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An Adaptive Slot TDMA MAC Protocol for Underwater Sensor Networks

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Abstract

In this study, we introduce a new media access control (MAC) protocol that adaptively changes time division multiple access (TDMA) frame size and slot duration in order to upgrade performance of underwater sensor networks. Throughput of underwater sensor networks is very low compared to a radio frequency (RF) network; the reason is a very long propagation delay and a very low bit rate. To solve these problems, we modified the TDMA protocol and introduce a new TDMA MAC protocol (aTDMA). Basically, the TDMA MAC protocol provides a time slot to each node, and the node transmits data in the allocated time slot so transmission does not collide with another node's transmission. But if a node has no data, it wastes its slot. For the propagation delay in underwater acoustic sensor networks, the length of each slot is very long, so the waste of a slot can cause a serious reduction in performance. The proposed protocol, aTDMA, can remove the wasting of slot times and can change slot duration according to the distance between nodes. Through experiments, aTDMA shows better performance than the conventional TDMA MAC protocol.

Keywords*: Underwater, MAC Protocol, TDMA, Slot Time, Reservation*

1. Introduction

The underwater sensor network (USN) has attracted a great deal of interest over the last few years, due to its variety applications in science and commercial exploration, for coast guards, and for the prediction of natural disasters [1-3]. In the underwater environment, a radio frequency (RF) is seriously attenuated because of the water's conductivity, so audio has proven to be the only way to go in long-distance communications [4]. However, underwater acoustic communications has the following problems: (A) limited bandwidth: a 40kbps modem, at most, is being used; (B) long propagation: the acoustic wave's speed is only 1500m/s, which is 2x105 times slower than an RF signal; and (C) very high energy consumption: most commercial acoustic modems are driven by a battery that after a few days, must be recharged. The problems with underwater acoustic communications have been the driving force for promoting media access control (MAC) protocol design.

Many kinds of MAC protocols have been proposed over the past few years, and they can be divided into three types: random access [5-6], reservation-based [7-9], and schedule-based [10]. A reservation-based protocol in slotted FAMA [7] was proposed in order to achieve high throughput with a high data load [11]. Reserving a slot via control packet exchange avoids collisions between packets to achieve a high throughput. However, by assuming a high data load, most of the nodes are expected to participate in transmission, which is not a realistic assumption in an actual underwater sensor network [7]. When some nodes participating in the sensor network have no transmission data, wasting the time slots assigned to the nodes decreases network throughput.

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When we try to increase the throughput of an underwater sensor network, the data generation rate also plays an important role. A low data-generation rate is connected to low throughput. Therefore, it is important to support the ability to intensively transmit data from a node where data is generated. In this study, by not using a slot for a node that has no transmission data, another node gets a chance to transfer data at high speed. Due to the long propagation delay, it is very important to prevent wasting slot times, which are longer in a USN. Therefore, a node from which data transmission is not expected, broadcasts a beacon signal for concessions on its slot. A node that has not conceded the slot after a predetermined time has elapsed may use its own slot again.

Long propagation delay in a USN makes a longer time period for a slot in the frame, and as a result, frame size is longer and longer if the distance between nodes in the network is greater. A time slot consists of both time of transmission and propagation, in order to prevent frame collision. Long propagation delay introduces a long slot duration in the USN, but propagation delay is determined by the maximum distance of the network. Traffic generated by a certain node is transmitted to the destination node, but the distance between both nodes is generally smaller than the maximum. We could shrink the time period of the slot in the frame by adaptively changing the distance of the sender and receiver nodes so we get a smaller frame size and better performance.

The remaining structure of the paper is as follows. In Section 2, we look briefly at MAC protocols in the underwater sensor network. In Sections 3 and 4, the aTDMA structure and concept, the results of simulations, and the calculated performance are described. Finally, we present the conclusions in Section 5.

2. Related Works

The schedule-based protocol is widely used in the USN due to its simplicity. A spatial-temporal MAC (ST-MAC) schedule-based time division multiple access (TDMA) protocol was proposed [12]. ST-MAC uses a temporal-space conflict graph and vertex coloring methods to deal with spatial uncertainty in the USN. Because of the long propagation delay of a USN, also proposed was an ordered carrier sense multiple access (CSMA) protocol in the single-hop USN environment [13], so the sending node does not wait too long. To transmit the data, each node has a transmission order that is distributed in a circular sequence [13] by detecting the carrier signal. The ordered CSMA is different from the conventional TDMA, where nodes must always keep their turn for data transmission. CSMA tries to improve throughput by making it possible for more than one node to transmit at the same time. In another schedule-based protocol for USN that was proposed [14], when one node sends its data, the other node is awake after sleeping according to the schedule. However, this method works well only when periodically transmitting data.

Contention-based protocols for the USN have also been proposed. In two studies [15-16], both contention-based MAC protocols were proposed on the basis of slotted ALOHA. Modified protocols to solve the space-temporal uncertainty and long propagation delay of the USN suppress collisions of the packets, thereby improving network throughput. T-Lohi is a tone-based contention protocol in a single-hop USN [17]. T-lohi distinguishes time-axis data periods and contention periods, where the contention period is composed of contention rounds (CRs). When a node has data, it first sends a tone during the CR. If it does not receive another tone from a neighboring node, the node is successful in channel reservation, and can transmit in the data frame of the subsequent data period. T-lohi protocol takes into consideration high latency relating to detecting conflicts and space-temporal uncertainty in order to achieve high throughput and low energy consumption. However, there is the problem of lowered throughput of the network if the CR interval is too long.

A hybrid MAC protocol for the USN was also presented. Code division multiple access (CDMA) is a most notable technique in the hybrid MAC because of its nature to complement a better multipath effect at the receiving node, and for tough characteristics in frequency selective fading. Another study [18] presented a protocol for transmitting coding data generated with a unique spreading code before transmitting request to send (RTS) and clear to send (CTS) signals. Thus, the destination node broadcasts one CTS packet to the accumulated RTS packet received, and simultaneously receives signals from multiple nodes. CDMA/ALOHA mixed sender-based CDMA MAC protocols have also been proposed [19]. In the [20], it proposed how to control ACK feedback frame based on the acoustic channel.

3. An Adaptive TDMA MAC Protocol

The aTDMA protocol proposed in this study allocates time slots through reservations to nodes participating in an underwater sensor network based on TDMA. This protocol eliminates the wasting of slots and provides a time slot long enough for the node that has a transmission, which can reduce packet delay time, which increases throughput of the network. TDMA allocates a time slot to a node that has joined the network, and if a node has data to send, the node sends them using the allocated time slot. In general, the entire node is synchronized so it transmits the packets at the slot's start time. At this time, no other node can use the time slot, even if it was allocated to a node that does not have data to transmit, so that slot is wasted. aTDMA is different from conventional TDMA, because it does not use the method of allocating a fixed time slot to every node in the network [21].

Let us assume a network with 10 nodes, and one time frame consists of 10 time slots allocated to each node. A node that has transfer data uses its slot, but the time slot of a node that does not have data is not used to send any data. Thus, if we know which node would join for data transmission and allocate the time slot to the node has data to transmit, it is possible to remove unneeded time wasted by not using a slot. If a contention period is provided to determine if a node will send data in the data period, then a control packet can be sent. We need a way to adjust the control packets so they do not collide with each other. Otherwise, the exchange of information for the node that would be transmitting is unclear, because of the collision of the control packets. We propose the aTDMA protocol, focusing on this point. If aTDMA does not need to transfer a data packet, it deletes the contention period.

In aTDMA, a node that is not participating in data transfer declares that it is not using its own time slot during a certain period of time. If declaring the information by using the node's own time slot, contention with the other nodes is not generated. The aTDMA protocol, as shown in Figure 1, has frames comprised of a control period and a data period for managing a network configuration, where the network consists of a set of frames. Figure 2 shows the slot structure of a yield-declaring data packet. You can sleep according to the sleep schedule or when there is time, plan to collect data. The node has declared that it will not use the allocated slot, while declaring the number of frames. When the declaration is broadcast, each node needs to reduce the number of time slots in a single frame. As shown in Figure 1, the n number of time slots is reduced to (n-1). At this time, the node simultaneously declares the number of the yield-period slot, so the yield node can declare when the node will return. When any other node in the network receives the yield-data slot, it will record the node name and the frame period of the node that yields the slot in the yield reservation table. As the frame progresses, by reducing the remaining yield frames, at some point, that node can know when the yield node will return to the frame.

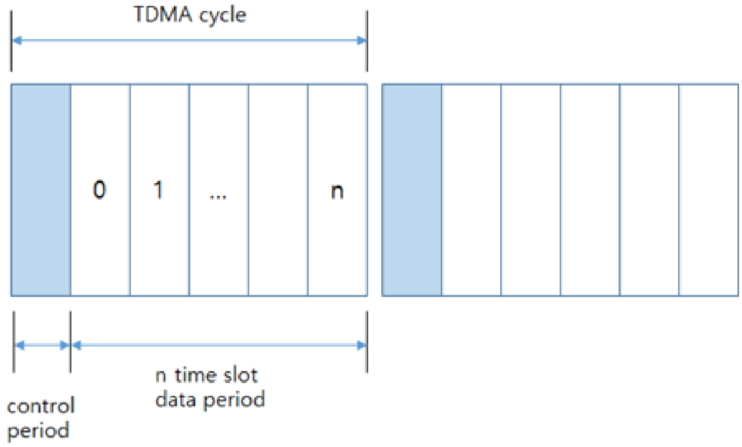

Figure 1. The Structure of an aTDMA Frame Consists of a Control Period and a Data Period

In order to get better performance, aTDMA adapts a second scheme, which tries to eliminate wasting slot times. The long propagation delay of a USN is 1500m/s, so if the distance between both nodes is 1000m, then propagation delay is about 0.67s, which is much longer than an RF propagation delay. As described earlier, a TDMA slot also consists of delay time, so the length of the slot in a USN is very long. We could change the slot time by continuously calculating distances when exchanging frames, and then we get the maximum distance during a certain time period. The time period, like the function of the TCP retransmission timeout value calculation, periodically calculates the maximum distance.

Monitoring the distances between nodes could be done at two points. The first point is the sink node that receives almost all traffic frames from sender nodes. The sink node can do the monitoring as a master node. The second point for monitoring is at each node, but this distributed method causes difficulty in synchronization of the slot size. So, in this study, we adopted the method with the sink node. The sink node continuously collects departure times in the arriving frames, and records the longest distances it can calculate from the difference between arrival time and departure time. When a periodically called timer expires, the sink node changes the slot duration and then broadcasts the new slot duration to the other nodes. Through the shrinking of the slot duration, we can get a smaller frame size, and this offers more chances to transmit data to nodes that have data frames.

In this paper, the proposed aTDMA protocol's performance can be verified through calculations according to the formula and simulations. Let us assume n nodes are participating in the network, and if we assume all the nodes continuously transmit data, all of the n time slots are used. Thus, it is possible to calculate throughput T as shown in equation 1.

$$T_{throughput} = \sum_{i=1}^{k} \frac{n \cdot Packet\ Length}{(n+1) \cdot Length\ of\ TimeSlot} / Total\ time \tag{1}$$

Time slots allocated to the nodes that are not forwarding data can be excluded from the length of the frame, based on the yield declaration, in accordance with the state that is not a yield declaration. This can be included in the configuration of the frame. In equation 2, pi is the possibility that the node will transmit data in the i'th frame, and μi is the number of the excluding node that declares a yield, which can calculate the performance of the aTDMA protocol. Removing a time slot of a TDMA frame that was allocated to the yielding node can increase throughput.

$$T_{throughput} = \sum_{i=1}^{k} \frac{np_i \cdot Packet\ Length}{\mu_i(n+1)(n-np_i) \cdot Length\ of\ TimeSlot} / Total\ time \quad (2)$$

Figure 2 is a throughput graph calculated through the formula of equation 2. Network parameters in the evaluation are the 10 nodes in the network, the bandwidth of the underwater modem at 14kbps, the maximum distance between nodes at 4 km, and the packet size of 256 bytes. The propagation delay in the network is 2.67 seconds, according to the 4 km distance, and transmission delay is 0.15 seconds. So, we set the length of the time slot at 2.82 seconds. In Figure 4, traffic load changes from 0.1 to 0.9, and aTDMA shows performance improving, especially under low traffic load status. Upon high traffic load, many nodes participate in the data-sending state, but the number of nodes declaring a yield decreased, so it is hard to get improvement.

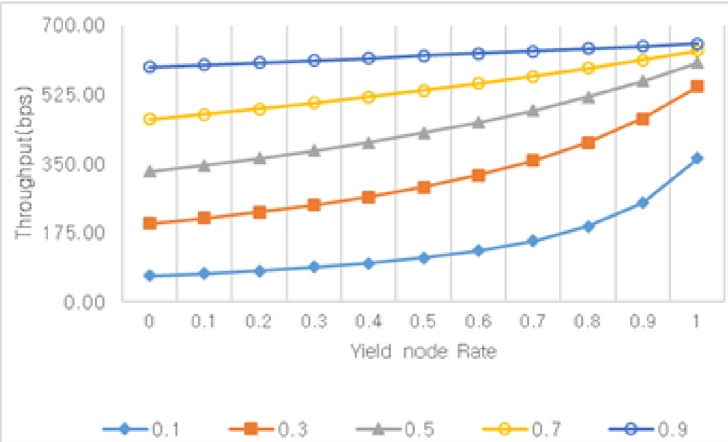

Figure 2. Throughput Graph for the Function of Yield Node Rate over Traffic Rate

Table 1 and 2 shows pseudo codes to shrink time slot size and number of time slot of the frame. In the Table 2, only sink node change the time slot size due to difficulty of synchronization among nodes in the networks.

Table 1. Pseudo Code for YIELD Frame Processing

```
// Pseudo code to reduce time waste by YIELD frame
// Sender node
// Input parameters: Time_y,
Begin
 A node get an information about how long it will be silent without data
 Yield time = Time_y;
 Make YIELD frame; frame_y(Time_y);
 Wait time slot to transmit;
 Transmit frame_y(Time_y);
 Go to Sleep;
End

// Receiver nodes
// Input parameters: frame_y(Time_y)
Begin
 When receive frame_y(Time_y) do
   Identify sender node;
   Decrease NoofSlotFrame;
```

```
   Shrink timer size of TDMA according to NoofSlotFrame
   Create Timer Message(Timer_m) ;
 End do
 When Timer_m event do
   Increase NoofSlotFrame;
   Enlarge timer size of TDMA according to NoofSlotFrame
 End do
End
```

Table 2. Pseudo Code for Slot Period Processing

```
// Pseudo code to reduce time period of time slot
// Sender node
Begin
 When transmit data frame additional do
  Add current time to frame as depart time;
 End do
End

// Receiver node
// maxdist = 0;
Set n min. timer to update time period of slot
Begin
 When receive frame in the sink node do
   elapsedTime = current time – depart time of frame;
   calculate distance dist = elapsedTime / propagation speed
   if maxdist < dist, maxdist = dist;
 End do
 When timer expired do
  delay_maxdist = maxdist / propagation speed;
  New time period of slot = delay_transmit + delay_maxdist;
 End do
When transmit data frame additional in the sink node do
  Include new time period of slot to other nodes
End do
End
```

4. Experiments

The proposed aTDMA protocol has both new techniques to improve performance in the underwater sensor network. To evaluate performance of aTDMA, we ran simulation experiments many times, and then obtained average performance data. The Qualnet simulator [20] was adopted as a platform because it is easy to apply underwater acoustic channel characteristics. We deployed 10 underwater sensor nodes, one of them being a sink node, and three CBR traffic applications were assigned randomly, but a CBR receiver is only a sink node. All CBR traffic has a 128-byte packet size, but the inter-packet interval differs, from 1.1 seconds to 4 seconds. The simulation run time was 1 hour, which is long enough to evaluate the performance of aTDMA.

Figure 3 shows the throughput results from three kinds of TDMA MAC protocols. The No. of slot bar means the first aTDMA protocol version. If one node determines it does not have data to transmit for a certain time period, it declares a yield of the slot time that was allocated to the node. Slot duration is a second aTDMA one, and in the protocol, the sink node continuously calculates propagation delay between sink node and sender node, then changes the time duration of the slot. Pure bar is the name of a conventional TDMA protocol, and we use it as a milestone to compare the performance of aTDMA. aTDMA shows better performance than conventional TDMA. aTDMA removes waste of slot times from the frame, and it can shrink the length of a TDMA frame, so the nodes that have data to transmit can more frequently use time slots allocated to other nodes. Slot duration protocols get the most enhanced results, because they use both techniques to adaptively include changes in the size of the slot duration, according to the distance between CBR client and server.

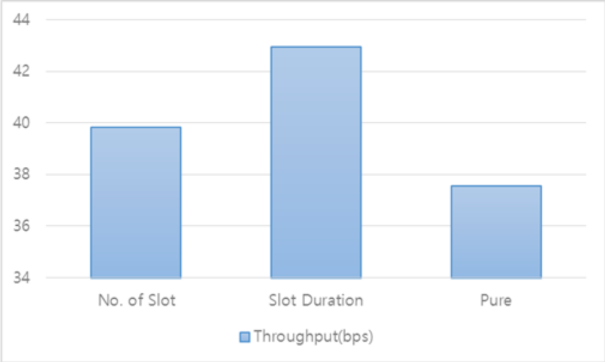

Figure 3. Throughput Performance over Three CBR Applications; Each CBR has a Different Transmission Frequency

Figure 4 shows the average end-to-end delay, and Figure 5 depicts total energy consumption during the simulation. Under conventional TDMA, pure bar shows almost three times longer end-to-end delay than the aTDMA protocol. It means the delay from an event happening to the sink node, and it is not helpful to transmit data in real time. The total energy consumption graph shows almost equal results, except for the slot duration of the aTDMA protocol, but it is a tiny difference compared to the others. It came from increased data recorded to support slot duration adaptation.

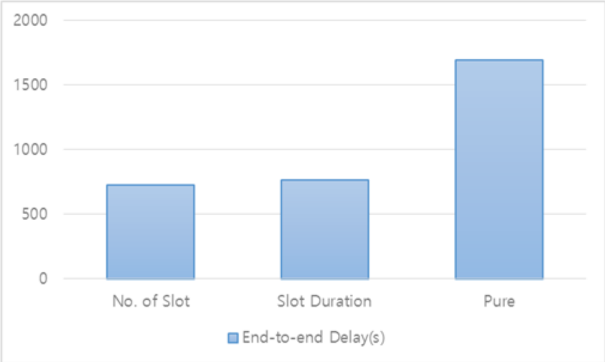

Figure 4. Average End-to-End Delay of Packets in the Experiment, which Shows the Conventional TDMA Protocol has a Longer Delay than aTDMA

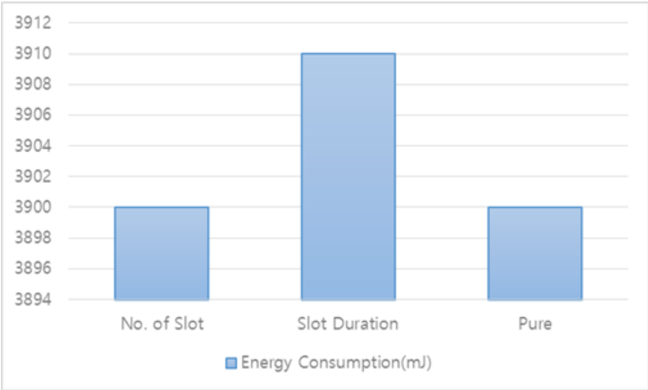

Figure 5. Total Energy Consumption Over All Nodes in the Simulation

5. Conclusion

Underwater sensor networks have very low bandwidth and long propagation delay because of acoustic channel characteristics, so we cannot use a lot of MAC protocols that are developed for RF channels. In this paper, we propose the aTDMA MAC protocol to solve the low-throughput problem, based on the TDMA protocol, because it has contention and collision-free properties. We use both schemes to solve the problems: first being removing waste of time slots in the frame through a yield declaration by a node, so we can shrink the time period of the frame. Second, another scheme adaptively changes the length of the time slot according to the distances between nodes. On low traffic load, a lot of nodes declare a yield, so we can check improvement of throughput. Very slow propagation delay causes a long time period for a slot, but it can be reduced by continuously collecting distance information at the sink node, to introduce better performance.

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