Design and Implementation of *Super*-TDMA: A MAC Protocol Exploiting Large Propagation Delays for Underwater Acoustic Networks

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ABSTRACT

Underwater acoustic networking research often demands the design of protocols and algorithms that enable a wide range of applications. In spite of research efforts over past decades, practical protocol design is still a challenge. We present the design, implementation and testing of *Super*-TDMA[1] protocol which exploits the large propagation delay in underwater acoustic channels by aligning most of the interference by the unintended messages in time domain. We study practical modem constraints and implement the *Super*-TDMA protocol on underwater acoustic modem. The inclusion of modem constraints results in the design which can be realized in practice. The optimal packet and time slot lengths are computed which result in maximum utilization of the time slots by minimizing the guard times. The time synchronization among the nodes using the ranging functionality of the modem is presented. Both analytical and simulation results are presented to show that the practical model used results in significant changes in design of the MAC protocol to be implemented on underwater acoustic modem.

Keywords

TDMA, Scheduling, Propagation Delays, Throughput, Wireless Networks, Underwater Acoustic Networks, Underwater Acoustic Modem

1. INTRODUCTION

Underwater wireless networks deployed in underwater environment mostly use acoustic waves to communicate among nodes. When compared to terrestrial wireless networks which typically use radio-frequency (RF) signals, the underwater acoustic networks (UANs) have low available bandwidth and large propagation delays. These unique characteristics do not allow us to use the network protocols designed for terrestrial networks directly in UANs. These challenges are addressed while designing network protocols for UANs in the literature [2, 13, 6, 3].

The adverse underwater environments pose significant challenges to design efficient medium access control (MAC) protocols for UANs. In particular, the large propagation delay of the acoustic channel and the half-duplex nature of the communication links [12] are challenging issues to be considered in the link scheduling problems. Rather surprisingly, the positive impacts of large propagation delays in underwater acoustic networks are presented in [5, 15, 9]. These sophisticated techniques in the literature are backed with theoretical analysis and simulations to show that if large propagation delays are exploited, it can result in achieving significantly higher throughput, even larger than what can be achieved in the terrestrial wireless networks with negligible propagation delays [5]. However, some problems caused by the characteristics of acoustic modems are overlooked in the protocol design. Not considering these factors in the design of MAC protocol may result in poor performance of the MAC protocols in practice when implemented on the underwater acoustic modems [16].

In [16], two practical issues caused by the underwater acoustic modems, low available transmission rates and long preambles are considered. However, there are other problems which are important when timing-sensitive protocols are to be implemented on the modem. The schedules exploiting large propagation delays demand the frequent transitions between transmission and reception times. This results in the frequent switching between transmission and reception modes in the modem. The time slots and the guard intervals need to be chosen carefully to maximize the utilization efficiency of the time slot, and hence the switching times are important in selecting the time slot lengths and in minimizing the guard times. The switching times may vary for different modems [10, 8, 14]. We present the optimization problem for selecting the time slot lengths to be used considering the practical modem constraints. The packet lengths are set to be the integer multiple of smallest incremental packet duration that can be set in the modem,

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[1] *Super*-TDMA was first termed in [11] to represent a concept - a form of TDMA that can utilize propagation delay unlike traditionally done.

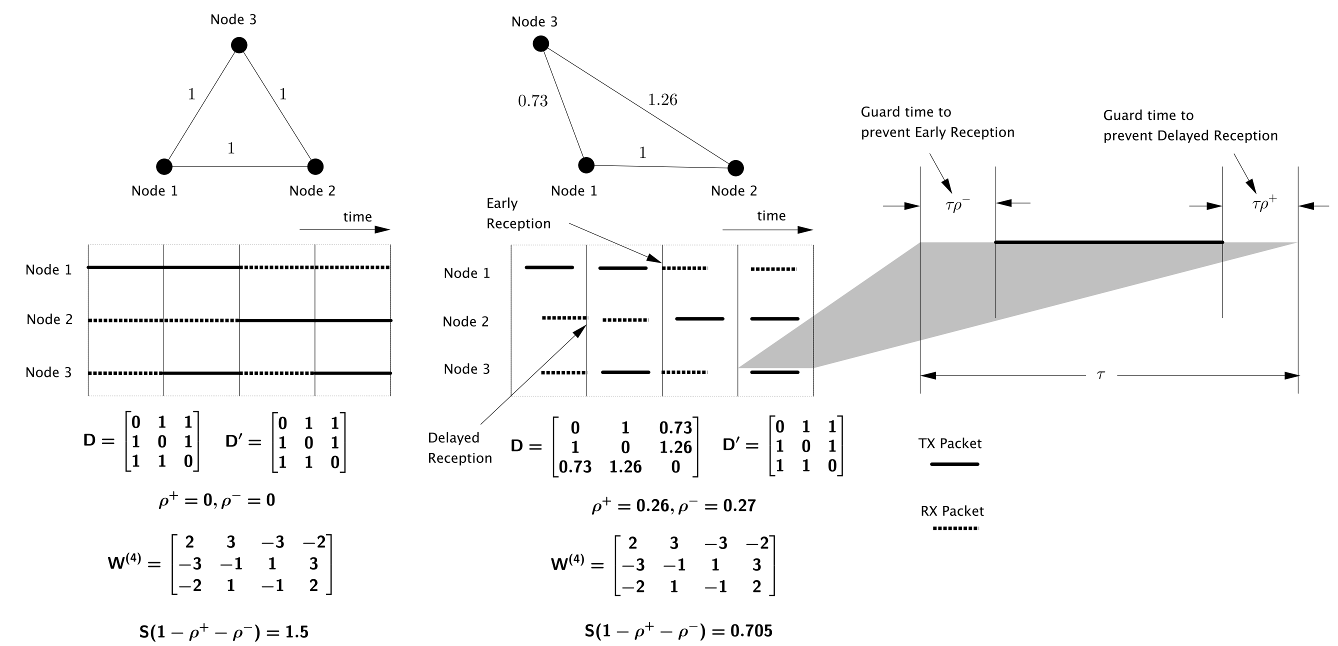

Figure 1: Effects of Approximation (Note that two different geometries adopt the same schedule but the guard times are essential to prevent packets being received across time slots. This illustrates the effect of approximating the non-integer delay matrix. The guard times at the start and end of the time slot can be expressed in terms of ρ^+ & ρ^-.)

which will effect the time slot length chosen. However, this assumption can be relaxed by considering the set of allowable packet lengths in the modem.

The rest of the paper is organized as follows. The system model is introduced in Section 2. In Section 3, we present the optimization problem to choose optimal time slot lengths for arbitrary network geometries after including the modem constraints. Case study with a sample network geometry from a sea experiment is considered in Section 4. Implementation details on underwater acoustic modem are presented in Section 5 and conclusions are drawn in Section 6.

2. SYSTEM MODEL

We consider an N-node network deployed in a 2D space of $H \times H$ meters. Let $\mathbf{x_j}$ be the position vector of node j.

2.1 Integer & Non-Integer Delay Matrices

The network geometry can be represented in the form of a delay matrix shown in [5], where each element of the delay matrix contains the propagation delay between the corresponding pair. We denote the delay matrix by $\mathbf{D}$ and the elements of $\mathbf{D}$ are written as:

$$D_{ij} = \frac{|\mathbf{x_i} - \mathbf{x_j}|}{c\tau}, \;\; i,j \in \{1,2,\ldots,N\} \tag{1}$$

where c is the speed of sound underwater and τ is the time slot length. It is important to note that the elements of the delay matrix are propagation delays between links in units of time slot length τ and can be non-integer, i.e., $\mathbf{D}$ can be a non-integer delay matrix. But with appropriate choice of time slot length τ, the given non-integer delay matrix can be approximated by an integer delay matrix $\mathbf{D'}$ [5]:

$$D'_{ij} = \left\lceil \frac{|\mathbf{x_i} - \mathbf{x_j}|}{c\tau} \right\rfloor, \;\; i,j \in \{1,2,\ldots,N\} \tag{2}$$

where by $\lceil a \rfloor$ we denote the closest integer to the real value a.

2.2 Schedules

A schedule is denoted by matrix $\mathbf{W}$ which determines the time slots in which each node in the network transmits and receives messages. It can be elucidated as follows:

1. If $W_{j,t} = i > 0$, then node j transmits a message to node i in time slot t.
2. If $W_{j,t} = -i < 0$, then node j receives a message from node i in time slot t.
3. If $W_{j,t} = 0$, then node j is idle during time slot t.

If $W_{j,t+T} = W_{j,t} \;\forall\; j,t$, then the schedule is periodic with period T. It can be written as a matrix of order $N \times T$ denoted by $\mathbf{W}^{(T)}$.

$$W_{j,t} = W^{(T)}_{j,(t \mod T)}.$$

2.2.1 *Necessary Condition for Transmission*

Node j transmits a message to node i during time slot t only if node i is able to successfully receive the message during time slot $t + D_{ij}$, i.e.,

$$W_{j,t} = i \Leftrightarrow W_{i,t+D_{ij}} = -j \;\;\forall\;\; i \neq j. \tag{3}$$

2.2.2 *Necessary Condition for Successful Reception*

To ensure successful reception at time slot t of a transmitted message from node j, it is required that no other nodes transmit messages that arrive at node i during time slot t. Therefore,

$$W_{i,t} = -j \Rightarrow W_{k,t-D_{ik}} \leq 0 \;\; k \neq i. \tag{4}$$

The scheduling algorithm in [5] finds schedules which satisfy above necessary conditions for successful transmissions and receptions.

2.3 Example Delay Matrix & Schedule

The delay matrix and schedule for a three node equilateral triangle are given below:

$$\mathbf{D} = \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}, \mathbf{W}^{(4)} = \begin{bmatrix} 2 & 3 & -3 & -2 \\ -3 & -1 & 1 & 3 \\ -2 & 1 & -1 & 2 \end{bmatrix}.$$

The above-mentioned delay matrix represents a network geometry where the nodes are placed such that they make an equilateral triangle (see Fig. 1), with the link propagation delays as one unit of time slot length. The schedule can be interpreted as follows: In first time slot, node 1 transmits a message to node 2, and in the second time slot, node 2 receives a message from node 1 and so on. Also, note that the period of the schedule in this example is $T = 4$ and the schedule repeats itself for every 4 time slots. The above schedule example is taken from [5] for illustration. We do not present the scheduling algorithm in this paper, instead use the algorithm from [5] to find schedules and compute throughput.

2.4 Effects of Approximating Delay Matrix

If the network has a non-integer delay matrix, packets transmitted on the time slot boundaries may be received across time slot boundaries. Fig. 1 illustrates this fact. For a non-integer delay matrix $\mathbf{D}$, the elements are rounded off to yield an integer delay matrix $\mathbf{D'}$ and the approximations, ρ^+ and ρ^- are given by:

$$\rho^+ = \max_{ij}(D_{ij} - D'_{ij}) \tag{5}$$

$$\rho^- = -\min_{ij}(D_{ij} - D'_{ij}) \tag{6}$$

where $i, j \in \{1, 2, \cdots, N\}$, for a fully-connected network. Note that in Fig. 1, although two slightly different geometries are represented by the same delay matrix $\mathbf{D'}$, and adopt the same schedule, the throughput achieved has a large difference. This is due to the inefficient utilization of time slots in the case where the non-integer delay matrix is approximated to the integer delay matrix, and the guard times are the cause of inefficiency.

2.4.1 Time Slot Lengths & Guard Times

Due to the approximations in the delay matrix the guard intervals are needed at the start and end of the time slots. ρ^+ and ρ^- are the worst delay-approximations made. The packet transmission on the links with delay-approximations will either yield in *early reception* of the packet or a *delayed reception* of the packet depending on whether propagation delay (in units of time slot length τ) of that link is approximated to a larger number or a smaller number respectively. In Fig. 1, the link between Node 1 and Node 3 has a propagation delay equal to 0.73 units of time slot length, but is approximated to 1 unit of time slot length. This would result in early reception of the packet transmitted on the link between Node 1 and Node 3. The early reception shown in the Fig. 1 is the transmission on the same link. It is obvious that $\tau\rho^-$ is the worst amount of time that must be left before transmission in order to prevent the early receptions and $\tau\rho^+$ is the worst amount of time that must be left after the transmission on the time slot in order to prevent the delayed reception. Hence, we denote these start and end guard times in the time slot by:

$$t_{\mathrm{s}} = \tau\rho^- \tag{7}$$

$$t_{\mathrm{e}} = \tau\rho^+. \tag{8}$$

Hence the packet duration denoted by t_{pd}, that must be set in the modem for transmission is given by:

$$\tau = t_{\mathrm{s}} + t_{\mathrm{pd}} + t_{\mathrm{e}}$$

$$\Rightarrow t_{\mathrm{pd}} = \tau(1 - \rho^+ - \rho^-) = t_{\mathrm{preamble}} + t_{\mathrm{payload}}$$

$$t_{\mathrm{payload}} = \tau(1 - \rho^+ - \rho^-) - t_{\mathrm{preamble}} \tag{9}$$

where t_{preamble} and t_{payload} correspond to the preamble duration and the payload/data duration constituting the packet duration in modem. In reality, the values of time slot length τ are constrained to those allowed by the underwater acoustic modems. To be more precise, the packet lengths are constrained by the modem configuration and capability. We denote the smallest incremental duration in the packet lengths which can be set in the modem by Δx. These constraints translate to restrictions on time slot lengths in order to efficiently utilize the slots. We denote the minimum and maximum possible time slot lengths that can be set by $\tau_{\min}$ and $\tau_{\max}$ respectively.

2.5 Throughput

The average throughput S of a schedule with period T can be computed by counting the number of receptions in the schedule $\mathbf{W}^{(T)}$.

$$S = \frac{1}{T}\sum_t \sum_j \mathbb{1}(W_{j,t}^{(T)} < 0) \tag{10}$$

where $\mathbb{1}(E)$ is the indicator function of an event E, with value of 1 if E is true and 0 otherwise. In the case where the period of the schedule computed is not known, the approximate throughput is computed by counting the number of receptions over a large number of time slots $T^{'}$. In that case, the approximate throughput $S^{'}$, computed over $T^{'}$ slots is given by:

$$S^{'} = \frac{1}{T'}\sum_{t=1}^{T^{'}} \sum_{j=1}^{N} \mathbb{1}(W_{j,t} < 0). \tag{11}$$

The throughput defined in (10) & (11) only count the number of receptions but do not take into account the utilization of the time slots. ρ-throughput denoted by S_ρ, and defined as:

$$S_\rho = S\eta = S\Big(\frac{t_{\mathrm{payload}}}{\tau}\Big) = S\Big(1 - \rho^+ - \rho^- - \frac{t_{\mathrm{preamble}}}{\tau}\Big) \tag{12}$$

where $\eta = \frac{t_{\mathrm{payload}}}{\tau}$ is the slot utilization efficiency, takes into account the time slot utilization.

3. OPTIMIZATION PROBLEM

3.1 Without Modem Constraints

We consider an N-node underwater acoustic network randomly deployed and is represented by its corresponding non-integer delay matrix $\mathbf{D}$. The approximate integer delay matrix needs to be computed by selecting time slot length τ

Table 1: Model Parameters

Notation	Description
τ	Time slot length
S_ρ	ρ-throughput
η	Utilization efficiency in a slot
N	Number of nodes in the network
t_s	Guard time at the start of time slot
t_e	Guard time at the end of time slot
t_pd	Packet duration
t_preamble	Preamble duration
t_payload	Payload duration
Δx	Smallest increment in packet duration
$t_\text{RX-TX}$	Delay to switch from RX mode to TX mode
$t_\text{TX-RX}$	Delay to switch from TX mode to RX mode
$t_\text{TX-TX}$	Delay to transmit a packet if already in TX mode
$t_\text{RX-RX}$	Delay to receive a packet if already in RX mode

as a result of which the values of ρ^+ and ρ^- are set. The ρ-throughput S_ρ is given by the number of successful receptions per time slot multiplied by the slot utilization efficiency. ρ-throughput is a function of time slot length and the delay matrix,

$$S_\rho = f(\tau, \mathbf{D}').$$

The optimization problem in this case is formally written as:

$$\begin{aligned} \underset{\tau}{\text{maximize}} \quad & S(1 - \rho^- - \rho^+ - \frac{t_\mathrm{preamble}}{\tau}) \\ \text{subject to} \quad & \tau = \{\tau_\mathrm{min} + m\Delta x \ ; \ m \in \{1, \cdots, \lfloor \frac{\tau_\mathrm{max} - \tau_\mathrm{min}}{\Delta x} \rfloor\}\}. \end{aligned}$$

For each value of the time slot length τ, we compute the values of ρ^- and ρ^+ and compute S from the schedule $\mathbf{W}^{(T)}$ computed using the scheduling algorithm from [5]. The time slot length corresponding to the maximum value of the objective function is chosen to be the optimal time slot length τ^* and corresponding packet duration is set.

3.2 Transition Times in Modem

The different parameters used in the model are denoted in the Table 1. The transitions between transmission and reception modes in the modem result in processing delays. The minimum time that is required for setting up the modem to transmit or receive correctly during different transitions between these modes are illustrated here.

1. **RX-TX transition**: The processing delay to switch from reception (RX) mode to transmission (TX) mode in modem is denoted by $t_\text{RX-TX}$. For example, to set up a packet transmission in UNET-II modem [8] from the default state which is receiver enabled (RX) state, the receiver needs to be disabled followed by switching ON the power amplifier for transmission, which contributes to $t_\text{RX-TX}$.

2. **TX-TX transition**: To set up a packet transmission immediately after the transmission in the previous slot, the power amplifier state need not be changed and can be left ON. This transition time is denoted by $t_\text{TX-TX}$.

3. **TX-RX transition**: To prepare the modem for reception after the packet transmission in the previous slot, power amplifier needs to be switched OFF and the receiver is enabled. The processing delay in modem to switch from RX mode to TX mode is denoted by $t_\text{TX-RX}$.

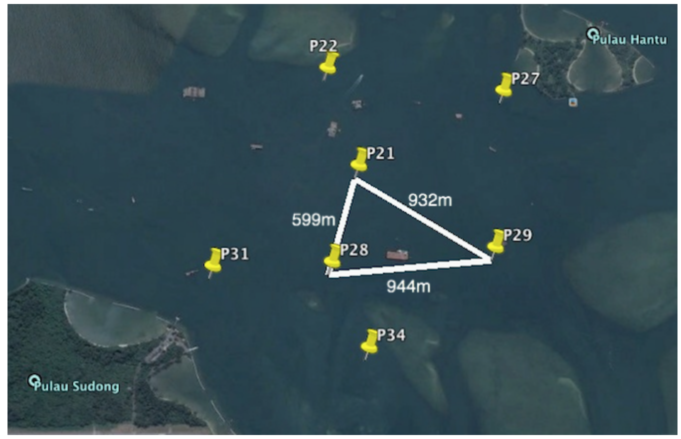

Figure 2: UNET network node locations during the MISSION 2013 experiment (deployment #1). Yellow markers are network nodes. The geometry considered for the case study is marked with the distances between the links.

4. **RX-RX transition**: A packet after the reception in the previous slot, can be set up after $t_\text{RX-RX}$ amount of time.

The values of these parameters may vary for different modems which will constitute different transition times. Since these times can be measured and are known prior, we can fix these parameters in the optimization problem presented next. The start and the end guard times need to be atleast greater than the time that it takes to prepare the modem for either transmitting or receiving the packet correctly. The guard time at the start of the time slot denoted by t_s need to be greater than the largest among the transition times $t_\text{TX-TX}$ and $t_\text{RX-TX}$, which are the times before a transmission mode can be set in the modem from different states, i.e.,

$$t_\mathrm{s} > \max\{t_\text{RX-TX}, t_\text{TX-TX}\}. \quad (13)$$

Similarly, after a packet transmission in the previous slot, the largest time to be waited for to set up the reception in modem is given by $\max\{t_\text{TX-RX}, t_\text{RX-RX}\}$ and hence it is enough to set

$$t_\mathrm{e} > \max\{t_\text{TX-RX}, t_\text{RX-RX}\}. \quad (14)$$

3.3 With Modem Constraints

The optimization problem to compute the optimal value of the time slot length is now modified to include the modem constraints presented.

$$\begin{aligned} \underset{\tau}{\text{maximize}} \quad & S(1 - \rho^- - \rho^+ - \frac{t_\mathrm{preamble}}{\tau}) \\ \text{subject to} \quad & \tau\rho^- > \max\{t_\text{RX-TX}, t_\text{TX-TX}\} \\ & \tau\rho^+ > \max\{t_\text{TX-RX}, t_\text{RX-RX}\} \\ & \tau = \{\tau_\mathrm{min} + m\Delta x; \ m \in \{1, \cdots, \lfloor \frac{\tau_\mathrm{max} - \tau_\mathrm{min}}{\Delta x} \rfloor\}\}. \end{aligned}$$

The solution of this problem provides the best utilization efficiency considering the modem constraints.

4. CASE STUDY

The UNET network deployed (see Fig. 2) during the MISSION 2013 experiment in Singapore waters consisted of a UNET-II modem [8] (node 21) mounted below a barge and

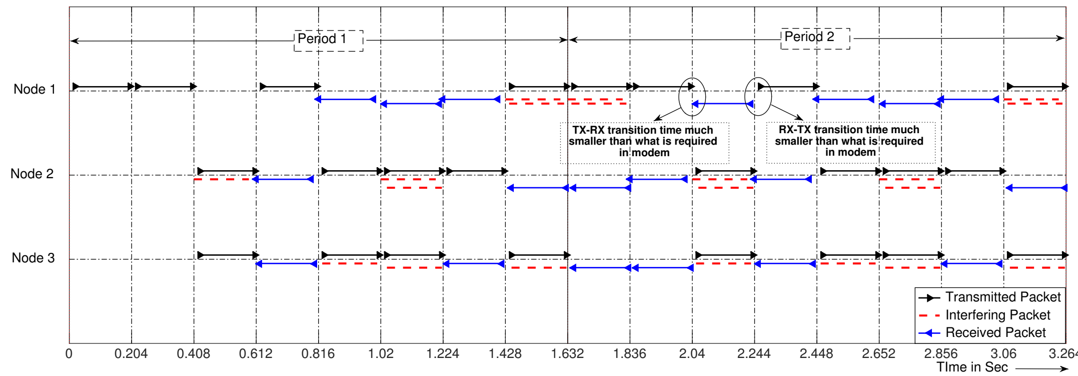

Figure 3: Schedule visualization without modem constraints (the guard times set in the time slot take care of only the early receptions and delayed receptions problem due to the approximations made in the delay matrix because of the network geometry).

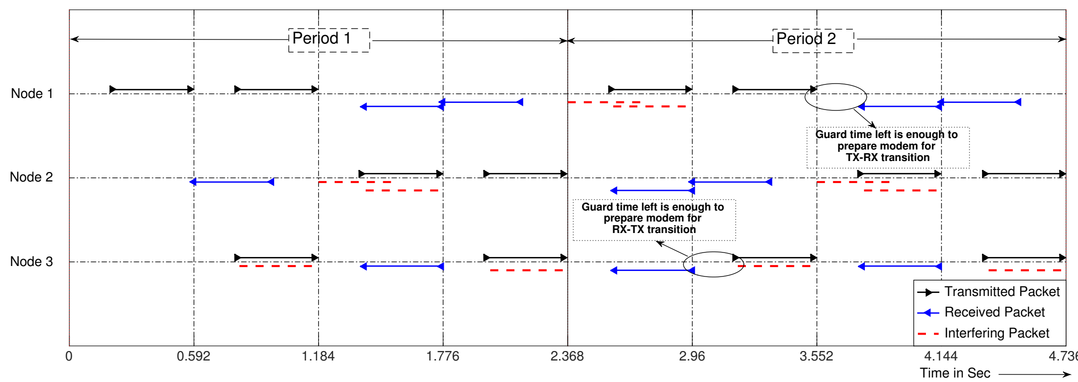

Figure 4: Schedule visualization with modem constraints (the guard times set in the time slot not only take care of the constraints due to geometry but also consider TX-RX and RX-TX transition times in modem).

six UNET-PANDA nodes [7] (nodes 22,27, 28, 29, 31 and 34) deployed at various locations within a 2 × 2 km area around the barge.

We consider a network geometry from this experiment as shown in Fig. 2, with distance matrix:

$$\mathbf{L} = \begin{bmatrix} 0 & 599 & 932 \\ 599 & 0 & 944 \\ 932 & 944 & 0 \end{bmatrix}$$

and apply the technique to find the optimal time slot lengths, visualize the schedule computed and verify the performance in the simulator with and without modem constraints. The modems labeled as P21, P28 and P29 in Fig. 2 are considered as Node 1, Node 2 and Node 3 respectively in the analysis.

4.1 Results

The optimization problem is solved to compute the optimal time slot length with and without modem constraints for the considered network geometry.

4.1.1 *Without Modem Constraints*

The time slot length τ is varied from $\tau_{\min} = 1$ ms to $\tau_{\max} = 3000$ ms, $t_{\text{preamble}} = 20$ ms and $\Delta x = 1$ ms is set. The optimal value of the time slot length along with other parameters are tabulated:

Parameter	Value without modem constraints
τ^*	204 ms
t_{pd}	184 ms
t_{s}	19.03 ms
t_{e}	0.97 ms
S_ρ	1.205

The delay matrix and the integer delay matrix corresponding to time slot length τ^* is

$$\mathbf{D} = \frac{\mathbf{L}}{c\tau^*} = \begin{bmatrix} 0 & 1.9067 & 2.9666 \\ 1.9067 & 0 & 3.0048 \\ 2.9666 & 3.0048 & 0 \end{bmatrix}, \quad \mathbf{D}' = \begin{bmatrix} 0 & 2 & 3 \\ 2 & 0 & 3 \\ 3 & 3 & 0 \end{bmatrix}.$$

For this delay matrix, the optimal schedule is computed using the algorithm presented in [5]. The schedule is

$$\mathbf{W}^{(8)} = \begin{bmatrix} 3 & 2 & -3 & 3 & -2 & -3 & -2 & 2 \\ -3 & -1 & 1 & -1 & 1 & 3 & 3 & -3 \\ -2 & -2 & 1 & -1 & 2 & 2 & -1 & 1 \end{bmatrix}.$$

This schedule is visualized in Fig. 3, using the optimal values computed for the network setting. Since we know the time slot length, guard times and period of the schedule, i.e., 8 slots, we can plot the transmitted packets, received packets and the interfered packets accurately. We leave t_{s} amount of time before the transmission in a transmitting slot and t_{e} amount of time at the end. We observe that all the receptions in the schedule are interference free as expected. Note

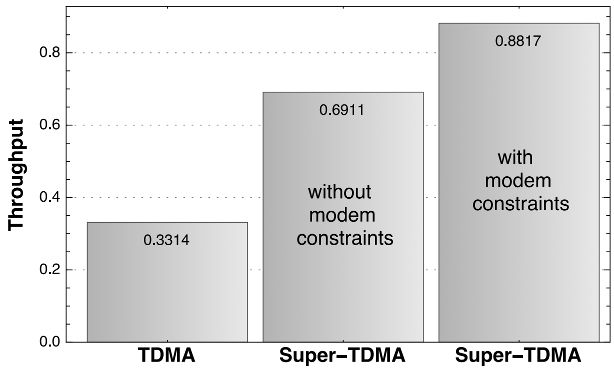

Figure 5: Throughput comparison of *Traditional*-TDMA and *Super*-TDMA protocols with and without modem constraints for the considered network geometry.

that in Fig. 3, the gap between end of the packet transmission in previous slot and start of the reception in next slot is very small at several time instances and in practice while implementing on modem this may not be achievable and hence the modem constraints need to be added to the optimization problem.

Effect of modem constraints on schedule computed: In order to implement the schedule $\mathbf{W}^{(8)}$ on the modem, the packet lengths need to be reduced and enough guard times need to be left in order to configure the modem correctly for transmission and reception. We set $t_{\text{TX-RX}} = 20$ ms, $t_{\text{RX-TX}} = 70$ ms, $t_{\text{TX-TX}} = t_{\text{RX-RX}} = 0$ ms. For this setting, $t_{\text{s}} > 70$ ms and $t_{\text{e}} > 20$ ms can be computed from equations 13 and 14. Hence, the maximum packet length that can be used without collisions with this schedule satisfying modem constraints is $t_{\text{pd}} = \tau^* - t_{\text{s}} - t_{\text{e}} = 114$ ms. Therefore, $t_{\text{payload}} = 94$ ms and the schedule computed $\mathbf{W}^{(8)}$ consists of 12 receptions in 8 time slots. Hence, $S = \frac{12}{8} = 1.5$. We can now compute the ρ-throughput,

$$S_\rho = S\eta = 1.5(\frac{94}{204}) = 0.6911.$$

The different parameter values computed considering the modem constraints to implement the schedule $\mathbf{W}^{(8)}$ on modem are tabulated:

Parameter	Value with modem constraints
τ^*	204 ms
t_{pd}	114 ms
t_{s}	70 ms
t_{e}	20 ms
S_ρ	0.6911

Note that although in theory the throughput computed for this schedule was 1.204, in order to implement on the modem, the packet length is reduced and guard intervals are left and hence the effective achievable throughput is 0.6911.

4.1.2 With Modem Constraints

If the modem constraints are considered in the optimization problem, we can find an optimal schedule which when implemented results in higher throughput than what is computed in the previous section. The time slot τ in this case is varied from $\tau_{\min} = 1$ ms to $\tau_{\max} = 3000$ ms, $t_{\text{preamble}} = 20$ ms and $\Delta x = 1$ ms is set as in previous section, also

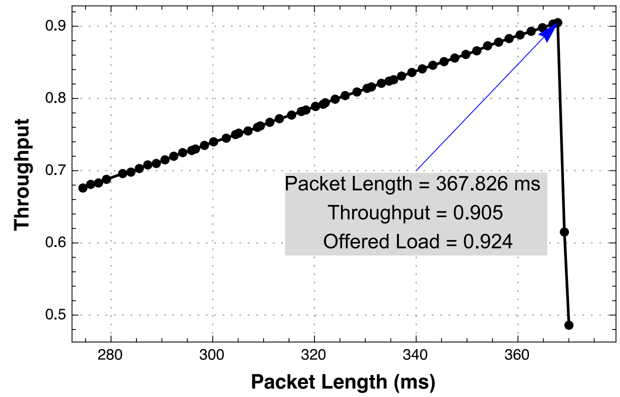

Figure 6: Throughput vs Packet Length in UnetSim with modem model `HalfDuplexModem` for the Geometry considered.

$t_{\text{RX-TX}} = 70$ ms, $t_{\text{TX-RX}} = 20$ ms and $t_{\text{TX-TX}} = t_{\text{RX-RX}} = 0$ ms are set. The optimal time slot length to be used are computed satisfying all the modem constraints. The optimal values are listed in the table below:

Parameter	Value with modem constraints
τ^*	592 ms
t_{pd}	368 ms
t_{s}	203.05 ms
t_{e}	21.01 ms
S_ρ	0.8817

The delay matrix and integer delay matrix for this optimal time slot length is given by:

$$\mathbf{D} = \begin{bmatrix} 0 & 0.6570 & 1.0223 \\ 0.6570 & 0 & 1.0355 \\ 1.0223 & 1.0355 & 0 \end{bmatrix}, \ \mathbf{D}' = \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}.$$

For this delay matrix $\mathbf{D}'$, the optimal schedule is computed:

$$\mathbf{W}^{(4)} = \begin{bmatrix} 2 & 3 & -3 & -2 \\ -3 & -1 & 1 & 3 \\ -2 & 1 & -1 & 2 \end{bmatrix}.$$

Note that for the same network geometry, due to the modem constraints a different schedule is adopted in this case with a period $T = 4$.

The scheduled transmissions and the receptions are visualized in Fig. 4. Enough time is available between transmission and reception of the packets to configure the modem. Note that $t_{\text{s}} = 203.05$ ms $> t_{\text{RX-TX}}$. Also, $t_{\text{e}} = 21.01$ ms $> t_{\text{TX-RX}}$.

***Traditional*-TDMA and *Super*-TDMA - Comparison:** The throughput of *Traditional*-TDMA is given by,

$$S_{\text{TDMA}} = \frac{t_{\text{payload}}}{t_{\text{pd}} + t_{\text{maxpd}}}$$

where, t_{maxpd} is the maximum propagation delay among the links considered in the network. Also, the time slot length $\tau = t_{pd} + t_{\text{maxpd}}$. If TDMA is implemented on the modem, enough guard times need to be included in the time slot, therefore,

$$S_{\text{TDMA}}^{\text{modem}} = \frac{t_{\text{payload}}}{t_{\text{pd}} + t_{\text{maxpd}} + t_{\text{RX-TX}}} = 0.3314.$$

The throughput for *Traditional*-TDMA and *Super*-TDMA with and without considering the modem constraints are

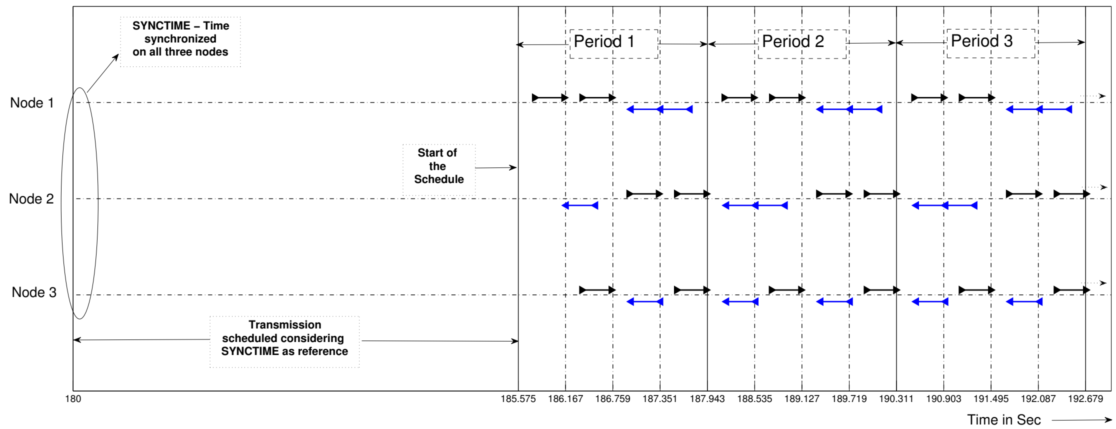

Figure 7: Schedule verified on UnetSim with modem model `ARLUNETModem` for time synchronization, accuracy of timed transmissions and reception times (the transmission and reception times used in the plot are taken from the clock notifications in the simulator [4].)

presented in Fig. 5. The poor performance of TDMA is because of the presence of large propagation delays in underwater acoustic networks. However, *Super*-TDMA protocol exploits the large propagation delay in order to improve the throughput.

5. IMPLEMENTATION ON UNET MODEM

The different modems [10, 8, 14] feature variety of physical and higher layer implementations. For example, the UNET-II modem is based on orthogonal frequency division multiplexing (OFDM), but also provides flexibility to choose between incoherent OFDM, coherent OFDM and frequency-hopped binary frequency shift keying (FH-BFSK) modulation schemes. Depending upon the need, these modems can be configured to some state, which in turn results in the allowable packet durations. Before implementing the code on modem, we develop and verify code on the Underwater Network Simulator (UnetSim) [4]. Once a protocol is developed and tested in simulation, it is ready to be deployed and tested at sea in any UnetStack-compatible modem.

5.1 Verification on UnetSim

The schedule computed is verified with the optimal set of values found with modem constraints in UnetSim, an open source underwater network simulator. In simulation, the physical layer offered by a modem is usually replaced by a simulation model that mimics the behavior of the modem in a given channel. We use the model `HalfDuplexModem` [1] for testing the performance of the considered network as the offered load increases (see Fig. 6). The channel model used is `ProtocolChannelModel`[1] which assumes constant performance with range until the communication range and any collision within the interference range causes a packet to be lost. The packet length is varied and the throughput is observed, which increases and reaches a maximum value of 0.905 at 367.826 ms as shown in Fig. 6. The throughput computed in simulator includes the preamble and hence it is greater than theoretically computed throughput 0.8817. The simulation result shows that when the packet lengths are smaller, than the optimal value $\tau = 368$ ms, the packets are transmitted and received without collisions and as the packet length becomes greater than the optimal packet length, the packets start getting interfered with and the throughput reduces due to increased collisions.

`HalfDuplexModem` is a generic modem physical layer simulation model and may not take into account specific practical issues arising from the implementation on a specific modem. We implement the protocol on UNET-II modems and hence we use a modem model for the ARL UNET-II modem (`ARLUNETModem`), for simulation in UnetSim, which accurately emulates the UNET-II modem behavior for verifying the performance.

5.1.1 Timed Transmissions & Time Synchronization

There is a need for timed transmissions in the modem to make sure the scheduled transmissions take place at accurate times. In the UNET-II modem, external trigger alarm can be set to accurately time the transmission start time of a packet. This makes sure that there is no delay in preparing the modem for transmission at the time scheduled. Timed packet transmissions according to different schedules were carried out in tank and were tested for accuracy.

```
PSEUDO CODE FOR SLOT SYNCHRONIZATION
------------------------------------
/*OFFSET is 0 for most advanced node in time*/
cuurenttime = phy.time + OFFSET
/*takes it to the most advanced clock*/
elapsedtime = currenttime % SYNCTIME
/*time elapsed out before the SYNCTIME
is reached*/
nextimmediateslot = currenttime +
   (SYNCTIME - elapsedtime)
localnextimmediateslot = nextimmediateslot
- OFFSET
currenttime = currenttime - OFFSET
syncslottime = localnextimmediateslot + SYNCTIME
transmitPacket(syncslottime)
/*transmit packet at syncslottime*/
```

Time slots on all the nodes must be synchronized and is an essential requirement. The ranging (feature which uses two-way travel time to measure the distance between the nodes) functionality in the modem is used to get the clock offset information and to adjust the timing offsets between clocks of the nodes. The information on offset between these clocks is one approach using which time slots can be synchronized. The synchronization is verified on UnetSim using `ARLUNETModem` model as well as on the modem.

The pseudo code is shown to understand the implementation of time synchronization among all the nodes in the network. The time at which all the three nodes are synchronized is SYNCTIME. Adding OFFSET to the current time at the node takes the current time of the node to a value which can be compared to the time of the node with most advanced clock in the network. OFFSET is computed at each node based on the information from the ranging functionality.The developed code is run on the simulator with the model selected as `ARLUNETModem`, to verify the implementation for accurate timed transmissions according to the schedule and time slot synchronization among the nodes in the network.

The results are shown in Fig. 7, the times at which the packets are transmitted and received are noted and are used to plot along with the known length of the packet, time slot length and the schedule to visualize the transmissions and receptions. The time slot length $\tau = 592$ ms and $t_{\text{pd}} = 368$ ms computed for the network geometry presented in Section 4 is considered. In Fig. 7, the right arrows show the transmitted packets and left arrows show the received packets. The SYNCTIME is marked when the slots are synchronized among all three nodes. Once, the time synchronization is achieved, the schedules start after approximately 5 sec, which is set arbitrarily.

6. CONCLUSIONS

The switching times in modem between transmission and reception modes play a critical role in selecting the optimal time slot lengths. The optimal setting of time slot length minimize the guard times for a schedule and eventually maximize the slot utilization efficiency. It is shown that if not taken into consideration, it can severely degrade the performance of *Super*-TDMA. The optimization problem is presented with and without modem constraints and its impact on the schedule are shown by visualizing the schedule in both the cases. The 3-node network is setup in the UNET simulator similar to the network geometry taken from MISSION 2013 experiment and the optimal values computed are used to implement the *Super*-TDMA protocol. The simulation results are shown to be consistent with the optimal values computed. Lastly, we also presented two implementation related problems on modem – time synchronization among nodes in the network and the need for accurate timed transmissions. The implementation is verified on modems mounted in the tank for timed transmissions and slot synchronization. The schedule exploiting the large propagation delays, which is computed for a sample network geometry considered from a sea trial is used to showcase the impact on the throughput if the design and implementation insights presented can be utilized in such experiments. This work helps in reducing the gap between theoretical and practical aspects of the protocol presented and brings it one step closer to reality.

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