A Distributed CDMA Medium Access Control for Underwater Acoustic Sensor Networks

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***Abstract*— In this paper, UW-MAC, a distributed Medium Access Control (MAC) protocol tailored for UnderWater Acoustic Sensor Networks (UW-ASNs), is proposed. It is a transmitter-based Code Division Multiple Access (CDMA) scheme that incorporates a novel closed-loop distributed algorithm to set the optimal transmit power and code length. UW-MAC aims at achieving three objectives, i.e., guarantee high network throughput, low channel access delay, and low energy consumption. Experiments show that UW-MAC outperforms existing MAC protocols tuned for the underwater environment under different architecture scenarios and simulation settings.**

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 [1]. Acoustic communications are the typical physical layer technology in underwater networks. In fact, radio waves propagate through conductive salty water only at extra low frequencies $(30 - 300\,\mathrm{Hz})$, which require large antennae and high transmission power. Optical waves do not suffer from such high attenuation but are affected by scattering. Thus, links in underwater networks are usually based on *acoustic wireless communications*, which pose unique challenges due to the harsh underwater environment such as limited bandwidth [2], high and variable propagation delays [3], high bit error rates and temporary losses of connectivity caused by multipath and fading phenomena [4], and asymmetric links.

A major challenge for the deployment of UnderWater Acoustic Sensor Networks (UW-ASNs) [1] 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*, and *low channel access delay* and *energy consumption*, in face of the harsh characteristics of the underwater propagation medium, while guaranteeing *fairness* among competing nodes.

Code Division Multiple Access (CDMA) is the most promising physical layer and multiple access technique for UW-ASNs since i) it is robust to frequency-selective fading, ii) compensates for the effect of multipath by exploiting Rake filters [5] at the receiver, and iii) allows receivers to distinguish among signals simultaneously transmitted by multiple devices. As a result, CDMA increases channel reuse and reduces packet retransmissions, which results in decreased energy consumption and increased network throughput.

For these reasons, in this paper we introduce UW-MAC, a transmitter-based CDMA MAC protocol for UW-ASNs that incorporates a novel closed-loop distributed algorithm to set the optimal transmit power and code length to minimize the *near-far effect*[1][6]. UW-MAC leverages a *multi-user detector* on resource-rich devices such as surface stations and underwater gateways, and a *single-user detector* on low-end sensors. 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 prove that UW-MAC manages to simultaneously achieve the three objectives in deep water communications, which are 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.

We also formulate the distributed power and code self-assignment problem to minimize the near-far effect, and propose a low-complexity yet optimal solution. UW-MAC uses locally generated chaotic codes to spread transmitted

[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.

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

signals on the available bandwidth, which guarantees a flexible and granular bit rate, secure protection against eavesdropping, transmitter-receiver self-synchronization, and good auto- and cross-correlation properties [7]. 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 existing papers [8][9] considered CDMA schemes merely from a physical layer perspective.

The main features that characterize UW-MAC are: i) it provides a *unique and flexible solution* for different architectures such as static two- and three-dimensional in deep and shallow water; ii) it is *fully distributed*, since spreading codes and transmit power are distributively selected by each sender without relying on a centralized entity; iii) it is *intrinsically secure*, since it uses chaotic codes; iv) it *fairly shares* the bandwidth among active devices; and v) it *efficiently supports multicast transmissions*, since spreading codes are decided at the transmitter side.

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

II. Related Work

There has been intensive research on MAC protocols for ad hoc [10] and wireless terrestrial sensor networks [11] in the last decade. However, due to the different nature of the underwater environment and applications, existing terrestrial MAC solutions are unsuitable for this environment. In fact, channel access control in UW-ASNs poses additional challenges due to the peculiarities of the underwater channel, in particular limited bandwidth, very high and variable propagation delays, high bit error rates, temporary losses of connectivity, channel asymmetry, and heavy multipath and fading phenomena. 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 [1]. Here, we mainly concentrate on previous work on CDMA, since this is the most promising physical layer and multiple access technique for UW-ASNs.

In [8], 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 different simultaneous communications use different hopping sequences and transmit on different frequency bands. Interestingly, [8] 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 [9], which may offer higher spectral efficiency than its single-carrier counterpart. 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 low. Remarkably, the above papers [8][9] 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. Instead, our contribution is to develop a dynamic multiple access protocol for UW-ASNs that efficiently shares the scarce underwater channel bandwidth by fully leveraging the CDMA medium access properties.

In [12], Slotted FAMA, a protocol based on a channel access discipline called Floor Acquisition Multiple Access (FAMA) is proposed. It combines both carrier sensing (CS) and a dialogue between the source and receiver prior to data transmission. Time slotting eliminates the asynchronous nature of the protocol and the need for long control packets, thus providing energy savings. However, guard times should be inserted in the time slot to account for any system clock drift. In addition, because of the high underwater acoustic propagation delay, the handshaking mechanism may lead to low system throughput, and the CS scheme may sense the channel idle while a transmission is still taking place, thus causing packet collisions.

A distributed CSMA-based energy-efficient MAC protocol for the underwater environment was recently proposed in [13]. 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, we decided not to incorporate it in the basic protocol to make it suitable for a variety of traffic, architecture, and deployment scenarios.

III. UW-MAC: A CDMA MAC for UW-ASNs

UW-MAC is a transmitter-based Direct Sequence CDMA (DS-CDMA) scheme for UW-ASNs that implements a novel *closed-loop distributed algorithm* to set the optimal transmit power and code length to minimize the near-far effect. UW-MAC leverages a *multi-user detector* on resource-rich devices such as uw-gateways and surface stations, 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. 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.

Single-user detection (SUD) devices use low-cost conventional Rake receivers [5] 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 [14]. These techniques, however, usually require channel estimation and knowledge of all the active user spreading codes, and have considerable computational cost. 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, UW-MAC relies on low-complexity single-user detectors on low-end underwater sensor nodes.

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. 1. Here, node i needs to transmit a data packet to j, without impairing ongoing communications from h to k and from t to n. Since the system efficiency is limited by the amount of total interference, it is crucial for i to optimize its transmission, in terms of transmit power and code length, to limit the near-far problem. The power and code self-assignment problem is formally introduced in Section 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

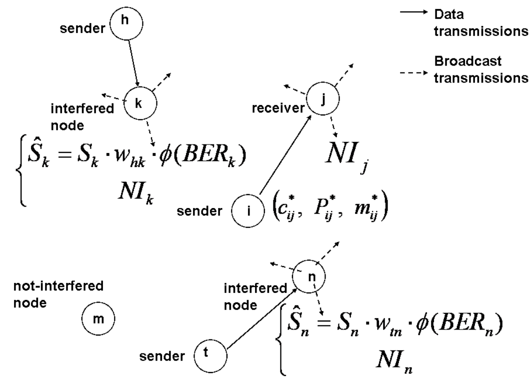


Fig. 1. Data and broadcast message transmissions

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 parameters that i will use to generate the *chaotic spreading code* for the actual data packet, of size L_D 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 $\overline{q} \approx 1500\,\mathrm{m/s}$, 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 synchronize to the signal from i, despread the EH using the common code, and 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 i used to send its data packet, and set its decoder according to this chaotic code in such a way as to decode the data packet. Once j has correctly received the data packet from i, it acknowledges it by sending an ACK packet, of size L_A bits, to j using code c_A. 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, i.e., $T_{out} \geq c_{EH} \cdot L_{EH}/r + c_{ij} \cdot L_D/r + 2d_{ij}/\overline{q} + c_A \cdot L_A/r$.

Note that if sender i does not have updated information 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., $c_{ij}^{N^T_{ij}} = \min[c_{ij}^{N^T_{ij}-1} \cdot 2^{\beta}, c_{max}]$, where $1 \leq N^T_{ij} \leq N^T_{max}$ and $\beta \in \mathbb{R}^+$. As will be shown in Section V, this mechanism guarantees stability and decreases transients, although it temporarily decreases the transmission data rate.

IV. Power and Code Self-assignment Problem

Hereafter, 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 that does not rely on feedback from the receiver would rely on the symmetric link assumption, which does not hold in the underwater environment.

A. Deep Water Channels

We consider a deep water acoustic channel, which is not severely affected by multipath, where the transmission loss TL_{ij} that a narrow-band acoustic signal centered at frequency $f\,[\mathrm{kHz}]$ experiences between nodes i and j at distance $d\,[\mathrm{m}]$ is described by the Urick propagation model [15], $TL_{ij} = d_{ij}^2 \cdot 10^{[\alpha(f)\cdot d_{ij}+A]/10}$, where $\alpha(f)\,[\mathrm{dB/m}]$ represents the *medium absorption coefficient*, and $A \in [0,5]\,\mathrm{dB}$ is the so-called *transmission anomaly*, which accounts for the degradation of the acoustic intensity caused by multiple path propagation, refraction, diffraction, and scattering of sound.

Each node i needs to i) limit the near-far effect when it transmits to j and ii) avoid impairing ongoing communications. These constraints are mathematically expressed by the following equations,

$$\begin{cases} \frac{N^0+I_j}{\frac{P_{ij}}{TL_{ij}}} \leq w_{ij} \cdot \Phi(BER_j) \\ \frac{N^0+I_k+\frac{P_{ij}}{TL_{ik}}}{S_k} \leq w_{t_k k} \cdot \Phi(BER_k),\ \forall k \in \mathcal{K}_i. \end{cases} \quad (1)$$

In (1), $N^0\,[\mathrm{W}]$ is the average noise power, I_j and I_k $[\mathrm{W}]$ 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, $P_{ij}\,[\mathrm{W}]$ represents the power transmitted by i to j when an ideal channel (without multipath, i.e., $A = 0\,\mathrm{dB}$) is assumed, i.e., when no power margin is considered to face the 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 $S_k\,[\mathrm{W}]$ is the power of the signal that receiver k is decoding, and $\Phi()$ is the MAI threshold, which depends on the target bit error rate (BER) at the receiver node (see [6]). We will 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 (1) 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 and MAI power level (NI_j). The second constraint in (1) states that the SINR^{-1} at receivers $k \in \mathcal{K}_i$ must not be above a threshold, i.e., the power P_{ij} transmitted by i must not impair the ongoing communications toward nodes $k \in \mathcal{K}_i$. By combining the constraints in (1), we obtain the following compact expression,

$$\frac{NI_j \cdot TL_{ij}}{w_{ij}\cdot\Phi(BER_j)} \leq P_{ij} \leq \min_{k\in\mathcal{K}_i} \left[(\hat{S}_k - NI_k)\cdot TL_{ik}\right]. \quad (2)$$

Consequently, 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. 1. In particular, to limit such broadcasts, a generic node n transmits only significant 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 (2) and to minimize the energy per bit $E_{ij}^b(P_{ij}, c_{ij}) = (P_{tx} + P_{ij}) \cdot c_{ij}/r\,[\mathrm{J/bit}]$. Here, $P_{tx}\,[\mathrm{W}]$ is a *distance-independent* component accounting for the power needed by the transmitting circuitry, and $r\,[\mathrm{cps}]$ the *constant* underwater chip rate, which is proportional to the available acoustic spectrum $B\,[\mathrm{Hz}]$ and to the modulation spectrum efficiency η_B, i.e., $r = \eta_B \cdot B$. Since E_{ij}^b decreases as transmit power and code length decrease, and since 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 $P_{ij}^* = NI_j \cdot TL_{ij}/[\alpha \cdot c_{min} \cdot \Phi(BER_i)]$, where we assumed the spreading factor to be proportional to the code length, i.e., $w_{ij} = \alpha \cdot c_{ij}$. 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*, see [3]) as it is often the case in shallow water [1]. In this environment, the signal fading can be modeled by a Rayleigh r.v., which accounts for a *worst-case scenario*, and the transmission loss between i and j is $TL_{ij} \cdot \rho^2$, where $TL_{ij} = d_{ij} \cdot 10^{[\alpha(f)\cdot d_{ij}+A]/10}$, with $A \in [5,10]\,\mathrm{dB}$, 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 $P_{ij}^* \cdot m_{ij}^2\,[\mathrm{W}]$ is the actual transmit power, while $P_{ij}^*\,[\mathrm{W}]$ represents the optimal transmission power in an ideal channel, as introduced in Section IV-A, i.e., the transmit power before applying the margin to face the fading dips. The packet error rate PER_{ij} experienced on link (i,j) when sender i transmits 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.,

$$PER_{ij} = \Pr\left\{\frac{P_{ij}^{*} \cdot m_{ij}^2}{TL_{ij} \cdot \rho^2} \leq \frac{P_{ij}{}^{*}}{TL_{ij}}\right\} = \Pr\left\{\rho \geq m_{ij}\right\} = \\ = 1 - D_{\rho}(m_{ij}) = \exp\left(-\frac{\pi m_{ij}^2}{4}\right). \tag{3}$$

Hence, the average number of transmissions of a packet such that receiver j correctly decodes it when it is sent with signal transmission margin m_{ij} is $N_{ij}^{T}(m_{ij}) = [1 - PER_{ij}]^{-1} = D_{\rho}(m_{ij})^{-1}$. 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. We can now cast the power and code self-assignment optimization problem in a Rayleigh channel.

$\mathbf{P}$: **Power and Code Self-assignment Optimization Problem**

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

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

$$P_{ij}^{min}(c_{ij}) \leq P_{ij} \leq \min\left[P_{ij}^{max}, P^{max}\right]; \tag{5}$$

$$P_{ij}^{min}(c_{ij}) \leq P_{ij} \cdot m_{ij}^2 \leq \min\left[P_{ij}^{max}, P^{max}\right]; \tag{6}$$

where

$$P_{ij}^{min}(c_{ij}) = \frac{NI_j \cdot TL_{ij}}{\alpha \cdot c_{ij} \cdot \Phi(BER_j)} = \frac{\Gamma_{ij}}{c_{ij}}, \tag{7}$$

$$\Gamma_{ij} = \frac{NI_j \cdot TL_{ij}}{\alpha \cdot \Phi(BER_j)}, \tag{8}$$

$$P_{ij}^{max} = \min_{k \in \mathcal{K}_i} \left[(\hat{S}_k - NI_k) \cdot TL_{ik}\right]. \tag{9}$$

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 minimum energy per bit E_{ij}^{b} monotonically decreases as P_{ij} and the code length c_{ij} decrease. $\mathbf{P}$ *may* admit a feasible solution if in (5) $P_{ij}^{min}(c_{ij}) \leq \min\left[P_{ij}^{max}, P^{max}\right]$ holds, i.e., if $c_{ij} \geq \frac{\Gamma_{ij}}{\min\left[P_{ij}^{max}, P^{max}\right]}$. Consequently, to minimize the objective function, we want the optimal code length[3] c_{ij}^{*} to be

$$c_{ij}^{*} = \max\left[\min\left[\frac{\gamma \cdot \Gamma_{ij}}{\min\left[P_{ij}^{max}, P^{max}\right]}, c_{max}\right], c_{min}\right], \tag{10}$$

where γ is a margin on the code length aimed at absorbing information inaccuracy. By substituting (10) into (7), given (5), we obtain the optimal transmit power *before* applying the margin to the channel, P_{ij}^{*}, as

$$P_{ij}^{*} = \min\left[\frac{\Gamma_{ij}}{c_{ij}^{*}}, P^{max}\right]. \tag{11}$$

Finally, by substituting (10) and (11) into the objective function, we obtain the energy per bit as a function of the margin only,

$$E_{ij}^{b}(m_{ij}) = \frac{P_{tx} \cdot c_{ij}^{*} + \Gamma_{ij} \cdot m_{ij}^2}{r \cdot \left[1 - \exp\left(-\frac{\pi m_{ij}^2}{4}\right)\right]}, \tag{12}$$

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

$$\frac{dE_{ij}^{b}}{dm_{ij}} = 0;\ \Rightarrow\ \frac{m_{ij}^{*}{}^2}{4} + \frac{\pi P_{tx} c_{ij}^{*}}{4\Gamma_{ij}} + 1 = \exp\left(\frac{\pi m_{ij}^{*}{}^2}{4}\right). \tag{13}$$

Note that $\mathbf{P}$ is feasible iff the optimal solution $(c_{ij}^{*}, P_{ij}^{*}, m_{ij}^{*})$ meets constraint (6), i.e., iff $P_{ij}^{*} \cdot m_{ij}^{*}{}^2 \leq \min\left[P_{ij}^{max}, P^{max}\right]$. Otherwise, an energy-efficient suboptimal solution, $(c_{ij}^{+}, P_{ij}^{+}, m_{ij}^{+})$, would be $c_i^{+} = c_{max}$ and $P_{ij}^{+} \cdot m_{ij}^{+2} = \min\left[P_{ij}^{max}, P^{max}\right]$.

The computational complexity of the proposed optimal closed-form solution is very low since the most computation-intense operation is finding the solution to (13). Many numerical algorithms such as the *Newton descending approximation* can be effectively used. 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. 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, as will be shown in Section V.

Differently from the deep water case, the energy per bit in a Rayleigh channel skyrockets when an adequate power margin is not used, because of the high number of packet retransmissions, as accounted by (4). 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.

V. Performance Evaluation

In this section, we discuss performance results of UW-MAC, presented in Section III, for two different UW-ASN architectures described in [1], the *two-dimensional deep water* and the *three-dimensional shallow water*. In addition, we evaluate the added benefit in terms of energy consumption, channel access delay, and network

[3]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.

throughput of multi-user detectors over single-user detectors, introduced in Section III, in a wide variety of conditions and scenarios 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 and surface stations implement a multi-user detector, while low-end sensor nodes implement a single-user detector.

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 $20\,\mu\mathrm{s}$ for 802.11 DSSS, a value of $0.18\,\mathrm{s}$ is needed to allow devices a few hundred meters apart to share the underwater medium. 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 $100\,\mathrm{kcps}$, the minimum code length c_{min} to 4 and the maximum c_{max} to 40, the maximum transmission power P^{max} to $10\,\mathrm{W}$, the data packet size to $250\,\mathrm{Byte}$, the control and header packet size to $10\,\mathrm{Byte}$, the initial node energy to $1000\,\mathrm{J}$, the queue size to $10\,\mathrm{kByte}$, the available acoustic spectrum to $50\,\mathrm{kHz}$, and the transmission anomalies caused by multipath in deep and shallow water to $0\,\mathrm{dB}$ and $5\,\mathrm{dB}$, respectively. Moreover, all deployed sensors are sources, with packet inter-arrival time equal to $20\,\mathrm{s}$, 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. Finally, we adopted the geographical routing algorithm tailored for UW-ASNs, which we proposed in [16], according to which each node selects its next hop with the objective of minimizing the energy consumption.

A. Two-dimensional Deep Water UW-ASNs

We considered a variable number of sensors (from 10 to 50) randomly deployed on the bottom of a deep water volume of $500\text{x}500\text{x}500\,\mathrm{m}^3$. 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 $10\,\mathrm{dB}$, according to data sheets of available long-haul hydrophones (underwater microphones).

Figures 2(a-b) depict the average packet delay and energy per received bit in the simulation transient state when 30 sensors are deployed. The proposed UW-MAC protocol versions outperform the competing MAC schemes in terms of both delay (one order of magnitude) and energy consumption ($25\mu\,\mathrm{J/bit}$ vs. $45\mu\,\mathrm{J/bit}$ and over), although the extremely harsh scenario leads to delays in the order of seconds and high energy per bit for all the MAC schemes. Figures 2(c) and 3(a-c) show the overall performance of the competing MAC protocols when the number of deployed sensors and uw-gateways increases. Figure 2(c) shows that both UW-MACsgl and Uw-MACmlt have a much smaller average packet delay than the competing schemes. 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. 3(a)).

The highest successfully received number of packets is associated with our UW-MACmlt (Fig. 3(b)), which takes advantage of its multi-user receiving capabilities. All the schemes relying on carrier sense (CSMA, CSMApw, and 802.11) perform poorly since this mechanism prevents collisions with the current transmissions only at the transmitter side. Consequently, the *hidden terminal* and the *exposed terminal* problems are the main causes for the low performance of MAC schemes relying on carrier sense. Figure 3(c) quantifies the dramatic decrease in terms of data packet collisions of our proposed UW-MAC schemes, which is motivated by the very low collision probability of the small EH randomly accessing the channel. Conversely, ALOHA experiences a high number of packet collisions since it directly accesses the medium whenever there is data to be transmitted. Moreover, the need for retransmissions increases the power consumption of sensors, as confirmed in Fig. 3(a), which ultimately reduces the network lifetime.

B. Three-dimensional Shallow Water UW-ASNs

We considered a variable number of sensors (from 10 to 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. We modeled the multipath phenomenon by considering a worst-case scenario consisting of a saturated fast fading Rayleigh channel with coherence time equal to $1\,\mathrm{s}$. As compared to the 2D deep water scenario, in

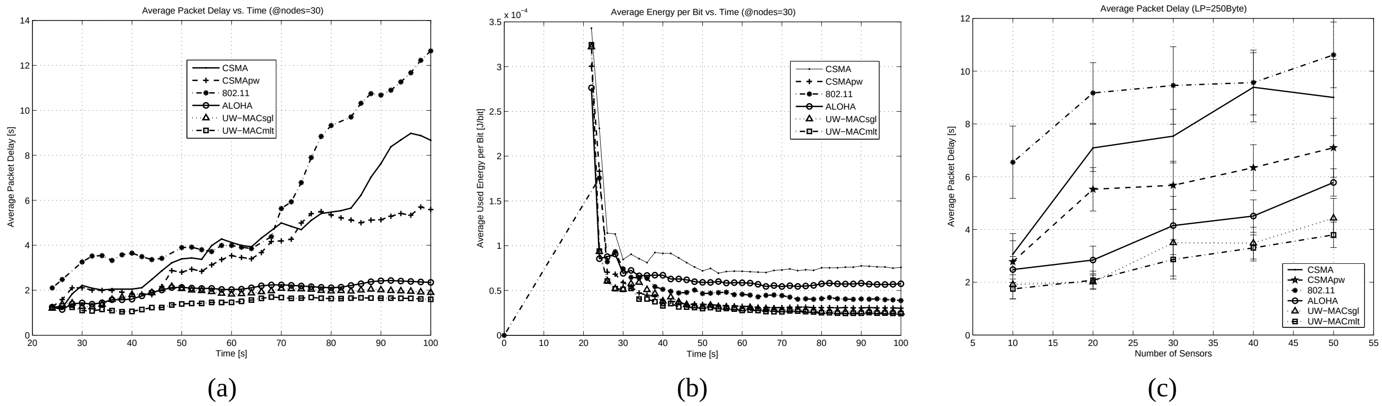


Fig. 2. **2D Deep Water UW-ASNs.** (a): Average packet delay vs. simulation time (30 sensors, 6 uw-gateways); (b): Average energy per received bit vs. simulation time (30 sensors, 6 uw-gateways); (c): Average packet delay vs. number of sensors

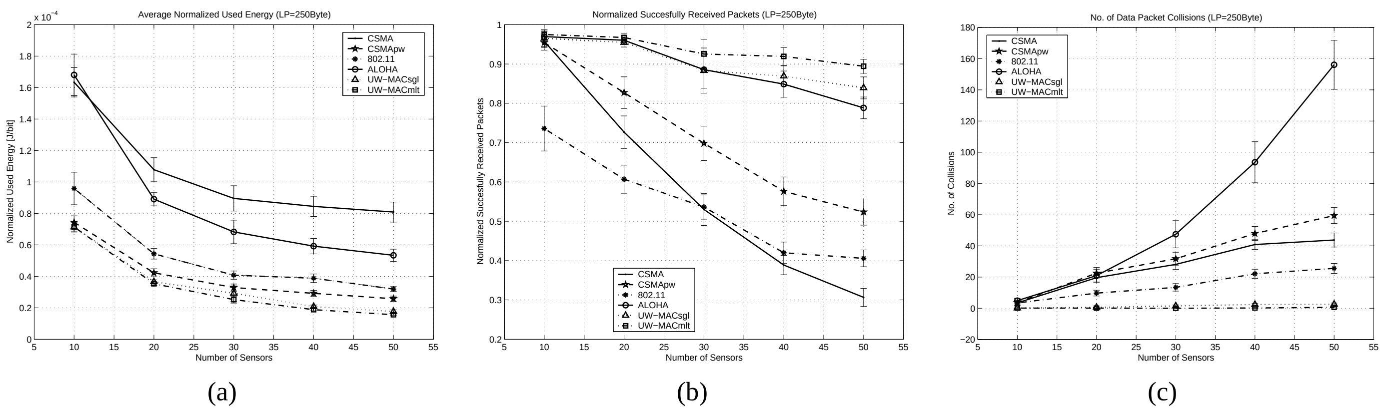


Fig. 3. **2D Deep Water UW-ASNs.** (a): Average normalized used energy vs. number of sensors; (b): Normalized successfully received packets vs. number of sensors; (c): Number of data packet collisions vs. number of sensors

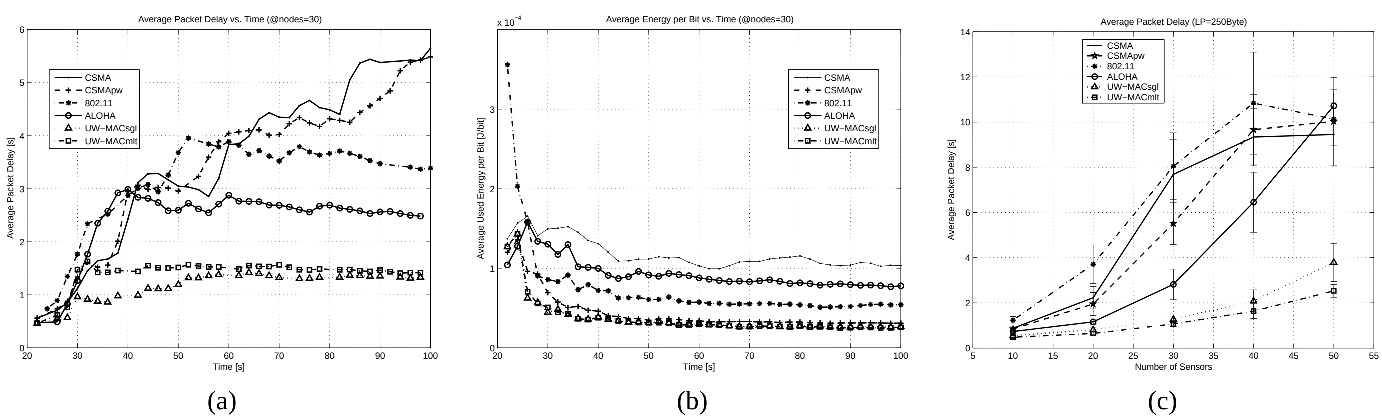
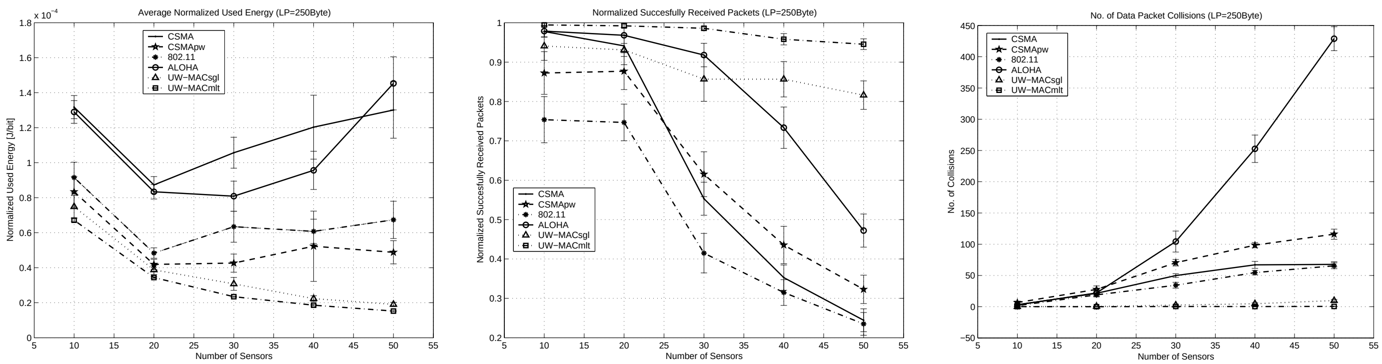


Fig. 4. **3D Shallow Water UW-ASNs.** (a): Average packet delay vs. simulation time (30 sensors); (b): Average energy per received bit vs. simulation time (30 sensors); (c): Average packet delay vs. number of sensors

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 [16] 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, 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 throughout the reported figures (Figs. 4-5). This phenomenon is particu-



(a) (b) (c)

Fig. 5. **3D Shallow Water UW-ASNs.** (a): Average normalized used energy vs. number of sensors; (b): Normalized successfully received packets vs. number of sensors; (c): Number of data packet collisions vs. number of sensors

larly evident in Fig. 5(b), where the normalized received packet metric drops below 0.45 in all the random-access MAC schemes when 50 sensors are deployed, while UW-MACsgl, and even more UW-MACmlt, have very high performance (UW-MACsgl over 0.80 and UW-MACmlt close to 0.95 with 50 sensors).

VI. Conclusions

UW-MAC, a distributed MAC protocol for underwater acoustic sensor networks, was proposed. It is a transmitter-based CDMA scheme that incorporates a closed-loop distributed algorithm to set the optimal transmit power and code length. It is proven that UW-MAC manages to simultaneously achieve high network throughput, limited channel access delay, and low energy consumption in deep water communications, 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.

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References

[1] I. F. Akyildiz, D. Pompili, and T. Melodia, "Underwater Acoustic Sensor Networks: Research Challenges," *Ad Hoc Networks (Elsevier)*, vol. 3, no. 3, pp. 257–279, May 2005.

[2] E. Sozer, M. Stojanovic, and J. Proakis, "Underwater Acoustic Networks," *IEEE Journal of Oceanic Engineering*, vol. 25, no. 1, pp. 72–83, Jan. 2000.

[3] J. Proakis, E. Sozer, J. Rice, and M. Stojanovic, "Shallow Water Acoustic Networks," *IEEE Communications Magazine*, pp. 114–119, Nov. 2001.

[4] M. Stojanovic, "Acoustic (Underwater) Communications," in *Encyclopedia of Telecommunications*, J. G. Proakis, Ed. John Wiley and Sons, 2003.

[5] E. Sozer, J. Proakis, M. Stojanovic, J. Rice, A. Benson, and M. Hatch, "Direct Sequence Spread Spectrum Based Modem for Underwater Acoustic Communication and Channel Measurements," in *Proc. of MTS/IEEE Conference and Exhibition for Ocean Engineering, Science and Technology (OCEANS)*, Nov. 1999.

[6] A. Muqattash, M. Krunz, and W. E. Ryan, "Solving the Near-far Problem in CDMA-based Ad Hoc Networks," *Ad Hoc Networks (Elsevier)*, vol. 1, no. 4, pp. 435–453, Nov. 2003.

[7] D. Broomhead, J. Huke, and M. Muldoon, "Codes for Spread Spectrum Applications Generated Using Chaotic Dynamical System," *Dynamics and Stability of Systems*, vol. 14, no. 1, pp. 95–105, Mar. 1999.

[8] L. Freitag, M. Stojanovic, S. Singh, and M. Johnson, "Analysis of Channel Effects on Direct-sequence and Frequency-hopped Spread-spectrum Acoustic Communication," *IEEE Journal of Oceanic Engineering*, vol. 26, no. 4, pp. 586–593, Oct. 2001.

[9] D. Kalofonos, M. Stojanovic, and J. Proakis, "Performance of Adaptive MC-CDMA Detectors in Rapidly Fading Rayleigh Channels," *IEEE Transactions on Wireless Communications*, vol. 2, no. 2, pp. 229–239, Mar. 2003.

[10] S. Kumar, V. S. Raghavanb, and J. Dengc, "Medium Access Control Protocols for Ad Hoc Wireless Networks: A Survey," *Ad Hoc Networks (Elsevier)*, vol. 4, no. 3, pp. 326–358, May 2006.

[11] K. Kredo II and P. Mohapatra, "Medium Access Control in Wireless Sensor Networks," *Computer Networks (Elsevier)*, vol. 51, no. 4, pp. 961–994, Mar. 2007.

[12] M. Molins and M. Stojanovic, "Slotted FAMA: a MAC Protocol for Underwater Acoustic Networks," in *Proc. of MTS/IEEE Conference and Exhibition for Ocean Engineering, Science and Technology (OCEANS)*, Boston, MA, Sept. 2006.

[13] V. Rodoplu and M. K. Park, "An Energy-Efficient MAC Protocol for Underwater Wireless Acoustic Networks," in *Proc. of MTS/IEEE Conference and Exhibition for Ocean Engineering, Science and Technology (OCEANS)*, Sept. 2005.

[14] Y. H. Kwang, B. Sharif, A. Adams, and O. Hinton, "Implementation of Multiuser Detection Strategies for Coherent Underwater Acoustic Communication," *IEEE Journal of Oceanic Engineering*, vol. 27, no. 1, pp. 17–27, Jan. 2002.

[15] R. J. Urick, *Principles of Underwater Sound*. McGraw-Hill, 1983.

[16] D. Pompili, T. Melodia, and I. F. Akyildiz, "Routing Algorithms for Delay-insensitive and Delay-sensitive Applications in Underwater Sensor Networks," in *Proc. of ACM Conference on Mobile Computing and Networking (MobiCom)*, Los Angeles, LA, Sept. 2006.