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Underwater Wireless Communications in Freshwater at 2.4 GHz

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***Abstract*—There are few equations for underwater communications in the related literature. They show that the speed propagation and absorption coefficient in freshwater are independent of the working frequency of the transmitted signals. However, some studies demonstrate that electromagnetic waves present lower losses when they are working at certain frequencies. In this paper, we perform a set of measurements of electromagnetic (EM) waves at 2.4 GHz in the underwater environment. In our study case, we fix the water conditions and we measure the behavior of EM as a function of several network parameters such as the working frequency, data transfer rates and modulations. Our results will show that higher frequencies do not mean worse network performance. We will also compare our conclusion with some statements extracted from other works.**

***Index Terms*— 2.4 GHz, electromagnetic waves, optimum frequency, underwater wireless network**

I. INTRODUCTION

ONE of the main research lines in ad-hoc networks is the increase of the network lifetime [1] by using several factors such as communication protocols [2] and hardware features [3]. Even though underwater wireless networks share some common properties with terrestrial wireless networks, the terrestrial network solutions cannot be directly deployed in underwater wireless networks. Recently there is an extensive ongoing research activity on underwater communications. The major challenges designing underwater wireless networks are the energy limitation, long propagation delays, short distances and low bandwidths.

The use of electromagnetic (EM) waves to transmit information under the water is characterized to be a fast and efficient communication method. Unlike acoustic waves, EM waves can be used in shallow water. In addition, they are unaffected by turbidity and pressure gradients and it is immune to acoustic noise [4]. This happens because EM waves do not need the movements of particles of medium to be propagated. Underwater communications based on EM waves are faster and can be used in higher working frequencies (which results in a higher bandwidth). However, they are susceptible to electromagnetic interferences (EMI). Their main problem is the high signal attenuation due to the conductivity of the water. This fact implies short communication distances between devices, so EM are never chosen for underwater communications.

We can find some surveys in the related literature where authors analyze the theory of this kind of communication [5]. Jiang and Georgakopoulos [5] demonstrated that the use of radio frequency (RF) communications from air to fresh water is possible. In their work, they studied the losses depending on the electromagnetic properties of the water between 23 kHz and 1 GHz, the incidence angle and the propagation depth. Authors conclude that there are some frequencies with minimum attenuation and maximum propagation depth from air to fresh water. That is, the total loss in 3 - 100 MHz frequency range is smaller than the loss at the lowest and highest frequencies of the studied frequency range. A. Al-Shammaa et al. [7] presented a new approach of EM wave propagation through seawater. The experimental results were conducted in the laboratory. Obtained measurements showed the relationship between the signal features and the frequency. A. A. Abdou et al. [8] analyzed if it is feasible to use EM waves in an underwater communication system using the unlicensed (ISM) frequency bands (6.7 MHz, 433 MHz and 2.4 GHz). In this paper, authors concluded that 6.7 MHz is a good frequency for wireless sensor network for environmental monitoring. Finally, some authors of this paper performed several studies on RF communication at 2.4 GHz ISM frequency band [9][10]. In that study, we only measured the number of lost packets and round trip time (RTT) for 1, 2, 5.5 and 11 Mbps between 2412 MHz and 2442 MHz. These measurements were carried out at 26°C. The maximum distance achieved between devices in that paper was 17 cm. In this case, we are going to perform similar tests but for 20ºC. We also add more modulations and data transfer rates.

The goal of this paper is to compare existing models of EM transmission in freshwater and the analytical models estimated from the measurements made in a controlled environment. These analytical models will let us estimate the distance as a function of the working frequency. Moreover, this paper complements our previous work by providing a detailed study which includes higher data bit rates and other coding techniques, obtaining lower RTTs and larger distances.

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To carry out our test, we have chosen the 2.4 GHz ISM band. Concretely, we will use the IEEE 802.11 b/g standard because it offers the highest bandwidth. We have analyzed IEEE 802.15.4 standard which also works on this frequency. But although it presents lower power consumption, our aim is to have higher data transfer rates than the ones offered by IEEE 802.14.5.

The rest of the paper is structured as follows. Section 2 shows the background of the used electromagnetic waves and the analytical models for freshwater. Section 3 explains the scenario used in our test bench and the strategies used to take measurements. Obtained measurements and our discussions are shown in Section 4. Finally, Section 5 shows the conclusion and future work.

II. UNDERWATER COMMUNICATIONS BASED ON ELECTROMAGNETIC WAVES

In this section, we show the main equations describing the behavior of EM waves in underwater environments for freshwater.

Freshwater is considered a medium that has low losses. The propagation speed c of the signals can be expressed by the following approximation (see equation 1). Meanwhile, some authors state that the absorption coefficient α for the EM waves propagation in freshwater can be approximated by expression 2 [11]:

$$c \approx \frac{1}{\sqrt{\varepsilon_r \varepsilon_0 * \mu_r \mu_0}} \qquad (1)$$

$$\alpha \approx \frac{\sigma}{2}\sqrt{\frac{\mu_r \mu_0}{\varepsilon_r \varepsilon_0}} \qquad (2)$$

ε_r: Relative permittivity
ε_0: Permittivity of the vacuum
μ_r: Magnetic permeability of the medium
μ_0: Magnetic permeability of the medium in free space
σ: Electrical conductivity of the material

As we can observe in equations (1) and (2), both parameters are independent to the working frequency. That is, the propagation speed and the absorption coefficient remain constant along the frequency spectrum. However, these parameters are affected by the variation of temperature and salinity in seawater [12].

We can analyze other works where authors study analytically the relationship of the maximum distance between devices as a function of the working frequency [4]. Following their process, our system should provide a maximum distance of 1.67 m. between devices, and the propagation speed should be maintained near the speed of light. But we know from previous studies that this is not entirely true. EM waves speed is higher (150,000 times greater) than the acoustic ones and this value is approximately $2.25*10^8$ m/s [9][13].

III. SCENARIO AND USED TOOLS

This section explains the scenario used to take our measurements.

A. Scenario

In order to take measurements, we have used a swimming pool with 32 m^2 surface and depths between 1.5 m. and 1.80 m. The size of this structure allows us to avoid any reflection on the walls, ground and water surface.

All measurements have been taken in fresh water. The water temperature is 20 °C and the amounts of chlorine and bromine dissolved in the water have been fixed to 0.3 mg/l. pH value is 7.2.

B. Hardware and software.

In order to perform our measurements, we have established an ad hoc wireless connection between two laptops.

We have placed two vertical monopole antennae inside the water. We have put each antenna in a sealed plastic box to make it both watertight and airtight. We have used a pigtail of 3 m. long to connect the antennae with each laptop, which is located outside the water. Antennae are placed under the water with enough depth to avoid any transmission to the open air. We placed them at 30 cm. In order to check this fact, we established an ad hoc wireless connection between both antennae outside the water. After that, we introduced one of these antennae progressively inside the water and checked it every 5 cm. We stopped when we did not detect any signal with the antenna placed outside the water from the antenna located inside the water. Then, we used that distance to make our test.

In order to take the measurements, we have used some MS-DOS shell commands that let us check the status of a network connection. Concretely we used the ping command which provides the round trip time (RTT) for each packet.

IV. TEST BENCH AND MEASUREMENTS RESULTS

In this section, we are going to present the measurements obtained with our test bench and discuss the obtained results. We want to highlight that the results shown in this section are novel and because we have not found previous works using these frequencies, we are not able to predict any results.

We have analyzed the RTT between both devices as a function of the distance between them. We have also measured this paramenter for different type of modulation techniques and frequency. Each test has been performed during 3 minutes. RTT average has been estimated taking into account only the packets that performed the round-trip successfully. When a packet was not received or was received wrong, we assigned 3,000 ms., but this value is not taken into account in the RTT average estimation. We have used a threshold value of 3,000 ms., because it is commonly used [14]. Tests have been performed at 2.4 GHz frequency band specified in the IEEE 802.11b/g standard (range between 2,412 MHz and 2,462 MHz). Table 1 shows the modulations and data rates used in our performance tests.

TABLE I
MODULATIONS OF IEEE 802.11B/G STANDARD

Modulation or scheme	Data transfer rate	Modulation or scheme	Data transfer rate	
BPSK	1Mbps	OFDM	6Mbps	9Mbps
QPSK	2Mbps		12Mbps	18Mbps
CCK	5.5Mbps		22Mbps	24Mbps
	11Mbps		36Mbps	48Mbps
			54Mbps	

A. Measurement results

Figure 1 shows the maximum distances for each frequency and each data transfer rate. As we can see, all data transfer rates present similar behavior showing distances of 25 cm. for frequency of 2412 MHz. We registered also a peak for all frequencies at 2427 MHz. However, the distance of 25 cm. is only reached by 1 Mbps, 2 Mbps and 5.5 Mbps data rates. The maximun distance has been 26 cm. for 12 Mbps. Finally, we note that 48 Mbps and 54 Mbps data rates reach their high values at 2432 MHz, while the rest of data rates register very small distances in this frequency.

We can estimate the average maximum distances for each modulation type. The estimation of each modulation is performed considering the results of all data transfer rates that use each modulation (see Figure 2). After analyzing the maximum distances for each data transfer rate and modulation, we analyze the behavior in terms of performance for each data transfer rate at each frequency. Figure 3 shows the RTT value in ms. for data transfer rates using BPSK modulation. In this case, only the rate of 1Mbps is shown.

As we can see, there are two peaks near the 25 ms. (at 2427 MHz and at 2447 MHz).

We can analyze this figure in conjunction with Figure 1 and it is easy to observe that the first peak corresponds to one of the points of maximum distance while the second peak corresponds to a point of small distances. The remaining frequencies present RTT values close to 5 ms.

Figure 4 shows the RTT values in ms. for 2 Mbps data transfer rate, which uses QPSK modulation. Figure 4 shows two peaks. The first one is located at 2417 MHz and has 55 ms., while the second peak is located at 2447 MHz with a RTT of 20 ms. The remaining frequencies present RTT values close to 5 ms.

Figure 5 shows RTT value in ms. when using CCK modulation scheme. First, we can see that both have their highest values in the same frequencies (2427 MHz and 2447 MHz). Moreover, we observe that at 2427 MHz the RTT value for 5.5 Mbps data transfer rate is approximately 2.5 times longer than the RTT values shown for 11 Mbps.

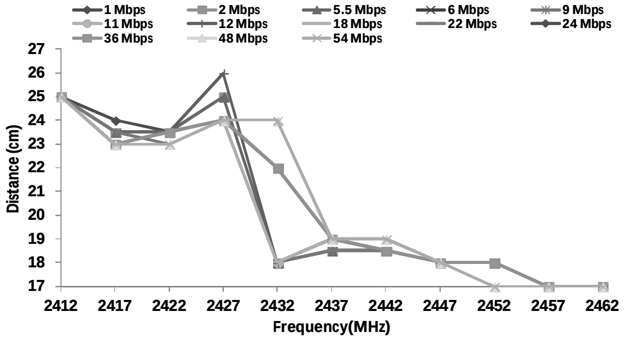

Fig. 1. Maximum distance for all data transfer rates.

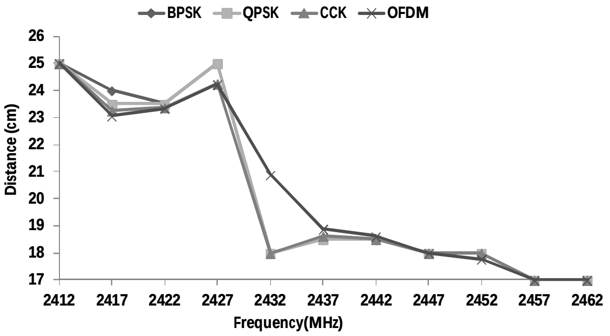

Fig. 2. Average value of maximum distance for each modulation

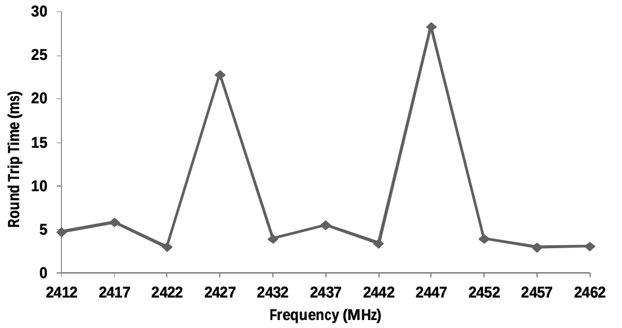

Fig. 3. Values of RTT in ms for 1Mbps (BPSK)

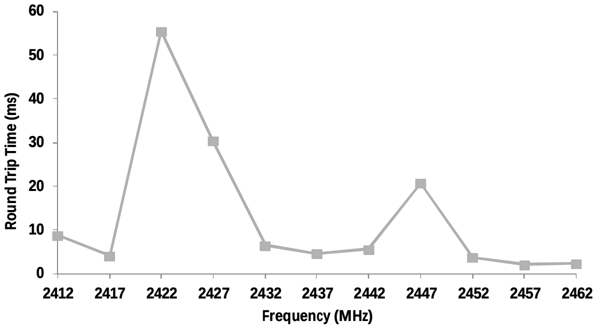

Fig. 4. Values of RTT in ms for 2Mbps (QPSK)

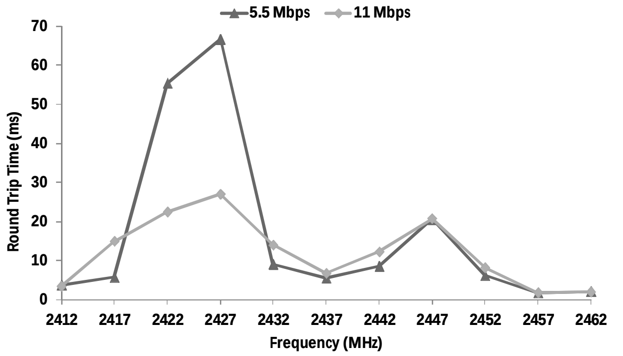

Fig. 5. Values of RTT in ms for 5.5Mbps and 11 Mbps (CCK)

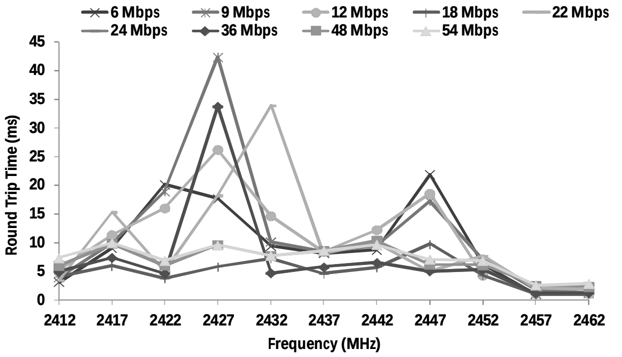

Fig. 6. Values of RTT for data transfer rates which use OFDM modulation

Figure 6 shows the RTT values in ms. for data transfer rates using OFDM modulation. As it happens in other cases, each data transfer rate defines 2 peaks. All data transfer rates show the second peak between 2442 MHz and 2447 MHz. RTT values for these peaks are placed between 5 and 20 ms. Regarding the first peak, each data transfer rate places it at different frequency.

Firstly, we should note that the highest RTT values are obtained for 9 Mbps (its maximum is located at 2427 MHz), with a value close to 43 ms. 36 Mbps data transfer rate had a maximum at 2427 MHz and 22 Mbps had a maximum at 2432MHz. Both had RTT values close to 35ms. 12Mbps data transfer rate had 25 ms., and the rest of data transfer rates presented RTT values lower than 20 ms.

B. Discussion

All our measurements and tests were carried out under controlled conditions. Our measurements let us draw several conclusions. Firstly, we can see that there is clear frequency dependence because at certain frequencies, the maximum distances are greater than others. This is contrary to the statement made by A.C. Balanis in [11]. In addition, we cannot conclude that higher frequencies deteriorate the network operation and that there will be shorter communication distances between devices. Throughout all graphics, we can see that at 2427 MHz we obtain greater distances than the ones obtained at 2412 MHz. We obtained worse results than the approximations estimated by X. Che et al. in [4]. The maximum obtained distance is 26 cm. This value is different to the value provided by X. Che et. al. Moreover, we have observed a relationship between the type of modulation and the network performance. There is better performance in some data transfer rates than others (as it is shown in Figures 5 and 6).

Finally, using the data shown in Figures 1 and 2, where we have seen the maximum distance as a function of the working frequency at 20ºC, we can model the behavior of the signal within the studied frequencies. Using Eureqa Formulize [15], we have estimated a model which relates the maximum distance as a function of the working frequency (Equation 3).

$$d(f) = 15483.1139 + 0.002532 \cdot f^2 \cdot 10^{\left(tan(sin(f))\right)\cdot cos(2.1676+f^2-0.005\cdot f)} - 12.5168 \cdot f \quad (3)$$

Where *d* is the distance in cm. and *f* is the frequency in MHz. This equation has a correlation coefficient of 0.9976 and an average absolute error of 0.172.

V. CONCLUSION

In this paper, we have analyzed the behavior of EM signals in underwater environments, with a fixed temperature of 20 degrees, and its dependence with the frequency. Although previous published works state that the EM behavior has no relationship with the frequency in fresh water, we have observed that there is an obvious relationship with the working frequency and the type of modulation used. We have not found any previous work where these modulations have been compared under the water.

In future work, we will extend our analysis to lower temperatures, because comparing the results presented in this paper with our previous works, which were taken at higher temperatures, now we have obtained better results [16]. We will also check other antennae in order to achieve greater distances between devices, because our aim is to apply all of these improvements in the aquiculture sector [17]. Our next step is to perform the same measurements in seawater.

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