Distributed CDMA-based MAC Protocol for Underwater Sensor Networks

Hwee-Xian TAN
Department of Computer Science
School of Computing
National University of Singapore
hweexian@comp.nus.edu.sg

Winston K. G. SEAH
Network Technology Department
Institute for Infocomm Research, A*STAR
21 Heng Mui Keng Terrace, Singapore 119613
winston@i2r.a-star.edu.sg

***Abstract*— Underwater Sensor Networks are typically distributed in nature and the nodes communicate using acoustic waves over a wireless medium. Such networks are characterized by long and variable propagation delays, intermittent connectivity, limited bandwidth and low bit rates. Due to the wireless mode of communication between the sensor nodes, a Medium Access Control (MAC) protocol is required to coordinate access to the shared channel and enable efficient data communication. However, conventional terrestrial wireless network protocols that are based on RF technologies cannot be used underwater. In this paper, we propose PLAN – a MAC *P*rotocol for *L*ong-latency *A*ccess *N*etworks that is designed for use in half-duplex underwater acoustic sensor networks. We utilize CDMA as the underlying multiple access technique, due to its resilience to multi-path and Doppler's effects prevalent in underwater environments, coupled with an RTS-CTS handshaking procedure prior to the actual data transmission. Using simulations, we study the performance and efficiency of the proposed MAC protocol in underwater acoustic networks.**

Keywords-underwater sensor networks, medium access control, CDMA, acoustic communications.

I. INTRODUCTION

Underwater Sensor Networks (UWSNs) can be used for a wide range of collaborative applications, such as environmental monitoring, early warning systems, tactical surveillance, assisted navigation and exploration of valuable minerals located underwater. They typically comprise groups of sensor nodes and/or Autonomous Unmanned Vehicles (AUVs) that communicate with each other via wireless multi-hop communications. Each node in the network acts as a host as well as a router to forward packets to other nodes in the network, thus forming a distributed network that is autonomous in nature. The sensed data is usually sent to one or more sinks that are located onshore and/or connected via high bandwidth links to backend servers, for real-time processing and analysis.

Due to the wireless mode of communications in UWSNs, the nodes are vulnerable to the hidden/exposed terminal problems that are intrinsic of ad hoc networks which communicate via a shared medium without centralized control. To alleviate the complications associated with the hidden/exposed nodes and to coordinate access to the shared communication channel in terrestrial wireless networks, various multiple access techniques such as TDMA, FDMA and CDMA, as well as their variants/combinations have been established [1]. While there have been vast research efforts dedicated to improve the Quality of Service (QoS) support in terrestrial wireless ad hoc networks at the Medium Access Control (MAC) layer, these protocols are unlikely to be directly applicable in UWSNs due to the distinct differences in the physical environment. UWSNs are more resource-constrained (in terms of energy and bandwidth) and suffer from long propagation delays that are at least five orders of magnitude of their terrestrial counterparts [2]. In addition, the temporal property of the underwater links makes UWSNs less predictable in terms of resource availability and reliability, and also makes it difficult to incorporate time synchronization between nodes.

Consequently, suitable access schemes have to be developed to enable efficient communication in underwater wireless environments. In the literature, there are increasingly more research efforts that focus on designing MAC protocols for underwater communications. However, most of these protocols still employ RF channel acquisition methods such as carrier sensing; hence they may not be very efficient in underwater acoustic environments with particularly low bandwidths, variable delays and severe energy constraints.

In this paper, we propose PLAN – a distributed MAC Protocol for Long-latency Access Networks which can be used for half-duplex wireless sensor networks. CDMA is used as the underlying multiple access technique due to its collision-free and multipath-resilient properties. We also study and compare the performance of the proposed protocol with existing MAC protocols through simulations.

The rest of this paper is organized as follows: Section II discusses related work and motivation. Some preliminaries are introduced in Section III. In Section IV, we detail the design of our CDMA-based MAC protocol. The performance of PLAN is studied via extensive simulations in Section V. We conclude with directions for future work in Section VI.

II. RELATED WORK AND MOTIVATION

A key reason why current terrestrial Radio-Frequency (RF) based MAC protocols [3][4][5] cannot be directly used in UWSNs is that they do not cater for the harsh physical characteristics of the underwater channel. There are a few proposed frameworks for underwater sensor MAC protocols, but generally very little analysis and research that explores their suitability in underwater networks.

In general, MAC protocols can be classified as deterministic (e.g. TDMA and FDMA) or non-deterministic (e.g. ALOHA, CSMA, MACA, MACAW and IEEE 802.11). The latter is also known as random access protocols, which are contention-based in nature, i.e. nodes compete to transmit data at various times and access to the channel is not guaranteed. As such, contention-based protocols are unable to provide the QoS guarantees required by real-time data transmissions.

A. Multiple Access Techniques

The three types of multiple access techniques are TDMA, FDMA and CDMA. In TDMA, only one user is granted channel access at any one time; any other node which attempts to transmit during the same time slot will result in collisions and packet losses. The main problem of utilizing TDMA schemes in UWSNs is that the communication channel is susceptible to long and variable propagation delays. Consequently, long time guards must be used to minimize the occurrence of collisions during data transmissions, leading to channel underutilization. FDMA is also unsuitable for underwater environments due to the limited bandwidth as well as prevalence of multi-path and fading effects. The use of CDMA in UWSNs has thus been advocated due to its resilience to multi-path and Doppler effects [6][7][8].

B. Existing Work on Underwater MAC Protocols

Majority of the existing underwater MAC protocols [6][9][10][11][12][13] adopt the handshaking protocol that was originally proposed in MACA (Multiple Access with Collision Avoidance). In MACA [14], a three-way handshake involving the exchange of RTS-CTS-DATA is used to establish connectivity between source-destination pairs. Some of these proposals also incorporate power control and ARQ (Automatic Repeat reQuest) techniques to improve their reliability and performance.

Hybrid CDMA/TDMA approaches that group nodes into clusters have also been proposed [15][16]; intra-cluster access is achieved via time scheduling while inter-cluster access makes use of CDMA. Other MAC protocols that have been designed for underwater networks include: a centralized CDMA-based approach [17]; the use of carrier sensing, ARQ techniques and acknowledgements [18]; and a distributed MAC protocol that makes use of sleep-wakeup schemes to achieve energy-efficiency [19].

C. Motivation

From the previous subsection, we can see that majority of the existing work adopt the three-way RTS-CTS-DATA handshaking protocol. A main drawback of this three-way handshake is that the control packets take quite long to propagate through the network, thus reducing the effective utilization of the communication channel. In addition, the use of TDMA as the underlying multiple access technique requires long guard times in underwater channels due to the long and variable propagation delays. The feasibility of CDMA as a collision-free and multipath-resistant multiple access technique in underwater channels thus motivates us to propose a CDMA-based MAC protocol to coordinate channel access efficiently in the harsh physical environment.

III. PRELIMINARIES

In Direct Sequence (DS) CDMA systems, each node encodes its signal with a unique pseudo-random noise codeword (PN sequence) before transmitting. The transmitted signal is spread over a larger bandwidth as compared to the original non-spread bandwidth. The receiver will then make use of a correlator to despread the individual signals, which passes through a narrow bandpass filter. This spread-spectrum technology that is being adopted by CDMA allows multiple nodes to transmit concurrently within the same time or frequency dimension, which is not achievable using TDMA or FDMA techniques. Hence, CDMA techniques are able to provide more capacity than other multiple access techniques due to their collision-free properties. In addition, CDMA is resilient to Doppler's effects and variable propagation delays, which are prevalent in UWSNs.

A. Network Model and Assumptions

We consider an underwater sensor network that is half-duplex in nature [20], i.e. nodes can either transmit or receive only at any one time. The network is modeled as an undirected graph $\boldsymbol{G} = (\boldsymbol{V}, \boldsymbol{E})$, where $\boldsymbol{V}$ represents the set of vertices (or nodes) and $\boldsymbol{E} \subseteq \boldsymbol{V} \times \boldsymbol{V}$ represents the set of edges in the network. Any two arbitrary nodes in the network $\boldsymbol{v_i}, \boldsymbol{v_j} \in \boldsymbol{V}$ share a common edge $\boldsymbol{e_{ij}} \in \boldsymbol{E}$ if they are within the transmission range of each other. If the source and destination nodes are not adjacent to each other, they may communicate using multi-hops via intermediate nodes, should such a path exist.

The propagation speed of acoustic waves underwater is taken to be the speed of sound (1500 ms^{-1}). The propagation loss model is taken to be the spherical spreading model [21]:

$$\mathrm{TL}_{\mathrm{spherical}} = 20 \log_{10} \boldsymbol{R}. \tag{1}$$

where $\boldsymbol{R}$ is the radial distance from the source. In addition, the signal suffers from attenuation loss:

$$\mathrm{TL}_{\mathrm{att}} = \alpha \boldsymbol{R}. \tag{2}$$

where $\boldsymbol{\alpha}$ is the attenuation coefficient defined by Thorp's equation [22].

B. CDMA Code Distribution

To allow for simultaneous transmissions within the system, nodes are expected to transmit and/or receive data over multiple codes. Due to the lack of infrastructure and centralized control in the sensor network, we assume the presence of a distributed TOCA (Transmitter-Oriented Code Assignment) based algorithm [23] which can assign a limited set of orthogonal PN codes to the individual nodes for signal modulation. The TOCA scheme is preferred over ROCA (Receiver-Oriented Code Assignment) or POCA (Pairwise-Oriented Code Assignment) schemes as the latter two are susceptible to hidden terminal effects. Considering any three arbitrary nodes $\boldsymbol{v_i}, \boldsymbol{v_j}, \boldsymbol{v_k} \in \boldsymbol{V}$ that are connected such that $\boldsymbol{e_{ik}}, \boldsymbol{e_{jk}} \in \boldsymbol{E}$, the code assignment algorithm should ideally assign a finite set of CDMA codes $\{\boldsymbol{c_1}, \boldsymbol{c_2}, \ldots, \boldsymbol{c_n}\} \in \boldsymbol{C}$ to all the nodes in the network such that any arbitrary pair of two-hop neighbors $\boldsymbol{v_i}$ and $\boldsymbol{v_j}$ use different codes, i.e. $\boldsymbol{v_i} \leftarrow \boldsymbol{c_x}$, $\boldsymbol{v_j} \leftarrow \boldsymbol{c_y}$ and

$x \neq y$. Hence, each node uses a single code for transmission, but is assumed to be equipped with a small number of receivers (or matched filters) such that it can decode the signals from its one-hop neighbors.

IV. PROTOCOL FOR LONG-LATENCY ACCESS NETWORKS

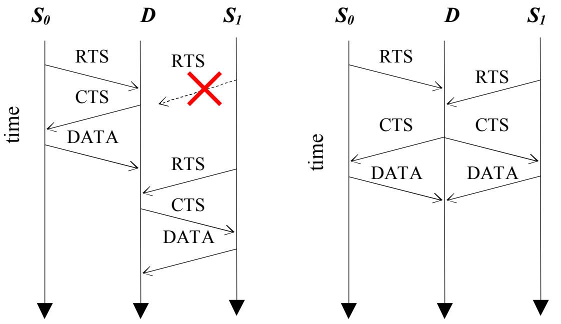
In this section, we provide the details of PLAN – our distributed CDMA-based MAC Protocol for Long-latency Access Networks.

A. *Control Messages*

1) RTS (Request-To-Send): A node that has unicast data packets to send will transmit a RTS to its intended destination.

2) CTS (Clear-To-Send): Upon receiving a RTS packet from its neighbor, the node will respond with a local broadcast CTS packet after a finite waiting time.

B. *Basic Algorithm Operation*



(a) (b)

Figure 1 Handshaking in (a) MACA (b) PLAN

PLAN makes use of the RTS-CTS dialogue, with the main difference being that multiple RTS packets from different source nodes (S_0 and S_1) are collated by the destination node D before the transmission of a single CTS (broadcast) packet (see Figure 1).

In this way, we can exploit the ability of CDMA-based systems to receive concurrently from multiple sources which utilize different codewords, and thus improve the network throughput while minimizing packet losses arising from unsynchronized data transmissions. Another advantage of this scheme is that it reduces the number of control packets being sent, by sending one CTS for a few accumulated RTS packets, in contrast to conventional MACA-based schemes which send one CTS for each received RTS. Consequently, the energy consumed by the nodes is also reduced.

C. *Timers*

The following timers are used in PLAN:

1) YIELD_TIMEOUT: When a node wants to send data, it waits for a YIELD_TIMEOUT period before transmitting a packet (either broadcast data packet or RTS packet for unicast data). The value of YIELD_TIMEOUT depends on the priority of the packet.

2) BACKOFF_TIMEOUT: A node which enters the backoff state has to defer for a BACKOFF_TIMEOUT period before it is allocated a chance to access the shared wireless channel again. The conditions under which a node enters the backoff state will be described in subsequent sections.

3) CTS_TIMEOUT: After sending a RTS, a node waits for a maximum of CTS_TIMEOUT for the corresponding CTS to arrive. If the CTS is not received when the CTS_TIMEOUT expires, the node will then perform a backoff.

4) RTS_TIMEOUT: The RTS_TIMEOUT is initiated when the node receives a RTS and is waiting for subsequent RTS packets from other nodes before transmitting a broadcast CTS. When the RTS_TIMEOUT expires, the node will send a CTS to all its neighbors to indicate that it is ready to receive data.

5) DATA_TIMEOUT: To prevent a node from waiting for data packets infinitely, the DATA_TIMEOUT is set as the maximum time that a node spends waiting for data.

The specific values of the different timer values are shown in Table I.

TABLE I
PARAMETERS USED IN PLAN

Parameter	Value
YIELD_TIMEOUT	Variable; depending on traffic and/or node priority.
BACKOFF_TIMEOUT	Variable; between the minimum and maximum backoff windows.
CTS_TIMEOUT	$2 \times \boldsymbol{delay}_{\text{max\_prop}}$ + RTS_TIMEOUT
RTS_TIMEOUT	$\beta \times \boldsymbol{delay}_{\text{max\_prop}}$ $(0 < \beta < 1)$
DATA_TIMEOUT	$2 \times \boldsymbol{delay}_{\text{max\_prop}}$

$\boldsymbol{delay}_{\text{max\_prop}}$ is dependent on the expected maximum inter-nodal distance and speed of communication (speed of sound ≈ 1500 ms^{-1}).

β is a parameter that can be adjusted based on the expected packet arrival rate of the nodes in the network; larger β values can be used for lower packet arrival rates to reduce overheads.

D. *Backoff Mechanism*

The backoff mechanism is triggered whenever any of the following conditions occur: (i) the channel becomes busy before the YIELD_TIMEOUT expires; or (ii) the CTS_TIMEOUT expires before a node receives CTS from its intended destination.

MACA and the IEEE 802.11 standard use the Binary Exponential Backoff (BEB) algorithm, which is known to suffer from fairness issues as nodes can achieve significantly varying levels of throughput. MACAW uses Multiplicative Increase Linear Decrease (MILD), which is able to provide a reasonable level of per-stream fairness. We use a slight variant of the MILD backoff mechanism, which works as follows:

$$F_{inc}(\text{counter}) = \min\{(2 \times \text{counter}),\, c_{max}\}. \tag{4}$$

$$F_{dec}(\text{counter}) = \min\{(\text{counter} - 1),\, c_{min}\}. \tag{5}$$

where c_{min} and c_{max} are the minimum and maximum backoff window sizes respectively; and counter is the backoff counter used to determine the value of BACKOFF_TIMEOUT.

Whenever the backoff is triggered, the node defers its channel access for a duration that is randomly selected within the value of counter (which is initially set to c_{min}). The counter is then incremented and the maximum backoff timeout is set to F_{inc}(counter). If the channel becomes busy before the BACKOFF_TIMEOUT expires, the remaining delay is saved and added to the YIELD_TIMEOUT the next time the node attempts to gain access to the channel. The maximum backoff timeout value is set to F_{dec}(counter) when any one of the following conditions occur: (i) the channel remains idle during the entire YIELD_TIMEOUT period; (ii) a node receives the corresponding CTS successfully before the CTS_TIMEOUT expires; or (iii) a node successfully transmits its data packet.

E. Transition Diagram

The simplified state transition diagram of the MAC protocol design for the transmission of unicast packets is shown in Figure 2. Nodes that are transmitting broadcast packets will bypass the handshaking procedure. The corresponding transition conditions and actions are listed in Table II.

TABLE II
TRANSITION CONDITIONS AND ACTIONS FOR MAC LAYER MODEL

	Transition Condition	Action
1	Network layer has data to send and radio is idle.	Set YIELD_TIMEOUT.
2	Medium is busy before YIELD_TIMEOUT expires.	Update backoff counter; Set BACKOFF_TIMEOUT.
3	BACKOFF_TIMEOUT expires or packet is received.	Update remaining BACKOFF_TIMEOUT.
4	YIELD_TIMEOUT expires.	Send RTS; Decrease backoff counter; Set CTS_TIMEOUT.
5	CTS_TIMEOUT expires (without receiving CTS).	Update backoff counter; Set BACKOFF_TIMEOUT.
6	Receive RTS.	Set RTS-In-Queue.
7	Receive CTS or (YIELD_TIMEOUT expires and sending broadcast packet).	Send DATA.
8	Receive CTS.	Decrease backoff counter; Send DATA.
9	Finished DATA transmission and no RTS-In-Queue.	
10	Finished DATA transmission and RTS-In-Queue.	Set RTS_TIMEOUT.
11	Receive RTS.	Set RTS_TIMEOUT.
12	Receive RTS.	
13	RTS_TIMEOUT expires.	Send CTS; Set DATA_TIMEOUT.
14	Receive DATA.	
15	DATA_TIMEOUT expires or finished receiving data.	
16	CTS_TIMEOUT expires and RTS_In_Queue.	Set RTS_TIMEOUT.

F. Key Characteristics

The key characteristics of our proposed MAC protocol are:

- Use of CDMA enables each node to receive packets from different neighboring nodes concurrently.
- Overheads are reduced by collating RTS from multiple nodes and sending a single broadcast CTS to indicate that a node is ready to receive data.

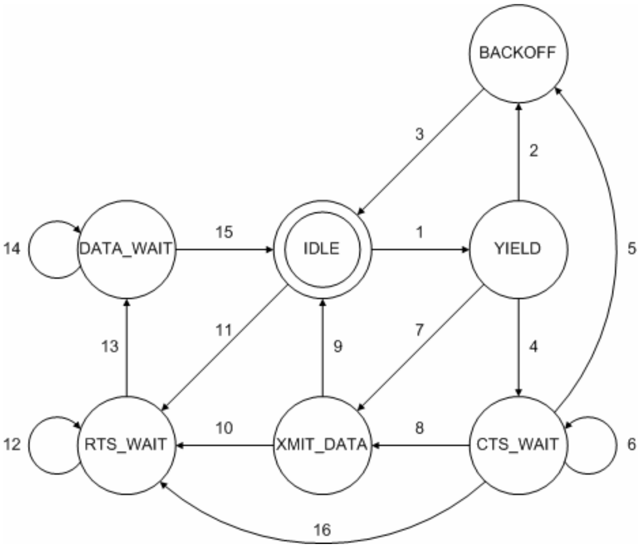


Figure 2 Simplified state transition diagram of PLAN

- Acknowledgements and data retransmissions are avoided to minimize the average end-to-end delays of a packet.
- MILD backoff algorithm is used instead of the BEB algorithm to ensure fairness among the data streams.
- Implicit prevention of starvation and/or deadlocks is achieved through the use of timeout values.
- Traffic and/or node prioritization is achieved with the use of varying values for the yield timers. A shorter YIELD_TIMEOUT allows nodes to send data earlier than its neighboring nodes.
- Traffic and/or node prioritization can also be achieved by adaptively adjusting the value of the RTS_TIMEOUT based on the priority of the received RTS packet.

V. PERFORMANCE ANALYSIS

We study the performance of PLAN using extensive simulations performed in Qualnet [24]. Each simulation is run with 20 different seeds to minimize any randomness.

A. Network Architecture and Environment

We consider the network architecture as illustrated in Figure 3 and Figure 4, which is similar to that in [25]. In Figure 3, two pairs of data streams are set up in the network; each source node sends data traffic at an arrival rate of λ packets per second to the corresponding sink (which is two-hops away). In Figure 4, a 10-node string topology is set up with a single pair of source and sink. The source node sends data to the sink via multi-hops at a rate of λ packets per second. In addition, we investigate the scalability of PLAN by studying its performance in a grid topology with varying network sizes (Figure 5.) The sink is placed at the top right hand corner of the network; all the other nodes transmit data to the sink via multihops. This simulates a monitoring application whereby all the sensor nodes send data to the sink periodically. The common simulation parameters are listed in Table III.

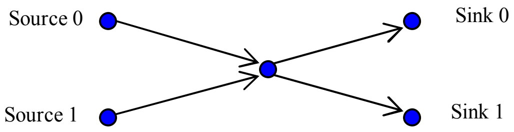


Figure 3 Two-hop network topology

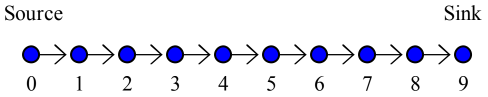


Figure 4 Ten-node string network topology

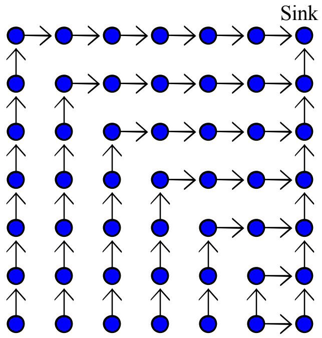


Figure 5 Grid network topology with 49 nodes

TABLE III
SIMULATION PARAMETERS

Parameter	Value
Inter-nodal distance	250 meters
Transmission range	≈ 300 meters
Interference range	≈ 600 meters
Data rate	300 kbps
Packet length	64 bytes
Channel frequency	15 kHz

For the purpose of comparison, we select Aloha with retransmissions (denoted as Aloha-R) and MACA protocols after modifying their parameters to suit the underwater environment. These two protocols are chosen for comparison as they are decentralized in nature and do not require carrier sensing, which can be unreliable in underwater acoustic conditions. In each of these protocols (Aloha-R, MACA and PLAN), we limit the number of control packets transmitted per data packet by limiting the number of permissible retransmission attempts. As two RTS attempts are allowed in MACA and PLAN, the maximum number of control packets per data packet is four (RTS-CTS-RTS-CTS-DATA). In Aloha-R, two data retransmission attempts are allowed; hence the maximum number of control packets per data packet is five (DATA-ACK-RETRANSMIT-ACK-RETRANSMIT-ACK).

As PLAN makes use of spread spectrum technology, each of its signals is spread by a factor ***F*** before transmission; consequently, the transmission time of the signal is ***F*** times that of the original signal. In our simulations, we consider ***F***=4. However, this value has to be varied according to network density. Larger ***F*** values should be used in dense networks to minimize MAI effects; however, this increases the packet length and transmission time of the packet by a factor of ***F***.

B. *Performance Metrics*

We evaluate the performance of the MAC protocols according to the following metrics:

- Normalized overheads – number of control packets generated as fraction of number of data packets received.
- Throughput – number of bits transmitted per second.
- End-to-end delay – time taken for a packet to be transmitted from the source to the destination.

C. *Simulation Results – Two-Hop Network Topology*

Figure 6 – Figure 8 show the performance of the network in the two-hop topology in Figure 3, under varying traffic conditions. As the packet arrival rate λ increases, the offered data load in the network increases correspondingly.

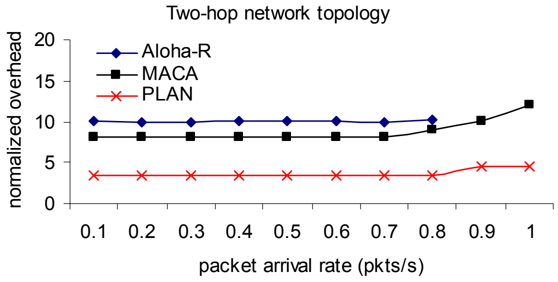


Figure 6 Normalized overhead vs packet arrival rate

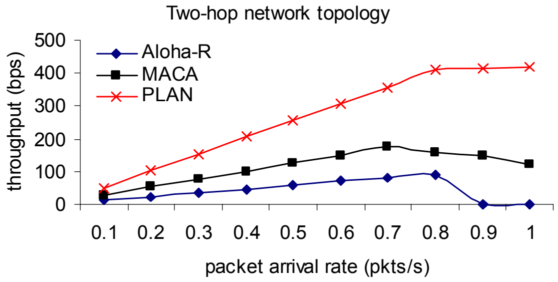


Figure 7 Throughput vs packet arrival rate

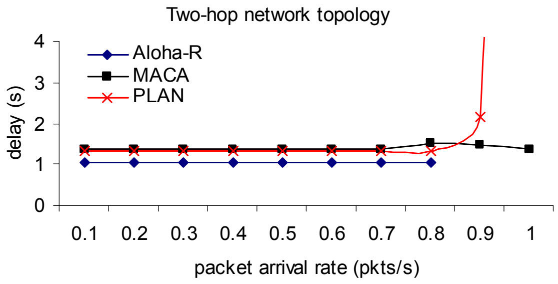


Figure 8 End-to-end delay vs packet arrival rate

The overheads in Aloha-R include both acknowledgements and retransmitted data packets. The lack of coordination in Aloha-R causes packet collisions, leads to retransmissions and contributes to high normalized overheads (see Figure 6). Hence, Aloha-R achieves very low throughput at low traffic loads and negligible throughput for λ≥0.9 (see Figure 7). The three-way handshake in MACA reduces collisions and packet loss in the network; subsequently, it can achieve better throughput at the expense of high normalized overheads. Although PLAN also utilizes the handshaking protocol, CTS is not sent immediately when a node receives RTS. Instead, a node collates multiple RTS packets (from Source 0 and Source 1 in our scenario) before sending a single broadcast CTS. In addition, its collision-free property allows it to receive packets from multiple sources simultaneously, thereby reducing packet losses and RTS retransmissions. Therefore, PLAN is able to achieve high throughput performance at low overheads.

MACA and PLAN incur higher delays than Aloha-R due to the long propagation delays incurred by the three-way handshake preceding each data transmission (see Figure 8). However, MACA and PLAN outperform Aloha-R in terms of throughput for all traffic loads. At high traffic loads, the performances of the three protocols differ significantly. At λ=0.7 and λ=0.8, MACA and Aloha-R reach saturation point respectively. For λ>0.7 and λ>0.8, throughputs of MACA and Aloha decrease respectively due to packet collisions. The delays for these two protocols decrease; however, this is due to less packets being transmitted successfully to their destinations.

For traffic loads of λ<0.9, PLAN incurs marginally less delays than MACA as the intermediate node collates multiple RTS packets which reduces propagation delays caused by transmission of individual CTS packets. As λ increases, the throughput of PLAN maintains at a maximum saturation level (note: unlike Aloha-R and MACA, whose throughputs decrease after saturation point) because the collision-free property of the underlying CDMA minimizes packet collisions and losses. However, the delay in PLAN increases exponentially after λ≥0.9 because the packet arrival rate exceeds the optimum capacity of PLAN.

D. *Simulation Results – String Network Topology*

We study the performance of the MAC protocols in the string network topology illustrated in Figure 4, where the source node sends data packets to the sink node via multiple hops in the network. In addition, we introduce traffic from the sink to the source at a rate of λρ packets per second, where 0<ρ<1. This is synonymous to simulating traffic from the sink, which is associated with time synchronization, querying or localization. Figure 9 to Figure 13 show the performance of the protocol for ρ=0.5. We have also studied the protocols using varying values of ρ (e.g. ρ=0.1) and obtained similar results.

In such string topologies where there is only a single source-destination pair, there are lesser packet collisions arising from transmission of packets to the same node. Hence, fewer retransmission attempts are required in Aloha-R as compared to the two-hop topology in Figure 3, resulting in low normalized overheads (cf: Figure 9).

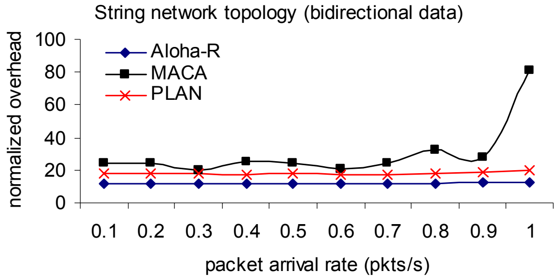


Figure 9 Normalized overhead vs packet arrival rate

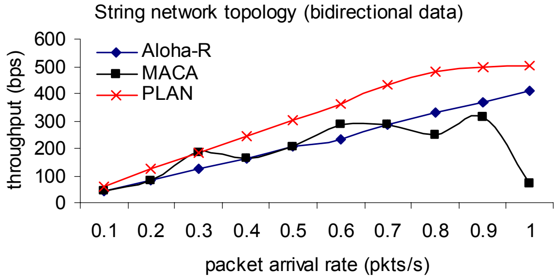


Figure 10 Throughput vs packet arrival rate

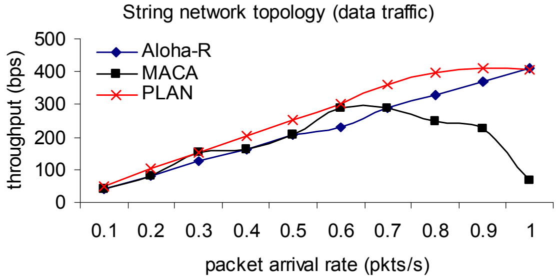


Figure 11 Data traffic throughput vs packet arrival rate

Although both MACA and PLAN make use of the RTS-CTS exchange before the actual data transmissions, the latter incurs lower normalized overheads as it is collision-free and requires lesser RTS retransmissions. Consequently, PLAN is able to achieve the best overall throughput performance (averaged from control and data traffic) among the three protocols (see Figure 10).

We also studied in further detail the individual throughput performances of the control and data traffic and found that Aloha-R and MACA were able to achieve reasonably good data traffic throughput performance (Figure 11). However, this is at the expense of erratic or negligible control traffic throughput (Figure 12). It can therefore be seen that PLAN is able to allocate bandwidth fairly to different traffic streams, while both Aloha-R and MACA suffer from fairness issues.

In Figure 13, PLAN incurs the highest delay because of the waiting time (i.e. RTS_TIMEOUT) to collate multiple RTS packets before responding with a single CTS. Collating RTS packets does not have additional benefits in string topologies where there is usually only one source-destination pair at any one time. Aloha-R achieves the lowest delay as it does not make use of handshaking.

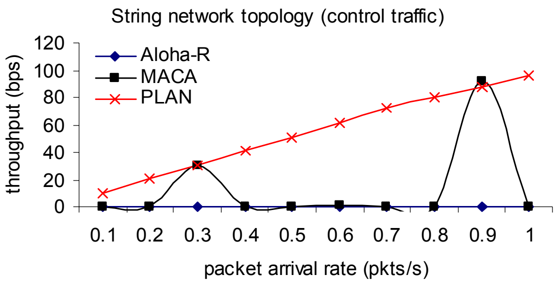


Figure 12 Control traffic throughput vs packet arrival rate

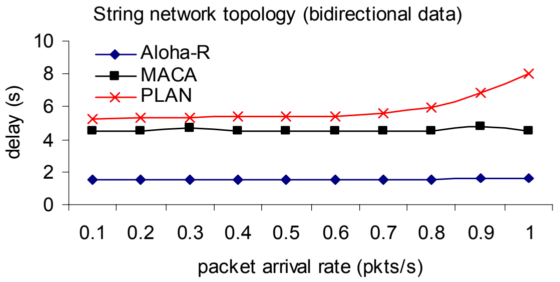


Figure 13 End-to-end delay vs packet arrival rate

E. Simulation Results – Grid Network Topology

We study the scalability of PLAN using a grid topology with varying network sizes and λ=1. Static routes are used to eliminate the effects of routing overheads. The CDMA code used by each node is also selected randomly; hence, collisions may still occur due to simultaneous transmissions by nodes that are using the same CDMA code.

From Figure 14, it can be seen that PLAN achieves the lowest normalized overheads as multiple RTS are collated before a CTS is transmitted. Despite the use of non-optimal possibly-conflicting CDMA codes, PLAN is still able to achieve the highest throughput as shown in Figure 15. This shows the effectiveness of PLAN as a multiple access protocol. The delay incurred by all the three MAC protocols is shown in Figure 16. PLAN incurs the highest delay as all intermediate destination nodes have to wait for at least RTS_TIMEOUT before transmitting CTS to the source nodes.

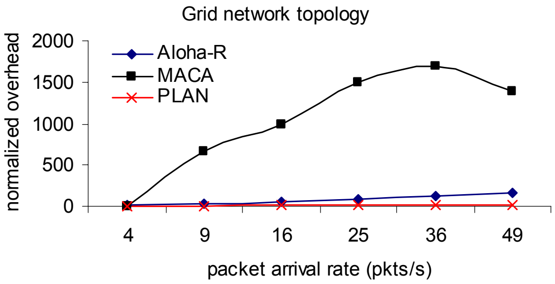


Figure 14 Normalized overhead vs network size

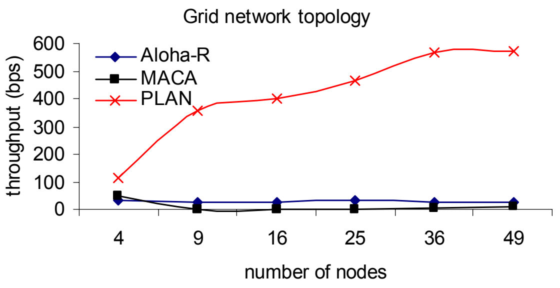


Figure 15 Throughput vs network size

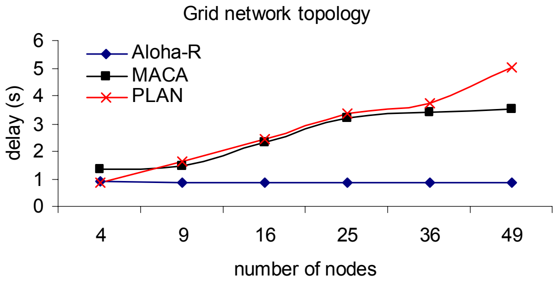


Figure 16 Delay vs network size

F. Discussion

Our simulation results show that the proposed MAC protocol is able to achieve good throughput performance under varying traffic loads and network sizes. As PLAN makes use of CDMA as its underlying multiple access technique, it is able to maintain its throughput at a maximum level after saturation point; generally, other protocols that make use of a common access channel will experience deteriorating throughput performance during high traffic loads (after saturation point).

In scenarios with multiple source-destination pairs, the advantages of collating multiple RTS packets are more significant and result in lower delays and overheads. However, in scenarios with single source-destination pairs, the RTS_TIMEOUT period which is used to collate multiple RTS may incur higher delays. As such, the RTS_TIMEOUT value should be adaptively adjusted based on the expected traffic arrival per node to achieve optimal network performance. Nevertheless, the use of a handshaking protocol for multiple access coordination is quintessential in half-duplex sensor networks without centralized control, as it can reduce packet losses and improve throughput performance significantly.

Although the exchange of RTS-CTS packets before data transmissions may incur higher delays due to the low propagation speeds of acoustic underwater networks, PLAN can reduce the overall end-to-end delay by minimizing packet collisions and retransmissions. One possible enhancement of PLAN is to aggregate multiple data packets during high traffic loads so that the handshaking process need not be performed for each data packet, which can further reduce the delays and overheads incurred. In addition, as shown from the simulations conducted using the string network topology with bidirectional traffic, PLAN is able to achieve fairness among various data streams without compromising the overall throughput performance.

VI. CONCLUSION AND FUTURE WORK

In underwater sensor networks, nodes face several constraints such as the harsh physical environment, energy limitations, long and variable propagation delays, as well as limited bandwidth. An efficient and effective MAC scheme is required to coordinate access to the shared communication channel. Typical terrestrial MAC protocols are unable to handle long propagation delays in underwater acoustic environments. Existing underwater MAC schemes are generally centralized in nature and therefore not scalable for large sensor networks, or have high control overheads.

In this paper, we propose ***PLAN*** – a distributed MAC ***P***rotocol for ***L***ong-latency ***A***ccess ***N***etworks which utilizes CDMA as the underlying multiple access technique to minimize multipath and Doppler effects which are inherent in underwater physical channels. The proposed MAC protocol involves a three-way handshake (RTS-CTS-DATA), which collates the RTS from multiple neighboring nodes before sending a single CTS. Despite its apparent simplicity as compared to other sophisticated sensor MAC protocols, it is able to achieve high throughput performance as it uses minimal overheads in view of severe energy constraints faced by sensor nodes. We have compared our scheme against Aloha (with retransmissions) and MACA which have been modified to suit the underwater scenario, and simulation results show that our scheme outperforms these two protocols in terms of higher throughput while incurring lesser overheads.

As future work, we will investigate the performance of PLAN with the integration of topology management schemes and/or suitable data dissemination protocols to prolong network lifetime and improve data delivery performance. We are also looking into a theoretical study of the protocol performance and the incorporation of a power control scheme to combat the near-far problem that is inherent in CDMA-based networks.

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