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The Usefulness of Overheard Information for Collision Avoidance in a Single-hop Underwater Acoustic Networks

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Abstract

A MAC protocol that depends on overheard information for its collision avoidance, such as Carrier Sense Multiple Access (CSMA) [1], may not work well in underwater, due to the long propagation delay characteristic of an underwater acoustic (UWA) channel. In such channel, the overheard information may already become obsolete by the time it reaches the node and, thus, should not be taken into account in the collision avoidance mechanism.

Intuitively, the degree of usefulness of overheard information plays an important role in determining the network performance for channel listening-based MAC protocols. In this paper, we analytically study the usefulness of overheard information for collision avoidance in two different channel listening-based MAC protocols: (1) CSMA [1] and (2) Aloha-CA [2]. From our study, it is shown that the overheard information is beneficial for collision avoidance only if certain conditions can be satisfied. More specifically, in order for a node that overhears an ongoing transmission to be able to utilize the extracted information for collision avoidance, the node must be within a bounded region that is determined by the relative positions of the sender and the receiver, the packet's transmission time, as well as the length of the packet's header. Based on this analysis, we also present the *"usefulness index (U)"* which is defined as the degree of usefulness of information overheard.

Keywords: Underwater acoustic network; MAC protocol design; Channel listening; Collision avoidance

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1. INTRODUCTION

Unlike terrestrial wireless networks that mainly rely on radio waves for communications, underwater sensor networks utilize acoustic wave which is characterized by its narrow available bandwidth and high propagation delay. Specifically, the amount of available bandwidth depends on both the communication range and the carrier frequency [3]; a long-range system that operates over several tens of kilometers may have a bandwidth of only a few kilohertz, while a short-range system operating over several tens of meters may have more than a hundred kilohertz of bandwidth [4]. The long propagation delay, on the other hand, is a result of the low speed of acoustic wave in underwater. In general, we assume that the speed is approximately 1500 m/s, which is five orders of magnitude slower than radio waves. The narrow bandwidth leads to low data rate while the low speed introduces a large propagation delay (6.7 s/km), which can lead to the low normalized throughput and the difficulty in sensing the channel's status. These undesirable characteristics of acoustic channel introduce a big challenge in designing a medium access control (MAC) protocol for underwater acoustic (UWA) channel.

In a MAC design, collision avoidance mechanism is one of the most important issues to be considered because the capability of avoiding collision can greatly improve network performance (e.g., throughput, packet delay etc.). For some particular networks such as UWA networks, collision avoidance mechanism is a must-have feature since a packet collision leads to a packet retransmission, which is very costly in term of bandwidth, transmission power as well as packet delay. In addition to the collision avoidance capability, the designed MAC protocol for UWA networks must also be simple enough to be able to be implemented in a sensor node that typically does not have very high computational capability.

Because of the reasons discussed above, we are interested in studying the collision avoidance mechanism provided by channel listening technique. Note that the channel listening will be used interchangeably with the term "*overhearing-based*" throughout this paper. To be more specific, in this paper, we analytically study the usefulness of overheard information for collision avoidance in two different overhearing-based MAC protocols: (1) CSMA [1] and (2) Aloha-CA [2]. From our study, it is shown that the overheard information is beneficial for collision avoidance only if certain conditions can be satisfied. More specifically, in order for a node that overhears an ongoing transmission to be able to utilize the extracted information for collision avoidance, the node must be within a bounded region that is determined by the relative positions of the sender and the receiver, the packet's transmission time, as well as the length of the packet's header. Based on this analysis, we also present the *"usefulness index (U)"* which is defined as the degree of usefulness of information overheard. Upon gaining the understanding of the usefulness of overheard information, it is possible to predict the throughput performance of the MAC protocol and even vary the parameter setting (e.g., the length of a packet), in order to increase the usefulness of the overheard information.

The remainder of this paper is organized as follows. In Section 2 and Section 3, we briefly review two channel-listening based schemes in underwater scenario: CSMA and Aloha-CA, respectively. We then attempt to analyze the usefulness of the information overheard for the purpose of collision avoidance in Section 4. The simulations are carried out in Section 5 to verify our analysis. Finally, we give our conclusion in Section 5.
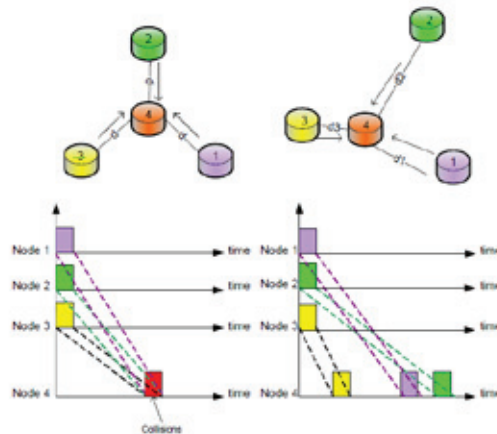
Fig. 1. Packets sent at the same time may or may not collide at receiver.

2. CARRIER SENSE MULTIPLE ACCESS (CSMA)

The channel listening technique, such as the one employed by CSMA, tries to avoid collisions by requiring each node to listen to the channel before transmitting a packet, and can only do so when no ongoing transmission is heard. However, this does not work well in underwater networks, due to the high propagation delay. The underwater channel may well be sensed to be idle while a transmission is already ongoing elsewhere, since the signal may not have reached the listening node yet. Nevertheless, even if the latter decides to transmit a packet, it may or may not result in a collision at the intended receiver, depending on the topology and separation of the nodes concerned. Note that a "collision", which leads to data corruption, only occurs when packets overlap at an intended receiver. Fig. 1 gives two examples to show that packets sent at the same instant may or may not collide. Suppose Nodes 1, 2 and 3 try to send packets to Node 4 at the same time, because each node thinks that the channel is idle. In the network on the left, Nodes 1, 2 and 3 are equidistant from Node 4, thus all the three packets collide at Node 4. In the network on the right, however, none of the packets collide at Node 4, because of the differences in propagation delays.

On the other hand, when a node senses that there is an ongoing transmission in the channel, it does not necessarily mean that it cannot transmit a packet. This is because its packet may not overlap with the previously sensed packet at the intended receiver. Fig. 2 shows an example in which a packet may be backed off unnecessarily when it is alright to transmit. The number pair inside the packet, e.g., "2-3", denotes that the packet's sender is Node 2, and its intended receiver is Node 3. Assuming that a packet is divided into 2 segments [2]: *"header segment"* and *"data segment"* and each segment can be decoded at the receiver/overhearing node independently. Here, Node 2 transmits a packet to Node 3, which is overheard by Node 1. Suppose Node 1 generates a packet that it wishes to send to Node 2 at the time when it overhears the packet "2-3". Based on pure channel listening without additional information, Node 1 may back off the packet "1-2", although it will not have resulted in collision at Node 3. Thus, from the above examples, we see that the way the node in CSMA uses the overheard information to avoid collision is not effective as there are certain circumstances in which pure channel listening in underwater networks not only does not help to avoid collision, but may also result in low throughput because it is overconservative.

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[1] **Maximum normalized throughput** refers to the peak point in the respective normalized throughput vs. load plot. It is noted that the peak may occur at different load for different pT-ratio.
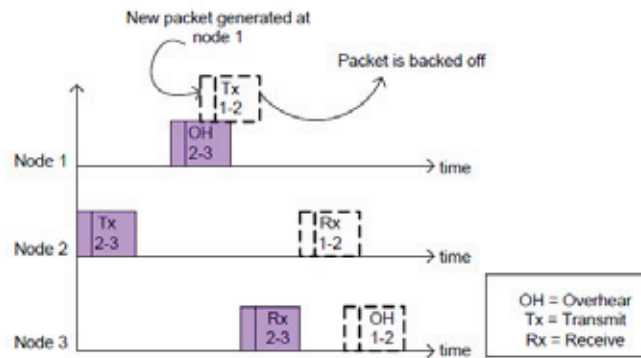
Fig. 2. Channel listening may back off a packet unnecessarily

3. ALOHA WITH COLLISION AVOIDANCE (ALOHA-CA)

Aloha-CA is designed to reduce the ineffectiveness of the collision avoidance mechanism used in CSMA, as discussed in the previous section. Although Aloha-CA [2] is also a channel-listening based MAC protocol, it takes the long propagation delay into account and, thus, the node does not rely its collision avoidance only on the channel's status like the ones in CSMA. In addition to the channel's status, the node in Aloha-CA utilizes the inter-nodal propagation delay to help it makes more accurate decision on when to defer a transmission to avoid a collision.

In Aloha-CA, each packet is divided into two distinct segments, namely, a *header* segment, and a *data* segment. The header segment must be decodableindependently1, and must be kept short so that the information it carries can be extracted and utilized as soon as possible by those nodes that overhear it. 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. 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 neighboring 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 neighboring 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 the random backoff technique.

Table 1. Notations use for explaining useful region

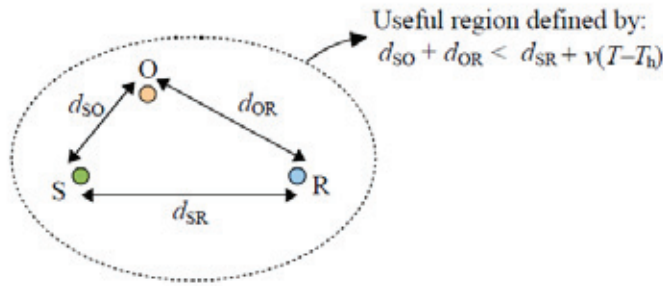| Notation	Meaning
d_{xy}	Distance between nodes x and y.
p_{xy}	Propagation delay between nodes x and y.
T	Transmission time of an entire packet.
T_h	Transmission time of a packet's header.
v	Speed of acoustic wave in underwater, assumed to be constant within the transmission range.

Fig. 3. Useful region in which overhearing can help avoid collision

4. THE USEFULNESS OF OVERHEARD INFORMATION

In this section, we provide the analysis of how the usefulness of overheard information can be derived. As will be shown later that CSMA can be thought of as an extension of Aloha-CA, we will only show the derivation of the usefulness of overheard information in Aloha-CA.

In order for a node in Aloha-CA that overhears an ongoing transmission to be able to utilize the extracted information for collision avoidance, the node must be within a bounded region that is determined by the relative positions of the sender and the receiver, the packet's transmission time, as well as the length of the packet's header. We shall now analyze this useful region. The notations used in the analysis are shown in Table 1. Referring to Fig. 3, suppose node S sends a packet that is destined for node R at time $t = 0$, and node O overhears the packet. Assuming an error-free transmission, and that the time taken to process the header information is negligible, node O will be aware of the sender-receiver information at time $t = p_{SO} + T_h$. On the other hand, the packet will be received by node R from time $t = P_{SR}$ to $t = p_{SR} + T$. Therefore, node O can utilize the information overheard to help avoid a collision if it refrains from transmitting any packet from $t = p_{SO} + T_h$ to $t = p_{SR} + T - p_{OR}$. It can be observed that the information overheard will only be useful if the following holds:

$$p_{SO} + T_h < p_{SR} + T - p_{OR}. \tag{1}$$

After some manipulation, we obtain

$$d_{SO} + d_{OR} < d_{SR} + v(T - T_h). \tag{2}$$

For a particular S-R pair, an overhearing node O can utilize the information overheard so long as the topology satisfies (2). Therefore, the useful region is defined by all possible locations of node O around the S-R pair that satisfies (2). By varying the position of node O, while keeping the rest of (2) constant, we observe that the RHS of (2) is a constant. The boundary of the useful region is thus an ellipse, with nodes S and R being the foci. Note that for 3-D deployment, where the nodes can be placed at different depths, the useful region becomes an ellipsoid; Fig. 3 then becomes its cross-section that cuts through nodes S, R and the particular node O being examined.

We can make two important observations from (2). Firstly, we see that the longer the packet length (directly proportional to T), the larger the useful region. This is intuitive because long packet length increases the likelihood that even by the time a distant node overhears the transmission, the receiver still has a long time to go before it finishes receiving the entire packet. The second observation is that, the

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[1] **Maximum normalized throughput** refers to the peak point in the respective normalized throughput vs. load plot. It is noted that the peak may occur at different load for different pT-ratio.

shorter the header (directly proportional to T_h, the larger the useful region. The reason is more subtle; it is because, if the header can be received sooner, then those nodes that are farther away will also be able to extract the information before it expires.

Although any node within the useful region that overhears a packet will be able to help avoid collision, the degree of usefulness is strongly dependent on the time window from the moment the information is extracted, to the moment it expires. This time window can be normalized by the packet transmission time, and we shall call it the "usefulness index (U)":

$$
\begin{aligned}
U &= (p_{SR} + T - p_{OR} - p_{SO} - T_h)/T, \\
&= (p_{SR} - p_{OR} - p_{SO})/T + (T - T_h)/T
\end{aligned} \tag{3}
$$

For a node O that resides within the useful region, U ranges from 0 to $(T - T_h)/T$, or approximately 1 if $T_h \ll T$. Note that U is at its maximum if node O falls directly between the sender and the receiver. For a node O that falls outside the useful region, U will be negative. By considering all node pairs acting as a sender-receiver (for an N-node network, there are the total of $j = C_2^N$ sender-receiver node pairs) with equal probability, while all other nodes acting as overhearing nodes. The average $U(U_{avg})$ across the entire network can be obtained as

$$
U_{avg} = \frac{U_1 + U_2 + ... + U_j}{j}, \tag{4}
$$

Where U_j denotes the usefulness index of node-pair j^{th}. (4) can be manipulated such that we can obtain

$$
U_{avg} = -p/T + (T - T_h)/T, \tag{5}
$$

where p is the average inter-node propagation delay. The ratio $p:T$, which we shall call the "pT-ratio", thus has an important significance in a channel listening-based MAC protocol's performance. According to (5), in order for the protocol to work well, the average U must be positive; this implies that the PT-ratio must be smaller than $(T - T_h)/T$, which is approximately 1.

The above analysis can also be extended to CSMA in general. Since a node exercising CSMA will refrain from transmitting its own packet so long as it overhears an ongoing transmission (i.e., without the need to decode the packet's header), its U_{avg} is simply

$$
-p/T + 1, \tag{6}
$$

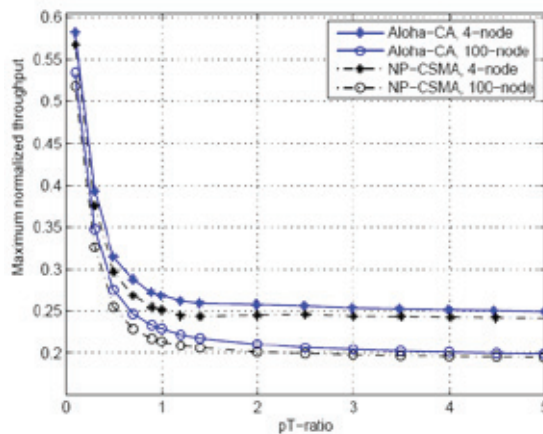meaning that CSMA can work well only if the pT-ratio is smaller than 1.

Fig. 4. Simulation results of the maximum normalized throughput vs. pT-ratio

5. VERIFYING THE ANALYSIS

In order to verify our analysis of the effect of pT-ratio on the throughput performance, we simulate two overhearing-based MAC protocols, namely, NP-CSMA [1] and Aloha-CA, in underwater environment. Furthermore, we consider two single-hop network topologies, namely, a small network with only four nodes, and a large network with 100 nodes. The results obtained from the 100-node network approximate what one would expect from a network with infinite number of nodes. On the other hand, the 4-node network resembles a more practical scenario whereby underwater sensor nodes are typically deployed in a sparse manner due to the high cost of each node. All the nodes are assumed to be static and randomly deployed with a uniform distribution, within a deployment area of 1000 m by 1000 m. Moreover, all nodes are assumed to be 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. Regardless of the packet length, we assume that each packet includes a 32-bit header. Since we focus our study on the single-hop networks, all nodes are within each other's range. Also, we assume that the channel is error-free, so that packet losses are only caused by collisions at the receivers. Finally, we do not consider any kind of packet retransmission when a collision occurs.

Figure 4 shows the simulation results of the maximum normalized throughput[1] of both NP-CSMA and Aloha-Ca when varying pT-ratio. Note that pT-ratio can be varied by varying the packet length (equivalent to vary T) while fixing the network topology (equivalent to fix p). As can be seen, maximum normalized throughputs for both NP-CSMA and Aloha-CA increases dramatically as the pT-ratio decrease below 1. This agrees with (5) that the pT-ratio threshold for overhearing-based protocol to perform well is approximately 1.

6. CONCLUSION

We have illustrated that channel listening technique can be beneficial for UWA (Underwater Acoustic) networks if certain conditions can be satisfied. Specifically, it is shown by both analysis and simulations, that in order for a node that overhears an ongoing transmission to be able to utilize the extracted information for collision avoidance, the node must be within a bounded region that is determined by the relative positions of the sender and the receiver, the packet's transmission time, as well as the length of the packet's header. Based on this analysis, we also present the *"usefulness index (U)"* which is defined as the degree of usefulness of information overheard.

As a guideline when using CSMA and Aloha-CA, our study suggests that it is important to ensure that pT-ratio of a given network should be at most 1. In order to vary pT-ratio, the network operator has a choice of changing network topology (equivalent to changing p) or increasing the length of the packet (equivalent to changing T).

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