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MAC Protocol for Underwater Sensor Networks Using EM Wave With TDMA Based Control Channel

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ABSTRACT Underwater communication (UWC) growing over the past few decades is the major tool for exploring the vast underwater space. Research and development of UWC networks are dominantly acoustic (Ac) wave based due to its long coverage capability. However, the demand of low latency and high throughput applications, and the emergence of short-range UWCs in modern times has drawn attention towards the development of electromagnetic (EM) wave based underwater sensor networks (UWSNs). In light of this, this paper proposes novel medium access control (MAC) protocols by integrating EM-based communications in UWSNs. Proposed protocols use one TDMA-based control channel and one or multiple data channel(s) for control and data packet transmissions respectively. The control channel uses EM wave, while the data channels use either EM or Ac wave for communications. Proposed MAC protocols are developed considering both protocol interference model and physical interference model by taking both propagation delay and underwater channel impairments into account. Performance of the protocols is evaluated through extensive simulations in terms of throughput, packet collision rate, waiting time, energy requirement and network coverage. Impact of system parameters including offered load, network size, data packet size, control packet power, water conductivity and channel bandwidth are analyzed thoroughly. A comprehensive feasibility study by comparing the proposed MAC protocols with the traditional protocols as well as with the full Ac-wave based counterpart is also presented for further validations.

INDEX TERMS EM wave, MAC protocol, TDMA, multi-channel protocol, UWSN.

I. INTRODUCTION

A. UNDERWATER SENSOR NETWORK (UWSN)

Over 70% of the Earth's surface is covered by water with nearly 97% seas and oceans [1]. The environment in underwater holds a great deal of uncertainty and is potentially hostile in many cases for human being. However, this huge underwater area is abundant in natural resources, both marine life and minerals. Underwater Sensor Networks (UWSNs) have become the ideal type of systems for efficiently exploring and studying this underwater environment. UWSNs are comprised of sensors, buoys, gateways, sinks, anchors, and autonomous underwater vehicles (AUVs). These underwater devices can communicate with each other and are coordinated to do specific tasks as a whole system. UWSNs can offer many civilian and military applications, such as ocean sampling, environmental monitoring, undersea explorations, disaster prevention, assisted navigation, distributed tactical surveillance, mine reconnaissance and so forth [2]–[4].

B. MEDIUM ACCESS CONTROL (MAC) PROTOCOL

An appropriate medium access control (MAC) protocol is critical for UWSNs as it plays important roles to achieve the quality of service (QoS). The main task of a MAC protocol is to prevent simultaneous transmissions or resolve packet collisions, while providing higher throughput, low channel access delays, longer network life-time and fairness among the nodes in a network [2], [5]. Terrestrial MAC protocols could not be used for UWSNs due to different channel

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dynamics, long and unpredictable propagation delay, energy constraint and high attenuation [5]–[7]. Therefore, designing efficient MAC protocols for UWSNs is of paramount importance, which is also a popular research area [2], [5], [6], [8], [9]. In contention-free MAC protocols, nodes of a network share the channel in a mutually exclusive manner leading to a collision free system. Whereas, contention-based MAC protocols allow the nodes to transmit randomly with no coordination among themselves and thus collisions are inevitable. On the other hand, hybrid MAC protocols combine the features of both collision-free and collision-inevitable MAC protocols [2], [5].

C. TDMA-BASED MAC PROTOCOLS

TDMA-based MAC protocols are contention-free MAC protocols. In such protocols, time is divided into fixed time intervals called frames, which are further divided into time slots. Each time slot is then assigned to an individual user. By adding guard times within every time slots, collisions of packets from adjacent time slots are prevented. Therefore, TDMA with its simplicity and flexibility is a good multiple access technique applied to UWSNs [2], [5]. However, due to the large propagation delay and delay variance over the acoustic (Ac) channels, guard time periods need be designed properly to minimize the probability of collisions in data transmissions. Moreover, a precise synchronization with a common timing reference is required for the TDMA, which is quite challenging to implement with the variable delay of Ac waves [4].

D. MULTI-CHANNEL MAC PROTOCOLS

Multi-channel MAC protocols utilize more than one data channel for communications. In recent time, designing multi-channel MAC protocols for UWSNs has drawn considerable attention due to the support of multiple channels in modern sensor platforms [5], [10]–[13]. Use of multiple channels leads to reduced collisions and higher throughput compared to those of single channel MAC protocols [10], [11], [13].

E. RATIONALE BEHIND THE PROPOSED RESEARCH

Acoustic (Ac), electromagnetic (EM) and optical signals are the main options for underwater communications (UWC) having relative advantgaes and disadvantages. However, most of today's UWCs are based on Ac wave technology mainly for its long-range communication capability in underwater [1], [2], [14]. Ac waves however result in poor performance in shallow water environments and have extremely low data rates due to lower bandwidth and long propagation time [15]–[17]. Ac transmission is affected by multipath propagation, susceptibility to environmental noise (e.g., marine life at the seabed and wind speed), turbidity, salinity gradients, pressure gradients, and has adverse impact on marine life. More importantly, increasing number of fast moving underwater vehicles and autonomous weapons around the world as well as requirement of faster data rates for modern applications [3], [18], there is an urgency for an alternative faster transmission media like optical or EM waves [17], [19]. Also, optical waves are impractical for major underwater applications as it requires line-of-sight (LOS) path with tight alignment and clear water between transmitter and receiver [20]–[22].

Therefore, how to exploit the EM wave's faster transmission and higher bandwidth capability in underwater to make real-time low latency and high-throughput applications feasible is grabbing the attention of the related scientific community [7], [17], [23]–[27]. Despite having a relatively shorter range in deep water, EM technology is a promising technology for UWSNs as they have the ability to provide much higher data rates than those achievable with Ac waves in harsh environments with no direct path. Also, unlike Ac UWSNs, EM based networks are unaffected by temperature, salinity, turbidity, pressure gradients and wind speed of the sea. Moreover, EM wave suffers less attenuation in shallow water enabling longer range UWSNs, whereas the seeming drawback of higher attenuation of EM wave in deep water can be exploited in a beneficial way for multi-user parallel data transmission enabling localized communications in UWSNs [17]. Further, the relatively lower cost of RF nodes adds to the aforementioned reliability making EM UWSNs a clear winner. Lastly, EM UWSNs have no known impact on the marine life and ecosystem. Therefore, this new breed of UWSNs can provide real-time deep-sea oil and gas explorations, military surveillance, search and rescue operations, and environmental monitoring, which Ac networks fail to afford [7], [17].

As discussed above and later as well, both research community and industries are extremely eager to introduce EM wave in underwater networking for supporting many modern underwater applications. As identified from our extensive literature survey, although several research projects and experiments are being conducted on EM UWSNs, to the best of our knowledge, there is no current work on the design and developing EM-based MAC protocol. Moreover, inherent differences in propagation characteristics between Ac and EM waves in underwater, high attenuation and salinity dependent propagation speed of EM wave in underwater, dissimilar delay characteristics as well as differences in network topology, deployment scenario and energy constraints, MAC protocols designed either for Ac UWSNs or for EM terrestrial sensor networks will not perform efficiently [2], [5]–[7], [14], [17], [19], [27]. Therefore, design of MAC protocols incorporating EM wave for communications over UWSNs is of extreme significance, which is the main motivation behind this research.

F. OUR CONTRIBUTIONS

The main focus of this research is to integrate EM wave in the designs of MAC protocols for UWSNs with the aims to improve the delay performance and network throughput. The proposed protocols use a separate TDMA-based control channel for signaling purpose along with one or multiple data channels for data packet transmissions. The control channel always uses EM communications, while the data channels use either Ac or EM communications. Thus the proposed MAC protocols can be either EM-Ac hybrid type or EM-EM type, which are then further divided into single-channel and multi-channel schemes. The objectives of this paper can be summarized as below.

- We propose single-channel and multi-channel type EM-Ac Hybrid and EM-EM MAC protocols for single-hop based UWSNs considering separate data and control channels. Proposed protocols consider underwater channel characteristics including propagation delay, propagation loss and shadow fading into design and performance evaluations.
- MATLAB-based platforms are developed for extensive simulations to evaluate the performance of the proposed MAC protocols. Protocol interference model as well as more realistic physical interference model are considered for the evaluations. Performance is evaluated in terms of throughput, packet collision rate, waiting time, energy requirement, network coverage and so forth.
- We also thoroughly investigate the impact of various network parameters, such as offered load, network size, data packet size, control packet power, water conductivity and channel bandwidth on the performance of the proposed MAC protocols.
- Finally, performance of the proposed MAC protocols is compared with that of the traditional protocols and the Ac-Ac counterpart. An extensive feasibility study for investigating the appropriateness of the proposed protocols in underwater environment including the practical network size is also presented.

G. ORGANIZATION OF THE PAPER

Section II presents the related works on EM-based underwater networks followed by the system model aspects in Section III. Proposed single-channel and multi-channel MAC protocols are explained in Section IV and Section V respectively. Performance metrics are outlined in Section VI. Section VII and Section VIII describe the simulation setup and simulation results with an in depth analysis. A comprehensive feasibility study of the proposed EM based MAC protocols is presented in Section IX. Finally, the paper is concluded in Section X by summarizing the key findings.

II. STATE-OF-THE-ART RESEARCH ON EM-BASED UWCs

UWCs using EM wave were explored with keen interest in the last century up until 1970s. Due to its high attenuation, significant breakthroughs with EM UWCs were not expected [28], [29]. However, in the modern digital era, benefits of short-range and high-bandwidth communications are becoming favorable to users, which can be achieved by coupling digital technology and signal compression techniques. Meanwhile, the oil industry, military and environmental operations are demanding reliable, connector-less and short-range data link applications [14], [17]. Thus, research on EM feasibility in the underwater environment has drawn considerable attention among researchers as well as in industries [17], [25], [30]–[32]. Several studies also suggest that a high data rate is possible to achieve over a relatively longer range by changing the antenna technology [32].

A. PROPAGATION MODELS FOR EM WAVE IN UNDERWATER

Several works have been reported on the underwater channel modeling for EM wave. For instance, a very simple attenuation model as a function of frequency in the MHz range was presented in [33]. Whereas a channel model for freshwater environment is proposed in [34]. A realistic path-loss model was developed in [35] by taking into account the variation of the seawater complex-valued relative permittivity with frequency as well as the impedance mismatch at the seawater-air boundary. Another work on the modeling of EM wave propagation in underwater suggested that the dominant propagation path to facilitate long-range communication is along the surface of the water-air interface [36]. On the other hand, authors in [37] presented a detail relationship between propagation characteristics of EM waves, skin depth, total path-loss and frequency for different values of distance and conductivity of the water medium. Their analysis suggests that optimum propagation distance in underwater can be achieved by proper selection of the signal frequency. On the other hand, multiple experiments found very different propagation loss for EM wave in underwater in near-field and far-filed regions. It was identified that due to the short-circuit behavior, a drastic power-loss occurs in the near field region, while the rate of path-loss in the far-field is much slower [38], [39].

B. COMMUNICATION RANGE USING EM WAVE IN UNDERWATER

A pioneering experimental research on EM wave propagation in shallow seawater using insulated antennas was carried out in [40]. It demonstrated the feasibility of receiving signals at 14 MHz over a range of 20 m or so. A research conducted at Liverpool John Moores Universit found that transmission at 5 MHz frequency is feasible in seawater up to 90 m range giving a data rate of 500 kbps that allows duplex video and data streams [38]. Two studies on the transmission of RF signal of MHz range was also presented in [26], [31]. A practical study on the behavior of EM signals in the 2.4 GHz industrial, scientific and medical (ISM) frequency band in underwater environments was performed by the authors in [30], [41]. They used devices that are compatible with the IEEE 802.11 standard. Furthermore, a study on the suitability of small size EM sensor developments in [25] showed that efficient communication between sensor nodes operating in the 4 GHz frequency band is theoretically possible for distances up to 2.6 m in underwater environment.

On the other hand, there are some commercial modems for underwater applications in 100 kHz band. For instance, two types of RF modems: a short-range model with 100 kbps up to 15 m range and a long range model with 100 bps up to 200 m range are produced by WFS Technologies [42]. Another experimental work [32] demonstrated a new concept of EM wave usage in sea. The antennas are designed as EM high-Q resonators and the lowest resonant frequency is used for power transfer. Results showed a power efficiency over 40% and a transmission rate of 20 Mbps via seawater of 5 cm thickness. It was suggested that the proposed concept can be used to achieve a compact and maintenance-free wireless usage between different underwater systems, such as AUVs. Furthermore in [36], it was demonstrated that an RF signal can be transmitted in 1-5 MHz frequency range over distances up to 100 m as an EM wave along the air-water interface. The results were found from simulations as well as independent measurements of EM wave propagation in seawater.

C. ANTENNA DESIGN FOR UNDERWATER EM COMMUNICATIONS

From the perspective of an antenna design for UWCs, the large conductivity and permittivity of water, especially in ocean, imply that any metallic antenna placed directly in contact with sea water gets ''shorted out,'' and it becomes extremely difficult to match the antenna and launch the EM wave efficiently into seawater. Furthermore, due to higher path-loss, high frequency is also difficult to use for underwater EM communications. Thus the antenna size is relatively higher for underwater applications. Considering the practical constraints, researchers preferably use loop antennas for underwater applications [23], [26], [38]. Research on the use of double loop antenna [26] and antenna with water insulating sheath [40] for better gain and longer coverage have also been carried out.

D. MAC PROTOCOL FOR EM UNDERWATER COMMUNICATIONS

Although several research projects on EM UWSNs have been conducted [17], [35], [43], [44], however based on our extensive literature survey, we have not found any proposal for MAC protocol for EM UWSNs. One very recent work approaching the issue of MAC protocol of EM UWSNs is presented in [27]. However, the authors did not propose any new MAC protocol. Rather, performance of some of the existing MAC protocols, namely, ALOHA, multiple access with collision avoidance (MACA), CSMA without acknowledgement (CSMAWithoutACK) and CSMA with acknowledgement (CSMAWithACK) in EM UWSNs was investigated. It was found that the MAC protocols do not perform as efficiently as in terrestrial sensor networks and thus the importance of designing new MAC protocols considering the characteristics of EM wave in underwater was established. In our previous works of [13], [45], we presented our preliminary works on two different MAC protocols by incorporating EM wave for communications, which used simple protocol interference model only. This paper further extends and thoroughly investigates those two MAC protocols by considering both physical and protocol interference models accompanied with a comprehensive feasibility study.

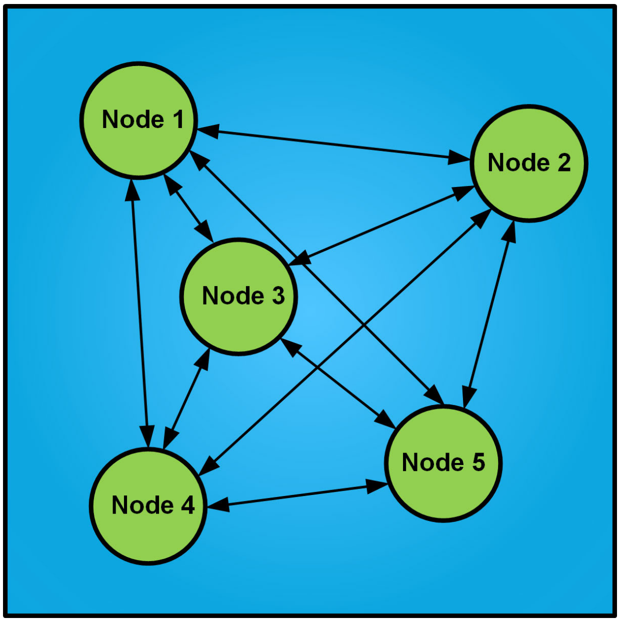

FIGURE 1. UWSN topology considered for the proposed MAC protocols.

III. SYSTEM MODEL

A. NETWORK MODEL

This paper develops MAC protocols for mesh topology based UWSNs as shown in Fig. 1, where the nodes can communicate with each other through unicast data transmission at a single-hop distance. All the nodes in the network are assumed to be static for the duration of packet transmissions. Nodes are considered scattered within the network area following an uniform distribution. It is also assumed that the nodes generate packets following Poisson distribution. Total offered load of the system is equal to the aggregated load generated by all the nodes. We also assume that the nodes are synchronized with each other and lost packets are not re-transmitted.

B. LINK MODEL

1) PROTOCOL INTERFERENCE MODEL

In protocol interference model, underwater wireless links are considered to be perfect. This implies that any transmitted packet reaches the destination without any error. Thus in this model, channel attenuation is ignored and hence, there is no packet loss due to attenuation. However, propagation delay of EM and Ac waves is considered to be present in the system.

2) PHYSICAL INTERFERENCE MODEL

In this modeling scheme, in addition to the propagation delay, signal impairment due to path-loss and shadow fading in the channel resulting in signal attenuation are taken into account. As the signal gets attenuated while propagates through the channel, if a receiver is beyond the range of a transmitter, the signal will not reach receiver with enough power to be successfully extracted. Consequently, collision of packets in data channels and packet loss can occur, which has been explained later in Section IV-C. Now, the received power at a distance from the transmitter can be calculated as below

$$P_R = P_T - P_L + \chi \tag{1}$$

where P_R is the power of the signal received at the receiver in dBm, P_T is the transmitted signal power in dBm, P_L is the path loss due to the attenuation in dB and χ is the shadow fading in dB.

C. PATH-LOSS MODEL

1) PATH-LOSS MODEL FOR EM WAVE

Path-loss P_L in dB for EM wave in underwater can be expressed as [34]

$$P_L = L_{\alpha,\epsilon} + L_R \tag{2}$$

where $L_{\alpha,\epsilon}$ is the attenuation loss in water due to water conductivity and complex permeability in dB and L_R is the reflection loss at the water–air boundary in dB due to the impedance mismatch between the two media. Considering all the nodes immersed into water, reflection loss L_R can be neglected. The propagation constant can be expressed as [46]

$$\gamma = j\omega\sqrt{\mu\epsilon - j\frac{\sigma\mu}{\omega}} \tag{3}$$

where μ is the permeability, ϵ is the permittivity, σ is the conductivity and $\omega = 2\pi f$ is the angular frequency. Thus P_L at a distance d can be given by [35]

$$P_L = L_{\alpha,\epsilon} = \rho(\gamma) \times \frac{20}{ln(10)} \times d \tag{4}$$

where $\rho(x)$ is the real value of x.

2) PATH-LOSS MODEL FOR ACOUSTIC WAVE

Propagation path-loss P_L for Ac wave in underwater expressed in dB can be given by [47]

$$P_L = 20log(r) + \alpha r \times 10^{-3} \tag{5}$$

where α represents the absorption coefficient in dB/km and r is transmission range expressed in meters. The absorption coefficient α can be calculated using Thorp's expression at frequencies above a few hundred Hz as below [48]

$$\alpha = \frac{0.1f^2}{1+f^2} + \frac{40f^2}{4100+f^2} + 2.75 \times 10^{-4}f^2 + 0.003 \tag{6}$$

where f is frequency in Hz.

IV. PROPOSED SINGLE-CHANNEL MAC PROTOCOL

A. CHANNELS

In the proposed single-channel MAC protocol, there are only one control channel and one data channel. The nodes are enabled to use two channels simultaneously. The control channel is used for signaling purpose, more specifically, for sending data channel reservation requests and confirmation messages. Whereas, the data channel is used for transmitting the data packets. Thus, with the objective of using EM wave for communications, two different combinations of transmission media for the control and the data channels are proposed. The first option is EM-Ac, where the control channel uses EM communications, while the data channel uses Ac-based transmissions. The second option we propose is EM-EM, where both the control channel and the data channel employ EM wave for communications. The control channel is TDMA-based having sequence of time frames and each time frame consists of several time slots. Total number of time slots within a time frame is given by the following equation

$$N = n_d + n_c \tag{7}$$

where N is the total number of slots in a time frame, n_d is the total number of nodes in the network and n_c is the number of data channels present in the network. The time slots are used by the nodes for sending data channel reservation requests and by a receiver to broadcast a confirmation message after receiving a data packet successfully. Duration of each of these slots is equal to the control packet duration plus the guard time duration.

B. OPERATION

To describe the operation of the proposed single-channel MAC protocol, a time-series diagram of the system for EM-Ac scheme is illustrated in Fig. 2. In addition, to aid better understanding, Table 1 (Universal table) is provided, which is actually a variable maintained by the developed simulation platform and holds various important information, e.g., sender & receiver as per data channel reservation sequence, sending time, receiving time and channel reservation slot. As illustrated in Figure 2, there are two channels - one EM based control channel and one Ac-based data channel. For the ease of illustration, a four-node system is considered as depicted in Fig. 1. Therefore, the control channel TDMA frame consists of five time slots, where the first four slots are for sending the data channel reservation requests by the four nodes respectively and the last one is for sending confirmation message of successfully receiving a data packet. For the sake of explanation, without losing the generality, it is assumed that at the activation of the network, the time series starts from zero second and every time frame duration is one second making every time slot duration equal to 0.2 second. Every node in the network maintains its own data channel reservation table (DCRT), where it queues the information of the senders and the receivers as well as the start time of data transmissions. This DCRT in each node is updated by adding a row each time a reservation request is sent by a sender as well as by deleting a row when a confirmation message is sent by a receiver indicating a completion of transmission and reception of a data packet.

For the scenario depicted in Fig. 2 and Table 1, node 2 has the first data packet to transmit generated at time 0.1 sec. However, to send the reservation request for the data channel, node 2 has to wait for its own control channel time slot 0.2-0.4 sec. It is assumed that all the nodes in the network will hear this reservation call of node 2. Consequently, all the

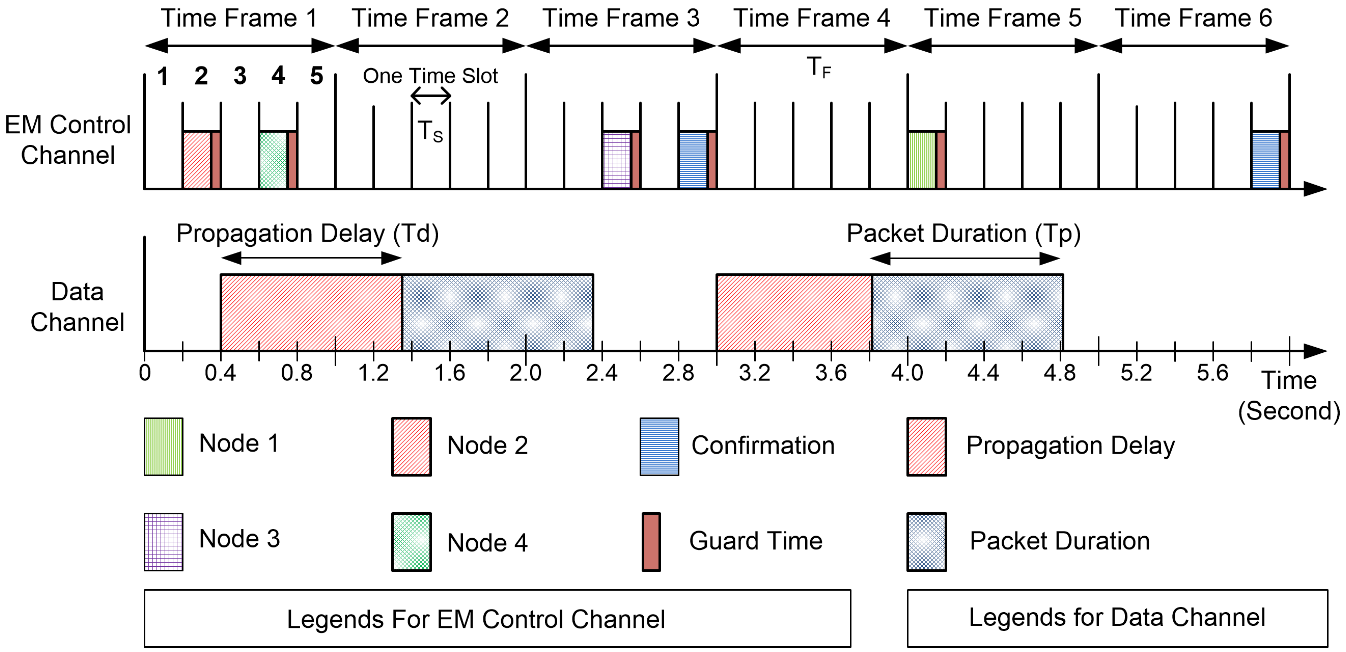

FIGURE 2. Time-series diagram of the proposed MAC protocol with single data channel.

TABLE 1. Universal table depicting the operation of the proposed single-channel MAC protocol.

Sender	Receiver	Packet generation time	Reservation time slot	Start time of data packet transmission	Start time of data packet reception	End time of data packet reception
2	3	0.1	0.2-0.4	0.4	1.35	2.35
4	3	0.3	0.6-0.8	3.0	3.82	4.82
...	...	...	...	...	...	...

nodes will update their DCRT and node 2 will be written in the first row of their respective tables. Since the data channel is free, node 2 will start transmitting data immediately after the reservation call starting at 0.4 sec. Now all the nodes will put a flag 'Sending' on node 2 in their DCRTs. Data of node 2 starts reaching node 3 starting at 1.35 sec with a propagation delay of (1.35-0.4) = 0.95 sec. For ease explanation, it is assumed that the data packet duration is one sec. Thus at the time of 2.35 sec in the time series, the data is fully received by node 3.

Now continuing through the time series diagram, it can be observed that the next data packet to be transmitted is from node 4 generated at 0.3 sec. Hence, node 4 makes a reservation through its respective time slot (slot 4, Time frame 1). All the nodes hearing it updates their respective DCRTs. Since the data channel is now occupied by node 2 (transmitter), node 4 will wait for the confirmation message from node 3 (receiver) before it can begin its transmission. Whereas in this waiting period, time flows and node 3 makes a data channel reservation request through time slot 3 of time frame 3. Now this request will be queued up in the DCRTs of all the nodes.

It can be seen that the first data packet sent from node 2 reaches its destination completely at 2.35 sec (including propagation delay and packet duration), which is before time slot 5 of the time frame 3. Time slot 5 is the confirmation slot for sending confirmation packet indicating that the data packet has been received successfully. Thus when node 3 receives the packet completely, it transmits a confirmation message through the time slot 5. This in return ensures that all the nodes get the information that the data channel is now free to use for transmission. Upon receiving the confirmation message, each node update their DCRTs by clearing the first row. Now the next transmitter in the queue is node 4, which starts transmitting its packet starting at 3 sec. In parallel, the nodes update their DCRTs by labeling node 4 as 'sending'. Now node 4 will be at the top of the DCRTs and node 3 will be in the queue for transmission. This process continues over time.

C. COLLISION SCENARIOS

For the case of protocol interference model where perfect communication is assumed with no attenuation, there will be no data packet collision under the proposed single-channel MAC protocol. However, in real-life UWCs, signals suffer attenuation and shadow fading as propagates in the channel, which is considered in physical interference model. Consequently, the protocol is susceptible to collisions of data packets.

To get an insight on the collision scenario, one such scenario where collision of data packet occurs is depicted

TABLE 2. Universal table depicting a collision scenario in the proposed single-channel MAC protocol.

Sender	Receiver	Packet generation time	Reservation time slot	Start time of data packet transmission	Start time of data packet reception	End time of data packet reception
2	3	0.1	0.2-0.4	0.4	1.35	2.35
4	3	0.3	0.6-0.8	0.8	1.62	2.62
...	...	...	...	...	...	...

in Table 2. Here, due to severe attenuation, node 4 has not heard the reservation request of node 2. Hence, node 4 in its own DCRT has set the start time of its own data packet transmission to 0.8 sec, which is just after the end of its control packet transmission. This is equivalent to say that the universal table (Table 1) is now changed to Table 2. Now, even though the data transmission of node 2 is ongoing, node 4 starts transmitting its data at 0.8 sec. Data packet from node 2 starts to reach node 3 at time 1.35 sec, while the data from node 4 starts to reach node 3 at time 1.62 sec. Thus, data packets from both node 2 and 4 are present in the channel as well as at the receiving antenna of node 3 from time 1.62 sec to 2.35 sec. This results in a collision of data packets and data packet from both node 2 and 4 will be lost.

D. DATA CHANNEL OCCUPATION TIME LIMIT

Apart from packet collisions, other situations may arise, which can stop the entire data transmission process. Say, a node has not successfully received a data packet destined to it due to collision and correspondingly, it has not sent a confirmation message for the other nodes in the network. However, other nodes are waiting for the confirmation message to update their DCRTs. This condition makes the network to get into 'locked' situation and no further data transmission can take place afterwards. Similar situation will arise when a confirmation message is lost due to high attenuation. Therefore, to get out of such locked scenarios, a data channel occupation time limit (COTL) is considered. When the nodes wait for a confirmation message from a particular node and this waiting time crosses the COTL, then all the nodes assume that the packet is lost and clear the corresponding row in their respective DCRTs indicating none is transmitting. Thereafter, the next node in the queue starts its data transmission.

For the convenience of understanding of the operation of the proposed single-channel MAC protocol including the packet loss due to collisions and locked situations is presented in a simpler way by a flow diagram as shown in Fig. 3.

V. PROPOSED MULTI-CHANNEL MAC PROTOCOL

A. CHANNELS

In the proposed multi-channel MAC protocol, there are only one control channel similar to the single-channel MAC protocol, but multiple data channels for parallel data transmissions. Once again, the control channel is EM-based, while the data channels can be either EM- or Ac-based. For, each data channel, one time slot is required in the control channel time frame for transmitting the confirmation message of successful packet reception. For instance, if the network has four nodes and two data channels, then there will be total $(4 + 2) = 6$ time slots in a TDMA frame of the control channel.

B. OPERATION

The operation principle of the proposed multi-channel MAC protocol is somewhat similar to the single-channel protocol. However, the scenario is much more complex. The major difference is now that the nodes will have to use more flags to trace the status of all the data channels. To explain the operation principal properly, a time-series diagram is presented in Fig. 4 for a network having two data channels and four nodes. The universal table for multiple data channels is presented in Table 3 with the aim to provide better understanding of the total procedure. This table now contains one extra column indicating which data channel is being used by a sending node.

As discussed before, when a node requires data channel for data packet transmission, it first requests for the reservation of the data channel using its assigned time slot in the EM-based TDMA frame. Data channels are allocated to the requested nodes as per the request message receiving 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 time duration.

Now, as shown in Fig. 4, node 2 first wants to send data packet and therefore, requests for data channel reservation through slot 2 of the control channel TDMA frame. Hearing this request from node 2, the DCRTs maintained by all the nodes are now updated as discussed above in the single-channel MAC operation. Similar to the universal table, DCRTs also contain one more column to indicate which data channel is currently in use by which sender. Now, as both the data channels are free as found in its own DCRT table, node 2 starts transmitting data using data channel 1 (at time 0.4 sec). In the DCRTs, node 2 is labeled as 'sending', while the channel 1 which is being used by node 2 is also recorded in the tables. 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

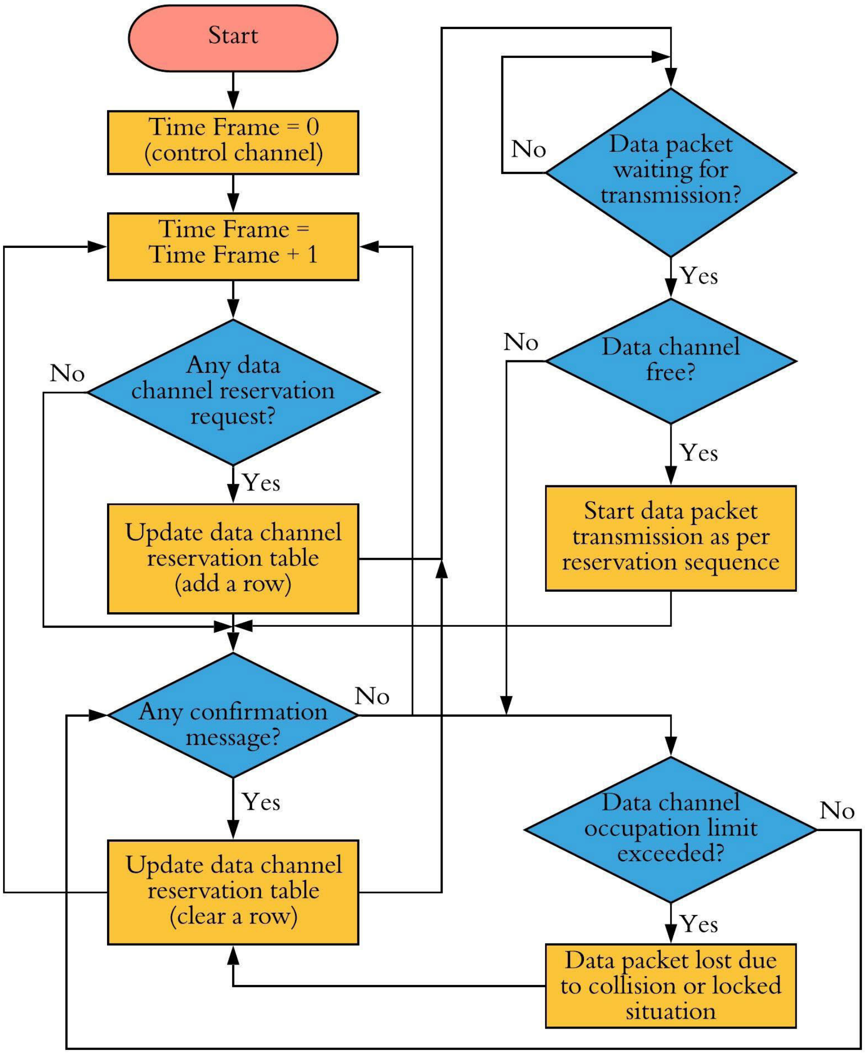

FIGURE 3. A flow diagram of the proposed single-channel MAC protocol.

TABLE 3. Universal table depicting the operation of the proposed multi-channel MAC protocol.

Sender	Receiver	Packet generation time	Reservation time slot	Start time of packet transmission	Data channel being used	Start time of data packet reception	End time of data packet reception
2	3	0.1	0.2-0.4	0.4	1	1.35	2.35
4	1	0.3	0.6-0.8	0.8	2	1.62	2.62
3	2	2.1	2.8-3.0	3.4	1	4.13	5.13
...	...	...	...	...	...	...	...

channel 2 starting at time 0.8 sec. Once again the DCRTs maintained by the nodes are updated, and this time both node 2 and node 4 are labeled as ‘sending’. Also, the flags maintained to keep track of the channel status now indicates that both the data channels are busy.

Now, as all the data channels are currently in use, the other nodes intended to transmit data continue their reservation process through their respective time slots and wait for the data channels to be freed. DCRTs maintained by the nodes are also updated corresponding to these reservation requests. We see from the diagram that the next transmitter in the list is node 3. It sends its reservation request for data channel through its given time slot starting at time 2.8 sec in time frame 3. Correspondingly, all the nodes update their tables once again. We see that the data transmitted through data channel 1 by node 2 starts to reach node 3 at 1.35 second

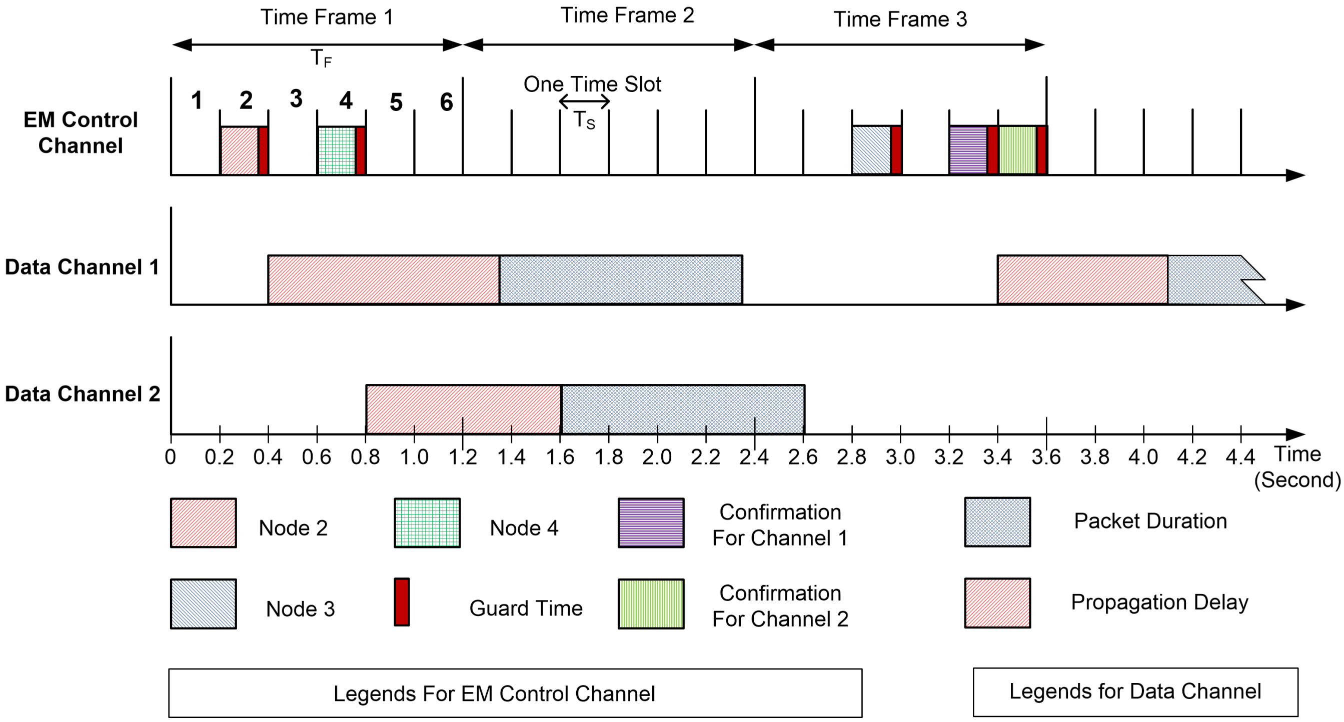

FIGURE 4. Time-series diagram of the proposed MAC protocol with multiple data channels.

and the full packet is received by 2.35 sec. Upon receiving the complete data packet, the receiver (node 3) now transmits a receive confirmation message using slot 5 of TDMA time frame 3. Through this confirmation message, all the nodes are now notified that the data channel 1 is free and subsequently, node 3 starts its data transmission through data channel 1 starting at 3.4 sec. 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 time frame 3 to let other nodes to know that channel 2 is now free. This process of transmission and reception of data goes on.

C. COLLISION AND LOCKED SCENARIOS

The collision scenario discussed for single-channel MAC protocol is also applicable for multi-channel case. However, for multi-channel scenario, collisions occurring in one data channel do not affect the data packet transmission of the other data channels. Also, collisions can occur simultaneously in the parallel data channels. On the other hand, similar to single-channel MAC protocol, data channel occupation duration is kept in track for all the data channels. Once this occupation duration for a data channel exceeds the data channel occupation limit, that particular data channel is considered as free for data transmission by other nodes in the queue. A flow diagram for the multi-channel case can also be drawn as given for single-channel protocol above, which has not been included for the sake of compactness.

VI. PERFORMANCE METRICS

A. THROUGHPUT

It is the percentage of successful channel utilization, which can be given by

$$\eta = \frac{T_U}{T_G} \tag{8}$$

where T_G is the total time over which packets are generated (i.e., simulation time) and T_U is the total time out of T_G which is used for successfully transmitting packets.

B. SUCCESS RATE

Success rate S_R can be defined as below

$$S_R = \frac{N_S}{N_{Tr}} \tag{9}$$

where N_S and N_{Tr} are the total number of successful data packet transmissions and the total data packet transmissions within T_G time.

C. COLLISION RATE

The collision rate C_R is the percentage of total packets which collided with each other resulting in loss of packets. This can be given by

$$C_R = \frac{N_C}{N_{Tr}} = 1 - S_R \tag{10}$$

where N_C is the total number of packets lost in collisions.

D. AVERAGE WAITING TIME

Every node has to wait for some time to send its packet. The time between the generation of packet and the start of transmission is defined as the waiting time. Thus, waiting time for a packet can be given by

$$T_W = T_{Tr} \sim T_{Gr} \tag{11}$$

where T_{Tr} is the instant of transmission and T_{Gr} is the instant of generation of the packet.

E. ENERGY CONSUMPTION

If total N_{Ctrl} number of control packets and N_{Data} number of data packets are sent over the total simulation time, then the total energy consumption is given by

$$E = E_C \times N_{Ctrl} + E_D \times N_{Data} \tag{12}$$

where E_C is the energy needed to transmit a control packet and E_D is the energy needed to transmit a data packet.

VII. SIMULATION SETUP

A. SIMULATION VARIABLES

The proposed MAC protocols are first evaluated under protocol interference model, which considers propagation delays, but ignores the channel attenuation effect. Then the proposed protocols are investigated for more realistic case using the physical interference model taking both propagation delay and channel attenuation into account. Results presented in the following sections are generated by averaging the results from 500 iterations. For simulating the proposed protocols, following system variables are considered.

1) Maximum network length, D_L = Distance between the two far most corners of the network
2) Maximum propagation delay for EM, $T_{EM,p} = \frac{D_L}{v_{EM}}$, where v_{EM} is the velocity of EM wave
3) Maximum propagation delay for Ac, $T_{Ac,p} = \frac{D_L}{v_{Ac}}$, where v_{Ac} is the velocity of Ac wave
4) Guard time of the time slots, $T_{Gd} = \frac{D_L}{v_{EM}}$
5) Control packet duration, T_{ctrl} = Control packet size / EM control channel data rate
6) Duration of control channel time slot, $T_{sl} = T_{ctrl} + T_{Gd}$
7) Total number of time slots, $N = n_d + n_c$
8) Frame duration, $T_f = N \times T_{sl}$
9) Data rate, $R_b = 2400$ bps (for Ac) or 40% of carrier frequency (for EM)
10) Data packet duration, $T_{Data} = \frac{L_d}{R_b}$, where L_d is the data packet length in bits
11) Total packet generation rate, $\lambda = \sum_{i=1}^{n_d} \lambda_i$, where λ_i is the data packet generation rate of i^{th} node
12) COTL for EM data channel, $T_{EM} = \text{ceil}(\frac{T_{Data}+T_{EM,p}}{T_f}) \times T_f + T_f$
13) COTL for Ac data channel, $T_{Ac} = \text{ceil}(\frac{T_{Data}+T_{Ac,p}}{T_f}) \times T_f + T_f$

TABLE 4. System parameters.

Parameter	Value/Description
Conductivity of water, σ	4.0 (sea water) [17]
Permeability of water, μ	$4\pi \times 10^{-7}$
Permittivity of water, ϵ	$81 \times 8.854 \times 10^{-12}$
Speed of EM wave, v_{EM}	$(f_{EM} \times 10^7/\sigma)^{1/2} ms^{-1}$ [17]
Speed of Ac wave, v_{Ac}	$1500 ms^{-1}$ [17]

TABLE 5. Network parameters.

Parameter	Value
Network area	$100m \times 100m$ - $3000m \times 3000m$
Packet generation time, T_G	100 sec
Control packet size	32 bits
Number of nodes n_d	4 (uniformly distributed)
Data Packet size, L_d	{2400, 4800, 9600} bits

TABLE 6. Power and bandwidth parameters.

Parameter	Value
Frequency of EM control channel	1 kHz
Frequency of EM data channel	6 kHz
Frequency of Ac data channel	6 kHz
Transmit power of EM wave	1W (30 dBm)
Transmit power of Ac wave	1W (30 dBm)
Threshold for EM wave detection	- 90 dBm
Threshold of Ac wave detection	- 90 dBm

B. SIMULATION PARAMETERS

Unless otherwise stated, following parameters summarized in Table 4 - 6 are used for the simulations. Shadow fading is also considered for performance evaluation when channel attenuation is taken into account. It is modeled as a Gaussian random variable with zero mean and standard deviation 8 dB.

VIII. SIMULATION RESULTS AND ANALYSIS

A. PERFORMANCE CONSIDERING PROTOCOL INTERFERENCE MODEL

1) SINGLE-CHANNEL MAC PROTOCOL

The network throughput characteristics of the proposed single-channel EM-Ac MAC protocol simulated using protocol interference model is depicted in Fig. 5. The legends in the figure holds specific meanings, the letter D means the data packet size and N means the length of a square shaped two dimensional network. Thus 'D 2400 N 1000' implies that the data packets are of 2400 bits length and the network size is $1000m \times 1000m$. The figure shows that with the increase of offered load, throughput of the network increases to a certain limit and then becomes nearly constant. This happens as after certain load, there are always some packets in the queue waiting for transmission and the data channel is used at its maximum capacity. Moreover, because of longer propagation times, throughput becomes smaller as the network size grows from 1000m to 3000m. On the other hand, throughput becomes progressively better with

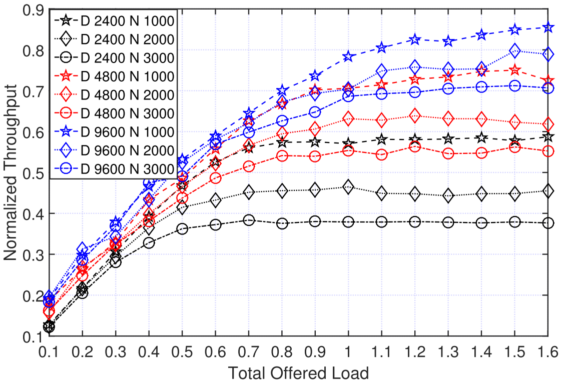

FIGURE 5. Throughput performance of the single-channel EM-Ac protocol under protocol interference scenario.

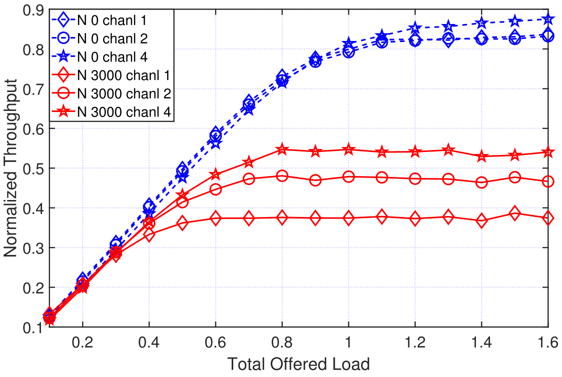

FIGURE 6. Throughput variation for the multi-channel EM-Ac protocol under protocol interference scenario.

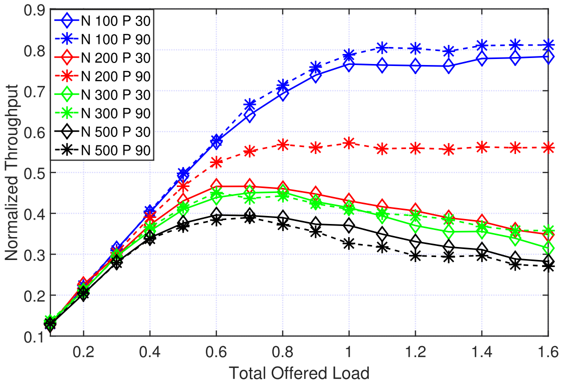

FIGURE 7. Throughput variation for single-channel EM-Ac protocol considering physical interference model.

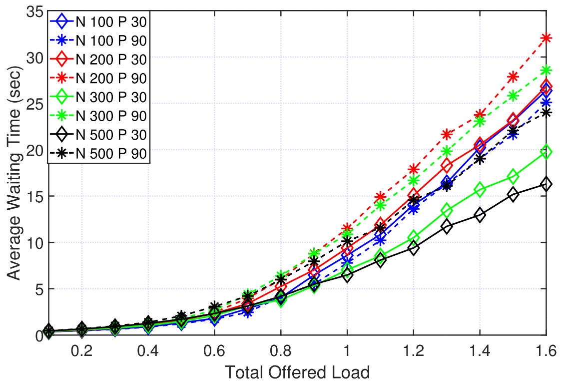

FIGURE 8. Waiting time variation for single-channel EM-Ac protocol considering physical interference model.

the increase of packet size as it results in the savings in the number of reservation packets, confirmation messages and guard times.

2) MULTI-CHANNEL MAC PROTOCOL

Fig. 6 presents the change in throughput with respect to the offered load for different number of data channels. Simulations are once again conducted for EM-Ac protocol. Here, the legend with 'N 0 chanl 4' means that the nodes are clustered (extreme case) and there are 4 parallel data channels for communication. Furthermore, multiple channels used here do not use extra bandwidth, rather the bandwidth of the single channel is divided equally among the channels. As expected, with the increase of the number of parallel channels, throughput improves. However, this improvement in throughput is more visible for larger network size.

B. PERFORMANCE CONSIDERING PHYSICAL INTERFERENCE MODEL

Depending on the carrier type of the data and control channels, we have proposed EM-Ac and EM-EM type single-channel and multi-channel protocols. Simulations of these various schemes considering physical interference model are carried out as presented in the following sections.

1) SINGLE-CHANNEL EM-AC PROTOCOL

Throughput and average waiting time under the proposed single channel EM-Ac MAC protocol are illustrated in Figs. 7-8. Simulations are conducted for four different network sizes with two different powers for the control packets. The legend 'N 100 P 30' means that the network size is 100 $m \times 100$ m and the control packet is transmitted with a power of 30 dBm. The data packet lengths are fixed to 2400 bits. From Fig. 7, it can be seen that only for network size of 100 m, throughput shows an increasing trend up to a certain value of the offered load and afterwords, it gets steady. For the case of 200m network size with very high control packet transmission power (90 dBm), throughput follows the same trend. However for all the other cases, even with really high control packet power, after an initial increment of throughput, it starts decreasing when the offered load crosses around 0.6. The reason behind this is that for a larger network size, control packet with its EM carrier becomes very weak to detect and the protocol suffers from loss of many control packets leading to poorer performance.

Fig. 8 presents the average waiting time, which also increases with the offered load. Also, boosting the transmit power of control packets results in higher waiting time as this increases the probability of successful reception of control

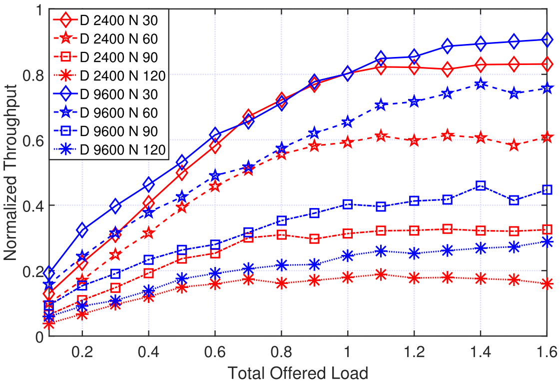

FIGURE 9. Throughput variation for single-channel EM-EM protocol.

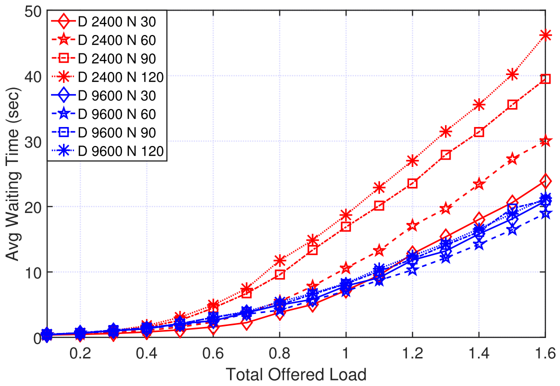

FIGURE 10. Waiting time variation for single-channel EM-EM protocol.

packets. This leads to a higher number of data packets in queue. Consequently, successful transmission of data packets increases causing higher throughput as evident from Fig. 7.

2) SINGLE-CHANNEL EM-EM PROTOCOL

Performance for the proposed single-channel MAC protocol considering EM-EM type configuration is illustrated in Figs. 9-10. Reduced network sizes are used here for the simulations, which is due to the much smaller propagation distance of data channel EM wave in underwater saline water. These figure show that the throughput decreases and the waiting time increases with the expansion of network size. Furthermore, bundling data packets to send more data at a time tends to increase throughput slightly, especially in the high offered load region. With the increment of network size, both collision rates and average waiting time increase, which is responsible for the poor performance of the protocol. These increment of collision rate is due to the high attenuation of EM wave of both control and data channels leading to increased probability of losing control and data packets. Also, as explained earlier, with larger networks, the packets need higher time to propagate to its destination resulting in increased waiting time.

3) MULTI-CHANNEL EM-AC PROTOCOL

Proposed Multi-channel EM-Ac type MAC protocol utilizes multiple Ac data channels with just one EM control channel.

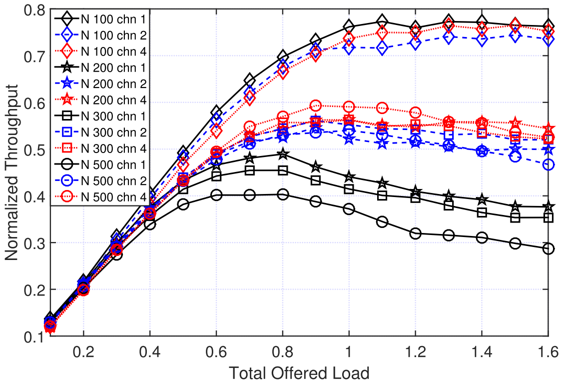

FIGURE 11. Throughput variation for multi-channel EM-Ac protocol.

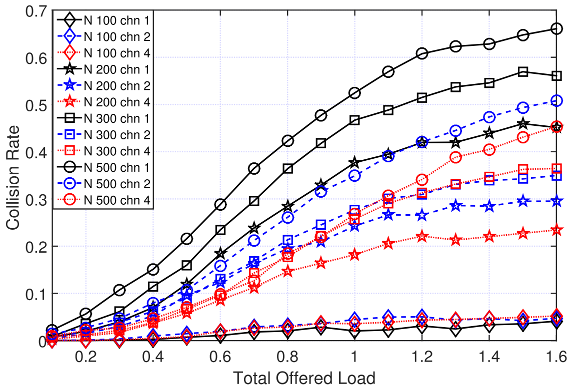

FIGURE 12. Collision rate variation for multi-channel EM-Ac protocol.

Figures 11-13 illustrate the performance of this protocol for different number of channels with different network sizes. The legend with ‘N 100 chn 2’ indicates that the network size is 100 $m \times 100$ m and two data channels in the network. Also, for the multi-channel scenarios, total bandwidth of single-channel case is equally divided among the multiple data channels.

Figure 11 illustrates that with the increase of the number of data channels, throughout significantly improves. However, the improvement is not linear as identified from the figure. For instance, for a network size of 500 $m \times 500$ m, improvement in throughput is much smaller when data channel increases from 2 to 4 compared to that when the channel number increases from 1 to 2. Furthermore, once again, the network throughput decreases with the increase in network size due to the increase in collision rate as shown in Fig. 12. On the other hand, the multi-channel protocol is efficient in the sense that even though the total bandwidth of one channel is divided among the multiple data channels, increasing in the number of data channels helps the nodes to decrease both waiting time and packet collisions as evident from Figs. 12-13.

4) MULTI-CHANNEL EM-EM PROTOCOL

Here, Figs. 14-15 provides the throughput and average waiting time of multi-channel EM-EM type protocol with respect to the offered load for varying number of channels. Though

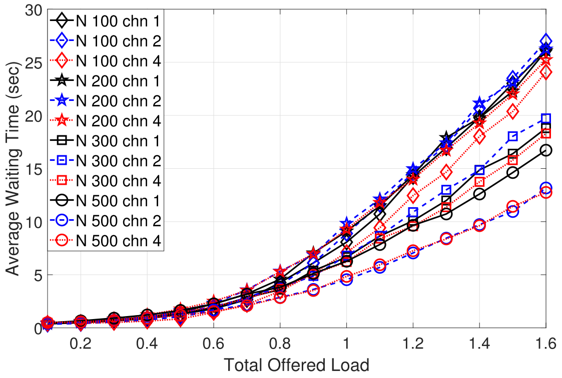

FIGURE 13. Waiting time variation for multi-channel EM-Ac protocol.

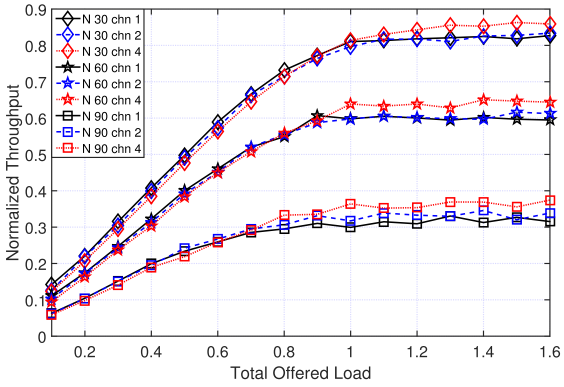

FIGURE 14. Throughput variation for multi-channel EM-EM protocol.

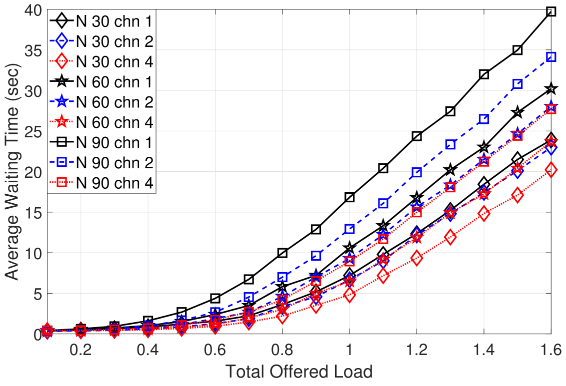

FIGURE 15. Waiting time variation for multi-channel EM-EM protocol.

in the case of multi-channel EM-Ac protocol, throughput has increased with the increment of parallel data channels, however it is not the case for EM-EM protocol as shown in Fig. 14. It can be seen that the data channel number does not have that much effect on throughput. On the other hand, average waiting time tends to decrease with the increase of channel numbers as shown in Fig. 15. However, this does not result in throughput performance improvement. This is because, though the nodes are waiting less time to transmit data, but the data packets are not being transmitted successfully due to the high attenuation of EM carrier.

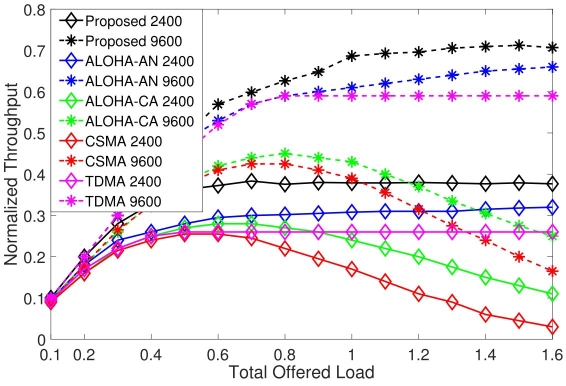

FIGURE 16. Comparison of the proposed single-channel MAC protocol with ALOHA, CSMA and TDMA schemes.

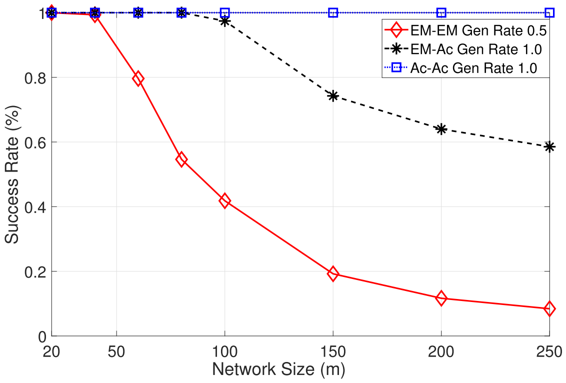

FIGURE 17. Success rate of the proposed MAC protocols with varying network size.

IX. A FEASIBILITY STUDY ON THE PROPOSED MAC PROTOCOLS

This section presents an in depth study on the feasibility of the proposed MAC protocols incorporating EM wave as a carrier in UWSNs.

A. COMPARISON WITH OTHER MAC PROTOCOLS

Performance of the proposed single-channel MAC protocol is compared with that of ALOHA-CS and ALOHA-AN [49], traditional CSMA, and traditional TDMA protocols in terms of throughput as shown in Fig. 16. The comparison is done assuming protocol interference model for a network size of 3000 m and using EM-Ac scheme. Two different data packet sizes, 2400 bits and 9600 bits are considered for the comparison. As seen from the figure, proposed MAC protocol outperforms the other protocols by a great extent for the shown range of offered load and packet sizes. Moreover, for higher loads, the proposed protocol shows consistent throughput similar to ALOHA-AN and TDMA, whereas the performance of other protocols degrades. Further comparisons of our proposed EM-Ac and EM-EM protocols are also compared with that of full acoustic-based Ac-Ac protocol from various aspects as presented in the following sections.

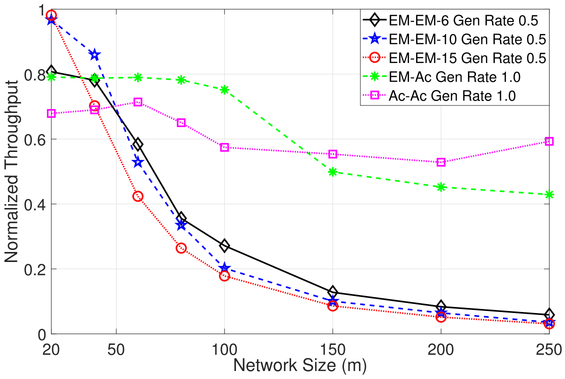

FIGURE 18. **Normalized throughput with varying network size.**

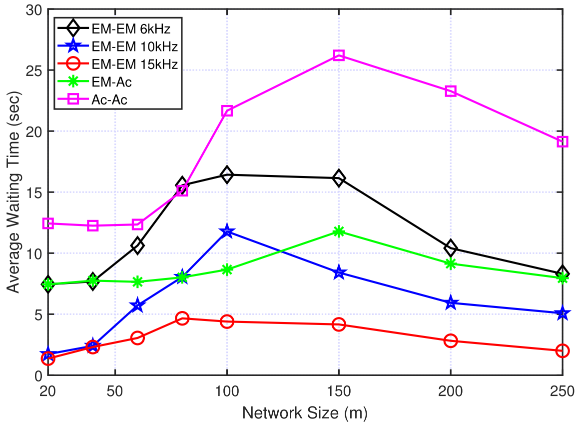

FIGURE 19. **Average waiting time with varying network size.**

B. NETWORK SIZE FEASIBILITY

Comparisons of the proposed single-channel EM-Ac and EM-EM MAC protocols with that of Ac-Ac protocol in terms of success rate, throughput and average waiting time are depicted in Figs. 17-19. Simulations are conducted considering realistic physical interference model. Control packet power and data packet size used for the simulations are 30 dBm and 2400 bits respectively.

Figure 17 compares the success rate among the three schemes. Success rate of a MAC protocol is important not only as it increases the throughput, but also it decreases the wastage of energy. It is evident from the figure that including EM in both channels of the protocol results nearly 100% success rate up to a network size of 40 m and thereafter, success rate decreases drastically due to high attenuation. The EM-Ac gives better success rate than EM-EM, while Ac-Ac has 100% success rate for all network sizes up to 250 m.

Fig. 18 compares the throughput performance of the proposed MAC protocols. For this figure, EM carrier frequency of 1 kHz is used for control channel. For the data channel, 6, 10 and 15 kHz are used for the EM data channel, whereas 10 kHz is used for the Ac data channel. As high frequency EM waves suffer more attenuation in sea water, we can see that for network sizes larger than 50 m, EM-EM offers very poor performance, whereas the performance of the other twos is subtly affected. Though EM-Ac uses EM carrier for control channel, low frequency EM control channel carrier has comparatively lower attenuation. Therefore, EM-Ac protocol faces much lower throughput degradation compared to EM-EM case over a relatively longer network size.

On the other hand, waiting time performance of the proposed protocols for the scenarios presented in Fig. 18 is compared in Fig. 19. Similar to throughput, once again, it can be identified that for smaller network size, EM-EM based MAC protocols outperform the others. Waiting time in EM-EM protocols gets further shorter with the increase of carrier frequency. It can also be seen that even if we make the control channel EM based and keep the data channel Ac-based, waiting time remains always much lower than that of Ac-Ac system demonstrating the advantage of EM wave based communications for UWSNs.

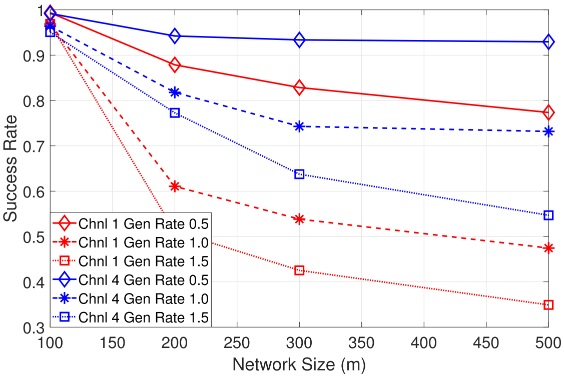

FIGURE 20. **Success rate with varying network size for the proposed EM-Ac protocol.**

C. SUCCESS RATE WITH CHANNEL NUMBERS

Up to this point, the most problematic parameter that hinders the performance of the proposed protocols is the attenuation of EM. To cope up and mitigate the effect, some steps can be taken. As shown Fig. 20 for the proposed EM-Ac protocol, the success rate of data packet can be boosted up by using multiple data channels. These multiple channels use the same total bandwidth of the single-channel. However with parallel communications, the data packet collision rate subsides substantially. For instance, success rate of single channel with total offered load of 0.5 can be boosted to 93% from 77% by using 4 parallel channels for a network size of 500 m. This increment of success rate is mainly due to the reduced number of collisions.

D. ENERGY REQUIREMENTS

Energy consumption is one of the crucial performance metrics for UWSNs. Here in Fig. 21, energy consumption in joule is presented for transmission energy only. This is the energy needed to transmit the packets generated within 50 seconds with data packet generation rate $\lambda = 1$ packets/sec. From the figure, it is evident that EM-Ac, EM-EM and Ac-Ac with

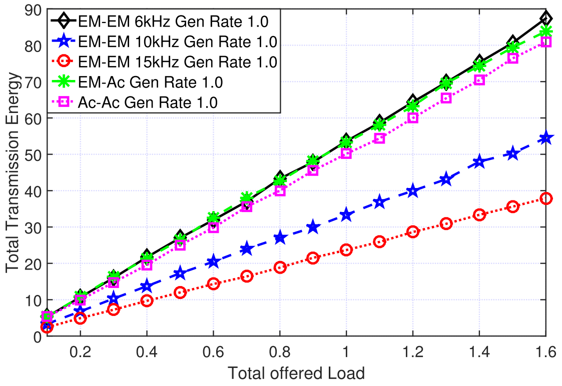

FIGURE 21. Total energy requirement with the offered load for varying EM channel bandwidth.

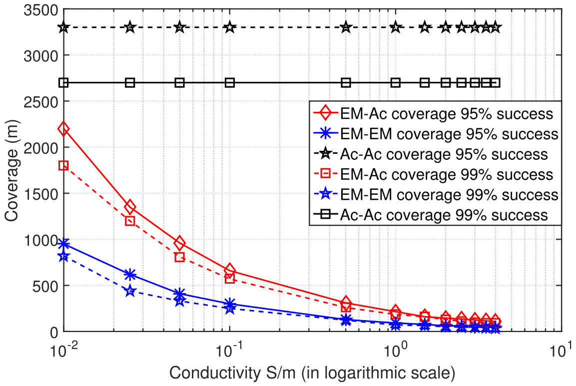

FIGURE 22. Network coverage with respect to the conductivity of water.

6 kHz data channel carrier consume nearly same amount of energy, whereas higher EM carrier frequency with its high bit rate consumes a much lower energy. The reason behind is that with higher bit rate, the transmitter can transmit the data in lesser time than before. Therefore EM with carrier frequency of 10 and 15 kHz requires significantly lower energy than the EM with 6 kHz carrier frequency.

E. COVERAGE ANALYSIS

With all the results and discussions presented so far, it can be said without any hesitation that the major limitation of EM-EM protocols is its significantly lower coverage due to its high attenuation in saline water, which further increases with the increase of carrier frequency. However, EM-EM protocols can have much larger coverage in water with low salinity. Figure 22 presents the network coverage for 95% and 99% success rates, which is equal to the maximum network size up to which packet transmission success rate is 95% and 99% respectively. The figure tells us that water with low conductivity (fresh water with very low salinity) can provide huge coverage for the proposed EM wave based MAC protocols. In fresh water (conductivity $\sigma = 0.01$) with the EM-EM protocol, coverage can be achieved as far as 1000 m, whereas the coverage is much higher 2200 m for EM-Ac case for 95% success rate. On the other hand, the coverage of Ac wave does not depend much on salinity and hence, Ac-Ac protocol shows a consistent coverage of 3300 m for 95% success rate.

X. CONCLUSION

This paper has proposed MAC protocols for single-hop mesh topology based UWSNs incorporating EM wave for communications. Proposed protocols use a TDMA-based control channel for signaling purpose and one or multiple channels for data transmission. The control channel always use EM wave as its carrier, while the data channels can be of either EM- or Ac-based. Both protocol interference model and physical interference model have been considered for the performance evaluation of the proposed protocols.

The proposed protocols with single data channel has shown high throughput, which is very susceptible to propagation delay (i.e., network size). However, use of larger data packets formed by combining smaller data packets can lower the susceptibility. For EM-Ac based single-channel protocol, it has been observed that with the increment of data packet size, almost always the throughput has increased, while the collision rate and average waiting time have decreased. On the other hand, with the increment of network size, the control packets have faced signal outage issue resulting in higher collision rates. With the case of EM-EM based single channel protocol, the terrible effect of path-loss has been the most dominating, which drastically reduces the network coverage as well as throughput. However, the proposed multi-channel MAC protocols have shown positive impact on the performance metrics due to the use of multiple data channels. The throughput of the multi-channel EM-Ac protocol has demonstrated increasing trend with the increment of data channels. Whereas, the average waiting time and collision rate have been found to decrease with the increment of the data channel number. On the other hand, though EM-EM multi-channel protocol has shown significant decrease in waiting time, improvement in throughput with the increment of data channels is not that much due to high attenuation.

An extensive feasibility study of the proposed MAC protocols considering realistic physical interference model has also been presented. Throughput performance of the proposed MAC protocols have been found superior than that of ALOHA-CA, ALOHA-AN, traditional CSMA and traditional TDMA. Moreover, it has been identified that a performance trade-off exists between our proposed protocols and Ac-Ac counterpart. For example, in terms of throughput, EM-EM works quite well for short-range communications, while EM-Ac is suitable for moderate size networks and Ac-Ac is the best option for long range communications for highly salinated water as in seas. However, in such saline water, the proposed EM-EM protocol has been found to use much lower energy and offer significantly lower waiting time than its Ac-Ac scheme. Interestingly, simulations have also found that the proposed EM-based protocols can support long range UWSNs in water with low salinity as in rivers.

This research work can be extended in several directions, including the consideration of multi-hop networks, multicast data transmission, dense node deployment, dynamic node mobility due to water current and duty cycling of nodes for energy efficiency, which will be included in our future works.

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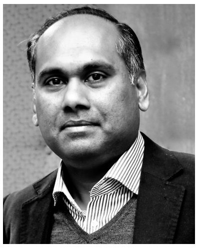

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