An Enhanced Full-Duplex MAC Protocol for an Underwater Acoustic Network

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***Abstract*— The existing half-duplex medium access control protocols take longer time to transmit and receive successful data packets, due to longer propagation delays. Therefore, we proposed an Enhanced Full-Duplex Medium Access Control protocol for the underwater acoustic network. The proposed protocol increases throughputs by decreasing the time for successful data transmission. The proposed protocol sets a back-off timer to access the transmission opportunity by transmitting the ID based RTS control packet to the target destination node. The target destination sends back the CTS control packet containing the data transmission and ID information, then both immediately exchange the data with each other, consuming less transmission time while performing FD communication. We evaluate the performance of the proposed protocol with respect to increase in number of underwater sensor nodes and payload size. Simulation results proved that the proposed protocol significantly increased the throughputs, compared to the existing convention medium access control protocols.**

Keywords—Medium Access Control (MAC); Request-to-send (RTS); Clear-to-send (CTS); Underwater acoustic communication network (UWACN); Full-Duplex (FD)

I. INTRODUCTION

Lots of Underwater Acoustic Communication Medium Access Control (UWAC-MAC) protocols and systems have been proposed, showing extensive development in the field of underwater communication [1-10]. However, most of these protocols are half duplex in nature, where the sender and receiver cannot share their data simultaneously, resulting in large propagation delays and interference. The underwater acoustic networks (UWANs) protocols are applicable to various applications such as natural disaster detection and marine monitoring systems etc.. But, due to long underwater propagation delay, narrow bandwidth, and multipath fading, it is difficult for these protocols to use an underwater channel efficiently [11-13]. For instance, the proposed half-duplex (HD) bidirectional medium access control (MAC) protocols are less efficient and have poor channel utilizations, and their hand-shake procedures are time consuming and unable to efficiently solve the long underwater (UW) propagation delays[14-16]. Distributed Coordination Function (DCF) technique is used to prevent collisions in the Underwater handshaking mechanisms by monitoring the channel before transmission, and transmits a frame if the channel is ideal for the transmission of new packets [17]. To enhance the performance of the IEEE802.11e model an enhanced distributed channel access with virtual collision handler, has been implemented to avoid the multiple collisions, utilizing the DCF and the binary back-off timer characteristics [18]. Further, an analytical IEEE802.11 model implements the back-off freezing mechanism with DCF collision avoidances characteristics, to enhance the throughputs of the overall system [19].

To reduce long underwater propagation delays in aquatic environments, the authors in [20] proposed slotted floor acquisition multiple access protocol, which uses different time slots for transmission and reception. The UWAC protocol in [2] has the ability to transmit a sequence of packets to multiple neighboring nodes. This protocol is based on multiple access collision avoidance algorithm, which reduces the time required during the control packet hand shaking process and improved the channel utilization [2]. The proposed reverse opportunistic packet appending protocol analyzed the system throughputs and transmission delay in an underwater acoustic environment [21], and reduces the propagation delay of data receiving from neighboring nodes [21]. In [14] a single-hop network based time-slotted BiC-MAC is proposed, which enhances the throughputs and minimizes the inter nodal delay. In [22], the author modeled a ring-based underwater network while considering the underwater propagation delay, and theoretically analyzed the network throughputs using MAC multiple RTS control and data packets.

All of the above mentioned protocols utilize back-off timer technique to avoid collisions and to improve the throughputs in harsh UW environment but these do not increase the overall efficiency of the system. Further, their hand-shaking procedures are time consuming and unable to solve long propagation delays issue. To address these issues we propose an Enhanced full-duplex medium access control (FD-MAC) protocol, utilizing full-duplex characteristics in an underwater acoustic network consisting of multiple underwater sensor nodes.

In our proposed protocol, the source node that acquires the transmission opportunity broadcasts an RTS packet including an ID of the target node, and to the neighboring nodes, in order to transmit information to the target destination node. The destination node that receives the RTS sends a clear-to-send (CTS) packet to the source node, informing it to perform FD communication. When the source node receives the CTS packet, the source and the destination nodes transmit the sensed information to each other according to the transmission order. The existing MAC protocols in the underwater environment take a lot of time to transmit information successfully, due to long propagation delays. Alternatively, the proposed FD-MAC protocol improves the throughputs of the network, by reducing the time required for successful transmission. In addition, we analyzed the network throughputs of the proposed enhanced FD-MAC protocol, and performed the comparative analysis with the pre-existing MAC protocols. Analysis showed that our proposed protocol outperformed, in terms of high throughputs while showing less propagation delays, as compared to pre-existing protocols.

The rest of the paper is organized as follows. In section II, we proposed the FD-MAC protocol, performing FD communications while transmitting the sensed information to the target nodes. In section III, we analyzed the throughputs of the proposed protocol. In section IV, we presented the simulation results of the proposed protocol with the varying number of UW sensor nodes and payload size. In section V, we concluded this paper.

II. System Model for An Enhanced Full-Duplex MAC Protocol

In this paper, we proposed an enhanced full-duplex medium access control (FD-MAC) protocol, and implemented it using n^{th} underwater sensor nodes. Fig.1 shows the working principle of our proposed FD-MAC protocol using the n^{th} UW sensors network. The i^{th} UW sensor node transmits the sensed information to the target node in a single hop. The source node performs the FD operation while holding the transmission opportunity due to the expiration of the back-off timer, and broadcasts the RTS frames including an ID, to the target destination node, and to the neighboring nodes in different time slots. The target destination node as well as the neighboring nodes receive the sent information. However due to the ID for the target UW sensor node, the communication initiates between the source and target destination nodes only, whereas the rest of the nodes remain silent during this communication process. While there is no transmission from rest of the UW sensor nodes, the sensors during this time reduce the value of their back-off timers to 1, or each UW sensor freeze its back-off timer.

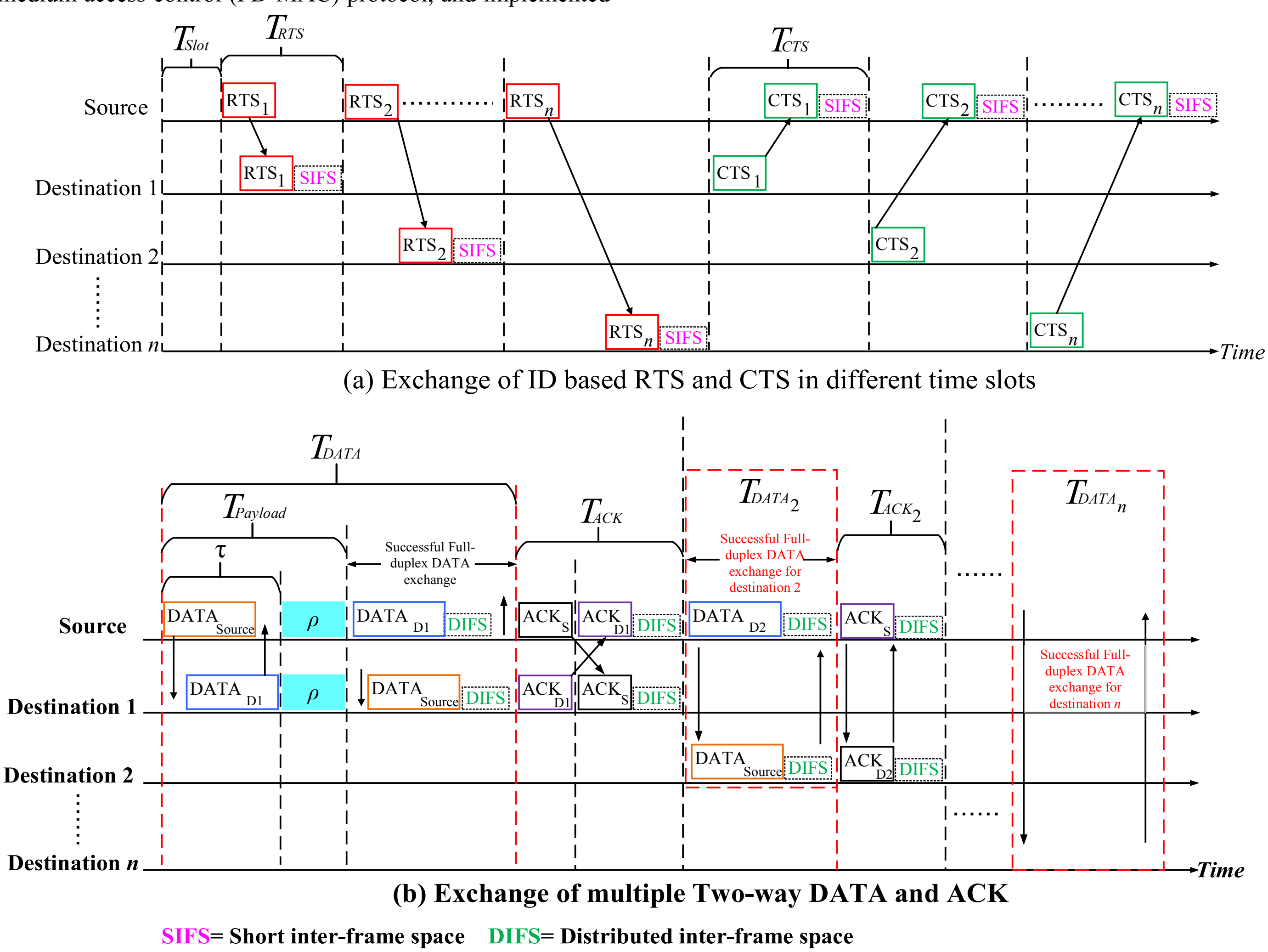

Fig 1. Proposed Full-Duplex MAC protocol Control and DATA packets transmission and reception machnasim

When the transmission of the RTS and DATA frames from the source to the target destination becomes successful, the value of the back-off timer of the UW sensor node is randomly chosen from integer '0' to W(i)-1. If data transmits from the i^{th} sensor node out of the n^{th} underwater sensor nodes, the size of the initial contention window $W_{initial}$ and M(i) of the back-off timer is set first, as shown by eq. (1). Further, the main contention window size ($W(i)$) randomly selects an integer value between 0 to W(i)-1 to set the back-off timer.

$$W(i) = W_{init} \times 2^{M(i)-1} \tag{1}$$

When the back-off timer of the UW sensor nodes reaches zero, the UW sensor transmits RTS frame containing the ID to the target destination node. The destination node extracts the information of the source node from the RTS frame, in which the DATA transmission order envelops. After reception of the clear-to-send (CTS) message from the source node and if the Short Inter-Frame Space (SIFS) passes, the source node and the destination node simultaneously start bidirectional data transmission with each other. Once the data reception completes, and if SIFS passes, the source node and the target node send an ACK packet to each other, and inform whether the data reception was successful or not. When the source node and the destination node receive the ACK of each other, and if Distributed Inter-Frame Space passes, a full-duplex bidirectional data communication process completes between these nodes. When there is no data to be transmitted from the destination node to the source node, one-way communication performs from the source node to the destination node, or if data transmission fails, the source node resets the back-off timer for data retransmission and participates in the transmission opportunity acquisition competition.

The maximum underwater propagation delay between transmitting and receiving sensor nodes is considered as τ. The underwater transmission rate is considered as R, while the sizes of RTS, CTS, and ACK are taken the same, as shown by L_{CRT}. The SIFS and DIFS are the intervals of the sensor nodes media access delays, with sizes of T_{SIFS} and T_{DIFS} respectively, and are used in Distributed coordination function (DCF) [17, 22]. The parameter T_{SLOT} indicates the slot time, while its size is indicated by τ+ (L_{CTR}/R) +T_{SIFS}. The T_{RTS}, T_{ACK} are the time intervals required for each successful transmission of the control packets. The size of T_{ACK} can be expressed by τ+(L_{CTR}/R)+T_{DIFS}, while the sizes of T_{RTS} and T_{CTS} is indicated by τ+ (L_{CTR}/R) +T_{SIFS}. The ρ corresponds to the time at which transmission and reception is performed simultaneously in FD communication mode. The time required for data transmission is indicated by $T_{payload}$ with the size of $\tau+\rho$. The T_{DATA} shows the time required for successfully transmission and reception of data, and is expressed by a size $T_{payload}+\tau+T_{SIFS}$. The detailed notations used in the system are shown in table I.

The channel congestion probability (P_C) is generated by at least one of n^{th} underwater sensor nodes while transmitting data, as shown as:

$$P_C = 1 - \prod_{i=1}^{n} \left[1 - 2 / W(i) + 1\right] \tag{2}$$

Here, eq. (2) indicates the probability of one of the n^{th} UW sensor nodes when its back-off timer expires and it gets a retransmission opportunity. However, the proposed protocol does not change the size of the contention window, if data transmission fails. In case of transmission failure, the probability of data retransmission from the i^{th} UW sensor node can be 2/W (i)+1.

TABLE I. VARIOUS STATETS IN FD-MAC PROTOCOL

Symbols	Description
T_{RTS}	Transmission time for RTS control packets
T_{CTS}	Transmission time for CTS control packets
T_{ACK}	Successful transmission of control packets
L_{CTR}	Size of RTS,CTS, and ACK control packets
T_{DATA}	Time required to transmit data packets
τ	Propagation delay time
T_{SIFS}	Short Inter-frame space between sensor nodes
T_{DIFS}	Distributed Inter-frame space between sensor nodes
T_{Slot}	The duration of the single time slot.
ρ	Simultaneous transmission and reception time
$T_{Payload}$	Time required for simultaneous data transmission
T_{DATA}	Successful time for data transmit and receive
ACK_S	Successful acknowledgement packet of source
ACK_D	Successful acknowledgement packet of destination

The P_S(i) indicates the probability of successful data transmission from the i^{th} UW sensor nodes, and can be written as:

$$P_S(i) = 2 / W_{(i)} + 1 \,\square \prod_{j \neq i} \left[1 - 2 / W(j) + 1\right] \tag{3}$$

In eq. (3), 2/W(i)+1 is the probability of the i^{th} UW sensor nodes which transmits data and act as source, while $\prod_{j \neq i} \left[1 - 2 / W(j) + 1\right]$ is the probability of the n^{th} UW sensor node which receives data. The normalized throughputs with the i^{th} and n^{th} UW sensor node in the single hop network for the successful payload transmission from the i^{th} UW sensor nodes to the n^{th} UW sensor nodes, is indicated by S_f(i), which can be expressed as:

$$S_f(i) = \frac{E_f \square (1 - P_E) \square P_S(i) \square T_{DATA}}{\begin{bmatrix} (1 - P_C) \square T_I + \sum_{\forall i} P_S(i) \square (1 - P_E) \square T_S \\ + \sum_{\forall i} P_S(i) \square P_E \square T_E + \left\{1 - \sum_{\forall i} P_S(i)\right\} \square T_C \end{bmatrix}}$$

$$T_S = T_E = T_{RTS} + T_{CTS} + T_{DATA} + T_{ACK}, \qquad T_C = T_{RTS} - T_{SIFS} + T_{DIFS} + \tau \tag{4}$$

Where E_f indicates the FD-UWAC efficiency, P_E expresses the frame error probability, T_I shows the idle time slot, T_S shows the transmission success time, T_C indicates the transmission failure time due to collision, and T_E expresses the transmission failure time due to the frame error [23]. The parameters T_{RTS}, T_{CTS}, T_{DATA}, and T_{ACK} are time duration of the control and data frames respectively, while T_{SIFS}, T_{DIFS} are the short inter-frame space and distributed inter-frame space, respectively [17, 24]. The numerator of eq.(4) demonstrates the time it takes for the underwater sensor node to successfully transmit data, while the denominator expresses the transmission update interval, considering idle slot time, transmission success time, and transmission failure time. The performance comparison of the proposed FD-MAC protocol, the HD-CSMA/CA MAC protocol [22], and the HD slotted BiC-MAC protocol [14], is provided in terms of throughputs, in with respect to various environments.

III. RESULTS AND DISCUSSIONS

The simulation and evaluation of the proposed FD-MAC ID based protocol for the UWACNs is performed, implementing the following parameters as described in the following table II [11, 14, 22]:

TABLE II. INPUT PAPAMETERS

Parameters	Values
UW sound speed	1500m/sec
Maximum propagation delay	3.3sec
Physical header	128bits
MAC header	272bits
RTS	128+112bits
CTS	128+112bits
ACK	128+112bits
SIFS	0.1sec
DIFS	0.2sec
Slot time	3.3+0.05sec
Data payload	13200bits
Bit Error Rate	0.01%
Data transmission speed	710bps
Channel bandwidth	0.1kHz
Maximum back-off stage	3

Fig. 2 shows the normalized throughputs comparison curve of the Enhanced FD-MAC protocol with the existing HD slotted BiC-MAC protocol [14], and the HD-CSMA/CA MAC protocol [22] with respect to varying number of UW sensor nodes. As the number of UW sensor nodes increases, the proposed FD-MAC protocol achieves higher throughput compared to HD slotted BiC-MAC and HD-CSMA/CA MAC protocols. This is because the proposed FD-MAC protocol can receive the successful transmission earlier, and takes less time to transmit and receive the control and the data packets.

Fig. 3 shows the normalized throughputs of the proposed Enhanced FD-MAC protocol, the HD CSMA/CA MAC protocol and the HD slotted BiC-MAC protocol with respect to the data payload size of 13200 bits, while the number of underwater sensor nodes is set to 30. As the data payload increases, the throughputs of the proposed protocol and HD slotted BiC-MAC increases equally, however, when the data payload size approaches to higher bits, the throughputs of the proposed FD-MAC protocol outperforms, because it operates on full-duplex mode of communication, transmitting and receiving data at much faster rates than the HD communication based protocols.

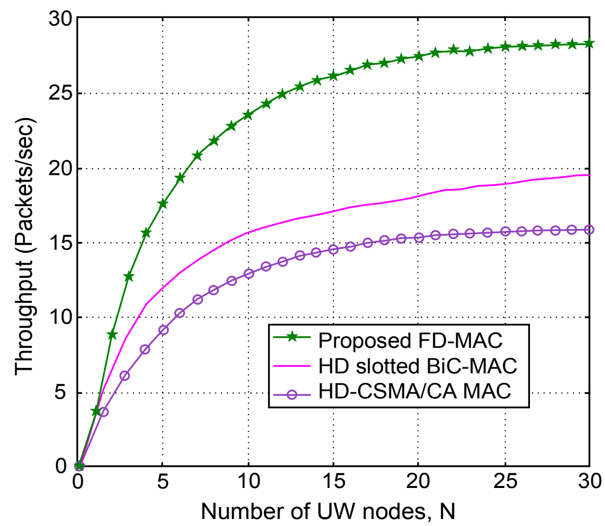

Fig. 1. Throughput analysis w.r.t to different number of underwater acoustic nodes.

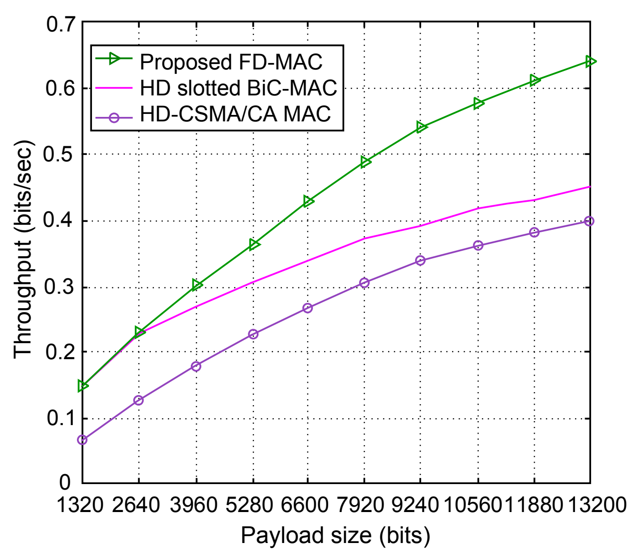

Fig. 2. Analysis of throughput w.r.t different values of payload.

IV. CONCLUSION

In this paper we proposed an enhanced full duplex FD-MAC protocol (also called bidirectional protocol), to simultaneously exchange the data packets in minimum time, utilizing the full-duplex communication channel. In the proposed FD-MAC protocol the source and the target destination nodes exchange data through sensed information in dual direction without being effected by the unexpected collisions. Simulation results indicate that proposed protocol outperforms the existing half-duplex MAC protocols, in terms of higher throughputs and less propagation delays in the underwater environment.

In future, while using the proposed protocol, we need to improve the energy efficiency and to reduce the end-to-end delay of the underwater sensor nodes.

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