Experimental Demonstration of *Super*-TDMA: A MAC Protocol Exploiting Large Propagation Delays in Underwater Acoustic Networks

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***Abstract*—The potential of exploiting large propagation delays in underwater acoustic (UWA) networks to maximize the network throughput is established in the recent past. Transmission scheduling strategies have been proposed to take advantage of large propagation delay. Super-TDMA is one among such Medium Access Control (MAC) strategies proposed. It is a form of Time Division Multiple Access (TDMA) protocol in which multiple transmissions are allowed in the same time slot and hence concurrently propagate in the medium. We present the implementation challenges of Super-TDMA on underwater acoustic modems and the experimental results demonstrating interference alignment, the crossing of simultaneously transmitted packets in water, and the time synchronization among the deployed nodes in the network.**

I. Introduction

Wireless networks deployed in underwater environments mostly use acoustic waves to communicate among the nodes. When compared to terrestrial wireless networks which typically use radio-frequency (RF) signals, UWA networks have the low available bandwidth and large propagation delays. These unique characteristics do not allow us to use MAC protocols designed for terrestrial networks directly in UWA networks. Detailed surveys on advancements in the physical and the upper layer design for UWA communications and networking are presented in [1]–[4]. The large propagation delay of the acoustic channel and the half-duplex nature of the communication links are challenging issues to be considered in the transmission scheduling problems. Rather surprisingly, the positive impacts of the large propagation delay in UWA networks are presented in [5]–[10]. These sophisticated techniques proposed in the literature are backed with theoretical analysis and simulations to show that exploiting large propagation delays can result in achieving significantly higher throughput, even larger than what can be achieved in terrestrial wireless networks with negligible propagation delays [6]. However, these techniques do not take into consideration the constraints imposed due to the practical underwater acoustic modems. Modem constraints were introduced and the problem in [6] was extended to provide implementable schedules on modems in [11]. Although, the computed schedules from [11] are implementable, they were only tested in a tank and the results were presented in [11]. In this paper, we compute schedule for a deployed network at sea, implement it on the underwater acoustic modem and test them at sea to compare against the expected performance.

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TDMA schedules computed in [6] that can utilize the propagation delay unlike traditionally done are termed as Super-TDMA schedules. In order to exploit the large propagation delay in UWA networks, the transmitted packet duration and the time slot length adopted are comparable to propagation delays among the nodes, which in absolute terms are in the order of few hundreds of ms for the practical network sizes [6], [11]. The implementation of such schedules with the selected time slot lengths and the guard periods is challenging due to the strict timing-accuracy required along with the least timing-jitter in the transmission of the scheduled packets at such small time scales. Moreover, these schedules require frequent transitions between transmission and reception modes in the modem. Modems need to be configured at accurate times to transmit and receive successfully.

We deployed a 3 node UWA network in Singapore waters and use the technique presented in [11] to compute the schedule along with the time slot length and the guard periods and implement it on all three nodes along with time synchronization. In Section II, we present the practical Super-TDMA schedule computed for the 3 node network deployed. Next, we present a detailed overview of the implementation and challenges in Section III, followed by the experimental results in Section IV.

II. Practical Super-TDMA Schedules

In [6], many illustrative network geometries along with throughput-optimal transmission schedules were presented. We consider a linear network and present the delay matrix $\mathbf{D}$ (defined in [6, p. 648]) and the corresponding transmission schedule. Each element of the delay matrix $\mathbf{D}$ contains the propagation delay between the corresponding node pair in units of time slot length, i.e., D_{ij} denotes the propagation delay between node i and node j. For example, the delay matrix of a particular linear network can be

$$\mathbf{D} = \begin{bmatrix} 0 & 1 & 2 \\ 1 & 0 & 1 \\ 2 & 1 & 0 \end{bmatrix} \tag{1}$$

where the propagation delay between node 1 and node 2 is 1 unit of time slot length whereas node 1 and node 3 are separated by 2 units while node 2 and node 3 are separated by 1 unit. Also, note the delay matrix consists of elements which are integers. To use the algorithm from [6, p. 654] and compute the transmission schedule, the elements of the delay matrix $\mathbf{D}$ must be strictly integers. The transmission schedule

TABLE I
TRANSMISSION SCHEDULE FOR 3-NODE LINEAR NETWORK

	Time Slot 1	Time Slot 2	Time Slot 3
Node 1	TX to 3	TX to 2	RX from 3
Node 2	TX to 3	IDLE	RX from 1
Node 3	TX to 1	RX from 2	RX from 1

TABLE II
DISTANCE MATRIX OF THE SEA-TRIAL 3-NODE NETWORK

	Node 31	Node 21	Node 22
Node 31	0	807 m	1574 m
Node 21	807 m	0	783 m
Node 22	1574 m	783 m	0

corresponding to (1) for the linear network is shown in Table I. The schedule can be interpreted as follows: node 1 and node 2 transmit a packet to node 3 while node 3 transmits a packet to node 1 in the first time slot followed by node 1 transmitting to node 2 and node 3 receiving a packet from node 2 in the second time slot. Node 2 remains idle, i.e., neither receives nor transmits in the second time slot and the rest of the schedule in the third time slot which are receptions as listed in the Table I can be interpreted similarly. If each time slot in the schedule is fully utilized, the achievable throughput can be computed using [6, equation 13] by counting the number of successful transmissions (or equivalently receptions) per frame. In Table I, note that there are 4 successful transmissions in 3 time slots (frame length is 3 time slots for this case) and hence, the throughput can be computed as $S = \frac{4}{3} = 1.33$. It is worth noting that the throughput achieved is greater than 1 since multiple transmissions are allowed in the same time slot (e.g., three simultaneous transmissions in the first time slot) and the transmitted packets cross in the water taking advantage of the large propagation delay among the nodes. However, this is assuming that the time slots are fully utilized. In reality, guard times are necessary due to the following reasons: (a) The nodes can be arbitrarily deployed resulting in arbitrary network geometries. The resulting delay matrix $\mathbf{D}$ can be a non-integer delay matrix. To compute the schedule using the algorithm in [6], the non-integer delay matrix is approximated to the closest integer delay matrix and the corresponding schedule is computed which is defined as the ρ-Schedule [6]. Due to approximations made in propagation delays, enough guard times at the start and end of the time slot are required to prevent the collision of packets [6], [11]. (b) The transitions between transmission and reception modes in the modem result in switching delays. There can be 4 different transitions at any time: RX-TX transition time to setup a packet transmission after the modem received a packet and the receiver was enabled in the previous time slot, TX-TX transition time to set up a transmission in the next time slot given that a packet was transmitted in the previous time slot, TX-RX transition time to configure the modem for the reception after a packet was transmitted in the previous slot and RX-RX transition time to set up a reception given a packet was received in the previous slot. For example, to setup a packet transmission in UNET-II modem [12] from the receiver enabled (RX) state, the receiver needs to be disabled and

Fig. 1. UNET network node locations during the experiment in Singapore waters. Yellow markers are network nodes. The links considered for demonstrating Super-TDMA are marked with distances between them.

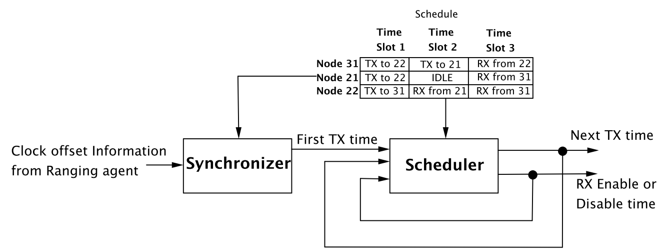

Fig. 2. Overview of the implementation showing the modules: synchronizer and scheduler. Both the modules are implemented on all 3 nodes with the objective to first achieve the time synchronization among the nodes and second to prepare the modems for accurately transmit and receive at scheduled times.

the power amplifier has to be switched ON for transmission, resulting in an RX-TX switching time of approximately 50 ms.

We deployed a network (see Fig. 1) during a recent at-sea experiment in Singapore waters consisting of a UNET-II modem [12] (node 21) mounted below a barge and two UNET-PANDA nodes [13] (nodes 22 and 31) deployed at locations as shown in Fig. 1. We considered node 31, node 21 and node 22 forming a 3 node network for demonstrating Super-TDMA and denote them as node 1, node 2 and node 3 respectively in the analysis. Distances among the nodes measured are represented in Table II as a distance matrix, where each cell of the table represents the distance between the corresponding nodes in its row and column. Considering the speed of sound, $c = 1540$ m/s, propagation delays are computed and represented in the form of a delay matrix in units of optimal time slot length computed using algorithm in [11]:

$$\mathbf{D} = \begin{bmatrix} 0 & 1.0207 & 1.9908 \\ 1.0207 & 0 & 0.9903 \\ 1.9908 & 0.9903 & 0 \end{bmatrix} \approx \begin{bmatrix} 0 & 1 & 2 \\ 1 & 0 & 1 \\ 2 & 1 & 0 \end{bmatrix}. \quad (2)$$

The optimal time slot length is 514 ms. Note the approximated integer delay matrix in (2) represents a linear network and hence we adopt the transmission schedule as shown in Table I and implement it on all three nodes. The packet duration is computed as 498 ms, and the guard times to be left at the start and end of the transmissions are computed to be 10.63 ms and 4.98 ms respectively (see [11] for details). Note that such small guard times are not sufficient for modem

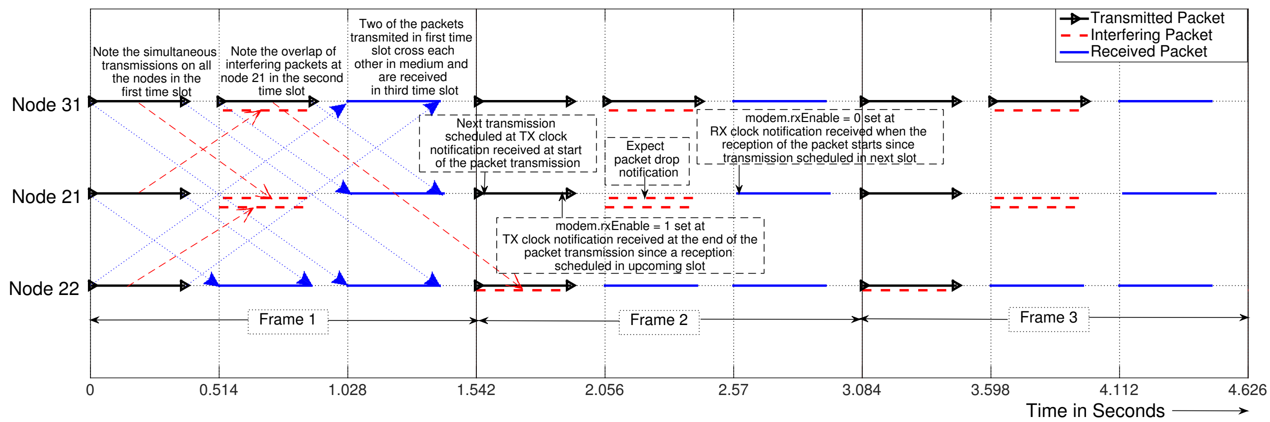

Fig. 3. Visualization of the expected scheduled events in time is shown. Note the crossing of the transmitted packets in the medium, interference alignment in the transmitting slots, zero interference during receiving slots and the scheduler job sequence to configure the modems to switch between transmission and reception modes at appropriate times.

switching times; these guard times only mitigate the effect of approximations made in propagation delays. For the purpose of this demonstration, we implement the schedule on UNET-II modems, for which the minimum guard period between two successive accurately timed-transmissions was measured to be approximately 120 ms. This duration is sufficient to configure the modem correctly for transmissions and receptions. Therefore, in the implementation, we use the time slot length to be 514 ms and select a packet duration which is close to $498 - 120 = 378$ ms. Hence, we expect a throughput, $S_\rho = \frac{4}{3} \times \frac{378}{514} = 0.97$. The transmission schedule is shown in Table I with the time slot length 514 ms and the packet duration set to 368 ms (closest packet duration setting available) is visualized in Fig. 3. The expected transmission and reception events are plotted in time. Note that all the time slots with packet receptions are interference-free and the interfering packets are aligned with the transmitting slots. After collecting the data from the experiment at sea, we plot the transmission and reception events as they happen in time on all the nodes and visualize it to compare it with the expected result as shown in Fig. 4.

III. Overview of the Implementation

The implementation of Super-TDMA schedules on the modem consists of two modules: synchronizer and the scheduler as shown in Fig. 2. The objective of the synchronizer is to achieve time synchronization among the nodes whereas the scheduler's job is to schedule various events required by the nodes for accurate transmissions and receptions in the appropriate time slots. The schedule used is the input to both modules as shown in Fig. 2.

A. Time Synchronization

The UNET-II modems are equipped with an oven-controlled crystal oscillator (OCXO) to maintain clock with a resolution of 1 μs and also provides a low drift (± 0.05 ppm drift) [12] timing reference for ranging, MAC and network protocols that need accurate time synchronization. We implement the synchronizer module to take into account the clock offset measured among the nodes. We do not compensate for clock skew since the drift is negligible over the period of this demonstration. The `Ranging` agent in UnetStack [14] uses two-way travel time to estimate range and clock offset between a pair of nodes. We use the `Ranging` functionality and estimate the clock offset between every pair of nodes. The most advanced node in time then broadcasts a time in future (computed on its local clock) to all other nodes and is used to schedule their first transmission. Synchronization accuracy achieved during the demonstration was 181 μs.

B. Scheduler

The scheduler configures the nodes at accurate times for transmissions and receptions in appropriate time slots. Since the time slot length and the packet duration are in the order of the propagation delay among the nodes, frequent switching from transmission to reception modes and vice versa is required and is challenging while implementing these schedules on the modem. For the schedule considered for this experiment, the time slot length is 514 ms. This demands the two successive transmissions in the first two time slots on node 31 to be 514 ms apart accurately. To achieve this objective, we use timed transmissions (see [15]) in UNET-II modem which allows us to schedule transmissions ahead of time and ensure the desired accuracy in transmission times.

UnetStack provides *notification* messages on successful transmissions and receptions. These can be used as event triggers to configure the modem correctly at appropriate times. Specifically, the notification messages received by the `SuperTDMA` agent at the start of the transmission, end of the successful transmission and start of the packet reception are utilized. A packet transmission is scheduled ahead of time at the start of the preceding packet transmission when the corresponding notification is received (see Fig. 3). Note that waiting until the end of the transmission reduces the time slot utilization and hence a feature allowing transmissions to be scheduled at the start of the packet transmission is useful. Similarly, when the modem is expected to receive a packet in the next time slot, the receiver is enabled at the notification message received at the end of the preceding

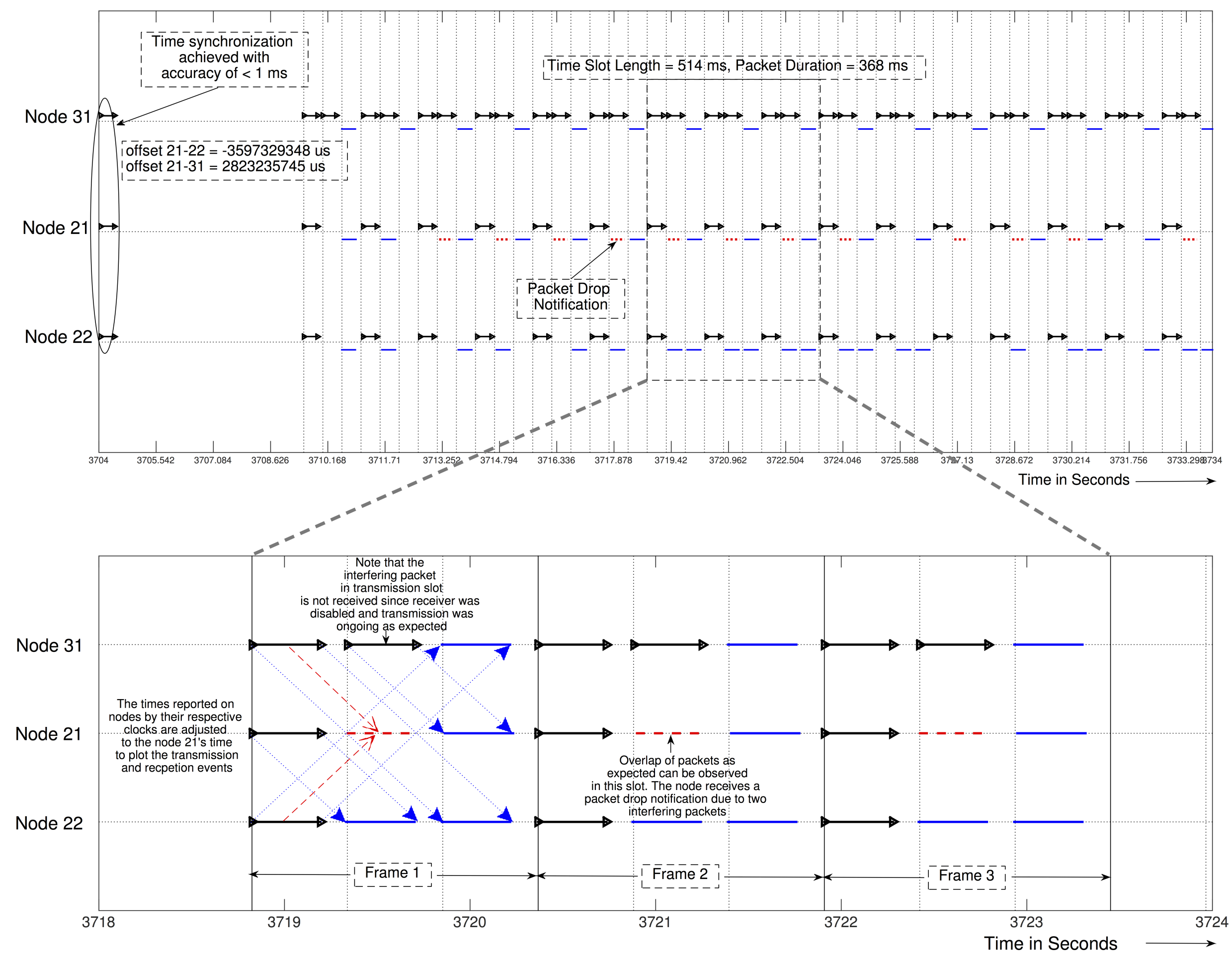

Fig. 4. Visualization of the actual events as happened at sea in time is shown. Note the crossing of the transmitted packets in the medium. The intended overlap of the interfering packets happened as expected in the corresponding time slots. The time synchronization is achieved perfectly as can be observed by looking at the first packets that are transmitted on all three nodes.

packet transmission. In Fig. 3, we show this in the first time slot of the second frame, where node 21 transmits a packet to node 22 in the first time slot. At the notification received indicating the start of the packet transmission, the next transmission is scheduled, which for node 21 is 3 slots ahead in time. Moreover, at the end of the packet transmission, the receiver is enabled since a reception is scheduled in the upcoming slot. Note that for this particular case, the second time slot expects two interfering packets and since the receiver is enabled, the intended overlap of the interfering packets is expected. A packet drop notification message is received, as expected when the two packets overlap. Note that, it is necessary to disable the receiver during the transmitting slot since the schedules are designed such that the interfering packets overlap with the transmitting slots. In case, the receiver is not disabled, it is possible that modem starts receiving the unintended interference message before it starts to transmit.

IV. Experimental Results

The schedule for a linear network along with the time slot length of 514 ms and the packet duration of 368 ms was used in the experiment. UnetStack allows logging of the notifications (carrying transmission and reception times) sent by the appropriate agents in the event of transmissions and receptions. These times are used to plot the transmission and reception events to visualize the schedule in Fig. 4. The zoomed-in events are also plotted to compare the result with the expected schedule plotted in Fig. 3. The packets cross in water and are received successfully at the intended nodes while the interference is aligned with the transmitting slots and the nodes are correctly configured to transmit in those slots. Note the time slot 2 at node 21, is expected to be an IDLE slot and receives two interfering packets at the same time. It is expected to receive packet drop notification message at this time slot. We mark this in Fig. 4, the packet drop notification is indeed received in this time slot. For the demonstrated schedule, the throughput is computed as $S_\rho = \frac{4}{3} \times \frac{368}{514} = 0.95$. Super-TDMA requires frequent switching of transmission and reception modes in the modem. If the underwater acoustic modems are equipped with hardware and software capabilities to achieve better switching times allowing lesser guard periods, the concept of Super-TDMA can prove to be very useful for consideration in future MAC protocols exploiting large propagation delays for UWA networks.

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