# COPE-MAC: A Contention-based Medium Access Control Protocol with Parallel Reservation for Underwater Acoustic Networks

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***Abstract*— Long propagation delays of acoustic signals in underwater networks pose grand challenges in medium access control (MAC) protocol design, often significantly undermining network performance if not handled appropriately. In this paper, we propose a novel MAC protocol, called COntention based Parallel rEservation MAC (COPE-MAC) for underwater acoustic networks. In COPE-MAC, we introduce "parallel reservation" and "cyber carrier sensing" techniques. The first method improves communication efficiency, while the latter one can detect and avoid collisions by mapping a physical channel to a virtual one in the cyber space. The performance of the proposed protocol is evaluated via simulations. Experiment results show that COPE-MAC can significantly increase the overall network throughput, and is especially suitable for larger networks with long distances.**

## I. Introduction

The underwater network is a promising technique that could connect underwater vehicles, sensors nodes and a variety of other devices working in an underwater environment. It has a wide range of applications, such as oceanographical data collection, oil/gas field monitoring, and undersea persistent surveillance [1]–[4]. Since radio does not work underwater due to high attenuation, acoustic signals are widely used in underwater networks. Compared with radio channels, acoustic channels features high error rates, low available bandwidth and long propagation delays (acoustic signals propagate 5 orders of magnitude slower than electromagnetic waves). Due to such unique characteristics, many commonly accepted assumptions in terrestrial wireless networks do not hold in underwater acoustic networks any more, and most existing network protocols for terrestrial networks cannot be applied into underwater environments. In short, underwater networks bring grand challenges [1]–[6] to the design of network protocols and require significant research efforts at almost every layer of the protocol stack.

In this paper, we focus on medium access control (MAC) protocols for underwater acoustic networks. A MAC protocol is used to coordinate the access to the shared acoustic channel among multiple nodes, which is very critical to the network performance. However, the adverse underwater environment makes efficient MAC design very challenging. On the one hand, the precious acoustic bandwidth and energy resources call for close cooperation among nodes for efficient channel access and collision avoidance; on the other hand, the long propagation delay and the high error probability of acoustic channel make the cooperation among nodes very time and resource consuming. Most of the recent research studies on MAC protocols in underwater networks tend to improve the system energy efficiency by using either RTS/CTS like handshaking approaches [7], [8] or channel reservation techniques [9]. For many applications, however, high network throughput is also desired. For the RTS/CTS like handshaking approaches, one time-consuming handshaking process usually only reserves the channel for one sender-receiver pair. Although the system energy efficiency is greatly improved in this way, the network throughput is usually low since a significant part of system time is used for the handshaking. For the reservation based protocols, strict synchronization among nodes is usually required, and the synchronization problem itself is often very challenging and costly in a long-delay underwater environment.

In this paper, we propose a novel **CO**ntention based **P**arallel r**E**servation MAC (COPE-MAC) protocol, which takes both energy efficiency and throughput into consideration. Our methods of addressing the long-delay and efficiency issues are two folds. On the one hand, we introduce parallelism into the protocol design and make concurrent transmission possible in underwater acoustic networks, which augments the system throughput. On the other hand, we adopt a contention based reservation approach to avoid collisions and improve the system energy efficiency. Besides, collisions can be detected in advance by checking the neighbors' activities recorded in local memory. In this way, COPE-MAC smoothly integrates "parallel reservation" and "cyber carrier sensing" techniques. We evaluate our protocol via simulations. The results show that COPE-MAC can achieve very high network throughput, especially in sparsely deployed multi-hop underwater network with relatively high traffic.

The rest of this paper is organized as follows. We first examine the long propagation delay issue in MAC design and motivate our approach in Section II. Then we present COPE-MAC in detail in Section III. After that, we evaluate the performance of COPE-MAC and review some related work in Section IV and V respectively. Finally, we summarize the paper and discuss some future research directions in Section VI.

## II. Motivations

### A. Impacts of Long Propagation Delays

The long propagation delays of underwater acoustic channels make efficient MAC design very challenging. Firstly, traditional collision detection mechanism such as carrier sensing

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is not that effective any more. For example, in a CSMA/CA collision detection approach, a node first listens to the channel before data transmitting in order to avoid sending data in a busy channel. However, in underwater acoustic networks, because of the long propagation delay, a node cannot even know the current channel condition of a remote one-hop neighbor. In other words, even when a node overhears some signal, it does not mean that its neighbors are experiencing the same thing at the moment. Thus the whole point of detecting collision by listening to the channel is not valid anymore.

Secondly, the performance of some advanced collision detection mechanisms for terrestrial wireless networks, such as RTS/CTS handshaking based approach, also often referred to as "virtual carrier sensing", is very low in underwater acoustic networks. The basic work flow of the classic RTS/CTS

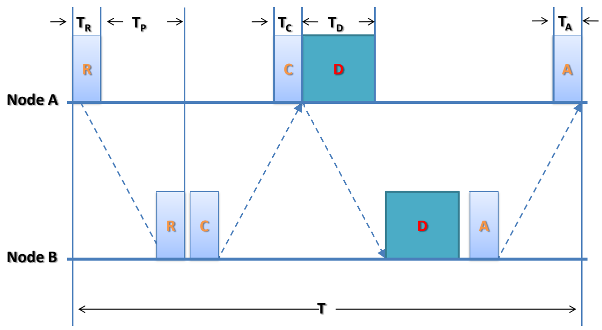


Fig. 1. Handshake in a Radio Wireless Network

approach is shown in Fig. 1. When sender, A, wants to talk to its neighbor B, it first transmits a RTS message, denoted as R in the figure. Once received, B responses with a CTS message to confirm the sender and triggers the data transmission. The CTS message also suppresses other neighbors, avoiding any potential collisions. After receiving the CTS message, A starts delivering the data packet. If everything goes well, an ACK is sent from B to A to conclude the communication process. Let's denote the time spent on RTS/CTS/DATA/ACK as $T_R, T_C, T_D$ and $T_A$ respectively. Further, we use $T_P$ to denote the propagation delay and $T_\epsilon$ to denote the total system delay when switching between sending and receiving. The total time spent on transmitting one packet, according to Fig. 1, is $T = T_R + T_C + T_A + T_D + T_\epsilon + 4 \times T_P$, without considering any collisions. In the IEEE 802.11 protocol, control messages, such as RTS/CTS/ACK, are designed to be very small, and can be neglected compared to $T_P$ and $T_D$. So does $T_\epsilon$. Then the system performance, in terms of channel utilization, will be bonded by,

$$\eta \leq \frac{T_D}{T} \leq \frac{T_D}{T_D + 4 \times T_P} = \frac{1}{1 + 4 \times \alpha}, \quad (1)$$

where $\alpha$ is defined as the ratio of propagation delay $T_P$ to transmission delay $T_D$, assuming no collisions and link errors. For RF wireless networks, $\alpha$ approaches zero, yielding high $\eta$. In underwater acoustic networks, however, $\alpha$ is much larger and non-negligible. When the propagation delay dominates the communication time, meaning $\alpha$ larger than 1, the channel utilization will be very low.

Recent technology improvements on underwater acoustic modems make the channel utilization of the RTS/CTS based handshaking scheme even lower. The maximum data sending rate of an acoustic modem, UWM1000 from LinQuest for example, can reach as high as $17.8kbps$ [10]. Assuming data packet size is 200 bytes, nodes are deployed 500 meters away, no collisions and no link errors, according to equation 1, the channel utilization $\eta$ is less than $6.4\%$! With the further development of underwater acoustic modems, the channel utilization of the RTS/CTS scheme will be even smaller. Although increasing the packet size would alleviate the problem to some extent, a long packet size usually is not desired in underwater networks with high error rates [11].

### B. *Our Approaches for Efficient MAC*

As we can see, the performance issues caused by long propagation delays essentially result from inefficiency of the handshaking mechanism in acoustic channels: with one round of "lengthy" handshaking process in underwater networks, only one data transmission is allowed in the one-hop neighborhood. Most handshaking-based MAC protocols would suffer severe performance loss in case of long propagation delays. If we can manage to arrange multiple data transmissions in one handshaking process, the channel utilization would be greatly improved. That is the basic driving idea of COPE-MAC, in which "parallel reservation" is introduced, raising the ceiling of $\eta$ much higher.

To further improve the MAC performance, we propose a technique called "cyber carrier sensing". In this technique, every node keeps track of its neighborhood activity by obtaining extra information from the handshaking process. In this way, the handshaking process of COPE-MAC not only arranges the data communication, but also carries neighbors' activities in the future. By looking at these information, potential collisions could be detected and avoided. We call it "cyber carrier sensing" because all collision detection and avoidance are done in the "cyber space", with computation rather than physical detection. Design details will be included in the Section III.

In short, to cope with the long propagation delay issues in underwater acoustic networks, COPE-MAC proposes "parallel reservation" to improve communication efficiency and "cyber carrier sensing" to detect and avoid collisions.

## III. COPE-MAC: Contention based Parallel Reservation MAC

In this section, we first give an overview of COPE-MAC. Then we present its key components: parallel reservation, cyber carrier sensing and data transmission in details, followed by some discussions on the fairness issue.

### A. *COPE-MAC Overview*

COPE-MAC has four phases, namely, neighbor discovery, parallel reservation, cyber carrier sensing and data communication. In the first phase, each node randomly selects a time point and broadcasts a neighbor discovery packet, ND. When the message is received by a neighbor, it responds with a ND-ACK packet which includes the information of the duration $T_{int}$ between receiving the ND packet and sending the ND-ACK. Assuming that the ND packet is sent at $T_1$ and the ND-ACK packet is received at $T_2$, the propagation delay could be calculated as $T_{prop} = \frac{T_2 - T_1 - T_{int}}{2}$. After a node obtains the propagation delays to all its neighbors, it can use this information to properly schedule communication time in the following phases. When a node has packet to others, it will initiate a "parallel handshaking process" with the receivers to reserve the time for transmissions. It should be noted that, different from the conventional one-to-one handshaking, the handshaking process here happens in parallel between multiple senders and transceivers and every handshaking will reserve its data transmission time. We will further elaborate the "parallel handshaking process"in Section III-B. During the parallel reservation process, every node will do "Cyber Carrier Sensing" to judge the potential collisions in the network, which will be described in Section III-C. In the final stage, every node transmit the data in its reserved transmission time, which will be described in Section III-D [1].

Fig. 2 illustrates how COPE-MAC works via a simple example. In Fig. 2(a), node A broadcast a multiple reservation (MREV) message to express the desire to communicate with node B and D. Node C also send a MREV to handshake with node D. Because the MREV-ACK message is short, the collision probability of MREV-ACK messages is low. Upon receiving the MREV, both B and D respond with reservation acknowledgement (MREV-ACK) messages, as shown in Fig. 2(b). Note that the MREV-ACK from D will schedule two packet sending windows from A and C. Since B and D are of different distance from A, even if they send out the MREV-ACKs at the same time, the MREV-ACKs will arrive at A at different times. According to the schedules that have been negotiated in the MREV and MREV-ACK handshake, in Fig. 2(c) and 2(d), A sends packets to D and B sequentially. Because node C is aware of D's communication with A, it will choose a time to send DATA packets to D and avoid any collision. At last, in Fig. 2(e), both B and D acknowledge the data packets received with MACK messages.

## B. Parallel Reservation

In the parallel reservation phase, each node tries to make multiple channel reservation within one multiple reservation packet MREV [2]. Based on these observations, in COPE-MAC, the MREV packet will be broadcasted to all neighbors, trying to arrange data sending with several nodes. Besides, MREV can also be used to reserve the channel for sending several packets to the same neighbor at different times. Every MREV message contains brief information regarding the data packets that the sender wants to transmit. For example, it has the desirable data sending time $T_{sd}$, expected receiver and duration of the packet $T_{tx}$. Note that $T_{sd}$ is defined as the delay between MREV and the data packet. And $T_{sd}$ should be larger than the maximum round trip time.

Back to the reservation process, after MREV is received, each node updates its schedule table *ST*, keeping track of what might happen in the network in the following seconds. When the expected data packet receiving node gets the MREV, it broadcast a multiple reservation acknowledge message (MREV-ACK) to confirm the reservations. Note that several MREVs may be received. So the receiver needs to wait for some $T_{rw}$ milliseconds, and satisfy $T_{sd} \geq RTT + T_{rw}$. When sending back the MREV-ACK, it also update the $T_{sd}$ as $T^*_{sd} = T_{sd} - T_{rw}$ to reflect the actual time elapsed. Once the MREV-ACKs received, the sender will transmit data packets to its neighbors at the agreed time point according to the results of the handshakes. Due to the propagation delays, the actual sending time would be $T^*_{sd} - RTT$. And the receiver(s) will be ready at the reserved time. If the receiver cannot allocate $T_{tx}$ time starting from sender's expected transmitting time point, it will not include the sender into the reservation list. So the sender will have to try another MREV message later to communicate with the receiver. When neighbor nodes overhear the MREV-ACK message, they mark the events in the reservation list on their own *ST* and avoid that time. Since the MREV-ACK carries $T^*_{sd}$ and $T_{rw}$ is a known value, if the neighbor has previously received the corresponding MREV message, by comparing $T^*_{sd}$ and $T_{sd}$, it can even know the RTT between the receiver and sender. This information could be useful for localization purpose. On the other hand, if MREV is heard but no MREV-ACK, one can tell that either this is an exposed terminal or sender cannot establish the connection to another node. Either way, it is safe for this neighbor to communicate with another node.

## C. Cyber Carrier Sensing

Cyber carrier sensing is a new concept introduced in this paper. It works in parallel with the reservation process and performs effectively with the extra information in the control messages Each node has a virtual channel in mind. By

[1]COPE-MAC does not have duty cycles or do frequent power mode switching. The reasons are two folds: on the one hand, the switching energy cannot be neglected [12] even for RF radio networks; on the other hand, the different characteristics of underwater acoustic modem make such practice inefficient for underwater networks [13].

[2]We assume that all sensor nodes know their own traffic. Since the underwater acoustic link is typically the bottleneck of the data communication, many packets, possibly designated to different receivers, are accumulated in the network protocol stack. This is especially true when higher layer protocols exchange information with neighbors. For example, some dynamic routing protocols may need to communicate with neighbors to update the routing tables. Some underwater localization protocols, e.g. [14], also need to talk with different beacon nodes to do localization. Moreover, recent research on network coding in underwater networks [15] also prefer to send packets to multiple neighbors, i.e. different routes, to provide better service in the lossy underwater channel.

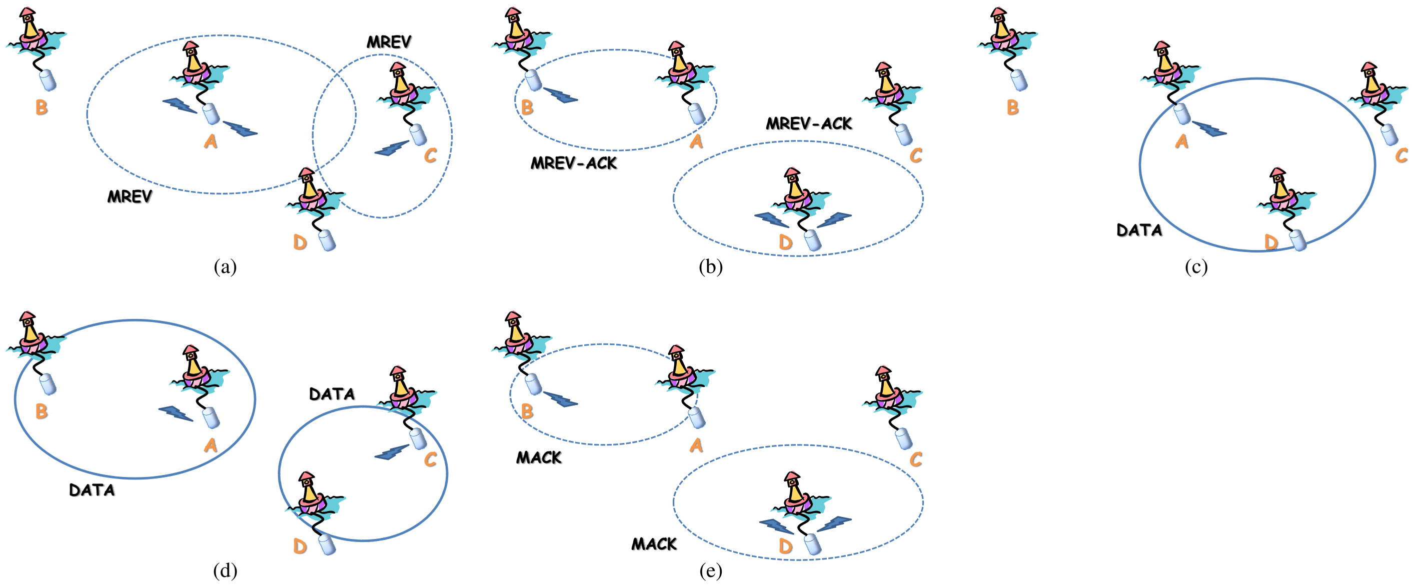


Fig. 2. COPE-MAC example

knowing the propagation delays to neighbor nodes in the first phase, one can map the neighbors' time to its own. After that, activities of a remote node on the "remote time" become activities happening in "local time". By calculating the time offset, a physically long delay network turns into a virtual non-delay network in the cyber space. With the extra information collected in the control messages, a node can put events in the neighborhood physical channel to its virtual one. By "carrier sensing" the virtual channel, it can detect and avoid collisions. In this way, the node can not only deliberately avoid its neighbors' "rush hours", but also utilize the idle time by calculation and message exchanges in other phases. No time synchronization is needed.

In our implementation, every node maintains a timeline of a virtual channel. By overhearing the reservation messages, the node can map the activities, adjusted by propagation delays, in the neighborhood to its own timeline. And now, the cyber carrier sensing begins. The node looks up the timeline for events in the virtual channel. The time interval corresponding to the events is marked in a reservation queue, the node can "sense" the virtual channel by checking the queue so that it can send out packets while avoiding the collisions. This is how cyber carrier sensing works and is one critical technique used in COPE-MAC.

### D. Data Transmission

After the MREV and MREC-ACK exchange, data communication is done in a unicast fashion. The header of DATA packet also includes all confirmed reservation for future data transmitting. In this way, its neighbor can differentiate the exposed terminal problem and reservation failure as well as capture the sender's future behaviors. In case of the reservation failure, the neighbor will be able to communicate with the sender immediately. If exposed terminal problem is detected, the neighbor has to wait $T_{tx} - RTT$ before it can talk with the sender. Since propagation delay dominate the communication time, as long as $RTT > T_{tx}$, the neighbor can always talk to the sender without collision. However, in COPE-MAC, we still require the neighbor to listen to the DATA packet, as least for the header[3]. This gives the opportunity for the neighbor to have an updated schedule of the sender and helps avoid future collisions.

Once DATA packets are received successfully, the receiver will respond with DATA-ACK messages. We design COPE-MAC in a way that the receiver broadcasts the DATA-ACK at a time point that could either be received by many senders or after a given time interval. The first one is possible because each node maintains a table that keeps tracking of the neighbors' behaviors. In fact, with the propagation delay information collected in the first phase, a node can map all neighbors' time to its own. So do their activities. The second criteria is to provide timely response to avoid unnecessary retransmissions.

**A Summary** To summarize, all control messages are broadcasted. They contain important information to let neighboring nodes be aware of the activities in the neighborhood. One handshake process can lead to multiple successful data transmissions. Although we still experience long propagation delays, we manage to schedule several communications in parallel. Thus the overall system performance, in terms of the system throughput and channel utilization, is improved.

### E. Discussions

We regard COPE-MAC as a fair MAC protocol in several ways. First, in long delay networks, many protocols try to

[3]This feature is available in some acoustic modems such as the OFDM modem [16] designed by University of Connecticut.

reduce system overhead in the long waiting time by assigning a longer transmission window for the winner of channel contention. COPE-MAC, on the other hand, randomly select packets for different destinations from outgoing queues. So all neighbors have equal opportunity to receive data. Second, when receiving MREV messages from different senders, the intended receiver will randomly pick the senders to establish connection. And thus all senders have equal opportunity to transmit data packets. Although the average delay may increase by the random approach, we consider it as the cost for providing fairness to all nodes. It is also possible to assign priorities to the packets so that packets carrying emergent information could get the first pick. This is not within the scope of this paper and we would leave it to our future work.

## IV. Performance Evaluation

In this section, we first discuss the implementation of our protocol, COPE-MAC, in the Aqua-Sim underwater simulator [17]. We then present and analyze the simulation results.

### A. Implementation

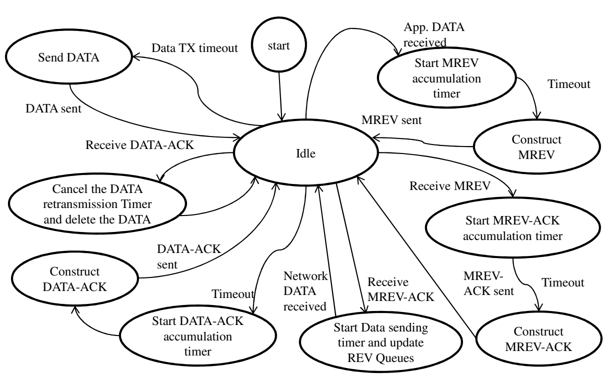


Fig. 3. COPE-MAC State Transitions

In COPE-MAC, every node maintains a reservation queue, which records the time intervals being reserved in its own timeline. There are four types of reservation intervals, which are PRE_RESV, SENDING, RECEIVING, AVOIDING.

| 0 1 | 2 3 4 5 6 7 | 8 9 10 11 12 13 14 15 |
|---|---|---|
| Packet Type | Entry number | Sender Address |
| Receiver Address 1 | | Packet Transmission Time 1 |
| Major Reservation Time 1 | | Backup Reservation Time 1 |
| . . . | | |
| Receiver Address n | | Packet Transmission Time n |
| Major Reservation Time n | | Backup Reservation Time n |

Fig. 4. MREV Frame Format

COPE-MAC works as shown in Fig. 3. From the flow chart, we can see that COPE-MAC will wait for certain time to accumulate more DATA packets. Then it includes the reservation information of multiple DATA packets in MREV and broadcasts it. In other words, MREV can request multiple reservations in parallel. The format of MREV is shown in Fig. 4. When generating MREV, the sender should decide when to send the DATA packet. The sending time can be chosen as a time interval which does not overlap with any reservation interval in the reservation queue. To increase the success probability of reservation, two reservation intervals are chosen for every DATA packet. After determining the sending time, both intervals are marked as PRE_RESV intervals.

| 0 1 | 2 3 4 5 6 7 | 8 9 10 11 12 13 14 15 |
|---|---|---|
| Packet Type | Entry number | Sender Address |
| Reservation Requestor 1 | | Packet Transmission Time 1 |
| Approved Reservation Time 1 | | Reservation Requestor 2 |
| Packet Transmission Time 2 | | Approved Reservation Time 2 |
| . . . | | |
| Approved Reservation Time n-1 | | Reservation Requestor n |
| Packet Transmission Time n | | Approved Reservation Time n |

Fig. 5. MREV-ACK Frame Format

When receiving MREV from neighbors, a node first checks if the requested interval collides with any one in its reservation queue. If there is no collision, the interval is approved and marked as a RECEIVING interval. Note that at most one request interval is approved per DATA packet. The approved request will be included in MREV-ACK, which is shown in Fig. 5. Based on the same design principle as MREV, a node will not reply MREV-ACK immediately but wait for certain time to accumulate more acknowledge information and then broadcast.

| 0 1 | 2 3 4 5 6 7 | 8 9 10 11 12 13 14 15 |
|---|---|---|
| Packet Type | Entry number | Sender Address |
| DATA Packet Sender Address 1 | | Sequence number of DATA packet 1 |
| DATA Packet Sender Address 2 | | Sequence number of DATA packet 2 |
| . . . | | |
| DATA Packet Sender Address n | | Sequence number of DATA packet n |

Fig. 6. DATA-ACK Frame Format

After being acknowledged by MREV-ACK, the PRE_RESV interval is marked as SENDING. If it is not acknowledged after RTT+MREV Accumulation Delay, the PRE_RESV interval will be removed from the reservation queue. From MERV-ACK, a node can also extract successful reservation intervals of other nodes. Using the delay information obtained in Neighbor Discovery period, a node can figure out the time interval it should not send packets. Otherwise, the packet will collide at the sender of MREV-ACK, which is shown in Fig. 3. Such interval is marked as AVOIDING.

A DATA packet will be sent when the approved interval arrives. Whenever receiving a DATA packet, similarly, a node defers the sending time of DATA-ACK to accumulation more acknowledgements. As shown in Fig. 6, DATA-ACK also includes multiple acknowledgement entries. As a result, it can acknowledge multiple DATA packets using a single DATA-ACK.

Once receiving the DATA-ACK, the data transmission is successful. If one DATA packet is not acknowledged for more than the expected acknowledgement time, it will be retransmitted later.

### B. Simulation Results

Through simulations, we would like to study the performance of COPE-MAC and compare it with FAMA [18] and UWAN-MAC [19] in underwater networks. FAMA is a typical handshake based protocol which makes sure RTS and CTS messages can be heard by all neighbors in the transmission range to detect and avoid collisions via the traditional carrier sensing technique. In case of long propagation delay underwater networks, this may not be an efficient design. The other one, UWAN-MAC, is an energy efficient MAC protocol designed for underwater networks. It takes a random access approach with no handshakes between senders and receivers. When sending a packet, the sender tells the receiver when it will send the next packet. And neighbors overhearing the packet could thus avoid the possible collisions.

In these simulations, we uniformly deploy 50 nodes into the network and compare the network throughput and energy overhead of all the three MAC protocols with different network scenarios by changing network sizes, traffic rates and propagation delays. The network throughput is defined as the total number of data packets successfully received in the whole network divided by the total simulation time. The energy overhead, or energy consumption, is calculated as the total consumed energy over the network throughput. The data generated from every node in the network follows a Poisson process, with average traffic generation rate $\lambda$. Each modem transmits data at a speed of $10kbps$ [4]. For power consumption, we also use the numbers from a practical acoustic modem as follows: transmitting power $50W$, receiving power $3W$, idle power $80mW$ [20]. All simulations last for 1000 seconds and all the results are obtained from the average of 100 runs.

In the first set of simulations, we fix the traffic rate $\lambda$ to 0.1 and change the network's physical size. The nodes are randomly deployed in a large square area. The network size could then be represented by the side-length of the square. The side-length ranges from 3000 to 6500 meters, which is typical in actual field tests. And the transmission range is fixed to 1000 meters. This simulation will show how the three protocols perform in practical underwater networks.

As we can see from Fig. 7, the network throughputs of both COPE-MAC and FAMA increase while UWAN-MAC increases at first and then decreases with larger network sizes. In the beginning, with long transmission range and relatively small network size, the number of one-hop neighbors is large. This leads to more intensive channel competition and lower throughput of all protocols. With the increase of network size, all three protocols show better performance. But when network size gets even larger, many nodes cannot be reached by one hop communication. As a result, the performance of UWAN-MAC degrades because of relatively increased hidden terminal problems. Although UWAN-MAC can detect receiver-receiver collisions when senders are neighbors of each other, it's not possible to address the same issue when senders are out of the transmission range of each other. This is mainly because UWAN-MAC doesn't do handshakes. On the other hand, with RTS/CTS like approach, both COPE-MAC and FAMA can detect hidden terminals and avoid the collisions. So the performance of both COPE-MAC and FAMA improves with the network size. By parallel reservations, COPE-MAC allows more communications with smaller number of handshakes than FAMA. For FAMA, its handshake process takes too much time to secure a conflict free channel, especially in underwater networks. So it is not surprising that COPE-MAC has much higher network throughput than FAMA.

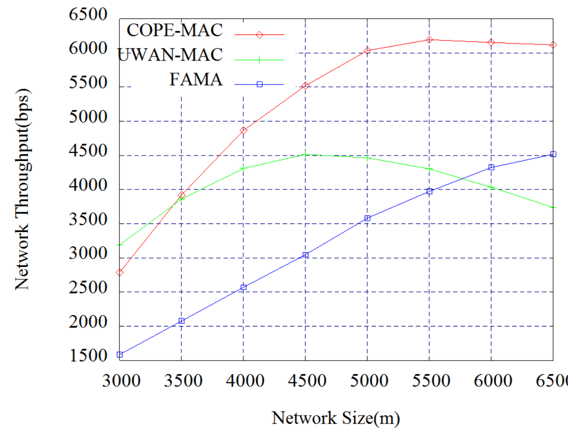


Fig. 7. Throughput vs Network Size

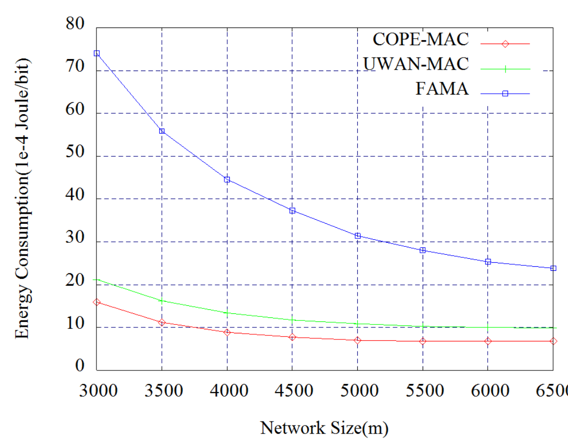


Fig. 8. Energy Consumption vs Network Size

With higher network throughput, more packets would be sent successfully in the network. The energy efficiency of both COPE-MAC and FAMA is improved, as shown in the decrease of energy consumption in Fig. 8. For UWAN-MAC, although

[4]We consider this as reasonable since some commercial modems has already achieved $17.8kbps$

its throughput decreases when network size is larger than 4500 meters, the energy consumption per bit still decreases, and is much lower than FAMA. We consider this as a result of UWAN-MAC's energy saving on node sleeping. According to this figure, COPE-MAC has the best energy efficiency among all protocols. This is due to the much higher throughput outweighs the cost of doing parallel reservations.

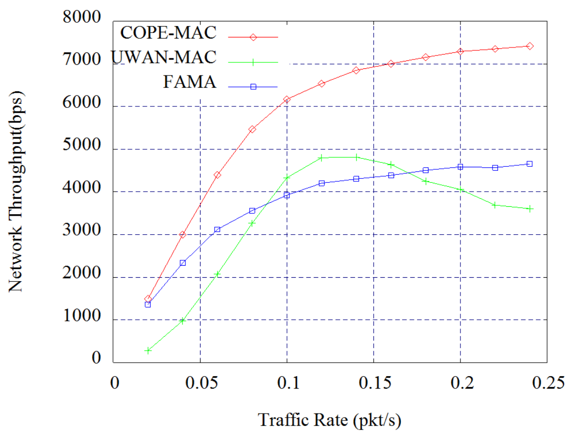


Fig. 9. Throughput vs Traffic Rate

Next, we study how traffic rate affects the performance. This time, we use the same number of nodes, as well as the transmission range, in a fixed $5500 \times 5500m^2$ area. The data generation rate $\lambda$ increases from 0.02 to 0.24 packet per second. As shown in Fig. 9, the network throughput of COPE-MAC and FAMA improves with the traffic rates, but the improvement slows down at even higher rates. For UWAN-MAC, its best performance occurs when $\lambda$ is around 0.12. The network throughput then decreases because of more intensive channel competitions. In fact, the throughput of all protocols will reach some threshold because the channel will be saturated at higher data generation rates. However, the actual maximum network throughput and the corresponding $\lambda$ depend on the designs of the protocols. It is clear from the figure that COPE-MAC can achieve higher network throughput using parallel reservations and cyber carrier sensing mechanism.

In Fig. 10, we observe that due to higher throughput, the energy overhead per bit of COPE-MAC is less than that of other two protocols. This is because of its higher network throughput. And also because its handshaking process and cyber carrier sensing reduce the collisions caused by the hidden terminal problem. So less energy is wasted on collisions. Another good thing about COPE-MAC is, when the traffic gets higher, the energy efficiency is very stable.

Finally, we would like to explore the effects of the long propagation delay in underwater networks. In previous simulations, the performance of FAMA increases with both network physical sizes and traffic rates. However, this may not be true when the average propagation delay of a node increases. This is because FAMA requires RTS to be no shorter than maximum propagation delay and CTS to be larger than RTS

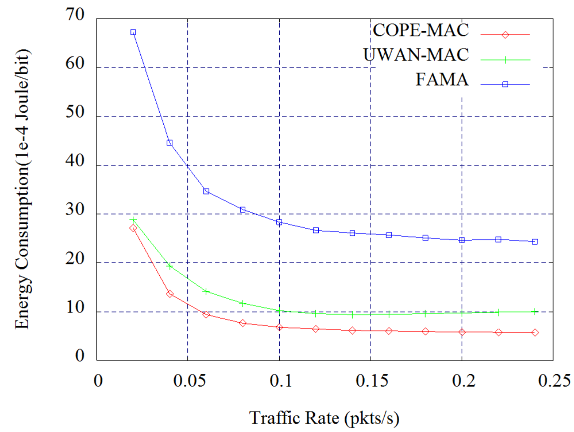


Fig. 10. Energy Consumption vs Traffic Rate

plus twice the maximum propagation delay. To study the propagation delay, we first obtain the following equation:

$$\bar{D} = \frac{\int_0^R r 2\pi r \frac{N}{A^2} dr}{\frac{N}{A^2}\pi R^2} = \frac{2}{3}R \qquad (2)$$

In equation 2, we assume that nodes are uniformly deployed in an $A \times A$ area, where $N$ is the total number of nodes in the network, $A$ is the side length of the square-shape network area, $R$ is the transmission range of a single node and $\bar{D}$ is the average distance between neighbors. Equation 2 indicates that, if we assume the signal propagation speed to be constant, the average propagation delay from a node to all of its neighbors is only related to the transmission range.

However, if we simply change $R$ while keeping the same $N$ and $A$, the effect of propagation delay on network throughput may be coupled with other factors. For example, If we have larger $R$, more nodes become one-hop neighbors and will contend for the channel. This increase collisions and thus makes the effect of propagation delay not so obvious. Similarly, changing either $N$ or $A$ along cannot yield expected results. Other words, we need to keep the average number of neighbors, given by $\frac{N}{A^2}\pi R^2$, and adjust average node distance to demonstrate the effect of the propagation delay.

In this simulation, we keep the total number of nodes unchanged and increase $R$ and $A$ at the same time to obtain the same average number of neighbors while having different average node distances. In this way, we essentially manage to change different average propagation delays without affecting the node density. In our simulation, we configure $A = 5.5 \times R$ and $R = \frac{3}{2}\bar{D}$, and increase $\bar{D}$ from 500 to 900 meters. Traffic $\lambda$ is set to 0.1 packet per second, $N$ equals 50.

From Fig. 11 we can see that, the network throughput of FAMA decreases rapidly with the increase of average node distance. This is due to the limit that with one handshake, only one communication pair can be established. This reduces the protocol efficiency significantly when propagation delay is very high. In this figure, COPE-MAC experiences slightly

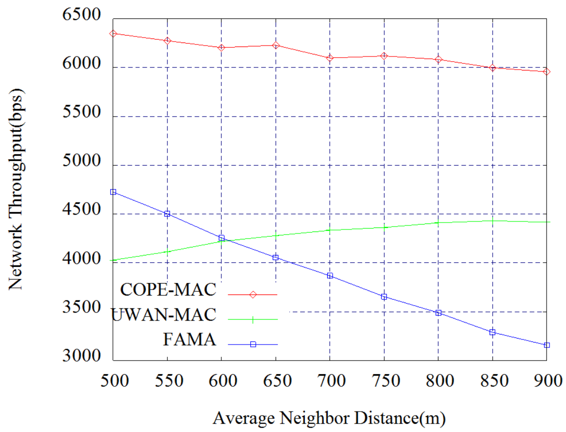


Fig. 11. Transmission Range vs Network Throughput

performance decrease as well. The decrease in performance is also because of the handshake process and long propagation delay. However, COPE-MAC has parallel reservations and is much more efficient than FAMA. That's why our COPE-MAC has the highest throughput among all protocols. UWAN-MAC, on the other hand, is not a handshake based protocol. So it receives no penalty from the longer distance between nodes. But its design limits the capability of delivering high network throughput.

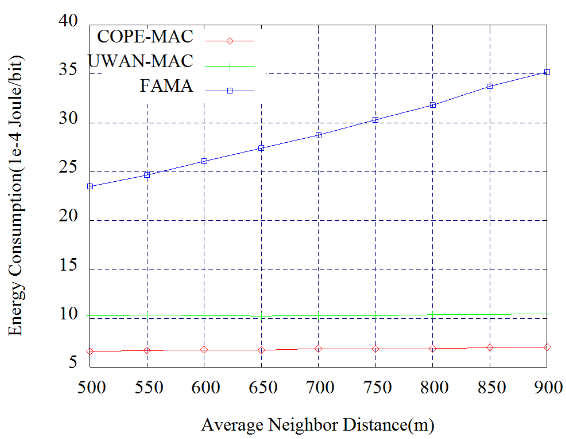


Fig. 12. Transmission Range vs Energy Consumption

Fig. 12 shows that COPE-MAC is still very efficient in energy consumption. FAMA requires long RTS and CTS messages and thus consumes much more energy than the other two. UWAN-MAC is more efficient than FAMA. But with less network throughput, the energy spent on each bit is still higher than COPE-MAC.

To sum up, the simulation results show that COPE-MAC works very well in large long delay networks. This is mainly due to the parallel reservation and cyber carrier sensing mechanism which work together to improve handshake efficiency while reducing collisions. Compared to a handshake-based but non-parallel protocol, e.g. FAMA and a random access based protocol with duty-cycle, e.g. UWAN-MAC, our protocol has higher throughput and energy efficiency.

## V. Related Work

In this section, we review some related work on MAC in terrestrial radio networks and underwater acoustic networks.

Parallelizing data transfer to improve the performance of handshaking based MAC protocols has long been investigated in terrestrial radio networks. In MACA-P [21], the authors propose to improve the system throughput of 802.11 DCF when two neighboring nodes are either both senders or receivers. They introduce a delay for control messages in exchange of allowing multiple sender-receiver pairs to talk at the same time. C-MAC [22] discovers that it is possible to have successful concurrent data transmissions within each other's interference range. It then exploits this phenomenon to improve MAC throughput with the help of empirical power and interference models. In [23], Son *et al* propose a protocol using opportunistic concurrent transmission to address the inefficiency when exposed terminal problem occurs in 802.11 wireless networks. The authors adopt a location-assisted approach for scheduling concurrent transmissions. Unfortunately, all of the aforementioned protocols are designed for radio wireless networks, and none of them can be used in underwater acoustic networks directly. For example, none of them considers the effects of long propagation delays; the differences in signal characteristics make the experience in [22] not applicable for underwater networks; and global positioning system (GPS) required by [23] is not available in underwater networks.

Recently, there are a lot of research studies on the MAC protocols specifically designed for underwater networks. Some protocols employ random access approaches. For example, in [19], Park and Rodoplu propose a Aloha-based MAC protocol. By carefully designing the duty cycles of every node, the protocol tends to keep nodes in a sleep mode as long as possible to save energy. This protocol, however, mainly work in extremely low duty cycle networks. Some other studies explore the RTS/CTS based handshaking approaches in underwater environments. In [7], a modified FAMA (floor acquisition multiple access), called Slotted FAMA, is proposed for underwater acoustic networks. In this protocol, time is divided into slots, and all packets including control packets and data packets are sent at the beginning of a slot. Compared with the original FAMA, slotted FAMA can achieve much higher energy efficiency in the long delay underwater environments. [8] proposes a MAC protocol based on minimizing the duration of a hand-shaking process. The protocol takes advantage of the receiver's tolerance to interference when the two nodes are closer than the maximal transmission range. Compared with Slotted FAMA, this protocol can achieve higher throughput while offering similar energy savings. Both the aforementioned protocols, however, require strict synchronization, which might be very costly.

Reservation based MAC protocols have also received a lot of attention for underwater networks. [24] proposes a tone-based protocol called T-Lohi. This protocol employs a tone-based reservation mechanism to exploit space-time uncertainty and high latency to detect collisions and count contenders. T-Lohi can achieve very good throughput across all offered loads. However, an extra tone hardware is needed. In [25], Xie *et al* propose a reservation-based protocol, R-MAC, for underwater networks. R-MAC carefully schedules the transmissions of control packets and data packets to avoid data packet collision completely.

Multi-channel based MAC protocol such as TDMA/CDMA have attracted research interests in underwater networks [26]–[29]. these protocols need strict synchronization among nodes and the channel assignment is fixed. CUMAC [30] takes a different approach to assign the data channels dynamically. It utilizes multiple channels to reduce collisions in the network. The protocol needs extra hardware, however, for cooperative collision avoidance.

Different from all the aforementioned MAC protocols for underwater networks, our COPE-MAC solution employs two novel techniques: "parallel reservation" and "cyber carrier sensing". Through transmission parallelism, COPE-MAC can improve the MAC performance in both network throughput and energy efficiency.

## VI. Conclusions

We have introduced a contention-based medium access control protocol with parallel reservation (COPE-MAC) for underwater acoustic networks. With careful design, COPE-MAC manages to improve the handshake efficiency with long propagation delays. We propose parallel reservation to establish communications with less rounds of handshakes. Cyber carrier sensing is used to detect and avoid collisions with computation rather than physical carrier sensing. Simulations show that the overall network throughput can be greatly improved by the parallel method. Energy efficiency of COPE-MAC is also very good compared with another efficient underwater MAC protocol. As future work, we will further explore the effect of parallelism on the network performance. We also plan to combine our protocol with some coding schemes to make it more efficient in the error-prone underwater communication channel.

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