Channel Access Probability Equalization Scheme for Contention based MAC Protocols in Underwater Acoustic Sensor Networks

SUNMYENG KIM
Department of Computer Software Engineering
Kumoh National Institute of Technology
61 Daehak-ro, Gumi, Gyeongbuk
SOUTH KOREA
sunmyeng@kumoh.ac.kr

Abstract: - Underwater acoustic sensor networks (UASNs) have become a very active research area in recent years. Compared with wireless networks, UASNs have long propagation delay of acoustic signals, which pose challenges to the design of medium access control (MAC) protocol. Most of the studies on MAC protocols focus on contention-based techniques. They are subject to long propagation delays. The long delays cause spatial-temporal uncertainty making spatial fairness a difficult problem. In the contention based MAC protocols, it is hard to provide the fairness to channel access among senders since the packet arrival time at the receiver depends on the distance between the sender and the receiver. In this paper, we propose a fair MAC protocol to solve the unfairness problem. In the proposed protocol, the packets arrive at the receiver in the transmission order regardless of the distance between the sender and the receiver. That is, all senders have the same propagation delay time. To do this, each sender computes a deferment time when sending a packet and sends it after postponing for this amount of time. A sender with close distance from the receiver has long deferment time, and a distant sender has short deferment time. The proposed protocol addresses the unfairness problem by equalizing channel access probabilities of all senders regardless of the distance. Performance evaluation is conducted using simulation, and confirms that the proposed protocol outperforms the previous protocol in terms of the fairness index.

Key-Words: Channel Contention, Deferment Time, Fairness, MAC, Equalization, UASN

1 Introduction

Underwater acoustic sensor networks (UASNs) are a class of sensor networks deployed in underwater environments [1]. UASNs have attracted much attention in recent years due to their potential in various applications. There are significant differences between UASNs and wireless networks because of the unique features such as low available bandwidth, long propagation delay, and dynamic channels in acoustic modems. These features pose challenges to medium access control (MAC) protocol design [2], [3]. And, MAC protocols for wireless networks cannot be directly applied to UASNs because the work is based on high data rates and negligible propagation delays. Especially, carrier sense multiple access / collision avoidance (CSMA/CA) cannot prevent packet collisions well among nodes due to the long propagation delays in UASNs. Therefore, it is necessary to design new MAC protocols to take into account the different features.

Significant efforts have been devoted to the underwater MAC protocol design to overcome the negative effects introduced by the harsh underwater environments. MAC protocols for UASNs are classified into two categories: contention-free protocols and contention-based protocols. Contention-free protocols require a centralized coordinator which schedules nodes to determine their network access order. Contention-free protocols include TDMA, CDMA, and FDMA, and assign different time slots, codes, and frequencies to different nodes, respectively. Therefore, contention-free MAC protocols can transmit packets without collisions. Contention-based protocols are communication protocols that enable nodes to use the same channel without pre-coordinating. Contention occurs when two or more nodes attempt to access the channel at the same time. Contention causes packet collisions.

Most of MAC protocols for UASNs focus on the contention-based techniques since they facilitate an easy deployment on nodes. They use control packets such as Request-to-Send (RTS) and Clear-to-Send (CTS) to contend and reserve channel for data transmissions. Ng, et al. proposed a bidirectional-concurrent MAC (BiC–MAC) protocol based on concurrent, bidirectional data packet exchange to improve the data transmission efficiency [4]. In the BiC–MAC protocol, a sender-receiver node pair is allowed to transmit data packets to each other for every successful handshake. Noh, et al. proposed a delay-aware opportunistic transmission scheduling (DOTS) protocol [5]. In DOTS, each node learns neighboring nodes' propagation delay information and their expected transmission schedules by passively overhearing packet transmissions. And then, it makes transmission scheduling decisions to increase the chances of concurrent transmissions while reducing the likelihood of collisions. In Reference [6], the authors proposed a multiple access collision avoidance protocol for underwater (MACA-U) in which terrestrial MACA protocol was adapted for use in multi-hop UANs. In the MACA-U protocol, a source node transmits a RTS packet to a destination node after channel contention. After receiving the RTS packet, the destination node transmits a CTS packet. And then, the source node transmits its own data packet to the destination node. When other nodes receive the RTS or CTS packets, they set their timer and do not participate in the data packet transmission process. The cascading multi-hop reservation and transmission (CMRT) transmits multiple data packets together with only one handshaking signal to improve channel utilization by [7].

In [8], authors indicated the spatial-temporal uncertainty problem in underwater environment. It significantly decreases network performance of contention-based protocols. In [9], authors described that the long propagation delay of acoustic media causes spatial unfairness problem. Senders near the receiver occupy the channel quickly. On the contrast, other senders away from the receiver rarely occupy the channel.

SF-MAC in [10] and RET-MAC in [11] protocols were proposed to solve the spatial unfairness problem. They adopt the RTS/CTS handshaking method and are based on receiver. Both protocols determine the earliest sender of RTS packet and transmit CTS packet to it. When a receiver receives an RTS packet from a sender, the receiver delays the CTS packet for the RTS contention period (CP) time without sending it immediately to avoid collision caused by the spatial-temporal uncertainty. The RTS CP time begins when the receiver receives the first RTS packet. The receiver continues to receive RTS packets from other senders for the RTS CP time. At the end of the RTS CP time, the receiver determines which sender sent the RTS packet first among the senders.

In SF-MAC and RET-MAC protocol, the period of RTS CP time is long. It seriously affects network performance.

In this paper, we propose a fair MAC protocol called Channel Access Probability Equalization (CAPE) to solve the unfairness problem. In the proposed protocol, the packets arrive at the receiver in the transmission order regardless of the distance between the sender and the receiver. Because nodes near the receiver have a short propagation delay, the packets sent from the nodes arrive at the receiver quickly. To prevent this, the nodes are penalized by having an extra delay before the packets are sent. To do this, each sender computes an extra delay time when sending a packet and sends it after postponing for this amount of time. A sender with close distance from the receiver has long extra delay time, and a distant sender has short time. The proposed protocol addresses the unfairness problem by equalizing channel access probabilities of all senders regardless of the distance.

The paper is organized as follows. We discuss related work on MAC of UASNs in section 2. In section 3, the proposed CAPE MAC protocol is described in detail. In Section 4, performance studies are carried out through simulation results. Finally, we draw conclusions in section 5.

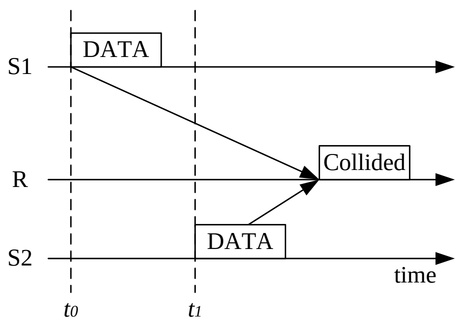
2 Related Work

In this section, we first discuss the spatial-temporal uncertainty and spatial unfairness problem. And then, we described the previous MAC protocols proposed to address the unfairness problem.

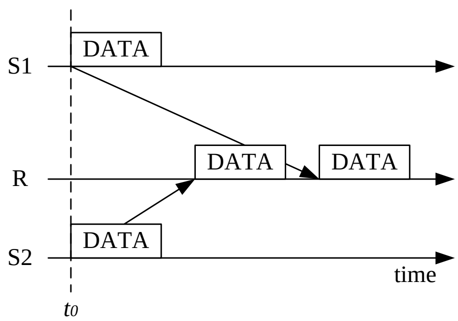
2.1 Spatial Unfairness Problem

Nodes in terrestrial wireless networks can estimate the channel status easily since the propagation delay is very short and negligible. However, in UASNs, it is essential to consider the location and transmission time of the node due to the long propagation delay of acoustic media [10]. Spatial-temporal uncertainty is defined as two-dimensional uncertainty in determining a collision at a receiver. The packet collision at the receiver depends on both the distance between the sender and receiver and the sender's transmission time. As the distance between the nodes increases, the current channel status cannot be clearly known due to the propagation delay. Even though nodes do not send packets at the same time, the packets may collide.

Fig. 1 shows an example of the spatial-temporal uncertainty. In Fig. 1, there are two senders (S1 and S2) and one receiver (R). In Fig. 1(a), two senders transmit their data packets at the same time. However, the receiver receives the packets at different time due to the different propagation delay. In another works, there are no collision at the receiver. On the other hand, two senders transmit their packets at the different time (see Fig. 1(b)). The packets arrive at the receiver at the same time and are collided.



(a) Different transmission time but collision at R



(b) Same transmission time, no collision at R

Fig. 1 Example of spatial-temporal uncertainty

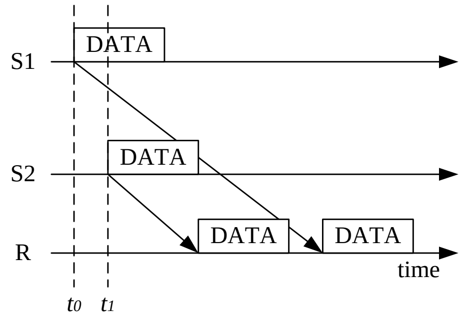


Fig. 2 Example of spatial unfairness problem

2.2 Spatial Unfairness Problem

In wireless networks, the node that sends a packet earlier gets the channel access right. However, the packet arrival time differs according to the distance from the receiver in UASNs. Therefore, the node that transmits first may not obtain the channel access right due to the propagation delay. The long propagation delay of acoustic media causes spatial unfairness problem. Nodes near the receiver occupy the channel easily. On the contrast, other nodes away from the receiver have very low channel occupancy probability.

Fig. 2 describes an example of the spatial unfairness problem. In Fig. 2, the sending time of the sender S1 is earlier than the sender S2. However, the receiver R receives the packet of S2 earlier than that of S1 since S1 has longer propagation delay than S2. Propagation delay of signal is proportional to the distance between sender and receiver.

2.3 Previous MAC Protocols

SF-MAC in [10] and RET-MAC in [11] protocols were proposed to solve the spatial unfairness problem. They adopt the RTS/CTS handshaking method and are based on receiver.

SF-MAC determines the earliest sender of RTS packet and transmit CTS packet to it. When a receiver receives an RTS packet from a sender, the receiver delays the CTS packet for the RTS contention period (CP) time without sending it immediately to avoid collision caused by the spatial-temporal uncertainty. The RTS CP time begins when the receiver receives the first RTS packet. The receiver continues to receive RTS packets from other senders for the RTS CP time. At the end of the RTS CP time, the receiver determines which sender sent the RTS packet first among the senders. SF-MAC protocol determines the earliest sender of RTS packet by probability rule.

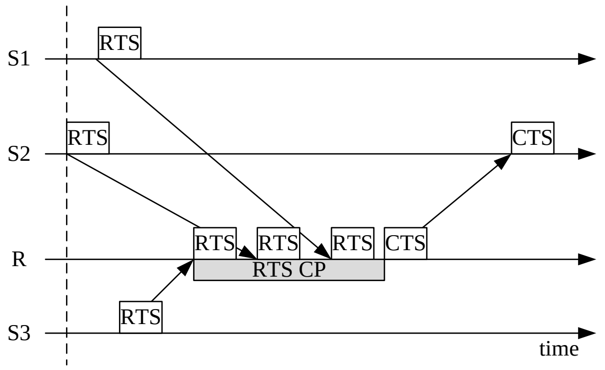


Fig. 3 Basic operation of SF-MAC protocol

Fig. 3 shows a basic operation of the SF-MAC protocol. In Fig. 3, there three senders (S1, S2, and S3) and one receiver (R). The receiver receives the first RTS packet from the sender S3 and starts its RTS CP time. It continues to receive RTS packets from the senders S1 and S2 during the RTS CP time. At the end of the RTS CP time, it determines that the sender S2 transmitted the RTS packet first, and then responds with a CTS packet to the sender S2. After receiving the CTS, the sender S2 transmits its data packet to the receiver R.

RET-MAC adopts adaptive RTS CP to determine the fastest sender of RTS packet. CTS delay phase (CTS DP) is also added to postpone CTS to avoid collisions. It also suggests a CTS backoff mechanism that adjusts the length of CTS DP as needed.

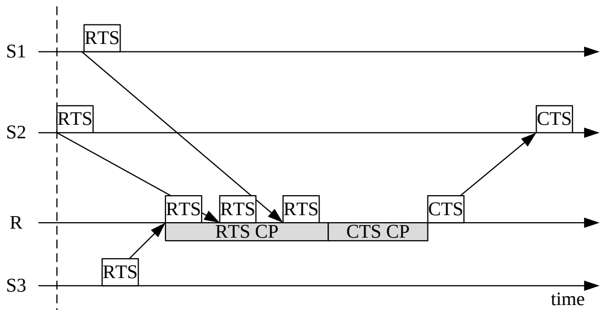


Fig. 4 Basic operation of RET-MAC protocol

Fig. 4 shows a basic operation of the RET-MAC protocol. The procedure to determine the fastest RTS packet during RTS CP in RET-MAC is the same as SF-MAC. Unlike SF-MAC, the RET-MAC does not transmit a CTS packet immediately after RTS CP termination. It postpones the CTS packet transmission during CTS CP time to avoid collisions. At the end of the CTS DP time, RET-MAC responds with a CTS packet to the sender S2. After receiving the CTS, the sender S2 transmits its data packet to the receiver R.

SF-MAC protocol determines the earliest sender of RTS packet by probability rule. RET-MAC protocol assumes that clocks are synchronized. In SF-MAC and RET-MAC protocol, the period of RTS CP time is long. It seriously affects network performance.

3 Proposed CAPE MAC Protocol

The proposed protocol uses the RTS/CTS handshaking method and is based on sender.

We use the distance between a sender and a receiver to equalize the channel access probability. We can obtain the distance by using the propagation delay and the speed of acoustic signal. Each node measures propagation delay with its receiver. Generally, the propagation delay is calculated by using round trip time (RTT). RTT is the time required for a packet to travel from a sender to a receiver and then back again. A node updates RTT measurements through the RTS/CTS packet exchange. RTT is calculated continuously as long as data is exchanged. A node computes the moving average of these measurements, referred to as SRTT (smoothed RTT). RTT_n is the RTT time during the nth packet transmission. $SRTT_n$ is as following:

$$SRTT_n = \alpha \cdot SRTT_{n-1} + (1-\alpha) \cdot RTT_n \quad (1)$$

where, $SRTT_{n\text{-}1}$ is the average RTT at the end of the (n-1)th packet transmission, and α is a smoothing factor in the range of [0, 1].

The propagation delay (PD) is half of the SRTT value. PD is as following:

$$PD = \frac{SRTT}{2} \quad (2)$$

After calculating the propagation delay, a node converts the propagation delay to the distance (*DIS*) as following:

$$DIS = \frac{PD}{v}$$
(3)

where, v is the sound speed and is 1,500 m/s.

A node transmits a data packet including the distance. Fig. 5 shows the data packet format used in the proposed protocol. Unlike the general format, we add a distance field.

Frame Control	Duration ID	Sender Address	Receiver Address	Distance	Frame Body	FCS

Fig. 5 Data packet format

As shown in Fig. 6, each node maintains a distance table, referred to as *DisTable*. The distance table contains 3 fields. The first field is MAC address of a sender ongoing packets. In thhe distance field, distance between a sender and a receiver is stored. In the time filed, time of the last packet received from the sender is recorded. If there is no new packet received for a certain period of time, then information on the relevant node is deleted.

MAC Address of Sender	Distance	Time
S_1	DIS_1	T_1
...	...	...
S_n	DIS_n	T_n

Fig. 6 Format of the distance table

In the proposed protocol, the packets arrive at the receiver in the transmission order regardless of the distance between the sender and the receiver. Because nodes near the receiver have a short propagation delay, the packets sent from the nodes arrive at the receiver quickly. To prevent this, the near nodes are penalized by having an extra delay, referred to as Deferment Time, before the packets are sent. To do this, each sender computes the deferment time when sending a packet and sends it after postponing for this amount of time. A sender with close distance from the receiver has long deferment time, and a distant sender has short deferment time. Therefore, the proposed protocol equalizes the channel access probabilities of all senders regardless of the distance.

In order for all nodes to have the same channel access probability, all nodes must have the same propagation delay time. To do this, a node has a delay time equal to the difference between the propagation delay time of the node farthest to the receiver and its own propagation delay time.

When a node i has a data packet to send, it first finds the node k with the greatest distance in the distance table as following:

$$max_{k \in V} \{DIS_k\}$$
(4)

where, V indicates the set of nodes in the distance table.

And then, the node i calculates the distance difference (*Diff*) between itself and the node k as following:

$$Diff = DIS_k - DIS_i$$
(5)

The node i converts the distance difference to the deferment time (*DFT*) by multiplying the distance difference by the speed of acoustic signal v.

$$DFT = Diff \times v$$
(6)

After obtainig the deferment time, the node i waits for this amount of time. And then it starts its backoff procedure. When the backoff procedure finishes, it transmits a RTS packet to a receiver. The subsequent procedure is the same as RTS / CTS / DATA / ACK handshaking.

Fig. 7 shows an example of equalizing the channel access probability in the CAPE protocol. There are 4 nodes: one receiver (R) and three senders (S1, S2, and S3). Every node is within the transmission range of each other. Node S1 is closest to receiver R and node S3 is farthest away. Each node calculates the distance difference by using Eq. (5) and its deferment time by using Eq. (6).

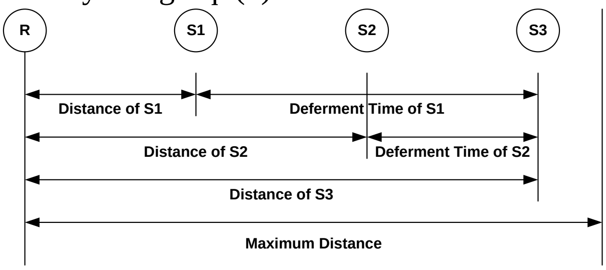


Fig. 7 Example of equalizing the channel access probability in the CAPE protocol

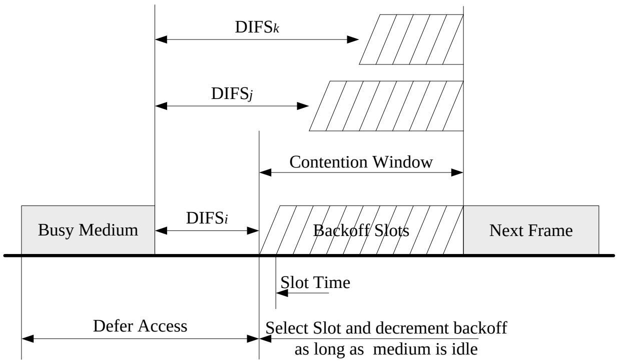


Fig. 8 DIFS relationships in CAPE protocol

The method of applying calculated deferment time is slightly different according to the operation of contention based MAC Protocols.

In CSMA based protocols, if the medium is sensed to be free for a DIFS time interval, a sender begins its backoff process. If the medium is busy, the sender defers its backoff process until the end of the current transmission and then it waits an additional DIFS interval. If the backoff counter reaches zero, the sender transmits an RTS packet to the receiver. The previous protocols use a fixed DIFS value as following:

$$\text{DIFS} = SIFS + (2 * aSlotTime) \quad (7)$$

where, *SIFS* is a short interframe space and *aSlotTime* is the duration of a slot time.

In the proposed CAPE protocol, the DIFS value is dynamically set according to the deferment time. The new DIFS value ($DIFS_i$) for the proposed protocol is calculated as following:

$$DIFS_i = \text{DIFS} + SN_i * aSlotTime \quad (8)$$

where, SN_i is a value obtained by changing the deferment time in slot time unit. It is calculated as following:

$$SN_i = \begin{cases} 0, & if\ DFT_i < aSlotTime \\ \lfloor DFT_i / aSlotTime \rfloor, & else \end{cases} \quad (9)$$

where, $\lfloor x \rfloor$ rounds to the largest integer smaller than or equal to x.

Fig. 8 shows DIFS relationships in the proposed CAPE protocol. Senders close to the receiver have large DIFS values, and distant senders have small DIFS values.

4 Simulation Results

In this section, we analyze simulation results of the proposed CAPE protocol. To study the performance of the CAPE protocol, we actually implemented the protocol in NS3. Performance of the CAPE protocol is compared with that of the MACA-U protocol.

The system parameters used in the simulation are listed in Table 1. We simulated a with a maximum data rate of 1,500 bps. The length of control packets such as RTS, CTS, and ACK is 40 bits. A constant data packet size of 256 bits was used. Sound speed is 1500m/s. The maximum transmission range (*TRmax*) is 1,500m.

To generate data packets, we used the saturated traffic model. In this model, queues of every node are always full of data packets.

Table 1. Simulation parameters

Parameter	Value
RTS	40 bits
CTS	40 bits
DATA	256 bits
ACK	40 bits
Slot Time	1500 ms
SIFS	200 ms
DIFS	3200 ms
Data Rate	1500 bps
Sound Speed	1500 m/s
CWmin	10
CWmax	40
Step Size	10

TRmax	1500 m

In the simulation, we consider the topology in which there are several sender nodes and one receiver node. The source nodes have data packets to send to the receiver node. The receiver node has no data packets to send. All sender nodes are deployed in a 2-D area of 1500m * 1500m. They are able to hear each other. The receiver node is placed at the point (0, 0). Source nodes are randomly distributed in the topology.

The main performance metrics of interest are throughput, end-to-end delay, and fairness index. The end-to-end delay is the time between a data packet arrival at the queue of a sender node and the successful data packet transmission to the receiver node. The Fairness index (*FI*) is a criterion showing how fair the nodes are. It is defined as following [12]:

$$FI = \frac{\left(\sum_{i=1}^{n} S_i\right)^2}{n \times \left(\sum_{i=1}^{n} S_i^{\,2}\right)} \quad (10)$$

where, n is the number of senders and S_i is throughput of node i. Ideally, if the channel access time is evenly distributed to all nodes, the fairness index is one.

Fig. 9 shows the change of fairness indices as the number of nodes increases. In the both CAPE and MACA-U protocols, fairness index gets lower as the number of nodes becomes larger. However, the proposed CAPE protocol always achieves better fairness than the MACA-U protocol regardless of the number of nodes. In the CAPE protocol, a node has an extra delay time equal to the difference between the propagation delay time of the node farthest to the receiver and its own propagation delay time. Therefore, all nodes have the same channel access probability. However, in the MACA-U protocol, senders near the receiver occupy the channel quickly, and other senders away from the receiver rarely occupy the channel. Consequently, the MACA-U protocol has low fairness index.

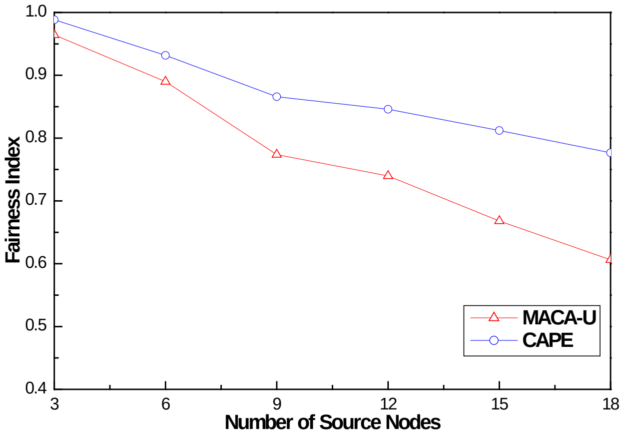


Fig. 9 Fairness index according to the number of nodes

Figs. 10 and 11 show the effect of the number nodes on delay and throughput, respectively. The proposed CAPE protocol has low throughput and delay than the MACA-U protocol. This is because the CAPE protocol waits an extra delay time before sending packets. This causes longer delay and low throughput compared to the MACA-U protocol. However, they are not so serious.

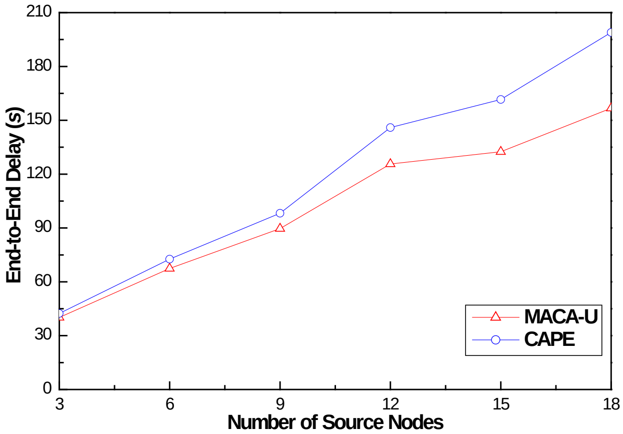


Fig. 10 Delay according to the number of nodes

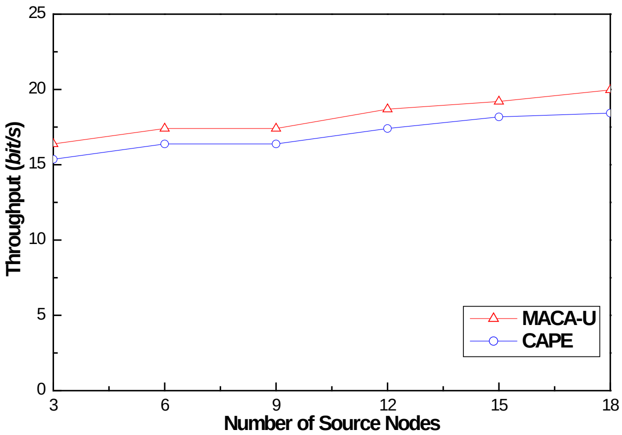


Fig. 11 Throughput according to the number of nodes

5 Conclusion

UASNs have long propagation delay of acoustic signals. Therefore, there is a spatial unfairness problem caused by spatial-temporal uncertainty. In this paper, we proposed a new MAC protocol to solve the unfairness problem. In the proposed protocol, each sender computes a deferment time when sending a packet and sends it after postponing for this amount of time. Therefore, packets arrive at the receiver in the transmission order regardless of the distance between the sender and the receiver. The proposed protocol addresses the unfairness problem by equalizing channel access probabilities of all senders. Performance evaluation is conducted using simulation, and confirms that the proposed protocol outperforms the previous protocol in terms of the fairness index.

Acknowledgments

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2015R1D1A1A01059644).

References:

[1] P. Casari and M. Zorzi, Protocol Design Issues in Underwater Acoustic Networks, *Computer Communications*, Vol. 34, No. 17, 2011, pp. 2013-2025.

[2] Y. Zhu, Z. Peng, J.-H. Cui, and H. Chen, Toward Practical MAC Design for Underwater Acoustic Networks, *IEEE Transactions on Mobile Computing*, Vol. 14, No. 4, 2015, pp. 872-886.

[3] L. Pu, Y. Luo, H. Mo, S. Le, Z. Peng, J.-H. Cui, and Z. Jiang, Comparing Underwater MAC Protocols in Real Sea Experiments, *Computer Communications*, Vol. 56, 2015, pp. 47-59.

[4] H.-H. Ng, W.-S. Soh, and M. Motani, A Bidirectional-Concurrent MAC Protocol with Packet Bursting for Underwater Acoustic Networks, *IEEE Journal of Oceanic Engineering*, Vol. 38, No. 3, 2013, pp. 547-565.

[5] Y. Noh, U. Lee, S. Han, P. Wang, D. Torres, J. Kim, and M. Gerla, DOTS: A Propagation Delay-Aware Opportunistic MAC Protocol for Mobile Underwater networks, *IEEE Transactions on Mobile Computing*, Vol. 13, No. 4, 2014, pp. 766-782.

[6] H.-H. Ng, W.-S. Soh, and M. Motani, MACA-U: A Media Access Protocol for Underwater Acoustic Networks, *IEEE Globecom 2008*, 2008, pp. 1-5.

[7] J.-W. Lee and H.-S. Cho, Cascading Multi-hop Reservation and Transmission in Underwater Acoustic Sensor Networks, *Sensors*, Vol. 14, 2014, pp. 18390-18409.

[8] C.-C. Hsu, M.-S. Kuo, C.-F. Chou, and K. C.-J. Lin, The Elimination of Spatial-Temporal Uncertainty in Underwater Sensor Networks, *IEEE/ACM Transactions on Networking*, Vol. 21, No. 4, 2013, pp. 1229-122.

[9] 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, 2008, pp. 1731-1743.

[10] W. H. Liao, C. C. Huang, SF-MAC: A Spatially Fair MAC Protocol for Underwater Acoustic Sensor Networks, *IEEE Sensors Journal*, Vol. 12, No. 6, 2012, pp. 1686-1694.

[11] S.-M. Xiong, C. Yuan, L. Tian, and Y. Zhan, RET-MAC: A New Fair MAC Protocol for Underwater Acoustic Sensor Network, *International Journal of Distributed Sensor Networks*, Vol. 9, No. 6, 2013.

[12] 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.