Design of networking protocols for shallow water peer-to-peer acoustic networks

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ABSTRACT

Communication between a set of underwater systems such as remote sensors, autonomous underwater vehicles and control vessels would enhance the effective use of such systems tremendously. As electromagnetic waves do not propagate well underwater, acoustics plays a key role in underwater communication. Although point-to-point acoustic links can be established via numerous modulation schemes, an acoustic communication network demands multi-user communication. In such an environment, orthogonal modulation schemes could provide a solution for multiple simultaneous acoustic links. As an alternative to orthogonal schemes, random shared access technology has proven successful in many wireless networks. Through numerical simulations, we compare the performance of orthogonal and random shared access for underwater networking.

Over the past few decades, numerous networking protocols have been developed for use in wired and wireless networks. Due to significant differences in the characteristics of electromagnetic and acoustic channels, these networking protocols require modifications to perform well in underwater networks. As sound waves are much slower than electromagnetic waves, the latency in communication is typically much higher. Due to the multi-path propagation and ambient noise, the effective data rates are lower and packet loss is much greater. In this paper, we simulate variants of some popular protocols for underwater use, focusing on the Physical and Datalink layers of the OSI protocol stack. The aim is to select an appropriate Physical Layer and Datalink layer model for a small underwater network to be implemented.

I. INTRODUCTION

As the underwater acoustic channel is significantly different from wired and wireless electromagnetic channels, it is expected that network protocols may perform very differently in underwater acoustic networks. In this paper, we present results from simulation of mainly the Datalink and Physical layers of an underwater network. Since the primary function of the Datalink layer in this simulation is Medium Access Control (MAC), we use the term MAC layer to mean the same. Other aspects of Datalink layer such as error correction were not simulated. A discrete-event simulation software was used to implement the models. The models of the Physical and MAC layers were adapted from the popular network protocols [1]. A simple underwater channel model was used to test network performance. The primary performance criterion used is network throughput. The aim is to compare the relative performance of various networking schemes for use in underwater networks.

II. SIMULATION DETAILS

A. Software Tool

The simulation was developed using the discrete event simulation package Omnet++ [2]. The physical layer and the MAC protocols had to be kept as light as possible due to bandwidth and data rates constraints in underwater systems. Hence the protocols were developed from ground up rather than modifying existing heavier protocols meant for radio networks. The Omnet++ package was used purely a discrete event simulation tool.

Accuracy of the tests have been verified through analysis of timing logs of packets send and received at each layer, graphical representation of protocol behaviour as well as numerical accounting of packets send, received and lost due to various means like Bit Errors (BER) and collisions.

B. The Protocol Stack

The simulation models three layers of the OSI stack – Network, Datalink and Physical. The acoustic channel is also modelled (see section C).

There are three variants of MAC protocols that are implemented in the Datalink Layer. These are described in the following sections E, F, G. The Physical layer uses two variants – orthogonal and non-orthogonal, as described in section D.

C. The Channel Model

A simple channel model was used to test the performance of the protocols. The channel propagates all packets to all nodes except the sender and accounts for the propagation delay and path loss. The path loss model used is the spherical spreading model:

$$path\ \ loss\ \ in\ \ dB = 20\log_{10}(range) \qquad ...(1)$$

More complicated models (e.g. [3]) could be implemented, but the above was deemed sufficient as a first order approximation for the scope of the simulation.

We have assumed additive white Gaussian noise (AWGN). Although warm shallow water channels tend to exhibit impulsive noise [4], the AWGN assumption may be considered reasonable for general underwater channels. Nevertheless the comparative results should provide a good estimate as to the protocols' relative performance.

D. The Physical Layer

The Physical Layer was assumed to be a half duplex system as is usually the case in many commercial acoustic modems [5]. BER and collisions were simulated. A simplified state diagram for the physical layer is shown in Figure 1.

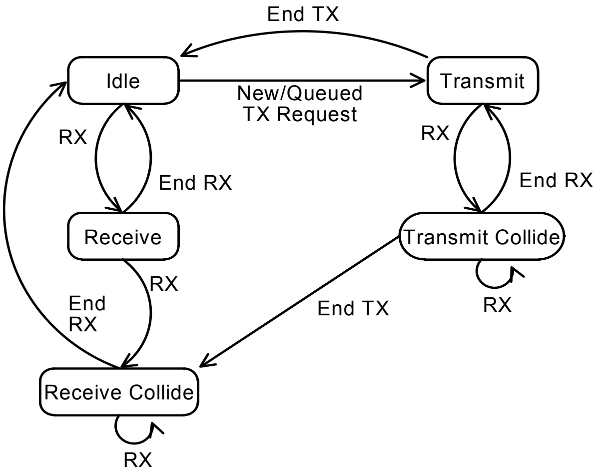

Figure 1. Simplified Physical Layer State Diagram

The physical layer has a buffer to store incoming packets. RX refers to reception of packets from other nodes and TX refers to transmission. Collisions that occur during transmissions do not interrupt the transmission, but the incoming packets will be lost due to the half duplex model. All collided packets are considered lost.

The SNR is computed from equation (2) where N_0 represents the ambient noise power spectral density. The E_b/N_0 ratio is computed from equation (3) and the associated BER is computed based on a QPSK modulation scheme in an AWGN channel. The packet loss probability is then computed from equation (4). A packet may be lost due to BER, receive collision or transmit collision.

$$SNR = \frac{\text{Received Power}}{N_0 \times \text{Bandwidth}} \qquad \ldots(2)$$

$$\frac{E_b}{N_0} = SNR \times \frac{\text{Bit Rate}}{\text{Bandwidth}} \qquad \ldots(3)$$

$$p_{loss} = 1 - (1 - BER)^N \qquad \ldots(4)$$

The Physical layer has two variants – orthogonal and non-orthogonal. Orthogonal channel model employs unique orthogonal channels for each recipient. In the non-orthogonal case, all nodes share the same channel. In case of orthogonal channels, the total available bandwidth is divided among the individual receive channels (one channel per node). Thus the orthogonal model could be considered like a deterministic FDMA system where the bandwidth is pre-allocated to each node.

E. ALOHA based half duplex protocol (MAC0)

The model described in this section is the first of the three variants of the MAC protocols in the Datalink Layer. This protocol is a reference model that is kept as close as possible to the simple ALOHA model. When the Datalink layer gets a packet from the network layer, it simply forwards to the Physical layer. There are no retries and the recipient does not send any Acknowledgements (ACK). The only complex behaviour thus comes from the Physical layer which is half duplex and does not transmit while a reception is in progress.

Note that unlike the theoretical ALOHA model that is commonly used to derive throughput statistics analytically, this protocol does not transmit entirely randomly, since the half duplex Physical layer does not transmit while reception is in progress. Since the Datalink layer behaviour in this model is trivial, the state transitions are similar to the Physical layer as shown in Figure 1.

F. ALOHA based half duplex protocol with acknowledgements and retries (MAC1)

This is the second MAC protocols under study in the Datalink Layer. The state diagram is shown in Figure 2.

This protocol adds retries and acknowledgements (ACK) to the protocol. Sender waits for a maximum Round Trip Time (RTT) for an ACK. If no ACK is received, it resends after a random wait using an appropriate random back-off delay. After a maximum number of retries, it drops the packet and transmits the next queued packet. Receiver sends an ACK to the sender if the received packet is error free. This is similar to the protocol described as ALOHA in [1].

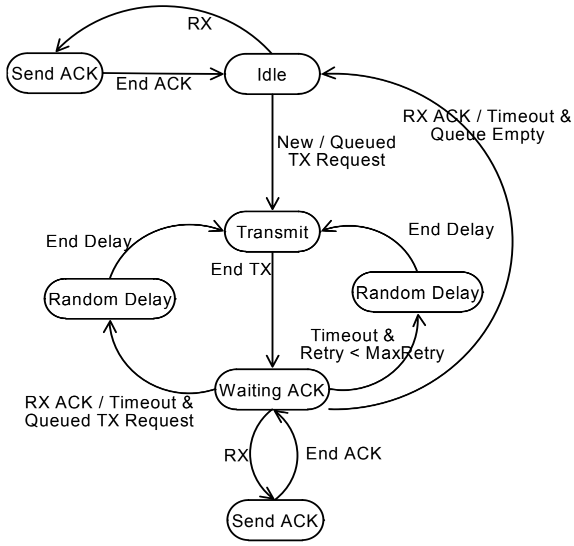

Figure 2. Simplified MAC1 State Diagram

G. MACA based half duplex protocol using RTS/CTS handshaking (MAC2)

This is the third MAC protocol under study in the Datalink Layer. This is a more complex protocol devised along the lines of MACA [1] and 802.11 wireless LAN protocols. It employs short (64 bits) Request-to-Send (RTS) and Clear-to-Send (CTS) packets to do an initial handshaking between sender and receiver before sending the actual data packet. It employs Physical Carrier Sense (PCS) and does not transmit when a reception or transmission is in progress at the Physical layer. It also employs Virtual Carrier Sense (VCS). If a node receives an RTS or CTS for other nodes, it will not transmit for the duration of that intended transmission. The state diagram is shown in Figure 3. Note that DIFS is a small delay (Distributed Interframe Space [6]) used after the completion of the PCS.

This protocol also employs power control. The CTS will send a recommendation of the minimum power to be used.

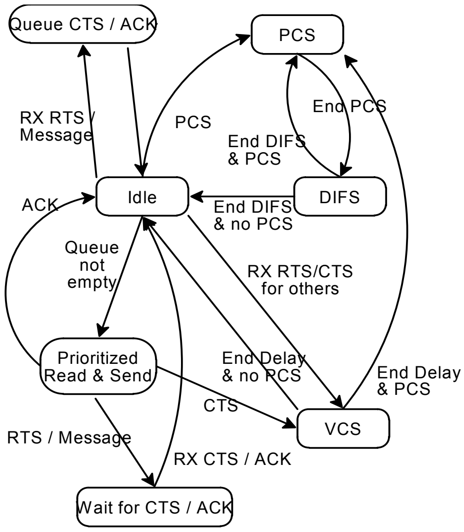

Figure 3. Simplified MAC2 State Diagram

H. Node locations and transmission model

The simulated nodes were randomly distributed over an area of roughly 50m radius. A small network of four nodes (numbered 1 to 4 in Figure 4), was used for most of the simulations except when we investigated the effect of increasing number of nodes on performance.

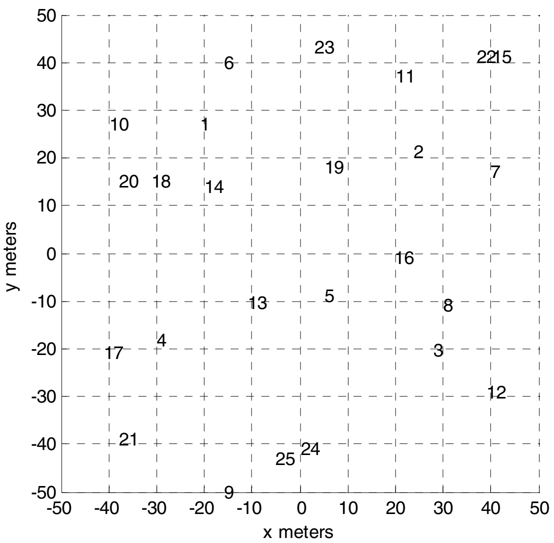

Figure 4. Node Locations

The average separation between nodes was changed during the study of effects of node separation on performance. Each node generated random traffic (Poisson arrivals with a specified mean). Each packet was transmitted to a randomly (uniform distribution) selected recipient node.

III. SIMULATION SCENARIOS

The three MAC protocols were used together with both orthogonal and non-orthogonal Physical layer models. Thus there were six protocol model combinations under study.

The scenarios for various simulations were as described in the following sections. Each scenario was repeated for the six protocol variants.

The following equations were used for offered load and throughput computations. Average Sent and Average Received refer to the total number of packets for the network (and not for each node).

$$\text{Offered Load} = \frac{\text{Average Sent / Simulation Time}}{\text{Bit Rate / Packet Length}} \quad \ldots(5)$$

$$\text{Throughput} = \frac{\text{Average Received / Simulation Time}}{\text{Bit Rate / Packet Length}} \quad \ldots(6)$$

The packet generation model at each node is related to the average packet transmission rate for the network:

$$\text{Average packet rate per node} = \frac{\text{Average for network}}{\text{Number of Nodes}} \quad \ldots(7)$$

All packet lengths are in given in bits.

A. Simulation1: Throughput v/s Offered load for various packet sizes

In this scenario, we studied the throughput for all the six protocol variants. The results are shown in Figure 5 to Figure 10. Both, packet rate and packet length, were varied. Each curve is plotted for constant packet length and varying packet rate. The bit rate was assumed to be 2400 bps; this is quite typical of some of the shallow water acoustic modems being considered for the network. The offered load is varied according to equation (5). The measured throughput is plotted against the measured offered load.

The main observation that we infer from these results is that orthogonal schemes could have much poorer performance compared to the non-orthogonal shared access schemes. The expected performance gain for orthogonal scheme through reduced collisions from orthogonal nodes is firstly countered by the reduced effective bandwidth and data rate per node.

Another reason behind the orthogonal scheme's poor performance is as follows. In the case of non-orthogonal scheme, since the Physical channel is half duplex and does not transmit during any reception, it prevents a node from transmitting while a transmission is in progress between two other nodes. Thus it effectively becomes a Virtual Carrier Sense (VCS) even for the MAC0 and MAC1 non-orthogonal protocols which do not explicitly sense the carrier like MAC2. In the scenario here, the propagation delay is of the order of 0.03 seconds (~50 m range with 1500 m/s sound speed) whereas the packet durations are of the order of 1 second. This makes the above effect possible. This VCS-like behaviour enhances the performance of the non-orthogonal scheme by reducing collision probability. In the orthogonal scheme, a node wishing to transmit to another has no way of sensing that another node could be transmitting to the same node at that time since the receive channels are orthogonal. And thus do not benefit from this pseudo VCS behaviour.

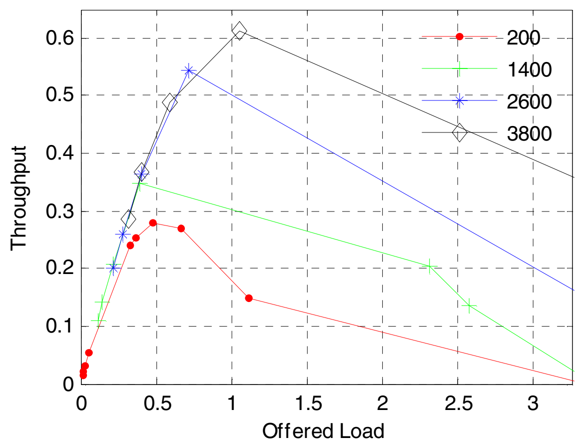

Figure 5. MAC0 non-orthogonal

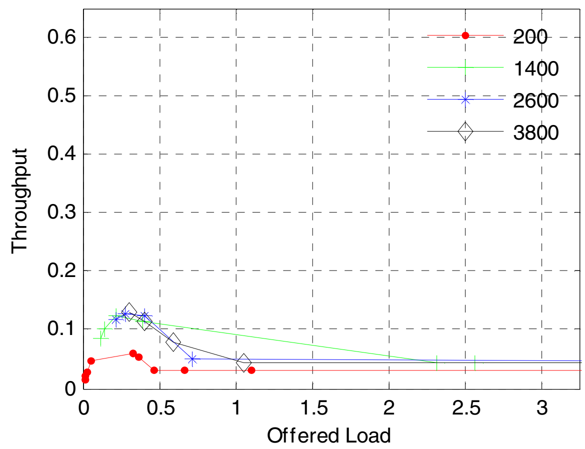

Figure 8. MAC0 orthogonal

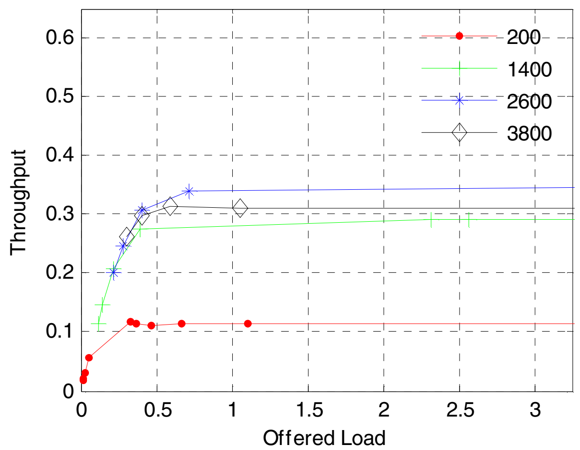

Figure 6. MAC1 non-orthogonal

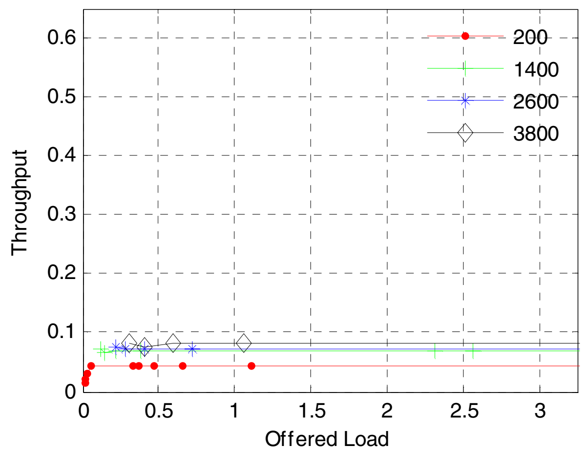

Figure 9. MAC1 orthogonal

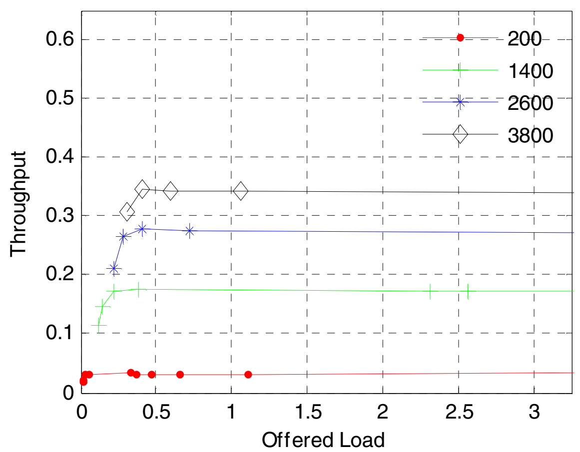

Figure 7. MAC2 non-orthogonal

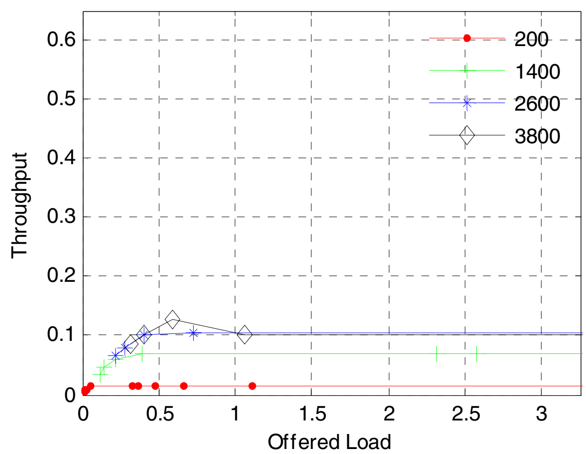

Figure 10. MAC2 orthogonal

We further look at the non-orthogonal results in greater detail. MAC0 throughput drops similar to the theoretical ALOHA for higher loads. MAC1 and MAC2 throughput saturates in the same way as protocols with acknowledgements like 802.11, at higher offered load [7]. Note that the throughput here for MAC0 is better than the theoretical ALOHA throughput of 18%. This is not an anomaly as the theoretical ALOHA does not employ the pseudo carrier sense inherent in our Physical layer (discussed earlier in this section). The throughput improves for larger packet sizes as can be seen in Figure 5 to Figure 7. This behaviour is further examined in the next section.

B. *Simulation2: For fixed offered load, compare the throughput for various bit rate rates and packet lengths*

In this simulation, we studied the effect of packet sizes for a fixed Offered Load (100%) for the non-orthogonal schemes. Figure 11 and Figure 12 show the results for bit rates 2400 bps and 9600 bps.

Note that "Ortho:0" and "Ortho:1" refers to non-orthogonal and orthogonal schemes respectively in all the following figures.

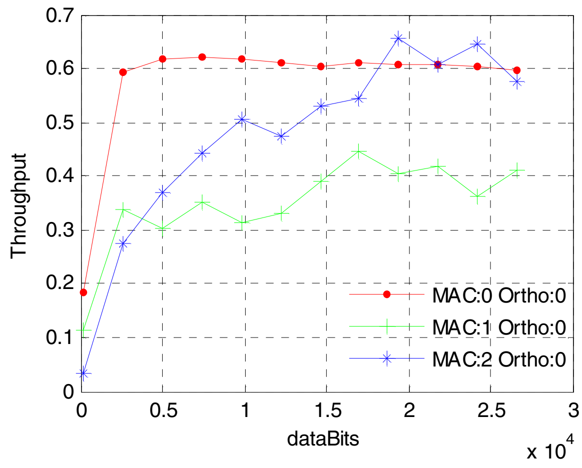

Figure 11. Throughput v/s Packet Size (2400 bps)

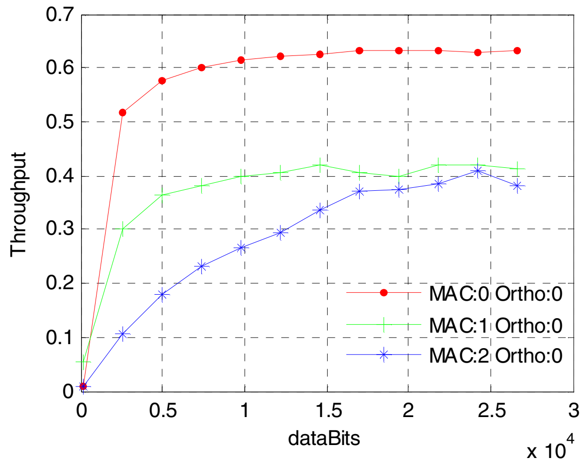

Figure 12. Throughput v/s Packet Size (9600 bps)

For the 2400 bps case, we can see that the throughput of MAC2 is lower than that of MAC1 at low packet size, but eventually exceeds it at larger packet sizes. For an appropriate packet size (more than 10,000 bits for 2400 bps) MAC2 has the best throughput of the three protocols. It is remarkable that MAC2 can demonstrate the same or better performance as MAC0 in spite of the overheads involved in acknowledgement and semi-guaranteed delivery through the retry mechanism (MAC0 has no acknowledgements and retries). The transmission slot reservation mechanism through the VCS makes this possible by reducing collisions during the data transmission. The throughput of all three protocols saturates after a certain packet size.

The behaviour at 9600 bps is similar except that the packet sizes at which MAC2 exceeds MAC1 is higher by a similar factor as the bit rate. The packet size at which throughput saturates is also higher by a similar factor. The maximum throughput does not change with bit rate (note that MAC2 throughput continues to grow to about 0.6 beyond what is displayed in Figure 12).

This prompts us to look at MAC2 non-orthogonal as the better performing scheme among the six compared protocols.

C. *Simulation3: For fixed offered load, study throughput variation with respect to number of nodes*

In this simulation, we examined the behaviour of the all protocols as the number of nodes was varied for a fixed offered load of 100%. Figure 13 shows the results. The bit rate is fixed to 2400 bps and packet size is set to 4000 bits.

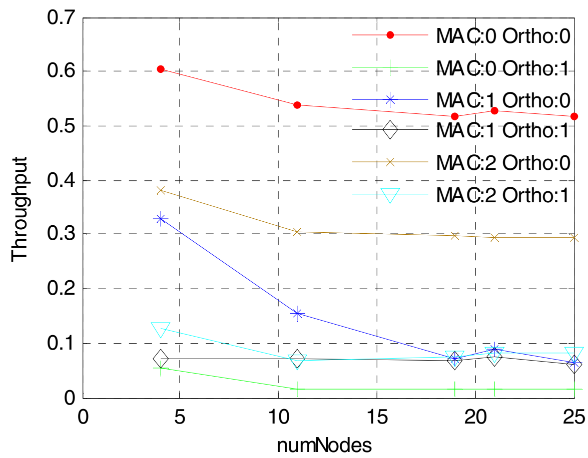

Figure 13. Throughput v/s number of stations

The results should be used only to interpret variations in throughput and not for throughput comparison. Absolute throughput is dependent on packet sizes used as we saw in the last section. It is seen that the MAC2 protocol throughput drops more slowly than MAC1 as number of nodes increase. This also favours the choice of MAC2 over MAC1. This is similar to the result for protocols with RTS and without RTS as shown in [7]. The reason is that collisions increase as number of nodes increase. For MAC2 added collisions affect mainly the short RTS packets and the performance degradation is not as severe as for MAC1 where collisions affect the large data packets.

As is generally known about shared access protocols, throughput drops with increasing number of nodes. This is very clear for the ALOHA-like MAC1. But for up to 25 nodes as in Figure 4, the MAC2 non-orthogonal throughput is still better than MAC2 orthogonal model as seen in Figure 13.

D. *Simulation4: For fixed offered load, study the throughput with respect to the node separation*

We examined the behaviour of the non-orthogonal protocols as the node separation (propagation delay) is varied for a fixed offered load of 100%. Figure 14 shows the results. The bit rate was set to 2400 bps and packet size was fixed at 4000 bits. We used the first six nodes from Figure 4 for this experiment. The distance factor is the factor by which the node coordinates are multiplied by, as compared to the locations in Figure 4. For example a distance factor of 5 means that the nodes' average separation is in the order of 250 meters as compared to the 50 meters in Figure 4.

The throughput of MAC0 and MAC2 generally seems to get poorer as the propagation delay increase. MAC1 seems to have better performance as delay increases. The above observations could perhaps be due to the following. MAC0 performance drop is mainly due to increased BER due to increased path loss. MAC2 relies on VCS for performance and as propagation delays increase, the carrier sensing is not timely and it also suffers from increased BER. MAC1 performance is expected to drop as BER increases with distance due to reduced receive power. However, the MAC1 performance seems to somewhat increase with distance and needs further investigation.

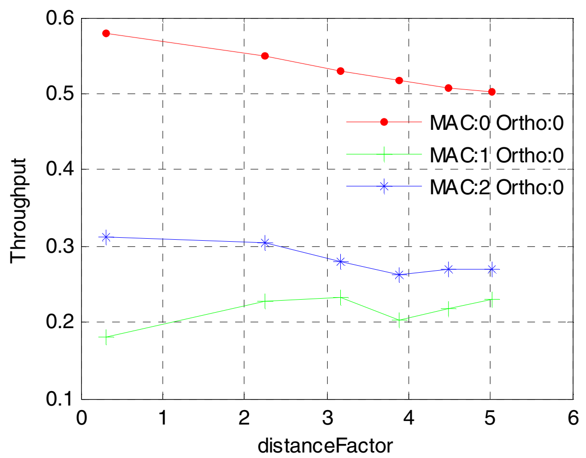

Figure 14. Throughput v/s node separation

IV. CONCLUSIONS

Our results point to the conclusion that non-orthogonal shared access schemes are good candidates for a small underwater network. A network with a fully shared channel also has the advantage that it is easily scalable and is easily adaptable to become a mobile ad-hoc network. Cellular orthogonal ad-hoc networks have to cater for channel allocation and associated signalling overhead as new nodes have to join the network. Shared channel system alleviates this problem and nodes need to know only the MAC address of the recipient and need not cater for different physical channels. This network model is also the essence of the popular 802.11 radio wireless LAN technology.

Among the non-orthogonal schemes MAC1 and MAC2, MAC2 emerges as the better performer for the simulated small underwater network. MAC0 is essentially a reference protocol and its seemingly better performance here is due to not having the overheads of acknowledgements and retries. For MAC0, acknowledgements will be needed in a higher layer for reliable communications and that will negate its apparent high performance. MAC2 non-orthogonal is shown to be a good choice for up to 25 nodes, under the conditions used here. MAC2 is also similar to the protocol used in [5] and this choice seems to be inline with the best schemes used so far for underwater networks.

The final choice of a protocol for implementation in a real system is also affected by key requirements such as scalability, mobility, ad-hoc networking, system complexity, power requirements and transmission latency. As we discussed at the beginning of this section, scalability, mobility and ad-hoc networking is easier with a non-orthogonal scheme. System complexity is also generally lower for a non-orthogonal shared channel scheme. MAC2 can employ power control and thus can conserve power effectively. By maximizing the throughput using an appropriate packet size, we can minimize the latency of the protocol. Thus MAC2 satisfies the primary requirements set out for this simulation study.

We intend to study the impact of power control further in the next phases of the study. The finding that orthogonal schemes perform worse than non-orthogonal schemes probably requires further investigation for CDMA based orthogonal schemes (the scheme here is similar to a deterministic FDMA). We also intend to use more accurate channel models developed at the Acoustic Research Laboratory in the next phase. These models include multi-path effects as well as impulsive noise due to snapping shrimp that are characteristic of the shallow water acoustic channels, where a practical implementation of the acoustic network is to be undertaken.

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REFERENCES

[1] Ethem M. Sozer, Milica Stojanovic, and John G. Proakis, “Underwater Acoustic Networks”, *IEEE J. Oceanic Eng.*, vol. 25, No. 1, pp. 72-83, Jan 2000.

[2] Omnet++, Discrete Event Simulation System, http://www.omnetpp.org/

[3] K. Raysin, J.R. Rice, E. Dorman and S. Matheny, Telesonar network modeling and simulation", in *Proc. Oceans'99*, 1999.

[4] M. Chitre, J. Potter, and S. H. Ong, "Underwater acoustic channel characterisation for medium-range shallow water communications," in *Proceedings of Oceans 2004 (MTS/IEEE)*, 2004, pp. 40-45.

[5] J. A. Rice et al, “Evolution of Seaweb Underwater Acoustic Networking,” in *Proc. IEEE Oceans Conf.*, vol.3, Sept. 2000, pp. 2007-2018.

[6] B. Crow, I. Widjaja, J. G. Kim, P. Sakai, “Investigation of the IEEE 802.11 Medium Access Control (MAC) Sublayer Functions”, in *Proc. INFOCOM '97*, Apr. 1997, pp. 126.

[7] C. Sweet, D. Sidhu, “Performance Analysis of the IEEE 802.11 Wireless LAN Standard”, M.S. thesis, University of Maryland, Baltimore, US, 1999.