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Multi-Channel MAC Protocol based on Dynamic Time Slot Allocation for Underwater Sensor Networks

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ABSTRACT

The underwater sensor networks (USNs) are becoming increasingly important in ocean exploration. Compared with wireless networks, USNs have long propagation delay of acoustic signals, which pose challenges to the design of medium access control (MAC) protocol and degrade network performance. In order to improve network performance, EM-MC MAC protocol was proposed. The EM-MC protocol uses a single electromagnetic (EM) channel to reserve data transmissions, and acoustic channels to transmit data packets. The EM-MC protocol does not work well in environments where node configurations change dynamically because the number of time slots to reserve data transmissions on the EM channel is fixed. To solve this problem, we propose a new MAC protocol, which allocates time slots dynamically according to node configurations. In the proposed protocol, time is divided into superframes. Time slots are allocated to each sensor node based on the node configuration at the start time of each superframe. Performance evaluation is conducted using simulation, and confirms that the proposed protocol outperforms the previous protocol in terms of throughput.

Key words : Acoustic Channel, Dynamic Time Slot, EM Channel, MAC, USN.

1. INTRODUCTION

Underwater sensor networks (USNs) are a class of sensor networks deployed in underwater environments [1]. USNs have attracted much attention in recent years due to their potential in various applications. Underwater communications are implemented using communication systems based on acoustic waves and electromagnetic (EM) waves [2]. EM waves are rapidly attenuated in seawater, seriously limiting the range of possible transmissions [3]. Given the difficulty of underwater communication via EM waves, acoustic waves have been widely adopted [4].

There are significant differences between USNs 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 [5-7]. MAC protocols for wireless networks cannot be directly applied to USNs because the work is based on high data rates and negligible propagation delays. Especially, carrier sense multiple access / collision avoidance (CSMA/CA) [8] cannot prevent packet collisions well among sensor nodes due to the long propagation delays in USNs. 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 [6,7,9]. MAC protocols for USNs are classified into two categories: contention-free protocols and contention-based protocols. Contention-free protocols require a centralized coordinator which schedules sensor 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 sensor nodes, respectively. Therefore, contention-free MAC protocols can transmit packets without collisions. Contention-based protocols are communication protocols that enable sensor nodes to use the same channel without pre-coordinating. Contention occurs when two or more sensor nodes attempt to access the channel at the same time. Contention causes packet collisions.

Most of MAC protocols for USNs focus on the contention-based techniques since they facilitate an easy deployment on sensor 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 [10]. 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

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opportunistic transmission scheduling (DOTS) protocol [11]. In DOTS, each sensor node learns neighboring sensor 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 collision probability. In Reference [12], 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 USNs. In the MACA-U protocol, a source sensor node transmits a RTS packet to a destination sensor node after channel contention. After receiving the RTS packet, the destination sensor node transmits a CTS packet. And then, the source sensor node transmits its own data packet to the destination sensor node. When other sensor nodes receive the RTS or CTS packets, they set their timer and do not participate in the data packet transmission process.

Due to the limitations of the low bandwidth and low data rate of acoustic waves, research using low frequency EM waves has been carried out. With propagation velocity, EM waves offer many advantages including bandwidth, data rate and better transmission [13]. The authors in [13] studied the feasibility of using EM waves in an underwater communication system. The authors in [4, 14] showed that EM communication in underwater environments is both feasible and effective for a specific set of applications.

In order to utilize both EM and acoustic waves at the same time for developing MAC protocol in USNs, EM-MC (EM controlled Multi-Channel) MAC protocol was proposed [15]. The EM-MC protocol uses a single EM channel and acoustic channels. The EM channel is used for transmitting control packets and the acoustic channels are used for transmitting data packets. The EM channel is based on TDMA to avoid collisions. The EM-MC protocol does not work well in environments where node configurations change dynamically because the number of time slots on the EM channel is fixed.

To solve this problem, we propose a new MC-DTSA MAC protocol, which allocates time slots dynamically according to node configurations. In the proposed protocol, time is divided into superframes. Time slots are allocated to each sensor node based on the node configuration at the start time of each superframe.

This paper is organized as follows. In section 2, we briefly describe related work. In section 3, the proposed MC-DTSA (Multi-Channel based on Dynamic Time Slot Allocation) protocol is presented in detail. In section 4, performance studies are carried out through simulation results. Finally, we draw conclusion in section 5.

2. RELATED WORK

In this section, we first discuss the architectures of USNs. And then, we describe the previous EM-MC MAC protocol, which combines the advantages of both acoustic and EM waves.

2.1 Architectures of USNs

Figure 1 shows an example topology of USNs. An underwater sensor network consists of a surface buoy, on-shore data center and sensor nodes. Sensor nodes collect data and transmit them to the surface buoy. The surface buoy forwards them to the on-shore data center. The surface buoy includes an antenna for RF transmission.

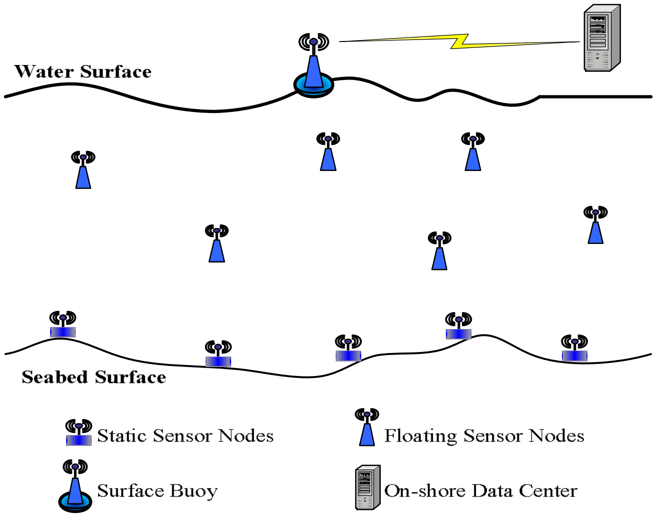


Figure 1: Illustration of a Generic Topology of USNs

Different possible architectures of USNs can be classified based on two principles: mobility of the sensor nodes and channel [2]. Based on these two principles, Figure 2 summarizes the possible architectures for USNs.

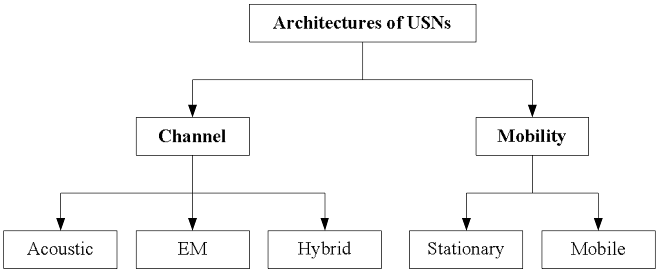


Figure 2: Architectures of USNs [2]

Current technologies for underwater communication include acoustic waves or EM waves [14]. Both of these technologies have advantages and limitations. Acoustic waves are a proven technology in underwater sensor applications, and provide a long range of up to 20 km, although limitations have been identified [2]. Acoustic waves have poor performance. Unlike acoustic waves, EM waves are more resistant to turbulence and turbidity effects in water, so they can provide fast propagation speed [2]. EM waves undergo severe attenuation in seawater and seriously limit possible transmission range. USNs consist of static sensor nodes and floating sensor nodes. The sensor nodes are fixed on the seabed, or floated using floating equipment. Static sensor nodes are immovable sensor nodes that operates in a fixed location. Floating sensor nodes move due to water currents [16].

2.2 Previous EM-MC MAC Protocol

The EM-MC protocol considers a single hop topology where all stations are in the transmission range of one another. Sensor nodes are static.

The EM-MC protocol uses a single EM channel and acoustic channels. The EM channel is used for transmitting control packets and the acoustic channels are used for transmitting data packets. The EM channel is based on TDMA to avoid collisions.

In the EM channel, time is divided into frames. Each frame has one slot per sensor node and one slot per acoustic channel. The number of slots in a frame (N) as follows;

$$N = n_c + n_d \tag{1}$$

where, n_c and n_d are the number of sensor nodes and the number of acoustic channels, respectively.

Each sensor node is allocated one slot. When a sensor node has a data packet to send, it transmits a request packet at its own slot to reserve an acoustic channel. It then transmits a data packet over an acoustic channel that is not occupied by another node. A receiving sensor node transmits a confirmation packet at the slot for the acoustic channel after receiving the data packet successfully.

3. PROPOSED MC-DTSA PROTOCOL

The EM-MC protocol does not work well in environments where node configurations change dynamically because the number of time slots on the EM channel is fixed.

Due to ocean currents, sensor nodes may move in typical underwater environments. Therefore, MAC protocols designed without consideration of the mobility of sensor nodes cannot have optimal performance.

In order to solve the problem of the EM-MC protocol, we propose a new MC-DTSA MAC protocol, which allocates time slots dynamically according to node configurations.

In this section, we present our proposed MC-DTSA protocol. Although the proposed MC-DTSA protocol has the similar procedure of exchanging packets to that of the EM-MC protocol, it uses a different method in allocating time slots.

The proposed MC-DTSA protocol uses two types of channels: single EM channel and n_d acoustic channels. Sensor nodes send and receive control packets over the EM channel, and data packets over the acoustic channels.

In the proposed protocol, EM channel time is divided into superframes (see Figure 3). Superframes are divided into one beacon and frames. A frame consists of reservation period and confirmation period. The periods are divided into time slots. Each sensor node is allocated one slot in the reservation period. In the confirmation period, a time slot is allocated to each acoustic channel.

Beacon is a management packet in the proposed MC-DTSA protocol. It contains all the information about the network. Beacon packets are transmitted periodically at the start of each superframe. Each beacon packet carries the following information in the body: 1) Beacon interval: This represents the amount of time between beacon transmissions. 2) The number of frames in a superframe. 3) The number of time slots in a reservation period. 4) MAC addresses of sensor nodes to which time slots are allocated in a reservation period.

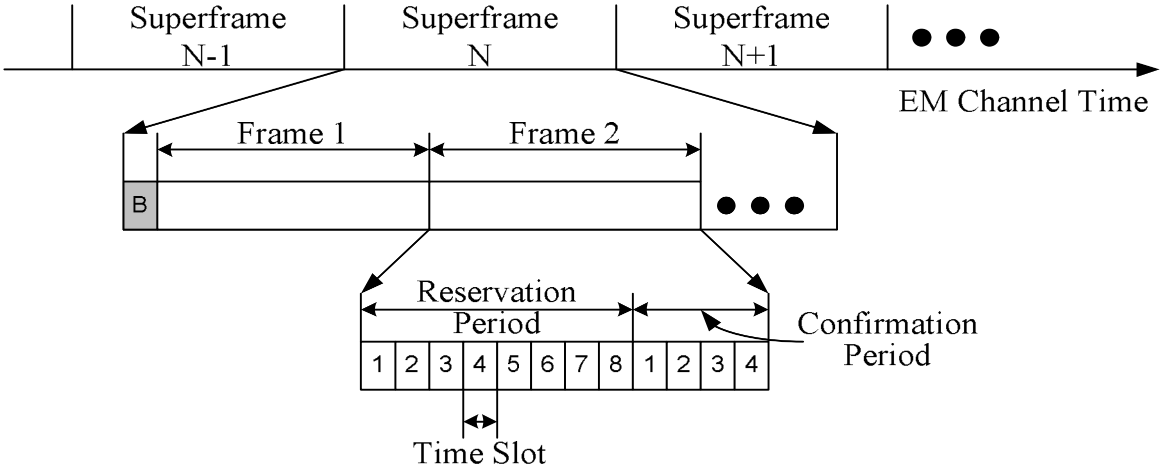


Figure 3: Superframe Structure

5) The number of time slots in a confirmation period. 6) Acoustic channel numbers to which time slots are allocated in a confirmation period.

In a reservation period, sensor nodes transmit request packets at their time slots when they have data packets to send. In a confirmation period, time slots are used to indicate that receiving sensor nodes have successfully received data packets.

Each sensor node maintains a FIFO (First-In-First-Out) queue and a data channel table. When a sensor node has a data packet to send, it transmits a request packet at its own time slot in a reservation period. After receiving the request packet, neighbor sensor nodes and the sending sensor node insert the MAC address of the sending sensor node at the rear of the queue. When there are idle acoustic channels, they remove the MAC address at the front from the queue. And the sending sensor node transmits its own data packet on the idle acoustic channel.

ID	Status	TX Time
1	busy	T1
2	busy	T2
3	idle	
...	...	...
n	idle	

Figure 4: Data Channel Table

The data channel table contains 3 fields (see Figure 4). The first field is ID of acoustic channels. The status field indicates whether an acoustic channel is idle or busy. Neighbor sensor nodes listening on the acoustic channel change their status to busy. And they change their status to idle after receiving confirmation packets from receiving sensor nodes or the TX time expires. The TX time field represents how long the sending sensor node intends to hold the acoustic channel busy. A data packet header contains a duration time that specifies the transmission time required for the packet. Neighbor sensor nodes listening on the acoustic channel read the duration time and set their TX time in the data channel table, which is an indicator for a sensor node on how long it must defer from accessing the channel. TX time is calculated as follows;

$$\mathit{TX\ Time} = \mathit{Duration\ Time} + \mathit{Tcon} \tag{2}$$

where, *Tcon* is the difference between the end time of the data packet transmission and the end time of the corresponding time slot in a confirmation period.

Figure 5 shows an example of TX time. A data packet is being transmitted on the acoustic channel 2. The receiving sensor node sends a confirmation packet at the time slot 2 in confirmation period.

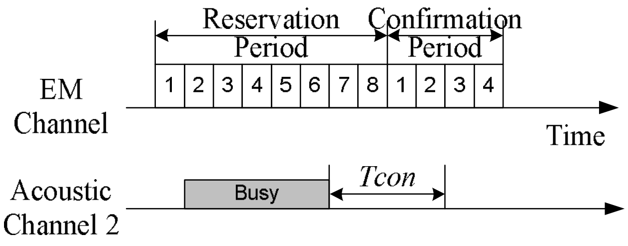


Figure 5: Example of TX Time

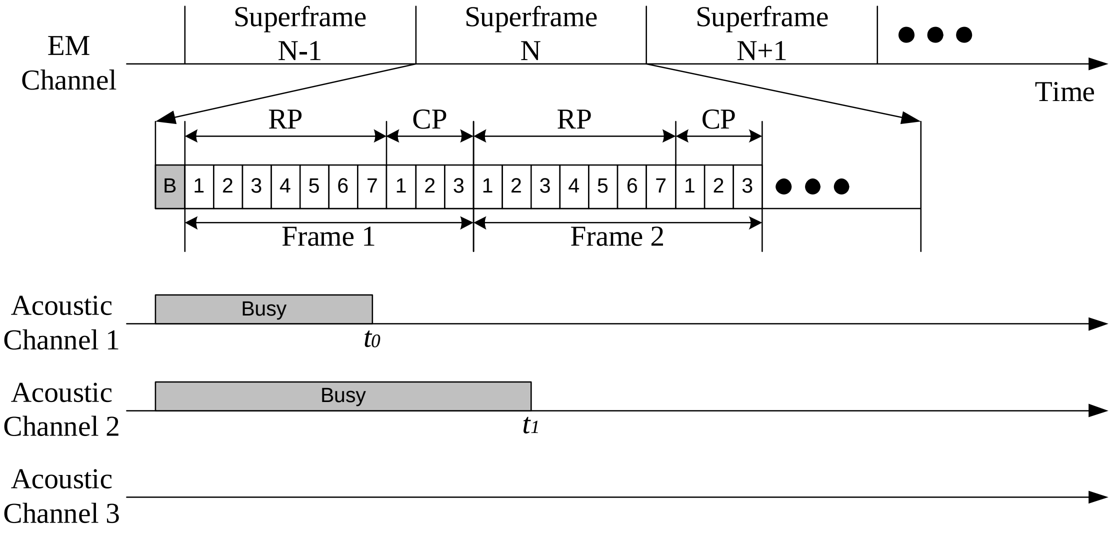
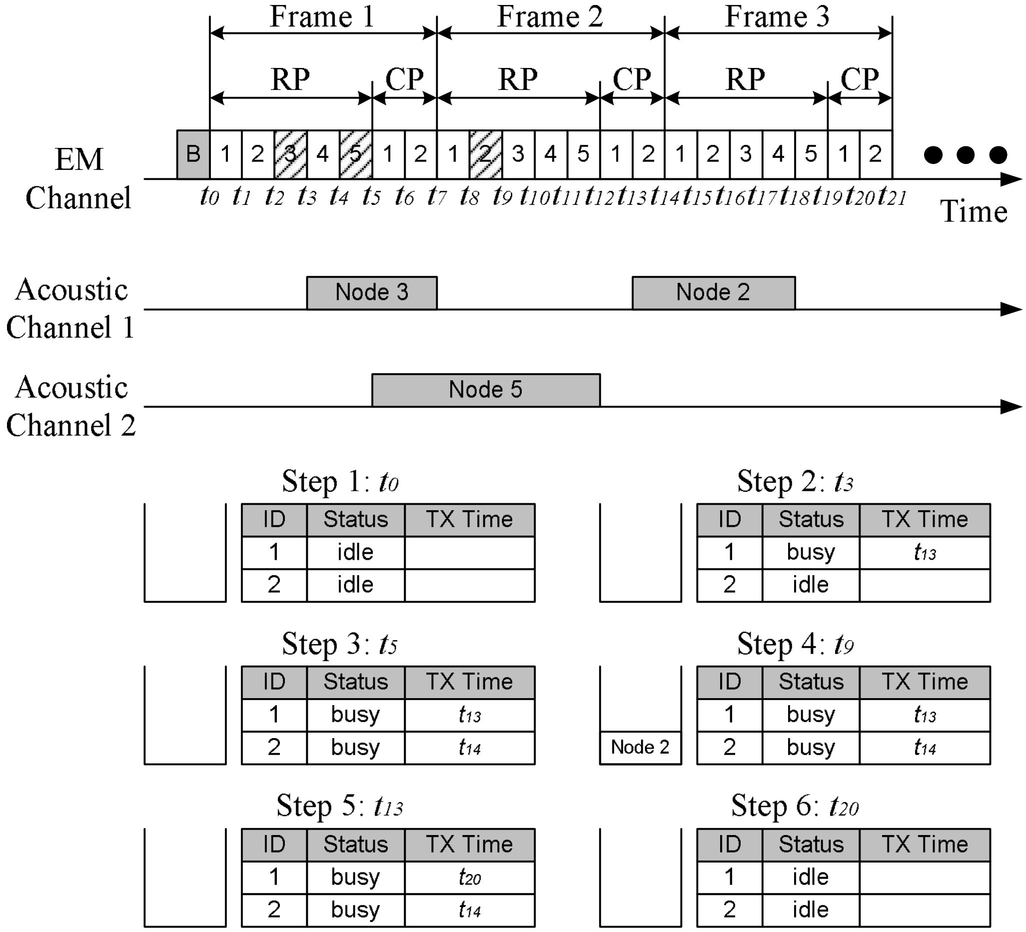


Figure 6: Example of Available Time Slots in Confirmation Period

Here, we describe how to dynamically allocate time slots in a reservation period according to node configurations.

Sensor nodes included in superframe N depend on activity during previous superframe N-1. If a sensor node included in superframe N-1 never transmits request packets, then it is not included in superframe N. If a sensor node not included in superframe N-1 wants to be included in superframe N, it sends an addition packet at a time slot in a confirmation period. To do this, the sensor node first determines when to transmit an addition packet. The sensor node transmits an addition packet at a time slot not used by receiving sensor nodes among the time slots in a confirmation period.

Figure 6 shows an example of available time slots in confirmation period. There are three acoustic channels. Data packets are being transmitted on the acoustic channels 1 and 2. A data packet on the acoustic channel 1 ends at t_0. And the corresponding receiving sensor node sends a confirmation packet at time slot 1 in a confirmation period in Frame 1. A data packet on the acoustic channel 2 ends at t_1. And the corresponding receiving sensor node does not send a confirmation packet at time slot 2 in a confirmation period in Frame 1. No one sends at time slot 3 since there is no data transmission on the acoustic channel 3. Therefore, time slots 2 and 3 are available. Consequently, a sensor node randomly chooses a time slot among the available time slots, and transmits an addition packet at the selected time slot. In Frame 2, the corresponding receiving sensor node sends a confirmation packet at time slot 2 in a confirmation period. Time slots 1 and 3 are available.



Step 1: t_0

ID	Status	TX Time
1	idle	
2	idle	

Step 2: t_3

ID	Status	TX Time
1	busy	t_{13}
2	idle	

Step 3: t_5

ID	Status	TX Time
1	busy	t_{13}
2	busy	t_{14}

Step 4: t_9

ID	Status	TX Time
1	busy	t_{13}
2	busy	t_{14}

Step 5: t_{13}

ID	Status	TX Time
1	busy	t_{20}
2	busy	t_{14}

Step 6: t_{20}

ID	Status	TX Time
1	idle	
2	idle	

Figure 7: Example of Data Packet Transmissions in MC-DTSA Protocol

Figure 7 shows an example of data packet transmissions in the proposed MC-DTSA protocol. There are a single EM channel and two acoustic channels. There are 5 sensor nodes. Every sensor node is assigned a time slot in a reservation period. In step 1 at time t0, there are no sensor nodes transmitting request packets or data packets. Therefore, the FIFO queue is empty and the status of every acoustic channel in the data channel table is idle. At time t2, sensor node 3 transmits a request packet, which ends at time t4. Sensor node 3 and its neighbor sensor nodes 1, 2, 4, and 5 insert the MAC address of sensor node 3 at the rear of the queue. Since every acoustic channel is idle, all the sensor nodes immediately remove the MAC address of sensor node 3 at the front from the queue. Sensor node 3 transmits its own data packet on the idle acoustic channel 1 (see step 2 at time t3). The TX time of the acoustic channel 1 is set to t13. At time t4, sensor node 5 transmits a request packet, and all the sensor nodes insert the MAC address of sensor node 5 at the rear of the queue at time t5. Since the acoustic channel 2 is idle, all the sensor nodes immediately remove the MAC address of sensor node 5 at the front from the queue. Sensor node 5 transmits its own data packet on the idle acoustic channel 2 (see step 3 at time t5). At time t8, sensor node 2 transmits a request packet and all the sensor nodes insert the MAC address of sensor node 2 at the rear of the queue at time t9. Since all the acoustic channels are busy, no sensor nodes remove the MAC address of sensor node 2 at the front from the queue (see step 4 at time t9). At time t12, receiving sensor node on the acoustic channel 1 transmits a confirmation packet, and every node changes the status of the acoustic channel 1 to idle at time 13. Therefore, sensor node 2 transmits a data packet at time 13. The status of the acoustic channel 1 becomes busy again (see step 5 at time t13). At time t13, receiving sensor node on the acoustic channel 2 transmits a confirmation packet, and every node changes the status of the acoustic channel 2 to idle at time 14. At time t20, every transmission ends, the queue is empty, and the status of the acoustic channels is idle (see step 6 at time t20).

4. SIMULATION RESULTS

In this section, we analyze simulation results of the proposed MC-DTSA protocol. To study the performance of the MC-DTSA protocol, we actually implemented the protocol. Performance of the MC-DTSA protocol is compared with that of the EM-MC protocol. In the simulation, there are one EM channel and two acoustic channels. We simulated a with a maximum data rate of 2,400 bps. Each sensor node generates data packets with the probability of 10%.

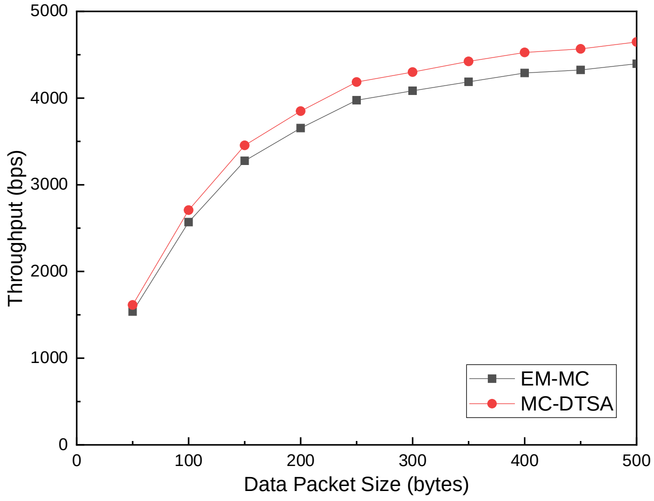


Figure 8: Throughput according to the data packet size

Figure 8 shows the results for the throughput according to the data packet size. There are 5 sensor nodes. From the figure, we can see that in the EM-MC and MC-DTSA protocols, the throughput increases as the data packet size is larger. The proposed MC-DTSA protocol always shows better performance than the EM-MC protocol. In the MC-DTSA protocol, if a sensor node does not transmit any request packet during a superframe, it is not allocated a time slot in the reservation period in the next superframe. When a sensor node has a data packet to send, it can be allocated a time slot through transmitting an addition packet. The proposed MC-DTSA protocol dynamically determines the number of time slots in a reservation period and assigns time slots to sensor nodes. However, the EM-MC protocol has a fixed number of time slots. The MC-DTSA protocol reduces the number of unnecessary time slots in a reservation period and allows the data packets to be transmitted more quickly compared to the EM-MC protocol. Therefore, the MC-DTSA protocol has a better performance.

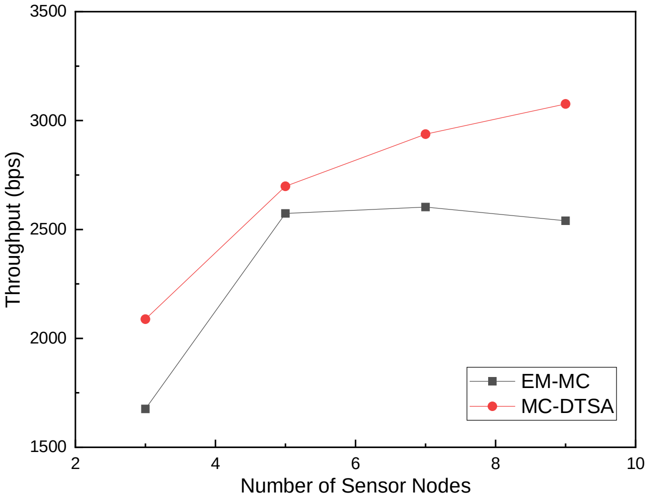


Figure 9: Throughput according to the number of sensor nodes

Figure 9 shows the results for the throughput according to the number of sensor nodes. Initially, there are 5 sensor nodes. Due to ocean currents, sensor nodes may move in underwater environments. Therefore, the number of sensor nodes continues to change dynamically. The EM-MC protocol always assigns 5 time slots for fixed 5 sensor nodes. The MC-DTSA protocol allocates time slots dynamically according to node configurations. Consequently, the MC-DTSA protocol always has higher performance.

5. CONCLUSION

In order to utilize both EM and acoustic waves at the same time for developing MAC protocol in USNs, the EM-MC MAC protocol was proposed. The EM-MC protocol uses a single electromagnetic (EM) channel to reserve data transmissions, and acoustic channels to transmit data. The EM-MC protocol does not work well in environments where node configurations change dynamically because the number of time slots in the EM channel is fixed. To solve this problem, we proposed the MC-DTSA protocol, which allocates time slots dynamically according to node configurations. Simulation result shows that the proposed MC-DTSA protocol significantly outperforms the previous protocol.

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