Reprint Series **CMRE-PR-2019-052**

Performance evaluation of underwater medium access control protocols: at-sea experiments

Roberto Petroccia, Chiara Petrioli, John Potter

June 2019

Originally published in:

IEEE Journal of Oceanic Engineering, volume: 43, issue: 2, April 2018, pp. 547-556, doi: 10.1109/JOE.2017.2695759

About CMRE

The Centre for Maritime Research and Experimentation (CMRE) is a world-class NATO scientific research and experimentation facility located in La Spezia, Italy.

The CMRE was established by the North Atlantic Council on 1 July 2012 as part of the NATO Science & Technology Organization. The CMRE and its predecessors have served NATO for over 50 years as the SACLANT Anti-Submarine Warfare Centre, SACLANT Undersea Research Centre, NATO Undersea Research Centre (NURC) and now as part of the Science & Technology Organization.

CMRE conducts state-of-the-art scientific research and experimentation ranging from concept development to prototype demonstration in an operational environment and has produced leaders in ocean science, modelling and simulation, acoustics and other disciplines, as well as producing critical results and understanding that have been built into the operational concepts of NATO and the nations.

CMRE conducts hands-on scientific and engineering research for the direct benefit of its NATO Customers. It operates two research vessels that enable science and technology solutions to be explored and exploited at sea. The largest of these vessels, the NRV Alliance, is a global class vessel that is acoustically extremely quiet.

CMRE is a leading example of enabling nations to work more effectively and efficiently together by prioritizing national needs, focusing on research and technology challenges, both in and out of the maritime environment, through the collective Power of its world-class scientists, engineers, and specialized laboratories in collaboration with the many partners in and out of the scientific domain.

Peer-Reviewed Technical Communication

Performance Evaluation of Underwater Medium Access Control Protocols: At-Sea Experiments

Roberto Petroccia, *Member, IEEE*, Chiara Petrioli, *Senior Member, IEEE*, and John Potter, *Senior Member, IEEE*

***Abstract*—In this paper, we investigate the performance of three medium access control (MAC) protocols (CSMA, T-Lohi, and DACAP) representing simple, intermediate, and fully negotiated protocols, to access the underwater acoustic channel, during two at-sea campaigns. Various tests were conducted in the waters surrounding Pianosa island during the NATO ACommsNet10 experiment in September 2010 and off the coast of the Palmaria island during the NATO CommsNet13 experiment in 2013. Different types of application loads and communication devices have been used to investigate the performance of the various protocols under different transmission rates and introduced overhead. The presence of more stable and reliable communication links and of a highly dynamic communication channel has also been explored. The collected results show that there is no single solution that is best for all the possible scenarios and configurations and that the selection of different protocols is required for different contexts. This highlights the importance of understanding the performance of each protocol at sea, under various conditions, to design novel and adaptive schemes, which are able to react in an efficient and effective way to possible changes in the network and in the communication channel.**

***Index Terms*—At-sea testing, MAC protocols, performance comparison, underwater acoustic networks, underwater communication.**

I. INTRODUCTION

UNDERWATER wireless networking has been recognized as an enabling technology with impact on a host of different applications that include ocean observation for scientific exploration or commercial exploitation, underwater safe CO_2 storage, coastline protection, and prediction of underwater seismic and volcanic events [1]. Low-cost, (quasi) real-time, medium/large scale monitoring systems are now possible through the deployment of underwater wireless sensor nodes equipped with acoustic modems. Even though underwater acoustical networks (UANs) share some common properties with terrestrial wireless sensor networks (WSNs), such as nodes with limited resources, they are significantly different from their terrestrial counterparts mainly because of the challenges posed by the very specific environment: Long propagation delay, low bandwidth, sound-speed variability, slow power signal attenuation, etc. Given the harshness of the underwater acoustical environment, managing and controlling a communication channel shared by many nodes to avoid or limit collisions and maintain reliable transmission conditions is a challenging task. Therefore, particular importance is given to the design of new medium access control (MAC) protocols for UANs. Solutions for terrestrial wireless (sensor) networks, using radio communication and thus assuming a larger bandwidth, a higher bit rate and negligible propagation delays, cannot be directly applied to UANs. For these reasons, novel protocol stacks need to be designed for both single-hop and multihop communications. Several MAC protocols have been proposed in the past that reuse the same or similar approaches used for terrestrial networks adapted to UANs or propose completely new ideas specifically addressing the challenges of underwater acoustical environment. We can group them into Aloha-based [2], [3], carrier sensing solutions (e.g., CSMA [4], DACAP [5], T-Lohi [6]), TDMA-based schemes [7]–[9], OFDM-based approaches [10], and CDMA-based approaches [11]–[13]. Hybrid schemes have also been proposed [14], [15]. Although a performance comparison among some sets of the best performing schemes have been made by means of simulations [16], [17], no extensive comparison has been performed so far by means of at-sea experiments. Moreover, existing simulators only approximately model the acoustic channel and the channel dynamics and do not capture constraints introduced by the use of real hardware, such an acoustic modem. Therefore, at-sea experiments are needed to validate the performance of different classes of MAC protocols. In [18], a first study of the gap between MAC protocol results obtained at sea and via simulations was presented, where constraints and limitations introduced by real acoustic modems have been considered. Starting from this initial work, several other papers have been published investigating the impact of real hardware on MAC protocol performance during field experiments [19]–[23]. Additional works have recently been presented that address the use of MAC and routing solutions during in field experiments [24]–[26].

In this paper, we perform an experimental evaluation of some of the best known MAC protocols to assess the impact of different design choices and the pros and cons of exchanging different levels of control information to limit collisions. Three MAC protocols (CSMA [4], T-Lohi [6], and DACAP [5]) have been considered, which represent simple, intermediate, and fully negotiated protocols to reserve the channel. These protocols have been evaluated during two NATO at-sea campaigns conducted in Italy: ACommsNet10 experiment in September 2010 and CommsNet13 sea trial in September 2013. To reach an understanding of which protocol is likely to perform better in a given environment and realistic scenario, we have considered the use of different commercial acoustic modems providing different achievable data rate, packet length, and additional delays: FSK Micro-Modems [27] during ACommsNet10 and Evologics S2C R 18/34 [28] during CommsNet13. Various scenarios have been considered including configurations where a low signal-to-noise ratio is experienced on some links, making them asymmetric, and where a highly dynamic acoustic channel is experienced. These effects can significantly affect MAC protocol performance.

Manuscript received November 16, 2015; revised November 30, 2016 and February 10, 2017; accepted April 13, 2017. Date of publication May 11, 2017; date of current version April 12, 2018. This work was supported in part by NATO Allied Command Transformation and by the EU FP 7 ICT project SUNRISE "Sensing, monitoring and actuating on the UNderwater world through a federated Research Infrastructure Extending the Future Internet." *(Corresponding author: Roberto Petroccia.)*

Associate Editor: J. Gomes

R. Petroccia and J. Potter are with the NATO STO Center for Maritime Research and Experimentation, La Spezia 19126, Italy (e-mail: roberto.petroccia@cmre.nato.int; john.potter@cmre.nato.int).

C. Petrioli is with the Dipartimento di Informatica, Università di Roma "La Sapienza," Roma 00198, Italy (e-mail: petrioli@di.uniroma1.it).

Digital Object Identifier 10.1109/JOE.2017.2695759

This paper is organized as follows. Section II describes the three MAC protocols we chose for evaluation. Performance metrics and experimental settings are described in Section III. The investigated scenarios and the collected results for the two different experimental campaigns are presented in Section IV. Finally, Section V concludes the paper.

II. MAC PROTOCOLS

In this section, we briefly review the three MAC protocols we selected for our comparative performance evaluation: CSMA, T-Lohi, and DACAP.[1] (Readers familiar with these protocols may skip this section.)

1) CSMA: Carrier sensing multiple access [4] is a well-known protocol for channel access that has the advantage of low overhead, as it does not perform extensive handshaking to avoid collisions. When a node has a data packet to transmit, it first checks whether the channel is idle or busy. In the first case, it starts the packet transmission. If the channel is busy, the node delays the transmission according to the CSMA exponential backoff mechanism. Acknowledgment (ACK) packets can be used to add robustness. If the ACK is not received within a given time ($\tau = 2T_p + T_{\text{ack}}$, where T_p is the propagation delay and T_{ack} the time needed to transmit the ACK), the data packet is retransmitted. This is repeated either until successful reception (every time choosing the backoff time in an interval twice as long as the previous one) or until the maximum limit of retries (`maxRetries`) has been reached. The value of T_p is initially set to an upper bound of the maximum propagation delay, `maxDelay` (computed based on the node maximum transmission range), and successively set to half the time difference between the packet transmission and the reception of its ACK. The backoff time is chosen randomly and uniformly in $[0, T]$, where $T = 2^{\texttt{txRetry}}(2\texttt{maxDelay} + T_{\text{data}} + T_{\text{ack}})$, where T_{data} is the time needed to transmit a DATA packet (in the CSMA version with no ACK T_{ack} is assumed to be zero). If an idle node overhears a data packet on the channel (and ACKs are used) it backs off, thus allowing the transmitter to correctly receive the ACK and enabling the receiver to forward the data that it has just received. A node that just received an ACK backs off to allow the destination to forward data and to let other nodes (if any are trying) to access the channel.
2) T-Lohi: Tone Lohi [6] is a protocol for single-hop underwater networks that uses a weak negotiation to reserve the channel. When a node has a data packet to transmit, it starts a reservation period (RP). An RP is made up of a certain number of slots called contention rounds (CRs). During a CR, the would-be sender transmits a short control packet (tone packet) to inform other nodes about its desire to access the channel. It then listens to the channel to detect if other nodes also have data packets to send. Each node contending for the channel counts how many other nodes do the same, based on the number of tone packets received during the CR. If no other tone is heard during the CR, the node transmits the data packet. If contention occurs, the contenders back off for a number of CR chosen randomly and uniformly between $[0, N]$, where N is the number of competitors. A node RP continues until successful channel access. The duration of a CR is set so that a node has enough time to detect as many contenders as possible. Of the many flavors of T-Lohi described in [6], we consider the most aggressive, i.e., the one that maximizes the channel utilization. In the aggressive T-Lohi, the CR lasts for the time needed to transmit a tone packet plus the maximum anticipated propagation delay.
3) DACAP: Distance aware collision avoidance protocol [5] uses the request to send/clear to send (RTS/CTS) handshake to reserve the channel for packet transmission, enriching this common mechanism with a method to accommodate the longer delays of underwater links. More specifically, when a node has a data packet to send, it checks the channel and if the channel is idle it transmits an RTS. If the channel is instead sensed busy, the sender computes a backoff time and after this time checks the channel again. Upon correctly receiving an RTS packet, a destination node replies right away with a CTS. It then waits for the data packet, which can be acknowledged or not, depending on the chosen version of the protocol. DACAP adapts to the underwater channel characteristics by using a warning mechanism, as follows. If while waiting for a data packet, a destination node overhears a control packet intended for some other node, it sends a very short WARNING packet to its sender, to alert it about possible interference that could affect the upcoming communication. Upon receiving a CTS packet, a sender waits for a time T_{warning} before transmitting the data packet. The time T_{warning} is defined as the minimum time allowing neighbouring nodes not to interfere. Its computation is dependent on the propagation time between source and destination (estimated by the sender through the RTS/CTS handshake time) and on other factors concerning the distance of potential interferers. If while waiting for a CTS the sender overhears a control packet, it aborts the data communication. It also aborts the data communication if while during T_{warning} it receives a WARNING packet from the destination, or overhears a control packet from some other nodes. In these cases, the sender computes a backoff time and tries again later (for a predefined number of times). Since a receiver that sent a WARNING packet does not know if this packet has reached the sender in time to make it abort the data transmission, it has to continue listening to the channel because the data packet could still be received correctly.
In the case of DACAP with ACKs, the sender backs off and retries if no ACK is received after data transmission within a specified time. The same happens if, while waiting for the ACK, the sender overhears an RTS, a CTS, or a DATA packet from other nodes. Potential interferers are blocked as usual in RTS/CTS schemes.

III. PERFORMANCE METRICS AND EXPERIMENTAL SETTINGS

To assess the performance of the selected protocols the following metrics have been considered.

1) Packet delivery ratio: Defined as the ratio between the number of packets delivered to the sink and the number of packets generated in the network.
2) Packet transmission attempts: Defined as the average number of times nodes need to access the channel to successfully deliver a packet to the next hop relay. For CSMA only transmission attempts related to data packets are considered while for DACAP and T-Lohi also RTS and Tone packets are included.
3) End-to-end delay: Defined as the average time between data packet generation and data packet reception at the sink.
4) Throughput: Defined as the number of bits delivered by the network to the sink per unit of time, including protocol overhead bits as well as retransmitted data packets.

---

[1] In the OSI model, there are two sublayers at the data-link layer: MAC and logical link control. It is a quite common cross-layer approach to combine these two sublayers in solutions designed for resource constrained networks, such as WSNs and UANs. This is the case for the three considered protocols.

5) $\overline{\text{Throughput}}$: Defined similarly to the throughput but including also the overhead bits added by the acoustic modem (i.e., modem header).
6) Goodput: Defined as the number of useful information bits delivered by the network to the sink per unit of time, excluding protocol overhead bits as well as retransmitted data packets. The goodput represents the application-level throughput.

A. Experimental Settings

In all the considered scenarios, traffic has been generated according to a Poisson process with aggregate (network-wide) rate λ packets per second. We define the normalized packet rate as $\overline{\lambda} = \lambda T_{\mathtt{data}}$, where $T_{\mathtt{data}}$ is the transmission duration for the data payload.[2] The normalized packet rate is then expressed in terms of packets per packet time. We have considered the use of the normalized packet rate since we investigate different packet lengths and bit rates in our analysis, due to the use of different commercial acoustic modems. Using the normalized packet rate, changing the packet size does not change the number of bits generated in the network for unit time.

A limit has been imposed on the number of packet retransmissions and it has been experimentally tuned for each protocol, according to the analysis conducted in [16]. Our implementation of CSMA discards a packet after four failed transmission attempts, or four failed attempts to access the channel.

A similar constraint holds for DACAP concerning RTS packets: After 7 (4) attempts to access the channel, or after 7 (4) failed retransmissions for RTS (DATA) packet, a data packet is discarded. For T-Lohi, a data packet is discarded after seven attempts to access the channel, or after seven consecutive transmissions with multiple contenders.

Additionally, the maximal queue size at each node has been set to 50. When the queue is full and a new packet arrives the oldest packet in the queue is discarded. In this way nodes do not fill their buffers with old information.

IV. AT-SEA EXPERIMENTS

Two at-sea campaigns have been considered to evaluate the performance of the selected protocols.

1) NATO ACommsNet10 experiment, conducted in September 2010 in the waters surrounding Pianosa island, which is part of a protected marine park on the west coast of Italy.
2) NATO CommsNet13 at-sea trial, performed off the coast of the Palmaria island (Italy) in September 2013.

During both these campaigns, the SUNSET framework [29] was used to implement the MAC protocols and to run the experiments at sea.

A. NATO ACommsNet10

Fig. 1. Static node positions (red icons M1, M2, and M3) and gateway mooring (yellow icons GB).

Fig. 1 shows the node deployment during the sea trial. Three static nodes (M1, M2, and M3) were cabled to shore for power supply and information transmission. The acoustic modem was moored on the seafloor[3] at a depth of $\sim$21 m for M1, $\sim$15 m for M2 and $\sim$30 m for M3. One WHOI gateway buoy was moored at gateway buoy (GB). Its acoustic modem was deployed at a depth of $\sim$5 m. All the devices were equipped with the incoherent FSK WHOI Micro-Modem. The maximal distance between the nodes was about 1000 m, while the distance from M1, M2, and M3 to GB ranges between 400 and 600 m.

Nodes at M1, M2, and M3 were used as data generators while the GB was used as collection point, sink.

Fig. 2 shows the sound-speed profile (SSP, on the left) collected in Pianosa on September 16, 2010 and the incoherent acoustic field predicted by Bellhop for a signal source located at a depth of 20 m. The bottom type in the area considered for the experiments is clay and silt.[4]

1) FSK WHOI Micro-Modem features and their impact on protocol implementation: The FSK WHOI Micro-Modem does not provide the possibility of choosing the data packet size [27]. Each packet has a size of 32 Bytes. The transmission power is 180 dB re 1 μPa at 1 m and the carrier frequency is centerd around 25 kHz in the bandwidth 23 to 27 kHz, with a transmission bit rate of 80 bps. Although the data transmission duration ($T_{\mathtt{data}}$) is approximately 3.2 s, the actual time to transmit a packet is much longer. To begin with, 0.87 s are needed for the preamble (training sequence, header modulation, etc.), then 0.7 s are taken for the packet header and about 1 s is needed to exchange control information before actual data transmission. The FSK WHOI Micro-Modem therefore introduces a delay of about 2.6 s for each data packet, corresponding to an 80% increase in transmission duration over that expected based on the message payload size alone. Without the possibility of transmitting packets shorter than 32 B and introducing a high overhead and long delays for each packet transmission, the performance of the MAC protocols which make use of short control messages are particularly impaired. The Micro-Modem does provide the option to use "mini packets," which have the capability to store 13 b of information and experience a total transmission duration of around 1 s (including all the overhead). To reduce the overhead associated with the different MAC operations, we have used mini packets to implement RTS, CTS, Tone, and ACK packets. Even using mini packets to reduce the overhead, control packets are still much longer than what could be possible with dedicated control packets. This in turn affects especially those MAC protocols, which

---

[2] $T_{\mathtt{data}}$ refers only to the actual data payload transmission without including any overhead introduced by the selected MAC protocol or by the acoustic modem.

[3] Each modem is deployed at 1.5 m from the seafloor.

[4] This bottom type has been also used to generate the acoustic field predicted by Bellhop, as displayed in Fig. 2.

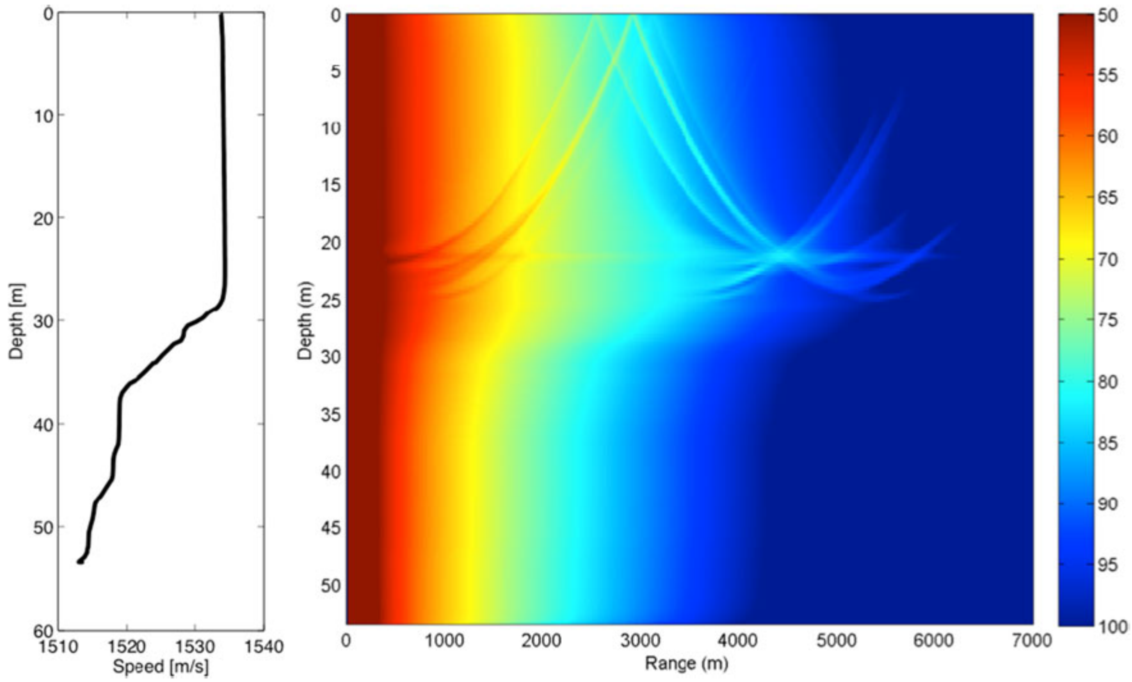


Fig. 2. Transmission loss (in dB re 1 μPa at 1 m—on the right) computed with Bellhop using the SSP (on the left) collected in Pianosa on September 16, 2010. The signal source is located at 20 m depth.

rely on significant amounts of control information for their operations, i.e., DACAP. When using the WHOI Micro-Modem, the time needed to complete the delivery of a data packet (including the propagation delay and the overhead introduced by the protocol and by the acoustic modem) is in the ideal case $\sim$11 s for DACAP and $\sim$8 s for both CSMA and T-Lohi. For the ACommsNet10 experiments, the considered traffic loads range from one packet generated in the network every 35 s to one packet every 15 s.

Another important factor to mention is that the FSK WHOI Micro-Modem cannot transmit continuously and the transmitting operation has to be limited to a duty cycle of about 50%, otherwise the modem may require reinitialization. The reinitialization process results in failing to transmit and receive packets for short periods of time (10–15 s on average, in some cases the modem may be not active for about 25 s). Again this mostly affects MAC protocols requiring the transmission of a larger number of control packets.

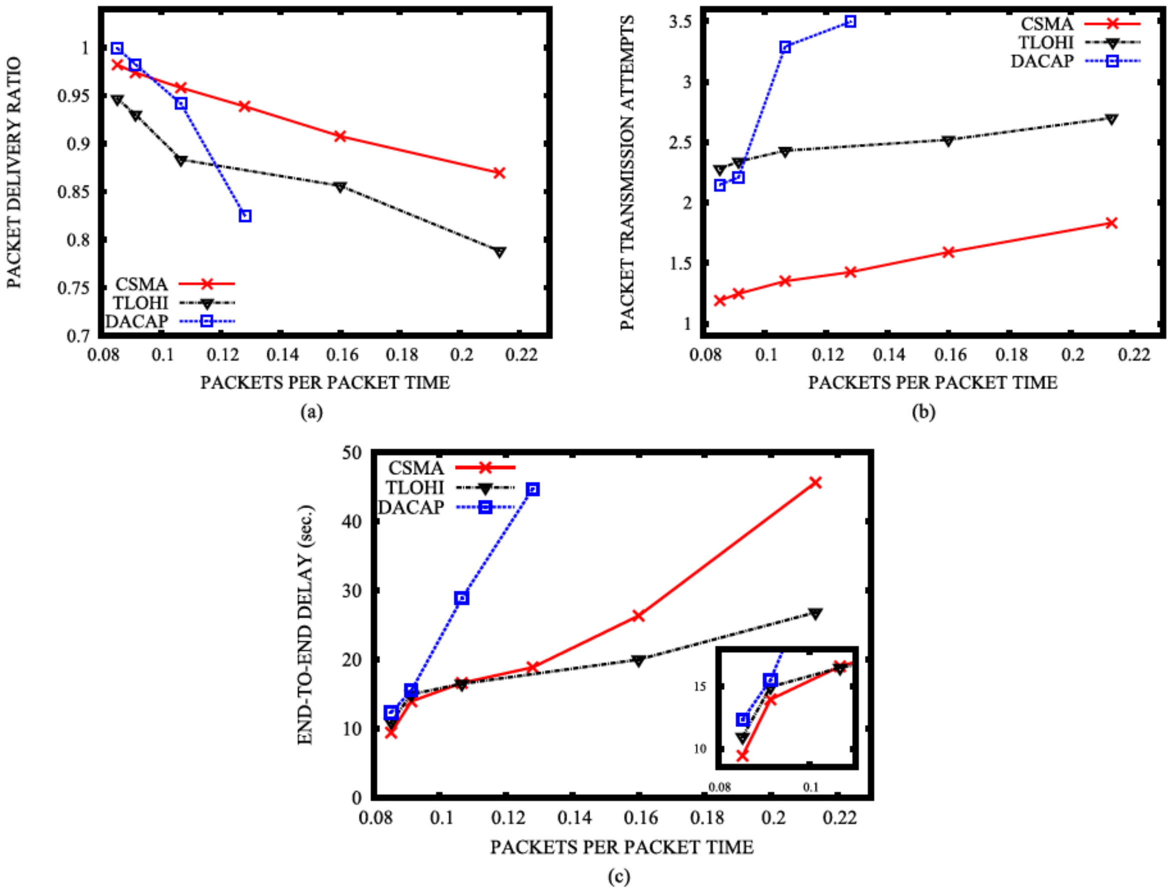
2) ACommsNet10 results: In this section, we report the results of the ACommsNet10 at-sea campaign. Several experiments were performed at different times of the day during the first three weeks of September 2010, collecting results for all the considered protocols and traffic loads. Unfortunately, after about ten days of operation the radio antenna on the gateway buoy failed. This cut short our experimental program and we were not able to investigate all the configurations for the different protocols, missing especially the results for DACAP with higher traffic loads.

For the investigated scenarios, the traffic loads are computed considering the payload transmission duration (3.2 s for the FSK Micro-Modem), while the actual time to transmit the packet is much longer (5.8 s). This results in an increased load at each node and in a higher occupation of the channel. Additionally, given the long time required to complete the transmission of each data packet, we are in a configuration where the packet transmission duration is always much longer than the maximum propagation delay. This results in having the nodes spending more time to transmit the data packet than waiting to receive replies (ACK or CTS).

During the various tests, the estimated average packet error rate (PER) introduced by the underwater acoustical channel was about 0.17 and it was quite stable for the different links over time.

The collected results are presented in Fig. 3. We can see that in all cases, when the traffic load increases the achieved packet delivery ratio reduces [see Fig. 3(a)]. DACAP is the most effective solution in delivering data packets at low traffic loads. Implementing a handshaking mechanism to reserve the channel, nodes around the transmitter and receiver are informed about the on going transmission and can avoid to interfere even in the presence of hidden nodes. Additionally, nodes missing the RTS packet due to errors on the channel can still receive the CTS message and keep the channel clear. Handshaking protocols are widely used and quite effective for terrestrial sensor networks, where the transmission rate is much higher and the propagation delay is negligible. In the underwater acoustical domain, however, as soon as the traffic load increases, the larger overhead introduced by DACAP starts detrimentally affecting the network performance. The overall time required to complete the handshake and reserve the channel becomes nonnegligible, thus reducing the available time for data transmissions. T-Lohi, making use of a reduced amount of control information to reserve the channel, suffers less at higher traffic loads. However, not supporting the use of ACK messages, it is not able to recover from possible data packet loss due to errors on the channel or collisions. CSMA is the only one of the selected protocols that does not assume any control message to reserve the channel; however, it supports the use of ACK packets. This helps reducing the effects of the introduced overhead and of possible errors or collisions in the channel when the traffic load increases.

Looking at these results it seems obvious that the use of ACK packets, as expected intuitively, helps to improve the packet delivery ratio in the network. However, Section IV-B shows that in the presence of asymmetric links this may be not always the case.



(a) (b) (c)

Fig. 3. ACommsNet10 results. (a) Packet delivery ratio, (b) packet transmission attempts, and (c) end-to-end delay, with a zoom in on the results for low traffic loads.

For all the protocols, when more packets are injected in the network, more packet collisions and interference occur, thus resulting in a larger number of transmission attempts [see Fig. 3(b)]. This is more evident when control messages are used to reserve the channel. For T-Lohi up to 57% of the transmission attempts is due to control packets while for DACAP the number of control packet attempts goes up to 62% of the overall transmission attempts.

CSMA, making use of only data packet to reserve the acoustic channel, results in a lower number of transmission attempts. However, every time there is a collision, the full data packet has to be retransmitted, which takes much longer than the control ones, thus affecting more significantly the end-to-end delay performance [see Fig. 3(c)]. Additionally, CSMA and DACAP make use of an exponential backoff when performing retransmissions. As soon as the number of retransmissions increases, the introduced delay increases rapidly. This is more evident for DACAP since the exponential backoff is used for both control and data packets. T-Lohi, not introducing any additional delay after the transmission of a data packet and not using an exponential backoff for Tone packet retransmissions, results in a shorter end-to-end delay for higher traffic loads. However, this comes at the price of a higher packets loss even at low traffic loads when errors and collisions occur on the channel.

Table I shows the throughput and goodput results for the three MAC protocols.[5] Both CSMA and DACAP, making use of ACK packets and incurring in data packet retransmissions, are able to deliver a larger number of bits and useful information bits (goodput) per unit of time. The throughput is higher for DACAP, since more control packets are used, and lower for T-Lohi, since only Tone packets can be retransmitted. When the control bits added by the acoustic modem are also considered (i.e., $\overline{\text{throughput}}$), the number of transmitted bits almost double, thus showing the impact of the selected modem on the protocol performance.

It is important to notice that increasing the number of attempts and retransmissions further increases the load in the network. Although the data packet generation rate was lower than the theoretical limit that should have been safely supported by the modems (50% duty cycle), several automatic modem reinitializations were experienced. DACAP, making use of a larger number of control packets, was more impaired by this phenomenon with respect to the other protocols. We have investigated this modem behavior for the following three MAC protocols considering:

1) D_{tx}: the number of data packet generated in the network;
2) MR: the number of modem reinitialization in the network;
3) P_{loss}: the number of packet (data and control) not received due to modem reinitialization.

Table II presents values for the different protocols and traffic loads, allowing the reader to better understand the impact of modem reinitializations on protocol performance.

It is evident that for DACAP, the effects of the modem reinitializations start affecting the protocol performance even at low-to-medium traffic loads. A higher number of reinitializations and lost packets is experienced with respect to the other protocols, resulting in a larger

---

[5] The hyphens indicate that the experiment was not performed for the corresponding protocol and traffic load. This was due to hardware failure as described in 2 when detailing "ACommsNet10 results."

TABLE I
ACommsNet10: Throughput and Goodput Results in Bits Per Second (BPS)

Traffic load (ppt)	$Throughput$			$\overline{Throughput}$			$Goodput$		
	CSMA	T-Lohi	DACAP	CSMA	T-Lohi	DACAP	CSMA	T-Lohi	DACAP
0.085	8.5	7.3	9	15.3	13.4	22.3	6.7	6.5	6.8
0.091	9.6	7.8	9.9	17.1	14.5	24.5	7.1	6.8	7.2
0.106	12.1	9.8	13.6	21.6	18	36	8.2	7.5	8
0.128	15.4	–	17.2	27.4	–	45.8	9.6	–	8.5
0.16	21.4	15.3	–	38.2	28	–	11.6	11	–
0.213	32.9	20.7	–	58.7	38.5	–	14.9	13.5	–

TABLE II
Modem Reinitialization Effects

Traffic load (ppt)	D_{tx}	MR			P_{loss}		
		CSMA	T-Lohi	DACAP	CSMA	T-Lohi	DACAP
0.085	72	4	3	5	1	0	2
0.091	80	4	3	7	1	0	9
0.106	90	5	5	9	4	4	27
0.128	110	6	–	12	8	–	35
0.16	135	8	6	–	11	7	–
0.213	180	9	7	–	30	10	–

number of packet retransmissions and longer end-to-end delays to complete the message delivery. For CSMA and T-Lohi, the modem reinitialization effects are quite similar with the exception of the higher traffic load scenario, where for CSMA a larger number of packets are lost. However, making use of ACK messages and of an exponential backoff, the time it takes to discard a data packet (due to reaching the maximum number of retransmissions) is longer that the time required by the modem to start working again. No packets are therefore discarded by CSMA; at the end of each test all the messages not correctly delivered are stored at the node queue waiting to be transmitted.

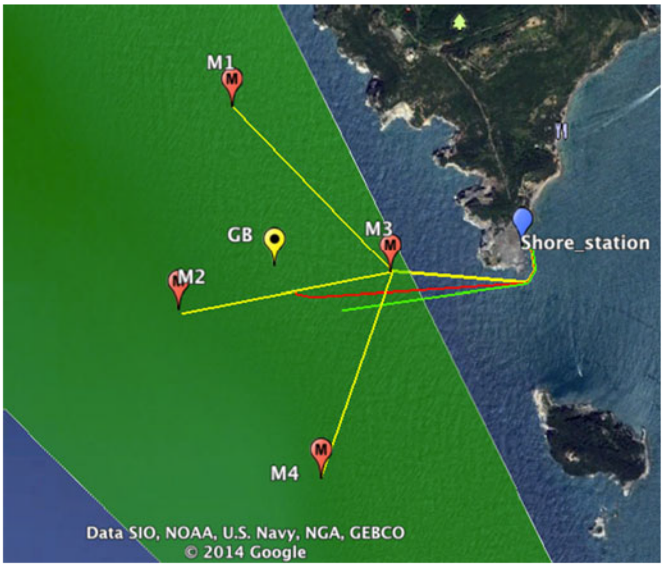


Fig. 4. Modem primary node (red icon M3) and satellite modem node sites (red icons M1, M2, and M4), gateway moorings (yellow icon GB). Shore station was on Palmaria island. The yellow lines represent the cables from the shore station to the modems, while the red line was used to connect environmental sensors.

B. NATO CommsNet13

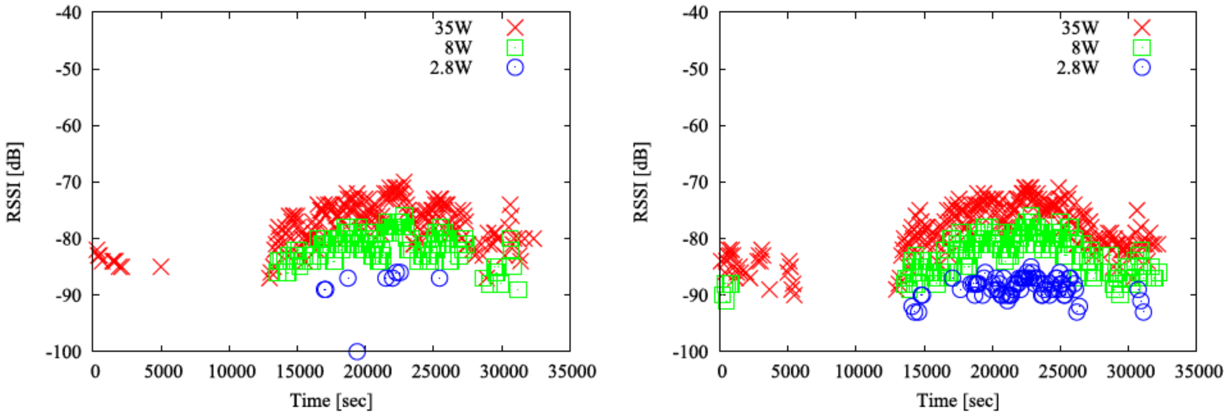
Given the challenges and the significant impact that the FSK WHOI Micro-Modem had on protocol performance, the use of a different acoustic modem was considered. A second set of MAC experiments was performed during the NATO CommsnNet13 sea-trial, conducted off the coast of Palmaria island in September 2013. The same MAC protocol solutions have been considered using the same SUNSET implementation and parameter settings. Evologics S2C R 18/34 acoustic modems [28] were used to transmit messages in water. Five underwater nodes have been considered, as depicted in Fig. 4, with a maximal distance between the nodes of about 1.7 km. The GB was used again as collection point with the acoustic modem deployed at a depth of about 5 m. The other underwater nodes (M1, M2, M3, and M4), moored on the seafloor[6] at a depth of about 30 m, were used as data generators.

1) Evologics modem features and their impact on protocol implementation: Differently from the FSK WHOI Micro-Modem, the Evologics modem uses a phase-shift-keying-modulated sweep-spread carrier signal, providing higher performance in terms of achievable data rate, packet length and delays. Additionally, the Evologics modem has a built-in MAC and, to enable the investigation of different MAC solutions, it has to be used in the "instant messages" mode. When operating in this mode, no built-in MAC is used and custom protocols can be tested. When using the instant messages mode, the modem supports an actual data rate of 480 bps and a maximum packet size of 64 B.[7] Similarly to the ACommsNet10 at-sea campaign, short control messages were used for RTS, CTS, Tone, and ACK packets.
The additional delay introduced by the Evologics modem to each packet transmission (for encoding and internal operations) is about 0.15 s.
Traffic loads similar to those investigated during ACommsNet10 were considered with a payload size of 50 B. However, it is important to notice that using the Evologics modem the data packet transmission duration is much shorter: 0.83 s with respect to the 3.2 s for FSK WHOI Micro-Modem. This means that for the same value of packets per packet time about four times more bits are generated in the network with respect to ACommsNet10 experiments. Additionally, with a shorter packet transmission duration with respect to ACommsNet10, the signal propagation delay was always similar to the packet transmission time. This results in increasing the portion of time nodes wait to receive ACK or CTS with respect to the actual data transmission time.

---

[6] Each modem is deployed at 1.5 m from the seafloor.

[7] Any packet size from 0 to 64 B can be used.



(a) (b)

Fig. 5. RSSI over the link M1–M4, considering three different transmission powers and a packet length of 50 B. (a) Link from node M1 to M4. (b) Link from node M4 to M1.

TABLE III
COMMSNET13 AVERAGE PER OVER THE LINKS TO AND FROM THE SINK

	M1	M2	M3	M4
GB incoming packets	0.27	0.23	0.59	0.71
GB outgoing packets	0.12	0.1	0.29	0.35

When using the Evologics modem, the time needed to complete the delivery of a data packet (including the propagation delay and the overhead introduced by the protocol and by the acoustic modem) is in the ideal case ∼3.3 s for DACAP and ∼2 s for both CSMA and T-Lohi. For the CommsNet13 experiments, the considered traffic loads range from one packet generated in the network every 10 s to one packet every 4 s.

Another important difference with respect to the ACommsNet10 experiment is related to the stability of the acoustic links experienced by the receiving nodes. During ACommsNet10, quite similar and stable link conditions were experienced by each receiver for the duration of the tests. In the Palmaria deployment, the acoustic link qualities were quite variable over time. Fig. 5 shows the variation in time of the acoustic signal strength (via received signal strength indicator, RSSI, provided by the modem) of the link between node M1 and node M4 (link length ∼1.7 km). Three different transmission power levels available on the Evologics modem have been considered; namely 2.8, 8, and 35 W.[8] We can clearly see that at different times the acoustic links can become asymmetric (e.g., from 13 500 to 32 000 s, at the lowest power) or can completely disappear (e.g., at 10 000 s, at any power).

It is important to notice that the presence of asymmetric links can have a profound impact on protocol performance since two configurations can be experienced.

a) Configuration 1: Having a bad link (high PER) for the delivery of data messages while the reverse link for ACKs is good (low PER). In this case, the use of ACK packets can significantly improve the packet delivery ratio at the price of longer delays due to the data packet retransmissions. This is the case mostly experienced during CommsNet13.

b) Configuration 2: Having a good link (low PER) for data delivery while the reverse link for ACKs is bad (high PER). In this case, protocols making use of ACK packets would keep losing the transmitted ACKs, retransmitting the same data packet multiple times, even when the destination node has already correctly received it. This results in wasting node resources and overuse of the acoustic medium. Protocols such as T-Lohi should be preferred in this case, since they guarantee the possibility of transmitting data without keeping the network stack on old packet retransmissions, which also increase rapidly the end-to-end delay in the network. Another option is the use of more sophisticated and cooperative ACK schemes to reduce the retransmission overhead and delay.

2) CommsNet13 results: Fig. 6 shows the results collected during the CommsNet13 experiment. Similar trends to those found in the ACommsNet10 campaign are evident.

As expected, increasing the traffic load results in a lower packet delivery ratio by all three protocols [see Fig. 6(a)]. Without implementing any retransmission mechanism and in the presence of a highly dynamic channel, T-Lohi shows a decrease in its capability to deliver packets through the network, starting at low traffic loads.

Although the results show similar trends to ACommsNet10, the link variability experienced during CommsNet13[9] more severely affects the performance of protocols making use of retransmission procedures, i.e., CSMA and DACAP. Fig. 6(b) shows that more packet retransmissions and channel access attempts are experienced by CSMA and DACAP with respect to ACommsNet10.

Looking in detail at the average PER experienced over the links to and from the sink (see Table III), we can clearly see that M3 and M4 incur a higher number of retransmissions and lost messages while for M1 and M2 the PER is lower. We have estimated that 75% of the packet loss and retransmissions are due to M3 and M4 (affecting also the end-to-end delay performance), while M1 and M2 are almost always able to deliver more than 90% of their packets to the sink with limited delay.

Fig. 6(c) clearly shows the effect of the link variability on the end-to-end packet delay performance of CSMA and DACAP. This reflects the discussion of Configuration 1 presented earlier. As soon as the traffic load increases, delays much longer than presented for ACommsNet10

---

[8] The lowest transmission power level has been used for the MAC tests to prolong the lifetime of the GB node, which was battery powered.

[9] During the CommsNet13 tests, asymmetric links have been experienced without, however, resulting in the presence of unidirectional links for long period of time.

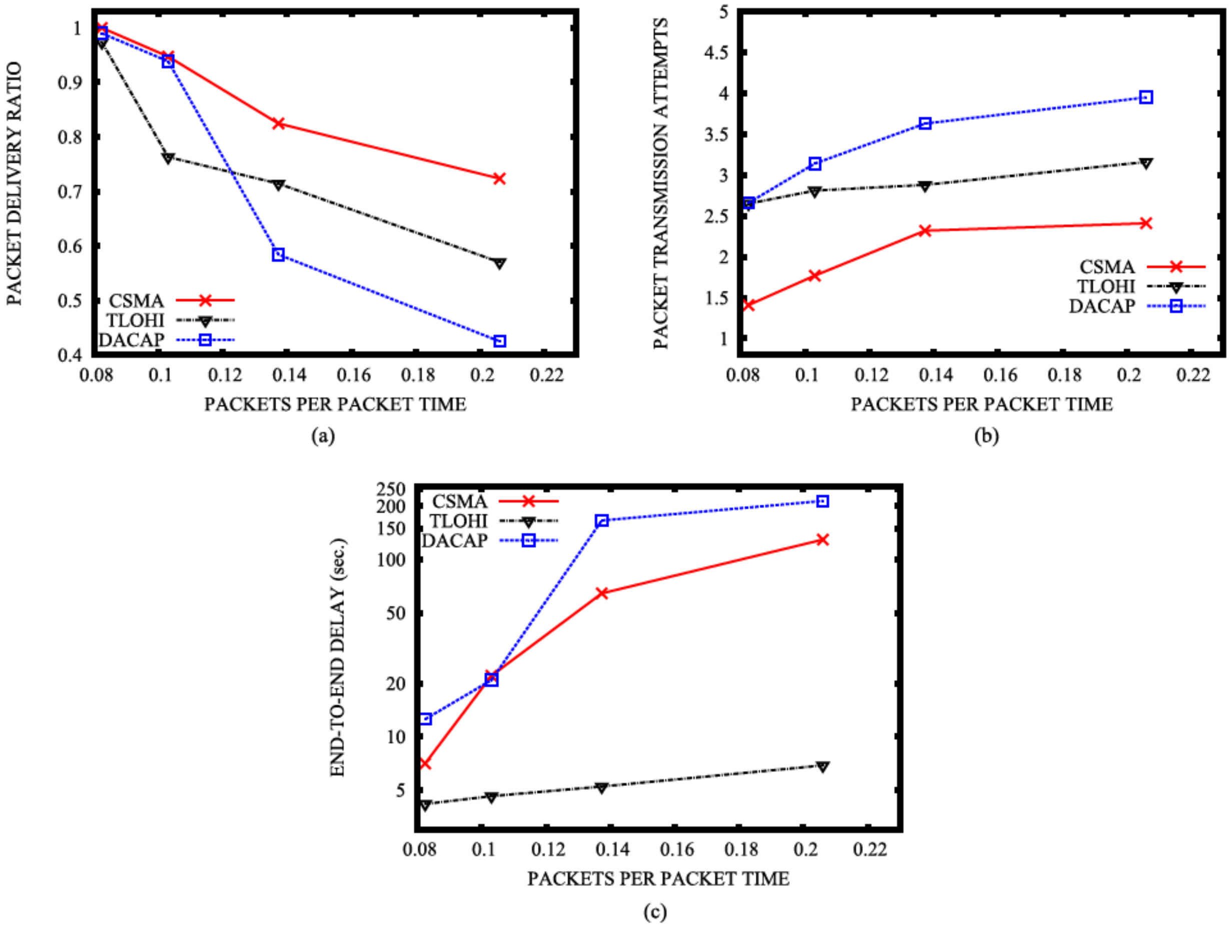


Fig. 6. CommsNet13 results. (a) Packet delivery ratio. (b) Packet transmission attempts. (c) End-to-end delay.

TABLE IV
COMMSNET13: THROUGHPUT AND GOODPUT RESULTS IN BPS

Traffic load (ppt)	$Throughput$			$\overline{Throughput}$			$Goodput$		
	CSMA	T-Lohi	DACAP	CSMA	T-Lohi	DACAP	CSMA	T-Lohi	DACAP
0.082	45.6	40.3	48.8	54.8	50	61.7	39.5	38.5	39.2
0.103	52.3	41.7	58.63	64.6	51.8	74.2	46.8	37.7	46.4
0.137	62.8	51.2	62.7	77	66	79.5	54.3	47	44.5
0.206	89.6	63.7	82	111	87.1	107.5	71.6	56.4	42

are experienced. The analysis of the average end-to-end delay per node shows that for M1 and M2 the delay in message delivery is always shorter than 6–7 s for CSMA and 9–11 s for DACAP. The performance of M3 and M4, suffering more from the presence of asymmetric links over time, are instead detrimentally affected. As soon as the traffic load increases, M3 and M4 start storing more and more packets, waiting to access the channel. Each new stored packet has to wait until all the previously stored messages are transmitted or discarded, before being pushed into the channel. This introduces cumulative delay up to several hundreds seconds, thus significantly increasing the overall average end-to-end delays in the network. The T-Lohi protocol, without introducing any data packet retransmission and packet cumulative delays, always presents a shorter latency in packet delivery.

Table IV shows the throughput and goodput results for the three MAC protocols. Similar trends to those found in the ACommsNet10 campaign can be noticed. However, a smaller gap between throughput and goodput results is experienced by the three MAC protocols. This is due to the presence of bad links toward the sink and good links from the sink. Although a higher number of packet retransmissions are performed, only a reduced number of bits are correctly delivered to the sink. Once messages are received by the sink, most of the times correct replies are received as well.

In such a scenario, when the traffic load increases, the use an exponential backoff results in having the nodes waiting longer to access the channel instead of delivering bits of information. This more severely affects DACAP, due to the use of a RTS/CTS handshake, thus incurring in a lower throughput with respect to CSMA at higher traffic loads. When reducing the amount of control bits added by the modem to each acoustic message, the gap between throughput and $\overline{\text{throughput}}$ is reduced as well.

V. CONCLUSION

We have performed a comparative performance evaluation of three of the best-known MAC schemes for UANs: CSMA, T-Lohi, and DACAP, spanning the range of operative mechanisms from the simplest (no handshaking) to full channel reservation. The performance of these three protocols has been evaluated based on extensive at-sea tests during the NATO ACommsNet10 experiment and the NATO CommsNet13 at-sea trial. Two different underwater acoustical modems, namely FSK WHOI Micro-Modem and Evologics S2C R 18/34 have been considered, to explore the effects that different transmission capabilities and limitations on the acoustic message size have on the considered protocols. The presence of more stale communication links and of more dynamic time varying conditions have been explored. Although different communication devices and environmental scenarios have been considered, similar trends can be noticed in the presented results, depending on the different designs and operations of the three considered MAC protocols.

The analysis shows that there is no champion solution for all the different scenarios. According to the considered traffic load, communication hardware, channel condition, and evaluation metric, some solutions perform better than others. Changing the scenario and the configuration, different solutions should be selected. As soon as the channel condition becomes more dynamic with the presence of asymmetric links, a different approach is preferable to acknowledge the packet delivery. This highlights the need to explore innovative software-defined schemes that are able to adapt in a distributed way to the various changes occurring in the network and in the communication channel (in space and time).

Additionally, at-sea experiments are needed to have a more accurate understanding of the performance of the designed solutions in highly dynamic scenarios, when making use of real hardware. As we have seen, the delays and overheads associated with the use of real acoustic modems significantly affect the overall protocol performance. To improve the current simulation tools for UANs, there is the need to have accurate models for the various acoustic modems. These models have to be based on the actual results and experience collected during at-sea campaigns, since many of the experienced modem behaviors are difficult to be predicted in advance. In-field experiments are therefore really important to validate not only the relative performance of different classes of MAC protocols, but also the validity of the simulation process itself. A combination of accurate simulation and experimental validation appears the most promising approach for assessing the performance and effectiveness of protocols proposed for UANs.

ACKNOWLEDGMENT

The authors would like to thank the Parco Nazionale Archipelago Toscano, the Engineering Division and the Ship Management Office at the NATO STO Center for Maritime Research and Experimentation, who made the experimental activities possible. The authors would also like to thank the Department of Computer Science, Rome University La Sapienza, Rome, Italy, where the core of the technical work presented in this paper was performed.

REFERENCES

[1] J. Heidemann, M. Stojanovic, and M. Zorzi, "Underwater sensor networks: Applications, advances, and challenges," *Roy. Soc.*, vol. 370, no. 1958, pp. 158–175, May 2012.

[2] N. Chirdchoo, W.-S. Soh, and K. C. Chua, "ALOHA-based MAC protocols with collision avoidance for underwater acoustic networks," in *Proc. 26th IEEE Int. Conf. Comput. Commun.*, Anchorage, AK, USA, May 6–12, 2007, pp. 2271–2275.

[3] N. Parrish, L. T. Tracy, S. Roy, P. Arabshahi, and W. L. J. Fox, "System design considerations for undersea networks: Link and multiple access protocols," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 9, pp. 1720–1730, Dec. 2008.

[4] S. Basagni, C. Petrioli, R. Petroccia, and M. Stojanovic, "Choosing the packet size in multi-hop underwater networks," in *Proc. IEEE OCEANS*, Sydney, NSW, Australia, May 24–27, 2010, pp. 1–9.

[5] B. Peleato and M. Stojanovic, "Distance aware collision avoidance protocol for ad-hoc underwater acoustic sensor networks," *IEEE Commun. Lett.*, vol. 11, no. 12, pp. 1025–1027, Dec. 2007.

[6] A. Syed, W. Ye, and J. Heidemann, "Comparison and evaluation of the T-Lohi MAC for underwater acoustic sensor networks," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 9, pp. 1731–1743, Dec. 2008.

[7] A. Syed, W. Ye, and J. Heidemann, "Understanding spatio-temporal uncertainty in medium access with ALOHA protocols," in *Proc. 3rd ACM Int. Workshop UnderWater Netw.*, Montréal, QC, Canada, Sep. 14, 2007, pp. 41–48.

[8] C.-C. Hsu, K.-F. Lai, C.-F. Chou, and C.-J. K. Lin, "ST-MAC: Spatial-temporal MAC scheduling for underwater sensor networks," in *Proc. IEEE 29th IEEE Int. Conf. Comput. Commun.*, Rio de Janeiro, Brazil, Apr. 19–25, 2009, pp. 1827–1835.

[9] M. Chitre, M. Motani, and S. Shahabudeen, "A scheduling algorithm for wireless networks with large propagation delays," in *Proc. IEEE OCEANS*, Sydney, NSW, Australia, May 24–27, 2010, pp. 1–9.

[10] Z. Zhou, S. Le, and J.-H. Cui, "An OFDM based MAC protocol for underwater acoustic networks," in *Proc. 5th ACM Int. Workshop UnderWater Netw.*, Woods Hole, MA, USA, Sep. 30, 2010, pp. 6:1–6:8.

[11] M. Stojanovic and L. Freitag, "Wideband underwater acoustic CDMA: Adaptive multichannel receiver design," in *Proc. MTS/IEEE OCEANS*, Washington, DC, USA, Sep. 17–23, 2005, vol. 2, pp. 1508–1513.

[12] D. Pompili, T. Melodia, and I. F. Akyildiz, "A distributed CDMA medium access control for underwater acoustic sensor networks," in *Proc. Mediterranean Ad Hoc Netw. Workshop, Med-Hoc-Net*, Corfu, Greece, Jun. 13–15, 2007, pp. 1–8.

[13] L.-C. Kuo and T. Melodia, "Medium access control for underwater acoustic sensor network with MIMO links," in *Proc. 12th ACM/IEEE Int. Symp. Model., Anal. Simul. Wireless. Mobile Syst.*, Tenerife, Spain, Oct. 26–30, 2009, pp. 204–211.

[14] J. Yackoski and C. Shen, "UW-FLASHR: Achieving high channel utilization in a time-based acoustic MAC protocol," in *Proc. 3rd ACM Int. Workshop UnderWater Netw.*, San Francisco, CA, USA, Sep. 15, 2008, pp. 59–66.

[15] R. Diamant and L. Lampe, "A hybrid spatial reuse MAC protocol for ad-hoc underwater acoustic communication networks," in *Proc. 2010 IEEE Int. Conf. Commun. Workshops*, Cape Town, South Africa, May 23–27, May 2010, pp. 1–5.

[16] C. Petrioli, R. Petroccia, and M. Stojanovic, "A comparative performance evaluation of MAC protocols for underwater sensor networks.," in *Proc. MTS/IEEE OCEANS*, Quebec City, Quebec, Canada, Sep. 15–18, 2008, pp. 1–10.

[17] P. Casari, B. Tomasi, and M. Zorzi, "A comparison between the tone-lohi and slotted FAMA MAC protocols for underwater networks." in *Proc. MTS/IEEE OCEANS*, Quebec City, QC, Canada, Sep. 15–18, 2008, pp. 1–8.

[18] C. Petrioli, R. Petroccia, and J. Potter, "Performance evaluation of underwater MAC protocols: From simulation to at-sea testing," in *Proc. IEEE/OES OCEANS*, Santander, Spain, Jun. 6–9, 2011, pp. 1–10.

[19] L. Pu, Y. Luo, H. Mo, Z. Peng, J.-H. Cui, and Z. Jiang, "Comparing underwater MAC protocols in real sea experiment," in *Proc. IFIP Netw.*, Brooklyn, NY, USA, May 22–24, 2013, pp. 1–9.

[20] M. Zuba, T. Yang, and J.-H. Cui, "The impact of intensity fluctuations on network throughput on selected MAC," in *Proc. 8th ACM Int. Conf. Underwater Netw. Syst.*, Kaohsiung, Taiwan, Nov. 11–13, 2013, pp. 1–2.

[21] S. Le, Y. Zhu, Z. Peng, J.-H. Cui, and Z. Jiang, "PMAC: A real-world case study of underwater MAC," in *Proc. 8th ACM Int. Conf. Underwater Netw. Syst.*, Kaohsiung, Taiwan, Nov. 11–13 2013, pp. 1–8.

[22] G. Qiao, J. M. Yang, X. F. Ma, Y. Zhang, and H. Dong, "Simulation and experimental verification of MAC protocols for underwater acoustic communication networks," in *Proc. 8th ACM Int. Conf. Underwater Netw. Syst.*, Kaohsiung, Taiwan, Nov. 11–13, 2013, pp. 1–5. [Online]. Available: http://doi.acm.org/10.1145/2532378.2532392

[23] P. Anjangi and M. Chitre, "Design and implementation of super-TDMA: A MAC protocol exploiting large propagation delays for underwater acoustic networks," in *Proc. ACM WUWNet*, Washington, DC, USA, Oct. 22–24, 2015, pp. 1–8.

[24] J. Alves, R. Petroccia, and J. R. Potter, "MPR: Multi-point relay protocol for underwater acoustic networks," in *Proc. 9th ACM Int. Conf. Underw. Netw. Syst.*, Rome, Italy, Nov. 12–14 2014, pp. 1–8.

[25] S. Basagni, C. Petrioli, R. Petroccia, and D. Spaccini, "CARP: A channel-aware routing protocol for underwater acoustic wireless networks," *Ad Hoc Netw.*, vol. 34, pp. 92–104, 2015.

[26] R. Petroccia and D. Spaccini, "A back-seat driver to remotely control the experiments in an underwater acoustic sensor network," in *Proc. MTS/IEEE OCEANS*, Bergen, Norway, Jun. 10–13, 2013, pp. 1–9.

[27] L. Freitag, M. Grund, S. Singh, J. Partan, P. Koski, and K. Ball, "The WHOI micro-modem: An acoustic communications and navigation system for multiple platforms," 2005. [Online]. Available: http://acomms.whoi.edu/umodem/, Accessed on: Mar. 2013.

[28] Evologics, "Evologics S2C acoustic modems." [Online]. Available: http://www.evologics.de/, Accessed on: Sep. 2016.

[29] C. Petrioli, R. Petroccia, J. R. Potter, and D. Spaccini, "The SUNSET framework for simulation, emulation and at-sea testing of underwater wireless sensor networks," *Ad Hoc Netw.*, vol. 34, pp. 224–238, 2015.

Roberto Petroccia (M'10) received the Laurea (highest Hons.) degree and the Ph.D. from Rome University "La Sapienza," Rome, Italy, in 2006 and 2010, respectively, both in computer science.

He was a Research Staff in Rome University "La Sapienza" until 2015. Since 2015, he has been a Research Scientist in the NATO STO Center for Maritime Research and Experimentation, La Spezia, Italy. He has participated in several EC projects including the EC IP projects E-SENSE, SENSEI, the FP7 STREP CLAM, and the FP7 SUNRISE. For the two latter projects on underwater networking, he was in charge of coordinating all underwater experimental activities. In the last five years, he has participated in more than 20 experimental campaigns at sea where innovative underwater solutions he developed have been extensively tested. He has been actively collaborating with several acoustic modem and underwater vehicle manufacturing companies and research labs to design novel technologies supporting cooperative underwater acoustic networks. He has supervised the work of several master thesis and Ph.D. students. His research interests include wireless sensor networks design, underwater communications and networking, where he has contributed over three-dozens papers published in leading venues (h-index = 14, i10-index = 20, Google Scholar, March 2017).

Dr. Petroccia was in the organizing committee of the IEEE UComms 2016, ACM WUWNet 2014, and ACM WUWNet 2012 conferences. He is also a member of ACM.

Chiara Petrioli (S'96–M'98–SM'06) received the Ph.D. in computer engineering from University of Rome "La Sapienza," Rome, Italy, in 1998.

She is currently a Full Professor in the Department of Computer Science, University of Rome "La Sapienza," where she leads the Sensor Networks and Embedded Systems Laboratory. She also leads the Cyber Physical System Lab of "La Sapienza" Center for Cyber Intelligence and Information Security, and is a Founding Partner of "La Sapienza" spinoff WSENSE S.r.l. She was a Fulbright Scholar. She has published more than 150 papers in prominent international journals and conferences (4700+ citations, h-index 36). She has also been PI of more than 20 national and international research projects, serving as coordinator of two EC projects (FP7 projects GENESI and SUNRISE). Her research interests include the design and optimization of wireless, embedded, and cyber physical systems.

Prof. Petrioli is member of the Steering Committee of the IEEE SECON, Program Co-Chair of the IEEE INFOCOM 2016, Workshop Co-Chair of ACM MobiCom 2014, General Chair of ACM WUWNET 2014, General Chair of ACM SenSys 2013. She has been a member of the Steering Committee and an Associate editor of the IEEE TRANSACTIONS ON MOBILE COMPUTING, member of the Steering Committee of ACM SenSys, an Associate Editor of the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, a member of the Executive Committee of ACM SIGMOBILE, an Associate Editor of Elsevier Computer Communications, Guest Editor of special issues for the IEEE Access, Elsevier Ad Hoc Networks, Elsevier Physical Communications, and has been the Program Co-Chair of leading conferences in the field, such as ACM MobiCom and IEEE SECON.

John Potter (SM'96) received joint honors BSc. degree in mathematics and physics from Bristol University, Bristol, U.K., in 1979 and the Ph.D. degree in glaciology and oceanography from the University of Cambridge, Cambridge, U.K., in 1985.

He received the Polar Medal for this work by Queen Elizabeth II in 1988. He worked in Italy on propagation fluctuations in underwater acoustics from 1986 to 1991, then sailed across the Atlantic and through the Panama canal to San Diego where he worked at the UCSD Scripps Institution of Oceanography on Ambient Noise Imaging and Marine Mammal Acoustics. In 1995, he sailed on with his family from San Diego to Singapore, where he founded the Acoustic Research Laboratory (ARL) and helped create the Tropical Marine Science Institute. He headed the ARL and was an Associate Director of the TMSI for 12 years, working on passive acoustic imaging, marine mammal acoustics, distributed autonomous intelligent sensing, underwater communications networking, and cooperative behavior. In 2004–2005, he took a year "sabbatical" with his family to circumnavigate the Indian Ocean by sailboat on a sponsored voyage of research, public outreach, and education with the aim of improving the awareness and quality of our species' stewardship of the ocean ecosystem. After co-chairing OCEANS Singapore in 2006, he returned to Italy, first as a Consultant, then as a Project Leader and currently as the Principal Strategic Development Officer at the NATO STO Center for Maritime Research and Experimentation.

Dr. Potter has been an active member of the IEEE OES for more than 20 years, serving three terms on the Administrative Committee. He is also an Associate Editor for the IEEE JOURNAL OF OCEANIC ENGINEERING and an International Fellow of the Explorer's Club.

Document Data Sheet

Security Classification		*Project No.*
Document Serial No. CMRE-PR-2019-052	*Date of Issue* June 2019	*Total Pages* 10 pp.

Author(s)

Roberto Petroccia, Chiara Petrioli, John Potter

Title

Performance evaluation of underwater medium access control protocols: at-sea experiments

Abstract

In this paper, we investigate the performance of three medium access control (MAC) protocols (CSMA, T-Lohi, and DACAP) representing simple, intermediate, and fully negotiated protocols, to access the underwater acoustic channel, during two at-sea campaigns. Various tests were conducted in the waters surrounding Pianosa island during the NATO ACommsNet10 experiment in September 2010 and off the coast of the Palmaria island during the NATO CommsNet13 experiment in 2013. Different types of application loads and communication devices have been used to investigate the performance of the various protocols under different transmission rates and introduced overhead. The presence of more stable and reliable communication links and of a highly dynamic communication channel has also been explored. The collected results show that there is no single solution that is best for all the possible scenarios and configurations and that the selection of different protocols is required for different contexts. This highlights the importance of understanding the performance of each protocol at sea, under various conditions, to design novel and adaptive schemes, which are able to react in an efficient and effective way to possible changes in the network and in the communication channel.

Keywords

At-sea testing, MAC protocols, performance comparison, underwater acoustic networks, underwater communication

Issuing Organization

NATO Science and Technology Organization
Centre for Maritime Research and Experimentation

Viale San Bartolomeo 400, 19126 La Spezia, Italy

[From N. America:
STO CMRE
Unit 31318, Box 19, APO AE 09613-1318]

Tel: +39 0187 527 361
Fax:+39 0187 527 700

E-mail: library@cmre.nato.int