This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE INFOCOM 2007 proceedings.

Aloha-based MAC Protocols with Collision Avoidance for Underwater Acoustic Networks

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Abstract— **Unlike terrestrial networks that mainly rely on radio waves for communications, underwater networks utilize acoustic waves, which have comparatively lower loss and longer range in underwater environments. However, the use of acoustic waves pose a new research challenge in the networking area. While existing network schemes for terrestrial sensor networks are mainly designed for negligible propagation delay and high data rate, underwater acoustic communications are characterized by high propagation delay and low data rate. These terrestrial schemes, when directly applied to the underwater channel, will under-utilize its already limited capacity. We investigate how the underwater channel's throughput may be enhanced via medium access control (MAC) techniques that consider its unique characteristics. Specifically, we study the performance of Aloha-based protocols in underwater networks, and propose two enhanced schemes, namely, Aloha with collision avoidance (Aloha-CA), and Aloha with advance notification (Aloha-AN), which are capable of using the long propagation delays to their advantage. Simulation results have shown that both schemes can boost the throughput by reducing the number of collisions, and, for the case of Aloha-AN, also by significantly reducing the number of unproductive transmissions.**

I. Introduction

Unlike the terrestrial wireless sensor networks that mainly rely on radio waves for communications, underwater sensor networks utilize acoustic waves, which present a much harsher environment for both the physical and the data-link layers. Acoustic waves appear to be a good choice for underwater communications because of their low loss when compared to radio waves. However, one major disadvantage is that acoustic waves travel at approximately 1500 m/s, which is five orders of magnitude slower than radio waves. Moreover, the underwater acoustic channel's bandwidth is very limited, typically in the order of several kilohertz. These undesirable characteristics are most significant at the data-link layer, because of the long propagation delay and packet transmission time.

Currently, the research efforts in underwater MAC protocols are still in their infancy stage. Some work in the literature, such as [1], has adopted a centralized control approach, which requires a master node to configure the data scheduling, and pass the control messages to its slaves. On the other hand, the distributed control approach, in which each node decides on its own whether to send out a packet, appears to be more attractive. In [2], Rodoplu and Park propose a MAC protocol that achieves energy efficiency by reducing the number of collisions. Each node schedules by itself the time to transmit the next packet, and broadcasts this information by attaching it to the current data packet. Upon hearing the broadcast, the other nodes will know when to wake up for the subsequent packet. However, in order to operate at a low collision rate, each node requires a small duty cycle, which makes throughput low. In [3], Morns *et al.* propose two scheduling protocols to control data packet transmission and arrival times. One protocol is based on CDMA, while the other one is based on TDMA. However, both protocols require clock synchronization between all the nodes. Also, the time slot allocation for individual nodes becomes hard to manage when the number of nodes grow. Guo *et al.* introduce the propagation-delay-tolerant collision avoidance protocol (PCAP) in [4], which is a handshaking-based protocol. It also requires clock synchronization between neighboring nodes. Besides the requirement of request-to-send (RTS) and clear-to-send (CTS) frames, the uniqueness is that it allows a sender to perform other actions during the long wait between the RTS and CTS frames. Although its maximum throughput is 20% higher than what the conventional handshaking protocol can achieve in underwater, this is merely comparable to Aloha's throughput. Molins and Stojanovic propose in [5] a slotted random access MAC protocol, which, yet again, requires clock synchronization. It is also handshaking-based, but an RTS or CTS frame can only be transmitted at the beginning of each time slot. Although the protocol achieves guaranteed collision avoidance for its data packets, the long slot length requirement and the handshaking mechanism itself affect the throughput. This is also supported by the work in [6].

The protocols above have generally focused on reducing or eliminating packet collisions, but have placed little emphasis on achieving high throughput. Those that employ handshaking inevitably amplify the effect of long propagation delay, which restricts the throughput. On the other hand, those that rely on time slot allocation generally require slot lengths that are larger than the maximum propagation delay, which again affect the throughput, in addition to problems due to clock drift. These led us to ponder whether simpler MAC protocols may be, in fact, more capable of achieving high throughput and low collision rate, in the face of peculiar underwater acoustic properties. In this paper, we study Aloha-based variant protocols and propose two Aloha-based random access MAC protocols, namely, Aloha with collision avoidance (Aloha-CA), and Aloha with advance notification (Aloha-AN).

The remainder of this paper is organized as follows. Section II describes the two MAC protocols that we propose for underwater networks with distributed topology. We then present in Section III the simulations that were carried out to compare the performance of the proposed schemes with several others. Finally, we give our conclusions in Section IV.

II. ALOHA-BASED SCHEMES

Ideally, the MAC protocols for underwater networks need to be able to combat high propagation delay, while offering high throughput and low collision rate. Moreover, the initial network setup needs to be completed as quickly as possible, because the network may lose synchronization as time passes, especially since underwater applications require long-term deployment. The protocol should also adopt a distributed network architecture, rather than one that requires centralized control. In the following, we first describe two simple Aloha-based variants, before presenting our proposed schemes.

In the pure Aloha scheme, a node will simply transmit a packet whenever it has anything to send, regardless of whether it is currently receiving a packet. This is very inefficient, since the packet being received will definitely be discarded, resulting in lower throughput, and energy wastage. A possible variant to the pure Aloha scheme, which we shall call "Aloha with half-duplex (Aloha-HD)" scheme, removes the abovementioned inefficiency. In Aloha-HD, when a node realizes that the packet being received is destined for itself, it will never switch to transmit mode to send a new packet. Hence, any new packet generated within this period will be backed off. On the other hand, if the packet being received is not destined for itself, the Aloha-HD behaves just like pure Aloha. Note that the above decision is only possible upon receiving the packet's header.

Another simple variant to the pure Aloha scheme is what we shall call "Aloha with carrier sensing (Aloha-CS)". It can be viewed as an extreme version of Aloha-HD, in which a node will never transmit any new packet so long as it is currently hearing a packet, regardless of whether it is the intended receiver of this packet. Although we use the term "carrier sensing" here, the Aloha-CS does not spend additional time to acquire the channel state. Instead, it simply checks whether its half-duplex modem is currently receiving a packet.

Here, we propose two distributed random access MAC protocols, namely, Aloha with collision avoidance (Aloha-CA), and Aloha with advance notification (Aloha-AN). In these protocols, each node attempts to make use of the sender-receiver information that it picks up from those packets that it overhears, so as to help avoid collisions. In fact, both protocols take advantage of the long propagation delay in underwater environments. In underwater acoustic networks, the long propagation delay creates a phenomenon such that the information obtained by a node from overhearing may still be useful in determining whether a packet it wishes to transmit is likely to result in a collision at an intended receiver. This helps to avoid collisions, and leads to better throughput performance.

In addition to the sender-receiver information that can be picked up from overhearing the packet headers, our protocols also require the knowledge of propagation delays between every node pair in the network. In static node network, this can be done during initialization by exchanging messages. The propagation delay information learnt will then be distributed throughout the network. With mobile nodes, the nodes can broadcast their location information, which can then be used for calculating inter-node propagation delays. The location information itself can be obtained from the mobile node's navigational system. It is important to note that we do not require precise information about the nodes' positions. Our schemes will be quite tolerable towards such positioning errors, since a ten-meter error only translates into approximately 6.7 ms of error in its propagation delay estimation, which is relatively small compared to the typical inter-node propagation delays (in the order of seconds).

A. Aloha with Collision Avoidance (Aloha-CA)

The Aloha-CA is designed with the intention of overcoming the disadvantages of Aloha-HD and Aloha-CS, while embracing the advantages of Aloha-CS that it does help sometimes to refrain from transmitting a packet when overhearing another. The Aloha-CS may be over-conservative at times – during which it could have transmitted its packet without causing a collision with the current packet it overhears, but yet it refrains from transmitting, because it does not have the intelligence to deduce this. On the other hand, Aloha-HD may sometimes transmit a packet that collides (at the intended receiver) with a packet it just overhears. In order to overcome these shortfalls, a node that implements the Aloha-CA pays close attention to every packet that it overhears, and extracts information about who are the sender and the intended receiver. Together with the knowledge of propagation delays between all node pairs, the node can then easily calculate the busy duration caused by this packet, at every other node. Note that time synchronization is not required, since each node maintains such information locally in its own database table, with respect to its own clock.

For Aloha-CA to work, each packet must be differentiated into two distinct segments, namely, a *header* segment, and a *data* segment. The scheme's performance will improve as the header segment becomes smaller, because it will shorten the time required for a node that overhears the packet to extract the useful sender-receiver information. Thus, the header segment should contain only the bare essential information, such as sender's ID, receiver's ID, packet size (if variable), and error correction bits for the header segment itself.

In each node's local database table, it maintains entries to monitor the busy durations of every neighboring node, along with indications of whether these busy states are caused by *transmitting*, *receiving*, or *overhearing* a packet. Note that each entry is only valid for at most one *data* segment's length from the time it was created, beyond which the obsolete entry can be overwritten by newer entries. This is because it is impossible for a packet transmitted after this time to collide with the previous packet it overheard that created this table entry. When a node has a packet to transmit, besides making sure that it is not currently receiving a useful packet itself, it also checks its database table to ensure that doing so at this instant does not result in a collision at any other nodes. Here, its intended receiver must not be busy by the time the packet arrives, regardless of whether the busy duration is due to transmitting, receiving, or overhearing. For any other node that is not an intended receiver, it is alright so long as the packet will not arrive at that node when it is busy *receiving* another packet. If any of the above checks fails, the packet transmission will be postponed using random backoff technique. Note that a collision is still possible because the table is maintained only based on the information that the node has already overheard, which is just a subset of the overall picture that is needed for collision-free decision-making.

B. Aloha with Advance Notification (Aloha-AN)

The Aloha-AN is built upon similar idea as Aloha-CA, that the information overheard by a node may sometimes help to reduce collisions. However, it goes one step further by providing the potentially useful information much earlier, and hence its name "Aloha with *advance notification*". Specifically, a small advance notification packet (NTF), which contains similar information as a normal header segment, will be transmitted first. The sender will then wait for a period of time, called the *lag time*, before sending out the actual DATA packet. As the lag time will be set as a network parameter, every node in the network that hears the NTF packet will know when to expect the associated DATA packet. The main advantage of having a lag time between the NTF and the DATA packets is that it is now possible for a node to extract information from multiple NTF packets. This gives the node a bigger subset of the overall picture compared to Aloha-CA, thus allowing it to make better decisions in trying to avoid collisions.

Similarly, Aloha-AN requires each node to maintain its own table to monitor the busy durations of every neighboring node. Each entry in the table identifies which node is making that neighboring node busy, and whether it is caused by *transmitting*, *receiving*, or *overhearing* a packet. Every time when a node successfully receives an NTF packet, it calculates the busy duration caused by the associated DATA packet at every node, including itself. Before it inserts the entry, it needs to check whether the associated DATA packet will cause any conflict with its own scheduled DATA packet transmissions. If there is no conflict, the entry will be inserted. Otherwise, a resolution mechanism will be invoked. Here, a conflict may arise if the impending DATA packet associated with the NTF overheard appears to collide with the node's scheduled DATA packet at the intended receiver, or when the node itself is the intended receiver but it is scheduled to transmit a DATA packet during this time. The conflict-resolution mechanism checks to see which node among the two that cause the conflict will transmit first. If the current node loses, it will refrain from sending its own DATA packet by applying random backoff, and inserts the entry into the table. Otherwise, the entry will be discarded. Note that a packet that is backed off will need to retransmit a fresh NTF packet.

Whenever a node has a packet to transmit, it will check its database table to ensure that the packet does not result in a collision at any other neighboring nodes. While this test is similar to that of Aloha-CA, an important difference is that the node also needs to make sure that the new DATA packet's schedule does not overlap with the other DATA packet transmissions already scheduled in the pipeline. If the node decides not to transmit after these tests, it applies random backoff to the packet concerned. In Aloha-AN, nodes are allowed to drop packets that have been backed off by a specific number of times (e.g., 10). A node that has dropped a significant number of packets inherently learns that the network is busy, and will then try to alleviate the problem, such as reducing its own packet generation rate temporarily.

III. Simulations and Results

The main goal of our simulations is to examine the throughput and collision rate for the different MAC schemes. We utilize two different network topologies, which consist of four nodes and ten nodes, respectively. However, we only show the results for the 4-node network, due to lack of space. The results for the 10-node network have very similar trends, although their throughput are lower. Here, all nodes are static and randomly deployed based on uniform distribution, over an area of 3000 m by 3000 m. Although the topology used is two-dimensional, we expect all the MAC schemes to have similar behavior when applied to three-dimensional network topologies as well. The average inter-node distance is 1341 m. All nodes are equipped with half-duplex and omnidirectional modems, with a fixed data rate of 2400 bps. The speed of underwater acoustic waves is assumed to be fixed at 1500 m/s. The packet generation rate at each node is assumed to be Poisson, and each packet's intended receiver is randomly chosen with equal probability. We also tried different packet sizes to examine its effects on each MAC scheme. In the case of Aloha-AN, the NTF packet size is assumed to be 32-bits always, regardless of the DATA packet size. For simplicity, we assume that the network is single-hop, such that all nodes can hear each other. Also, we assume that the channel is error-free, therefore all packet losses are caused by collisions. Finally, we do not consider any packet retransmission.

A. Aloha-HD

From Fig. 1, we see that the Aloha-HD's maximum throughput is around 25%, which is better than pure Aloha's throughput of 18% in underwater (as obtained in [4]). This improvement is achieved by simply refraining from transmitting a packet when a useful packet is being received. It can also be observed that its maximum throughput only increases slightly as we increase the packet size from 2400 bits to 9600 bits.

B. Aloha-CS

When compared to Aloha-HD, we can see from Fig. 1 that Aloha-CS is always better for the same packet size used. This is also why we choose to benchmark our proposed schemes against the Aloha-CS in subsequent simulations.

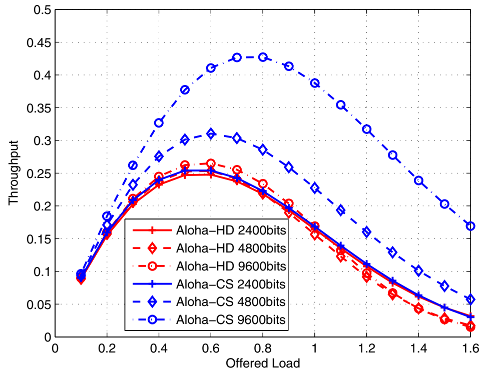

Fig. 1. Throughput of Aloha-HD and Aloha-CS in the 4-node network.

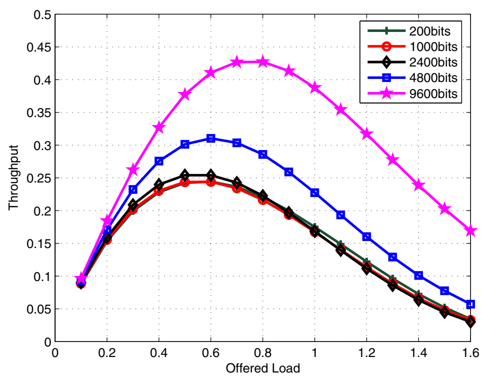

Fig. 2. Throughput of Aloha-CS in the 4-node network.

In Fig. 2, we examine the effects of varying the packet size on Aloha-CS, which shows that when the packet size is between 200 bits to 2400 bits, increasing the packet size does not have much effect on the throughput. However, when the packet size is beyond 2400 bits, increasing the packet size also increases the throughput significantly. In order to understand this, we introduce the term "*PT-ratio*", which is defined as

$$\text{PT-ratio} = \frac{\text{Average propagation delay } (P)}{\text{Packet transmission time } (T)}. \quad (1)$$

In general, the PT-ratio can be viewed as the average number of packets that can be transmitted back-to-back into the channel, before an intended receiver starts receiving the first bit. As can be seen from Fig. 3, it plays an important role in the Aloha-CS's maximum throughput performance[1]. When PT-ratio < 1, which means that the propagation delay is smaller than the transmission time, the maximum throughput is quite good. However, it decreases dramatically as the PT-ratio increases, until the latter reaches a turning point which is around 1. From then on, P becomes more significant than T, and the maximum throughput stays low.

Here, we did not consider bit error rate (BER) in our simulations. In a real scenario, for any given BER, we expect the throughput to grow with packet size up to a certain threshold, beyond which the throughput drops again due to significantly more packets being lost from data corruption.

[1]It should be noted that the maximum throughput for different PT-ratio values do not occur at the same offered load.

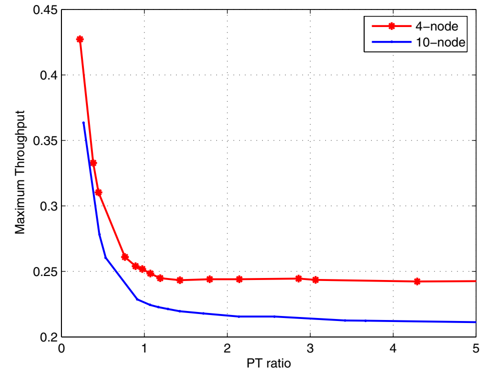

Fig. 3. Throughput vs. PT-ratio for Aloha-CS in both networks.

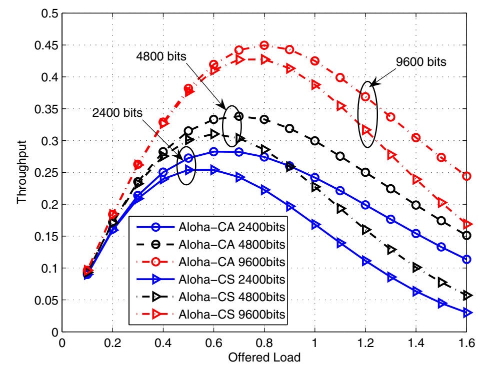

Fig. 4. Throughput of Aloha-CA compared to Aloha-CS in 4-node network.

C. Our Proposed Scheme #1: Aloha-CA

Fig. 4 shows that our Aloha-CA consistently outperforms Aloha-CS for different packet sizes. It also has better stability than Aloha-CS at high load regions, as its throughput does not fall as steeply when the load increases.

In order to better understand why Aloha-CA is superior to Aloha-CS, we introduce two performance metrics below:

$$\text{Tx-ratio} = \frac{\text{No. of packets sent by studied scheme}}{\text{No. of packets sent by Aloha-CS}} \quad (2)$$

$$\text{Collision-ratio} = \frac{\text{No. of collisions by studied scheme}}{\text{No. of collisions by Aloha-CS}} \quad (3)$$

The Tx-ratio and Collision-ratio tell us how actively are our schemes transmitting packets, and how often do they encounter packet collisions, relative to those numbers obtained for Aloha-CS. As seen in Fig. 5, although our Aloha-CA transmits as many packets as Aloha-CS, the number of collisions can be reduced by 6-9% from those of Aloha-CS. Depending on the acoustic modem, the power consumed when transmitting can be 10 to 20 times larger than the power consumed when receiving. Therefore, the amount of energy saved by reducing the number of collisions can be quite significant.

It should be noted that Aloha-CA performs better than Aloha-CS because it allows a node to transmit a packet even when it is currently overhearing another packet, if it thinks that the new packet will not collide with the overheard packet at an intended receiver. It is also noted that, our Aloha-CA has similar dependence on the PT-ratio as Aloha-CS.

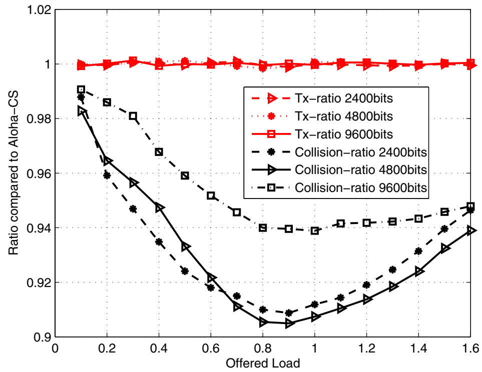

Fig. 5. Tx-ratio and Collision-ratio of Aloha-CA in 4-node network.

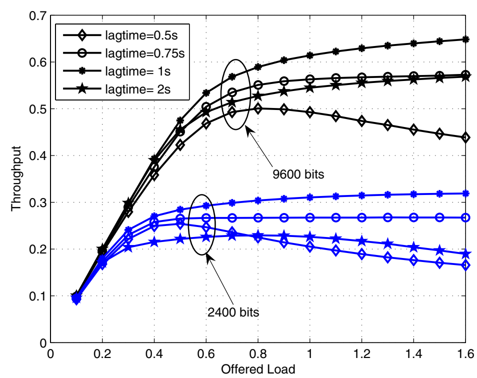

Fig. 6. Throughput of Aloha-AN in 4-node network.

D. Our Proposed Scheme #2: Aloha-AN

From Fig. 6, we see that Aloha-AN offers even better results than Aloha-CA. The throughput is now much higher, along with better stability in the high load region. When the offered load ranges from 0.1 to 0.4, the throughput is almost as high as it could get. On the other hand, in the high load region, even when the offered load goes above 1, the throughput does not fall steeply. Note that its throughput is always smaller than the offered load, because we do not count the NTF packets towards throughput, as they are overhead incurred.

In Fig. 6, we also observe that different *lag time* will give us significantly different throughput and stability. When the lag time is too small, the throughput is low because the nodes do not have sufficient windows to acquire enough NTF packets from their neighbors, which subsequently degrade their ability to make informed decisions about packet transmissions. This in turn leads to higher collisions. On the other hand, when the lag time is too long, the throughput will again become lower, because each node will spend a lot of time listening for NTF packets, such that the channel bandwidth becomes under-utilized. Due to the limited space, we do not explain here how to pick a suitable lag time.

From Fig. 7, we can see that the number of packets sent by our Aloha-AN is actually much lower than those sent by Aloha-CS, while the number of collisions is also reduced by more than 40%. This is indeed a highly desirable behavior, because a lot of energy can be saved by not transmitting

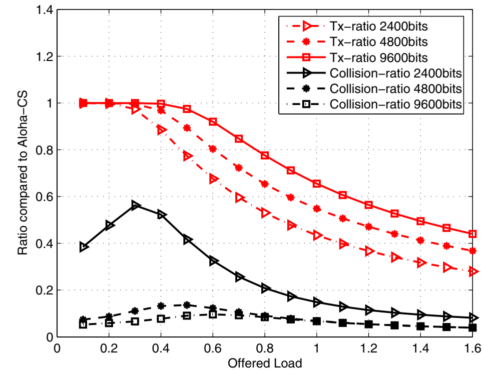

Fig. 7. Tx-ratio and Collision-ratio of Aloha-AN in 4-node network.

packets that are expected to result in collisions anyway. Furthermore, by allowing packets to be dropped if they have been repeatedly backed off, the protocol is very stable even in the face of high traffic load.

IV. Conclusion

In this paper, we presented two Aloha-based random access MAC protocols, namely, Aloha-CA and Aloha-AN, for underwater acoustic networks. Both are inspired by the simplicity of Aloha. There is no handshaking involved, and no clock synchronization. Between our two protocols, Aloha-CA is simpler and more scalable, as it only needs a small amount of memory, and does not rely on additional control messages. Aloha-AN, on the other hand, requires the use of additional NTF packets, which serve as advance notification to neighboring nodes, so that they can avoid transmitting packets that could result in collisions. The Aloha-AN needs to collect and store more information, therefore it requires more resources than Aloha-CA. Due to the need to select a suitable lag time for a given network setting, the scheme is less scalable as it needs to check if its lag time is still appropriate whenever there are any significant topology changes. However, the extra cost allows the Aloha-AN to achieve much better throughput and collision avoidance.

Our future work includes studying the effects of delay variance using the proposed protocols, as well as testing and adapting the protocols in a multi-hop network.

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