MACA-U: A Media Access Protocol for Underwater Acoustic Networks

Hai-Heng Ng, Wee-Seng Soh, Mehul Motani
Department of Electrical and Computer Engineering
National University of Singapore
Email: {g0600158, elesohws, motani}@nus.edu.sg

***Abstract*—Unlike terrestrial wireless communication which uses radio waves, underwater communication relies on acoustic waves. The long latency and limited bandwidth pose great challenges in underwater Media Access Control (MAC) protocol design. As a result, terrestrial MAC protocols perform inefficiently when deployed directly in an underwater environment. In this paper, we examine how an existing asynchronous handshaking based protocol called Multiple Access Collision Avoidance (MACA) can be adapted for use in multi-hop underwater networks. Three areas of improvement are investigated, namely, the state transition rules, the packet forwarding strategy, and the backoff algorithm. Throughput performance is also evaluated through extensive simulation in multi-hop underwater networks. Due to its simplicity and throughput stability, our proposed MAC protocol can be adopted as a reference MAC protocol for underwater networks, with which a more sophisticated underwater MAC may benchmark its performance.**

I. Introduction

While wireless MAC protocols have been studied extensively for more than a decade [1]–[3], underwater MAC protocols still have many open problems. Generally, acoustic communication poses challenges such as long latency and limited bandwidth to the MAC protocol design. Orthogonal MAC schemes such as Frequency Division Multiple Access (FDMA) is not suitable for underwater networks due to the narrow bandwidth in underwater channel, and the vulnerability of limited band systems to fading. On the other hand, Time Division Multiple Access (TDMA) requires precise time synchronization and long guard time. Furthermore, orthogonal MAC schemes have scalability problem when some nodes join or leave a network. Therefore, a contention based MAC protocol is more preferable for large scale networks. Existing underwater contention based MAC solutions mainly revolve around either Aloha based [4] or handshaking based [5]–[8] protocols. In this paper, we have chosen to investigate handshaking based protocol, as hidden and exposed nodes are prevalent in multi-hop networks.

From the literature, there are a few research works carried out to adapt handshaking based protocols for underwater networks. Sozer *et al.* [8] proposed a MAC protocol based on MACA, which uses exchanges of control packets, and error detection via Stop-and-Wait Automatic Repeat Request (ARQ). The authors introduce a WAIT control packet to alleviate the problem of repetitive transmission requests. Molins and Stojanovic [5] proposed Slotted FAMA; the protocol requires precise time synchronization and long guard time, which leads to low throughput. Shahabudeen and Chitre [6] studied both Aloha and handshaking based protocol along with orthogonal and non-orthogonal physical layer models. Xie and Cui [7] performed an analytical study on random access and handshaking based protocol in single hop networks. Matsuno *et al.* [9] examined and proposed state transition changes to MACA in a large propagation delay channel. The authors derived a theoretical upper and lower bound for MACA's throughput performance. However, the analysis is limited to single hop networks.

While the original MACA is widely adopted as a reference MAC when evaluating more advanced terrestrial MAC protocols, it does not yield any meaningful insight, since the MACA was not designed for underwater networks where long propagation delays are prevalent. Specifically, there are some problematic scenarios that may show up in MACA in such environments, which have not been addressed previously. Therefore, there is a need to modify the original MACA to accommodate such scenarios, before it can be used as a meaningful benchmark. In this paper, we examine how the original MACA can be adapted for use in underwater networks, as well as investigate its throughput performance in a multi-hop scenario. In our work, we have identified three areas of modification, namely, the state transition rules, the packet forwarding strategy, and the backoff algorithm. The resulting MAC is known as MACA for Underwater (MACA-U).

The remainder of this paper is organized as follows. In Section II, the original MACA protocol is briefly described. MACA's adaptation for multi-hop underwater networks is described in Section III. In Section IV, the simulation results for MACA-U are presented and discussed. Finally, we present in Section V the conclusion drawn, as well as our future work.

II. Original MACA Overview

In MACA, a source node that has packet to send will contend for floor reservation by sending a Request-To-Send (RTS) control packet to the destination node. Upon receiving the RTS, the destination node immediately replies a Clear-To-Send (CTS) control packet back to the source node. MACA adopts the packet sensing mechanism, in which the proposed data transmission's length is embedded in the control packet. After receiving the CTS, the source node immediately sends data to the destination node. Any neighboring node that overhears a control packet that is intended for another node (xRTS or xCTS) will defer its transmission, and transit to QUIET state.

The neighboring nodes remain in QUIET state until the corresponding CTS or data packet transmission would have finished. Therefore, data collision is minimized through the transmission deferment. In the event of CTS failure, which could either be due to CTS packet corruption or the destination node is busy, the source node shall schedule a packet retransmission using Binary Exponential Backoff (BEB) algorithm. As mentioned in the previous section, there is a need to adapt the original MACA to accommodate some problematic scenarios in multi-hop underwater networks.

III. Proposed MACA Adaptation For Multi-hop Underwater Networks

In this section, we introduce MACA-U and its associated adaptations for underwater networks. MACA-U has five distinct states, namely, IDLE, CONTEND (CTD), WFCTS, WFDATA and QUIET. From IDLE state, a source node goes to CONTEND state when it has packet to send. Upon timer expiry in CONTEND state, the source node transmits a RTS, and transits to WFCTS state. The source node waits for returning CTS and sets its timer to $2\tau_{\text{max}} + T_{\text{cts}}$, where τ_{max} is the maximum propagation delay, and T_{cts} is the CTS duration. Similarly, after the receiver node returns the CTS to the source node, the receiver node goes to WFDATA state and sets its timer to $2\tau_{\text{max}} + T_{\text{data}}$, where T_{data} is the data packet duration. To avoid packet collision, every neighboring node is required to stay in QUIET state upon overhearing an xRTS or xCTS packet. Depending on the overheard control packet, a neighboring node shall set its silent duration to either QUIET_RTS or QUIET_CTS. MACA-U's timing diagram is shown in Fig. 1. Note that the curly arrow indicates that a node releases itself from the current handshake.

A. MACA-U State Transition Rules

MACA-U consists of state transition rules adapted from the terrestrial MACA. Specifically, the modified state transition rules of MACA-U are summarized in Table I. According to the formal specification described by MACAW and FAMA for terrestrial MACA, the deferral rule has a higher order of precedence over the control and timeout rules [2], [3]; that is, when a node in terrestrial MACA overhears any xRTS or xCTS packet, it transits directly to the QUIET state. In contrast, a long propagation delay (i.e., $T_{\text{rts}} \ll \tau_{\text{max}}$ or $T_{\text{cts}} \ll \tau_{\text{max}}$) often causes a node to receive packets other than the intended CTS or DATA, during WFCTS and WFDATA states, respectively. Therefore, we propose the following state transition rule modifications to improve MACA-U's throughput efficiency (refer to the shaded cells in Table I).

1) In WFCTS state, a source node employs a persistent waiting strategy for the expected CTS. The source node disregards any RTS or xRTS packet. However, the persistent waiting strategy is abandoned when it overhears an xCTS; the source node goes to QUIET state.
2) In WFDATA state, a receiver node employs a persistent waiting strategy for the incoming DATA. The receiver node disregards any RTS, CTS, xRTS and xCTS.

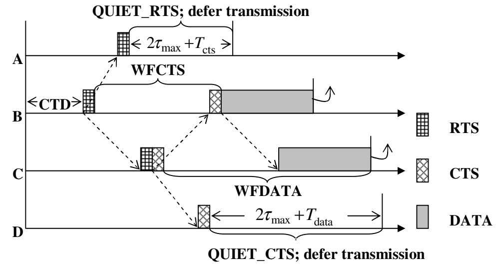

Fig. 1. Timing diagram for MACA-U.

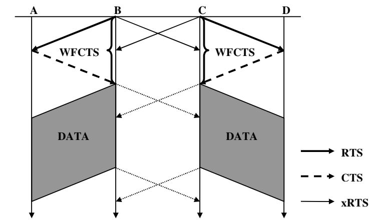

Fig. 2. Throughput is improved by allowing concurrent transmission at node B and C; a node disregards overheard xRTS in WFCTS state.

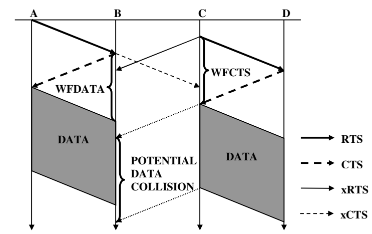

Fig. 3. Potential data collision is avoided by deferring transmission at node C; a node transits to QUIET state after it overhears xCTS in WFCTS state.

3) In QUIET state, a node remains in QUIET state for an extended period when it overhears xRTS or xCTS. The node computes $\max\{Q_{\text{lo}}, Q_{\text{ov}}\}$, where Q_{lo} is the local quiet duration, and Q_{ov} is the overheard control packet's quiet duration. The node shall stay in QUIET state corresponding to the larger of these two variables.

The above state transition rules cater for some scenarios that are much more likely to occur in underwater networks. In the first modification, while a source node resides in WFCTS state, it is reasonable to employ persistent waiting strategy for the expected CTS. As can be seen in Fig. 2, two neighboring source nodes transmit the RTS packets at around the same time. In this scenario, by allowing the source node to disregard any overheard xRTS during the WFCTS state, the system throughput can be improved due to the concurrent transmission in the neighborhood. In contrast, terrestrial MACA always prioritizes the deferral rule upon overhearing any xRTS or xCTS, i.e., a node transits to QUIET state, and defers its transmission. If we were to follow strictly with the terrestrial MACA's state transition rules, both source nodes shall transit to QUIET state upon overhearing xRTS. Therefore, both nodes waste their data transmission opportunities. However, an exception to the persistent waiting strategy occurs when the source node overhears an xCTS while it is in WFCTS state. In this scenario, the source node shall transit to QUIET state,

TABLE I
STATE TRANSITION RULES OF MACA-U

State \ Event Type	Receives RTS	Receives CTS	Overhears xRTS	Overhears xCTS	Timer Expired
IDLE	Transmit: CTS WFDATA	Disregard packet	Set Timer : QUIET_RTS QUIET	Set Timer : QUIET_CTS QUIET	–
CONTEND	Transmit: CTS WFDATA	Disregard packet	Set Timer : QUIET_RTS QUIET	Set Timer : QUIET_CTS QUIET	Transmit: RTS Set Timer: QUIET_RTS WFCTS
WFCTS	Disregard packet	Decrement BEB Transmit: DATA Send Data→IDLE	Disregard† packet	Set Timer : QUIET_CTS QUIET	Increment BEB Backoff for Retransmit IDLE
WFDATA	Disregard packet	Disregard packet	Disregard† packet	Disregard† packet	– IDLE
QUIET	Disregard packet	Disregard packet	QUIET*	QUIET*	– IDLE

† In the terrestrial MACA, these three cells transit to QUIET state.

NOTE: QUIET_RTS $= 2\tau_{\max} + T_{\text{cts}}$
QUIET_CTS $= 2\tau_{\max} + T_{\text{data}}$
QUIET* duration = $\max\{Q_{\text{lo}}, Q_{\text{ov}}\}$

and abort its data transmission. As can be seen in Fig. 3, a potential data collision is very likely to occur at node B, if node C were to transmit its data packet after persistently waiting for node D's CTS. Therefore, by deferring the data transmission at node C, the potential data collision at node B can easily be avoided. In the second modification, it is reasonable to employ persistent waiting strategy for the expected data packet during WFDATA state, as a successful RTS-CTS handshake has already been established. More specifically, a node shall disregard any control packet received while it is in WFDATA state. For example, node B disregards the overheard xRTS, and persistently waits for the expected data packet (Fig. 3). Lastly, a node may overhear xRTS or xCTS while it is deferring its data transmission in the QUIET state. In this scenario, a node shall consider the overheard control packet's quiet duration, and extend its quiet duration if the overheard control packet requires a longer silent duration.

B. *MACA-U's Packet Forwarding Strategy*

In fully distributed multi-hop networks, each node may act as a relay node to assist a source node in packet forwarding. Any packet drop that occurs in a relay node is costly as the packet has already consumed valuable channel resources to reach this node. To improve the end-to-end throughput, each node maintains two separate First-In-First-Out (FIFO) queues to differentiate two classes of data traffic; one for data originated from the node itself, and the other for relay data. Higher priority is given to the relay data's queue. For instance, an RTS packet that corresponds to a relay data packet is marked by a higher priority flag.

The long propagation delay in underwater makes it more likely to have two ready neighboring nodes transmit RTS successfully towards each other at around the same time. Without the packet priority assignment, both nodes may wait for the WFCTS timer to expire, and retry several times before giving up. Clearly, this is an undesirable event which leads to low throughput, high latency and energy wastage. This is alleviated by the packet priority assignment which is based on traffic classes.

C. *MACA-U's Backoff Algorithm*

Backoff algorithm is a collision resolution methodology to minimize packet collision probability. It is employed during packet retransmission or during the initial contention period, when a node has queued packets to be sent. Similar to terrestrial MACA, when a source node does not receive returned CTS in response to its previous RTS, the source node shall increase its backoff counter, B_{cnt}, according to BEB schemes. Based on the backoff counter value, the node will perform packet retransmission at a later time.

In BEB, each node doubles its backoff counter in the event of RTS failure, and resets its backoff counter to a minimum backoff counter, $B_{\min}$, upon a successful RTS-CTS handshaking. The backoff counter is bounded by a maximum backoff counter, $B_{\max}$. The BEB algorithm can be described by,

$$\begin{cases} B_{\text{cnt}} \leftarrow \min\{2 \times B_{\text{cnt}}, B_{\max}\}, \text{ upon collision} \\ B_{\text{cnt}} \leftarrow B_{\min}, \text{ upon successful transmission} \end{cases} \tag{1}$$

In underwater networks, the retransmission or contention slot duration is defined by $T_{\text{rts}}+\tau_{\max}$. Therefore, the backoff interval, T_{bk}, of the node can be expressed as,

$$T_{\text{bk}} = \textit{uniform}\{0, B_{\text{cnt}}\} \times (T_{\text{rts}} + \tau_{\max}) \tag{2}$$

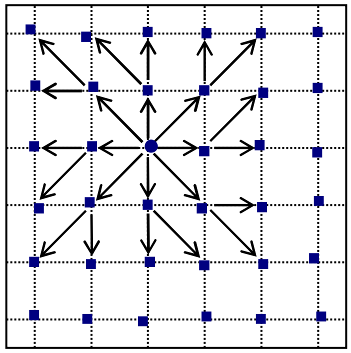

Fig. 4. The multi-hop network topology used in our simulations.

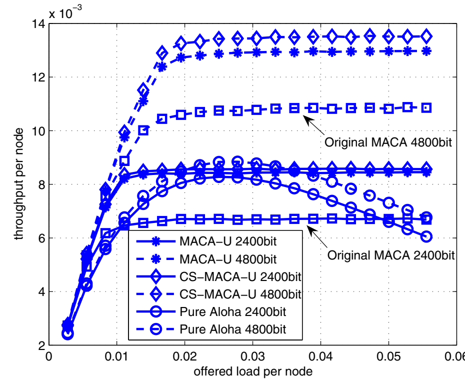

Fig. 5. Throughput comparison for MACA-U, CS-MACA-U, Pure Aloha and Original MACA.

If the large propagation delay is not considered in defining the slot length, it may lead to a more aggressive contention, and result in higher packet collision rate. In our work, we compare the BEB's throughput performance against Multiplicative Increase Linearly Decrease (MILD), Exponential Increase Exponential Decrease (EIED), Linearly Increase Linearly Decrease (LILD), and IEEE 802.11-alike rotating backoff.

IV. Simulations And Results

A. Simulation Model

In our simulation, the multi-hop network topology comprised of 36 static nodes with a grid spacing of 700m as shown in Fig. 4. Instead of precisely placing each node at the grid intersection point, we introduce some degree of randomness by allowing each node to deviate from the grid intersection point by a maximum of 10% of its grid spacing, in both vertical and horizontal directions. The maximum transmission range for each node is 1.75 times the grid spacing, or 1225m in our simulation topology. Hence, each node has exactly 8 one-hop neighboring nodes and 16 two-hop neighboring nodes. A wrap-around strategy is applied to all boundary nodes in order to distribute network load evenly and eliminate boundary effect. For every packet generated by each node, the node randomly selects one of the 16 two-hop neighbors as an end destination with equal probability. In the figure, we only show the static routing pattern for one node (the round node). Every other node in the network topology assumes the same static routing pattern. All nodes are assumed to be equipped with a half duplex omni-directional antenna. The bit rate of each node is assumed to be 2400 bps. The acoustic propagation speed is 1500 m/s. Every node operates independently of each other and traffic load is divided evenly among all nodes according to the Poisson distribution. The channel is assumed to be error free. Thus, packet losses are contributed by packet collision. For MACA-U simulations, all control packets' lengths are 100 bits, i.e., RTS and CTS are of equal length in our simulation. Data packet lengths of 1200, 2400, 4800 bits have been simulated. For BEB backoff parameters, B_{min} is 1, and B_{max} is 64. Each node maintains two separate FIFO buffers for every one-hop neighbor with maximum size of 100 packets. There is no ACK involved in our simulations. To avoid transient effect, simulation results are collected from $200,000$s to $1,000,000$s.

B. Simulation Results

The simulation's objective is to study MACA-U's performance, specifically on its throughput in underwater networks. Note that the throughput per node is a unitless metric, as it has been normalized to single-hop channel capacity, i.e., 2400 bps. As presented in Fig. 5, we benchmark our MACA-U against the conventional pure Aloha protocol. We observe that the pure Aloha scheme only has a maximum throughput per node of $0.0080 - 0.0085$. In addition, its throughput per node drops as the offered load per node increases beyond its maximum throughput operating point. This is reasonable as pure Aloha does not deploy any collision avoidance mechanism in the presence of hidden nodes.

In contrast, MACA-U maintains its stable throughput as the offered load increases, at the expense of small communication overhead (exchanges of control packets). The stabilized throughput characteristic can be explained by its efficient collision avoidance mechanism, and collision resolution mechanism in packet retransmission. In the presence of hidden nodes, the probability of data packet collision at higher offered load is minimized by prior exchange of short RTS-CTS packets, which are used for virtual carrier sensing. Next, we simulated an improved carrier sensing variant, CS-MACA-U. This protocol performs physical state verification; the node only transmits when the physical state is IDLE. By performing physical state verification, the protocol eliminates potential data packet collision which may have occurred in packet sensing. For instance, data collision may result if a source node happens to transmit its own RTS packet even though it is in the middle of receiving an incoming RTS packet. Lastly, we compare the performance of MACA-U against the original MACA protocol (without the state transition rules adaptation). For both simulated packet lengths, MACA-U outperforms the original MACA by around 20% for the saturation throughput. Note that the original MACA protocol for 2400 bits actually has a lower throughput per node than the pure Aloha counterpart at the offered load region of $0.01 - 0.05$.

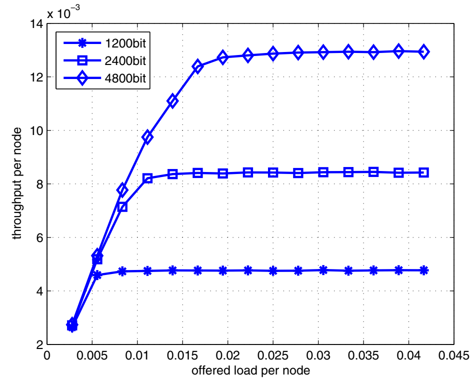

Fig. 6. Effects of different data packet sizes.

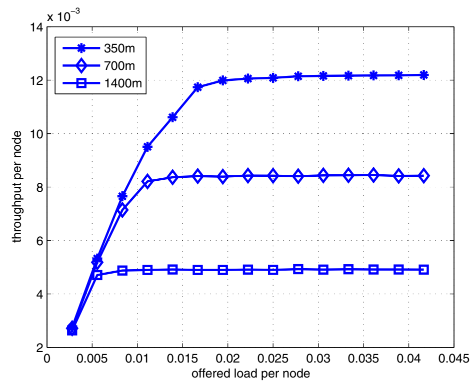

Fig. 7. Effects of different grid sizes.

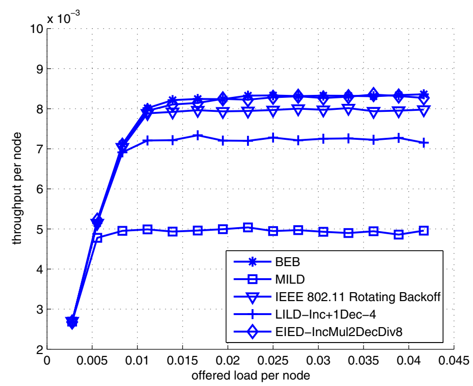

Fig. 8. Performance evaluation of various collision resolution schemes.

Next, we study the effects of data packet sizes in MACA-U with the assumption of fixed control packet size. As illustrated in Fig. 6, MACA-U exhibits a stable throughput per node for all ranges of data packet sizes. It is not surprising that the throughput increases as we send a larger data packet upon a successful handshake. The observation suggests that MACA-U may be improved using a packet-train concept. Obviously, it is very costly to only send a single data packet upon a successful handshake.

Fig. 7 shows the effects of grid sizes when the data packet length is 2400 bits. As can be seen, MACA-U is rather sensitive to the inter-node distances. The explanation for the lower throughput as separation distance increase is due to a larger propagation delay in the exchange of RTS-CTS packets. Hence, this suggests that handshaking based protocol is more appropriate in short range multi-hop underwater networks.

Fig. 8 illustrates the performance of various backoff algorithms in MACA-U. For EIED and LILD schemes, we have simulated various combinations of factors, i.e., additive increase or decrease factors, multiplicative increase or decrease factors. Here, we present the optimal cases due to space constraint. From the plot, as opposed to terrestrial MACAW, MILD actually performs worse than BEB in terms of throughput efficiency. The reason is that MILD requires more time steps in the decrement back to a smaller contention window. We observed that a better throughput is achieved when the backoff algorithm assumes a drastic decrement, i.e., BEB, EIED. However, we notice that fairness remains as an issue that needs to be solved.

V. Conclusions and Future Work

In this paper, we propose and study the MACA-U protocol, which is an adaptation of terrestrial MACA for multi-hop underwater networks. Three areas of improvement are investigated, namely, the state transition rules, the packet forwarding strategy, and the backoff algorithm. The simplicity and throughput stability of MACA-U make it an appropriate reference MAC protocol, which a future, more advanced underwater MAC may benchmark its performance against. From the simulation results, we see that MACA-U achieves a stable throughput, and it is a suitable candidate for dense underwater multi-hop networks. Our future work for MACA-U includes an investigation of unfairness in the backoff algorithm, as well as a theoretical analysis of the throughput and delay characteristics.

Acknowledgement

The research reported in this paper was supported by the Ministry of Education of Singapore, AcRF Tier 1 funding, under Grant No. R-263-000-370-112.

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