WSF-MAC: A Weight-based Spatially Fair MAC Protocol for Underwater Sensor Networks

Fei Dou[1], Zhigang Jin[1], Yishan Su[1], Jian Liu[2]
[1]School of Electronic and Information Engineering, Tianjin University, Tianjin 300072, China
[2]School of Information Engineering, Wuhan University of Technology, Wuhan 430070, China
doufei123@gmail.com, zgjin@tju.edu.cn, suyishan_tj@hotmail.com, super.liujian@gmail.com

Abstract—**The high propagation delay in Underwater Sensor Networks (UWSNs) causes space-time uncertainty, making spatial fairness a challenging problem in UWSNs. In this paper, we propose a weight-based spatially fair MAC protocol (WSF-MAC) for UWSNs. It postpones sending the underwater-reply (UW-REP) packet for a silence duration time, and then determines the node to send UW-REQ first according to the sending time and competition count of the underwater-request (UW-REQ) packets and send UW-REP to get ready for transmission. The simulation results show that WSF-MAC can achieve a better performance in terms of the spatial fairness by about 10%.**

Keywords-media access control; fairness; underwater sensor network; weight-based

I. INTRODUCTION

Underwater sensor network (UWSN) has got much attention in recent years due to the applications in those areas from water pollution monitoring to underwater exploration and from tsunami forecast to national defence and security. Related studies have shown that acoustic waves are used as the primary carrier for UWSN because of the relatively low absorption in underwater environment. However, in UWSNs, the propagation of acoustic signals is about 1500 m/s, which is several times slower than RF propagation (i.e., 3×10^8 m/s) in terrestrial environment, leading the propagation delay of UWSN being several times longer than that of terrestrial wireless networks [1].

For UWSN, due to the long propagation delay of acoustic signals, we must consider the locations of both the receiver and the potential interferers. Literature [2] presented the space-time uncertainty in UWSNs, which depends on both the packet transmitting time and the propagation delay from transmitters at different locations. Traditional MAC protocol for terrestrial networks considers only transmitting time uncertainty since the propagation latency is only about microseconds. However, spatial uncertainty cannot be ignored in UWSN for the fact that earlier sent packet may arrive at the receiver later due to location and the long propagation delay. The sensor nodes nearer to the receiver may occupy the channel quickly while transmitters farther to the receiver can hardly capture the channel. In the worst case, it may even be the condition that a single node or data stream monopolizes the channel bandwidth resources, while the others are in a completely hungry state, leading to spatial unfairness.

In this article, we propose a weight-based spatially fair MAC protocol for UWSNs to tackle the problem of spatial unfairness. It postpones sending the underwater-reply (UW-REP) packet for a silence duration time, which aims at capturing the underwater-request (UW-REQ) packets of all the potential contenders, to avoid collision. WSF-MAC then determines the node to send UW-REQ first according to the time tag and competition weight of UW-REQ and send UW-REP to get ready to transmit data with it.

II. RELATED WORKS

A number of MAC protocols for UWSNs have been proposed in recent years. These protocols can be divided into two main categories: contention-free MAC and contention-based MAC. The latter can be divided into random access MAC and handshake-based MAC.

Contention-free MAC mainly includes FDMA, TDMA and CDMA. FDMA is feasible for short distance communication but the narrow bandwidth and large attenuation of the underwater acoustic channel result in low throughput and inefficiency [3]. To solve the problems of TDMA-based protocol, which include strict synchronization and long enough time guard of every slot, literature [4] presented a mechanism that nodes adjust time guard according to the distance between nodes, but it can only be used in single-hop networks. Ian F. Akyildiz proposed a CDMA based medium access control for underwater acoustic sensor networks aiming at achieving high network throughput, low channel access delay and low energy consumption [5].

For random access MAC, literature [6] explored the performance of Aloha-based protocols in underwater networks, and proposed two enhanced schemes: Aloha-CA and Aloha-AN. Each node extracts the information of the transmitters and receivers from the packets it senses and avoids collision according to the information and propagation delay while such schemes cause energy and channel bandwidth waste. Recently, a tone-based MAC protocol, called T-Lohi, has been proposed in [7]. Each frame consists of two parts: reservation period and data transmission period, to avoid data collision and reduce energy consumption.

A number of works have adapted the handshake scheme for UWSNs. Molins and Stojanovic [8] considered using additional delay to deal with the delivery problems and proposed a slotted random access MAC protocol, called slotted FAMA, which combines CS with RTS/CTS handshake

---

This paper is partly supported by NSFC under grant No. 61162003 and by Science Hall of Qinghai.

mechanism. The length of the slot should be long enough to ensure that it can receive all the packets sent by the node within its communication range. Recently, a spatially fair MAC protocol, named SF-MAC, has been proposed in [9] to solve the space uncertainty problem in UWSNs, which determines the earliest transmitter with a probability rule. The SF-MAC also postpones sending CTS to avoid collision and capture RTSs from the transmitters.

III. WSF-MAC: WEIGHT-BASED SPATIALLY FAIR MAC PROTOCOL

We note that node which sends packets first will usually arrive at the receiver first in terrestrial networks. However, in UWSNs, earlier sent packet may arrive at the receiver later due to location and the long propagation delay, leading to the spatial unfairness. To solve this problem, we introduce a weight-based spatially fair MAC protocol for UWSNs in this section. It postpones sending the underwater-reply (UW-REP) packet for a silence duration time, and then determines the node to send UW-REQ first according to the time tag and competition weight of UW-REQs and send UW-REP to get ready to transmit data with it. We detailed illustrate this protocol in the following sub-sections.

A. Middle UW-REP

The receiver will postpone sending UW-REP after receiving UW-PEQ to avoid collision. However, the hidden nodes are beyond the listening range of the transmitter, while they are within the communication range of the receiver. Hence, these nodes will not sense any transmission before they hear the UW-REP. It may bring data collision if hidden nodes have data to send, causing retransmission of the packets, which will lead to decrease of channel utilization. In WSD-MAC, we use a Middle UW-REP to solve this problem caused by hidden nodes. When the receiver receives the first UW-REQ, it broadcasts a Middle UW-REP at once to inform its neighbours that it is ready for data transmission. The hidden nodes will keep silent when they hear the Middle UW-REP.

To illustrate it more clearly, as shown in Fig. 1 and Fig. 2, node *A* is transmitting data with node *R*. The hidden node *A'* sends UW-REQ before it hears the UW-REP of node *R*, causing collision with the data packet of node *A* at *R*. If we use a Middle UW-REP, like Fig. 2, node *A'* can only send UW-REQ before it senses the Middle UW-REP, and the UW-REQ of *A'* will arrive at *R* during UW-REQ SD (Silence Duration).

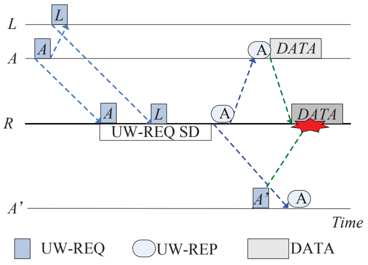

Figure 1. Hidden node's UW-REQ may collide with the transmitting data.

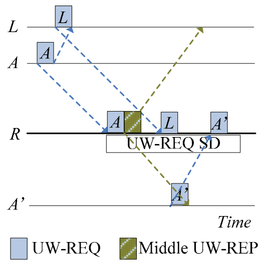

Figure 2. Using Middle UW-REP, The hidden node's UW-REQ will be received during UE-REQ SD and won't cause collision.

B. UW-REQ SD

The receiver will postpone sending UW-REP for a UW-REQ SD time to avoid collision due to the long propagation delay. In addition, we must ensure that UW-REQs of all contenders arrive at the receiver during the UW-REQ SD time. In WSF-MAC, we can easily calculate the propagation delay of the first arrived UW-REQ since there is a time tag which records both the sending and receiving time in UW-REQ. Then we estimate the last arrival time according to the largest available propagation delay, which can also be calculated. Therefore, UW-REQ SD can be the duration from the arrival time of the first UW-REQ to that of the last UW-REQ.

We illustrate an example of the UW-REQ SD calculation in Fig. 3, where node *L* is the farthest node from node *R*, *L'* is also the farthest node while it is hidden to node *L*, PD_{first} is the propagation delay of the first UW-REQ that arrives at node *R* and $PD_{\max}$ is the maximum delay of node. Let T_{contr} be the length of control packet. Assuming that node *L* is within the communication range of node *A* while *L'* is beyond of that. *L'* can send UW-REQ only before it receives the Meddle UW-REP from node *R* and *L* can send its UW-REQ before it receives the UW-REQ from node *A*. From Fig. 3, we can calculate the UW-REQ SD duration from the arriving time of node *A*'s UW-REQ to that of node *L'*.

$$2PD_{\max} + 2T_{contr}\,. \tag{1}$$

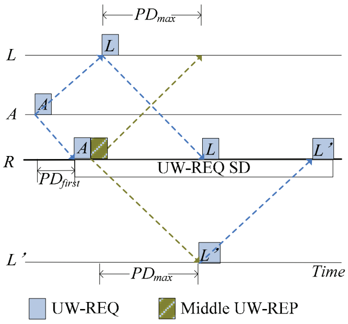

Figure 3. UW-REQ SD calculation.

In fact, our aim is to find the UW-REQ to be sent earliest. However, there will be some UW-REQs that will definitely not be the first to send if the UW-REQ SD duration is determined by Eq. (1). As a result, there is a chance to shorten the period of UW-REQ SD according to the first arrived UW-REQ.

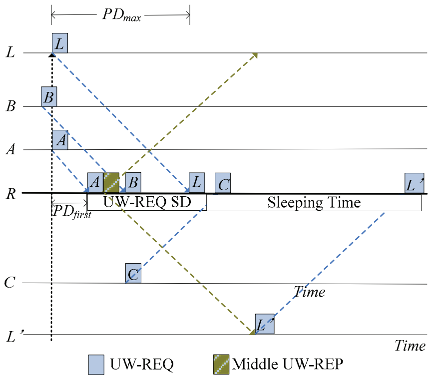

Figure 4. A shorten UW-REQ SD calculation.

As is shown in Fig. 4, *A*'s UW-REQ first arrives at node *R* and node *L*, the farthest node, sends its UW-REQ at the same time with *A*. Therefore, within the communication of node *R*, if the UW-REQ's arriving time of a transmitter is later than the arrival time of *L*'s UW-REQ, then it is impossible for that contender to send its UW-REQ earlier than *A*. Then the UW-REQ SD can be modified by:

$$PD_{\max} - PD_{first} + T_{contr}. \tag{2}$$

We can assure that all UW-REQs which may be sent earlier than node *A* will arrive at the receiver during the UW-REQ SD, shown in Eq. (2).

After the duration of UW-REQ SD which keeps the listening state, the receiver turns to sleeping state, guaranteeing that UW-REQs of all contenders will arrive before the end of the Sleeping Time, which is given by :

$$\begin{aligned}&(2PD_{\max} + 2T_{contr}) - (PD_{\max} - PD_{first} + T_{contr})\\&= PD_{\max} + PD_{first} + T_{contr}\end{aligned}. \tag{3}$$

When the Sleeping Time ends, node *R* sends a UW-REP to the node sending UW-REQ earliest and transmits data with it.

C. *The First Ttransmitter Judgement*

The UW-REP of every node contains the information of competition times. The receiver sets the competitive weight according to competition times of every received UW-REP when UW-REQ SD comes to an end. Assuming there are two weight queues: the high weight queue, HWQ; the low weight queue, LWQ. The receiver inquires whether the competition times of a node exceed the threshold. If the number is larger than the threshold, the competitive weight is set to 1.5(the high weight) and the corresponding UW-REP will be put into HWQ. Otherwise, the competitive weight is set to 0.8(the low weight) and the corresponding UW-REP will be put into LWQ.

Every UW-REQ has a time tag recording both the sending time from the transmitter and the arriving time at the receiver. It will be easy to determine the node that sends the UW-REQ first. In WSF-MAC, when there are UW-REQs in HWQ, the receiver only needs to check the time information of these UW-REQs and finds out the first node to send packet, without checking the UW-REQs in LWQ. On the contrary, if there is no UW-REQ in HWQ, the receiver has to inquire the sending time of all the received UW-REQ. After the first node being decided, the receiver sends a UW-REP to the node and gets ready to transmit data.

D. *Back-off*

When the Sleeping Time ends, the receiver sends UW-REP to the node sending UW-REQ earliest and other contenders must wait for the next competition. Hence, we propose a back-off scheme, where a node has more opportunity to access the channel if it has already contended and sent its UW-REQ earlier during the former round. Let *CW* be the contention window size, *CT(X)* be the contention times of node *X*, α be constant number 1 and *TD(X)* be the time difference of sending time between node *X* and the earliest node to send UW-REQ. The higher the value *CT(X)* is, the more node *X* has contended. Meanwhile, the lower is the *TD(X)*, the earlier is the transmission of *X*'s UW-REQ. Hence, the contender with higher *CT(X)* and lower *TD(X)* could probably send its UW-REQ earlier than others. The back-off is given by:

$$backoff = (random[0,1] + \frac{1}{CT(X) + \alpha} + \frac{TD(X) + \alpha}{PD_{\max}}) \times CW. \tag{4}$$

E. *Periodically Modify the UW-REQ SD*

Owing to the fact that we cannot exactly know the maximum propagation delay of the farthest node to the receiver, we should periodically modify the UW-REQ SD to ensure that all the needed UW-REQs could arrive at the receiver during the UW-REQ SD time. According to the time tag of every UW-REQ, we can easily calculate the largest available propagation delay. Therefore, we examine the largest propagation delay at intervals and replace the former one in order to receive packets more accurately.

We use Eq. (2) to calculate the UW-REQ SD duration and the receiver has a Sleeping Time. However, at regular intervals, the UW-REQ SD turns to be the condition shown in figure 4(by Eq. (1)) and the receiver has no Sleeping Time, which aims at collecting information of the maximum propagation delay of the farthest node to modify UW-REQ SD.

IV. SIMULATION EXPERIMENT

In this section, we use a fairness index as defined in [10] to measure the transmission order fairness. We compare the fairness of WSF-MAC with schemes that is non-weight-based. And we run simulations in terms of competition threshold.

A. *Fairness Index*

We analyze the fairness of the proposed WSF-MAC and focus on the fairness of the transmission order. Assuming there are *n* transmitters which contend for data transmission to a single receiver with order s_i (i=1, 2, ⋯, n). Let r_i be the order of contender that successfully transmit data with the receiver. We use x_i to represent the delay of contenders:

$$x_i = r_i - s_i + n. \tag{5}$$

The Fairness Index (*FI*) proposed in [10] has been widely used for the measurement of fairness in MAC protocol. The result of *FI* is between 0 and 1, where the performance is of greater fairness if it is closer to 1, which means that the contenders transmit data in the order of their contention. *FI* is defined as follows:

$$FI = \frac{(\sum_{i=1}^{n} x_i)^2}{n \times (\sum_{i=1}^{n} x_i^2)}. \tag{6}$$

B. Simulation Environment

The simulation environment consists of *n* contenders and a single receiver. We assume that a transmission is always successful when the UW-REQ and UW-REP succeed in transmitting by neglecting the packet loss in the acoustic channel. The receiver is at the centre of the network while the contenders are randomly distributed in a radius of 500 m, which is the transmission range of the modem. The propagation speed of acoustic signal is 1500 m/s. Each node sends packets at a constant rate by 1 packet/s, where the packet length is 128 bytes, and each node sends 1000 packets in total. We run the simulation for 1000s.

C. Simulation Results

We compare the fairness of our WSF-MAC with those schemes which are non-weight-based and use first-come-first-served for the contention. Our protocol is a weight-based scheme, which could be considered as a scheme of priority and we analyze the *FI* of our scheme. In Fig. 6, simulation results show that WSF-MAC can achieve a *FI* of about 0.9. With the increasing number of contenders, the *FI* decreases, but it is still higher than the other schemes without priority by about 10%.

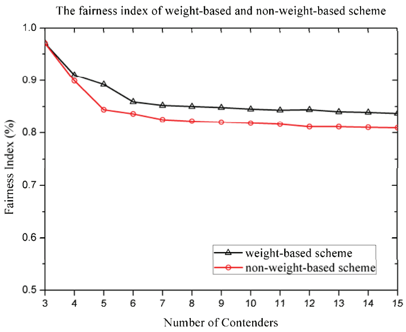

Figure 5. The fairness index of weight-based and non-weight-based scheme.

In addition, we analyze the performance of our protocol in terms of competition threshold. Fairness is affected by the configuration of competition threshold. As is shown in Fig. 7, when there are 6 contenders, the optimal fairness can be 0.899 while competition threshold is set to 5. Similarly, it can achieve 0.91 *FI* when the competition threshold is set to 5 for a 7 contenders' scenario. What's more, for 8 contenders, better fairness could be realized by setting the threshold to 6. Simulations show that there is always an optimal competition threshold in our WSF-MAC to realize better fairness.

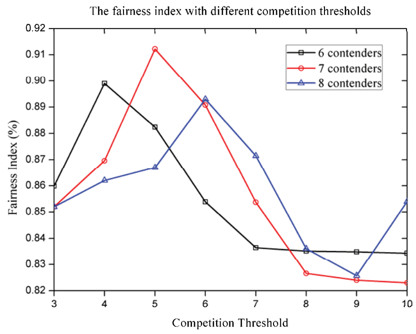

Figure 6. The effect of competition threshold for 6, 7 and 8 contenders.

V. CONCLUSION

In this paper, we focus on the problem of spatial unfairness in UWSNs and propose a weight-based spatially fair MAC protocol for UWSNs. The proposed protocol can operate in large-scale sensor networks and simulation results show that the proposed protocol can achieve higher fairness. In addition, different competition thresholds cause different fairness, and there is always a competition threshold which can bring a greater fairness.

REFERENCES

[1] J. Heidemann, Y. Li, A. Syed, J Wills, and W. Ye, "Research Challenges and Applications for Underwater Sensor Networking," Proceedings of the IEEE Wireless Communications and Networking Conference. Las Vegas, NV, vol. 3-6, pp. 228-235, April 2006.

[2] A. Syed, W. Ye, B. Krishnamachari, and J. Heidemann, "Understanding Spatio Temporal Uncertainty in Medium Access with ALOHA Protocols," ACM the Second Workshop on Underwater Networks (WuWNet). ACM New York, NY, USA, pp. 41-48, 2007.

[3] J. Rice et al, "Evolution of seaweb underwater acoustic networking," Proc. IEEE Oceans 2000. Providence, RI , USA, vol. 3, pp. 2007-2017, September 2000.

[4] L. Hong, F. Hong, Z. Guo, X. Yang, "A TDMA-Based MAC Protocol in Underwater Sensor Networks," Proceedings of WiCOM, Dalian, China, pp. 1-4, October 2008.

[5] D. Pompili, T. Melodia, and I. Akyildiz, "A CDMA-Based Medium Access Control for Underwater Acoustic Sensor Networks," IEEE Trans. Wireless Commun., vol. 8, no. 4, pp. 1899-1909, April 2009.

[6] N.Chirdchoo, W-S.Soh, and K.C.Chua, "Aloha-based MAC Protocols with Collision Avoidance for Underwater Acoustic Networks," INFOCOM 2007. Anchorage, Alaska, USA, pp. 2271–2275, May 2007.

[7] A. A. Syed, W. Ye, and J. Heidemann, "T-lohi: A new class of mac protocols for underwater acoustic sensor networks," IEEE INFOCOM. Phoenix, AZ, pp. 231-235, April 2008.

[8] M. Molins and M. Stojanovic, "Slotted FAMA: a MAC protocol for underwater acoustic networks," OCEANS 2006-Asia Pacific. Singapore, pp. 1–7, May 2007.

[9] Wen-Hwa Liao, and Chih-Chien Huang, "SF-MAC: A Spatially Fair MAC Protocol for Underwater Acoustic Sensor Networks," Sensors Journal, IEEE, pp. 1-1, 2011.

[10] R. Jain, D. Chiu, and W. Hawe, "A Quantitative Measure of Fairness and Discrimination for Resource Allocation in Shared Computer Systems," Digital Equipment Corp. Hudson, MA, DEC Res. Rep. TR-301, 1984.