Poster Abstract: A Frugal Time-Division MAC Protocol for Underwater Acoustic Networks

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I. Introduction

In underwater acoustic networks (UWANs), a packet's propagation delay generally exceeds its transmission delay, often by an order of magnitude. Time-division MAC protocols designed for RF networks waste at least one propagation delay of time for every packet transmitted due to medium acquisition via RTS/CTS or the guard times required in TDMA. Though negligible in RF networks, this waste is excessive in UWANs due to the long propagation delays. While an improvement over RF-designed protocols, existing UWAN time-division MAC protocols still have poor channel utilization due to this waste, or incur other undesirable costs.

In this work, we discuss these issues and present a frugal time-division MAC protocol for UWANs where nodes cooperate to build a TDMA-like transmission schedule, without tight clock synchronization or large guard times. Using a trial-and-error approach to build a transmission schedule and reconsidering the ways that guard times and exclusive channel access are used in RF networks, we advocate that a TDMA-like MAC protocol can be effective for UWANs in terms of hardware simplicity, channel utilization, and energy usage.

II. Motivation and Related Work

Several time-division MAC protocols have been adapted from RF networks for use in UWANs. UWAN-MAC [1] is a single-hop MAC protocol where nodes transmit at a randomly chosen initial time but with a common interval, effectively creating a repeating transmission schedule. While this approach is effective at reducing energy usage, it does not seek to maximize channel utilization and in fact only operates effectively under very low demand. [2] proposes a "pipelined" CSMA-based protocol where the RTS, CTS, and DATA frames of competing sender-receiver pairs may be interleaved to better utilize the channel during the otherwise wasted propagation delay which normally separates these frames. Like [2], we observe that the interleaving of transmissions is necessary for time-division MAC protocols to be effective for UWANs. However, our approach is more similar to TDMA and allows the continual contention of CSMA, which wastes both energy and channel capacity, to be eliminated. Energy in particular becomes a factor for nodes with limited resources deployed for extended periods of time, where a transmission schedule, once determined, allows efficient long-term operation through sleeping and a lack of collisions and control messages.

We base our protocol on two observations. First, MAC protocols for RF networks achieve "exclusive access", where only one node in a given region may transmit at a time. Due to the short propagation delays in RF networks, concurrent nearby transmissions on the same channel almost certainly will not be received successfully due to interference. In contrast, it is possible in UWANs for two nodes with half-duplex transceivers to transmit concurrently on the same channel and successfully receive each other's transmission. Due to the long propagation delays, each node is likely no longer transmitting when the other node's transmission is received. In addition, consider three nodes A, B, and C, which are near each other, as in Fig. 1. In many cases, if A is currently receiving interference from B's transmission to C, A can immediately begin transmitting to C, and C will receive both A's and B's transmissions without interference (i.e. frames #2 and #6). Unless A and C are located in almost the same direction relative to B, the difference in propagation delays will often separate C's reception of the two signals.

This motivates the use of a "non-exclusive access" protocol, where nodes may transmit concurrently, even if the channel is busy. To do this, nodes must know whether or not the channel is busy due to a transmission intended for itself, which leads to a TDMA-like design where the transmission schedule can provide this information. A repeating schedule is suitable for underwater sensing applications, many of which are isochronous, generating data with a fixed size and period. Assuming a transmission delay of one time unit and the propagation delays in Fig. 1, our approach can, for example, allows adjacent nodes to transmit and receive 10 data frames in a schedule 9 time units in length. This "above 100%" efficiency is possible due to the effects of propagation delay, suggesting that a TDMA approach can be very effective in UWANs provided the size of the guard times can be reduced to a fraction of the transmission delay, as is the case in RF networks.

Our second observation relates to guard times, which, in TDMA protocols for RF networks, are equal in length to the maximum propagation delay between nearby nodes and separate the exclusive access periods in which transmissions take place. While the optimal guard time size between a given pair of transmissions is dependent on factors such as the location and clock skew rate of the transmitting and receiving nodes, it is not productive to consider these subtleties in most RF networks. We have already established that exclusive access is not required for UWANs, thus we more carefully define guard times in UWANs to be, at a given receiver, the gaps before and after the reception of a transmission intended for this receiver, during which interference from other

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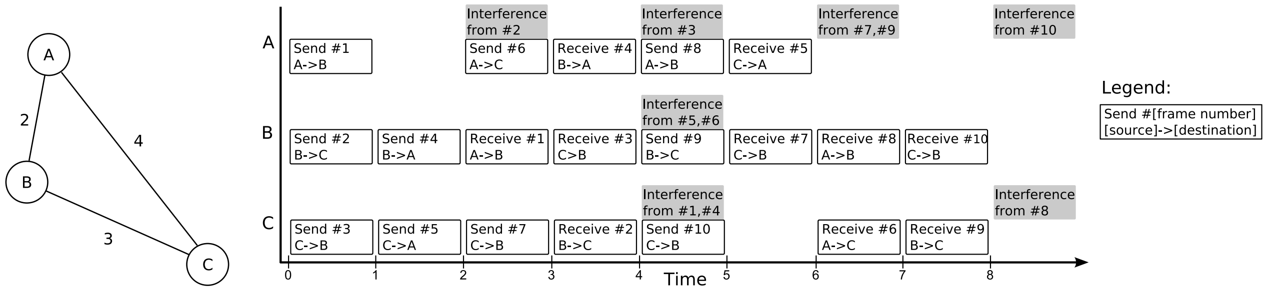

Figure 1: **(left)** Example topology and propagation delays and **(right)** one possible transmission schedule.

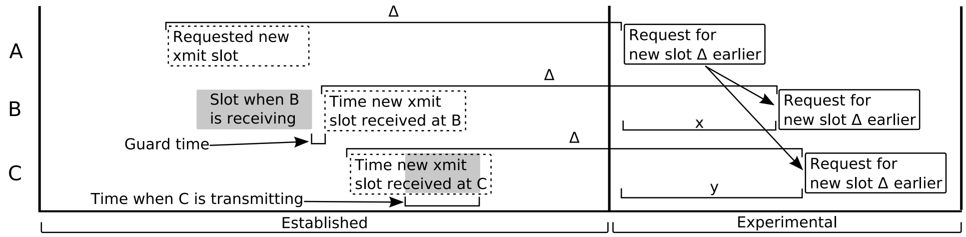

Figure 2: Example where node A transmits a request for a new slot. Times are **not** drawn to scale.

nodes should not also be received. This definition only indirectly specifies when other transmissions may take place relative to the time of the transmission intended for the receiver in question. These guard times are therefor intended to avoid collisions not due to the fixed propagation delays between nodes, but due to clock skew and small or gradual fluctuations in individual propagation delays. Collisions in the acoustic medium due to the fixed propagation delays can not be efficiently addressed by guard times, instead our protocol addresses collisions on an individual basis when transmissions are being scheduled.

III. Protocol Overview

In our protocol, time is divided into cycles of fixed size as in TDMA, but transmission slots may have arbitrary offsets and sizes. The cycle is divided into a small experimental period with a duration equal to several propagation delays, and an established period with a duration much longer than the experimental period (e.g. 20 times longer). We assume boundaries between these periods are agreed upon to within one propagation delay using a protocol such as [3]. New slots are acquired as illustrated in Fig. 2, where node A sends a request at a random time during the experimental period. Node A selects a potential new slot in the established period and includes Δ on the request, the difference in time between the desired slot and when the request is sent. Using only Δ and the time the request was received, other nodes can determine the *exact* offset in the established period at which a transmission during A's requested slot will be received, *without* precise clock synchronization or knowledge of propagation delays x and y. This information is spread through A's neighborhood either by A transmitting at a low data rate, or by some nodes which can decode A's request forwarding both the Δ on A's request and the approximate offset when A's request was sent. Nodes which observed the channel to be busy but could not decode A's request can then use the forwarded Δ and observed busy time to precisely determine the slot being requested.

Each node then checks for conflicts, based on the observed signal strength and known times when the node is receiving transmissions for itself. If a conflict exists, the node sends a negative response to A in the next experimental period, suggesting one or more alternate Δ values which do not cause a conflict. Node A then sends a new request based on this feedback. Once no negative responses are received, A begins using the new slot. In the example in Fig. 2, A's request is approved because at node B the requested slot will be received at least one guard time away from B's existing receive slot, and at node C the requested slot will be received at a time when C is transmitting, which is allowed.

Over time, the transmission schedule is gradually built until all nodes are satisfied or no free times are available. Transmissions in the established period, which comprises the majority of the cycle, have a high success rate and can be tightly packed due to the small guard times. The relatively small experimental period only contains transmissions when the schedule is being changed, allowing this energy cost to be amortized over long periods of time. Thus, our protocol achieves high energy and channel efficiency.

References

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[3] A. Syed and J. Heidemann, "Time synchronization for high latency acoustic networks," in *IEEE Infocom*, Barcelona, Spain, April 2006.