A CDMA-Based Medium Access Control for Underwater Acoustic Sensor Networks

Dario Pompili, *Member, IEEE,* Tommaso Melodia, *Member, IEEE,* and Ian F. Akyildiz, *Fellow, IEEE*

***Abstract*—UnderWater Acoustic Sensor Networks (UW-ASNs) consist of sensors and Autonomous Underwater Vehicles (AUVs) performing collaborative monitoring tasks. In this article, UW-MAC, a distributed Medium Access Control (MAC) protocol designed for UW-ASNs, is introduced. The proposed MAC protocol is a transmitter-based Code Division Multiple Access (CDMA) scheme that incorporates a novel closed-loop distributed algorithm to jointly set the optimal transmit power and code length. CDMA is the most promising physical layer and multiple access technique for UW-ASNs because it is robust to frequency-selective fading, it compensates for the effect of multipath at the receiver, and it allows receivers to distinguish among signals simultaneously transmitted by multiple devices.**

UW-MAC aims at achieving three objectives, i.e., guarantee i) high network throughput, ii) low channel access delay, and iii) low energy consumption. It is demonstrated that UW-MAC simultaneously achieves these three objectives in *deep water* communications (where the ocean depth is more than 100 m), which are usually not severely affected by multipath. In *shallow water* communications, which may be heavily affected by multipath, it dynamically finds the optimal trade-off among these objectives according to the application requirements. UW-MAC is the first protocol that leverages CDMA properties to achieve multiple access to the scarce underwater bandwidth, while other protocols tailored for this environment have considered CDMA merely from a physical layer perspective. Experiments show that UW-MAC outperforms many existing MAC protocols tuned for the underwater environment under different architecture scenarios and simulation settings.

***Index Terms*—Wireless networking, sensor networks, underwater acoustic communications, MAC, CDMA, performance.**

I. INTRODUCTION

UNDERWATER sensor networks enable applications for oceanographic data collection, ocean sampling, environmental monitoring, offshore exploration, disaster prevention, tsunami warning, assisted navigation, distributed tactical surveillance, and mine reconnaissance [2]. Acoustic wireless communications are the typical physical layer technology in underwater networks, although they pose unique challenges due to the harsh underwater environment such as limited bandwidth [3], high and variable propagation delays [4], high bit error rates and temporary losses of connectivity caused by multipath and fading phenomena [5], and asymmetric links. Other physical layer technologies are often impractical in this environment due to several reasons. In fact, radio waves propagate through conductive salty water only at extra low frequencies $(30 - 300 \text{ Hz})$, which require large antennae and high transmission power. Optical waves do not suffer from such high attenuation but are affected by scattering. Moreover, transmission of optical signals requires high precision in pointing the narrow laser beams.

UnderWater Acoustic Sensor Networks (UW-ASNs) [2] consist of sensors and Autonomous Underwater Vehicles (AUVs) deployed to perform collaborative monitoring tasks. A major challenge for the deployment of UW-ASNs is the development of a Medium Access Control (MAC) protocol tailored for the underwater environment. In particular, an underwater MAC protocol should provide *high network throughput*, *low channel access delay*, and *low energy consumption*, in face of the harsh characteristics of the underwater propagation medium, while guaranteeing *fairness* among competing nodes [6].

Code Division Multiple Access (CDMA) is the most promising physical layer and multiple access technique for UW-ASNs because i) it is robust to frequency-selective fading, ii) compensates for the effect of multipath at the receiver by exploiting Rake filters, which can collect the transmitted energy spread over multiple rays [7], and iii) allows receivers to distinguish among signals simultaneously transmitted by multiple devices. For these reasons, CDMA increases channel reuse and reduces packet retransmissions, which results in decreased energy consumption and increased network throughput.

In this article, we introduce UW-MAC, a transmitter-based CDMA MAC protocol for UW-ASNs that incorporates a novel closed-loop distributed algorithm to jointly set the optimal transmit power and code length to minimize the *near-far effect*[1] [8]. One of the novelties of UW-MAC, which is motivated by the huge propagation delay affecting the underwater environment, is that it is not a pure distributed CDMA protocol; rather, it is a distributed *hybrid* MAC that combines both ALOHA and CDMA. The word 'hybrid' refers to the fact that each data packet (from each node), which is composed

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D. Pompili is with the Department of Electrical and Computer Engineering at Rutgers, The State University of New Jersey, 94 Brett Road, Piscataway, NJ 08854 (e-mail: pompili@ece.rutgers.edu).

T. Melodia is with the Department of Electrical Engineering, University at Buffalo, The State University of New York, 332 Bonner Hall, Buffalo, NY 14260 (e-mail: tmelodia@eng.buffalo.edu).

I. F. Akyildiz is the director of the Broadband Wireless Networking Laboratory, School of Electrical and Computer Engineering, Georgia Institute of Technology, 75 5th Street, Atlanta, GA 30332 (e-mail: ian@ece.gatech.edu).

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[1] The *near-far effect* occurs when the signal received by a receiver from a sender near the receiver is stronger than the signal received from another sender located further. In this case, the remote sender will be dominated by the close sender.

of *header* and *payload*, simultaneously accesses the channel using a random-access ALOHA-like MAC scheme (header) and adapting its power and code length in a distributed manner as in CDMA schemes (payload). Also, no control packets are transmitted before the actual data packet is sent, hence no handshaking occurs. While other MAC protocols can be considered hybrid *in space* (in the sense that two different medium access schemes are used in different locations of the network [9]), our UW-MAC is hybrid *in time* as it switches at each sender node from an ALOHA-based scheme, to transmit the header, to a CDMA-based scheme, to transmit the payload. Note that the payload and the header are transmitted *back-to-back* in a single atomic transmission.

UW-MAC aims at achieving three objectives, i.e., guarantee i) high network throughput, ii) low channel access delay, and iii) low energy consumption. We demonstrate that UW-MAC manages to simultaneously achieve these three objectives in *deep water* communications, which are usually not severely affected by multipath. In *shallow water* communications[2], which may be heavily affected by multipath, it dynamically finds the optimal trade-off among these objectives according to the application requirements.

We also formulate the *distributed power and code self-assignment problem* to account for the near-far effect, and propose a low-complexity *yet optimal* solution. UW-MAC uses locally generated chaotic codes[3] to spread transmitted signals on the available bandwidth, which guarantees a flexible and granular bit rate, secure protection against eavesdropping (as packets cannot be decoded without the proper chaotic code, which in turn depends on the secret initial conditions), transmitter-receiver self-synchronization, and good auto- and cross-correlation properties [10]. To the best of our knowledge, UW-MAC is the first protocol that leverages CDMA properties to achieve multiple access in the bandwidth-limited underwater channel, while other MAC protocols [11][12] have considered CDMA merely from a physical layer perspective.

The remainder of this paper is organized as follows. In Sect. II, we discuss the suitability of the existing ad hoc and sensor MAC protocols for the underwater environment. In Sect. III, we describe UW-MAC, while in Sect. IV we formulate the distributed power and code self-assignment problem. In Sect. V, we compare through simulation UW-MAC with many existing MAC schemes for sensor networks tuned for the underwater environment. Finally, in Sect. VI, we draw the conclusions.

II. RELATED WORK

There has been intensive research on MAC protocols for ad hoc [13] and wireless terrestrial sensor networks [14] in the last decade. However, due to the unique characteristics of the propagation of acoustic waves in the underwater environment, existing terrestrial MAC solutions are unsuitable for this environment. Channel access control in UW-ASNs, in fact, poses additional challenges due to the limited bandwidth, very high and variable propagation delays, high bit error rates, temporary losses of connectivity, channel asymmetry, and heavy multipath and fading phenomena.

Existing MAC solutions are mainly focused on Carrier Sense Multiple Access (CSMA) or Code Division Multiple Access (CDMA). This is because Frequency Division Multiple Access (FDMA) is not suitable for UW-ASNs due to the narrow bandwidth in UnderWater Acoustic (UW-A) channels and the vulnerability of limited band systems to fading and multipath. Moreover, Time Division Multiple Access (TDMA) shows a limited bandwidth efficiency because of the long time guards required in UW-A channels. Furthermore, the variable delay makes it very challenging to realize a precise synchronization with a common timing reference [15]. For a thorough discussion on the reasons why several multiple access techniques widely employed in terrestrial sensor networks such as TDMA, FDMA, and CSMA, are not suitable for the underwater environment, we refer the reader to [2]. Here, we mainly focus on previous work on CDMA, as this is the most promising physical layer and multiple access technique for UW-ASNs.

In [11], two spread-spectrum physical layer techniques, namely Direct Sequence Spread Spectrum (DSSS) and Frequency Hopping Spread Spectrum (FHSS), are compared for shallow water communications. While in DSSS data is spread to minimize the mutual interference, in FHSS simultaneous communications use different frequency hopping sequences, thus transmitting on different frequency bands. Interestingly, [11] shows that in the underwater environment FHSS leads to a higher bit error rate than DSSS. Another attractive access technique combines DSSS CDMA with multi-carrier transmissions [12], which may offer higher spectral efficiency than its single-carrier counterpart. In this way, high data rate can be supported by increasing the duration of each symbol, which reduces Inter Symbol Interference (ISI). However, multi-carrier transmissions may not be suitable for low-end sensors because of their high complexity. Therefore, we focus on single-carrier CDMA to keep the complexity of resource-limited sensor transceivers lower. Unfortunately, the above papers [11][12] merely consider CDMA from a physical layer perspective, i.e., they analyze the suitability of different forms of CDMA-based transmission techniques with respect to the challenges raised by the underwater channel. *Our contribution is, instead, to develop a dynamic multiple access protocol for different UW-ASN architectures and traffic scenarios that efficiently shares the scarce underwater channel bandwidth by fully leveraging CDMA medium access properties.*

In [9], a solution for underwater networks with AUVs is devised. The scheme is based on organizing the network in multiple clusters, each composed of adjacent vehicles. Interference among different clusters is minimized by assigning orthogonal spreading codes to different clusters. Inside each cluster, TDMA is used with long band guards to overcome the effect of propagation delay. Because vehicles in the same cluster are assumed to be close to one another, the negative effect of the very high underwater propagation delay is limited. The proposed solution, however, assumes a clustered network architecture and proximity among nodes within the same cluster, while we seek a more general and flexible solution

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[2] In oceanic literature, *shallow water* refers to water with depth lower than 100 m, while *deep water* is used for deeper oceans.

[3] Chaotic codes are sequences of chips usually generated using maps that exhibit some sort of chaotic behavior, whose key characteristic is the great sensitivity to initial conditions.

suitable for different network sizes and architectures.

In [16], the impact of the large propagation delay on the throughput of selected classical MAC protocols and their variants is analyzed, and PCAP, Propagation-delay-tolerant Collision Avoidance Protocol, is introduced. Its objective is to fix the time spent on setting up links for data frames, and to avoid collisions by scheduling the activity of sensors. Although PCAP offers higher throughput than widely used conventional protocols for wireless networks, it does not provide a flexible solution for applications with heterogeneous requirements.

A distributed CSMA-based energy-efficient MAC protocol for the underwater environment is proposed in [17]. Its objective is to save energy based on sleep periods with low duty cycles. The solution is tied to the assumption that nodes follow sleep periods and is aimed at efficiently organizing the sleep schedules. Conversely, we are interested in optimizing the utilization of the shared medium to maximize throughput and reduce the energy consumption. Moreover, while our proposed MAC protocol may be enhanced with a sleep schedule algorithm for dense deployment scenarios and/or very low duty-cycle monitoring applications, we decided to not incorporate it in the basic protocol to make it suitable for a variety of traffic, architecture, and deployment scenarios.

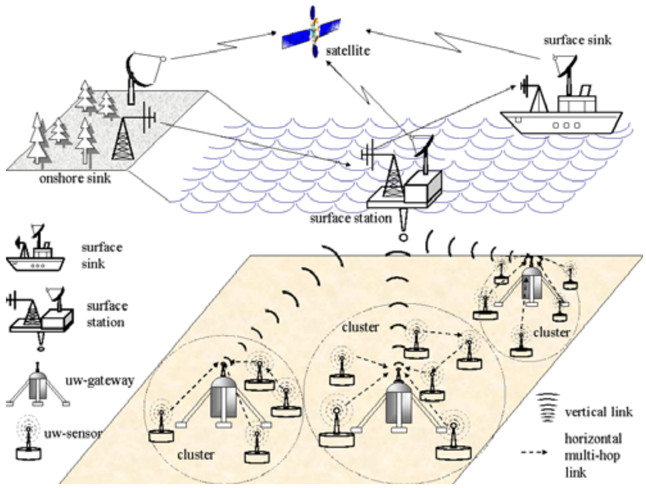

Fig. 1. Reference architecture for 2D UW-ASNs.

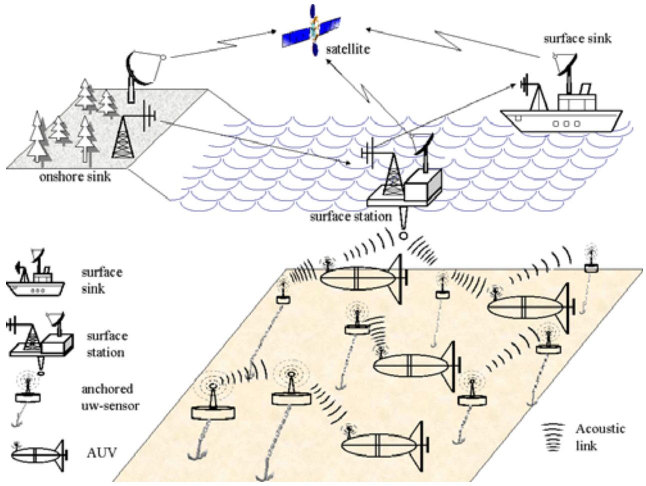

Fig. 2. Reference architecture for 3D UW-ASNs with mobile AUVs.

III. UW-MAC: A CDMA MAC FOR UW-ASNS

A. *Reference Architectures for UW-ASNs: Two- vs. Three-dimensional Architectures with AUVs*

A reference architecture for two-dimensional underwater sensor networks is shown in Fig. 1, where deployed sensor nodes are anchored to the bottom of the ocean. Underwater sensors may be organized in a cluster-based architecture, and be interconnected by means of wireless acoustic links to one or more *underwater gateways (uw-gateways)*, which are in charge of relaying data from the ocean bottom network to a surface station. They are equipped with a long-range *vertical* transceiver, which is used to relay data to a *surface station*, and with a *horizontal* transceiver, which is used to communicate with the sensor nodes to send commands and configuration data, and to collect monitored data. The surface station is equipped with an acoustic transceiver, which may be endowed with multi-user receiver capabilities to handle multiple parallel communications with the uw-gateways, and with a long-range radio transmitter and/or satellite transmitter, which is needed to communicate with an *onshore sink* and/or to a *surface sink*.

Conversely, in three-dimensional underwater networks, winch-based sensor devices are anchored to the bottom of the ocean, and float at different ocean depths covering the entire monitored volume region. This architecture is used to detect and observe phenomena that cannot be adequately observed by means of ocean bottom sensor nodes, i.e., to perform cooperative sampling of the 3D ocean environment.

Figure 2 depicts a three-dimensional architecture with mobile AUVs. AUVs can function without tethers, cables, or remote control, and therefore they have a multitude of applications in oceanography, environmental monitoring, and underwater resource studies. Previous experimental work has shown the feasibility of relatively inexpensive AUV submarines equipped with multiple underwater sensors that can reach any depth in the ocean.

B. *Basics: Single- vs. Multi-user CDMA Detectors*

UW-MAC is a transmitter-based Direct Sequence CDMA (DS-CDMA) scheme for UW-ASNs that implements a novel *closed-loop distributed algorithm* to jointly set the optimal transmit power and code length to account for the near-far effect. UW-MAC may leverage a *multi-user detector* on resource-rich devices such as uw-gateways, surface stations and AUVs, and a *single-user detector* on low-end sensor nodes. In DS-CDMA communication systems, the information-bearing signal is directly multiplied by a spreading code with a larger bandwidth than the data. The receiver despreads the transmitted spread spectrum signal using a locally generated code sequence. To perform the despreading operation, the receiver must know the code sequence used to spread the signal. Moreover, the received signal and the locally generated code must be synchronized. This synchronization must be accomplished at the beginning of the reception and maintained until the whole signal has been received. In a

DS-CDMA scheme the major problem encountered is the Multiuser Access Interference (MAI), which is caused by simultaneous transmissions from different users. In fact, the system efficiency is limited by the total amount of interference and not by the background noise exclusively [18]. Therefore, low cross-correlation between the desired and the interfering users is important to reduce the MAI. Moreover, adequate auto-correlation properties are required for reliable initial synchronization. Unfortunately, cross-correlation and autocorrelation properties cannot be optimized simultaneously.

Single-user detection (SUD) devices use low-cost conventional Rake receivers [7] to detect one user without regard to the existence of other users, which are treated as noise. Although these receivers leverage multipath diversity, there is no sharing of multi-user information or joint signal processing. Conversely, *multi-user detection (MUD)* devices simultaneously despread signals from several users. Consequently, the two problems of *channel equalization* and *signal separation* are jointly solved to increase the signal-to-interference-plus-noise ratio (SINR) and achieve good performance. MUD techniques have been studied extensively and a number of optimal and suboptimal algorithms have been proposed [19]. These techniques, however, usually require channel estimation and knowledge of all the active user spreading codes, and have considerable computational cost. While this may be feasible for the surface station, and in general for resource-rich devices, it contrasts with the desire to keep low-end sensors simple and power efficient. For these reasons, MUD techniques may be suitable for resource-rich devices such as uw-gateways and surface stations, but not for low-end underwater sensors. Thus, on low-end underwater sensor nodes, UW-MAC relies on low-complexity single-user detectors.

C. Protocol Description

Our proposed distributed closed-loop solution aims at setting the optimal combination of transmit power and code length at the transmitter side relying on local periodic broadcasts of MAI values from active nodes, as shown in Fig. 3. Here, node i needs to transmit a data packet to j, without impairing ongoing communications from h to k and from t to n. Because the system efficiency is limited by the amount of total interference, it is crucial for i to optimize its transmission, in terms of both transmit power and code length, in order to limit the near-far problem (e.g., node i is closer to n than t). The power and code self-assignment problem is formally introduced in Sect. IV, where a distributed low-complexity *yet optimal* solution is proposed.

In UW-MAC, nodes *randomly access* the channel transmitting a short header called the *Extended Header (EH)*. The EH, of size L_{EH} bits, is sent using a *common chaotic code* c_{EH} known by all devices at the maximum rate (minimum code length). Sender i transmits to its next hop j, located d_{ij} meters apart, the short header EH. The EH contains information about the final destination, i.e., the surface station, the chosen next hop, i.e., node j, and the subset of parameters[4] that i will use to generate the *chaotic spreading code* for the actual data packet, of size L_{Data} bits, that j will receive from i. Immediately after the transmission of the EH, i transmits the data packet on the channel, which is characterized by a raw chip rate r [cps] and sound velocity $\overline{q} \approx 1500$ m/s, using the optimal transmit power P^*_{ij} [W] and code length c^*_{ij} set by the power and code self-assignment algorithm. If no collision occurs during the reception of the EH, i.e., if i is the only node transmitting an EH in the neighborhood of node j, j will be able to 1) synchronize to the signal from i, 2) despread the EH using the common code, and 3) acquire the carried information. At this point, if the EH is successfully decoded, receiver j will be able to locally generate the chaotic code that is used by i to send its data packet, and set its decoder according to this chaotic code. Once j has correctly received the data packet from i, it acknowledges it by sending an ACK packet, of size L_{Ack} bits, to j using code c_{Ack}. These ACK packets are needed to ensure high link reliability and to minimize end-to-end retransmissions, which cause low throughput and high end-to-end delays in the underwater environment [20].

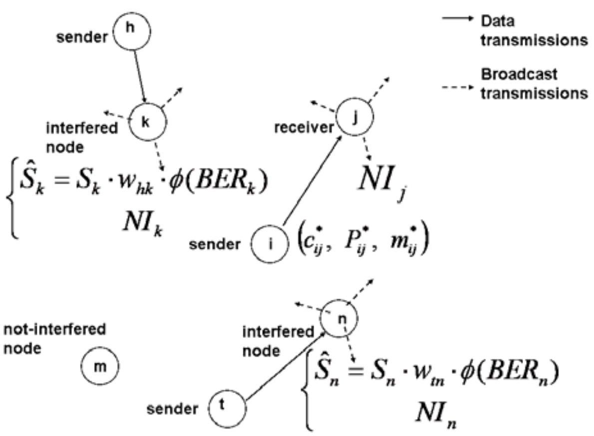

Fig. 3. Data and broadcast message transmissions.

Three possible strategies can be followed by j to set c_{Ack}, each with its own pros and cons: 1) use the same short common code c_{EH} used by the EH (collisions can occur but are unlikely as the ACK transmission time is small), 2) use c^*_{ij} (however, this code length was optimized by i for the transmission to j considering the SNIR at j and not for the transmission from j to i), and 3) optimize c^*_{Ack} using information of SNIR at i, if available. In Sect. V, results refer to the first case in which $c_{Ack} = c_{EH}$ and $P_{Ack} = P^{max}$, which is the node maximum transmission power.

In case i does not receive the ACK before a timeout T_{out} expires, it will keep transmitting the packet until a maximum transmission number N^T_{max} is reached. The timeout must be tuned considering the long propagation and transmission delays in UW-A channels,

$$T_{out} \geq \frac{c_{EH}}{r} \cdot L_{EH} + \frac{c_{ij}}{r} \cdot L_{Data} + \frac{2d_{ij}}{\overline{q}} + \frac{c_{Ack}}{r} \cdot L_{Ack}. \quad (1)$$

Note that if sender i does not have updated information

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[4] Other parameters needed to generate the code at the receiver are known *a priori* by all the *legitimate* nodes of the system so to avoid eavesdropping by nodes that do not belong to the system.

about the MAI in j, it increases the code length every time a timeout expires to improve the probability that the packet is successfully decoded, i.e.,

$$c_{ij}^{N_{ij}^T} = \min\left[c_{ij}^{N_{ij}^T-1}\cdot 2^{\beta}, c_{max}\right], \qquad (2)$$

where $N_{ij}^T \in [1, N_{max}^T]$ represents the transmission number (number of timeout expired plus one), while $\beta \in \mathbb{R}^+$ sets the aggressiveness of the mechanism, i.e., the higher β the more 'conservative' the mechanism is. As shown in Sect. V, this mechanism guarantees stability and decreases transients, although it temporarily decreases the transmission data rate. Algorithm 1 reports the pseudo-code executed by sender i.

Algorithm 1 UW-MAC pseudo-code executed by sender i

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Execute Power and Code Self-assignment Algorithm ⇒ $(c_{ij}^*, P_{ij}^*, m_{ij}^*)$
Generate chaotic code $c_{ij}^*$ and spread the data packet
Send an EH packet to node $j$ using common code $c_{EH}$
Transmit the data packet (back-to-back after the EH) using power $P_{ij}^*$ and power margin $m_{ij}^*$[2]
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As a final remark, it is worth noting that UW-MAC does not rely on handshaking mechanisms such as RTS/CTS. While handshaking limits to some extent the *hidden* and *exposed terminal problems*[5], thus reducing collisions and improving channel reuse, respectively (*positive effect*), it decreases the channel utilization efficiency because of the huge acoustic propagation delay, which leads to lower net bit rates (*negative effect*). Whether the positive or the negative effects would prevail in this environment actually depends on the network density and traffic conditions. *Our CDMA-based MAC can decouple the two effects, i.e., it can increase the channel reuse and decrease the number of collisions while keeping the channel utilization efficiency high.*

IV. POWER AND CODE SELF-ASSIGNMENT PROBLEM

In this section, we formulate the distributed power and code self-assignment problem, and propose a low-complexity yet optimal *closed-loop* solution. An *open-loop* power control algorithm (which does not use information via feedback from the receiver) would rely on the symmetric link assumption, which does not hold in the underwater environment. For this reason, our protocol periodically collects information on the state of the channel from the neighborhood and feeds the algorithm with the required information, as explained in the following.

A. Deep Water Channels

We consider a deep water acoustic channel, which is usually not severely affected by multipath, where the transmission loss TL_{ij} that a narrow-band acoustic signal centered at frequency f [kHz] experiences between nodes i and j at distance d [m] is described by the Urick propagation model [21], $TL_{ij} = d_{ij}^2 \cdot 10^{[\alpha(f)\cdot d_{ij}+A]/10}$, where $\alpha(f)$ [dB/m] represents the *medium absorption coefficient*, which describes the dependency of the transmission loss on the frequency band, and $A \in [0,5]$ dB is the so-called *transmission anomaly*, which roughly accounts for the degradation of the acoustic intensity caused by multiple path propagation, refraction, diffraction, and scattering of sound caused by particulates, bubbles, and plankton within the water column. Its value is higher for shallow-water horizontal links (up to 10 dB), which are more affected by multipath [21]. More details can be found in [22] and [23].

Each sender i needs to 1) transmit enough power so that receiver j correctly decode the signal, and 2) avoid impairing ongoing communications (e.g., h to k and t to n in Fig. 3), thus accounting for the near-far effect. These guidelines are mathematically expressed by the following set of constraints,

$$\begin{cases} \dfrac{N^0+I_j}{\frac{P_{ij}}{TL_{ij}}} \le w_{ij}\cdot\Phi(BER_j), \\ \dfrac{N^0+I_k+\frac{P_{ij}}{TL_{ik}}}{S_k} \le w_{t_k k}\cdot\Phi(BER_k),\ \forall k\in\mathcal{K}_i. \end{cases} \qquad (3)$$

In (3), N^0 [W] is the average noise power, I_j and I_k [W] are the MAI at nodes j and $k \in \mathcal{K}_i$, with $\mathcal{K}_i$ being the set of nodes whose ongoing communications may be affected by node i's transmit power. Then, w_{ij} and $w_{t_k k}$ are the bandwidth spreading factors of the ongoing transmissions from i to j and from t_k to k, respectively, where t_k is the node transmitting to k. Furthermore, P_{ij} [W] represents the power transmitted by i to j when an ideal channel (without multipath, $A = 0$ dB) is assumed, i.e., when no power margin is considered to contrast the signal fading dips. Finally, TL_{ij} and TL_{ik} are the transmission losses from i to j and from i to $k \in \mathcal{K}_i$, respectively, while S_k [W] is the power of the signal that receiver k is decoding, and $\Phi()$ is a monotonically increasing function of the bit error rate (BER) representing the MAI threshold, which depends on the target BER at the receiver node [8]. We denote the noise and MAI power of a generic node n as $NI_n = N^0 + I_n$, and the normalized received spread signal, i.e., the signal power after despreading, as $\hat{S}_n = S_n \cdot w_{t_n n} \cdot \Phi(BER_n)$.

The first constraint in (3) states that the SINR^{-1} at receiver j needs to be below a certain threshold, i.e., the power P_{ij} transmitted by i needs to be sufficiently high to allow receiver j to successfully decode the signal, given its current noise, MAI power level (NI_j), and desired BER. The second constraint in (3) states that the SINR^{-1} at receivers $k \in \mathcal{K}_i$ must be below a threshold, i.e., the power P_{ij} transmitted by i must not impair the ongoing communications toward nodes $k \in \mathcal{K}_i$, given their normalized received user spread signals $(\hat{S}_k)$, and noise and MAI level (NI_k). By combining the constraints in (3), we obtain the following compact expression,

$$\frac{NI_j\cdot TL_{ij}}{w_{ij}\cdot\Phi(BER_j)} \le P_{ij} \le \min_{k\in\mathcal{K}_i}\left[(\hat{S}_k - NI_k)\cdot TL_{ik}\right]. \qquad (4)$$

Consequently, in order to set the transmit power P_{ij} and spreading factor w_{ij}, node i needs to leverage information on the MAI and normalized receiving spread signal of neighboring nodes. This information is broadcast periodically by active nodes, as depicted in Fig. 3. In particular, to limit the number of such broadcasts, a generic node n transmits only significant

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[5] The *hidden terminal problem* arises when the channel is sensed free by the sender although the receiver is already receiving another packet from another node, while the *exposed terminal problem* is encountered when the channel is sensed busy by the sender although the receiver is free to receive.

TABLE I
PACKET ERROR RATE AND NUMBER OF TRANSMISSIONS VS. SIGNAL AND POWER MARGINS

$\mathbf{m_{ij}}$	$\mathbf{m_{ij}^2}$	$\mathbf{PER_{ij}}$	$\mathbf{N_{ij}^T}$
0.5	0.25	0.8217	5.6093
0.75	0.5625	0.6429	2.8002
1	1	0.4559	1.8380
1.25	1.5625	0.2931	1.4147
1.5	2.25	0.1708	1.2060
1.75	3.0625	0.0902	1.0992
2	4	0.0432	1.0452

values of NI_n and $\hat{S}_n$, i.e., out of predefined tolerance ranges.

To save energy, node i will select a transmit power P_{ij} and a code length c_{ij} in such a way as to satisfy the set of constraints in (4) and to minimize the energy per bit $E_{ij}^b(P_{ij}, c_{ij}) = (P_{tx} + P_{ij}) \cdot c_{ij}/r$ [J/bit]. Here, P_{tx} [W] is a *distance-independent* component accounting for the power needed by the transmitter circuitry, and r [cps] is the *constant* underwater chip rate[6]. Because E_{ij}^b decreases as transmit power and code length decrease, where the relation between the spreading factor w_{ij} and the code length c_{ij} depends on the family of codes, i.e., $w_{ij} = \mathcal{W}^{\mathcal{C}}(c_{ij})$, the optimal solution is $c_{ij}^* = c_{min}$ and, from (4), $P_{ij}^* = \frac{NI_j \cdot TL_{ij}}{\alpha \cdot c_{min} \cdot \Phi(BER_i)}$, where we assumed the spreading factor to be proportional to the code length, i.e., $w_{ij} = \alpha \cdot c_{ij}$, and c_{min} to be the shortest chaotic code used. Note that this solution achieves the three objectives of minimizing the energy per bit E_{ij}^b that i needs to successfully communicate with j in the minimum possible time, i.e., minimize the energy consumption while transmitting at the highest possible data rate, i.e., r/c_{min}.

B. Shallow Water Channels

We assume now that the channel is heavily affected by multipath (*saturated condition* [4]) as it is often the case in shallow water [2]. In this environment, when the number of multiple rays goes to infinity, the signal fading can be modeled by a Rayleigh r.v. with unit mean, which accounts for a *worst-case scenario*. Under this assumption, the transmission loss between i and j is $TL_{ij} \cdot \rho^2$, where in shallow water $TL_{ij} = d_{ij} \cdot 10^{[\alpha(f) \cdot d_{ij} + A]/10}$, with $A \in [5, 10]$ dB, and ρ has a unit-mean Rayleigh cumulative distribution $D_\rho(\rho) = 1 - \exp(-\pi\rho^2/4)$. Let us define the *signal transmission margin* for link (i, j) as m_{ij}, where $P_{ij}^* \cdot m_{ij}^2$ [W] is the actual transmit power, while P_{ij}^* [W] represents the optimal transmission power in an ideal channel, as defined in Sect. IV-A, i.e., the transmit power before applying the margin to face the signal fading dips. The packet error rate PER_{ij} experienced on link (i, j) when sender i transmits at power $P_{ij}^* \cdot m_{ij}^2$ can be defined as the probability that the received power at node j be smaller than that required in an ideal channel (where no multipath is experienced), i.e.,

$$PER_{ij} = \Pr\left\{\frac{P_{ij}^* \cdot m_{ij}^2}{TL_{ij} \cdot \rho^2} \leq \frac{P_{ij}{}^*}{TL_{ij}}\right\} = \Pr\left\{\rho \geq m_{ij}\right\} = \\ = 1 - D_\rho(m_{ij}) = \exp\left(-\frac{\pi m_{ij}^2}{4}\right). \tag{5}$$

Hence, the average number of transmissions of a packet such that receiver j correctly decode it when it is transmitted using signal transmission margin m_{ij} is $N_{ij}^T(m_{ij}) = [1 - PER_{ij}]^{-1} = D_\rho(m_{ij})^{-1}$. Table I reports packet error rate and number of transmissions associated with different signal and power margins. This relation assumes independent errors among adjacent packets, which holds when the channel coherence time is shorter than the retransmission timeout, i.e., the time before retransmitting an unacknowledged packet. This assumption holds in most shallow-water environments where the channel coherence time is usually less than 0.5 s and the timeout, according to (1), is around 1 s for distances over 300 m, chip rates around 100 kcps, average code lengths of 20, and control and data packet sizes of 10 and 250 Byte, respectively.

We can now cast the power and code self-assignment optimization problem in a Rayleigh channel.

P: Power and Code Self-assignment Optimization Problem

Given : $i,\ j,\ P^{max}, r,\ TL_{ij},\ NI_j,\ BER_j;\ \hat{S}_k,\ NI_k, \forall k \in \mathcal{K}_i$
Find: $c_{ij}^* \in [c_{min}, c_{max}],\ P_{ij}^* \in \mathbb{R}^+,\ m_{ij}^* \in \mathbb{R}^+$
Minimize: $E_{ij}^b(c_{ij}, P_{ij}, m_{ij}) = \frac{(P_{tx} + P_{ij} \cdot m_{ij}^2) \cdot c_{ij}}{r} \cdot N_{ij}^T(m_{ij})$
Subject to:

$$N_{ij}^T(m_{ij}) = D_\rho(m_{ij})^{-1} = \left[1 - \exp\left(-\frac{\pi m_{ij}^2}{4}\right)\right]^{-1}; \tag{6}$$

$$P_{ij}^{min}(c_{ij}) \leq P_{ij} \leq \min\left[P_{ij}^{max}, P^{max}\right]; \tag{7}$$

$$P_{ij}^{min}(c_{ij}) \leq P_{ij} \cdot m_{ij}^2 \leq \min\left[P_{ij}^{max}, P^{max}\right]; \tag{8}$$

where

$$P_{ij}^{min}(c_{ij}) = \frac{NI_j \cdot TL_{ij}}{\alpha \cdot c_{ij} \cdot \Phi(BER_j)} = \frac{\Gamma_{ij}}{c_{ij}}, \tag{9}$$

$$\Gamma_{ij} = \frac{NI_j \cdot TL_{ij}}{\alpha \cdot \Phi(BER_j)}, \tag{10}$$

$$P_{ij}^{max} = \min_{k \in \mathcal{K}_i} \left[(\hat{S}_k - NI_k) \cdot TL_{ik}\right]. \tag{11}$$

Note that, in constraints (7) and (8), the transmit power *lower bound*, P_{ij}^{min}, is a *function* that depends on the chosen code length c_{ij}, which is a solution variable of $\mathbf{P}$, whereas the transmit power *upper bound*, $\min\left[P_{ij}^{max}, P^{max}\right]$, is a *constant* only depending on the node maximum transmit power, P^{max}, on the broadcast MAI, NI_k, and on the normalized received spread signal, $\hat{S}_k$. This means that by increasing the code length c_{ij} in (9), the lower bound P_{ij}^{min} decreases proportionally leading to a larger interval for the feasible output power, as defined by constraints (7) and (8).

While $\mathbf{P}$ may seem a fairly complex optimization problem, it admits a *low-complexity yet optimal closed-form solution*. To find it, we rely on a property of the objective function, i.e., the energy per bit $E_{ij}^b(c_{ij}, P_{ij}, m_{ij})$ monotonically decreases as P_{ij} and the code length c_{ij} decrease.

In order for $\mathbf{P}$ to admit a feasible solution, the constraint $P_{ij}^{min}(c_{ij}) \leq \min\left[P_{ij}^{max}, P^{max}\right]$ in (7) must hold, i.e.,

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[6] The chip rate r [cps] is proportional to the available acoustic spectrum B [Hz] and to the modulation spectrum efficiency η_B [cps/Hz], i.e., $r = \eta_B \cdot B$.

$c_{ij} \geq \frac{\Gamma_{ij}}{\min[P_{ij}^{max}, P^{max}]}$, where (9) was used. Consequently, to minimize the objective function, we want the optimal code length[7] c_{ij}^* to be

$$c_{ij}^* = \begin{cases} c_{min} & \text{if } \frac{\gamma \cdot \Gamma_{ij}}{\min[P_{ij}^{max}, P^{max}]} < c_{min}, \\ c_{max} & \text{if } \frac{\gamma \cdot \Gamma_{ij}}{\min[P_{ij}^{max}, P^{max}]} > c_{max}, \\ \frac{\gamma \cdot \Gamma_{ij}}{\min[P_{ij}^{max}, P^{max}]} & otherwise, \end{cases} \tag{12}$$

which can also be written in a compact form as,

$$c_{ij}^* = \max\left[\min\left[\frac{\gamma \cdot \Gamma_{ij}}{\min[P_{ij}^{max}, P^{max}]}, c_{max}\right], c_{min}\right], \tag{13}$$

where γ is a margin on the code length aimed at absorbing information inaccuracy. By substituting (13) into (9), given (7), we obtain the optimal transmit power *before* applying the margin to the channel, P_{ij}^*, as

$$P_{ij}^* = \min\left[\frac{\Gamma_{ij}}{c_{ij}^*}, P^{max}\right]. \tag{14}$$

Finally, by substituting (13) and (14) into the objective function, we obtain the energy per bit as a function of the margin only,

$$E_{ij}^b(c_{ij}, P_{ij}, m_{ij}) = E_{ij}^b(m_{ij}) = \frac{P_{tx} \cdot c_{ij}^* + \Gamma_{ij} \cdot m_{ij}^2}{r \cdot \left[1 - \exp\left(-\frac{\pi m_{ij}^2}{4}\right)\right]}, \tag{15}$$

which can be minimized to obtain the optimal margin m_{ij}^* as numeric solution of the following equation,

$$\frac{dE_{ij}^b}{dm_{ij}} = 0; \quad \Rightarrow \quad \frac{{m_{ij}^*}^2}{4} + \frac{\pi P_{tx} c_{ij}^*}{4\Gamma_{ij}} + 1 = \exp\left(\frac{\pi {m_{ij}^*}^2}{4}\right). \tag{16}$$

Note that $\mathbf{P}$ is feasible iff the optimal solution $(c_{ij}^*, P_{ij}^*, m_{ij}^*)$ meets constraint (8), i.e., iff $P_{ij}^* \cdot {m_{ij}^*}^2 \leq \min[P_{ij}^{max}, P^{max}]$. Otherwise, an energy-efficient *suboptimal* solution, $(c_{ij}^+, P_{ij}^+, m_{ij}^+)$, would be $c_i^+ = c_{max}$ for the code length and $P_{ij}^+ \cdot {m_{ij}^+}^2 = \min[P_{ij}^{max}, P^{max}]$ for the output power.

The computational complexity of the proposed optimal closed-form solution is low as the most computation-intense operation is finding the solution to (16). Many numerical low-complexity iteration-based algorithms such as the *Newton descending approximation* can be effectively used to this end. Moreover, a transmitting node does not have to adjust its transmit power and code length every time it needs to communicate, but only if any of the inputs of $\mathbf{P}$ has consistently changed. In fact, while it is true that the solution of problem $\mathbf{P}$ depends on many inputs (data traffic, channel status, neighborhood, etc.), the algorithm does not need to run every time the channel status changes because it uses power margins at the transmitter to absorb small channel variations; rather, it needs to run only when the interference levels of neighboring nodes change significantly, i.e., mainly when the traffic changes. Not only does this make the computational burden on low-end sensors easily affordable, but it also helps reach system stability while limiting the signaling overhead. In addition, as shown in Section V, the solution is more traffic dependent than channel dependent, which is a good feature because the traffic in UW-ASN applications is in general less dynamic than the underwater channel.

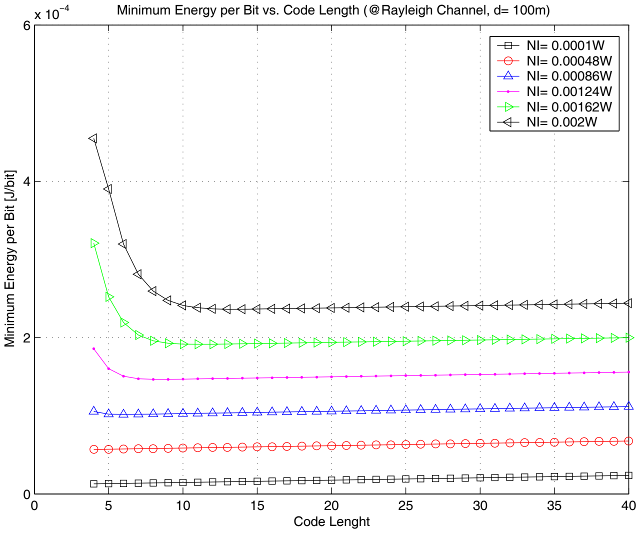

Fig. 4. Minimum energy per bit vs. code length (Rayleigh Channel).

Differently from the deep water case, analyzed in Sect. V-A, the energy per bit in a Rayleigh channel skyrockets when an adequate power margin is not used. This is because of the high number of packet retransmissions, as accounted by (6). Moreover, a trade-off between the optimal transmit power and code length occurs, which suggests that it is not always possible to *jointly* achieve the highest data rate and the lowest energy consumption, as it is possible in a channel that is not affected by multipath.

This non-trivial result is confirmed by Fig. 4, where the minimum energy per bit in a Rayleigh channel under different MAI power levels (NI_j) at receiver j is reported, when the code length c_{ij} ranges from $c_{min} = 4$ to $c_{max} = 40$. As previously anticipated, when the MAI at the receiver side is higher than a certain threshold $(NI_j \geq 0.86 \text{ mW})$ it is not possible anymore to select the highest data rate, i.e., the shortest code, to achieve the minimum energy per bit. Conversely, with low MAI at the receiver, this twofold objective can still be achieved. In fact, the lowest two monotonic curves in Fig. 4, which are associated with NI_j equal to 0.1 and 0.48 mW, show that the minimum energy per bit is achieved when the code length is minimum $(c = c_{min})$, i.e., when the transmit rate is maximum. Conversely, the upper curves have minima that are not associated with the lowest code length, which shows the need to find a trade-off between energy consumption and transmission rate. This trade-off will depend on the specific application requirements (e.g., maximize the network lifetime or maximize the network performance, respectively).

V. PERFORMANCE EVALUATION

In this section, we discuss performance results of UW-MAC, presented in Sect. III, for two different UW-ASN architectures introduced in [2] and summarized in Sect. III-A, the *two-dimensional deep water* and the *three-dimensional*

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[7] Note that, by using *chaotic codes* as opposed to *pseudo-random sequences*, a much higher granularity in the choice of the code length can be achieved; code lengths, in fact, do not need to be a power of 2.

shallow water with mobile AUVs. In addition, we evaluate the added benefit in terms of energy consumption, channel access delay, and network throughput of multi-user over single-user detectors on high-end devices. A wide variety of conditions and scenarios have been considered to capture relevant underwater setups. To accomplish this, we evaluate two versions of our proposed MAC solution. In particular, we refer to *UW-MACsgl* as the case where all nodes implement a single-user detector, and to *UW-MACmlt* as the case where resource-rich devices such as uw-gateways, surface stations and AUVs implement a multi-user detector, while low-end sensor nodes implement a single-user detector. We will show that, while both UW-MACsgl and UW-MACmlt consistently outperform competing MAC schemes, their performance is similar in most architecture and traffic scenarios, although UW-MACmlt shows slightly better results in dense and high traffic scenarios as it compensates for the traffic concentration problem occurring at the surface station and at the uw-gateways.

We implemented the entire protocol stack of a sensor node in a C++ based discrete-event simulator to simulate the characteristics of UW-ASNs in the underwater environment. We accurately modeled the underwater transmission loss, the transmission and propagation delays, and the physical layer characteristics of underwater receivers, as well as all other communication functionalities. We decided to not implement the MAC protocol proposed in [17] since its objectives differ from those of our CDMA MAC solution, as described in Sect. II, and a fair comparison would not be possible. Rather, we compare the two versions of UW-MAC, UW-MACsgl and UW-MACmlt, with four existing random access MAC protocols, which we optimized to the underwater environment, i.e., CSMA, CSMA with power control (CSMApw), IEEE 802.11, and ALOHA. In particular, in IEEE 802.11, the value of the slot time in the backoff mechanism has to account for the propagation delay at the physical layer. Hence, while it is set to 20 μs for 802.11 DSSS, a value of 0.18 s is needed to allow devices a few hundred meters apart to share the underwater medium. This implies that the delay introduced by the backoff contention mechanism is several orders of magnitude higher than in terrestrial channels, which in turn leads to low channel utilization efficiencies. In addition, we set the values of the contention windows CW_{min} and CW_{max} to 8 and 64, respectively, whereas in 802.11 DSSS they are set to 32 and 1024, and the binary backoff coefficient to 1.5, whereas it is usually set to 2 in terrestrial implementations.

In all the simulation scenarios, we considered a common set of parameters, which is reported in the following, whereas specific parameters for each architecture are reported in the appropriate section. We set the chip rate r to 100 kcps[8], the minimum code length c_{min} to 4 (i.e., the maximum shared data rate to 25 kbps) and the maximum c_{max} to 40 (i.e., the minimum shared data rate to 2.5 kbps), the maximum transmission power P^{max} to 10 W, the data packet size to 250 Bytes, the control (EH and ACK) and header packet size to 10 Bytes, the initial node energy to 1000 J, the queue size to 10 kBytes, and the transmission anomalies caused by multipath in deep and shallow water to 0 and 5 dB, respectively. Moreover, all deployed sensors are sources, with packet inter-arrival time equal to 20 s, which allows us to simulate a *low-intensity background monitoring traffic* from the entire volume toward the surface station, which is centered on the surface of the underwater volume.

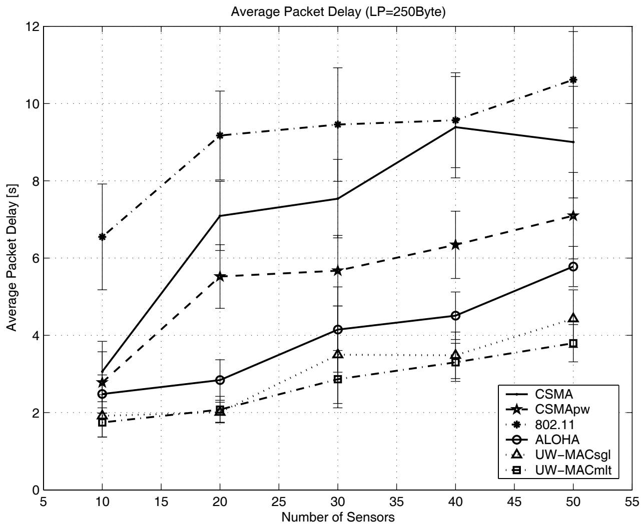

Fig. 5. **2D Deep Water UW-ASNs:** average packet delay vs. number of sensors.

Finally, we adopted a geographical routing algorithm tailored for UW-ASNs, which we proposed in [24], according to which each node selects its next hop with the objective of minimizing the energy consumption. The routing algorithm aims at exploiting those underwater links that guarantee a low packet error rate to maximize the probability that a packet be correctly decoded at the receiver, and thus minimize the number of required packet retransmissions. In order to provide statistical meaning to the collected performance data, simulation results are averaged on several experiments to obtain small 95% confidence relative intervals, which are showed in the figures.

A. Two-dimensional Deep Water UW-ASNs

We consider a variable number of sensors $(10, 15, \cdots, 50)$ randomly deployed on the bottom of a deep water volume of $500\text{x}500\text{x}500\ \text{m}^3$. The underwater gateways are randomly deployed on the bottom as well, and their number is varied in such a way as to be 20% of the total number of deployed sensors. The antenna gain at the transmitting and receiving side of a vertical link is set to 10 dBi, according to data sheets of available long-haul hydrophones (underwater microphones) [2]. Different deployment strategies for two-dimensional and three-dimensional communication architectures for UW-ASNs are proposed in [25], where statistical deployment analysis for both architectures is also provided.

Figures 5, 6, and 7 present the overall performance of the competing MAC protocols when the number of deployed

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[8] A chip rate of 100 kcps can be achieved using a M-QAM modulation technique with spectral efficiency $\eta = 4$ cps/Hz (i.e., with constellation $M = 4$) and available acoustic bandwidth $B = 25$ kHz. By moving to a higher-order constellation, it is possible to transmit more bits per symbol using the same bandwidth (*higher spectral efficiency*), although at the price of higher energy per bit required for a target BER (*lower power efficiency*).

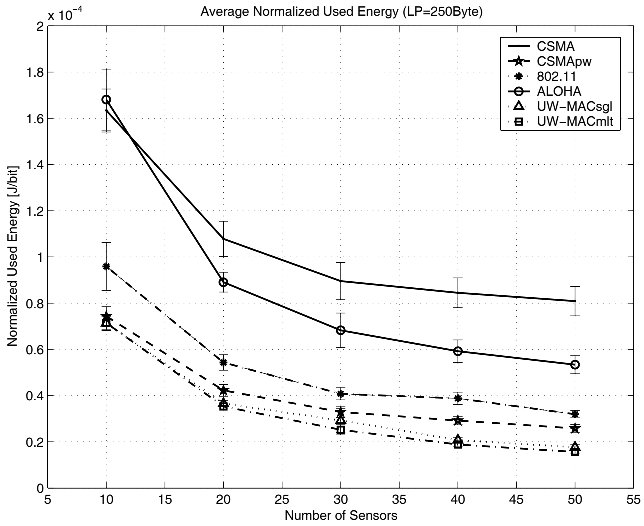

Fig. 6. **2D Deep Water UW-ASNs:** average normalized used energy vs. no. of sensors.

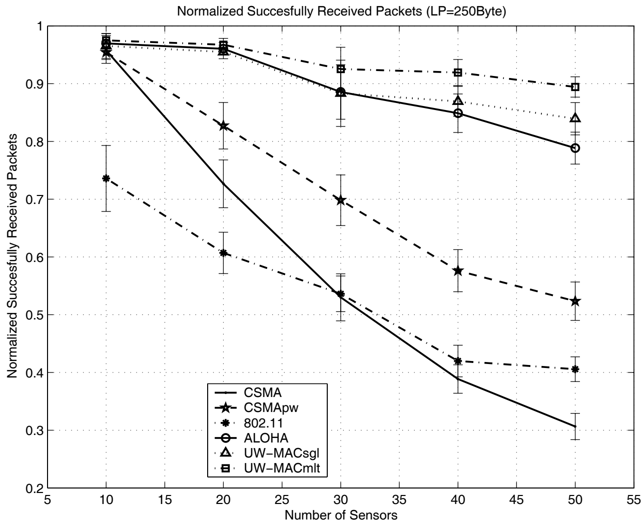

Fig. 7. **2D Deep Water UW-ASNs:** normalized successfully received packets vs. no. of sensors.

sensors and uw-gateways increases. Figure 5 shows that both UW-MACsgl and Uw-MACmlt have a much smaller average packet delay than the competing schemes, and that for this architecture scenario their performance is very similar. In particular, it is pointed out that the RTS/CTS handshaking of 802.11 yields high delays in the low-bandwidth high-delay underwater environment. As far as the energy per successfully received bit is concerned, we note that our MAC solutions are the most energy efficient (Fig. 6).

The highest successfully received number of packets is associated with our UW-MACmlt (Fig. 7), which takes advantage of its multi-user receiving capabilities. All the schemes relying on carrier sense (CSMA, CSMApw, and 802.11) perform poorly as this mechanism prevents collisions with the current transmissions only at the transmitter side. To prevent collisions at the receiver side it would be necessary to add a guard time between transmissions dimensioned according to the maximum propagation delay in the network, which would make the protocols dramatically inefficient in the underwater environment. Consequently, the *hidden terminal* and the *exposed terminal* problems are the main causes for the low performance of MAC schemes relying on carrier sense.

As a final remark, the use of contention-based techniques that rely on handshaking mechanisms such as RTS/CTS in shared medium access (e.g., MACA, IEEE 802.11) is impractical in underwater, for the following reasons: i) large delays in the propagation of RTS/CTS control packets lead to low channel utilization efficiency and throughput; ii) because of the high underwater acoustic propagation delay, when carrier sense is used, it is more likely that the channel will be sensed idle while a transmission is taking place, as the signal may not have reached the receiver yet; iii) the variability of delay in handshaking packets makes it impractical to accurately predict the start and finish time of other nodes' transmissions.

B. Three-dimensional Shallow Water UW-ASNs with Mobile AUVs

We consider a variable number of sensors $(10, 15, \cdots, 50)$ randomly deployed in the 3D shallow water with volume of $500\text{x}500\text{x}50\ \mathrm{m}^3$, which may represent a small harbor, and 3 AUVs moving in the entire volume according to the Random Waypoint mobility model. We set their velocity to $3\ \mathrm{m/s}$ and no pause between consecutive movements. Note that the high velocity and the continuous movement simulate a worst-case mobility scenario. In all MAC schemes, AUVs broadcast location update messages when their position has changed by more than $20\ \mathrm{m}$. We modeled the multipath phenomenon by considering a worst-case scenario consisting of a saturated fast fading Rayleigh channel with coherence time equal to $1\ \mathrm{s}$. Compared to the 2D deep water scenario, in this shallow water scenario the overall performance of our solution is even better with respect to the competing MAC schemes mainly because of the higher channel reuse achieved. When the number of sensors increases, the implemented routing algorithm [24] has a higher flexibility in the choice of data paths, which rely more on multi-hop communications, thus increasing their average number of hops. While at the routing layer this decreases the expected end-to-end energy to forward packets [24], higher interference is generated at the MAC layer. Interestingly, both versions of our UW-MAC solution show very good robustness to this effect, while their competing MAC schemes are negatively affected, as shown in Figs. 8, 9, and 10. Further cross-layer communication protocol interactions are analyzed in [26].

Specifically, these figures report the overall performance in this simulation setting, and show the robustness of our MAC solutions against inaccurate node position and interference information mainly caused by mobility, traffic unpredictability, and packet loss due to channel impairment. In particular, Figs. 9 and 10 show the significant improvements of UW-MAC over other MAC solutions, both in terms of energy ($15\ \mu\mathrm{J/bit}$ vs. $30 - 40\ \mu\mathrm{J/bit}$ and over) and normalized received packets $(0.7 - 0.9$ vs. 0.3 for more than 35 sensors).

VI. CONCLUSIONS

In this article, UW-MAC, a distributed Medium Access Control (MAC) protocol for underwater acoustic sensor net-

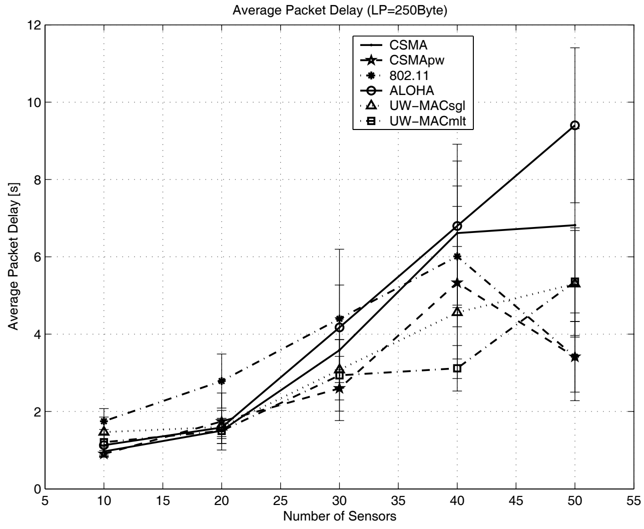

Fig. 8. **3D Shallow Water UW-ASNs with AUVs:** average packet delay vs. number of sensors.

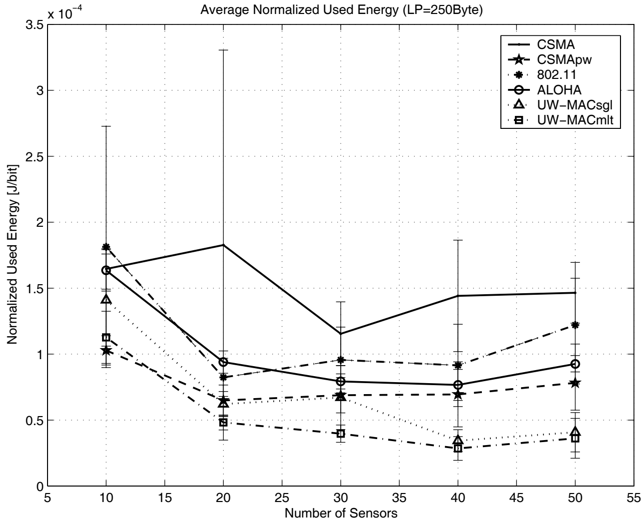

Fig. 9. **3D Shallow Water UW-ASNs with AUVs:** average normalized used energy vs. no. of sensors.

works, was introduced. The proposed MAC protocol is a transmitter-based Code Division Multiple Access (CDMA) scheme that incorporates a closed-loop distributed algorithm to jointly set the optimal transmit power and code length. It is demonstrated that UW-MAC manages to simultaneously achieve high network throughput, limited channel access delay, and low energy consumption in deep water communications (where the ocean depth is more than 100 m), which are not severely affected by multipath. In shallow water communications, which are heavily affected by multipath, UW-MAC dynamically finds the optimal trade-off among these objectives according to the application requirements. Experiments showed that UW-MAC outperforms competing MAC protocols under all considered network architecture scenarios and simulation settings.

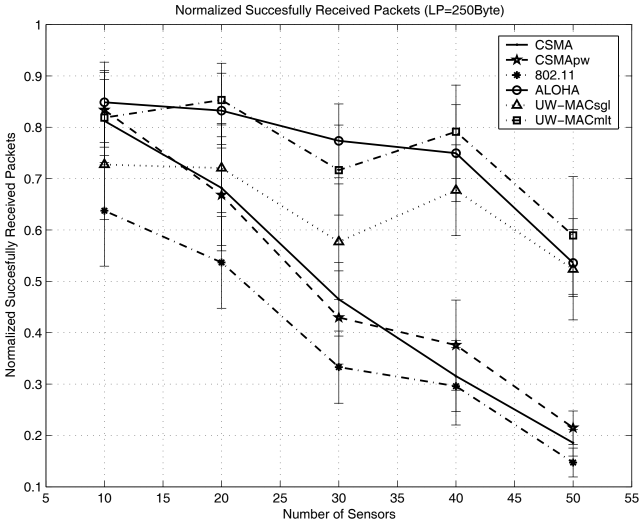

Fig. 10. **3D Shallow Water UW-ASNs with AUVs:** normalized successfully received packets vs. no. of sensors.

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Dario Pompili joined the faculty of the Electrical and Computer Engineering Department at Rutgers, The State University of New Jersey, as Assistant Professor in Fall 2007. He received his Ph.D. in Electrical and Computer Engineering from the Georgia Institute of Technology in June 2007 after working at the Broadband Wireless Networking Laboratory (BWN-Lab) under the direction of Prof. I. F. Akyildiz. In 2005, he was awarded Georgia Institute of Technology BWN-Lab Researcher of the Year for “outstanding contributions and professional achievements.” He had previously received his ‘Laurea’ (integrated B.S. and M.S.) and Doctorate degrees in Telecommunications Engineering and System Engineering from the University of Rome “La Sapienza,” Italy, in 2001 and 2004, respectively. His research interests include ad hoc and sensor networks, underwater acoustic communications, wireless sensor and actor networks, and network optimization and control. He is author and co-author of many influential papers in these fields. He is on the editorial board of AD HOC NETWORKS (Elsevier) journal and on the technical program committees of several international conferences on networking. He is also member of the IEEE Communications Society and the ACM.

Tommaso Melodia is an Assistant Professor with the Department of Electrical Engineering at the University at Buffalo , The State University of New York (SUNY), where he directs the Wireless Networks and Embedded Systems Laboratory. He received his Ph.D. in Electrical and Computer Engineering from the Georgia Institute of Technology in June 2007 after working at the Broadband Wireless Networking Laboratory (BWN-Lab) under the direction of Prof. I. F. Akyildiz. He had previously received his ‘Laurea’ (integrated B.S. and M.S.) and Doctorate degrees in Telecommunications Engineering from the University of Rome “La Sapienza," Rome, Italy, in 2001 and 2005, respectively. He is the recipient of the BWN-Lab Researcher of the Year award for 2004, and he is the author of about 40 publications in leading conferences and journals on wireless networking. He is an Associate Editor for the COMPUTER NETWORKS (Elsevier) Journal and for the Hindawi JOURNAL OF SENSORS and he serves on the technical program committee of several leading conferences in wireless communications and networking. He is the technical co-chair of the Ad Hoc and Sensor Networks Symposium for IEEE ICC 2009. His current research interests are in modeling and optimization of multi-hop wireless networks, wireless multimedia sensor and actor networks, underwater acoustic sensor networks, and cognitive radio networks.

Ian F. Akyildiz is the Ken Byers Distinguished Chair Professor with the School of Electrical and Computer Engineering, Georgia Institute of Technology and Director of Broadband Wireless Networking Laboratory. He is Editor-in-Chief of Computer Networks, Ad Hoc Networks, and Physical Communication Journals (all with Elsevier). Dr. Akyildiz is an IEEE Fellow (1995) and an ACM Fellow (1996). He served as a National Lecturer for ACM from 1989 until 1998 and received the ACM Outstanding Distinguished Lecturer Award for 1994. Dr. Akyildiz received the 1997 IEEE Leonard G. Abraham Prize award (IEEE Communications Society) for his paper entitled “Multimedia Group Synchronization Protocols for Integrated Services Architectures” published in the IEEE JOURNAL OF SELECTED AREAS IN COMMUNICATIONS (JSAC) in January 1996. Dr. Akyildiz received the 2002 IEEE Harry M. Goode Memorial award (IEEE Computer Society) with the citation “for significant and pioneering contributions to advanced architectures and protocols for wireless and satellite networking”. Dr. Akyildiz received the 2003 IEEE Best Tutorial Award (IEEE Communication Society) for his paper entitled “A Survey on Sensor Networks”, published in IEEE Communication Magazine, in August 2002. Dr. Akyildiz received the 2003 ACM SIGMOBILE award for his significant contributions to mobile computing and wireless networking. Since June 2008 he is an Honorary Professor with the School of Electrical Engineering at the Universitat Politecnico de Catalunya, Barcelona , Spain. His current research interests are in cognitive radio networks, sensor networks, and nanonetworks