# MAC Protocols that Exploit Propagation Delay in Underwater Networks

Shiraz Shahabudeen
Department of Electrical
and Computer Engineering,
National University of Singapore,
Singapore 117576.
shiraz@nus.edu.sg

Mandar Chitre
Acoustic Research Laboratory,
and Department of Electrical
and Computer Engineering,
National University of Singapore,
Singapore 119227.
mandar@nus.edu.sg

Mehul Motani
Department of Electrical
and Computer Engineering,
National University of Singapore,
Singapore 117576.
motani@nus.edu.sg

***Abstract*—This paper discusses novel medium access control (MAC) protocols for underwater acoustic networks that utilize propagation delay to increase the network throughput. Traditional MAC design considers propagation delay as undesirable and attempts to mitigate its impact on throughput. The essential idea in this paper is to do simultaneous pairwise transmissions and utilize the propagation delay to avoid collisions at the receiver. The throughput and queueing delay performance of the protocols proposed here is superior compared to the corresponding traditional protocols. We discuss static and dynamic variations of time division multiple access (TDMA) based protocols we call Twin-TDMA and Twin-DTDMA. We shall also see how the same concept can be utilized in an ALOHA-like protocol, which we term Twin-ALOHA. The protocols are primarily designed to have utility in large propagation delay underwater networks, where the performance of traditional MAC protocols is significantly degraded due to the large propagation delays.**

## I. INTRODUCTION

As a result of the low speed of sound in water, propagation delays in underwater acoustic networks (UANs) can be large. The negative impact of large propagation delays on medium access control (MAC) layer protocols which prevent all data collisions has been discussed in [1]. Conventional MAC protocol design for such networks focuses on mitigation of the impact of propagation delay [2]–[5]. In networks with negligible propagation delays, MAC protocols endeavor to avoid simultaneous transmissions in a collision domain. When networks have significant propagation delays, simultaneous transmissions do not cause any harm as long as they do not collide at an intended receiver. Recently, it was shown that the presence of large propagation delays opens up the possibility of designing transmission schedules that allow much greater network throughput than networks of the same size with no propagation delay [6]. For a network with $N$ nodes, the normalized throughput (henceforth just called *throughput*) without propagation delay is upper bounded by 1, while the throughput for networks with large propagation delay is upper bounded by $N/2$. Inspired by this remarkable finding, we explore the design of novel MAC protocols that exploit this opportunity.

In order to benefit from large propagation delays, we must utilize simultaneous transmissions while avoiding collisions at the receiver. Although this may be easy to do in network topologies with special geometrical constraints, our interest here is to design MAC protocols that are applicable in general networks with minimal constraints. In this paper, we present three protocols with utility in large propagation delay underwater networks. The first protocol is a static TDMA based protocol called Twin-TDMA. The second protocol is a dynamic variant that we call it Twin-DTDMA. The third protocol is an ALOHA based protocol called Twin-ALOHA. All three protocols allow pairs of nodes in the network to transmit simultaneously without colliding. To illustrate how this is achieved, we present two examples that have previously appeared in [6].

*Example 1:* Consider a 2-node network with propagation delay $D$ between the nodes. The idea of allowing nodes to transmit simultaneously and letting their packets “cross in flight” was been considered in [7]. When we set the duration of the packet $L$ equal to the propagation delay $D$, the simultaneous transmissions occur as shown in Fig. 1. Since in time $2D$, 2 packet exchanges of duration $L = D$ complete, we have a throughput of 1, the maximum possible throughput for a network with only two nodes.

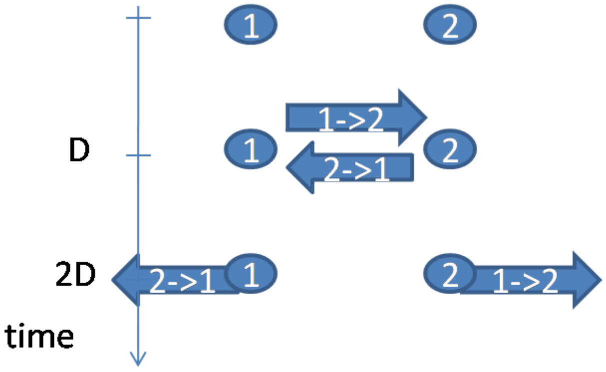

Fig. 1. Simultaneous transmissions in a two-node network

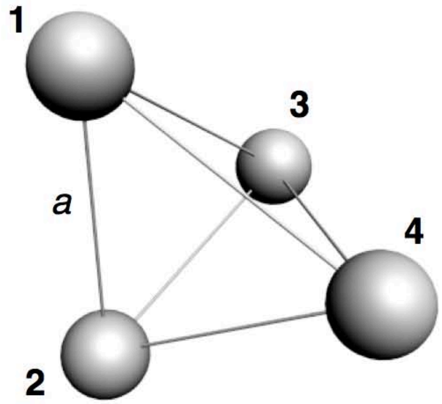

Fig. 2. Regular tetrahedron network

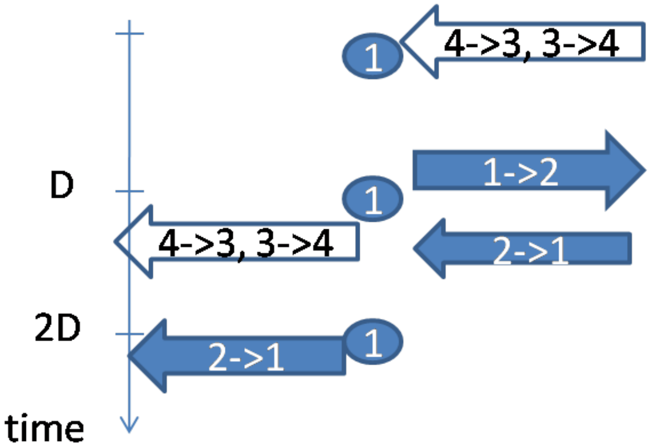

Fig. 3. Simultaneous transmissions in a regular tetrahedron network

*Example 2:* Consider a 3-dimensional network with 4 nodes placed at the vertices of a regular tetrahedron as shown in Fig. 2. If we allow only slotted transmissions in this network, we can easily represent the transmission schedule in terms of a matrix with rows representing the nodes and columns representing the time slots. If the schedule is periodic, the matrix has to only have sufficient columns to represent one period of the schedule. Positive entries in the matrix represent a transmission from the node given by the row to the node number specified in the entry. For example, if the entry at location (3,1) is 2, we understand that node 3 transmits to node 2 during time slot 1. Negative entries represent receptions; an entry -1 at location (2,3) denotes that node 2 receives a packet from node 1 during time slot 3. Setting the duration of the time slots in the schedule to be equal to the propagation delay $D$ between any two nodes in this network, we ensure that every transmission starting at a slot boundary is received at a slot boundary. We can therefore use the entire slot duration for transmission, and therefore set the packet duration $L = D$. By using the following periodic transmission schedule $\mathbf{Q}$ for the network, a throughput of 2 can be achieved!

$$\mathbf{Q} = \begin{bmatrix} 2 & -2 \\ 1 & -1 \\ -4 & 4 \\ -3 & 3 \end{bmatrix} \tag{1}$$

It can be observed that in this simple example, nodes 1 and 2 send packets to each other simultaneously in the first slot and receive them simultaneously in the second slot. Nodes 3 and 4 send packets to each other simultaneously while nodes 1 and 2 are receiving. This causes no collisions since the transmissions arrive at nodes 1 and 2 only in the next time slot when they are transmitting (see Fig. 3). The same reasoning applies to transmissions from 1 and 2 not resulting in collisions on nodes 3 and 4. If considered separately, pair (1,2) and pair (3,4) behave exactly as discussed in the isolated two node case of Fig. 1. Over two time slots, all four nodes transmit and receive a packet each successfully; the network throughput is therefore $4/2 = 2$.

These simple examples clearly illustrate the possibility of high throughput by using the concept of simultaneous transmissions in pairs of nodes. A larger network is broken down into two node sub-units, and each sub-unit can utilize simultaneous transmissions while avoiding interference with other sub-units. This concept will be referred to as “Twin-TX” in our discussion. Although algorithms to find schedules that harness the high throughput potential of networks with large propagation delay have been developed [6], random access protocols that can benefit from this potential remain elusive. The protocols presented in this paper take a step towards tapping some of the potential, though they cannot always achieve the optimal throughput for networks with arbitrary geometries.

In order to keep the protocols and analysis in this paper simple, we assume time synchronization among nodes and ignore the effect of packet loss due to bit errors. The only packet loss modeled is due to collisions.

## II. TWIN-TDMA

### A. Throughput

A key performance metric used in the study of MAC protocols is throughput. A simple expression (considering only propagation delay and discounting effects such as clock drift) for TDMA throughput is given by

$$T = \frac{BL}{BL + D_{max}} = \frac{BL}{S} \tag{2}$$

where $L$ is the TDMA packet duration, $B$ is the number of packets transmitted in a burst (back-to-back in a single slot), $D_{max}$ is the maximum one way propagation delay in the network and $S = BL + D_{max}$ is the slot duration. For a network without propagation delay, $D_{max} = 0$ and $T = 1$. However, as $D_{max}$ increases, the throughput $T$ decreases.

In a two-node network, the nodes can exchange data packets simultaneously (provided the packet length is equal to the

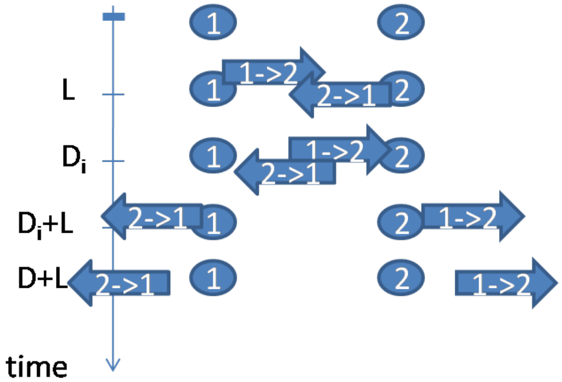

Fig. 4. Twin-TDMA

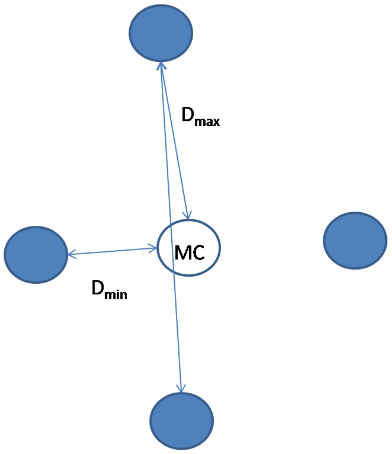

Fig. 5. Centralized topology

propagation delay) to get the maximum throughput as discussed in Example 1. In Twin-TDMA, this concept is extended to an arbitrary sized network. In traditional TDMA, in one slot, only one node transmits. In Twin-TDMA, in each slot, a pair of nodes exchanges bursts of data packets simultaneously. Just like traditional TDMA, the slot duration $S = BL + D_{max}$. There is an additional constraint that $BL \leq D_{min}$, where $D_{min}$ is the minimum delay among any pair of nodes. Since there are $2B$ packets transmitted in one slot, Twin-TDMA has an throughput given by

$$T = \frac{2BL}{BL + D_{max}} \tag{3}$$

This exchange of packets in one pair of nodes in the network is illustrated in Fig. 4. We assume $B = 1$ and that the two nodes shown are separated by a delay $D_i \geq L$ and $D_i \leq D_{max}$. The sequence illustrates how after time $L$, the packets have been completely transmitted, after time $L + D_i$ receptions start, and after time $D_i + L$ receptions complete. After time $D_{max} + L$, all nodes in the network will be clear of the transmissions and the next pair starts the Twin-TX transmissions.

In [7], such a simultaneous transmission concept was used, but restricted to only two nodes and not extended to a general $N$-node TDMA. In another related work called STUMP [8], a set of scheduling constraints are imposed, and the solution yields a schedule. We compare the performance of traditional TDMA, STUMP and Twin-TDMA using an example network from [8] with 12 nodes and a sink. Since that network is a centralized topology, we present a set of expressions for the throughput performance of TDMA and Twin-TDMA in a centralized topology shown in Fig. 5. In this topology, $D_{min}$ and $D_{max}$ refer to the minimum and maximum distances from the central node (MC) to any other node. For traditional TDMA, the throughput

$$\begin{aligned} T &= \frac{(B_1 + B_2)L}{B_1 L + D_{max} + B_2 L + D_{max}} && (4) \\ &= \frac{(B_1 + B_2)L}{(B_1 + B_2)L + 2D_{max}} && (5) \end{aligned}$$

where $B_1$ is the number of packets the client sends to the MC in one slot and $B_2$ is the number of packets the MC sends to the client in the same slot. For Twin-TDMA, the number of packets from MC to a node and from the node to MC in a single slot are equal, i.e., $B_1 = B_2$. The throughput is given by

$$T = \frac{2B_1 L}{B_1 L + D_{max}} \tag{6}$$

For the example network in [8], the round trip propagation delay $2D_{max} \approx 6$ seconds, the packet duration (called slot duration) $L = 0.4$ seconds and $(B_1 + B_2) = 11$ as 10 packets were used by a client and 1 by the sink. This gives a throughput $T = 0.42$ for traditional TDMA. The STUMP schedule was shown to improve upon this to about $T = 0.56$. We assume a minimum propagation delay $D_{min} = 2$ seconds (the minimum separation for the example network is of the order of 3500 m, i.e., 2 seconds). Since Twin-TX requires $B_1 L \leq D_{min}$, we use a batch size of $B_1 = B_2 = 5$. The Twin-TDMA throughput therefore is $T = 0.8$, significantly better than that of STUMP in this example.

### *B. Queuing Delay*

Although throughput is an important metric, another equally important metric is network latency or equivalently the queuing delay in a single hop network[1]. If the queuing delay was not a concern, choosing arbitrarily large TDMA slot duration (large $B$) would increase throughput in traditional TDMA, allowing the throughput to be arbitrarily close to 1 irrespective of the $D_{max}$ of the network. For the example in [8], one can increase the $B1$ and the corresponding throughput would increase even without the STUMP schedules. If we set $B1 = 49$, this would give us a throughput $T = 0.77$. So what prevents us from using a high batch size to get high throughput? With a fixed rate Poisson arrival model at each node, larger frames means greater total queuing delay. Since we do not wish to have arbitrary large queuing delays, we

---

[1] In this paper, we only concern ourselves with single hop networks where all nodes are within a single collision domain.

cannot select arbitrarily high batch size and therefore limit the throughput. Clearly, there is a trade-off between throughput and queuing delay.

For an $M/M/1$ system, the total queueing delay $W_T$ is

$$W_T = \frac{1}{\mu - \lambda} \tag{7}$$

where $\mu$ is the poisson service rate and $\lambda$ is the arrival rate. $\mu = 1/s$, where $s$ is the service time. From (7), we can see that for $\lambda \to 0$, $W_T \to s$. For $\lambda$ much lesser than the saturation limit ($\mu$), we can use $s$ as a lower bound of $W_T$ for a quick insight. For batch transmission system such as the TDMA system considered here, models such as $M/D^B/1$ (Poisson arrival, deterministic batch service) should be used for accurate analysis. In such systems, the service time $s$ may be used as a lower bound of $W_T$ for low $\lambda$.

In a batch transmission deterministic system, as we discussed above, assuming no other overheads or losses, the service time $s$ for $N$ nodes is

$$s = N((B_1 + B_2)L + 2D_{max}) \tag{8}$$

Then the waiting time $W_T$ is

$$\min W_T \approx N((B_1 + B_2)L + 2D_{max}) \tag{9}$$

Thus we can see that as $B_1 + B_2$ increases, throughput increases and at the same time waiting time also increases. A middle ground with reasonable $B_1 + B_2$ leads to an acceptable queuing delay and throughput. This is of course the criteria used in papers such as [8] implicitly. The waiting time for Twin-TDMA $W_T$ is

$$\min W_T \approx s = N(B_1 L + D_{max}) \tag{10}$$

Apart from the improved throughput of Twin-TDMA with respect to STUMP in the previous example, we also have a benefit in terms of waiting time. For STUMP, $\min W_T \approx N(11L + 2D) = 124.8$ seconds. For Twin-TDMA, $\min W_T \approx N(5L + D) = 60$ seconds. For a fairer comparison, we need the total traffic supported to be identical and use 10 slots in total for client and sink in the STUMP example. That gives us $\min W_T \approx N(10L + 2D) = 120$ seconds, which is about about 50% worse than the queuing delay of Twin-TDMA.

It is important to note that the topology in the STUMP example is centralized, i.e., all transmissions occur between clients and a sink. In the Twin-TDMA example, there is a difference that the sink and clients get equal slots of 5 each, whereas the STUMP example has asymmetric 10 slots for clients and 1 for the sink. Although we illustrated a centralized topology for Twin-TDMA for comparison with STUMP, distributed topology pair-wise transmissions are also possible in Twin-TDMA.

## III. DYNAMIC TWIN-TDMA

For ad hoc networks, static TDMA is not suitable. We outline an extension to Twin-TDMA to provide dynamic slot allocation. In an ad hoc network, nodes may join and depart from the network and may need different bandwidths. As discussed in [9], assuming we have time synchronization, we can use a dynamic form of TDMA. The scheme can be represented as shown in Fig. 6, where time is slotted and the slots are assigned as contention or data slots. Nodes contend for data slot allocation during the contention slots.

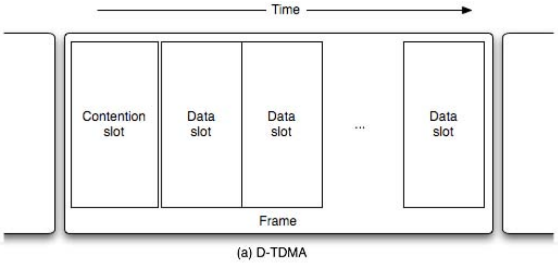

Fig. 6. Dynamic TDMA

### A. Centralized Dynamic Twin-TDMA

The dynamic Twin-TDMA can be used in a centralized mode where the Twin-TX can occur in data exchanges between a client and the sink (termed Master Controller – MC) or in peer-to-peer mode, between two clients. We shall consider the centralized topology and data exchanges between clients and the MC in this section. The MC is responsible for dynamic slot allocation. In the contention slot, nodes use random access with a uniform window back-off and send a RTS (Request for Slot) packet to the MC. The MC assigns a slot (or multiple slots) per frame for $M$ frames. After $M$ frames, those slots are no longer reserved and can be re-assigned to another node. The start of the contention slot may be indicated by the MC through a beacon packet. Upon receiving the beacon packet, the clients can start a back-off for sending the RTS. Initially there will be collisions between client RTS packets. But as clients get assigned to their slots, the contention will decrease.

Such centralized topology dynamic TDMA schemes are not by themselves novel and terrestrial radio wireless systems have employed them [10]. But the novelty introduced here is the simultaneous transmission by the MC and the client in the assigned slots, which is only possible because of the large propagation delays in UANs.

### B. Performance

Let us first ignore the contention process and take a look at the performance related to the assigned TDMA slots. The analysis is similar to the static case. Nevertheless, we look at an example, with the number of nodes (excluding the MC) $N = 10$, the packet length $L = 0.4$ seconds, the propagation delays $D_{min} = 2$ seconds (3 km) and $D_{max} = 4$ seconds (6 km). In traditional dynamic TDMA, 5 slots for uplink and 5 for downlink imply $B_1 + B_2 = 10$. Thus the throughput $T = 0.33$ and the waiting time $\min W_T \approx 120$ seconds. For dynamic Twin-TDMA, we have $B_1 = B_2 = 5$ for the same uplink and downlink capacity. Therefore $T = 0.67$ and the waiting time $\min W_T \approx 60$ seconds. In both respects the new protocol performs better than the traditional dynamic TDMA.

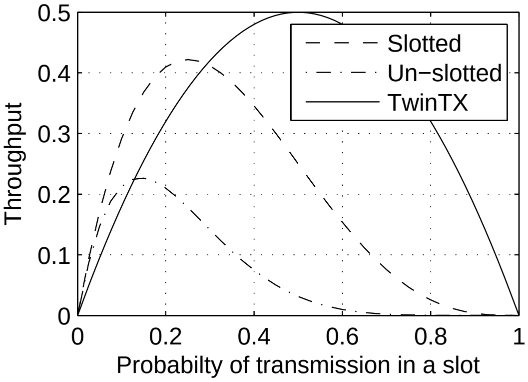

Fig. 7. Throughput for slotted Aloha, un-slotted Aloha and twin-Aloha in a four node network

When contention is taken into account, the performance depends on the exact contention model used. In a model where the slot allocations are changed infrequently, we expect no more than one node to contend during most contention slots. Since the round trip time for the RTS/CTS exchange during the contention slot is $t_A \leq 2L{+}2D_{max}$, we can set the duration of the contention slot $C = 2L{+}2D_{max}$. The effective throughput will drop due to the contention process. If there are $n_s$ slots in each frame, the throughput for dynamic Twin-TDMA is

$$T = \frac{2B_1Ln_s}{n_s(B_1L + D_{max}) + C} \tag{11}$$

$$= \frac{2B_1Ln_s}{n_s(B_1L + D_{max}) + 2L + 2D_{max}} \tag{12}$$

Typically, a frame would be designed to have sufficient slots for all nodes in the network to have a chance to transmit, i.e., $n_s \sim N$. The effect of contention on the waiting time is then to increase its expected value over one frame by $C$. If $s'$, $s' = s + C$ where $s$ is given by (10). The waiting time $\min W'_T \approx s'$, i.e.,

$$\min W'_T \approx N(B_1L + D_{max}) + 2L + 2D_{max} \tag{13}$$

Taking the same example analyzed earlier in this section, but taking contention into account, for Twin-TDMA we get a slightly reduced throughput $T = 0.58$ and a waiting time $\min W_{T'} \approx 69$ seconds.

## IV. TWIN-ALOHA

Next, we explore how the Twin-TX concept can be utilized in an ALOHA-like protocol. Consider a scenario in which a pair of nodes are always deployed together and require sporadic communication among themselves. During some deployments, these nodes are in a geographical area where they have to co-exist with other network nodes and therefore need a MAC protocol. Due to the sporadic transmission needs, a simple protocol such as ALOHA is perhaps well suited to the application. However, the Twin-TX concept can enhance the performance of ALOHA in this situation.

ALOHA traditionally uses randomly chosen transmission times at each node. Instead of one node choosing a transmission time independently, if pairs can simultaneously transmit, then throughput can be improved. Take an example network with 4 nodes arranged as a tetrahedron. In traditional slotted-ALOHA, each node will transmit with a probability $p = 1/N$, $N$ is the number of nodes, for optimal throughput. The maximum throughput is about 0.42 as shown in Fig. 7. The throughput $T$ can be expressed as follows where $p$ is the transmission probability:

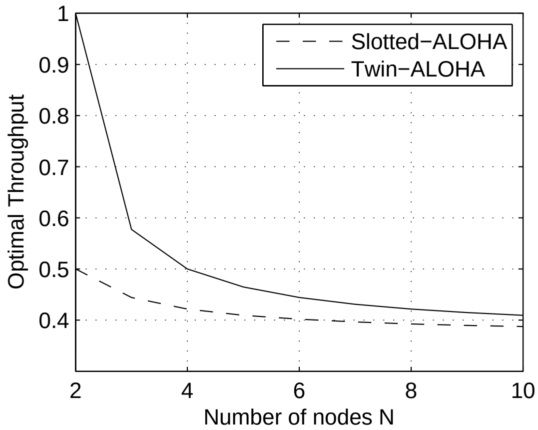

Fig. 8. Optimal throughput for Aloha and Twin-Aloha

$$T = Np\left((1-p)^{N-1}\right) \tag{14}$$

In our example scenario, the data exchange is between pairs and they know about each other. Assuming that the nodes are time synchronized, both nodes in each pair can be started off on the same pseudo-random number generation seed. Based on this they chose the same random slot for transmission. Each pair also knows not to transmit in the subsequent reception slot. So there is no *self-collision*. As long as the other pairs do not transmit in the next slot, the transmission will be successful. The throughput is then:

$$T = \frac{N}{2}p\left((1-p)^{N/2-1}\right) \tag{15}$$

This is shown in Fig. 7. Essentially, the performance is that of a network with half the number of nodes. If pairs are not equal in separation and or placed such that transmissions cross slot boundaries, we need to use guard periods. As a first approximation, we ignore the effect of such guard periods and see how the optimal performance of such a scheme would be for $N$ nodes as compared to standard slotted ALOHA using (14) and (15) in Fig. 8. As seen, for a small number of nodes, there is a clear improvement.

## V. CONCLUSION AND FUTURE WORK

We presented three Twin-TX variants of traditional protocols (TDMA, dynamic TDMA and ALOHA) that endeavor to harness the high throughput potential of large propagation delay networks. Although the throughput benefits from these protocols is modest as compared to the upper bound of $N/2$ for a $N$-node network, this work lays important foundations for further research into how random access networks may potentially benefit from propagation delay. Although the $N/2$ upper bound may not be achievable in many network geometries, an awareness of the potential and the insights into schedules that support a high throughput, may lead to the design of novel MAC protocols that are able to benefit from large propagation delays. The protocols we presented in this paper utilizes simple pairwise simultaneous transmission, and are only the first steps in this line of research.

## REFERENCES

[1] C. Fullmer and J. Garcia-Luna-Aceves, "Floor acquisition multiple access (FAMA) for packet-radio networks," *ACM SIGCOMM Computer Communication Review*, vol. 25, no. 4, pp. 262–273, 1995.

[2] H. Peyravi, "Medium access control protocols performance in satellite communications," *IEEE Communications Magazine*, vol. 37, no. 3, pp. 62–71, 1999.

[3] B. Peleato and M. Stojanovic, "Distance aware collision avoidance protocol for ad-hoc underwater acoustic sensor networks," *Communications Letters, IEEE*, vol. 11, no. 12, pp. 1025–1027, December 2007.

[4] A. A. Syed, W. Ye, J. Heidemann, and B. Krishnamachari, "Understanding spatio-temporal uncertainty in medium access with ALOHA protocols," in *WuWNet '07: Proceedings of the second workshop on Underwater networks*. New York, NY, USA: ACM, 2007, pp. 41–48.

[5] X. Guo, M. Frater, and M. Ryan, "Design of a propagation-delay-tolerant MAC protocol for underwater acoustic sensor networks," *IEEE Journal of Oceanic Engineering*, vol. 34, no. 2, pp. 170–180, 2009.

[6] M. Chitre, M. Motani, and S. Shahabudeen, "A scheduling algorithm for wireless networks with large propagation delays," in *OCEANS 2010*, Sydney, 2010.

[7] B. Hou, O. Hinton, A. Adams, and B. Sharif, "An time-domain-oriented multiple access protocol for underwater acoustic network communications," in *OCEANS '99 MTS/IEEE. Riding the Crest into the 21st Century*, vol. 2, 1999, pp. 585–589 vol.2.

[8] K. Kredo, P. Djukic, and P. Mohapatra, "STUMP: Exploiting position diversity in the staggered TDMA underwater MAC protocol," in *INFOCOM 2009, IEEE*, 2009, pp. 2961–2965.

[9] S. Shahabudeen, M. Chitre, and M. Motani, *Underwater Acoustic Sensor Networks*. CRC Press, 2010, ch. Dynamic TDMA and MACA based Protocols for Distributed Topology Underwater Acoustic Networks.

[10] http://en.wikipedia.org/wiki/Dynamic_TDMA, "Time Division Multiple Access: Dynamic TDMA."