A MAC Protocol for Ad-Hoc Underwater Acoustic Sensor Networks

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ABSTRACT

A medium access control (MAC) protocol is proposed that is suitable for non-synchronized ad-hoc networks, and in particular for the energy-constrained underwater acoustic networks which are characterized by long propagation delays. The protocol exploits the difference in the link lengths between the nodes instead of using waiting times proportional to the maximal link length. To do so, it relies on a receiver's ability to tolerate a certain level of interference. By minimizing the length of the hand-shake procedure preceeding the data transmission, the throughput efficiency is increased as compared to the previously proposed protocols, while collision avoidance minimizes the energy consumption.

Categories and Subject Descriptors: C.2.1 [Computer-Communication Networks]: Network Architecture and Design—network communications, wireless communications; C.2.2 [Computer-Communication Networks]: Network Protocols—protocol architecture (OSI model)

General Terms: Algorithms

Keywords: underwater acoustic networks, ad-hoc networks, hand-shake, long propagation delays, medium access control (MAC), tolerance to interference

1. INTRODUCTION

The power required for transmission of a data packet in an underwater acoustic system is much greater than that required for its reception. In an energy-constrained underwater system it is therefore imperative that the number of packet collisions that would necessitate retransmission be minimized. For this reason, MAC protocols that include a collision avoidance mechanism have been considered for underwater sensor networks, despite the fact that they rely on a hand-shake procedure which increases the delay and lowers the throughput efficiency. The hand-shake consists of an exchange of requesto-to-send (RTS) and clear-to-send (CTS) control packets. In a protocol called Slotted FAMA [1], time is divided into slots of length equal to the maximal expected propagation delay, and transmissions are initiated at the beginning of slots. In a protocol called PCAP [2] the receiver waits before sending the CTS control packet so as to fix a constant time for the hand-shake, such that the CTS reaches the receiver exactly after the maximal round-trip time. The S-MAC protocol [3] addresses further energy savings available from sleep cycling, and schedules a period for each of the control packets in the listening interval. All of these protocols require some level of synchronization between the nodes. We propose a protocol that relaxes this requirement and allows a node to use different handshake lengths for different receivers.

To minimize energy consumption, control packets of short duration are considered. Due to the slow propagation of sound in water, the duration of such control packets becomes negligible when compared to the propagation delays. Hence, the hand-shake length is determined by the distance between the nodes. To avoid collisions, the existing protocols lengthen the hand-shake procedure beyond the minimum needed, by setting transmission parameters in accordance with the maximal propagation delay. When most of the network links are shorter than the transmission range, this approach is inefficient.

The proposed protocol takes advantage of the greater received power over short links to reduce their handshake length. For example, a packet coming from a distance of 7 km does not threaten the reception of a packet coming from a node located ten times closer. A hand-shake thus only needs to avoid collisions from nodes closer than a certain distance. Hence, hand-shakes between close neighbors can be made shorter but those between far-apart nodes need to become increasingly longer.

2. PROTOCOL DESCRIPTION

We define a minimum hand-shake length t_{min} that will allow us to optimize the protocol for a given network. For a network in which most links are close to the transmission range, t_{min} needs to be nearly as long as the round-trip time corresponding to the maximal range. When some links are shorter, it can be reduced.

The protocol is specified as follows. Upon receiving an RTS, a receiver immediately replies with a CTS, then listens to the channel waiting for the data packet. If during this listening period it hears an RTS meant for some other node, it sends a very short warning packet to its partner (the node to whom it had sent the CTS).

Upon receiving a CTS, a node waits some time before transmitting the data packet. If it hears another CTS or a

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warning from its partner during this time, the node aborts transmission. The length of the waiting period will depend upon the distance between the nodes, which the sender can learn by measuring the RTS/CTS round-trip time.

Fig. 1 illustrates the protocol operation. Node B wants to transmit to node A, and node D wants to transmit to node C. B and A are within each other's range, and so are D and C. However, nodes B and C can hear each other, which is a potential source of interference. Nonetheless, collision is avoided through the use of a short warning.

Let U be the distance between two nodes performing a hand-shake, and let U+D be the minimal distance to an interfering node for which correct reception is still possible. The corresponding propagation times are obtained by dividing the distances by c, the speed of sound underwater. Denoting by t_{data} the duration of a data packet, the waiting period is determined from

$$T_w = \begin{cases} t_{min} - 2U/c, & U/c < t_1 \\ 2(U+D)/c - t_{min}, & U/c \in (t_1, t_2) \\ 2D/c + t_{data}, & U/c > t_2 \end{cases} \quad (1)$$

where

$$\begin{aligned} t_1 &= \frac{t_{min} - \min(D/c, t_{data})}{2} \\ t_2 &= \frac{t_{data} + t_{min}}{2} \end{aligned} \quad (2)$$

and there is an additional restriction that $T_w > 2D/c$ to avoid collisions with control packets.

Due to the different hand-shake lengths, a fairness issue arises. If necessary, it can be solved by setting t_{min} to $2T$. With such a value, all hand-shakes have equal length and no warnings are needed, but the overall throughput is reduced.

3. SIMULATION RESULTS

The protocol performance was simulated using the following scenario. The network covers a 5 km by 5km area, divided into 16 squares with a node at a random location within each square. Control packets (RTS and CTS) are 48 bits long, warnings are 24 bits long, and data packets have 9600 bits. The transmission rate is 4800 bits per second.

Each node generates packets for random destinations according to a Poisson distribution, and has an infinite transmit queue. Minimum hop routing and noiseless channel are assumed. The transmission range is 7 km, so that every node can hear each other. As most of the links are much shorter than that, we will use $t_{min} = T$, the maximal one-way propagation time (half the round-trip time).

The minimum SIR that the receiver requires for a correct reception is set to 20 dB. Assuming a carrier frequency of 35 kHz, a path loss exponent of 1.5 corresponding to practical spreading, and absorption according to Thorp, we obtain that a difference in distances of D=1.75 km in such an environment guarantees the required SIR. This value corresponds to $D/c = T/4$, which we use in the expressions (1) to obtain the waiting time T_w.

The performance of the protocol was compared to that of the carrier sensing ALOHA and Slotted FAMA, all without acknowledgments. In CS-ALOHA, nodes transmit their packets to the medium whenever they see it idle and therefore do not waste time on hand-shaking. As for Slotted FAMA, it is based on dividing the time into slots whose length equals T. The packets are sent only at the beginning of a slot, and collisions with data packets are completely avoided unless the CTS is lost. To avoid this possibility, slotted FAMA makes the nodes back-off when they receive a corrupted control packet.

The performance metric that we use is the throughput as a function of the offered load, defined as follows:

$$\begin{aligned} \text{throughput} &= \frac{\text{total correct packets} \cdot t_{data}}{\text{simulation time}} \\ \text{offered load} &= \frac{\text{total generated packets} \cdot t_{data}}{\text{simulation time}} \end{aligned} \quad (3)$$

The simulation time was set to 30 minutes, and the results were averaged over six simulation runs, each obtained with a different initial deployment of the nodes within a network.

Fig. 2 shows that the achieved throughput of the proposed protocol (marked "configurable hand-shake") is several times higher than the one obtained with slotted FAMA. The throughput of CS-ALOHA is higher initially, but it degrades as the load increases. CS-ALOHA also wastes too much energy on collisions (over 50% unless the offered load is very low). The power efficiencies of both slotted FAMA and our protocol are very similar, always over 95% for the present simulation scenario.

4. CONCLUSION AND FURTHER WORK

We have proposed a channel sharing protocol for ad-hoc underwater networks which saves energy by avoiding collisions while maximizing throughput. It is based on minimizing the duration of a hand-shake by taking advantage of the receiver's tolerance to interference when the two nodes are closer than the maximal transmission range. Nodes do not need to be synchronized, can move, are half-duplex, and use the same transmission power.

The throughput with this protocol is several times higher than the one achieved with slotted FAMA, while offering similar protection to collisions, i.e. savings in energy. Although CS-ALOHA offers higher throughput in fully connected networks and low loads, it wastes too much power on collisions. When the range is reduced or the load increased, the protocols based on hand-shaking improve their throughput over the one achieved by CS-ALOHA.

In further work, acknowledgments will be introduced and the possibility of adaptively adjusting the hand-shake parameters will be explored.

Acknowledgment

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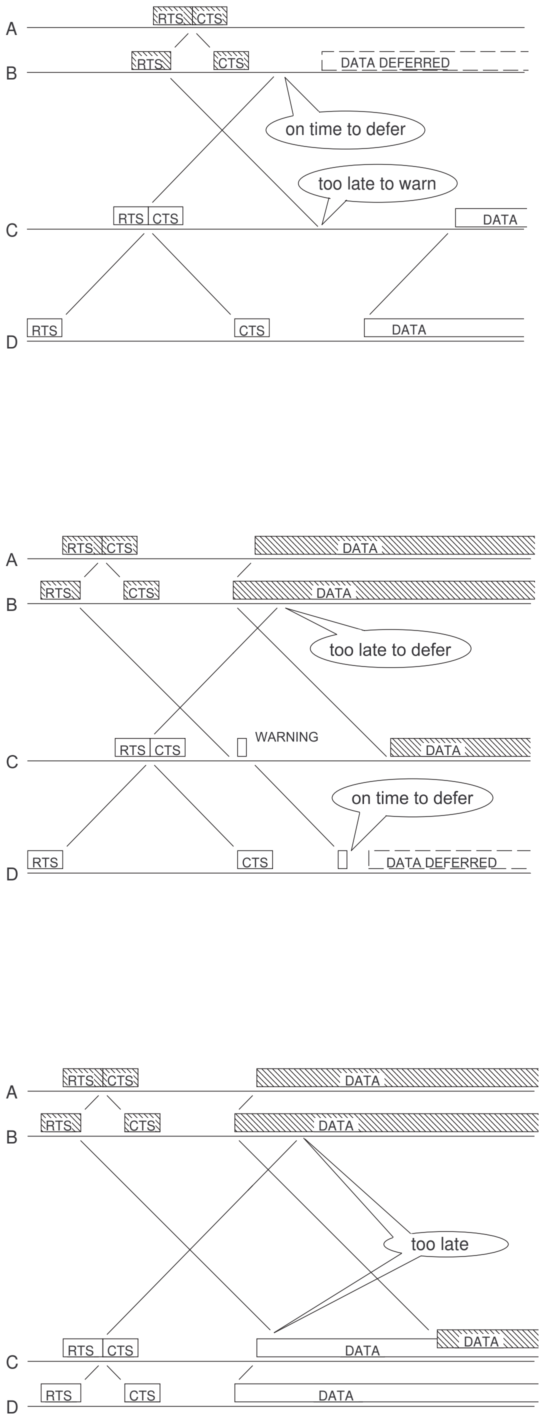

Figure 1: In the first two cases, C and D are far from each other. The packet from B is a potential source of collision. Either C or B will hear the RTS from the other one, and defer their transmission. In the third case (bottom), the data packets from B and D collide at C. However, the SIR is high because D and C are close.

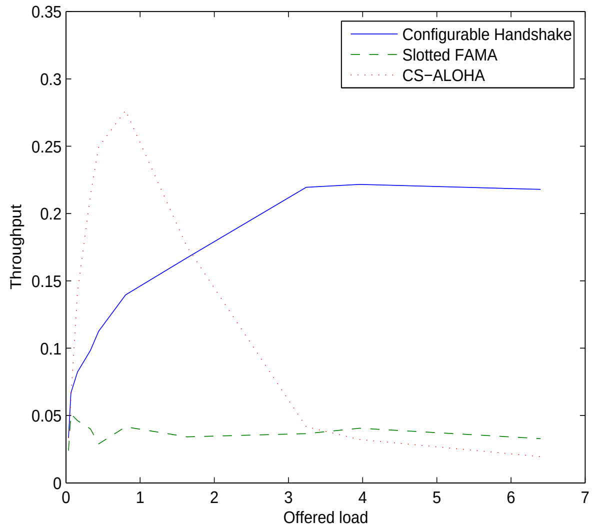

Figure 2: Throughput as a function of offered load for $t_{min} = T$ and $D/c = T/4$.