codewords are selected, the power of users near the base station will also directly annihilate users far away from the base station. So CDMA is not suitable for UWSN without improvement. TDMA has been applied in a certain range in UWSNs, but it cannot be applied to UWSNs in centralized scenarios due to the underwater bandwidth problem and the clock synchronization problem of nodes. For this reason, Dhongdi et al. Proposed a cluster head based CB-TDMA protocol [9], which solved the problem of node collision caused by spatiotemporal unsynchronization, but only applicable to aggregation classification networks with cluster heads. In recent years, Alfouzan et al. Proposed a map coloring based MAC protocol [9], which first assigns different time slots to nodes, and then assigns different colors to different time slots, so that nodes with the same color can avoid collision through concurrent transmission. However, this kind of time slot allocation can not dynamically adjust the network, so it can not adapt to the harsh and changeable underwater network scenarios.

Random multiple access protocol refers to a channel that a user can access at random; There are two basic types: ALOHA [10] and CSMA [11]. Among them, ALOHA protocol can be divided into ALOHA and slot ALOHA [12]. The original ALOHA will be sent as soon as there is an idle node packet arriving, which will greatly increase the conflict when the network load increases or there is no conflict avoidance mechanism. The improved slotted ALOHA protocol divides a cycle into multiple slots, and only transmits data at the beginning of the slot. Although the collision is reduced, when multiple nodes send in the same slot, collision still occurs. The CSMA protocol senses the channel state through carrier detection and only transmits data when the channel is idle. It uses a backoff mechanism to avoid conflicts. When the underwater propagation delay is large, CSMA can avoid conflicts caused by multiple nodes accessing the channel at the same time. However, when the channel state is good, conflicts caused by multiple nodes accessing the channel at the same time will continue to increase. Thus, Lenka et al. proposed CSMA_TDMA hybrid MAC protocol [13], which adopts a distributed slot scheduling method, first finds out the two hop neighbors of each node, and then allocates a specific slot to each node. Compared with the separate TDMA or CSMA protocol, the performance is improved. However, due to the limitation of low bandwidth and high delay of the underwater network, it is difficult to determine the precise clock synchronization required by the two hop neighbors. When the network load continues to increase, The performance of the protocol began to decline significantly.

The reservation based multiple access protocol means that the user reserves the required resources before transmitting data. After the user reserves the resources, the user can start the conflict free transmission. In order to solve the node collision problem when the data packet is large, Karn et al. proposed a MACA protocol [14] that uses the handshake mechanism to reserve the channel. It improves the successful transmission rate of large data packets by including the length of the data packet to be sent in the short RTS control packet. However, this protocol increases the probability of collision of RTS control packets, and the high delay of underwater acoustic signals will waste a lot of bandwidth in the process of waiting for feedback.

In order to solve this problem, Peleto et al. Proposed a Distance Aware Collision Avoidance protocol (DACAP) [15]. After sending RTS control packets, DACAP protocol delays an average handshake time, thus avoiding conflicts with unrelated data packets. However, this time needs to be pre-configured and cannot dynamically adapt to the dynamically changing network topology.

In order to better solve a series of problems such as hidden terminals in the MACA protocol, the American scientist Fullmer et al. Proposed the FAMA protocol [16],which avoids collision by extending the length of the control message to eliminate the problem of the hidden terminals. However, its random handshake and backoff mechanism will greatly in-crease the collision in the cenario of increasing the number of underwater nodes or high delay. Therefore, After improving the FAMA protocol, M. Molins et al. Proposed a slotted FAMA protocol that can be applied to underwater [17]. However, in the underwater network with high time delay, the efficiency of the handshake mechanism is still low. Therefore, Wen et al. Proposed an MR- SFAMA protocol based on the time slot FAMA protocol [18], in which the receiving node receives multiple data packets through multiple handshakes, which greatly improves the efficiency of the handshake mechanism. However, when the number of network nodes increases, The backoff mechanism of this protocol will lead to an increase in conflicts and a sharp drop in throughput. In order to make this protocol applicable to a wider range of scenarios, Huang et al. Proposed a SFAMA-MM protocol [19] that can be used in multi diving acoustic networks in 2018. This protocol can avoid conflicts with new notification control packets based on the multi reception mechanism of MR-SFAMA protocol, thus further reducing the energy consumption and improving throughput.

In addition, the multiple access channel can also be regarded as a multi input single output queue. The data of each node is arranged into an orderly queue before entering the channel to improve the channel utilization. For example, in 2019, Zhu et al. proposed an adaptive scheduled media access control (DQA-MAC) protocol [20] based on delay and queue wareness. It improves the fairness of the network through the adaptive scheduling of queues.

The above protocols require handshaking before the nodes enter the transmission stage. However, in the underwater acoustic network with low bandwidth and high delay, the long handshaking process will waste a lot of originally very limited bandwidth, which will seriously affect the performance of the MAC protocol based on handshake. To solve these problems, this paper proposes a new MAC protocol based on hybrid game backoff.

III. SSGTB-MAC DESIGN

A. NETWORK MODEL

This protocol is suitable for clustered networks with surface relay nodes. The underwater node can reserve the channel, ensure the certian node that can be sent successfully, in the data transmission phase, it can transmit the data to the receiving node. As is shown in Figure 2, The underwater node is transmitted to the receiving node in a single-hop manner. The receiving node transmits the collected data to the water buoy, and the water buoy transmits the data to the shore base station through satellite communication. Finally, the base station performs data fusion and other data processing.

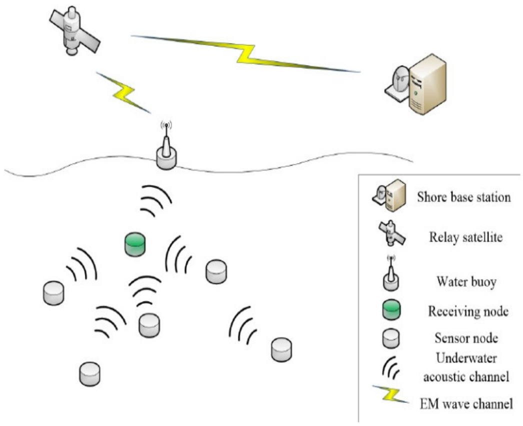

FIGURE 2. Network model of the proposed protocal.

B. CHANNEL RESERVATION AND ASSIGNMENT PROCESS

The transmission of data can be divided into two phases: reservation period and transmission period. A reservation period is divided into one or more competition periods (Contention Time, CT), in a competition period, multiple nodes that need to send data will first send a short message tone to reserve the channel while listening to the channel. Due to the long propagation delay of UWSNs, different competing nodes tend to reach the receiver at different times. In this way, each competing node can make statistics on the nodes in this round of competition. After the N competing nodes are counted, the N nodes play the game according to the mixed Nash equilibrium strategy, and then decide which node chooses to send and which one chooses to wait. After the game, only one node will enter the data transmission phase. After the data transmission is completed, the channel reservation competition cycle of the second node is recycled.

Specific process is shown in Figure 3, there are three nodes named A, B and C to participate in the channel competition,

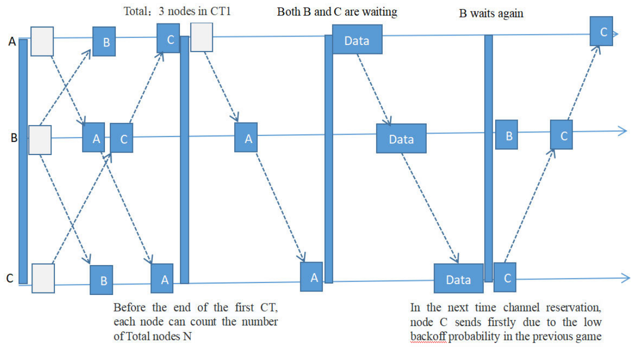

FIGURE 3. Channel reservation and data transmission process.

before the end of the first competition period, each sending node can count the total number of nodes N in this round of competition, then, according to the total number of nodes N, the game backoff algorithm is called, so as to finally decide that node A will send with the maximum sending probability. Nodes B and C both wait with different probabilities. Then, in the second CT, node A detects that only itself participates in the competition, and enters the data transmission phase. After the data transmission is completed, the second channel reservation's first CT begins, at this time, both node B and C can obtain different but optimal backoff probabilities through the hybrid game strategy algorithm, that is, node B chooses to send because of the low probability of backoff, but node C chooses to continue to wait again because of its high probability of backoff. Thus, the number of CT in the new channel reservation is reduced and the efficiency of successful transmission is improved.

C. NODE BACKOFF MECHANISM ON HYBRID GAME STRATEGY

In this section, we will discuss in detail how each member node can choose to send or wait by game when the total number of nodes N is counted after the first round of free competition.

1) NODE BACKOFF MECHANISM UNDER EVENLY DISTRIBUTION OF NODES

Assuming that the nodes are uniform distribution, then the underwater nodes have two choices: wait or send. If the node chooses to wait, it can choose to wait for 1 or 2 periods. If it chooses to wait for 1 period, set its income as R_1, if there are two backoff periods, set its payoff as R_2, if the node choose to send again, then In the next competition phase. There may be a collision or a successful sending, if there is a successful sending, set its payoff as S, if not, set its payoff as W, If a node chooses to send and sends successfully, the revenue S is the maximum revenue, Then the node chooses to send but fails to send, the revenue W must be the minimum, When a node chooses to wait, its payoff is smaller than the S which sends successfully, but larger than the payoff W which failed to send, Therefore, the revenue relation of nodes under different circumstances is $W < R_2 < R_1 < S$.

Let's first analyze how nodes choose to wait or send when there are only two nodes i and j during the monitoring period of the first round of node competition. Assume that the maximum propagation delay of the underwater network is T_{total}, the time delay for a node to send a short signal control tone is T_s, and the probability of collision when a node sends a short signal control tone is P_c, when the nodes are uniformly distributed, By the time difference between T_{total} and T_s, we can find the collision probability P_c using the following formula:

$$\mathrm{Pc} = \frac{\mathrm{Ttotal} - \mathrm{Tc}}{\mathrm{Ttotal}} \tag{1}$$

2) GAME THEORY UNDER THE HYBRID STRATEGY

when node j chooses to send, node i also chooses to send, the expected revenue is: $WP_c + (R_1 + R_2 + S)(1\text{-}P_c)$, and then, we can obtain the payoff of the game when two nodes are competing for channels, as is shown in Table 1. Since the uniformly distributed nodes j and i are symmetrical, when node i chooses to send, the expected payoff of node j is also $WP_c + (R_1 + R_2 + S)(1\text{-}P_c)$.

TABLE 1. Game payoffs when two node compete for channels.

Node j Node i	Send	Wait 1ct	Wait 2ct
Send	WP_c + $(R_1+ R_2+ S)(1-P_c)$, WP_c + $(R_1+ R_2+ S)(1-P_c)$	S，R_1	S，R_2
Wait 1ct	R_1，S	R_1，R_1	R_1，R_2
Wait 2ct	R_2，S	R_2，R_1	R_2，R_2

According to the Table 1, under all game circumstances in which nodes exist, if the total revenue of the whole network is set to U, then U can be calculated as follows:

$$\begin{aligned} U_{total} = {} & P_{\mathrm{i}}^{\mathrm{WP_c+(R_1+R_2+S)(1-P_c)}} P_{\mathrm{j}}^{\mathrm{WP_c+(R_1+R_2+S)(1-P_c)}} \\ & * (U_{\mathrm{i}}^{\mathrm{WP_c+(R_1+R_2+S)(1-P_c)}} + U_{\mathrm{j}}^{\mathrm{WP_c+(R_1+R_2+S)(1-P_c)}}) \\ & + \mathrm{P_i^S P_j^{R_1}}(U_{\mathrm{i}}^{\mathrm{S}} + U_{\mathrm{j}}^{\mathrm{R_1}}) + \mathrm{P_i^S P_j^{R_2}}(U_{\mathrm{i}}^{\mathrm{S}} + U_{\mathrm{j}}^{\mathrm{R_2}}) \\ & + \mathrm{P_i^{R_1} P_j^S}(U_{\mathrm{i}}^{\mathrm{R_1}} + U_{\mathrm{j}}^{\mathrm{S}}) + \mathrm{P_i^{R_1} P_j^{R_1}}(U_{\mathrm{i}}^{\mathrm{R_1}} + U_{\mathrm{j}}^{\mathrm{R_1}}) \\ & + \mathrm{P_i^{R_1} P_j^{R_2}}(U_{\mathrm{i}}^{\mathrm{R_1}} + U_{\mathrm{j}}^{\mathrm{R_2}}) + \mathrm{P_i^{R_2} P_j^S}(U_{\mathrm{i}}^{\mathrm{R_2}} + U_{\mathrm{j}}^{\mathrm{S}}) \\ & + \mathrm{P_i^{R_2} P_j^{R_1}}(U_{\mathrm{i}}^{\mathrm{R_2}} + U_{\mathrm{j}}^{\mathrm{R_1}}) + \mathrm{P_i^{R_2} P_j^{R_2}}(U_{\mathrm{i}}^{\mathrm{R_2}} + U_{\mathrm{j}}^{\mathrm{R_2}}) \end{aligned} \tag{2}$$

When only two nodes i and j participate in the competition, approximately, there is no other backoff period for these two nodes, so the following equation can be obtained:

$$\begin{aligned} Pi &= P_i^S = 1 - P_i^{R_1} - P_i^{R_2} \\ P_j &= P_j^S = 1 - P_j^{R_1} - P_j^{R_2} \\ P_i^{R_2} &= P_j^{R_2} = 0 \end{aligned} \tag{3}$$

Moreover, since we assume that all nodes are uniformly distributed in the network model, each node has the same revenue according to the symmetrical equivalence of nodes, thus, the following equation can be obtained:

$$\begin{aligned} U_i^{R_1+R_2} &= U_j^{R_1+R_2} = U^{R_1+R_2} \\ U_i^S &= U_j^S = U^S \\ U_i^W &= U_j^W = U^W \end{aligned} \tag{4}$$

When there are only two nodes competing for the channel, R_2 can be approximated by 0, Substituting (1), (3) and (4) into(2), the total revenue after simplification can be obtained as follows:

$$\begin{aligned} U_{total} = {} & Pi^{\mathrm{WP_c+(R_1+S)(1-P_c)}} Pj^{\mathrm{WP_c+(R_1+S)(1-P_c)}} \\ & * (Ui^{\mathrm{WP_c+(R_1+S)(1-P_c)}} + Uj^{\mathrm{WP_c+(R_1+S)(1-P_c)}}) \\ & + (Pi + Pj - 2PiPj)(U^S + U^{R_1}) \\ & + 2(1 - Pi)(1 - Pj)U^{R_1} \end{aligned} \tag{5}$$

In order to observe the probability value of the game strategy selected by node i, j, Observe the situation when the partial derivative of total revenue U_{total} with respect to P_i and P_j is zero:

$$\frac{\partial Utotal}{\partial Pi} = 0, \quad \frac{\partial Utotal}{\partial Pj} = 0 \tag{6}$$

Substituting equation(6) into equation (5), we can obtain:

$$Pi = \frac{U^S - U^{R_1}}{2U^S + 3U^{R_1} - [WPc + (R + S)(1 - Pc)]} \tag{7}$$

According to the symmetry of variables i and j in equation (5), $P_i = P_j$,and from formula (1), P_c which is based on the known quantity of underwater node propagation delay can be obtained, therefore, when there are only two nodes in the channel competition by game, When any node sends short signal control tone with the probability in formula(7), the probability of collision will be minimized. at the same time, according to the formula (7), The best probability $P_{R1} = 1\text{-}P_i$ for another node to wait can be obtained, that is:

$$PR1 = 1 - \frac{U^S - U^{R_1}}{2U^S + 3U^{R_1} - [WPc + (R + S)(1 - Pc)]} \tag{8}$$

During the first round of short signal tone competition in the reservation phase, if there are N nodes competing for the channel,The game between them can be extended from the above game between nodes i and j. Assume that when nodes i and j are sending signals, there are k other nodes in the channel that also send signals to compete for the channel. If only the node k is considered, assuming that its collision probability is P_c and its backoff probability is P_{R1}, then this node's probability of successful transmission is $1\text{-}P_c - P_{R1} - P_{R2}$. Therefore, the probability that all the k nodes fail to send successfully is its reverse $(P_c + P_{R1})$, The probability of all these nodes sending successfully can be expressed as Ck n$(1\text{-}P_c - P_{R1} - P_{R2})^k(P_c + P_{R1} + P_{R2})^{n-k}$, According to the assumption of uniform distribution and symmetric equivalence of underwater nodes at the beginning of this chapter, we assume that the node k is the node i, and there are remaining i-1 nodes around it, so the probability that all the i-1 nodes can send successfully is as follows:

$$\begin{aligned} Pi - 1 = {} & \mathrm{C_n^k(1 - Pc - PR_1 + PR_2)^k} \\ & * \mathrm{(Pc + PR_1 - PR_2)^{n-(i-1)}} \end{aligned} \tag{9}$$

Therefore,the revenue function U_i of any node i choosing three strategies can be further calculated, on the premise that all the above i-1 nodes are successfully sent.

$$\begin{aligned} U_i = {} & \mathrm{Pi - 1(1 - Pc - PR_1 - PR_2)S +} \\ & \mathrm{+ Pi - 1(Pc + PR_1 + PR_2)(R1 + R2)} \end{aligned} \tag{10}$$

Set $(1\text{-}P_c - P_{R1} - P_{R2})$ is X, then $(P_c + P_{R1} + P_{R2})$ is (1-X), then equation (10) can be reduced to:

$$U_i = \mathrm{Pi\text{-}1XS + X(1 - Pi - 1)(R1 + R2)} \tag{11}$$

Substituting equation (9) into equation (11), we can get:

$$\begin{aligned} U_i = {} & C_n^{i-1} S X^i (1 - X)^{n-i+1} \\ & + C_n^{i-1}(R1 + R2)X^{i-1}(1 - X)^{n-i+2} \end{aligned} \tag{12}$$

Find the X value when the partial derivative of U_i with respect to X is zero, we can get:

$$\frac{\partial Ui}{\partial X} = 0 \tag{13}$$

Substituting equation (13) into equation (12), we can get:

$$X = 1 - \frac{1}{C_n^{i-1}(S - R1 - R2)^{1/n}} - o(S, R1, R2) \tag{14}$$

As X is replaced by $(1\text{-}P_c - P_{R1} - P_{R2})$, That is, the probability of successful transmission of any node i in the underwater network. Therefore, when there are n underwater nodes to send data through the game, and any node i sends data with the probability of formula (14), the total revenue of the whole network will reach the optimal.

Next,we observe the relationship between the probability X corresponding to any node i to send data successfully and the total number of nodes n in the multi-node game. In Formula (13), when the number of n is small, then, $S \gg (R_1 + R_2)$, that is, $S\text{-}(R_1 + R_2)$ is a large positive number, and 1/n is also large, so the denominator is larger, thus the whole fraction is smaller, the value of X is larger, that is, the node will send with a high probability. Therefore, when n = 1, the denominator value in the fraction is the smallest, and the probability of X sending is the largest, Which is close to 100%. When the total number of underwater nodes n gradually increases, 1/n gradually decreases and the value of X becomes smaller, that is, the node will send with a small probability. However, the node number n can not increase without limit. When the value of S approaches the sum of ($R_1 + R_2$), the denominator approaches 0, and the whole fraction approaches $+\infty$, the value of X approaches 0. That is, when N continues to increase to $S \rightarrow (R_1 + R_2)$, the number of underwater nodes is too dense. At this time, the underwater node can draw the conclusion that the node can send with a probability close to 0 to avoid collision through the game strategy.

If we want to find the maximum value of n at this time, then, in Equation (14):

$$\frac{1}{C_n^{i-1}(S-R1-R2)^{1/n}} = 1 \tag{15}$$

$$n = \left\lfloor e^{(R_1+R_2)\ln\frac{1}{s-R_1-R_2}} \right\rfloor \tag{16}$$

Therefore, in the process of multi-node game, the number of nodes n can be increased from 1 to n in the formula (16), However, the sending probability of any node through the game strategy also increases with the number of nodes n, From initially sending with 100% probability, to finally most nodes backing off with different probability.

After node i have chosen the sending strategy, it will enter the data transmission phase according to the sending probability calculated by the above game strategy, after that, the network starts the process of reserving channel for node short signal for the second time. Then, count the number of competing nodes again according to the same method as counting the number of nodes in the first round of CT in the first channel reservation process, however, in the first game, all the different nodes except the sending node can choose the best backoff probabilities, and the node with the smallest backoff probability will be the first node to send in the new round of reservation, Therefore, the number of competing nodes in the first round CT of the second time channel reservation is reduced to a most reasonable way, so as to further shorten the number of CT in the second time channel reservation.

IV. SIMULATION AND PERFORMANCE ANALYSIS

In order to prove the effectiveness of the designed protocol, we conduct simulation experiments on the algorithm. In this paper, we use the Aqua-Sim simulation software based on NS2 [21] to conduct simulation analysis on SSGTB, TDMA_CSMA and SFAMA protocols. By comparing the average throughput, packet delay and successful delivery rate of the three protocols, the performance of these protocols in underwater acoustic sensor subnets are analyzed.

A. AQUA-SIM SIMULATION PLATFORM

Aqua-Sim is a simulation software designed to simulate and analyze underwater acoustic sensor networks. It was developed by the Underwater Acoustic Sensor Network Laboratory at the University of Connecticut in 2009 based on NS2. A protocol simulation on Aqua-Sim platform generally goes through the following steps:

1. Wrote OTCL simulation code, including setting simulation parameter information and network topology, etc.

2. Run the Aqua-Sim load simulation script for simulation and it will be generated after successful execution. Tr file and .nam file. The .tr file is Trace tracking file, which records the detailed information of the whole simulation process. The .nam file records the NAM animation input information, which can be used to show the whole simulation process.

3. Prepared GAWK code to analyze network performance for analyzing TRACE tracking files generated by simulation.

B. COMPARISON OF SIMULATION RESULTS AND PERFORMANCE ANALYSIS

This paper uses NS2 simulation platform to compare and analyze the performance of SSGTB, TDMA_CSMA, CSMA and SFAMA.

As shown in Figure 4, after three protocols are transmitted in the channel, they finally arrive at the access point. Assuming that the location coordinates of the access point are the origin (0, 0, 0), there are 21 terminal nodes and 1 receiving node, distributed in the space with the origin as the center, the range of 3500 meters as the radius, and (x, y, z) as the coordinates.

The 21 sending nodes are evenly distributed in space with the receiving node as the center of the circle and the spacing between them is 600 meters.

When the data packets collide, the data packets with high power may absorb the data packets with low power, which is called the acquisition effect. Due to the poor communication condition of the underwater channel, the transmitted data packets may fail to be transmitted without collision.

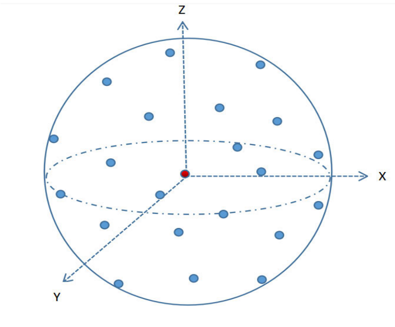

FIGURE 4. Underwater wireless sensor network structure.

Assuming that the length of the data packet is 1024 bit, the length of the control packet is 160bit, and the longest contention period is 0.06s,the minimum signal power required by the access point for correct signal demodulation is 10W. After successfully receiving 3000 data packets, the simulation ends. We mainly compare and analyze the network throughput, end-to-end delay and successful delivery rate of the three protocols under the scenario of 2 terminal nodes or 21 terminal nodes with 1 receiving node, that is, 22 nodes or 3 nodes.

C. THROUGHPUT

In this section, we discuss the changes of the throughput of the three MAC protocols under different loads in the scenarios of three nodes and 22 nodes. When the simulation value of the throughput is 1, it means that the channel is fully utilized, so the value range of the throughput is between 0 and 1. The simulation results are shown in Figure 5, when there are 21 sending nodes and 1 receiving node, that is, there are 22 nodes in the channel, the throughput of the three MAC protocols increases with the load, They are all rapidly increased to the saturation value, and then slowly decreased. In the process of slow reduction, they are accompanied by slight ups and downs.

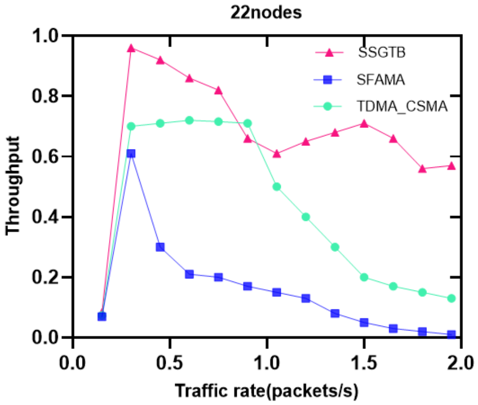

FIGURE 5. Throughput of three protocols over 22 node channels.

Next, we analyze the throughput changes of the three protocol nodes in Figure 5 in detail. When the load of the three protocols is small at the beginning, the throughput increases rapidly. When the load is 0.31, the throughput of the three protocols reaches the highest. However, it is found that the throughput of SSGTB is close to the maximum value 1 under the simulation considering the capture effect. Because TDMA_CSMA combines the advantages of the two basic protocols, a backoff algorithm is adopted on the basis of time slot division, and the maximum throughput can reach 0.71. Similarly, the throughput of SFAMA also reaches the maximum value of 0.61 when the load is small, which is similar to that of TDMA_CSMA. But when the load continues to increase, the throughput of SFAMA begins to decrease sharply to close to zero. This is because the random backoff mechanism of SFAMA increases the delay infinitely when there are more and more nodes, which further increases the probability of sending collision. When the load is within the interval of (0.31, 1), since TDMA_CSMA combines the time slot listening and the backoff algorithm when the channel is not empty to update the listening time, the throughput has been kept at a stable value of about 0.7. In this interval, although the throughput of SSGTB begins to decline, it declines slowly, and the lowest value after the decline is still the same as the highest value of TDMA_CSMA. The throughput of TDMA_CSMA begins to drop sharply to below 0.2, because when the number of nodes continues to increase, the backoff windows of the algorithm adopted by TDMA_CSMA are rapidly expanded, resulting in the aggravation of conflicts between nodes, and thus the throughput is seriously reduced. At this stage, only the throughput of SSGTB protocol remains at a stable stage of 0.55-0.65. This is because the protocol adopts a hybrid game strategy. When the number of nodes increases, it can also enable the sending node to choose to send or to backoff with the best probability, thereby reducing conflicts between nodes and keeping the throughput within a high stable range.

We should note that there is a concave on SSGTB protocol When the load is 1.1,This is because this protocol sends node signal tones by probability, there is still a probability trap problem on SSGTB protocol.

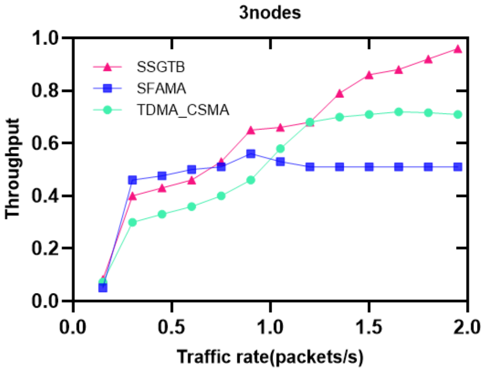

FIGURE 6. Throughput of three protocols over 3 node channels.

Next, we analyze the throughput of the three protocols under three node channels in detail. As shown in Figure 6, when the network load increases from 0 to 1,the throughput of SSGTB and SFAMA protocols is basically the same, and both are slightly higher than TDMA_CSMA protocol. When the network load is greater than 1, the throughput of the TDMA_CSMA protocol is higher than that of the SFAMA protocol, but still lower than that of the SSGTB protocol. This is because even in the case of sparse nodes, the performance of the SFAMA protocol will still decline when the load increases, and the SSGTB protocol can better select transmission or wait with the most appropriate probability when the nodes are sparse.

To sum up, in the scenario of large or small number of nodes, with the increase of network load, SSGTB protocol can perform better than the other two protocols, and its average throughput can be about 35% higher than TDMA_CSMA protocol and about 40% higher than SFAMA protocol.

D. SUCCESSFUL DELIVERY RATE

Successful delivery rate reflects the ability of the network to handle conflicts between nodes in different environments, especially under high load and high time delay. Improving the successful delivery rate is obviously an important indicator to improve the network performance. Here we first analyze the scenario of 22 nodes.

As shown in Figure 7, when the distance is within 1400m, the successful delivery rates of the SSGTB protocol and the TDMA_CSMA protocol have basically reached 1, while the SFAMA protocol can guarantee almost 100% of the delivery rate within the range of 1200m. However, from a distance greater than 1400m, the successful delivery rate begins to drop sharply to 0.53, which is significantly lower than the other two protocols. This is because the SFAMA protocol increases with the distance, Its own random wait mechanism will add a larger delay on the basis of waiting for twice the transmission delay of the control packet, resulting in more conflicts. As the distance increases, the successful delivery rate of the TDMA_CSMA protocol is higher than that of SFAMA protocol but lower than that of SSGTB protocol. This is because SSGTB protocol uses the best transmission probability and game backoff to avoid collision. Therefore, when the distance increases, conflicts between nodes can still be effectively avoided.

We should note that there is a concave when the distance is within 2000m, This is because When the conflict distance of SFAMA protocol exceeds a certain length, the probability of node collision in space decreases, but its own avoidance mechanism will eventually lead to the increase of collision probability.

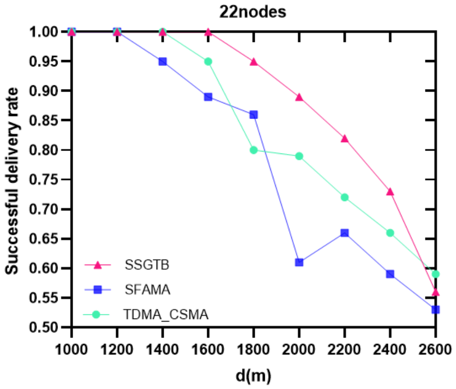

FIGURE 7. Successful delivery rate with 22 node channels.

Next, we continue to analyze the successful delivery rate in the 3-node scenario. As is shown in Figure 8, at this time, the difference in the successful delivery rate between TDMA_CSMA protocol and SFAMA protocol is not large, because when the nodes of SFAMA protocol are sparse, its own waiting and backoff mechanism will not cause too much conflict, thus maintaining a high successful delivery rate, while in TDMA_CSMA protocol, the mechanism of time slot listening after backoff will also reduce its successful delivery rate. Therefore, in the scenario of sparse nodes, the successful delivery rate of SSGTB protocol is still the highest among the three.

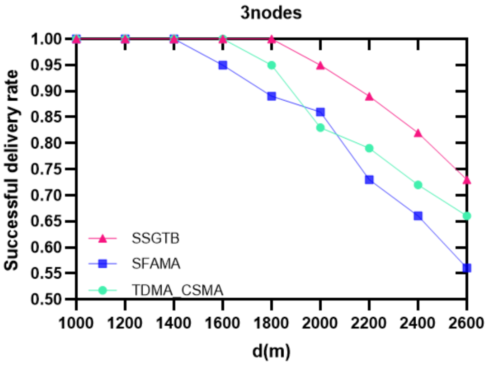

FIGURE 8. Successful delivery rate with 3 node channels.

E. END TO END DELAY

The delay is an important indicator of the internal performance parameters of the network. The shortening of the end-to-end delay means the improvement of the speed and ability of the network processing node to send data packets. When the sending node has only two nodes, the end-to-end delay of the three protocols is kept below 35s because the node collision probability is very small. At this time, the delay index has little impact on the network performance. Therefore, in this section,we mainly observe the end-to-end delay of the three protocols in the 22 node scenario, as shown in Figure 9. because the TDMA_CSMA protocol first uses the method of dividing fixed time slots, and selects to send at the beginning of the time slots, and the nodes need to reallocate the time slots after random backoff, the end-to-end delay of the protocol increases rapidly with the increase of network load, and is much larger than the other two protocols.

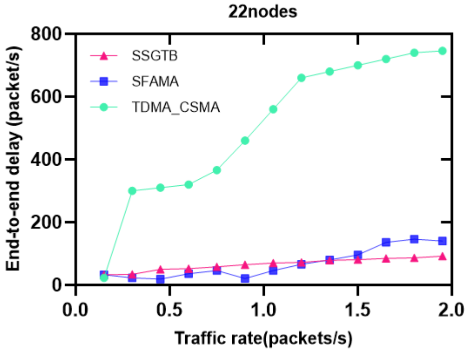

FIGURE 9. Latency of the three protocols in the 22-node scenario.

In comparison, the end-to-end delay of SFAMA protocol and SSGTB protocol is basically maintained in a low time period. However, the difference between SFAMA protocol and SSGTB protocol is that when the load is low, SFAMA protocol can maintain a lower delay than SSGTB. However, when the network load continues to increase to more than 1.35, SFAMA own conflict avoidance mechanism will lead to an increase in conflicts, and the network delay will also start to be larger than SSGTB protocol, Since SSGTB does not adopt handshake mechanism, it does not need to back off when multi-node handshake, and saves the time waiting for handshake. Therefore, with the continuous increase of network load, the delay can still be maintained in a low range below 90s.

V. CONCLUSION

Due to the long propagation delay of UWSNs and the poor performance of its MAC protocol handshake feedback mechanism, this paper proposes a MAC protocol based on short signal backoff game, the agreement through the way of reservation multiple access, based on the number of nodes in competition, make a node to send in the first round of the competition with the best probability. Furthermore, the rest of the nodes reduce the sending conflict of nodes in the new channel contention, according to the backoff probability in the previous round of game. Thus, it not only solves the problem of infinite delay of random backoff mechanism in other MAC protocols, but also solves the problem of long delay of waiting for feedback confirmation in handshake mechanism. The simulation results show that the protocol can greatly improve the throughput with low delay and high delivery rate, it has a higher network performance than other MAC protocols. However, since this protocol sends node signal tones by probability, there is still a probability trap problem. Therefore, we need to further solve the node sending conflict problem caused by probability trap in the future.

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