A TDMA based EM Controlled Multi-Channel MAC Protocol for Underwater Sensor Networks

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Abstract—**Successful wireless communications in underwater with high throughput possess a great challenge still today. Due to the unique environment in underwater, medium access protocols (MAC) for terrestrial networks are not suitable for such environment. High attenuation of electromagnetic (EM) wave in water makes acoustic wave a more appropriate choice for communication in underwater. However, the low available bandwidth, high propagation delays and spatial-temporal uncertainty of the nodes make the MAC protocols with acoustic channel a vast area for research. In this paper, we propose a novel multi-channel MAC protocol for underwater sensor networks (UWSNs) employing both acoustic and EM waves. The proposed MAC protocol has a single EM based control channel which is used for managing the node data transmission times and confirmation messages. On the other hand, multiple acoustic channels are used as the data communication channels. In the proposed protocol, time division multiple access (TDMA) technique is used for control channel to prevent any collision between control signals of the nodes. Because of the nature of zero collision in the control channel, the whole MAC scheme remains in a collision-less state. Extensive simulations are carried out for evaluating the performance of the proposed MAC protocol demonstrating its validity.**

Index Terms—**Multi-channel MAC protocol; EM wave; underwater sensor networks; time division multiple access;**

I. INTRODUCTION

Most of the surface area of our Earth is encompassed by the sea. The environment under the sea holds a great deal of uncertainty and research areas. If we can closely monitor the seismic activity in underwater, we might be able to predict the tsunami as well as earthquake. The chemical, biological and nuclear pollution in underwater can be monitored and we can get an idea of the overall pollution of our environment. We can identify hazards on seabed, locate mine, shipwrecks and can detect intrusion by the communication in underwater. Therefore extracting information from underwater is essential for us. To acquire these signals, we need underwater sensors. Underwater sensor networks (UWSNs) consists of nodes that has the ability to communicate between each other and can sense and process data. MAC protocols used in terrestrial communications become unfeasible for underwater environment because of the different environment in underwater. As Electromagnetic (EM) waves diminishes rapidly in underwater, acoustic waves with its higher range is a better option to use for underwater communication. EM waves though used sometimes in fresh water communication are almost always neglected in the research of underwater (sea) communication [1], [2], [3].

The development of MAC protocols for underwater communication (UC) became a popular research area from the beginning of this century. There are mainly three types of MAC protocols for underwater, namely; contention based, contention free and hybrid type [3]. Among the contention based MAC protocols, the ALOHA technique is the simple of all. This technique allows any node to send its generated data instantly without any delay. pure ALOHA and slotted ALOHA were analyzed mathemtically for underwater accoustic networks in [1]. The output of the paper was that slotted ALOHA cannot give much higher performance than pure ALOHA in underwater. The reason behind is mainly the high propagation delay in underwater.

In paper [4], it was suggested that the scheduled protocols consumes small amount of power by eliminating collisions. However it failed to adapt in changing traffic conditions compared to the random protocols. They took the initiative to merge these two ideas by dividing time into scheduled and unscheduled access periods to gain the benefits of each protocol. The authors in [5] confirmed that the performance of slotted ALOHA degrades because of spatio-temporal uncertainty and guard bands can be used to improve the performance a lot. Almost at the same time in paper [6] two schemes namely ALOHA-advanced notification (AN) and ALOHA-collision avoidance (CA) were proposed.

Afterwards, an intelligent method of handshaking was proposed in [7], which saves a lot of power by ensuring very low collision rate and excels in throughput performance. In this method, the receiver sends clear to send (CTS) packet for the transmitter which is then follwed by another short packet to mitigate the collision of data. Later the authors of paper [8] schemed a method named T-Lohi MAC, which fights the uncertainty of the time space and node deafness. The reservation mechanism for this method is tone based. Normally the nodes are in sleep state, whenever they have a data to receive, a short tone is send beforewards to wake up the respective node and ensure proper reception. On the other hand, the proposal in paper [9] was that with the help of mobiltiy prediction, scalable localization of nodes can be done. Afterwards, to improve the transmission efficiency, bidirectional data communication were suggested. The idea was to use burst packets for bidirectional communications within the transmitter-receiver pair for multiple times [10]. Among the current trends in underwater communication, estimation of time dependent propagation delay has become significant. By utilizing spatial correlation of underatwer nodes this delay can be assessed, which helps to synchronize between the nodes [11]. The practicality of the MAC protocols, proposed in different papers was assessed in [12]. With thorough research it was found that MAC protocols with time sharing techniques are quite promising. However, none of the above works on underwater MAC protocols has considered EM wave.

In recent works, the viability of EM in underwater communication is being researched extensively. The researchers are working tirelessly to find a way to efficiently merge EM in UC. In [13], they have studied the feasibility of using EM in underwater. The researchers in [14] suggested that EM is a viable solution for short range UC, where the high velocity and Bandwidth of EM can be used. Furthermore, in paper [15] it was urged that it is high time to re-evaluate the role of EM in UC. They discussed about many beneficial features that EM have over acoustic and optical fibre communications. The authors in [16] proposed the use of EM in distant sensor and underwater localization systems.

On the other hand, TDMA based protocols are also being researched extensively nowadays and are showing promising performance [17-20]. The authors of paper [17] have proposed STUMP, a TDMA based MAC protocol which utilizes node position diversity to increase channel utilization. In paper [18], they have studied continuous time scheduling based TDMA which eventually lead to better network throughput and efficiency. In continuation of research in underwater communication based on TDMA technique, r-MAC, GSR-TDMA, aTDMA etc. are the modern trends [19-20].

In light of this, the main objective of this paper is to combine the advantages of both acoustic and EM waves. The EM waves, though attenuate rapidly in underwater, can propagate in the order of several times faster than acoustic waves. Whereas acoustic waves are very slow, but can propagate a longer distance compared to EM waves. Therefore, it is apparent that we can use EM for a very short duration, while the acoustic wave needs to do the rest. In one of our recent work we have checked the feasibility of the proposed scheme for single data channel, with varying data and control packet rate [21]. In this paper we have evaluated the functionality of the proposed MAC protocol for multiple data channel and varying Bandwidth.

This paper thus aimed in utilizing both EM and acoustic channels at the same time for developing MAC protocol for UWSNs. To the best of our knowledge, this is the first approach of this kind. We propose two types of channels; the EM channel is used for signalling purpose and the acoustic channel for data transmission. Due to the requirement of much higher transmit power attributed to the rapid attenuation property of EM wave in underwater; we propose to use it for a very short duration only for transmitting control packets. The control packets are sent by the nodes for reserving the acoustic channel or to send the confirmation message of data packet reception. On the other hand, the acoustic band is divided into multiple numbers of channels with equal bandwidth, which can transmit data in parallel. Furthermore, the control channel is based on TDMA technique and thus avoids any possibility of collisions. Therefore the protocol provides us a collision free network and the extra power consumed by the EM wave can be mitigated by some degree.

The rest of the paper is organized as follows. The system model of the proposed underwater MAC is described in Section II. It also includes the node distribution of the network and the time series diagram of the protocol. Section III describes all the system parameters. The simulation results and comparison of proposed protocol with other MAC protocols are done in section IV. To conclude, Section V has the summary with all the key findings.

II. System Model

The underwater network considered here have nodes which are static in nature and are scattered within a fixed area following a uniform distribution. The node distribution and the communication topology of the considered underwater network are depicted in Fig. 1. As seen, we focus to develop a MAC protocol for a group of certain type of nodes in an UWSN, which can communicate with each other at single-hop distance in both directions. The nodes when transmitting a signal is assumed to be heard by all the other nodes. The nodes can control half-duplex antennas of both EM and acoustic channels at the same time. It is assumed that all the nodes have equal packet generation rate and the packet generation rate maintains Poisson distribution. Total offered load is equal to the aggregated load generated by all the nodes.

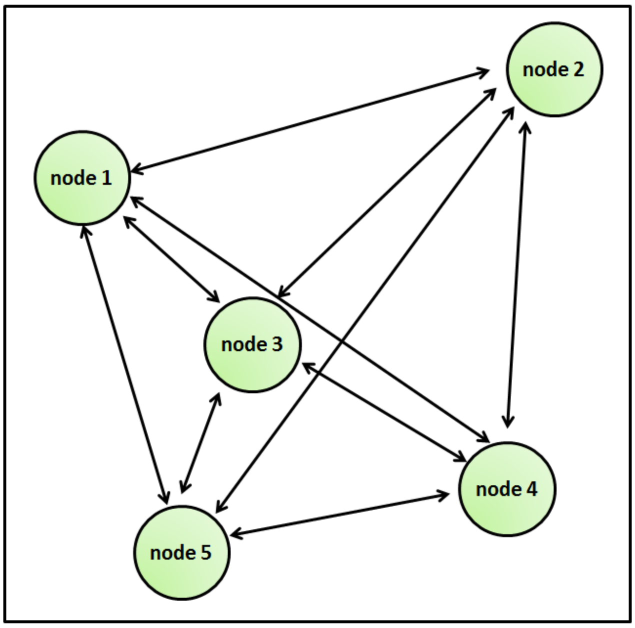

Fig. 1: Network Topology of the network

When the network is in active mode, the nodes are transmitting and receiving two types of signals, one is the control signal transmitted through the EM channel and another one is the data packets sent over the acoustic (data) channel. The EM control channel is TDMA based with N slots per frame. We assume an assigned time slot (T_S) for each node to request the reservation of acoustic data channel and one slot per acoustic data channel to send the successful data reception message. This confirmation message sent by a receiver also indicates the release of a data channel. Thus, the frame size (number of time slots in a frame) of the EM control channel becomes $N = n_c + n_d$, where n_c is the number of nodes in the network and n_d is the number of parallel data channels. All the nodes in the network are proposed to maintain a table with two types of entries - the reservation sequence and the free data channels. Each node updates its table upon listening any request message from an intended sending node as well as any confirmation message from a receiver of releasing a data channel. The operation principle of the proposed MAC protocol is presented in Fig. 2 for a network having two data channels and four nodes. When a node requires channel for data transmission, it first requests for reservation of data channel using its assigned time slot in the EM wave based TDMA frame. Data channels are allocated to the requested nodes as per the request message received sequence. We assume that in the TDMA frame, time-slot 1 to 4 are assigned for sending reservation request of nodes 1 to 4 respectively, while slot 5 and 6 are for sending confirmation message of releasing data channels 1 and 2 respectively. Duration of each of these slots is equal to the control packet duration plus the guard band duration.

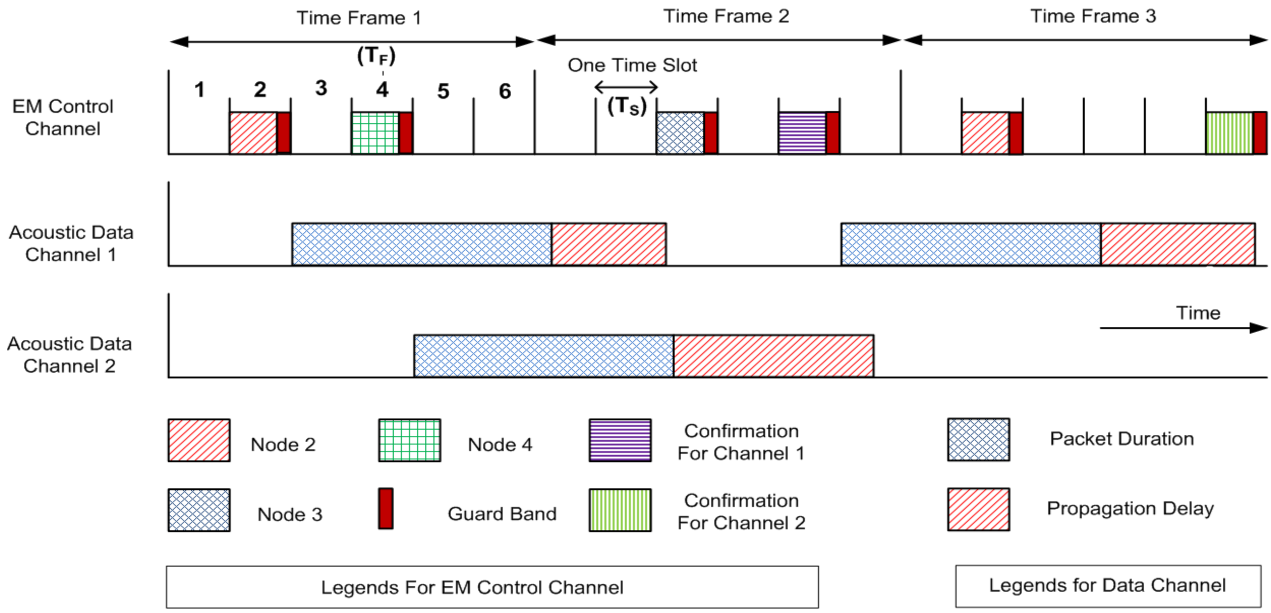

Fig. 2: Time Series diagram of the proposed MAC protocol using two acoustic wave based data channels.

For instance, let figure 2 depicts the beginning of the system. At first, node 2 wants to send data packet and therefore requests for reservation through slot 2 of the EM channel TDMA frame. Now as both the data channels are free as found in its own table, node 2 starts transmitting data using acoustic data channel 1. Now if another node wants to transmit data, it can start transmitting data through data channel 2. For example, we can see in the figure that node 4 wants to transmit data after a while. As the data channel 1 is now occupied by node 2, node 4 transmits the request message for reserving a data channel and then starts transmitting its data through the data channel 2. Once again the tables maintained by the nodes will be updated, and this time with the entry of no free data channel. Now as all the data channels are booked, the other nodes intended to transmit data will maintain the reservation process through their respective time slots and wait for data channel to be freed. These reservation calls will also be updated on the tables maintained by the nodes.

We see from the diagram that the next transmitter in the list is node 3. It will send its reservation for data channel through its given time slot and all the nodes are assumed to have heard it. Now every node will update their table once again. Then after a while, we see that the data transmitted through data channel 1 by node 2 is completed. However, the channel 1 remains busy for the duration of data packet plus the time required to propagate the data signal from node 2 to the desired destination, which is also shown in Fig. 2. After this time period, the channel 1 can be freed. Therefore, upon receiving the complete data packet, the receiver now transmits a receive confirmation message using slot 5 of TDMA frame. Through this confirmation message, all the nodes are now notified that data channel 1 is free and then node 3 starts its transmission through data channel 1. Now if we look at the time series of data channel 2, we see that upon the reception of the data packet, the receiver sends a confirmation message using slot 6 of TDMA frame to let others nodes to know that channel 2 is now free. As we can see from the time series that the data packet of channel 2 was received during time slot 6, therefore the confirmation message is sent during the 6th slot of the next time frame (T_F). This process of transmission and reception of data will go on for the rest of the time series.

III. System Parameters

The underwater network upon which the simulation is done has its own distinguishable characteristics. Here the control channel is EM based and the propagating velocity of EM can be calculated from the following equation [16],

$$v_{EM} = \sqrt{f \times 10^7 / \sigma} \tag{1}$$

where, v_{EM} is the propagation velocity of the EM wave, f is the frequency of the EM and σ is the conductivity of the medium. Therefore the guard band (T_G) needed for every time slot (T_S) of the control channel can be calculated from the following equation,

$$T_G = \frac{D_m}{v_{EM}} \tag{2}$$

where, D_m is the maximum allowable distance between two nodes in the simulation platform. On the other hand the propagation velocity of acoustic wave (v_{acst}) is assumed to be constant with the value of 1500 ms^{-1}.

In the assumed network scenario, the nodes generate data packets on their own, the accumulation of these data generation makes the total traffic load (L_T).

$$L_T = \frac{P_L}{2400} \times G_T \tag{3}$$

where, P_L is the packet length and G_T is the data packet generation rate of the total network. In equation 3, the division by 2400 is done to normalize the data length with respect to 2400 bits data packet. Now these data packets are transmitted through the data channels. However all the packets generated within a particular time period cannot be transmitted within that time period. Hence comes the success rate (S_{SR}), which is defined as

$$S_{SR} = \frac{S_S}{S_T} \tag{4}$$

where, S_S is the number of successful data packet transmitted in the total simulation time (T_T) and S_T is the total number of data packets generated in T_T. With the total traffic load and success rate, it is possible to define the throughput (η_T) for the total network,

$$\eta_T = S_{SR} \times L_T \tag{5}$$

After the data packets are generated in the nodes, sometimes the nodes cannot transmit the data instantly, due to the unavailability of the data channel. It is labelled as the waiting time (T_W) of the nodes. The average waiting time is just the average of all the waiting time of the nodes within T_T.

$$T_W = T_{Gn} \sim T_{Tr} \tag{6}$$

where, T_{Gn} is the generation time of a data packet and T_{Tr} is the start time of transmission of that very packet. When the nodes are transmitting data, the acoustic bandwidth (BW) of the network can be changed to see the impact on performance of the protocol. To evaluate the performance of BW variation, the normalized BW efficiency is quite important, which can be defined for 2400 bps BW as,

$$\eta_{BWn} = \left(\frac{\eta_C}{R_C}\right) \div \left(\frac{\eta_{2400}}{R_{2400}}\right) \tag{7}$$

where, η_c is the throughput for the current BW allocation, R_c is the data rate for the current BW, η_{2400} is the throughput with BW 2400 bps and R_{2400} is the data rate of 2400 bps channel, which is simply 2400.

IV. Simulations and Results

A. *Simulation setup*

We evaluate the performance of the proposed multi-channel MAC protocol through extensive simulations in MATLAB. Without losing the generality, we consider a network topology having four static nodes distributed uniformly in a 3000 meter by 3000 meter area. The data packet lengths of all the nodes are fixed and it is 2400 bits for performance evaluation. However for comparison purpose with other protocols the data packet lengths were varied. The size of the control packet is 32 bits and data rate for the control channel is 480bps. The data channel rate used are 2400 bps, 4800 bps, 6400 bps and 9600 bps. The EM wave used is assumed to have a frequency of 10000 Hz and thus a propagating speed of $1.52\times10^5 ms^{-1}$, which is calculated from equation 1. From this speed of EM we can calculate the guard band time (0.028s). The control packet duration (0.0667s) can be calculated from the control channel data rate (480bps) and control packet data length (32bits). Now this control packet duration along with guard band time makes one time slot (.095s). With four nodes, the TDMA frame contains ($4 + n_d$) number of time slots. The data packet duration is calculated from data packet length and data rate of the data channel. The propagation delay is found by dividing the distance between communicating nodes by v_{acst}. The total load can be calculated from equation 3. The parameters P_L, G_T are varied in such way that the total load varies from 0.1 to 1.6 in the whole simulation process. The normalized bandwidth efficiency is normalized against 2400 bps because that is the least BW used in the simulation program. The run time of the simulation is 200 seconds and the number of iterations for averaging the results is considered to be equal to 500.

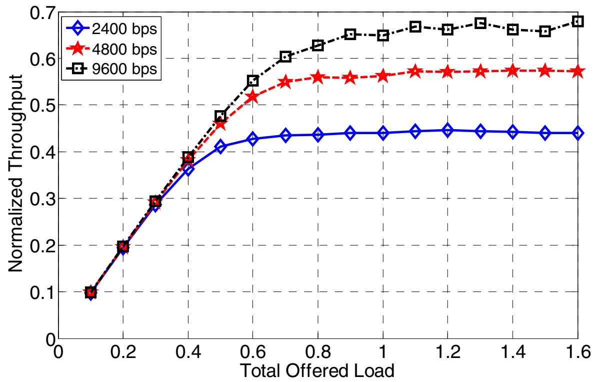

Fig. 3: Throughput curve for different bandwidth.

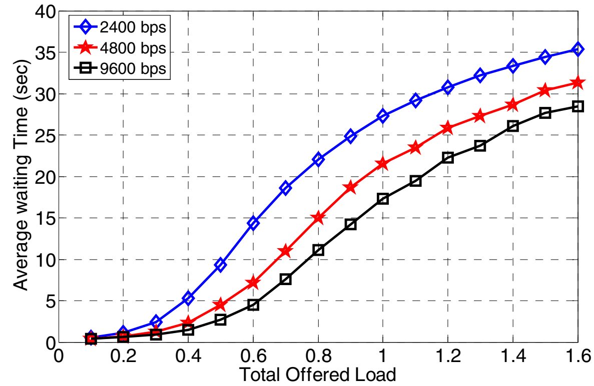

Fig. 4: Average waiting time for different bandwidth.

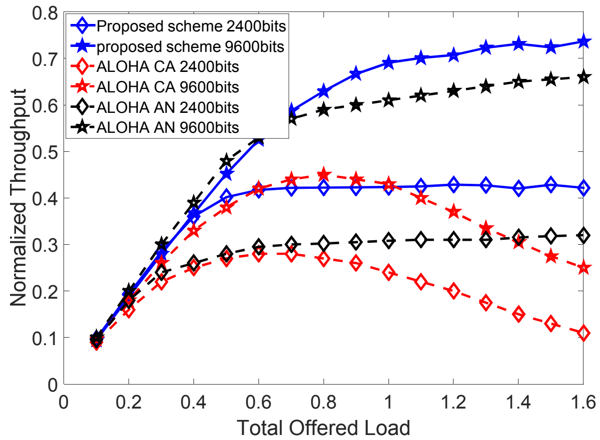

Fig. 5: Comparison of the proposed protocol with ALOHA CA and ALOHA AN

B. *Results and Analysis*

i) Impact of data channel bandwidth: In Fig. 3, variation of system throughput with the total ofered load for various BW of data channel is presented. The simulated data channel BWs are 2400 bps, 4800 bps and 9600 bps. In the figure, it is easy to see that with the increase of offered load, throughput increases and becomes nearly constant beyond a certain value of load. This is because, with the increase of offered load, success rate starts to decrease. As througput is the multiplication of offered load and the success rate, the two opposite effects cancel each other resulting in constant throughput. Constant throughput implies that the system is in saturation and no matter how much we increase the offered load, number of packets succesfully transmitted remains unchnaged resulting in increasingly lower success rate. On the

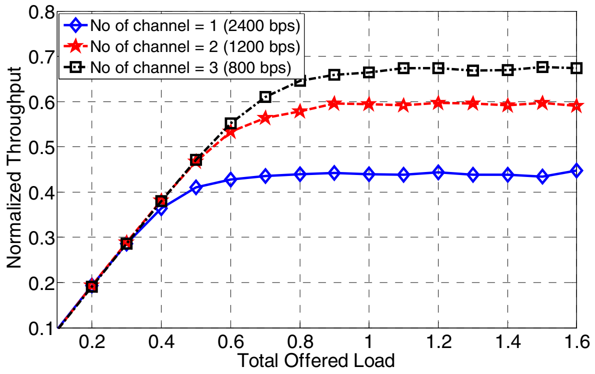

Fig. 6: Throughput curve for different number of data channels.

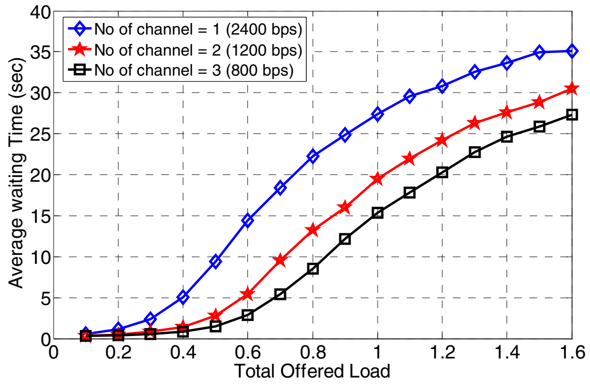

Fig. 7: Average waiting time for different number of data channels.

other hand, it is evident that increasing the amount of BW increases the amount of throughput. However the amount of increment in throughput is not linear. When BW was made twice of 2400 bps, the throughput jumped a quite. But when it is made double once again from 4800 bps to 9600 bps, the throughput did not increase that much.

From Fig. 4, it is clearly demonstrated why the increment of BW has improved the throughput. Waiting time of a node is defined as, the time gap between generation of a data packet and availability of a data channel for transmission of that packet. It is evident that with the rise of BW, the average waiting time of nodes decreases. Therefore a node has to wait shorter time for being allocated a data channel for transmitting new packets. Also it is noteworthy that with the addition of BW, the decrease in waiting time gets smaller. It is the reason why we do not get four times throughput when we increases the BW four times.

From Fig. 5, it can be seen that our proposed protocol with single channel is compared with two well-known protocols, namely; ALOHA-CA and ALOHA-AN. From the figure it is evident that the proposed protocol has higher throughput for high traffic loads. Also for low traffic loads it surpasses ALOHA-CA and almost catches the performance of ALOHA-AN. In this comparison two data packet lengths have been used, namely; 2400 bits and 9600 bits. In our following analysis it will be seen that with multiple channel, the proposed protocol can attain a lot higher throughput.

ii) Impact of number of data channels: In this part, we evenly divide the available data channel bandwidth into a number of data channels and observe the throughput variation. In particular, we consider the case of total data channel bandwidth equal to 2400bps. We assumed that no bandwidth is wasted due to the bandwidth distribution.

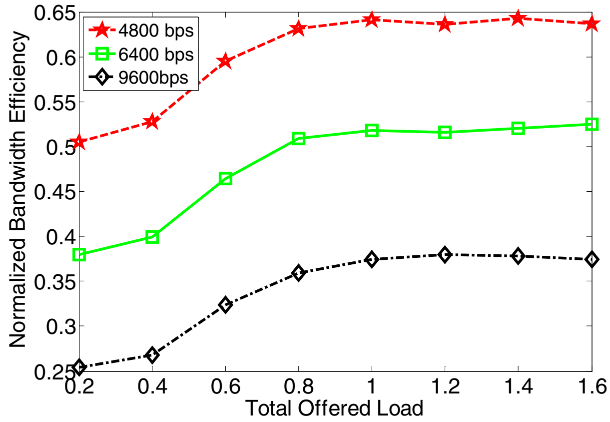

Fig. 8: Normalized bandwidth efficiency for different data channel bandwidth.

As we can observe in Fig. 6, system throughput increases with increment of channel number. When the entire 2400 bps is accumulated in only data channel, the system could not utilize the channel capacity properly. However, when the channel is divided into more than one number of channels (e.g., 2 channels with bandwidth 1200 bps and 3 channels each of 800 bps), the system with these lower speed channels achieves much higher throughput.

Figure 7 also supports the results in Fig. 6. Here we can note that with the increase in the number of channels, average waiting time for a node decreases. Thus the nodes now have low data rate channels, but with comparatively lower waiting time. Therefore, they can start transmission of their packets earlier than the previous condition and achieves higher throughput.

iii) Bandwidth efficiency of the system: We also evaluate the protocol performance in terms of normalized bandwidth efficiency as shown in Figure 8. The presented values in the figure are normalized by 2400 bps BW. From the figure, it can be observed that the increment of data channel bandwidth has negative effect in bandwidth efficiency. Though increasing bandwidth improves the throughput, the effectiveness of the band diminishes. In accordance to the plot, we can say that it is better to use four separate channels rather than increasing the bandwidth by four.

From the result of our simulation we can say that increasing the number of channels is the best way to improve throughput. However from practical point of view, we know that it is quite difficult to increase the number of channel without wasting some of the bandwidths. Therefore an optimum combination of BW and number of channels can be achieved to get the maximum throughput of the overall MAC protocol.

V. Conclusion

This paper has proposed a TDMA based novel hybrid multi-channel MAC protocol for UWSNs. To exploit the advantage of both EM and acoustic wave, the proposed scheme has employed EM wave for the control channel and acoustic wave for the data channel. Performance of the MAC protocol has been evaluated with extensive simulations. After comparing with ALOHA-CA and ALOHA-AN in terms of throughput, it is seen that our proposed protocol has higher throughput. A positive trend in throughput has been observed with the increase of bandwidth, which becomes less noticeable with much higher bandwidths. On the other hand, it has also been found that dividing the bandwidth in several parallel channels keeping the total bandwidth same gives higher throughputs. Moreover, the improvement in throughput has been found diminishing with the increment of bandwidth and the number of data channels. Our future works will focus on developing analytical model of the system integrating mobility of nodes, utilizing node idle times, etc. we will also extend the proposed MAC protocol for multi-hop networks.

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