Short Paper: A Reservation MAC Protocol for Ad-Hoc Underwater Acoustic Sensor Networks

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ABSTRACT

In this paper we propose a new MAC protocol for ad-hoc underwater acoustic sensor networks that segregates the available bandwidth into a (small) control channel and a (majority bandwidth) data channel. Reservations for main channel time are made by transmission of Request-to-Send(RTS) packets on the control channel. The effects of channel segregation are explored and simulation results are presented. We find that such a reservation MAC generally achieves good channel utilization with an optimal control channel bandwidth for a given data bandwidth.

Categories and Subject Descriptors

C.2 [**Network Protocols**]: Protocol Architecture

General Terms

Algorithms, Design

Keywords

Underwater Sensor Network, MAC Protocols, Reservation MAC, Acoustic Communications

1. INTRODUCTION

Underwater (UW) observatories such as the NEPTUNE [1] project are being increasingly planned and deployed as a critical component of monitoring our ocean environment. Naturally, this entails design and deployment of wide area UW sensor networks whereby a mix of fixed and mobile (autonomous undersea vehicles) nodes are interconnected using acoustic communications for cost effective data transport. The acoustic channel, however, is characterized by long propagation delays, large delay spreads, and frequency dependent fading. The combination of these effects - specially, the large end-to-end propagation delay for any reasonable network size - sets it apart from traditional terrestrial wireless communication scenarios. Consequently, the design of a suitable MAC with high throughput as well desired energy efficiency for this challenging environment is still a work-in-progress.

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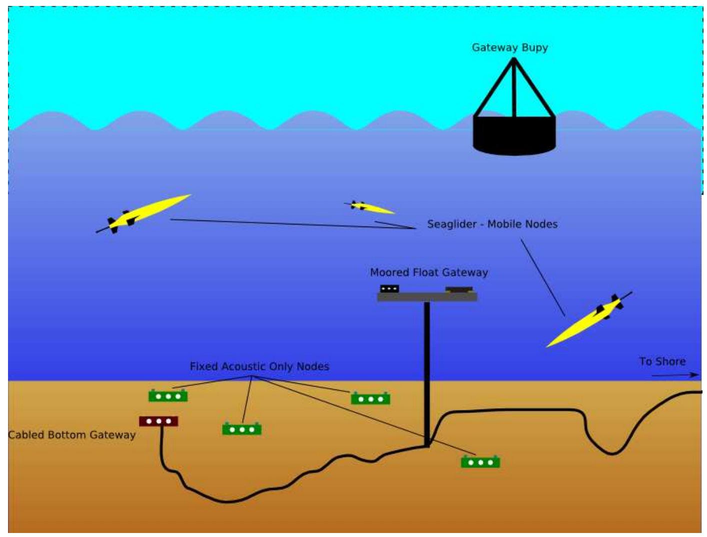

Figure 1: Common underwater network scenario

In this paper, we consider a simple underwater sensor network (USN) consisting of gateway (a node connected directly to the backbone network via wire) and non-gateway nodes (whose primary task is to relay data wirelessly towards the gateway nodes) as shown in Fig. 1. The gateway nodes may be cabled to the sea floor with wired connectivity to shore or surface buoys equipped with RF modems and significant battery power; the other fixed and mobile non-gateway nodes are typically much more power limited.

MAC protocol design for such a network faces interesting challenges not found in terrestrial networks. Long propagation delays amplify the throughput penalty of handshaking protocols. The acoustic channel is severely band limited (usually on the order of a few kilohertz), resulting in data rates much lower than those expected in terrestrial networks. Finally, due to excessive medium attenuation, acoustic modems generally require transmission power that are an order of magnitude larger than terrestrial RF for the same ranges.

As befits our preliminary investigations, we limit ourselves to the simplest of network scenarios for evaluation of our proposed MAC protocol: a single 'cell' where all nodes are in mutual range. The UW channel is ideal, i.e. we ignore attenuation effects and packet loss due to channel fading to focus solely on the impact of packet collisions [1] Several UW MAC protocols have been proposed to mitigate collisions in the UW channel which come largely in two flavors. The first - such as, [2] and [3] use variants of Aloha for fully distributed, random channel access. On the other hand, [4], [5] and [6] propose handshaking based protocols - e.g. use CTS/RTS exchanges - prior to data transmission. A general consensus has emerged that while pure random access techniques (e.g. Aloha variants) achieve good efficiency under light loads, channel reservation approaches are the better choice in denser networks with medium to heavy loads and/or bursty traffic [7]. In this work we focus on MAC design for moderately dense networks with the need to scale to heavy load conditions. Hence we propose a new protocol termed Reservation Channel Acoustic Media Access Protocol (RCAMAC) based on RTS/CTS handshaking. Our MAC seeks to improve channel utilization via the introduction of a separate (control) channel for RTS/CTS transmissions. By transmitting short RTS packets on an orthogonal low bandwidth control channel, we maximize utilization of the majority bandwidth main channel by minimizing the probability of data packet collisions. We seek to attain performance benefits similar to those reported in [6] without requiring a priori time synchronization or node placement information.

We first provide a description of our proposed MAC protocol, then derive an upper bound on throughput, and finally present the simulation results. While we believe RCAMAC to be applicable to more complex multi hop, multi gateway networks, this initial work provides a proof of concept for single hop, single gateway networks.

2. MAC DESCRIPTION

Nodes wishing to access the common channel send short RTS packets on the dedicated control channel to schedule time on the data channel. The gateway nodes receive all such RTS packets and schedules future data packet transmissions while concurrently receiving previously scheduled data packets. We also exploit a-priori information regarding which nodes are fixed and mobile, respectively, to further increase throughput via optimized scheduling.

We next invoke a few key assumptions underlying the MAC design:

- A node can transmit on both channels simultaneously.
- Data and control channels are truly orthogonal and simultaneous reception on both channels is allowed.
- However, a node transmitting on the data channel may not receive on the control channel and vice versa (i.e. full duplex communication is not allowed since nodes only have a single radio interface).

2.1 Basic MAC Operation

A typical timeline for data transmission in the proposed protocol is shown in Fig. 3. The basic tenet of MAC operation is simple: non-gateway nodes with data to transmit request reservation slots on the main channel by transmitting an RTS packet on the control channel. Nodes may queue packets and request to send multiple data frames via a single RTS packet. Gateway nodes will monitor the control channel for incoming RTS packets while not transmitting and will schedule contiguous blocks for incoming data packets. After receiving all currently scheduled packets, the gateway will send out CTS packets to nodes who are scheduled for the next cycle. Acknowledgement frames will be sent out after reception of all successful data packets prior to sending CTS packets for the next cycle. The contents and sizes of control packets are shown in Fig. 2.

Non-gateway nodes first associate themselves with a gateway node by transmitting a short GWPING packet. Gateway nodes which receive the GWPING packet will communicate amongst themselves to determine which gateway should receive data from the sensor node. This may be either the gateway closest (shortest propagation delay) to the non-gateway node or possibly the gateway which receives the GWPING packet with highest SNR. The optimum gateway will respond with a CTS packet when the node is scheduled.

RTS and GWPING packets are sent on the control channel randomly (i.e. via Aloha access). If a CTS packet is not heard within a specified timeout period - RTSTO - the RTS packet must be resent. We impose a simple exponential backoff algorithm in which a node invokes an additional random backoff period beyond RTSTO to avoid future collisions.

2.2 Scheduling

In order to facilitate scheduling of frames from multiple nodes, the gateway includes in the CTS packet a value for the delay-until-transmission (with respect to the transmission of the CTS frame); this defines the transmission time of the data frame for that node. In order to ensure collision free reception of all acknowledgements and CTS packets, nodes must not begin transmission of data frames until all CTS frames have 'passed' the transmitting node in the water. This is accounted for in [6] and [8] by allowing a full propagation delay between the end of CTS transmission and beginning data transmission. In RCAMAC the measured propagation delay in the handshaking is included in the data packet header. This previously measured propagation delay is then used as the minimum delay between the end of the final CTS transmission and the time a node may begin transmitting a data packet. This is sufficient to avoid collisions due to the fact that no nodes within range of the gateway transmit on the data channel unless a CTS is received. A transmission cycle is begun by scheduling the (fixed) node nearest to the gateway to transmit first. For mobile nodes and nodes without a previously recorded propagation delay, the maximum possible propagation delay is assumed.

Coarse synchronization is achieved by including time stamps in RTS, GWPING, and CTS packets. The RTS/CTS exchange allows the requesting node to induce the offset between its own clock and the gateway clock [9]. The propagation delay learned from the timestamps in RTS and CTS packets is then included in the data packet. This method of computing offset does not account for clock drift, so a Short Interframe Spacing (SIFS) is introduced between scheduled data packets to account for timing errors introduced by clock drift, variable propagation delays and processing delays over a packet duration.

[1]We conservatively assume that any two (or more) overlapping packets are lost.

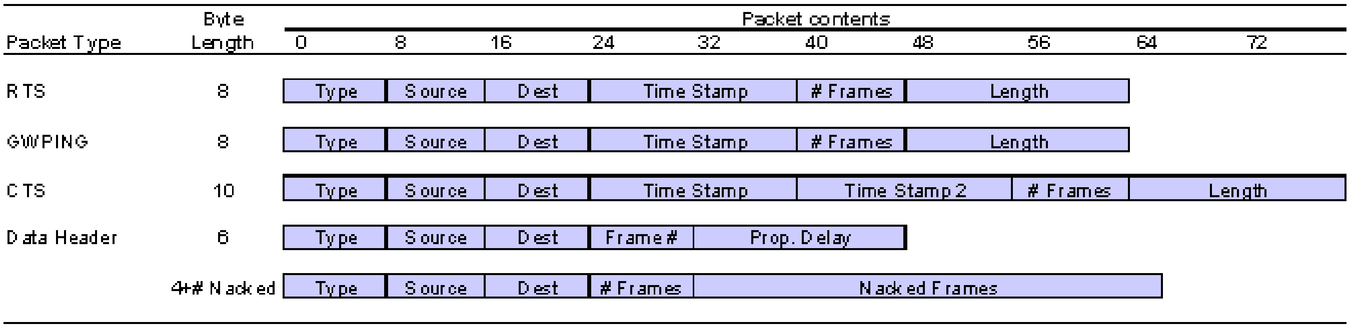

Figure 2: Contents of control packets

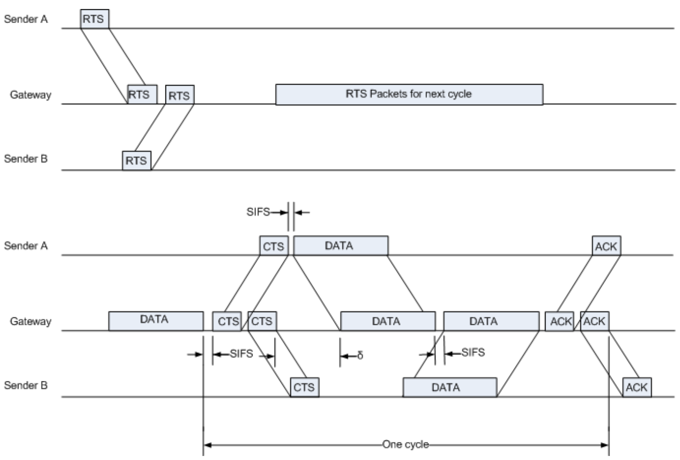

Figure 3: Typical cycle using dedicated control channel. *Top:* Control channel, *Bottom:* Main channel

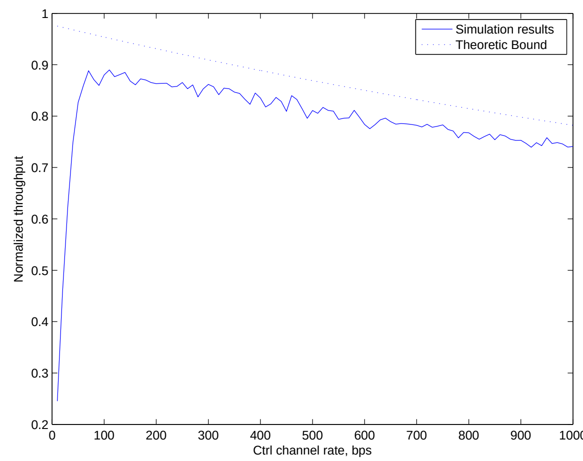

Figure 4: Throughput vs Control Channel Rate at offered load of 1.0

3. LONG TERM AVERAGE CHANNEL UTILIZATION

We assume the total available system bandwidth corresponds to a net rate of R, that is split into control channel rate R_c and data channel rate R_m. Furthermore we assume that $R = R_c + R_m$. Referring to Fig. 3 we see that over a single cycle, the utilization of the data channel given N scheduled packets is

$$U_m = \frac{\gamma T_{data}}{T_{cts} + T_{data} + T_{ack} + 3SIFS + \frac{2\delta}{N}} \qquad (1)$$

where T_x is the transmission delay of packet type x. γ is the fraction of useful data contained in a data packet, and δ is the one-way propagation delay allowed for CTS packet reception. For N large, the long term throughput will begin to approach

$$S = \frac{R_m \gamma T_{data}}{R(T_{cts} + T_{data} + T_{ack} + 3SIFS)} \qquad (2)$$

which gives an upper bound for performance of this protocol. Simulation results presented later show that measured utilization nearly achieves the above analytical limit for a fixed number of nodes when nodes are allowed to queue data. Under these circumstances, the average length of data frames per RTS grows which effectively implies large T_{data}.

4. SIMULATION

We implemented our protocol in the popular freeware network simulator ns2; the simulation code is available at [10]. For these simulations, new link and MAC layers were developed that follow the assumptions described earlier. The speed of sound was assumed to be a constant 1500 m/s. We ran simulations of 32-node single hop networks in which nodes were uniformly distributed in a 2km by 2km square region with a gateway node at the center of the region. Packets were generated according to a Poisson distribution at nodes and were destined for the gateway node. We limited the gateway node to scheduling 30 seconds of data packets and set RTSTO to 35 seconds. Results reported are based on an average of seven 2000 second simulations.

We first ran simulations with 1 KB packets and altered the data rate of the control channel from 10bps to 1000bps while keeping the data channel bandwidth fixed at 4 Kbps. For each control channel rate, we simulated Poisson traffic at an offered load of 1.0. Fig. 4 shows throughput at each of the control channel rates. We see from the plot that the optimum throughput of approximately 0.89 was attained at

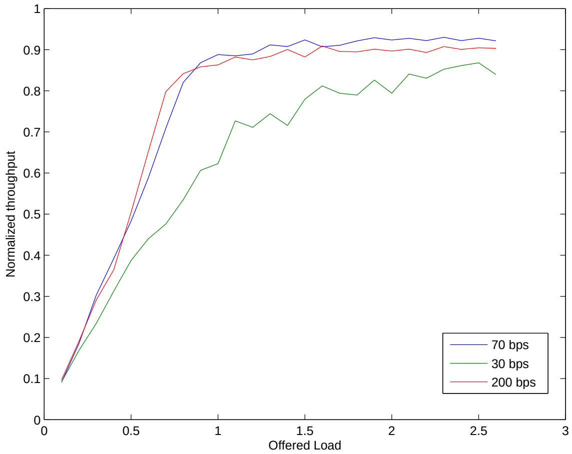

Figure 5: Throughput vs Offered load at several control channel rates

a control channel rate of 70 bps. Fig. 5 shows the simulated throughput at several different control channel rates over offered loads from 0.1 to 2.6.

In order to measure protocol energy efficiency we assumed that the (transmit) power budget available to each node for the entire available bandwidth is P_t watts. A node transmitting on the control channel thus consumes $P_c = R_c P_t / R$ watts and the data channel $P_m = R_m P_t / R$ watts. We also note that in typical UW networks, the overall power budget is dominated by power consumed during transmission, as compared to receive and idle powers [11]. We can then estimate the power efficiency of the protocol at non gateway nodes to be

$$P_{energy-eff} = \frac{\sum_i \frac{R_m}{R} T_{data,i}}{\frac{R_c}{R}(\sum_j T_{rts,j} + \sum_k T_{gwping,k}) + \frac{R_m}{R}\sum_l T_{data,l}}$$

where $T_{data,i}$ is the time spent receiving received packet i and $T_{rts,j}$, $T_{gwping,k}$ and $T_{data,l}$ are the time spent sending RTS, GWPING, and data packets respectively.

Over offered loads 0.1 to 2.5 at the optimal control channel rate of 70 bps, the power efficiency was approximately 0.98 confirming our hypothesis. We note that we observed no collisions in our simulations. This feat was made simple due to the lack of timing errors in our simplified model, however this may be feasible by including a SIFS period large enough to account for any errors induced by clock drift and variations in propagation delay.

5. CONCLUSION

Our presented MAC protocol provides an efficient method for moving data from sensor to gateway nodes in UW ad hoc sensor networks. Our work presents a potential new direction for good channel utilization and power efficiency without requiring a priori time synchronization for a small, dense single-hop network. Future work will focus on extending this design to multi-hop ad hoc UW sensor networks.

6. ACKNOWLEDGEMENTS

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