In underwater acoustic sensor networks (UASNs), the propagation delay of acoustic signals is much longer than Radio Frequency (RF). There is spatial unfairness problem caused by space-time uncertainty. Hence, the design of Medium Access Control (MAC) is a challenging issue. In underwater, it not only considers transmission time but also takes location into account. In this paper, we propose Response to the Earliest Transmitter of RTS MAC (RET-MAC) protocol to solve the problem. RET-MAC adopts adaptive RTS Contention Phase (RTSCP) to determine the earliest transmitter of RTS. And CTS Delay Phase (CTS DP) is added to postpone sending CTS in order to avoid collision. In addition, we propose CTS back-off mechanism to adjust the length of CTS DP as needed. Contention back-off mechanism is used to reduce network congestion and increase fairness further. The simulation results show that our scheme can achieve higher fairness and throughput; at the same time it also guarantees lower energy consumption and delay.

1. Introduction

Recently, with the development of the computer technology, microelectronics technology, and communication technology, underwater acoustic sensor networks (UASNs) have also got great progress. There are a wide range of applications of UASNs, such as oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation, and tactical surveillance applications [1]. A Media Access Control (MAC) protocol is used to coordinate the access to the shared acoustic channel among multiple nodes, which is very critical to the network performance [2]. However, unlike the terrestrial wireless sensor networks that mainly rely on radio waves for communications, underwater sensor networks utilize acoustic waves, which present a much harsher environment for both the physical and the data-link layers [3]. In fact, underwater acoustic communications are characterized by three major differences with respect to terrestrial radio: the very low propagation speed; the strongly anisotropic nature, whereby horizontal channels are usually harsher than vertical channels; the significant difference between the power required to operate acoustic transducers and the power required to receive or listen to an acoustic signal [4].

In designing resource-sharing schemes for underwater networks, one needs to keep in mind the peculiar characteristics of the acoustic channel [5]. In [6], Syed et al. point out that the long propagation delay of acoustic media leads to spatial unfairness problem. The nodes nearer the receiver occupy the channel quickly. On the contrast, other nodes away from receiver may be in “starvation” state for a long time. And sensor nodes are battery-powered, which makes the energy of nodes very limited, especially the energy cost required by communications [7]. In addition, compared with terrestrial wireless sensor networks, replacement of these low cost batteries in underwater is a challenging task and uneconomical too [8]. Therefore, there is an important significance to design the fairness and low energy consumption of UASN MAC protocol.

MAC protocols decide how multiple nodes share the underlying acoustic channel, which is critical to the overall network performance [9]. In this paper, we propose Response
to the Earliest Transmitter of RTS MAC (RET-MAC) protocol, which can ensure node to contend the channel fairness. According to the sending time of RTS packet, the protocol uses RTS Contention Phase (RTS CP) to determine the earliest transmitter of RTS in order to satisfy spatial fairness. On the other hand, our protocol postpones the transmission of CTS packet by CTS Delay Phase (CTS DP) to avoid collision. Above all, we adopt adaptive RTS CP and CTS DP to reduce delay. In addition, contention back-off mechanism is added to increase fairness further. The simulation results show that RET-MAC not only achieves higher fairness and lower delay, but also has better throughput and energy efficiency.

The rest of this paper is organized as follows. In Section 2, the related work is introduced. In Section 3, we discuss the spatial unfairness issue in UASNs and present our RET-MAC protocol. Then we analyze the protocol parameters in Section 4. After that, we evaluate the performance of RET-MAC in Section 5. Finally, we conclude this paper and discuss some future research in Section 6.

2. Related Work

Currently, there are many MAC protocols for terrestrial RF-based sensor networks, which are devoted to conserve energy and increase system performance by avoiding collision, such as S-MAC [10], CC-MAC [11], and Z-MAC [12]. However, they are not applicable to UASN due to long propagation delay and the characteristics of underwater environment [13]. The MAC protocol design of UASNs is facing many greater challenges, gradually attracting researchers’ attention.

In [14], Peng et al. introduce a contention-based MAC protocol with parallel reservation (COPE-MAC) for UASN. In order to establish communication with less rounds of handshakes, they propose parallel reservation, while using cyber carrier sensing to detect and avoid collisions with computation. COPE-MAC can improve MAC performance in both network throughput and energy efficiency. In [3], Chirdchoo et al. study Aloha-based variant protocols, proposing two Aloha-based random access MAC protocols, namely, Aloha-CA and Aloha-AN, for UASN. The two protocols combine Aloha with carrier sensing, use short reservation frame to contend channel, and add some relevant information of data to reservation frame. Other nodes sense the channel to achieve the information which will be sent from neighbor nodes and calculate the busy time of the channel. In the busy time, they take into sleep state in order to reduce energy consumption. Both schemes can boost the throughput by reducing the number of collisions. In [15], Park and Rodoplu propose UWAN-MAC protocol suitable for UASN.
It uses relative time stamps, not only in the transmission of data but also in the establishment of communication with newcomers, ingeniously solving synchronization problem between nodes sending and receiving data. And at the same time, it effectively saves energy and reduces the data collision rate. In [16], Hsu et al. propose a Spatial-Temporal MAC (ST-MAC) protocol, which is designed to overcome spatial-temporal uncertainty based on TDMA-based MAC scheduling for energy saving and throughput improvement. They construct the Spatial-Temporal Conflict Graph (ST-CG) to describe the conflict delays and propose the Traffic-based One-step Trial Approach (TOTA) to solve the coloring problem. Through a comprehensive study, ST-MAC has better network throughput and energy cost compared with existing schemes. In [17], Azar and Manzuri propose a MAC protocol based on reserved time slot. It employs a synchronization algorithm to synchronize all nodes and uses the listen/sleep periodic operation for saving energy. In addition, the protocol uses short ranges of underwater acoustic communication links to achieve higher throughput. In [18], Cho et al. propose a PR-MAC protocol, in which nodes exchange information between 2hop neighbor nodes in random accesses period. According to predetermined priority, each node is assigned transmission opportunities with contention free method by TDMA scheme. The reservation period is divided into several slots to transfer data reducing collision. PR-MAC can also reduce energy consumption by reducing period with active mode. In [19], Hong et al. propose an efficient continuous time scheduling TDMA protocol (ECS), including the continuous time based and sender oriented conflict analysis model, the transmission moment allocation algorithm, and the distributed topology maintenance algorithm. By using continuous time based transmission moment allocation scheme, differences of link delays are further utilized and channel utilization of receiver node is improved. At the same time, ECS has higher network throughput and better efficiency.

However, these research works of underwater acoustic sensor networks MAC protocols mainly focused on collision avoidance, throughput, and energy efficiency, but most of them rarely consider fairness. In contention protocols, the long propagation delay of acoustic media leads to spatial unfairness problem. Xie and Cui propose a reservation-based MAC protocol (R-MAC) in [20]. R-MAC has three phases to allocate the channel resources including latency detection, period announcement, and periodic operation. Nodes transfer data at its own slots. At the beginning, node in latency detection phase detects the propagation latency to all its neighbors. In the period announcement phase, each node randomly selects its own listen/sleep schedule and broadcasts this schedule. The data are transmitted in the periodic operation phase. In R-MAC, an intended receiver randomly selects one reservation from the reservations it collects to support fair access of the channel. However, it has low throughput and is not suitable for intensive network. Later, in [6], Syed et al. point out the problem that is long propagation delay of acoustic channel leading to spatial unfairness. They propose the T-Lohi MAC protocol to solve the problem. T-Lohi uses the random back-off method to ensure the fair access of the channel, to overcome the problem of “the nodes nearer the receiver occupy the channel quickly.” However, T-Lohi does not consider hidden terminal problem, resulting in that network throughput becomes lower. In [13], Liao and Huang propose SF-MAC protocol to solve the spatial
3. RET-MAC Protocol Design

In this section, we first discuss space-time uncertainty and spatial unfairness problem in UASNs. Secondly, we introduce network model and the basic idea of RET-MAC protocol. Then we analyze RTS CP and CTS DP. Finally, CTS back-off mechanism is used to adjust CTS DP. And we propose contention back-off mechanism to increase fairness further and reduce network congestion.

3.1. Spatial Unfairness of UASN. In terrestrial short-range RF network, propagation delay is negligible. While in UASNs it is essential to consider the location of nodes and transmission time due to the long propagation delay of acoustic media. In [21], Syed et al. first propose that due to long propagation delay of acoustic media, a collision at receiver has space-time uncertainty. In Figure 1(a), when nodes A and B transmit packets at different time, owing to the low propagation delay between A and N, the signals of A and B arrive N at the same time. There happens collision at N. In Figure 1(b), both nodes A and B transmit packets at the same time, owing to different propagation delay node N may successively receive the signals of A and B without collision. These examples show that in UASNs a collision in receiver not only depends on packets transmission time, but also depends on the location of nodes.

Propagation delay of signal is proportional to the distance between nodes, in competition protocol node nearer the receiver easily obtain channel leading to spatial unfairness problem. As shown in Figure 1(c), nodes A and B request the channel, B sends request earlier, and A sends later, while the request packet of A arrives N earlier, node A may first obtain the channel. Therefore, the nodes nearer the receiver occupy the channel quickly, which make relatively distant nodes that cannot fairly use channel. That is spatial unfairness problem.

According to the above discussion of spatial unfairness problem, especially when all nodes frequently require for sending data, nodes away from the receiver cannot effectively obtain the channel. So, this paper proposes RET-MAC protocol to satisfy the spatial fairness. And it adopts adaptive RTS CP and CTS DP to achieve lower energy consumption and delay.

3.2. UASN Model. RET-MAC adopts receiver-based protocol and mainly handles the spatial unfairness. Therefore, in this paper network model consists of a single receiver and n contenders; contenders send RTS to receiver in order to obtain channel and then send data later. This paper assumes that network has these following properties.

(1) All nodes have a unique ID and are relatively fixed.
(2) All nodes have similar capabilities (processing/com- munication), and clock is a weak synchronization.

(3) All contenders contend channel and send their data to the receiver.

(4) Contenders are randomly distributed in the largest transmission range of the receiver.

The third and fourth properties of network mainly proceed from the receiver. The protocol allocates the channel resources according to the sending time of RTS packet, satisfying that the channel is allocated to the earliest request node.

3.3. RTS Contention Phase (RTS CP). Based on RTS/CTS method RET-MAC responds to the earliest transmitter of RTS packet to allocate the channel, and all the control packets contain sending time of this packet. During RTS CP the receiver determines the contender which first sent RTS. Then, in order to avoid collision the receiver postpones CTS DP to send CTS. Other contenders which failed competition continue to contend channel after this communication is over. Figure 2 describes the basic idea of the RET-MAC protocol. Assuming that node N is receiver, nodes A, B, and F are contenders. Node N received RTS from A, B, and F in RTS CP and determined A that first sent RTS. Then, receiver N postponed CTS DP to send CTS to A. Finally, node A sent data to N.

Due to long propagation delay of acoustic media, receiver captures the first RTS which may not be the earliest sent, so we add RTS CP to determine the earliest transmitter of RTS packet.

Properties. The length of RTS CP is determined by both the currently earliest sending time of RTS and the time of the first captured RTS. And it is changing dynamically according to currently earliest transmitter.

Proof. Assuming that the length of RTS CP is \( \delta \), the maximum transmission range of acoustic signal is \( R \). The velocity of underwater acoustic is \( V \). So, the maximum propagation delay is \( T = R \times V \). In Figure 3, node N is receiver. Nodes A, B, C, and F are contenders. The distance between N and F is \( R \).

Firstly, node N captures the first RTS from A at time \( t \). At this time, N regards A as the earliest transmitter of RTS. Because the maximum length of propagation time is \( T \), if the sending time of RTS is earlier than \( t_a \), it certainly reaches N in the period of \( T - (t - t_a) \). So, \( \delta \) is equal to \( T - (t - t_a) \). Then, node N captures RTS from B, while \( t_b > t_a \), this RTS is ignored. At time \( t' \), N captures RTS from C, and \( t_c < t_a \), so C is regarded as the earliest transmitter of RTS. If there is earlier RTS, it certainly arrives at N in the period of \( T - (t' - t_a) \) after time \( t' \). At this time, \( \delta \) is equal to \( T - (t - t_a) \) less than \( T - (t - t_a) \). As you see, the length of RTS CP is contraction. And so on, we can achieve the earliest transmitter of RTS packet.

Therefore, the length of RTS CP is determined by both the earliest send time of RTS and the time of the first captured RTS. And it is changing dynamically according to currently earliest transmitter.

The pseudo-code of RTS CP algorithm determining the earliest transmitter of RTS and the end time of RTS CP is shown in Algorithm 1. The input of the algorithm is current captured RTS packet (\( r_{frame} \)).

3.4. Beforehand CTS (BCTS). In RET-MAC, contenders listen to any control packets from other nodes before sending RTS. In this case the channels have been occupied, and the contenders keep silent and do not participate in this competition. In order to avoid collision, RET-MAC postpones CTS DP to send CTS. However, the hidden contenders that is out of the maximum propagation range of some contenders keep silent until hearing CTS. If these contenders have data to send before receiving CTS, there may cause collision at receiver. Therefore, we add a Beforehand CTS (BCTS) to prevent collision caused by hidden nodes. When the receiver captures the first RTS, it immediately broadcasts BCTS to notify its neighbor that the channel is occupied.

In Figure 4, node N is receiver. Nodes A, B, and F are contenders. Node A achieved the channel and sent data, while node B was out of the maximum propagation range of A, and node B sent RTS (\( B_t \)) before hearing CTS. In this case, there may cause collision. Thus, when receiver captures the first RTS from A, it immediately broadcasts BCTS. Node B keeps silent after hearing BCTS. When the length of CTS DP is longer, it can effectively avoid collision caused by hidden nodes.

3.5. CTS Delay Phase (CTS DP). Due to adding BCTS in RET-MAC, and when the length of CTS DP is longer, it can effectively avoid collision. However, the longer handshake time increases energy consumption and seriously affects network throughput. So, in order to reduce delay and energy consumption and improve network throughput, the protocol should consider how to shorten the length of CTS DP without collision. Assuming that the length of CTS DP is \( q \), all control packets (RTS, CTS, and BCTS) have equal size and their transmission times are \( T_f \).

In Figure 5, node N is receiver. Nodes A, B, and F are contenders. The instance between N and B is the maximum transmission range, and the propagation delay between them is \( T \). During RTS CP N determines the earliest transmitter F, and the length of RTS CP (\( \delta \)) is equal to \( T - (t - t_f) \). The propagation delay between F and N is \( t' - t_f \); we can conclude that the time interval from \( t_f \) to the time of receiving CTS of F is \( T + q + (t' - t_f) \), where the processing time of node is
negligible. In order to avoid CTS collision, it must meet the constraints of

\[ T + q + (t' - t_f) \geq 2T + T_c \implies q \geq T + T_c - (t' - t_f). \] \hspace{1cm} (1)

In addition, the time interval from \( t \) to the time of receiving data of \( N \) is \( \delta + q + 2(t' - t_f) + T_c \), and the last RTS may arrive \( N \) at \( t'' \). In order to avoid data collision, it must meet the constraints of

\[ \delta + q + 2(t' - t_f) + T_c \implies q \geq 2T + T_c - 2(t' - t_f). \] \hspace{1cm} (2)

We have \( 0 \leq t' - t_f \leq T, \delta = T - (t - t_f) \), and \( t' - t_f \geq t - t_f \). Thus, when we take \( q \geq T + T_c \), it can fully satisfy (1) and (2). However, when the length of CTS DP is longer, the handshake time is larger. In this case the network throughput becomes very poor. Therefore, in RET-MAC, in order to reduce delay and improve network throughput we take the initial value of \( q \) equal to \( T + T_c \).

BCTS is added, and node \( N \) may capture the last RTS at time \( t'' \). After time \( t'' \) there will not be any RTS which arrive at \( N \). However, we take the initial value of \( q \) is \( T + T_c \) and have

\[ \delta + q = 2T + T_c - (t - t_f) < 2T + 2T_c. \] \hspace{1cm} (3)

From (3), at the end time of CTS DP, there may be RTS which arrive at \( N \). Therefore, if \( N \) is in receiving state at the end time of CTS DP, we need to dynamically extend the CTS DP. This paper proposes CTS back-off mechanism to extend CTS DP.

### 3.6. CTS Back-off Mechanism

When receiver sends CTS at the end time of CTS DP, it may be receiving RTS. This paper proposes CTS back-off mechanism to extend CTS DP in order to be ready for sending CTS again. As the above discussion, the initial value of \( q \) is \( T + T_c \), and when \( q \geq 2T + 2T_c - \delta \), not any control packets arrive at receiver. Therefore, the length of CTS DP \( q \) is shown in

\[ q = k_i = \begin{cases} 
T + T_c, & i = 0, \\
T + T_c + \frac{k_{i-1} - \delta}{2}, & i > 0, \ k_{i-1} + \delta < 2T, \\
2T + 2T_c - \delta, & i > 0, \ k_{i-1} + \delta \geq 2T, 
\end{cases} \] \hspace{1cm} (4)

where \( i \) is the number of extending CTS DP. In fact, at the end time of CTS DP, the probability of receiving RTS is low. And with the length of CTS DP increasing, the probability decreases. In the part of analysis, this paper analyzes the maximum probability of extending CTS DP when \( q \) takes the initial value.

### 3.7. Contention Back-off Mechanism

Receiver only communicates with one contender in each communication. In other words, other failed contenders continue to contend the...
channel after this communication ends. The failed contenders calculate the end time of this communication according to the send time of CTS and propagation delay. And in order to save energy, the failed contenders enter into sleep state until this communication ends. In order to satisfy the fairness of contending channel and avoid network congestion caused by all nodes sending RTS in short time, we propose contention back-off mechanism which makes all contenders postpone $\alpha(x)$ time to send RTS. In contention back-off mechanism, we take the number of contending channel of current data packet into $\alpha(x)$ that can increase the fairness of access channel further. The value of $\alpha(x)$ is given by

$$\alpha(x) = \left( \text{random} \ [0, 1] + \left( 1 - \frac{\text{CN}(x)}{n} \right) \right) \times \text{CW},$$

where $n$ is the number of receiver’s neighbor nodes, which is included in BCTS to notify neighbors. $\text{CN}(x)$ is the number of what the current data packet contend channel. If data packet is sent successfully, $\text{CN}(x)$ is 0, and the maximum value of $\text{CN}(x)$ is $n$. CW is the size of contention window, we take it as $T$ in simulation. From (5) it can be seen that when $\text{CN}(x)$ is larger, $\alpha(x)$ is smaller. Contenders send RTS earlier and more easily achieve channel.

4. Analysis of Protocol Parameters

In this section, we first discuss the maximum probability of extending CTS DP in order to explain that the probability of extending CTS DP is very lower under the initial case. In addition, we also analyze the maximum throughput of network in detail under the above network model.

4.1. The Maximum Probability of Extending CTS DP. The Maximum Probability of extending CTS DP (MP-CD) is defined as the maximum probability of what CTS DP is extended to be ready again for sending CTS, because receiver may be receiving control packet at the end time of CTS DP. In Figure 6, node N is receiver. Nodes A, B, C, and F are contenders. The distance between C and N is the maximum propagation range. Nodes B and C are out of the max propagation range of F. We analyze MP-CD under the condition of $q = T + T_c$.

As shown in Figure 7, node N in RTS CP determined F which first sent RTS. The time interval from the sending time of F’s RTS to the end time of CTS DP is $2T + T_c$. And at the end time of CTS DP, BCTS packet have been sent out for about $2T + \Delta t$, where $\Delta t = t - t_f$, and we define $r = (2T - \Delta t - T_c)/2$. Therefore, the control packets of all contenders in shadow area of Figure 6 cannot arrive at N at the end time of CTS delay phase. The contenders in the white areas of Figure 6 only in certain time send RTS that may arrive at N at the end time of CTS DP.

We assume that all contenders have data packets to send at the end of each communication and send RTS to contend channel. According to contention back-off mechanism, the maximum length of contention windows is $2T$. And some contenders send RTS in the time interval of the red areas of Figure 7 that may lead to extend CTS DP. Therefore, one contender may lead to the probability of extending CTS DP is

$$\epsilon = \frac{T_c}{2T}.$$  

In addition, we assume that the distance between receiver and the earliest transmitter of RTS is $d$. We can conclude $0 < \Delta t \leq d/C$, and the blank areas of Figure 6 are given by

$$s = \pi R^2 - 2R^2 \arcsin \left( \frac{1 - d^2}{4R^2} \right) + d \sqrt{R^2 - \frac{d^2}{4}} + 2 \left( R^2 - r^2 \right) \arccos \frac{R^2 + d^2 - r^2}{2dr} - \frac{2r^2 \arccos \frac{R^2 + r^2 - d^2}{2Rr}}{2d^2} - \frac{R^2 + d^2 - r^2}{2d^2} \sqrt{4R^2d^2 - (R^2 + d^2 - r^2)^2}.$$
The number of nodes in the blank areas of Figure 6 satisfies \( N = \lceil n \times s / \pi R^2 \rceil \); \( n \) is the number of the receiver’s neighbor. Thus, the maximum probability of extending CTS DP is given by

\[
\beta = 1 - (1 - \varepsilon)^N. \tag{8}
\]

Assuming that the maximum propagation range of nodes \( R \) is 500 meters, acoustic velocity \( V \) is 1500 meters per second, \( d \) set \( R/2 \). The size of control packets is 40 bit. Each modem transmits data at a speed of 10 kb/s, and \( n \) increases from 1 to 50. We can calculate that \( T_\chi \) is equal to 0.004 seconds, \( T \) is equal to 1/3 seconds, and the value of \( \varepsilon \) is 0.006, \( 0 < \Delta t \leq 1/6 \). At this time, the relationship of \( n \), \( \Delta t \), and \( \beta \) is shown in Figure 8.

As shown in Figure 8, when \( n \) is constant, \( \Delta t \) is larger, and the value of \( \beta \) is larger. For example, we take \( n = 20 \), \( \Delta t = 1/6 \) seconds, so \( \beta = 0.0413 \). We can see that the probability of extending CTS DP is very low. So, the length of CTS DP mostly is equal to \( T + T_\chi \). And according to (3), RET-MAC shortens the length of the sum of RTS CP and CTS DP. That is said that RET-MAC reduces delay and then improves network throughput. In fact, the value of \( \beta \) is far small than theoretical value. First of all, not all nodes have data packets to send at the same time. Secondly, contenders keep silent after hearing other RTS or BCTS. Finally, we conclude the theoretical value is larger than the fact value, because our assuming is the highest possible.

4.2. Maximum Throughput. This section estimates the maximum throughput of RET-MAC in the above network model. In this network model, the maximum throughput can be shown as the maximum packet which the receiver has received. We assume that the network is in ideal state without any collision. The processing delay of node is negligible. Every node has data packets to send and fairly transfer packets.

Figure 9 describes a data communication cycle. \( t_i \) is the idle time interval between the \((i - 1)\)th communication and the \(i\)th communication. \( T_{wi} \) is the propagation delay between receiver and the earliest transmitter of RTS in \(i\)th communication. \( T_d \) is transmission delay of data packet. \( q_i \) is the length of CTS DP in \(i\)th transmission. So, the \(i\)th data packet is received successfully that need time \( T_{ri} \), which is given by

\[
T_{ri} = t_i + 2T + q_i + T_{x} + T_c + T_d. \tag{9}
\]

Assuming that the network operation time is \( T_i \), \( \eta \) is throughput of receiver, so we can conclude that

\[
T_i = \sum_{i=1}^{\eta} t_i + 2\eta T + \sum_{i=1}^{\eta} q_i + \sum_{i=1}^{\eta} T_{x} + \eta T_c + \eta T_d
\]

\[
\implies \eta = \frac{T_i}{(1/\eta) \sum_{i=1}^{\eta} (t_i + q_i + T_{x}) + 2T + T_c + T_d}. \tag{10}
\]

From (10), the maximum throughput is relative to \( q \) and \( T \). However, in specific operating conditions the value of \( T \) is fixed. There is no idle time with short CTS DP that can achieve high throughput. So, we take \( t_i = 0, q = T + T_c \), and the theoretical maximum throughput of network is

\[
\eta_{max} = \frac{T_i}{3T + 2T_c + T_x + T_d}, \tag{11}
\]

where \( T_x \) is the average propagation delay between receiver and contenders. In simulation section, the difference between simulation result of RET-MAC throughput and the value of analysis is small. It is said that RET-MAC can effectively use channel resource and have lower collision rate.
5. Protocol Performance Evaluation

In this section, we first present main performance evaluation index. According to fairness index [18], we define Spatial Fairness Index and Delay Fairness Index. Secondly, simulation environment and working parameters are present. Finally, we analyze and compare RET-MAC with other MAC protocol by evaluating some important medium access metrics such as fairness, delay, throughput, and energy consumption.

5.1. Main Performance Evaluation Index. Fairness is an important aspect of underwater network protocol. RET-MAC is to solve spatial unfairness problem. This paper analyzes spatial fairness from throughput. If contenders have very good spatial fairness, when they have equal traffic rate, all nodes have equal data packets to send not because of their distance from the receiver. Therefore, this paper uses throughput to react spatial fairness. In addition, the transmit delay of data packets is also an important aspect of underwater network protocol; lower and fairness transmit delay can effectively improve network performance. The fairness index [22] has been widely used as a standard to deal with fairness problem. Thus, we also define the spatial fairness index and the delay fairness index based on it.

(1) Spatial Fairness Index. In this section, we analyze spatial fairness from throughput. We assume that in aforementioned network model there are \( n \) contenders. According to this paper needs, we define Spatial Fairness Index (SFI) as follows:

\[
SFI = \frac{\left(\sum_{i=1}^{n} S_i \right)^2}{n \times \left(\sum_{i=1}^{n} S_i^2\right)},
\]

where \( n \) is the number of contenders, and \( S_i \) is throughput of \( i \)th node. If all contenders can fairly access channel, their throughput is equal, at this time SFI set 1. If one node always occupies channel, SFI set \( 1/n \). In short, if the value of SFI is close to 1, the spatial fairness of network is better.

(2) Delay Fairness Index. The transmit delay of packet includes waiting delay, transmission delay, and propagation delay. In UWSN, propagation delay is longer. And it is proportional to the distance between nodes. Therefore, under network model of Figure 10 we analyze delay fairness. In this way, transmission delay and propagation delay of packet are equal, so delay fairness of packet depends on fairness of waiting time.

We still use the fairness index [22] to define Delay Fairness Index (DFI) as follows:

\[
DFI = \frac{\left(\sum_{i=1}^{n} d_i \right)^2}{n \times \left(\sum_{i=1}^{n} d_i^2\right)},
\]

where \( n \) is the number of packets which is received successfully. If delay is equal, DFI set 1. If delay jitter is larger, DFI is small. In short, if the value of DFI is close to 1, fairness of waiting delay is better.

5.2. Simulation Environment and Working Parameters. We implement RET-MAC protocol in Aqua-Sim [23], an NS-2 based simulator for UWSN, developed at the Underwater Sensor Network (UWSN) Lab at the University of Connecticut. The simulation environment consists of a single receiver and \( n \) transmitters. All transmitters are randomly dispersed in the sensing region of receiver. Each transmitter will transmit data, which follows the Poisson arrival process with average traffic generation rate \( \lambda \). For power consumption, we also use the numbers from a practical acoustic modem as follows: transmitting power 50 W, receiving power 3 W, and idle power 80 mW [24]. All simulations last for 1000 seconds and all the results are obtained from the average of 100 runs. The setting of key simulation parameters are listed in Table 1.
We compare RET-MAC with another MAC protocol by evaluating the important medium access metrics such as fairness, throughput, energy consumption, and delay. For first three aspects, we consider two different scenarios where Scenario-1 has 20 transmitters, and the data generation rate \( \lambda \) of each transmitter increases from 0.01 to 0.1 packets per second. In Scenario-2, we fix traffic rate \( \lambda \) to 0.05, and the number of contenders increases from 5 to 40. For delay simulation environment, we adopt 4 contenders and one receiver based on Figure 10. The data generation rate \( \lambda \) in this scenario increases from 0.01 to 0.05 packets per second.

### 5.3. Analysis of Simulation Results.

In this section, through simulations, we would like to study the performance of RET-MAC and compare it with COPE-MAC [14], R-MAC [20], and RET-MAC-L in UWSN. COPE-MAC protocol is a new MAC protocol based on RTS/CTS. It adopts parallel reservation to improve communication efficiency and uses cyber carrier sensing to detect and avoid collisions. In the long propagation delay of UASNs especially, COPE-MAC has better performance than other protocols. It can avoid collisions by using a fixed length of sum of RTS CP and CTS DP, under avoiding collision which can effectively shorten the length of handshake time to improve network throughput. Furthermore, in Figure 14 data line of “Analytical” is drawn according to (11) and simulation environment parameters. There is only a small gap between RET-MAC throughput and analytical thought in Figure 14. There are two main reasons: first, owing to adopt contention back-off mechanism, there is a small idle time between twice data communications; second, the data line of “Analytical” is calculated under the ideal state.

COPE-MAC can achieve higher network throughput with using parallel reservations and cyber carrier sensing mechanism, but it is still lower than RET-MAC. Due to using a fixed length of sum of RTS CP and CTS DP, the handshake time of RET-MAC-L becomes longer than RET-MAC. Therefore, its throughput becomes lower. R-MAC uses listen/sleep mechanism which seriously impact on the network throughput. And R-MAC does not apply to intensive networks; otherwise there is lower throughput.

### (4) Energy Consumption.

Energy consumption is another important aspect of UASNs, because lower energy consumption can effectively extend lifetime of network. From Figure 15(a), we can see that for all protocols, average energy...
consumption of packet decreases at first with traffic rate increasing. When traffic rate is equal to 0.01 pkt/s, in idle state energy consumption accounts for most of all energy consumption. So, average energy consumption of packet is higher. After traffic rate arrived at 0.04 pkt/s, the data lines of average energy consumption leveled off. Figure 15(a) also shows that RET-MAC can achieve much higher energy efficiency than other protocols. From Figure 15(b), we can see that average energy consumption increases with number of contenders increasing. Compared with other protocols, RET-MAC has lower energy consumption. Although R-MAC adopts listen/sleep mechanism to save energy, network collision increases with contenders. Therefore, when the number of contenders arrives at 40, average energy consumption of packet is higher. In addition, because RET-MAC shortens handshake time and reduces waiting time of contenders, average energy consumption of RET-MAC is lower than RET-MAC-L.

6. Conclusion

This paper discussed spatial unfairness problem and proposed Response to the Earliest Transmitter of RTS MAC (RET-MAC) protocol to achieve fairness. RET-MAC adopts adaptive RTS CP to determine the earliest transmitter of RTS. And CTS DP is added to postpone sending CTS in order to avoid collision. We also proposed CTS back-off mechanism to adjust the length of CTS DP as needed. In addition, contention back-off mechanism is used to reduce network congestion and increase fairness further. The simulation results show that our scheme can achieve higher fairness and throughput. At the same time, it also guarantees lower energy consumption and delay. As future work, we will still explore fairness problem when time is not synchronization, and study fairness control is based on network load and amount of sensed information in order to enhance fair using of network bandwidth.

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References

[1] I. F. Akyildiz, D. Pompili, and T. Melodia, “Underwater acoustic sensor networks: research challenges,” Ad Hoc Networks, vol. 3, no. 3, pp. 257–279, 2005.

[2] Z. Peng, Y. Zhu, Z. Zhou, Z. Guo, and J. H. Cui, “COPE-MAC: a Contention-based medium access control protocol with Parallel Reservation for underwater acoustic networks,” in Proceedings of the IEEE Oceanic Engineering Society (OCEANS ’10), pp. 1–10, May 2010.

[3] N. Chirdchoo, W. S. Soh, and K. C. Chua, “Aloha-based MAC protocols with collision avoidance for underwater acoustic networks,” in Proceedings of the 26th IEEE International Conference on Computer Communications (INFOCOM ’07), pp. 2271–2275, May 2007.

[4] P. Casari and M. Zorzi, “Protocol design issues in underwater acoustic networks,” Computer Communications, vol. 34, no. 17, pp. 2013–2025, 2011.

[5] J. Heidemann, M. Stojanovic, and M. Zorzi, “Underwater sensor networks: applications, advances, and challenges,” Philosophical Transactions of the Royal Society A, vol. 370, pp. 158–175, 1958.

[6] A. A. Syed, W. Ye, and J. Heidemann, “Comparison and evaluation of the T-Lohi MAC for underwater acoustic sensor networks,” IEEE Journal on Selected Areas in Communications, vol. 26, no. 9, pp. 1731–1743, 2008.

[7] L. Chen, X.-J. Li, Y.-B. Guo, and L.-M. Wang, “RUF-MAC: related and urgent first MAC for wireless sensor networks,” Applied Mathematics & Information Sciences, vol. 7, no. 3, pp. 1237–1244, 2013.

[8] G. A. Shah, “A survey on medium access control in underwater acoustic sensor networks,” in Proceedings of the International Conference on Advanced Information Networking and Applications Workshops (WAINA ’09), pp. 1178–1183, May 2009.

[9] Z. Zhou, Z. Peng, P. Xie, J.-H. Cui, and Z. Jiang, “Exploring random access and handshaking techniques in underwater wireless acoustic networks,” EURASIP Journal on Wireless Communications and Networking, 2013.

[10] W. Ye, J. Heidemann, and D. Estrin, “Medium access control with coordinated adaptive sleeping for wireless sensor networks,” IEEE/ACM Transactions on Networking, vol. 12, no. 3, pp. 493–506, 2004.

[11] M. C. Vuran and I. F. Akyildiz, “Spatial correlation-based collaborative medium access control in wireless sensor networks,” IEEE/ACM Transactions on Networking, vol. 14, no. 2, pp. 316–329, 2006.

[12] I. Rhee, A. Warrier, M. Aia, J. Min, and M. L. Sichitiu, “Z-MAC: a hybrid MAC for wireless sensor networks,” IEEE/ACM Transactions on Networking, vol. 16, no. 3, pp. 511–524, 2008.

[13] W.-H. Liao and C. Huang, “SF-MAC: a spatially fair MAC protocol for underwater acoustic sensor networks,” IEEE Sensors Journal, vol. 12, no. 6, pp. 1686–1694, 2012.

[14] Z. Peng, Y. Zhu, Z. Zhou, Z. Guo, and J. H. Cui, “COPE-MAC: a Contention-based medium access control protocol with Parallel Reservation for underwater acoustic networks,” in IEEE Oceanic Engineering Society (OCEANS’10), May 2010.

[15] M. K. Park and V. Rodoplu, “UWAN-MAC: an energy-efficient MAC protocol for underwater acoustic wireless sensor networks,” IEEE Journal of Oceanic Engineering, vol. 32, no. 3, pp. 710–720, 2007.

[16] C. C. Hsu, K. F. Lai, C. F. Chou, and K. C. J. Lin, “ST-MAC: spatial-temporal MAC scheduling for underwater sensor networks,” in Proceedings of the 28th Conference on Computer Communications (IEEE INFOCOM ’09), pp. 1827–1835, April 2009.

[17] Z. Azar and M. T. Manzuri, “A latency-tolerant MAC protocol for underwater acoustic sensor networks,” in Proceedings of the International Conference on Control, Automation and Systems (ICCAS’10), pp. 849–854, October 2010.

[18] H.-J. Cho, J.-I. Namgung, N.-Y. Yun, S.-H. Park, C.-H. Kim, and Y.-S. Ryuh, “Contention free MAC protocol based on priority in underwater acoustic communication,” in Proceedings of the
IEEE Oceanic Engineering Society (OCEANS '11), pp. 1–7, June 2011.

[19] L. Hong, F. Hong, Z. Guo, and Z. Li, “ECS: efficient communication scheduling for underwater sensor networks,” Sensors, vol. 11, no. 3, pp. 2920–2938, 2011.

[20] P. Xie and J. H. Cui, “R-MAC: an energy-efficient MAC protocol for underwater sensor networks,” in Proceedings of the 2nd Annual International Conference on Wireless Algorithms, Systems, and Applications (WASA '07), pp. 187–195, August 2007.

[21] A. A. Syed, W. Ye, J. Heidemann, and B. Krishnamachari, “Understanding spatio-temporal uncertainty in medium access with ALOHA protocols,” in Proceedings of the ACM the 2nd Workshop on Underwater Networks, pp. 41–48, ACM, September 2007.

[22] R. K. Jain, D.-M. W. Chiu, and W. R. Hawe, “A quantitative measure of fairness and discrimination for resource allocation in shared computer systems,” Tech. Rep. TR-301, Digital Equipment Corporation, Hudson, Mass, USA, 1984.

[23] P. Xie, Z. Zhou, Z. Peng et al., “Aqua-sim: an NS-2 based simulator for underwater sensor networks,” in Proceedings of IEEE/MTS Oceans (IEEE OCEANS '09), pp. 1–7, October 2009.

[24] L. Freitag, M. Grund, S. Singh, J. Partan, P. Koski, and K. Ball, “The WHOI Micro-Modem: an acoustic communications and navigation system for multiple platforms,” in Proceedings of the IEEE Oceans Conference, vol. 2, pp. 1086–1092, September 2005.