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Integrated Time Synchronization and Multiple Access Protocol for Underwater Acoustic Sensor Networks

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ABSTRACT Due to the limited energy and mobility of the traditional sensor nodes, autonomous underwater glider (AUG) is widely used in underwater acoustic sensor networks to achieve long-term and large-scale marine environmental monitoring. In the communication between AUGs, time synchronization (TS) and multiple access control process (MACP) both need control frames to guarantee the data transmission. However, the independent execution of these two processes causes the control frames to be sent repeatedly, resulting in more transmission delay and energy cost. In order to communicate between AUGs more efficiently, an integrated TS with multiple access (TSMA) protocol is proposed in this paper. Within the AUG group, an AUG is selected as the beacon node to provide a standard clock to complete the intra-group TS process, while inter-group TS adopts the non-beacon synchronization method. In the TS process, the effect of the relative movement between AUGs is considered to improve the accuracy of synchronization. Besides, we create a new control frame that can fuse the message exchange of TS and MACP. Simulation results show that TSMA has a better performance in terms of the packet delivery fraction, synchronization errors, and energy efficiency.

INDEX TERMS Underwater acoustic sensor networks, autonomous underwater glider, time synchronization, multiple access control.

I. INTRODUCTION

In the past few years, the application of underwater acoustic sensor networks (UASNs) in environmental monitoring, marine resource exploration, and national defense security has been highly valued by academic and industrial circles [1], [2].

However, the communication environment in UASNs is more complicated than terrestrial wireless sensor networks (TWSNs). For example, the speed of sound in water is approximately 1500 m/s (five orders lower than speed of light which is 3×10^8 m/s) [3]. Moreover, the Doppler effect in underwater acoustic channel increases the signal transmission delay significantly. Due to the influence of complex water environment and limited energy and mobility of the traditional sensor nodes, mobile underwater acoustic sensor networks (MUASNs) consist of mobile underwater vehicles to complete long-term and large-scale

marine environment monitoring. Autonomous underwater glider (AUG) has become one of the important mobile underwater vehicles for dynamic ocean monitoring with its long battery life and a dive capability of several thousand meters [4]. However, the applications with AUGs still have some key problems to be solved [5]. For instance, AUGs can periodically float to the surface to use global positioning system (GPS) in general for time synchronization (TS). But in certain military applications, they usually cannot surface to avoid being detected, which results in the AUGs not being able to synchronize using GPS directly [6]. Hence, proposing a protocol that the AUGs can synchronize in MUASNs without GPS is very important.

Recently, some TS algorithms have been proposed for UASNs [7]. These algorithms basically solve the problem of long transmission delay, however, node movement problems are usually ignored. For instance, TS for high latency algorithm (TSHL) [8] assumes that sensor nodes are fixed, which makes it not suitable for MUASNs. A cluster-based TS algorithm, called “MU-Sync”, is designed for mobile

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underwater networks [9]. However, delay estimation in this paper is not very accurate. MU-Sync uses half of the round-trip time as the one-way transmission delay, which causes large errors and affects the accuracy of TS.

Accuracy is one of the major concerns when design a TS algorithm. In order to ensure the accuracy and reliability of data transmission between AUGs, the members in the AUG group need to be synchronized, and the AUG groups that communicate with each other also need to be synchronized. However, the proposed TS method cannot solve the synchronization problem within and among AUG groups at the same time.

In addition, underwater acoustic channel resources are very limited. For sensor nodes to communicate reliably, the media access control (MAC) protocol must be used to share the underwater acoustic channel efficiently and reasonably [10]. An OFDMA-based MAC protocol named G-MAC [11] is a method to complete the process of transmitting data among the AUGs by means of multiple access control process (MACP), reduce the transmission delay and increase the throughput of UASNs. The data transmission completed by MACP is called multiple-access data transmission (MADT).

Moreover, TS and MACP for UASNs are often closely related. For example, the G-MAC protocol requires good synchronization among the sensor nodes to ensure the accuracy and effectiveness of the data transmission. The process of the TS and multiple access control both need control frames. However, the above two processes are often carried out independently which leads to more transmission delay and energy resource consumptions in the whole system.

To solve the issues above in MUASNs, we design a protocol that integrates TS with MACP protocol, named as TSMA in this paper. The TSMA protocol not only realizes TS within an AUG group (called intra-group TS, IGTS) but also implements TS process between AUG groups (called inter-group TS). In IGTS, the Doppler factor estimation method is used to achieve accurate synchronization within the AUG group considering the effect of the relative movement between AUGs. The inter-group TS uses the local TS based on the Doppler method and only AUGs that communicate with each other are synchronized. Moreover, TSMA also combines the message exchanged in TS and MACP to form an effective underwater data transmission system, which reduces the number of messages exchanged between two AUGs, saves time and reduces the energy consumption.

The main contributions of this paper can be summarized as follows:

- (1) We propose a new protocol called TSMA in this paper. In TSMA, control frames of TS and MACP are combined into a new frame which contains the parts used both for TS and MACP. TSMA forms an effective underwater data transmission system, thereby reducing the number of exchanged message and saving time and energy consumption.
- (2) We adopt a local inter-group TS for the first time, in which only the AUG groups along the

communication link do the TS so that the global inter-group TS is avoid. Therefore, the number of control packets to do inter-group TS is reduced which lead to reduction in packet collision and the cost.

The rest of this paper is organized as follows: in Section II, the existing TS protocols and MAC protocols for UASNs are studied. In Section III and IV, the TSMA is described in detail. The simulation results are shown and discussed in Section V. Finally, we conclude this paper in Section VI.

II. RELATED WORK

Recently, a lot of studies have been done on TS algorithms for UASNs [12], [13]. Many protocols have been proposed to solve the unique challenges of underwater acoustic environment such as long transmission delay and limited energy. According to different message exchange procedures among the sensor nodes in TS, the previously proposed TS algorithms can be divided into two categories: the transmission-reception based approach and the hybrid interaction-based approach, which is a combination of single transmission and transmission-reception. In this section, we provide a review on studies that have been done on this topic.

A. TIME SYNCHRONIZATION ALGORITHMS

TS for High Latency (TSHL) algorithm [8] adopts the hybrid interaction-based approach. It is first proposed to solve the problem of the slow propagation speed of the underwater acoustic signal. TSHL tries to minimize the synchronization error by estimating and compensating both the clock skew and clock offset, using the MAC-layer time stamps and bidirectional message exchange. The clock skew is the clock frequency skew, and the clock offset is the clock phase offset. While the algorithm assumes that all sensor nodes in the network are static, it is not suitable for mobile networks. It is necessary to design a TS algorithm for underwater mobile networks.

A cluster-based TS algorithm, called MU-Sync [9], is an example of the transmission-reception based TS algorithms for MUASNs. MU-Sync divides the whole network into several clusters. The cluster head node and the nodes in the cluster use the sending-receiving message interaction method to complete the TS. MU-Sync calculates the clock skew and offset of the nodes in the cluster by 2 linear regressions. Although MU-Sync takes into account the mobility of underwater nodes, it assumes that the round-trip transmission delay among nodes is a constant value, which affects the accuracy of TS. In addition, the need for more beacon nodes in actual deployments results in high network deployment costs. In order to make the TS algorithm more economical and scalable, an energy efficiency distributed TS algorithm (E^2 DTS) is proposed [14] for underwater mobile networks. E^2 DTS uses autonomous underwater vehicle (AUV) as a beacon node and the main TS message sender, which can save energy consumption in the entire sensor network.

However, it assumes that AUVs move at a constant speed during TS period, limiting the accuracy of synchronization. An AUV-aided joint localization and TS algorithm for underwater acoustic sensor networks [15] is also proposed to employ AUV as a mobile anchor to localization and then complete the TS by the help of GPS. However, when the AUG formation completes a long-term specific work in MUASNs, the AUG cannot always float on the water surface. Therefore, the AUG cannot directly use GPS to complete the TS process.

In addition, the sensor nodes under water are subject to movement caused by factors such as ocean currents. Therefore, assuming that the nodes are fixed or that the nodes are moving at a certain speed will affect the accuracy of TS. The Doppler-based TS for mobile underwater sensor networks (D-Sync) [16] takes advantage of the Doppler shift caused by the relative motion of sensor nodes in an underwater environment to account for the above problems. In the process of estimating the Doppler scale factor, D-Sync does not consider the influence of skew, which affects the accuracy of TS as the accuracy of TS becomes worse when the initial skew increases. A Doppler-enhanced TS algorithm for mobile underwater sensor networks, called DE-Sync [17], directly substitutes the Doppler scale factor into linear regression to achieve a more accurate estimation of the clock skew and offset. The influence of the clock skew during the process of estimating the Doppler scale factor is considered in this algorithm. Thus, DE-Sync is superior to existing TS algorithms in terms of accuracy and energy efficiency.

B. MAC PROTOCOLS

Moreover, designing a suitable MAC protocol is also an important and challenging issue due to the special channel characteristics for UASNs. The typical underwater MAC protocols include scheduling-based MAC, such as the spatial-temporal MAC (ST-MAC) [18]. ST-MAC uses spatial-temporal conflict graphs and vertex coloring methods to solve spatial-temporal uncertainties in UASNs. In addition, the slotted floor acquisition multiple access (SFAMA) protocol is an example of contention-based MAC protocols which require TS [19]. All nodes using SFAMA share time slots and initiate a three-way handshake mechanism at the beginning of the time slot. By using a slot-based handshake mechanism, SFAMA reduces the latency to a certain extent, but the network throughput decreases fast when the traffic load increases. In order to improve the network throughput, an OFDMA-based MAC protocol, named G-MAC, is proposed in [11]. The G-MAC protocol is a multichannel MAC protocol dedicated to mobile underwater centralized networks that use AUGs to perform complex missions. This protocol allows concurrent data transmissions by applying Nash Equilibrium to allocate transmission subchannels and adjust the related power. Therefore, G-MAC achieves the goal of maximizing the overall network throughput while avoiding the unnecessary consumption of high transmission power. The data transmission with this MAC protocol is MADT.

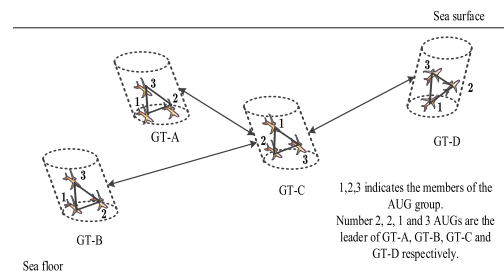


FIGURE 1. Network topology.

From the analysis above, we observe that many proposed TS algorithms are not suitable for communication between AUG groups in long-term and large-scale underwater applications where AUG can't rise to the water surface frequently to use GPS to complete the synchronization. Furthermore, TS and MACP are closely related while the process of them are often inseparable. However, TS process and MACP are often carried out independently, which greatly increases the number of frame exchanges, resulting in waste of time resources and energy resources. Therefore, the development of a TS integrates with MACP for communication between AUG groups is of importance.

III. SYSTEM MODEL AND PROBLEM DESCRIPTION

A. SYSTEM MODEL

The network topology considered in this paper is shown in Fig. 1 where four AUG groups (GT-A, GT-B, GT-C and GT-D) are working together to complete the long-term and large-scale marine environment monitoring. Each AUG team consists of three member AUGs (AUG-1, AUG-2 and AUG-3) and sails in a certain formation [20]. During the monitoring period, the AUG is not allowed to surface, so it is not possible to complete the TS directly via GPS. Each member of the AUG group sails according to certain rules. There is a special member in each group called leader. The leader serves as the beacon node to provide the standard clock for other members within the group. After a fixed time, the four AUG groups use IGTS for intra-group TS. Moreover, when one group wants to send a packet to another group (e.g. GT-A wants to send a packet to GT-C), the TMAC sees the AUG group as a whole and uses a local TS algorithm (without beacon nodes) to achieve TS between the two AUG groups.

B. PROBLEM DESCRIPTION

1) THE SIGNIFICANCE OF TS FOR AUGS

In the scenario where multiple AUG groups work, two situations occur. Case A is that the AUG can periodically float to the surface of the water and use GPS for positioning. However, in certain military applications, AUGs do not often float to the surface of the water, and they operate underwater for a long time to avoid being discovered. This situation is defined as Case B. There is a significant difference in the time error produced by AUGs synchronization in the two cases.

In Case A, the AUGs float to the surface periodically so they can be positioned and synchronized using GPS directly. For example, an AUG with a 0.02ppm crystal oscillator, synchronized every 3.2hours, produces a time error of only 0.32ms. Then, the time error multiplies the speed of sound, resulting in a distance deviation of only 0.345m, which is a very small value with little noticeable impact. In Case B, AUGs cannot surface for a long time, so AUG cannot directly use GPS for TS. Thus, the AUG network does not have a global clock to provide a unified time base, so that the AUGs will determine the time according to the local clock. However, the AUG network cannot guarantee TS for a long time since different AUGs have different local clock values due to the drift of the crystal oscillators and the different timing rates in different AUGs. The calculation formula of AUG crystal drift is as follows:

$$SK(\Delta t) = \Delta T(1) - \Delta T(2) = \Delta t \cdot (f_1 - f_2), \quad (1)$$

where f_1 and f_2 represent the crystal frequencies of AUG-1 and AUG-2 in time $\Delta t = t - t_0$, respectively. According to the above principle, Davis and Chang [21] used 50 ppm as the frequency deviation of the crystal oscillators, and the crystal drift caused a deviation of about 130s in one month. Therefore, when the AUG is in Case B, a TS algorithm is needed to calibrate the local clock of the AUGs. In this case, the usual practice is to use the global TS method to synchronize the AUGs in the entire network using the same time standard. However, the global TS method needs to send a large number of control frames to complete the synchronization process, so we propose a local TS method to reduce the number of control frames needed for TS. The method only requires local TS between AUGs communicating with each other, and then the local time information is spread to the entire communication link until sending the message to the sink node. The method can reduce overheads in the network with a large number of AUG groups than the global TS method.

2) THE SIGNIFICANCE OF INTEGRATED TS AND MACP

The TS process requires frame exchange at the MAC layer to exchange time stamps among the nodes. MACP also requires the exchange of control frames for communication purposes. However, in the study of underwater acoustic communication, TS process and MACP are usually performed independently, causing control frames to be repeatedly transmitted to achieve connections among the nodes. Due to the scarcity of underwater spectrum resources, the above situation will lead to waste of time and energy resources. An example is given below.

For example, the transmission power is 2W and the reception power is 0.75W. The round-trip times of message exchange process between AUG and beacon node for TS and of data transmission are shown in Fig. 2. In MACP, assuming that one process of sending and receiving RTS/CTS/ACK frames takes $t_0 = t_s + t_r + t_p$ totally, where the transmission, reception and propagation times are t_s , t_r and t_p , respectively.

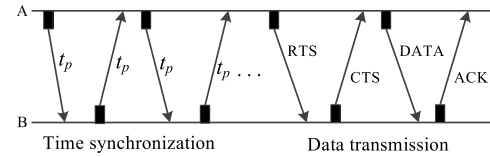


FIGURE 2. Message exchange procedure.

The length of the RTS, CTS and ACK control frames are the same. And assuming that one process of sending and receiving DATA frames takes $t_0' = t_{sd} + t_{rd} + t_p$ totally, where the transmission, reception and propagation times are t_{sd} , t_{rd} and t_p . In TS process, the one process of sending and receiving control frames also takes t_0 totally. It is calculated that the round of message exchange for TS takes $4t_0$, and the MACP takes $3t_0 + t_0'$. Therefore, when the methods of TS and MADT are separately performed, the total time taken for the entire process is $7t_0 + t_0'$. When using the method of integrated TS and multiple access proposed in this paper, the total time spent on the whole process is about $3t_0 + t_0'$. Because the control frames of data transmission and TS are both 500 bytes before integrated. After integrated, the REQUEST frame adds only 65 bits of Sync_time to the RTS control frame in the data transmission, which is 1.625% longer than the original control frame length, thus the impact on time is negligible. So, the integrated method is saved by about $4t_0$ time resources than the original method.

In addition, assuming that the number of times of TS in one month is m , and the number of data transmissions is n . The energy consumed by an AUG in one-round message exchange of TS is $(4t_s \times 2 + 4t_r \times 0.75) \cdot m = (8t_s + 3t_r) \cdot mJ$, and the energy consumed by data transmission is $(3t_s \times 2 + t_{sd} \times 2 + 3t_r \times 0.75 + t_{rd} \times 0.75) \cdot n = (6t_s + 2t_{sd} + 2.25t_r + 0.75t_{rd}) \cdot nJ$. In the separated way, the total energy consumption is the sum of the energy consumption of the two processes, which is $(8t_s + 3t_r) \cdot m + (6t_s + 2t_{sd} + 2.25t_r + 0.75t_{rd}) \cdot nJ$. However, the number of TS process is less than the number of data transmissions process within one month, that is, $m < n$. Besides, the effect of size change in the control frame on energy is negligible. Thus, the total energy consumption will be $(6t_s + 2t_{sd} + 2.25t_r + 0.75t_{rd}) \cdot nJ$ in the integrated method. The total energy saved approximately $(8t_s + 3t_r) \cdot mJ$.

Assuming that the computational overhead is negligible, the energy efficiency is defined as follows:

$$\rho = \frac{\tau}{k\zeta\gamma}, \quad (2)$$

where κ represents the number of resynchronizations required to keep the clock skew below a certain value for τ seconds, ζ represents the number of messages per synchronization process, and γ is the total packet length. It can be seen from equation (2) that the greater the message overhead, the lower the energy efficiency.

TS is necessary in MUASNs, based on the analysis of the above two problems. At the same time, separating TS and data transmission increases the number of messages exchanged,

resulting in greater time consumption and energy consumption and lower energy efficiency. To solve this problem, this paper proposes a TSMA protocol which combines TS process and MACP. The Sync frame required for TS and the RTS frame for MACP are combined to one frame exchanged by AUGs. The protocol can complete the TS process and MACP simultaneously in a small number of exchanges.

IV. PROTOCOL DESCRIPTION ON TSMA

TSMA is divided into two main processes, namely, the intra-group TS process (IGTS) and the other is the integration process of inter-group TS and MACP (TMAC) for communication between AUG groups. When the working time is greater than the fixed time threshold t_c , the members within an AUG group require intra-group TS by IGTS algorithm. The fixed time threshold is determined jointly based on the time deviation threshold between AUGs and the cumulative synchronization accuracy in one day. According to the application scenario of multiple AUGs working in this paper, we set the time deviation threshold to 4.18×10^{-1} s and set the cumulative synchronization accuracy to 8.64×10^{-3} s. Then the AUG needs to be synchronized about 48 times a day, that is, it is synchronized every 30 minutes on average. Then, t_c is set to 1800s in this paper. Different thresholds t_c can be set for different application scenarios. In IGTS, the leader, which is selected from all the members of the AUG group by the low-energy adaptive clustering hierarchy (LEACH) algorithm [22], is responsible for providing standard time. Then the Doppler factor estimation method is used to achieve TS within the AUG group. When two AUG groups communicate with each other, TMAC regards each AUG group as a whole node. The sender, which is the AUG group that initiates the message exchange, needs to check the history first to find out whether it has communicated with the receiver before. The sender sets REQUEST according to the result of its history and then sends the REQUEST packet to the receiver. The receiver analyzes the received REQUEST packet and performs different processes according to the value of the Sync obtained by the analysis. The detail description of TMAC is described in Section IV.B. The overall procedure of the TSMA is shown in Fig.3.

A. IGTS ALGORITHM

IGTS algorithm includes two steps. The first step is to exchange the time stamp between the leader AUG and other member AUGs in the same group. Then Doppler factor estimation is used to calculate the relative speed between members, the clock skew and the clock offset based on the time stamp obtained considering the mobility of the AUG and the time error caused by the synchronization. By this way, the accuracy of IGTS is increased.

Let's consider the step to exchange time stamp first. IGTS algorithm is for message exchange between the leader AUG and the member AUGs in the AUG group. In the following description, the member AUG is called an ordinary node, and the leader AUG is called a beacon node. For an AUG group,

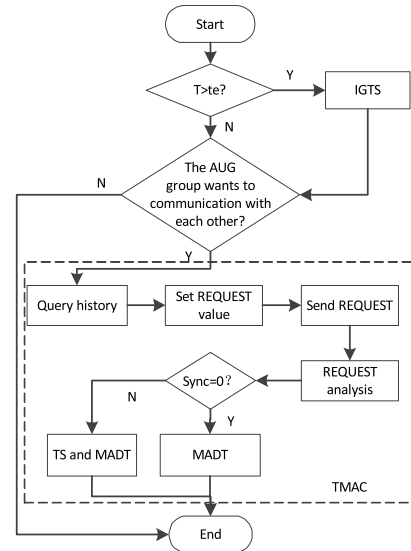


FIGURE 3. Specific flow of TSMA.

the local clock of the beacon is used as the standard clock. The exchange process of the control frames and the calculation of synchronization parameters are as follows:

The beacon node periodically broadcasts a number of frames containing time stamp of MAC layer. For the m th frame, the time at which beacon node starts to send is recorded t_m . The ordinary node records the time when the frame is received as T_m , and parses the frame to obtain t_m . This step is repeated until enough time stamps are recorded for subsequent TS calculations.

After obtaining the time stamps, the ordinary node can calculate the relative velocity between the nodes according to the Doppler factor estimation method, then calculate the clock skew.

The formula [23] using the Doppler factor to estimate the relative velocity v_m between the nodes is given as:

$$v_m = \tilde{\sigma} v_t, \tag{3}$$

$$\tilde{\sigma} = \hat{\sigma} + \delta, \tag{4}$$

where v_m represents the relative speed between the two synchronizing nodes and $\tilde{\sigma}$ represents the estimated value of the Doppler factor. $\hat{\sigma}$ is the Doppler spread factor and δ is the offset of the Doppler factor estimation. v_t represents the speed of sound under water.

The relationship between the local time of the beacon node and the local time of the ordinary node that needs to be synchronized is [24]:

$$T = a \cdot t + b, \tag{5}$$

where a is the clock skew and b represents the clock offset. Moreover, a is related to the angular frequency of the crystal oscillator and b is affected by the starting time of the system. The relationship between the local clock of the ordinary node and the standard clock of beacon node can be transformed

from equation (5) to equation (6):

$$T_m = a \cdot (t_m + t_{dm}) + b, \quad (6)$$

where t_{dm} represents the propagation delay of the m th frame. Due to the mobility of the nodes under water, the relative movement speed between the nodes will lead to the change of the distance between the nodes. The difference in the distance between the two synchronizing nodes in two adjacent frame transmission processes equal to the integral value of the relative velocity and time of the node, which can be expressed by the formula:

$$D_m - D_{m-1} = \frac{1}{a} \int_{T_{m-1}}^{T_m} v_m dt, \quad (7)$$

where D_m and D_{m-1} represent the distance at the m th and $(m-1)$ th frame transmission processes, respectively. Equation (7) can be transformed to equation (8):

$$\Delta D_m = \frac{1}{a} v_m (T_m - T_{m-1}), \quad (8)$$

The relationship between the propagation delay and the distance between the nodes can be expressed as:

$$t_{dm} = \frac{D_m}{v_t}, \quad (9)$$

Similarly, equation (9) can be transformed to:

$$\Delta t_{dm} = \frac{\Delta D_m}{v_t}, \quad (10)$$

By combining the equations (8) and (10), the following formula can be obtained:

$$\Delta t_{dm} = \frac{v_m (T_m - T_{m-1})}{a v_t}, \quad (11)$$

Equation (11) represents the relationship between the difference in delay of the frame in the m th and $(m-1)$ th frame transmission processes and the clock skew a . However, since Δt_{dm} and a are unknown in the equation, the transformation according to equation (11) can be obtained:

$$T_m - T_{m-1} = a \cdot (t_m - t_{m-1} + \Delta t_{dm}), \quad (12)$$

Finally, the clock skew can be obtained by combining equation (11) and equation (12):

$$T_m - T_{m-1} = a \cdot (t_m - t_{m-1}) \left(\frac{v_t}{v_t - v_m} \right), \quad (13)$$

The value of a can be obtained by equation (13), which is related to the two-transmission time difference of the signal at the beacon node and the corresponding two reception time difference at the ordinary node. According to the reference message transmitted by the beacon node multiple times, several clock skews are obtained. Finally, the final value of a is determined by the average of several clock skews.

The calculation of clock offset b is as follows: the ordinary node sends a request frame to the beacon node at time t_1 . The request frame contains the transmission time t_1 . After a period of time, the beacon node receives this request frame, records

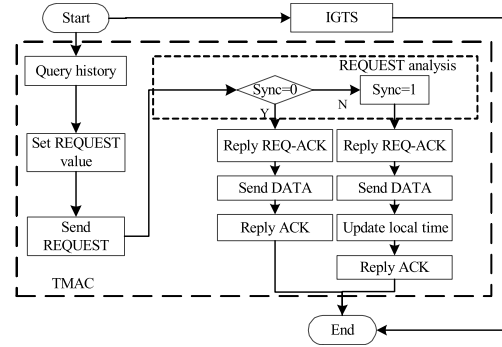


FIGURE 4. Specific flow of TMAC.

the receiving time as t_2 . Then the beacon node replies the ordinary node a frame at time t_3 , including the time stamps of t_1 , t_2 and t_3 . After receiving this response frame, the ordinary node records the receiving time as the local time t_4 .

The clock offset is calculated using t_1 , t_2 , t_3 and t_4 obtained by one frame exchange between the ordinary node and the beacon node and the relative velocity v_m obtained by the Doppler estimation method. Let the position of the ordinary node at the local time t_1 be denoted as $P_o(t_1)$, the position of the ordinary node at the local t_4 time as $P_o(t_4)$, and the position of the beacon node at the standard time t_2 and t_3 be denoted as $P_B(t_2)$ and $P_B(t_3)$, respectively. Then $d_{OB}(t_1, t_2)$ is defined as the distance between the ordinary node at time t_1 and the beacon node at time t_2 . Similarly, $d_{OB}(t_4, t_3)$ is defined as the distance between the ordinary node at time t_4 and the beacon node at time t_3 . From the relationship between time and distance described above, it is available:

$$\|P_o(t_1) - P_B(t_2)\| = d_{OB}(t_1, t_2), \quad (14)$$

$$\|P_o(t_4) - P_B(t_3)\| = d_{OB}(t_4, t_3), \quad (15)$$

$$d_{OB}(t_1, t_2) = v_t \left(t_2 - \frac{t_1 - b}{a} \right), \quad (16)$$

$$d_{OB}(t_3, t_4) = v_t \left(\frac{t_4 - b}{a} - t_3 \right), \quad (17)$$

The relationship between the difference of the two-frame propagation distance and the relative velocity of the nodes is shown in equation (18):

$$\Delta d = d_{OB}(t_3, t_4) - d_{OB}(t_1, t_2) = \int_{t_1}^{t_4} v_m dt, \quad (18)$$

The values of the clock offset can be obtained by the simultaneous equations (16) and (17) and (18).

B. INTEGRATED INTER-GROUP TS WITH MACP PROCESS

In integrated inter-group TS with MACP (TMAC) process, in order to simplify the complexity of the problem, each AUG group is considered as a node. The overall process of TMAC is shown in Fig. 4.

1) REQUEST FRAME DESIGN

When a node (e.g. GT-A) wants to transfer data to a node (e.g. GT-C), the first step is to query its own history to

TABLE 1. Format of communication records.

Destination node		Time		Frame value		
Node number		Local time when GT-A sends the frame		0/1		

Type	Destination_id	Source_id	Hops	Sync_time	Backup
8 bits		8bits	8bits	4bits	65bits	16bits

Time stamp	Sync
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FIGURE 5. The structure of REQUEST frame.

find that whether itself (GT-A) has communicated with the receiver (GT-C) before. The format of communication records is shown in Table 1. There are two possible values for the frame value slot, 0 and 1. Value 0 indicates that the node sent a control frame to the destination node at the recorded time. Value 1 indicates that the node sent a DATA frame to the destination node at the recorded time.

If GT-A cannot find any communication records related to GT-C, which means GT-A has never communicated with GT-C before, it should finish TS with GT-C first before transmitting data to GT-C. In addition, if GT-A has communicated with other nodes after the last communication with GT-C, TS is needed before data transmission. If the latest record of GT-A is to communicate with GT-C and the time exceeds the time synchronization threshold, then TS is also needed before data transmission. In the above cases, the Sync slot in REQUEST frame is set to 1 when TS needs to be performed. Otherwise the Sync slot is set to 0. The complete structure of REQUEST frame is shown in Fig. 5.

If TS is required, GT-A will first send a REQUEST frame to the GT-C. After the GT-C receives the REQUEST frame and analyzes it, if the Sync is 0, the GT-A only completes the MADT process with the GT-C. Otherwise, GT-C will synchronize its clock based on the time stamp information in the REQUEST frame.

2) INTER-GROUP TS PROCESS

When GT-A and GT-C need to do TS, GT-A first sends a REQUEST and then GT-C reply a REQ-ACK frame to GT-A which is the process to collect the time stamps used to calculate the propagation delay between GT-A and GT-C. Then, GT-A sends the DATA frame with the time of sending and receiving one frame and propagation delay. By adding the time, the GT-C’s local time can be updated to keep the time synchronized with the GT-A. Combined with the Doppler estimation method described in Section IV.A, the relative velocity can be obtained from equation (3).

The distance between two synchronizing nodes D_α , which can be estimated based on the time difference of the received REQ-ACK, is calculated as:

$$\begin{aligned} \Delta t_g &= t_{g4} - t_{g3} + t_{g2} - t_{g1}, \\ D_\alpha &= \frac{\Delta t_g}{2} v_t, \end{aligned} \tag{19}$$

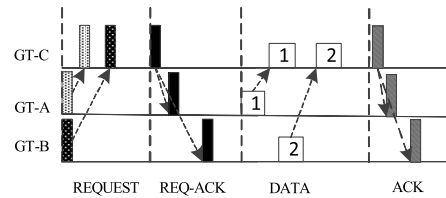


FIGURE 6. The transmission process of MADT.

where t_{g1} is the time at which GT-A sends REQUEST frame, t_{g2} is the time at which GT-C receives REQUEST frame, t_{g3} is the time at which GT-C sends REQ-ACK frame and t_{g4} is the time at which GT-A receives the REQ-ACK. These two time stamps are collected in the step of collecting time stamps.

However, the distance between two nodes may be changed due to node movement. Therefore, the relative distance between GT-A and GT-C caused by the relative velocity needs to be considered when calculating the distance between GT-A and GT-C. Then, the true distance D_β between GT-A and GT-C can be expressed as:

$$D_\beta = D_\alpha + \frac{v_m \Delta t_g}{2}, \tag{20}$$

Then we can calculate the propagation delay by simultaneous equation (19) and (20):

$$\varphi = \frac{2D_\alpha + v_m \Delta t_g}{2(v_t + v_m)}, \tag{21}$$

Therefore, the total time required to transmit a frame is:

$$t_{total} = t_s + \varphi + t_r, \tag{22}$$

where t_s represents the time required for node to send one frame and t_r represents the time required for node to receive one frame.

Supposed that GT-A’s local time is g , when GT-A calculates the transmission delay and send DATA frame which contains the transmission delay to GT-C, GT-C should adjust the local clock to $(g + t_{total})$ after receiving the DATA frame. Then, GT-C and GT-A keep time synchronized. After that, spread in the same way until the entire communication link remains synchronized.

C. MULTIPLE-ACCESS DATA TRANSMISSION PROCESS

This paper uses the idea of G-MAC protocol to complete the MADT process of TSMA. The MADT process is divided into four phases. In this method, time is divided into time slots, and control frames are transmitted at the beginning of each time slot. In this part, control frames refer to REQUEST, REQ-ACK and ACK. Moreover, both GT-A, GT-B and GT-D are within the communication radius of GT-C. For example, the overall process among GT-A, GT-B and GT-C of the MADT is shown in Fig.6.

Phase 1:

When GT-A and GT-B want to transfer data to GT-C at the same time, the REQUEST frame including channel information which contains acoustic channel gain and channel state is first sent to GT-C at the beginning of the time slot.

TABLE 2. GT-C's history record.

Sender	Time
Node number	GT-C's updated clock

Phase 2:

Once the GT-C successfully receives and decodes the REQUEST frames, it will distributed run a joint channel allocation and power control algorithm to adjust the transmission frequency and allocate channel for each sender. The detailed adjustment method is described in [11]. GT-C uses the TS method described in Section B to update the local time and records the updated clock in the history of GT-C. GT-C has a table recoding all the updated clock by different AUG groups. When the local clock of the GT-C is updated by one sender, the table entity related to this sender will be updated. In this way, GT-C can keep different local clock updated by different sender at the same time. Then, GT-C sends a REQ-ACK frame to GT-A and GT-B respectively, to tell them their own transmission power and channel information. The history record of GT-C is shown in Table 2.

Phase 3:

The AUG group that first receives the REQ-ACK frame first sends a DATA frame to the GT-C with the given transmission power on the given channel. In this scenario, GT-A first sends DATA frame to GT-C.

Phase 4:

After the GT-C successfully receives the DATA frame, it feeds back an ACK frame to the sender. At this point, a complete communication process between the two AUG groups has been completed.

The throughput of MADT is defined as:

$$S = \frac{\delta}{\frac{1}{1-P_e} \left[\delta + d + \left(4 - \frac{d}{\gamma + \tau} \right) \frac{1 - e^{-\lambda(\gamma + \tau)}}{\lambda} \right] + \frac{1}{\lambda}}, \quad (23)$$

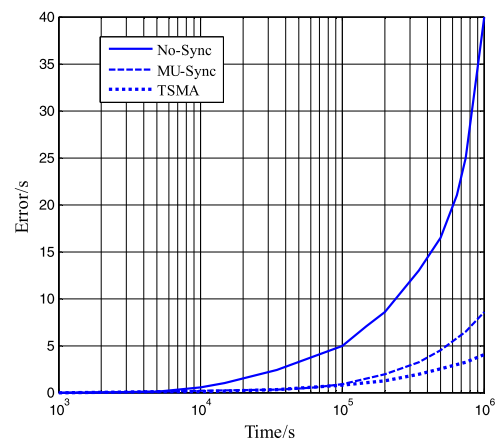
where λ is the frame delivery rate subject to the Poisson process, δ indicates the transmission time of the DATA frame, γ indicates the transmission time of the control frame and τ represents the maximum propagation delay. In addition, P_e represents the bit error rate of acoustic channel and d represents the average propagation delay between nodes in the network.

V. SIMULATION RESULTS

In this section, we evaluate the performance on packet delivery fraction (PDF) of the TSMA protocol and compare it with MU-Sync [9] and the G-MAC protocol with non-synchronization (No-Sync) [11] in the underwater acoustic simulation software Aqua-Sim which developed with C++ and OTCL scripting language. And we evaluate the performance of the TSMA and compare it with separating TS and MADT processing of G-MAC protocol. The TS algorithm for this part is the same as the TS algorithm for TSMA. Three indicators: error with varying time after TS, energy efficiency

TABLE 3. Simulation parameters.

Name	Value
Clock skew	40 ppm
Clock offset	10 ppm
Clock granularity	1 μ s
Transmission power	2 w
Receiving power	0.75 w
The transmission time of DATA frame	4 s
The maximum propagation delay	4.2 s
The transmission time of control frame	0.16 s
Data frame size	500 bytes
Control frame size	20 bytes
Transmission rate	1 kbps

**FIGURE 7.** Comparing three algorithms with time error.

and throughput are used to show the performance of TSMA protocol versus separating TS and G-MAC protocols.

A. SIMULATION SETTING

In our simulations, 12 AUGs are deployed in a 5 km \times 5 km \times 2 km three-dimensional underwater space. They are divided into four AUG groups. Each group is composed of three AUGs in accordance with a certain planning formation. The maximum transmission range is 1km. The speed of sound is 1500m/s. During TS, each AUG records its local time before sending message or upon receiving message. The maximum speed of the AUGs (V_{max}) is 0.5m/s. The AUGs change its speed randomly within the range of (0, V_{max}]m/s. The simulation parameters are listed in Table 3.

B. RESULTS AND ANALYSIS

Assuming the system is synchronized with the global standard time at time 0. The time error between the local clock and the global standard time for TSMA, MU-Sync and No-Sync algorithms are shown in Fig. 7. The process of time synchronization is performed periodically, so the figure shows the error during the process of completing multiple time synchronizations. Over time, the time error of the three algorithms increases, but the growth rates are different. Among the three algorithms, the time error of No-Sync increases fastest. This is because the method of not considering TS will result in a large error. Although the error of the TSMA and MU-Sync

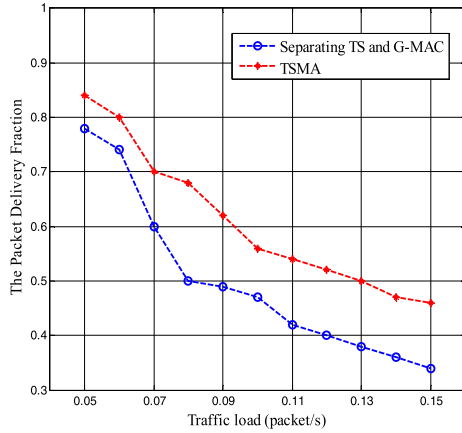


FIGURE 8. Comparison of PDF between two method.

synchronization algorithms also increase, the growth rates are relatively flat comparing to No-Sync. After 10^5 s, the error of No-Sync is around 5s, while the error of MU-Sync and TSMA is only about 1s. Moreover, the error of TSMA is always smaller than that of MU-Sync. This is because MU-Sync uses only half of the round-trip time to determine the one-way propagation delay and does not consider the relative motion between two AUG groups which causes a large error. And MU-Sync method causes more errors when the nodes move faster. TSMA considers the relative motion between AUGs and uses Doppler factor estimation to calculate the moving speed to improve the accuracy of propagation delay estimation.

The PDF, vs. the various traffic loads for each AUG group in the network is shown in Fig. 8. The formula to calculate PDF is:

$$PDF = \frac{N(R_d)}{N(G_s)}, \quad (24)$$

where $N(R_d)$ is the number of successfully received data packets by the receiver, and $N(G_s)$ is defined as the total number of data packets generated from the sender.

As can be seen from Fig. 8, when the traffic load is low, the PDF of TSMA and separating TS and G-MAC are at a high level. Moreover, as the traffic load increases, the PDFs of TSMA and separating process continue to drop. However, the PDF of TSMA is always about 13% higher than that of separating process in the traffic range [0.05 0.15] packets/s. This is because when the AUGs work under water for a long time and cannot directly correct their own clocks through the GPS, the local time error among the AUGs will become larger and larger. Good TS is an important prerequisite for time-slot based reservation transceiver method. The MADT in the G-MAC requires the AUGs to be synchronized with each other by good TS method. The TS algorithm of TSMA uses the Doppler factor estimation method to make the calculation and division of time slots more accurate in the process of transmitting and receiving packets, improves PDF.

The energy efficiency of TSMA versus TS and G-MAC in separate state is shown in Fig. 9. The definition of energy

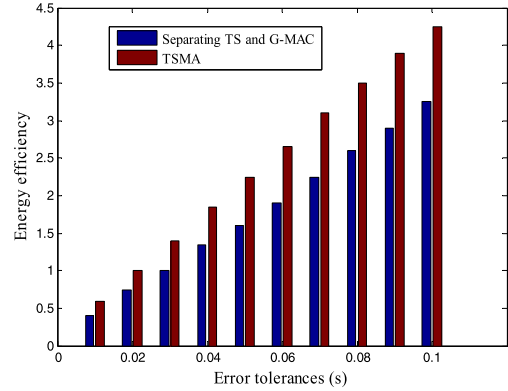


FIGURE 9. Comparison of energy efficiency between two method.

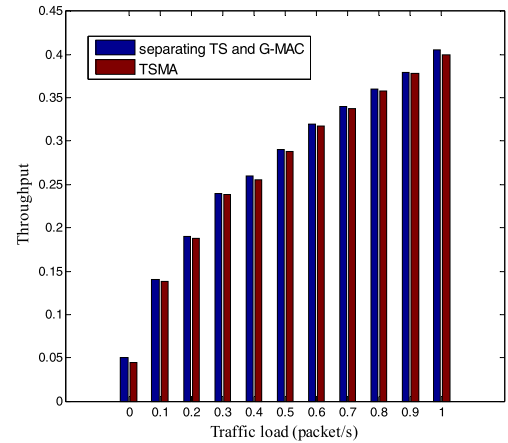


FIGURE 10. Comparing two methods with the throughput.

efficiency is shown in equation (2). As the time fault tolerance performance improves, the value of κ will be smaller. This is because the time error increases with time and the number of TS in a certain period is determined by the accuracy of the error estimation. As the accuracy of the time error estimation increases, the amount of TS requirement decreases and energy efficiency ρ increases. In addition, TSMA combines the frame exchange process of TS and MADT to reduce the duplicate message overhead. However, since in G-MAC, TS and MADT processes are separated, G-MAC needs to send more control frames to finish a job comparing to TSMA. Therefore, the number of exchanged messages ζ of the G-MAC protocol, where TS and MADT processes are separated, is always higher than TSMA. Thus, energy efficiency ρ of G-MAC is always lower than TSMA for this reason.

Throughput is a basic performance indicator of the MAC protocol. The definition of MADT throughput is shown in equation (23). In the simulation, we set the length of control frames is 500bytes, the length of DATA frame is 20bytes and the transmission rate of frames is 1kbps. Therefore, according to the calculation, δ is set to 4, γ is set to 0.16, τ is set to 4.2. The throughput versus the traffic load in the two cases, where the MADT of G-MAC is combined with TS and not combined with TS is shown in Fig. 10. It can be seen from

the figure that with the increase of traffic, the multiple access method without joint TS, the throughput is continuously improved, and the method has good packet transmission performance. The throughput of the TSMA is very close to that of the unjointed mode, and is basically the same. Therefore, the TSMA protocol does not affect the throughput metrics of the normal protocol. There is a very small difference between the throughputs of the two modes. This is because the frame required for TS is added to the control frame exchanged among the AUGs, thereby increasing the length of the control frame. However, the length of the integrated control frame is 1.625% longer than the original control frame so that the throughput is slightly affected.

VI. CONCLUSION

In UASNs, it is a key challenge to establish efficient TS and multiple access control for AUGs, while separating TS and MADT processes both need exchange the control frames to guarantee the data transmission, which increases the number of unnecessary exchanges of control frames and causes the waste of time and energy resources. In this paper, we propose TSMA protocol for UASNs. There are two processes in TSMA protocol. One is IGTS used within the AUG group, another is an TMAC used between AUG groups. In IGTS, an AUG is selected as the beacon node to provide a standard clock to complete the intra-group TS process, while inter-group TS adopts the non-beacon and local time synchronization method. In the TS process, the effect of the relative movement between AUGs are considered to improve the synchronization accuracy. Besides, we create a new control frame which can fuse the message exchange of TS and MADT. The simulation experiment proves that the TSMA protocol performs better in terms of packet delivery ratio and synchronization accuracy when compared with MU-Sync and No-Sync, reduces unnecessary energy waste, improves energy efficiency, and its integrated idea does not affect the original throughput performance of the normal protocol.

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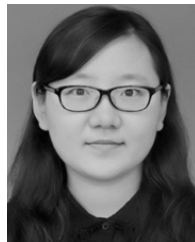
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