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A Distributed OFDMA Medium Access Control for Underwater Acoustic Sensors Networks

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***Abstract*—In this paper, we propose UW-OFDMAC, a distributed Medium Access Control (MAC) protocol tuned for UnderWater Acoustic Sensor Networks (UW-ASNs). It is a transmitter-based Orthogonal Frequency Division Multiple Access (OFDMA) scheme that integrates an original power and OFDMA parameters self-assignment algorithm to set the optimal transmit power, subcarrier spacing and guard interval duration. UW-OFDMAC aims at achieving two objectives, namely, guarantee high bandwidth efficiency and low energy consumption. Simulation results show that UW-OFDMAC outperforms the basic OFDMA protocol tuned for the underwater environment.**

***Index Terms*— Underwater Acoustic Sensor Networks, energy conservation, Bandwidth Efficiency, OFDMA protocol, collision free access.**

I. Introduction

Two thirds of the earth surface consist of water. Most of which remain unexplored. Increasingly research efforts are devoted to Underwater Acoustic Sensor Networks due to their important applications for military and commercial purposes. Broad applications of UNDERWATER sensor networks include among others: offshore exploration, tsunami warning, and mine reconnaissance [1]. Acoustic communication is the most suitable physical layer technology for underwater networks. Indeed, electromagnetic waves propagate through conductive salty water only at very short range due to the high attenuation and absorption effect in underwater environment. 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.

Conceiving a Medium Access Control (MAC) protocol is a major challenge for the deployment of UnderWater Acoustic Sensor Networks (UW-ASNs) [1]. Ideally, an optimal underwater MAC protocol should provide high network throughput, and low energy consumption, taking into account the harsh characteristics of the underwater propagation medium.

We believe that Orthogonal Frequency Division Multiple Access (OFDMA) is the most promising physical layer and multiple access technique for UW-ASNs. Recall that, OFDMA is a special case of multicarrier modulation in which multiple user symbols are transmitted simultaneously using different subcarriers with overlapping frequency bands that are mutually orthogonal. The inner nature of the OFDMA protocol makes it the most appropriate technology for underwater communications since i) it is robust to frequency-selective fading due to subcarriers' orthogonality, ii) compensates for the effect of multipath by inserting guard interval between the OFDMA symbols, thus eliminating the Inter-Symbol Interference, and iii) allows simultaneous collision free transmissions between neighboring nodes. As a result, OFDMA enables the most efficient use of the scarce acoustic spectrum and reduces packet retransmissions, which results in decreased energy consumption and increased network throughput.

For these reasons, in this paper we propose UW-OFDMAC, a transmitter-based OFDMA MAC protocol for UW-ASNs that integrates an original power and OFDMA parameters self-assignment algorithm so as to maximize bandwidth efficiency while minimizing energy consumption. The objective of UW-OFDMAC is twofold: i) guarantee high bandwidth efficiency and ii) guarantee low energy consumption. We prove that UW-OFDMAC manages to simultaneously achieve the two objectives in shallow water communications, which may be heavily affected by multipath fading.

We also formulate and resolve the distributed power and OFDMA parameters self-assignment problem to maximize bandwidth efficiency while providing collision free access. UW-OFDMAC uses locally generated OFDMA parameters to spread transmitted signals on the available bandwidth, which guarantees high bandwidth efficiency.

To the best of our knowledge, UW-OFDMAC is the first protocol that leverages OFDMA properties to achieve multiple access in the bandwidth-limited underwater channel. Previous works [5] [6] considered OFDMA schemes from a physical layer perspective. The main features that characterize UW-OFDMAC are: i) it is fully distributed, since OFDMA optimal parameters and transmit power are distributively selected by each transmitter without relying on a centralized entity; and ii) it guarantees low energy consumption and high bandwidth efficiency while avoiding interferences.

The remainder of this paper is organized as follows. In Section II, we discuss the suitability of existing ad hoc and sensor MAC protocols for the underwater environment. Section III presents the OFDMA system studied in this paper. In section IV, we introduce UW-OFDMAC, and in Section V we formulate and resolve the distributed power and OFDMA parameters self-assignment problem. In Section VI, we compare through simulation UW-OFDMAC with a basic OFDMA scheme tuned for the underwater environment. Finally, Section VII concludes this paper.

II. Related Work

There has been intensive research on MAC protocols for ad hoc [7] and wireless terrestrial sensor networks [8] 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 and OFDMA, since they are attracting more and more the attention of the UW-ASNs research community.

A distributed CDMA-based energy-efficient MAC protocol for the underwater environment was recently proposed in [9]. It is a transmitter-based Code Division Multiple Access (CDMA) scheme called UW-MAC. It integrates a closed-loop distributed algorithm to optimize the transmit power and code length to mitigate the near-far problem. UW-MAC aims at guaranteeing high network throughput with low channel access delay, and low energy consumption. However, UW-MAC requires that all nodes have knowledge of all other nodes' multiple access interference (MAI) which may be restrictive for energy constrained sensor devices. Moreover, in CDMA based systems, multipath fading is combated leveraging RAKE filters at the receivers. Rake receivers typically detect a fixed number of multipath components and coherently combine them. Besides, the CDMA interference can be mitigated by means of equalizer which increases the system complexity.

Orthogonal Frequency Division Multiple Access (OFDMA) is one of the recently proposed methods. It is the primary choice for future broadband communication networks (WiMAX and IEEE 802.11n). The main feature of the OFDMA protocol is its robustness to multipath fading. In OFDMA system, the number of multi-path components does not limit the performance of the system as long as all these multipaths are within the guard interval duration. Therefore, in underwater wireless systems where multipath effect is very common, OFDMA systems are more robust and less complex than CDMA systems.

A few research activities applied OFDMA to underwater acoustic applications [5] [6]. Most of these works focus on the modulation aspect and not on the multiple-access aspect. In other words, OFDMA has been mostly regarded as a modulation technology.

Hayajneh. et. al recently proposed an OFDMA based MAC protocol for underwater acoustic sensor networks [10]. The main idea of this work is to carefully assign the available subcarriers among neighboring nodes so that collision is completely avoided.

However, in our work, we assume that each sensor device is assigned a subchannel and the OFDMA parameters as well as the transmission power are determined each time a new transmission is triggered. In other words, each sensor can dynamically adapt OFDMA parameters depending on the receiver location and motion. The main objective of our work is to guarantee high bandwidth efficiency and low energy consumption while providing collision free access.

III. OFDMA Parameters

Orthogonal Frequency Division Multiplexing (OFDM) is a multiplexing technique that subdivides the available bandwidth into multiple orthogonal frequency sub-carriers. The input data stream is divided into several parallel sub-streams of reduced data rate (increased symbol duration) and each sub-stream is transmitted on a separate orthogonal sub-carrier. In an OFDM system, resources are available in the time domain by means of OFDM symbols and in the frequency domain by means of subcarriers. The time and frequency resources can be organized into sub-channels for allocation to individual users. OFDMA is a multi-user version of OFDM digital modulation scheme. Multiple access is achieved in OFDMA by assigning subsets of subcarriers to individual users. This allows simultaneous low data rate transmission from several users.

A. Sub-Carrier Spacing : Δf

In OFDMA, the sub-carrier frequencies should be chosen so that the sub-carriers are orthogonal to each other, meaning that cross-talk between the sub-carriers is eliminated or in other words Inter-Carrier Interference (ICI) is avoided. The orthogonality requires that the sub-carrier spacing Δf is much larger than the Doppler Shift which is mainly caused by the sender and receiver motion. In other words, the Doppler shift is the source of frequency deviation between the transmitter and the receiver. An OFDMA system can only tolerate a frequency offset that is much smaller than the carrier spacing. Any residual frequency offset causes loss of orthogonality between the carriers, and the resulting intercarrier interference (ICI) leads to performance degradation.

B. Guard Interval Tg

One key principle of OFDMA is to transmit a number of low-rate streams in parallel instead of a single high-rate stream. By doing so, Inter-Symbol Interference caused by multipath is reduced. Consequently, since the duration of each symbol is long, it is feasible to insert a guard interval between the OFDMA symbols, thus eliminating the Inter-Symbol Interference (ISI).

By fixing the subcarrier spacing and guard interval duration, the basic unit of physical resource (time and frequency) is fixed. One immediate advantage stemming from OFDMA parametrization is the flexibility of deployment. In fact, OFDMA parameters can be adapted according to the receiver location and motion in order to maximize the bandwidth efficiency. Indeed, the bandwidth efficiency can be highly improved with closely located receiver moving with the same velocity and through the same direction as the sender. CDMA based systems however, do not provide such a natural flexibility.

IV. UW-OFDMAC: An OFDMA MAC for UW-ASNs

Our proposed UW-OFDMAC protocol aims at setting the optimal combination of transmit power, subcarrier spacing and guard interval duration at the transmitter side so as to minimize the energy consumption and completely mitigate the ICI and ISI effects. For this purpose, we assume that each user is initially assigned a sub-channel (consecutive set of sub-carriers). Note that, in order to avoid Multi-user Access Interference the whole set of sub-channels must be mutually exclusive. To illustrate, assume that M users share the available bandwidth which is evenly divided into M sub-channels. I_m represents the m^{th} sub-channel assigned to user m. Clearly to avoid that a given sub-channel is shared by different users, the sets $\{I_m\}$ must be mutually exclusive, i.e., $I_m \cap I_j = \varnothing$ for $m \neq j$. The sub-channel assigned to each user can be subdivided into multiple orthogonal frequency sub-carriers. Therefore, with N sub-carriers, the total passband bandwidth of user m will be $I_m \approx N \cdot \Delta f(Hz)$. Note that the total number of sub-carriers for each user (N) mainly depends on the receiver location and motion. In other words, each user can dynamically adapt the

OFDMA parameters (in terms of sub-carrier spacing and guard interval duration) as well as the transmission power depending on the receiver location and motion. Consequently, we highly improve the resulting bandwidth and energy efficiency while minimizing users' interference. In fact, nearer receivers need much less power consumption in order to successfully deliver the data packets. Moreover, with near receivers, the guard interval can be highly reduced while avoiding the inter-symbol interference hence improving the total network throughput.

Adopting such sub-carrier allocation strategy imposes that the sub-carrier frequency spacing chosen by a given transmitter should be communicated to the receiver in order to adjust its window to the transmitter sub-carriers number.

In UW-OFDMAC protocol, a sensor node randomly accesses the channel transmitting a notification packet (NP), whenever a new transmission is triggered. The NP of size L_{NP} symbols, is sent using common OFDMA parameters known by all devices $(\Delta f_c = \frac{1}{T}, Tg_c = \frac{d_{\max}}{c})$, where T is the symbol duration, $d_{\max}$ is the maximal inter-node distance and $c = 1500 m/s$ is the sound velocity of the channel. Sender i sends to its next hop j, d_{ij} meters distant, the notification packet NP. The NP incorporates information about the final destination (i.e., the surface station), the chosen next hop (i.e., node j), and the OFDMA parameters $(\Delta f_{ij}, Tg_{ij})$ that i will use to transmit the actual data packet of size $L_D = (p * \frac{Ii}{\Delta f_{ij}})$ symbols. Taking advantage of the received information, node j will be able to synchronize with the signal from i by adjusting its window to user i sub-carriers number.

Immediately after the transmission of the NP, i transmits the data packet on the channel using the optimal transmit power P^*_{tij}, Δf^*_{ij} and Tg^*_{ij} set by the power and OFDMA parameters self-assignment algorithm.

Once j has correctly received the data packet from i, an ACK packet is immediately sent to acknowledge the successful reception. Note that, ACK packet of size $L_A = (q * \frac{Ij}{\Delta f_c})$ symbols is sent using P^*_{tij}, Δf^*_{ij} and Tg^*_{ij}. In case i does not receive the ACK before the expiration of a timeout T_{out}, it will keep transmitting the data packet until a maximum transmission number N_{max} is reached. The timeout must be adjusted considering the long propagation and transmission delays, i.e., $T_{out} \geq p(T + Tg_{ij}) + 2 * d_{ij}/c + q(T + Tg_c)$. Note that every time a transmission fails, sender i increases the transmission power to improve the probability that the packet is successfully received.

V. Power and OFDM parameters Self-assignment Problem

We consider a shallow water acoustic channel, which is severely affected by multipath [1]. In such environment, the signal fading can be modeled by a Rayleigh model. It is worth noting that such model (Rayleigh model) accounts for the worst-case scenario. The corresponding transmission loss TL_{ij} that an acoustic signal centered at frequency f $[Hz]$ experiences between nodes i and j ; $d_{ij}[m]$ distant, is

$$TL_{ij} = d_{ij} \cdot 10^{[\alpha(f) \cdot d_{ij} + A]/10} \cdot \rho^2 \qquad (1)$$

where $\alpha(f)$ represents the medium absorption coefficient, $A \in [5, 10]$ 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 and ρ has a unit mean Rayleigh cumulative distribution $D_\rho(\rho) = 1 - \exp(-\pi\rho^2/4)$. ρ is a normalized random variable that represents the power gain of the fading. Since ρ is random, the received signal is also random. Hence, correct reception of a signal can be guaranteed only on a probabilistic basis. In our work, we require that $Pr\{P_{rij} \geq \tau\} \geq \delta_l$ for reliable reception, where P_{rij} is the power of the received signal, τ is a predefined power threshold, and δ_l is the required link reliability.

Given that the transmission power is P_{tij}, the corresponding received energy P_{rij} is

$$P_{rij} = \frac{P_{tij}}{TL_{ij} \cdot \rho^2} \qquad (2)$$

The link-reliability requirement can be expressed as

$$\begin{aligned} \delta_l &\leq Pr\{P_{rij} \geq \tau\} \\ &\leq Pr\{\rho \leq \sqrt{\tfrac{P_{tij}}{\tau \cdot TL_{ij}}}\} \\ &\leq 1 - \exp(-\tfrac{\pi P_{tij}}{4\tau \cdot TL_{ij}}) \end{aligned} \qquad (3)$$

$$P_{tij} \geq -\frac{4\tau \cdot d_{ij} \cdot 10^{[\alpha(f) \cdot d_{ij} + A]/10} \cdot \log(1 - \delta_l)}{\pi} \qquad (4)$$

Recall that the objective of UW-OFDMAC protocol is twofold: first minimizing energy consumption and second guaranteeing high bandwidth efficiency. In this work, we aim at minimizing the energy consumption per symbol $(P_{tij}(T + Tg_{ij}))$. To evaluate the bandwidth efficiency, let us consider the symbol rate R_{ij} relative to transmitter i and receiver j, $R_{ij} = \frac{I_i}{\Delta f_{ij}(T + Tg_{ij})}$ symbol per second, and user i bandwidth is defined as I_i. The resulting bandwidth efficiency is $\frac{R_{ij}}{I_i} = (\Delta f_{ij}(T + Tg_{ij}))^{-1}$.

Now, in order to combine both of our objectives into a single objective function, we propose to minimize $\left(\frac{P_{tij}}{P_{\max}}(T + Tg_{ij}) - \left(\frac{\Delta f_{ij}}{\Delta f_c}(T + Tg_{ij})\right)^{-1}\right)$, where $P_{\max}$ and Δf_c are only normalizing constants. Consequently, our optimization problem can be stated as follows:

$$\begin{aligned} & given\ d_{ij}, \delta_l, \tau, v_{ij}, c, P_{\max}, T, I_i, f_{i0} \\ & Find\ \Delta f^*_{ij}, P^*_{tij}, Tg^*_{ij} \\ & \min_{\Delta f_{ij}, Tg_{ij}, P_{tij}} \left(\frac{P_{tij}}{P_{\max}}(T + Tg_{ij}) - \left(\frac{\Delta f_{ij}}{\Delta f_c}(T + Tg_{ij})\right)^{-1}\right) \\ & \text{subject to} \end{aligned} \qquad (5)$$

$$Tg_{ij} \geq \frac{d_{ij}}{c} \qquad (6)$$

$$\Delta f_{ij} \geq \max\left(\frac{1}{T}, \frac{f_{ik} v_{ij}}{c}\right) \quad \forall k, 0 \leq k \leq \frac{I_i}{\Delta f_{ij}} \qquad (7)$$

$$-\frac{4\tau \cdot d_{ij} \cdot 10^{[\alpha(f_{ik}) \cdot d_{ij} + A]/10} \cdot \log(1 - \delta_l)}{\pi} \leq P_{tij} \leq P_{\max} \quad \forall k, 0 \leq k \leq \frac{I_i}{\Delta f_{ij}} \qquad (8)$$

$$f_{ik} = f_{i0} + k \Delta f_{ij} \qquad (9)$$

The first constraint (6) states that the guard interval must be at least longer than the propagation delay in order to avoid ISI. The second constraint (7) states that the sub-carrier spacing should be i) larger than the Doppler shift of the considered users i and j in order to avoid ICI and ii) larger than $\frac{1}{T}$ in order to guarantee orthogonality. The Doppler shift of users i and j depends on v_{ij} denoting the velocity of the transmitter i relative to the receiver j in meters per second. Precisely, the Doppler Shift that an acoustic signal centered at frequency f $[Hz]$ experiences between nodes i and j with relative velocity v_{ij} is $\frac{f \cdot v_{ij}}{c}$. Finally, the third constraint (8) guarantees a reliable reception of a data packet.

While our problem formulation may seem a fairly complex optimization problem, it admits a low complexity optimal solution. To find it, we rely on a major property of the objective function, namely $f(\Delta f_{ij}, Tg_{ij}, P_{tij}) = \frac{P_{tij}}{P_{\max}}(T + Tg_{ij}) - \left(\frac{\Delta f_{ij}}{\Delta f_c}(T + Tg_{ij})\right)^{-1}$ is monotonically and independently increasing with $\Delta f_{ij}, Tg_{ij}$ and P_{tij}. Hence, we are interested in taking the minimum values for $\Delta f_{ij}, Tg_{ij}$ and P_{tij} in order to minimize $f(\Delta f_{ij}, Tg_{ij}, P_{tij})$. Regarding the first constraint, it is clear that the minimum value of Tg_{ij} is $\frac{d_{ij}}{c}$. Hence, we get

$$Tg_{ij}^* = \frac{d_{ij}}{c} \tag{10}$$

According to the second constraint

$$\Delta f_{ij} \geq \frac{f_{ik} v_{ij}}{c} \quad \forall k, 0 \leq k \leq \frac{I_i}{\Delta f_{ij}} \tag{11}$$

$$\Delta f_{ij}\left(1 - k \cdot \frac{v_{ij}}{c}\right) \geq \frac{f_{i0} v_{ij}}{c} \quad \forall k, 0 \leq k \leq \frac{I_i}{\Delta f_{ij}} \tag{12}$$

In this case, the most rigorous inequality is achieved when $k = \frac{I_i}{\Delta f_{ij}}$. In other words, if $\Delta f_{ij}\left(1 - k \cdot \frac{v_{ij}}{c}\right) \geq \frac{f_{i0} v_{ij}}{c}$ is satisfied for $k = \frac{I_i}{\Delta f_{ij}}$ then it will be automatically satisfied for all the remaining k's values. Therefore

$$\Delta f_{ij} \geq \frac{v_{ij}}{c}(f_{i0} + I_i) \tag{13}$$

$$\Delta f_{ij}^* = \max\left(\frac{1}{T}, \frac{v_{ij}}{c}(f_{i0} + I_i)\right) \tag{14}$$

Finally, regarding the third constraint, we have

$$-\frac{4\tau \cdot d_{ij} \cdot 10^{[\alpha(f_{ik}) \cdot d_{ij} + A]/10} \cdot \log(1 - \delta_l)}{\pi} \leq P_{tij} \tag{15}$$

$$10^{[\alpha(f_{ik}) \cdot d_{ij} + A]/10} \leq -\frac{\pi P_{tij}}{4\tau \cdot d_{ij} \cdot \log(1 - \delta_l)} \tag{16}$$

In fresh water, $\alpha(f_{ik}) = f_{ik}^2 \cdot C_{fresh}$, $(C_{fresh} = 2.175 \times 10^{-13})$, hence, we get

$$1 \leq \frac{10 \cdot \log_{10}\left(-\frac{\pi P_{tij}}{4\tau \cdot d_{ij} \cdot \log(1-\delta_l)}\right) - A}{(f_{i0} + k\Delta f_{ij})^2 \cdot C_{fresh} \cdot d_{ij}} \tag{17}$$

Here again, the most rigorous inequality is achieved when $k = \frac{I_i}{\Delta f_{ij}}$, hence we get

$$P_{tij}^* = -\frac{4\tau \cdot d_{ij} \cdot 10^{\left[(f_{i0}+I_i)^2 \cdot C_{fresh} \cdot d_{ij} + A\right]/10} \cdot \log(1 - \delta_l)}{\pi} \tag{18}$$

VI. Performance Evaluation

In this section, we evaluate the efficiency of our proposed UW-OFDMAC protocol for 3D shallow water architecture. To achieve this, we use the classical OFDMA protocol as baseline to which the UW-OFDMAC improvements can be compared. By classical OFDMA protocol we mean the basic version with no dynamic OFDMA parameters $(\Delta f, Tg)$ assignment. In other words, the OFDMA parameters will be fixed during the network setup. Note that, since the objective of our protocol is to provide a collision free access for under-water sensor nodes, we also tune, for fairness purposes, the basic OFDMA protocol to guarantee no collision for sending sensors.

We consider 20 sensors initially deployed according to fig. 1, in a 3D shallow water with volume of $100 \times 100 \times 50m^3$, which may represent a small harbor. The surface station which represents the final destination for each sent packet is centered on the surface of the underwater volume. The routing schema is depicted by the arrows in fig. 1. We model node's motion by a sinusoidal speed function with random amplitude varying between 0-5m/s.

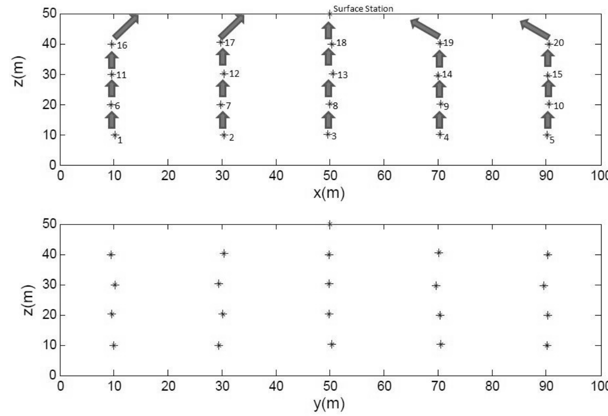

Fig. 1. Underwater sensor nodes deployement.

We set the maximum transmission power $P_{\max}$ to 10W, the data packet size to 250 Bytes, the ACK and notification packet size to 10 Bytes, the available acoustic spectrum to 50 kHz, and the transmission anomalies caused by multipath in shallow water to 5 dB. Moreover, all deployed sensors are sources, with packet inter-arrival time equal to 20 s. Since the handled traffic increases with nodes' depth (Z(m)), the nodes' sub-channel assignment schema provides increasing spectrum for each depth level. Accordingly, nodes at the first depth level (Z = 10m) will be assigned consecutive sub-channels of 1KHz, nodes at the second depth level (Z = 30m) will have 2KHz spectrum. Finally, each node in the third and fourth depth levels will acquire spectrum of 3 and 4 KHz respectively.

Fig. 2 compares the energy consumption per sensor node for both protocols UW-OFDMAC and basic OFDMA. The most striking result is that UW-OFDMAC is achieving a considerable energy savings (up to 96.7% for node 18) compared with the basic OFDMA protocol, which justify the usefulness of our dynamic OFDMA parameters assignment scheme. As explained above, the basic OFDMA protocol has fixed parameters since nodes deployment. Dealing with the energy consumption (see eq. 18), the distance separating any two communicating nodes is tuned to the maximal possible distance between any sensor and its corresponding next hop. As such, reliable transmission is guaranteed even with the basic OFDMA protocol for each pair of nodes.

Now, let's focus on the energy consumption achieved by the UW-OFDMAC protocol. According to fig. 3, the energy consumption per node for UW-OFDMAC mainly depends on the maximal distance between a node and its corresponding next hop. In our simulations, before each new transmission, d_{ij} is chosen to be the maximal distance between i and j in the time domain. Recall that each node in our simulations has a variable trajectory with time. Consequently, a rigorous application of our UW-OFDMAC protocol requires OFDMA parameters computing for each transmitted byte which highly increases protocol complexity. Instead, we propose using the maximal possible parameters during a packet transmission. For instance, to compute the optimal transmission power we need to know the current distance between a node and its next

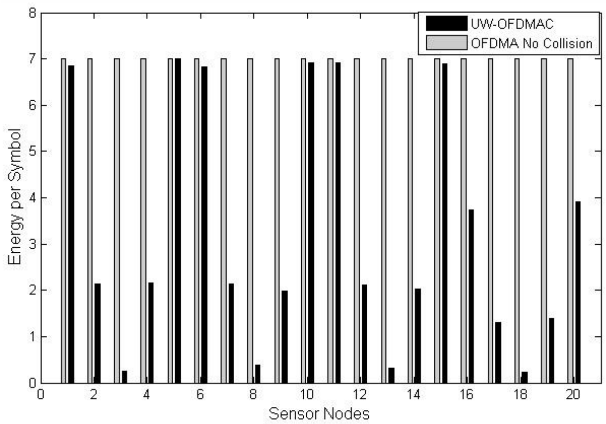

Fig. 2. Energy Consumption per sensor node.

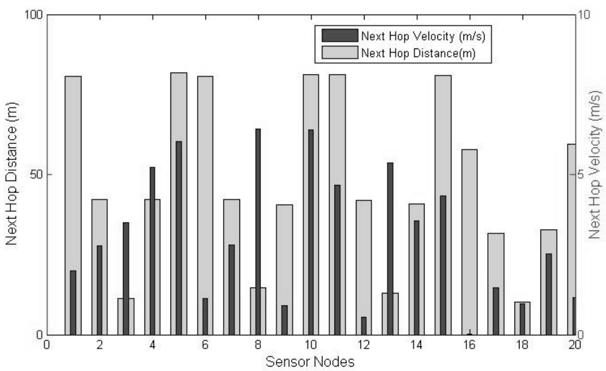

Fig. 3. Next hop distance vs. Next hop velocity.

hop. Knowing that the speed period is lower than the packet transmission time, allows us to choose the maximal distance in order to ensure collision free access during packet transmission. To summarize, the basic OFDMA protocol will be tuned to the maximal possible parameters between any nodes and its corresponding next hop. However, UW-OFDMAC chooses the maximal parameters between a given node and its corresponding next hop.

Fig. 4 compares the bandwidth efficiency per node for both protocols UW-OFDMAC and basic OFDMA. Here again, UW-OFDMAC clearly outperforms the basic OFDMA. Recall that the bandwidth efficiency $((\Delta f_{ij}(T + Tg_{ij}))^{-1})$ depends on Δf_{ij} and Tg_{ij} which in turn depends on nodes relative velocity and the separating distance respectively. According to fig. 3, the bandwidth efficiency is inversely proportional to the distance with a fair modulation by nodes' relative velocity.

VII. Conclusion

Conceiving efficient MAC protocols is a critical issue in underwater acoustic networks. In this paper, UW-OFDMAC, a distributed MAC protocol for underwater acoustic sensor networks, was proposed. It is an OFDMA based scheme that incorporates a distributed algorithm to set the optimal transmit power and OFDMA parameters. We have demonstrated that UW-OFDMAC manages to simultaneously achieve low energy consumption and high bandwidth efficiency in shallow water communications, known to be heavily affected by multipath fading.

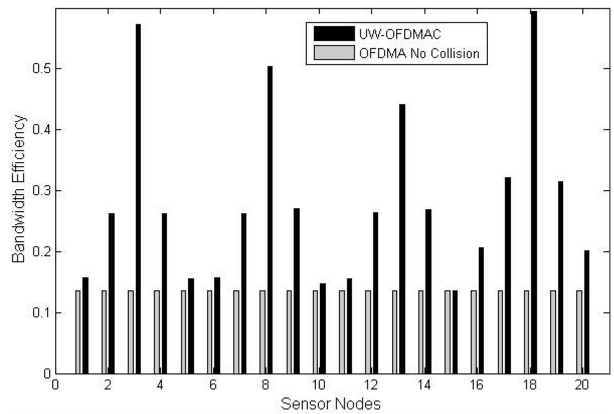

Fig. 4. Bandwidth Efficiency per node.

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