Improving the Signal Propagation at 2.4 GHz using Conductive Membranes

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***Abstract*—When IEEE 802.11 at 2.4 GHz signal crosses different surfaces, it is generally reduced, but we have seen that it does not happen for all material. Conductive membranes are able to transport electric charges when they are submerged into water with electrolytes, so we take profit of their features in order to know in which cases the Received Signal Strength Indicator (RSSI) can be improved. In order to achieve our goal, the RSSI is measured at different distances using different environments for the membranes, air and water environment with different conductivities (distillated water, tap water and salty water). Results show that different membranes environment produce different signal strength. Moreover, they can be positive or negative depending on the environment of the membranes and the distance from the Access Point. In some cases, we registered an increase of more than 14 dBm of the signal when we were using those membranes.**

***Index Terms*—Wireless signals propagation, RSSI, wireless networks, Conductive membranes, water environment.**

I. Introduction

A SYNTHETIC membrane is a barrier which separates two phases and restricts the transport of different chemical species. A membrane can be homogeneous or heterogeneous, and symmetric or asymmetric in structure. It can be solid or liquid. There are several kinds of membranes. On the one hand, it can be neutral, but membranes are also able to transport positive or negative charges. It is possible to find bipolar membranes [1].

In electrically charged membranes, called ion-exchange membranes, ions that carry the same charge as the membrane material are more or less excluded from the membrane phase. Therefore, they will be unable to penetrate the membrane [1]. A polymeric ion exchange membrane, with fixed ion exchange groups on the surface, acquires surface charge by ionization of the fixed ion exchange groups when brought into contact with an aqueous medium. This charge influences the distribution of ions at the membrane solution interface. Co-ions are repelled from membrane surface while counter-ions are attracted to it [2].

In an ion-exchange membrane, the fixed anions are in electrical equilibrium with mobile cations in the polymer interstices. In contrast, the mobile anions, called co-ions, are almost completely excluded from the polymer matrix because of their electrical charge which is identical to that of the fixed ions (Donnan exclusion phenomenon). Due to the exclusion of co-ions, a cation-exchange membrane only permits transfer of cations. Anion-exchange membranes carry positive charges fixed on the polymer matrix. Therefore, they exclude all cations and are only permeable to anions. Thus the selectivity of ion-exchange membrane results from the exclusion of co-ions from the membrane phase [3]. Cation exchange membranes contain negatively charged groups such as $–SO_3^{\,-}$, $–COO^-$, $–PO_3^{\,2-}$, $–PO_3H^-$, $–C_6H_4O^-$, etc. These are fixed to the membrane backbone and allow the passage of cations but reject anions. Anion exchange membranes contains positively charged groups such as $–NH_3^{\,+}$, $–NRH_2^{\,+}$, $–NR_2H^+$, $–NR_3^{\,+}$, $–PR_3^{\,+}$, $–SR_2^{\,+}$, etc. These positive charges are fixed to the membrane backbone and allow the passage of anions but reject cations. According to the connection way of charge groups to the chemical matrix structure, ion exchange membranes can be homogenous and heterogeneous membranes where the charged groups are chemically bonded or physically mixed with the membrane matrix, respectively. However, most of ion exchange membranes are rather homogenous and integrated of either hydrocarbon or fluorocarbon polymer films hosting the ionic groups [4].

The Donnan exclusion phenomenon, and thus membrane selectivity, depends on the concentration of the fixed ions; the valence of co-ions; the valence of counter-ions; the concentration of the electrolyte solution and the affinity of the exchanger with respect to the counter-ions [5]. When an electric current flows through an ion exchange membrane, there arises a concentration gradient of electrolyte in boundary layers of solution. This is due to the difference between transport numbers for ionic components in the membrane and solution. In turn, this concentration gradient is the reason whereby a potential is generated near the membrane surface shifting away from its equilibrium value. A similar phenomenon takes place in electrode systems [3].

Ion exchange membranes are traditionally used for concentrating or desalting of electrolyte solutions. The basic

This work has been partially supported by the “Ministerio de Ciencia e Innovación”, through the “Plan Nacional de I+D+i 2008–2011” in the “Subprograma de Proyectos de Investigación Fundamental”, project TEC2011-27516.

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applications of the ion exchange membrane have paid attention to solve two important environmental problems: the recovery and enrichment of valuable ions and the removal of undesirable ions from waste water, especially to extract toxic metal ions from effluents [6]. Such membranes have the potential applications as new functional materials on the separation of ionic materials mainly used on the solutions containing multicomponents, such as electrodialytic concentration of seawater to produce sodium chloride, demineralization of saline water, desalination of cheese whey solutions, demineralization of sugarcane juice, among others. Apart from these applications, several trials have been carried out where ion exchange membranes are used as sensors. Membranes can be used for detecting parameters such as humidity, carbon monoxide, drugs, enzymes or solid polyelectrolytes. They can also be used to carrier functional materials and for generating photovoltage and photocurrent which are new phenomena. These might lead to new applications of the ion-exchange membranes [5].

Charged synthetic membranes with high conductivity and selectivity are also used as separation film in various electromembrane devices such as electrodialyzers, fuel cells and electrolyzers [7]. Fuel cells represent a clean alternative to current technologies for utilizing hydrocarbon fuel resources. Polymer electrolyte membrane fuel cells (PEMFCs) have acquired high importance as they are best suited solution for applications where a quick start up is required such as in automobiles [8].

The purpose of this paper is to study the effect of two ion exchange membranes barriers on the propagation of electromagnetic waves (EM) at 2.4GHz frequency band. Furthermore, from the results obtained, we determined the affected parameters. The tests were conducted changing the distance to the access point (AP), and the electric conductivity of the water that surrounds the membranes. Finally, in order to check the relationship between these parameters we performed various statistical analyses. To the extent of our knowledge, there is no study published such as the one presented in this paper. The main goal of this study and tests is to improve the signal propagation and wireless coverage. These topics have being investigated from different point of views such as improving the efficiency of the protocols [9], but in our case, we want to solve the problem improving the transmitter side. On one hand, there are several applications where the increase of signal propagation can be useful. It can suppose the reduction of the needed APs to cover high areas such universities or shopping centers. Moreover, there will be a reduction on the energy consumption. On the other hand, the reduction of the coverage can be used to avoid undesired connections increasing the security. Limiting the coverage to the building area, will avoid eavesdropping from outside the building. This can be very useful for banks, government buildings or military purposes.

The rest of the paper is structured as follows. Section II presents some previous works where authors discover that some types of membranes affect to the electromagnetic fields. Moreover, we also introduce some previous studies about wireless coverage at 2.4 GHz in indoors and underwater environments. Section III details the test bench used in our analysis and explains the characteristics of the membranes and the used environmental conditions. Section IV shows the results of the performed tests. It also presents the statistical analyses obtained from our measurements. Finally, the conclusion and future work are presented in Section V.

II. Related Work

This section shows several works related to the effect of some types of membranes when using Radio Frequency (RF) signals. Then we show some studies of coverage and position estimation in indoor environments, and we will show some studies about underwater communication at 2.4 GHz. These are some environments where our work can be applied.

A. Conductive membranes used in RF propagation

In last decade, several studies have been reported some interesting information on the influence of static magnetic fields (SMF) on membrane systems. Kavanagha et al. [10] reported that using Wireless Radio Frequency (WRF) detection, the inherent conducting nature of polyvinylchloride (PVC) based polymeric membranes and the incorporation of ionic liquid (IL) membranes can be exploited as a signal sensor. WRF is a novel detection technique which wirelessly monitors the conductivity of a given sample allowing non-contact detection and measurement of IL-PVC membranes as they pass through the channel. Various co-ordinated membranes produce a discriminatory drop in the resulting signal which is a direct function of the specific metal ion (Cu^{2+}, Co^{2+} or a mixture) co-ordinated to the IL. The results of the novel WRF technique have been validated principally by electrochemical impedance spectroscopy (EIS) and by portable X-ray fluorescence (XRF).

Ohata et al. [11] attempted to study the effect of relatively weak SMF on ion transport in a porous cellulose membrane. This kind of membrane was selected by the authors because this seems to be a suitable model material for studies on both biological and non-biological systems. An accelerating effect of SMF on the ion transport occurred as a result of stabilized hydration layer on the cellulose surface.

Poulidi et al. [12] used membrane reactors for “wireless” electrochemical promotion. They employed a dual chamber membrane reactor for the control of catalyst activity. Different sweep gases were used in order to create oxygen chemical potential differences across the membrane and induce the spill-over of oxygen species onto the catalyst surface. Authors achieved wireless electrochemical promotion on a system that uses the reactants as the means to control the promoter supply and removal and to regulate the catalytic activity.

Depending on the orientation of the SMF, the SMF can be applied in such a way that the incident wave from the transducer is perpendicular to the membrane surface. This configuration seems to be appropriate to achieve high scale removal efficiency, where a magnetic field into the membrane process was employed as a strategy to prevent and eliminate scale formation on the membrane surface [13]. In other cases, the direction of propagation of the incident field was parallel to the plane of the membrane [14]. This configuration is mainly used when studying biological systems.

B. Coverage and position estimation in indoor environments.

S. Sendra et al. [15] [16] analyzed the signal strength in indoor environments (and different scenarios) for several IEEE 802.11a/b/g/n variants in order to know the technology that provides better coverage features. In addition, authors compared the interferences between channels for each technology in order to know the number of available channels that can be used to plan the wireless network. The results show that the best technology in the closest zones were IEEE 802.11b and IEEE 802.11n, while the worst one were IEEE 802.11g and IEEE 802.11a. Furthermore, IEEE 802.11b was the one with highest signal strength in larger distances and the worst ones were IEEE 802.11g and IEEE 802.11n. Finally, authors conclude that the hardware used is more significant in the packet loss than the technology. Considering this analysis, S. Sendra et al. [17] developed a method for estimating indoor signal strength that will help researchers determine the best position for indoor wireless sensors. The method can save about 15% in the number of sensors needed to cover an area.

In [18], S. Sendra et al. performed a research study about the optimum location of the APs inside a building of the ”Universitat Politecnica de Valencia” (UPV) in order to provide better wireless Internet access to the students. Authors used the analytical study of the building in order to know the wireless signal behaviour in the building. These measures allowed them to develop new techniques for indoor network designs. An enhancement of this work was presented in [19]. In this case, S. Sendra et al. used the previous study for proposing a redesign of the wireless network of the Centre of resources for the research and learning (CRAI) of the Higher Polytechnic School of Gandia. They proposed a new APs distribution with a new channel scheme based on the RSSI. The results of new measurements show that the problems of wireless coverage were solved and the mathematical model extracted from the test bench could be used for other purposes.

M. Garcia et al. proposed two approaches in [20] [21] where the wireless sensor nodes can find their position using WLAN technology inside a building. The scenario was an indoor environment with walls, interferences, multipath effect, humidity, temperature variations, etc., and both approaches are based on the Received Signal Strength Indicator (RSSI). The first approach uses a training session and the position is based on a heuristic system using a training system. The second approach uses the triangulation model with some fixed APs, but taking into account wall losses and signal variations. Finally, authors considered the variations measured to obtain the biggest accuracy in the sensor localization and compared real measurements of their proposals with the measurements taken by the Ekahau system.

N. Deshpande [22] described a two-tiered approach for a wireless sensor network based localization methods by using WSN–Autonomous mobile robots interaction for navigation. This approach utilizes only the topology of the network and the received signal strength (RSS) among the sensor nodes to create the target-directed pseudogradient. Authors show that, Autonomous mobile robots can successfully navigate toward a target location using only the RSS in their local neighbourhood to compute an optimal path.

Finally, within the field of coverage studies in indoors and sensors location based on signal coverage, J. Lloret et al. [23] proposed a new stochastic approach based on a combination of deductive and inductive methods whereby wireless sensors could determine their positions using WLAN technology inside a floor of a building. The authors' goal was to reduce the training phase in an indoor environment, but, without any loss of precision. Finally, authors compare the measurements taken using their proposed method in a real environment with the measurements taken by other developed systems.

We can also find in the related literature RSSI combined with other systems for localization [24] and distance estimation [25] purposes.

C. Underwater communications at 2.4 GHz.

Regarding to underwater communications at 2.4 GHz, some authors of this paper have previously investigated the signal propagation in underwater environments.

S. Sendra et al. [26] addressed some tests at different frequencies and modulations in order to check various parameters such as minimum depth, distance between devices and signal transmission characteristics at 26 ºC. Results show that BPSK modulation presents greater stability than the other ones. It has the best results compared to other modulations because it has lower error probability.

J. Lloret et al. [27] developed a wireless sensor node based on 2.4 GHz ISM frequency band for underwater fresh water communications. They tested it in a real scenario for different frequencies, modulations and data transfer rates. They measured the maximum distance between sensors, the number of lost packets and the average round trip time. The results provide useful information. On the one hand, the modulations (and thus the data transfer rates) with better performance are BPSK and QPSK. They have less than 30% of lost packets for distances shorter than 16 cm. In addition, the results show that the RTT values for 16 cm were around 25 ms when the wireless sensor nodes were working at 2.432 GHz.

In [28], S. Sendra et al. also performed some tests at different frequencies and modulations in order to check various parameters such as minimum depth, distance between devices and signal transmission characteristics. Tests were performed in the first seven frequencies (from 2.412 GHz to 2.442 GHz). In this case, a Personal Computer (PC) and an AP were used in order to monitor the activity of the underwater point-to-point link. Results shows that EM waves are able to transmit higher data transfer rates, by using higher frequencies than using acoustic waves.

Finally, S. Sendra et al. [29] extended their study to other temperatures (20 ºC), obtaining new results. On the one hand, they observed that at certain frequencies, the maximum distances are greater than others. In addition, higher frequencies may not deteriorate the network operation and maybe there are not shorter communication distances between devices. They also observed better performance in some data transfer rates than others. Finally, authors extracted a mathematical model to estimate the maximum distance as a function of the working frequency at 20 C.

As we have seen there is very few works where membranes are used in combination with wireless signal propagation. We have not found any study about how the signal propagation is affected by the presence of membranes and how the combination of conductive membranes provides higher RSSI.

III. Test Bench

This section presents the material and scenario used in our tests.

The ion exchange membranes used in the present study are heterogeneous HDX membranes (provided by Hidrodex®). The anion exchange membrane (AEM, HDX 200) contains quaternary amine groups attached to the membrane matrix. The cation-exchange membrane (CEM, HDX 100) is charged with sulfonic acid groups and has a similar morphology to that of HDX 200. Both membranes have remarkable high ion exchange capacities, which are 1.8 and 2.0 mmol·gr^{-1} for the AEM and the CEM, respectively [30]. The structure of both membranes is reinforced with two nylon fabrics for increasing their mechanical resistance.

Measurements were taken in a corridor without any corner and pillars that has a total length of 40 m, with 2 m width and 2 m high. We placed an AP in the corridor at 0.5 m from the floor and 0.30 m from the wall. RSSI values were taken at 10 different distances from 1m to 34m. We used a D-Link DWL-2100AP using a dipole antenna with 2dBi gain. The measurements were gathered using a laptop with a Broadcom 802.11n wireless interface card. All tests were performed using IEEE 802.11g wireless technology. The working frequency was 2,412MHz and the transmission power was configured at 100mW. Fig. 1 shows the scenario where measurements were taken.

In this experiment, we analyze how different environmental conditions of the membranes can produce several effects on the signal propagation. In this study, we test four different environments: air (dry membranes), distilled water, tap water and salty water (wet membranes). Fig. 2 shows the membranes disposal around the AP antenna and the membranes environment. The container has an external diameter of 12.5 cm, an internal diameter of 1.4 cm, and 8.2 cm high. All liquids have been stored in the refrigerator for several hours at a temperature of 5ºC.

In order to avoid the multipath effect and extract from the results only the effect of the membrane (in air or water), we performed the measurements with and without the membranes. The results are calculated as the subtraction between the value of the RSSI without membrane and the value of the RSSI with membrane. In this way, we obtain the membranes effect. Each measurement is repeated five times.

IV. Result and Statistical Analyses

In this section, we are going to analyze the experimental results with different kinds of environmental conditions for the membranes.

Table I shows the average value of the RSSI in dBm, carried out in each position.

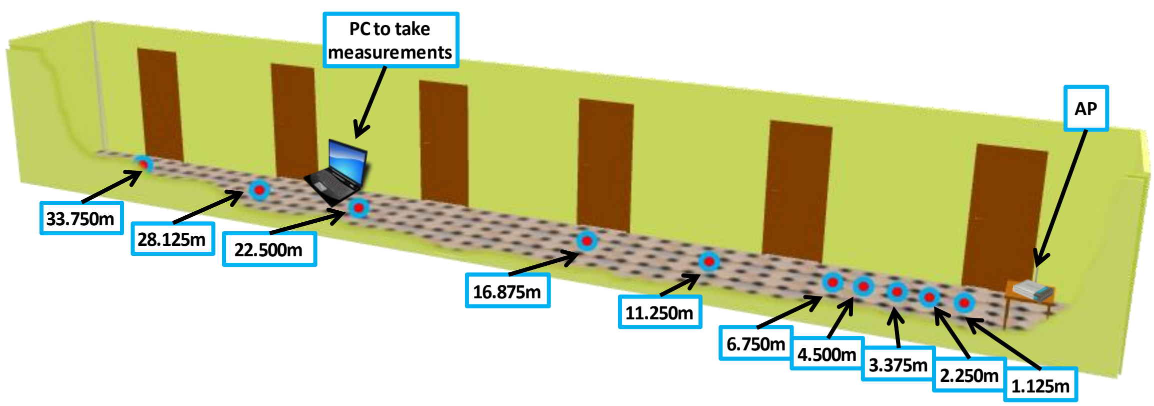

Fig. 1. Scenario where the measurements were taken

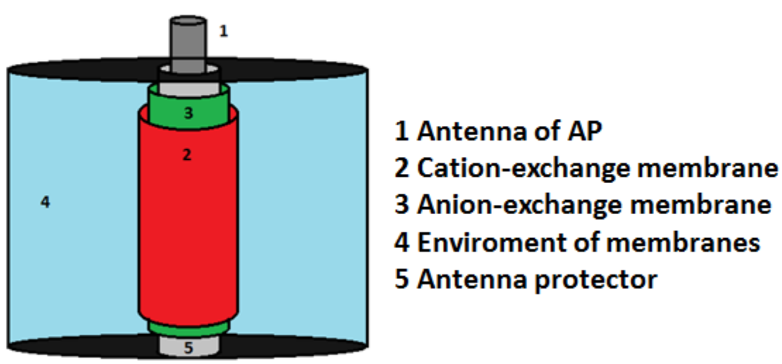

TABLE I
OBTAINED VALUES

Nº	Distance (m)	RSSI (dBm)							
		Air		Distillate water		Tap Water		Salty water	
		NM	M	NM	M	NM	M	NM	M
1	1.125	-25.0	-25.2	-25.4	-25.2	-27.4	-25.0	-25.0	-26.2
2	2.250	-25.0	-25.2	-35.8	-39.4	-42.2	-43.8	-27.4	-40.4
3	3.375	-25.2	-26.0	-44.2	-43.0	-48.8	-45.2	-42.2	-43.6
4	4.500	-27.2	-27.0	-37.2	-43.2	-53.6	-50.0	-43.0	-42.6
5	6.750	-39.4	-25.0	-45.8	-48.0	-53.6	-49.8	-46.4	-47.4
6	11.250	-50.2	-36.8	-47.0	-49.6	-58.0	-57.6	-49.8	-55.2
7	16.875	-41.8	-41.4	-50.2	-52.6	-60.0	-57.4	-53.2	-55.2
8	22.500	-39.6	-50.2	-56.0	-54.6	-66.8	-55.0	-58.6	-57.6
9	28.125	-41.2	-50.2	-47.8	-57.8	-68.0	-56.0	-58.2	-58.0
10	33.750	-47.4	-49.8	-51.6	-53.6	-68.0	-63.6	-57.6	-61.6

TABLE II
EFFECT OF THE MEMBRANES

Distance (m)	Difference of RSSI in different environments (dBm)			
	Air	Distillated water	Tap water	Salty water
1.125	-0.2	0.2	2.4	-1.2
2.250	-0.2	-3.6	-1.6	-13.0
3.375	-0.8	1.2	3.6	-1.4
4.500	0.2	-6.0	3.6	0.4
6.750	14.4	-2.2	3.8	-1.0
11.250	13.4	-2.6	0.4	-5.4
16.875	0.4	-2.4	2.6	-2.0
22.500	-10.6	1.4	11.8	1.0
28.125	-9.0	-10.0	12.0	0.2
33.750	-2.4	-2.0	4.4	-4.0

Fig. 2. Membranes disposal

The values included in Table I are the mean value of five measurements. It includes the RSSI values with and without membranes in different environments and at different distances from the AP. According to the theory, the RSSI decreases with the distance from the AP, but this effect is different in each environment when the membranes are present. The highest signal value (-25dBm) is registered at 1.125m with and without membrane, for all environments. The lowest RSSI value (-68dBm) is registered at 28.125m and 33.75m for tap water when membranes are not present.

In most cases, the RSSI value decreases with the distance. However, in some cases the RSSI value presents a peak in comparison with the previous and posterior values. This effect is observed in distillated water at 4.5m when there are no membranes. It is also observed in the air at 6.75m when membranes are used. On the other hand, we have found points where the RSSI value was lower than the previous and posterior distance. This is shown in the air at 11.25m without membranes and in the tap water at 11.25m with membranes. Those abnormal values could be related with the effects of the multipath effect.

In order to see the effect of the membranes and the alteration on the RSSI values when the membranes are present, we analyze Table II. Each value shows the difference between RSSI values without the membrane minus the RSSI values with the membrane. Positive values correspond to cases when the use of the membranes increases the RSSI while negative values show the opposite effect. We can see that different environmental conditions for the membranes generate different effects. In some cases, the same environmental condition produces in membranes different effects at different distances. The maximum positive value is registered for dry membranes at 6.45m while the most negative value is gathered at 2.25m with salty water.

All these data are going to be analyzed in the next subsections. The values are going to be analyzed for each environment separately. We will also obtain the equations that model each behavior and we will perform and discuss the statistical analysis.

A. *Tests in Air*

Now, we are going to analyze the RSSI values obtained in air. Fig. 3 shows the different RSSI values gathered at each distance. Using the average value and using a mathematical program (Eureqa [31]), we have adjusted these data to the following equations. Equation 1 presents the RSSI value when the membrane is not used (with a correlation coefficient of 0.955) while equation 2 shows the RSSI as a function of the distance when membranes are used (with a correlation coefficient of 0.987).

$$RSSI = -0.003818 \cdot D^3 + 0.2264 \cdot D^2 - 4.205 \cdot D - 16.64 \quad (1)$$

$$RSSI = 0.002128 \cdot D^3 + 0.093574 \cdot D^2 - 25.02 \quad (2)$$

Where RSSI is expressed in dBm, and distance D in meters. If the RSSI values obtained with and without membranes are compared, we observe that the RSSI does not decrease with the distance according to the logarithmic equation. This can be caused because we are in an indoor environment and the multipath effect could generate interferences. However, to avoid this dependency, measurements, with and without membranes, are performed on the same place. Thus, the refraction and reflection effects should be the same. Considering these assumptions, the difference between the obtained data can only be caused by the presence of the membranes and its effect when wireless signal cross through them. These differences can be seen in Fig. 4.

In Fig. 4 the RSSI values are different when membranes are used than when they are not. There is a statistically significant effect caused due to the use of membranes. This effect changes with the distance. In distances up to 20m, the use of membranes increases the RSSI value. From 20m, the RSSI values are higher when membranes are not used. So, the use of membranes generates two different effects, one positive and one negative depending on the distance.

In order to prove the veracity of our results, measurements are subjected to a set of statistical analyses to ensure that the difference between the values with membranes and the values without membranes are significantly different. The statistical analysis performed is a simple ANOVA. This statistical test analyzes the variability of two series of values and gives the results as a parameter called p value. The p value indicates if the series of values present a difference statistically significant. When the p value is lower than 0.005, we can assume that the data with and without membrane are statistically different. Our results show that these pairs of data are statistically different for next distances: 6.75m, 11.25m, 22.5m and 28.125m. The results are presented in Table III. It shows the RSSI values with membrane (M) and without membrane (NM). It also shows the Change, it means the variation of RSSI when membranes are present, the pValue is the result of the statistically analysis that determinates if this change is statistically significant or not. Effect details if this change is statistically significant or not. If this change is significant the arrows indicates if it is positive (↑), increasing the RSSI, or negative (↓), decreasing the RSSI. These results confirm that the changes generated by using the membranes vary as a function of the distance. We can find some distances where the effect is positive (between 6.75m and 11.25m) and distances where this effect is negative (between 22.5m and 28.125m).

B. *Test in Distillated Water*

In next case we study the RSSI measurements when membranes are submerged in distillated waster. Fig. 5 shows the RSSI values for distillated water at each distance. Each presented value is calculated from 5 measurements. This behavior is modeled by Equation 3, which represents the obtained data without membranes, and Equation 4, which shows the obtained data with membranes. Equation 3 has a correlation coefficient of 0.981 and Equation 4 of 0.992.

$$RSSI = -0.0562 \cdot D^2 + 3.353 \cdot D - 21.07 \cdot ln(D) - 26.62 \quad (3)$$

$$RSSI = 0.0191 \cdot D^2 - D + 22.19/D^2 - 41.63 \quad (4)$$

Where RSSI is expressed in dBm, and the distance D in meters. The effect of the membranes in distillated water is shown in Fig. 6.

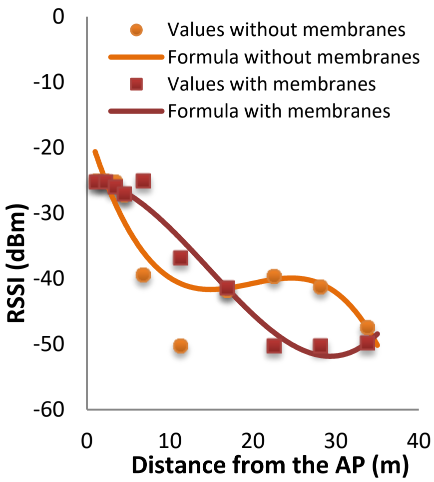

Fig. 3. RSSI values in the air

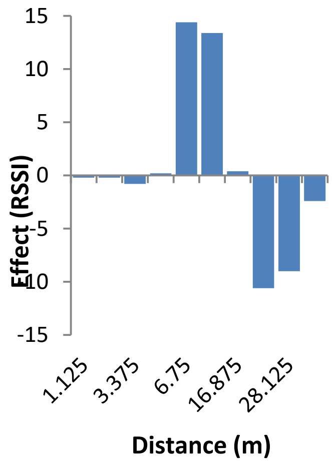

Fig. 4. Changes in the air

TABLE III
STATISTICAL ANALYSIS IN THE AIR.

Distance (m)	RSSI value		Change	p Value	Effect (p value)
	NM	M			
1.125	-25	-25.2	-0.2	0.374	No
2.25	-25	-25.2	-0.2	0.374	No
3.375	-25.2	-26	-0.8	0.099	No
4.5	-27.2	-27	0.2	0.749	No
6.75	-39.4	-25	14.4	9E-06	↑RSSI
11.25	-50.2	-36.8	13.4	2E-05	↑RSSI
16.875	-41.8	-41.4	0.4	0.74	No
22.5	-39.6	-50.2	-10.6	3E-05	↓RSSI
28.125	-41.2	-50.2	-9	0.004	↓RSSI
33.75	-47.4	-49.8	-2.4	0.08	No

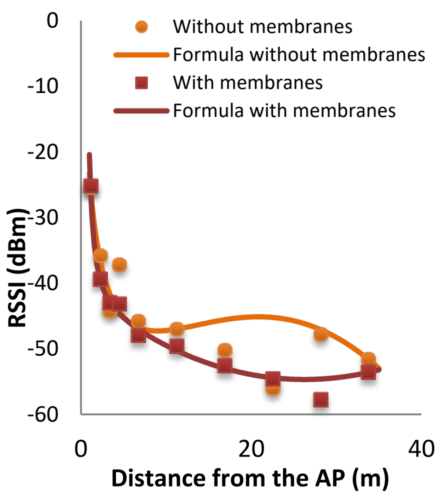

Fig. 5. RSSI values in distillated water

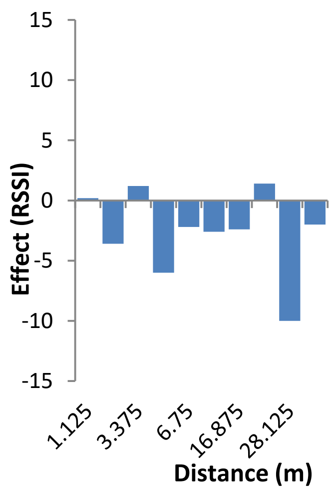

Fig. 6. Changes in distillated water

TABLE IV
STATISTICAL ANALYSIS IN DISTILLATED WATER.

Distance	RSSI value		Change	p Value	Effect (p value)
	NM	M			
1.125	-25.4	-25.2	0.2	0.704	No
2.25	-35.8	-39.4	-3.6	0.133	No
3.375	-44.2	-43	1.2	0.304	No
4.5	-37.2	-43.2	-6	0.003	↓RSSI
6.75	-45.8	-48	-2.2	0.108	No
11.25	-47	-49.6	-2.6	0.04	No
16.875	-50.2	-52.6	-2.4	0.08	No
22.5	-56	-54.6	1.4	0.263	No
28.125	-47.8	-57.8	-10	0.005	↓RSSI
33.75	-51.6	-53.6	-2	0.129	No

As in the case of membranes in air, in distillated water, the effect in signal propagation also changes with the distance. In distillated water, in most cases the effect is negative. It means that membranes in distillated water generate a RSSI reduction. There are only three distances (1.125m, 3.375m and 22.5m) where the effects are positive. In all cases, the improvement is lower than 1.5dBm.

Statistical analyses of these results are shown in Table IV. The results of this analysis show that only the pairs of data obtained at 4.5m and 28,125m are statistically different. In both cases, the effect was negative. So, we can conclude that when membranes are submerged in distillated water, the effect is almost null or negative.

C. *Tests in Tap Water*

Fig. 7 presents different RSSI values gathered in tap water. We used Eureqa with this data in order to extract the equations that model the behavior. Equation 5 models the data behavior without membranes (with a correlation coefficient of 0.997), while Equation 6 shows the data behavior using membranes (with a correlation coefficient of 0.986).

$$RSSI = 0.003755 \cdot D^3 + 0.2733 \cdot D^2 - 7.206 \cdot D - 32.16 \cdot \ln(D) - 31.04 \quad (5)$$

$$RSSI = \frac{37.43}{D} - 1.416 \cdot 10^{-14} \times e^D \quad (6)$$

Where RSSI is given in dBm, and distance D in meters.

The differences between the data with and without membrane are presented in Fig. 8. In tap water, in most of cases, the effect of the membrane is positive. It means that the RSSI value when the membrane is present is higher than the RSSI value without membrane. To be sure of this effect, the statistical analysis of data is performed. The results are shown in Table V. When tap water is used, this effect is positive and statistically significant at 1.125m, 3.375m, 22.5m and 28.125m. At 2.25m the effect is negative. But this effect is not statistically significant. We can conclude that membranes in tap water produce the increase of the signal propagation. This increase depends on the distance, where the maximum differences are observed between 22.5m and 28.125m with a value of +11.8dBm and +12dBm, respectively.

D. *Tests in Salty Water*

Finally, we are going to analyze the results and the statistical analysis when the membranes are used in salty water. On the one hand, Fig. 9 presents the RSSI values as a function of the distance from the AP when using membranes and without them. From these values, we have modeled the signal losses as a function of the distance. Equation 7 shows the RSSI value in salty water when membranes are not used meanwhile Equation 8 models the RSSI in salty water when using membranes. Equation 7 and Equation 8 present a correlation coefficient of 0.973 and 0.989, respectively.

$$RSSI = \frac{12.79}{D} - 35.76 \cdot \ln(D) \quad (7)$$

$$RSSI = \frac{1.26}{\ln(D)} - 36.06 - 7.47 \cdot \ln(D) \quad (8)$$

Where RSSI is given in dBm, and distance D in meters.

In this case, the effect of the membrane on the signal propagation is negative but low.

Assuming again that the difference between both values is only caused by the effect of the membranes, we are going to analyze those differences which can be seen in Fig. 10. As in previous cases, Fig. 10 shows the difference between the registered RSSI values when membranes are used or not. Table VI shows the results of the statistical analysis. There is only two distances where the effect of the membranes is statistically significant. At 2.25m, it is observed a signal reduction of -13dBm and at 33.75m, the signal reduction is around -4dBm. For 4.5m, 22.5m and 28.125m this effect is positive but around 1dBm. These values are not statistically significant. The rest of cases and results for salty water are not statistically significant.

E. *Comparisons*

We have observed that different environmental conditions of the membranes cause different wireless signal propagation behavior. This effect is seen even when we put water between the antenna and the air.

Fig. 11 shows the water container with its dimensions and the places at different distances, where the measurements are taken. We can see that the signal crosses only 5.55cm of water before it arrives to the air environment. The membranes are placed between the antenna and the water (in the water side of the container).

Fig. 12 shows the RSSI values at different distances when membranes are not present while Fig. 13 shows those data when membranes are incorporated. Those figures let us know the effect of different environments to the signal propagation and how it can change significantly the RSSI value at distances of 30m. This change is observed in Fig. 12, where there are no membranes. Then, we performed the same comparison but using membranes. Obtained data are shown in Fig. 13. The obtained values for RSSI are completely different in the air than in the water environment. The best values are shown in the air, in the nearest meters (until 16.875m). For distances from 28.125m, the RSSI values are similar in all environments. In this case, the best results in water environments were obtained in tap water, so there is no the same effect than without membranes where the higher conductivities produce higher RSSI reductions. WE have observed that conductive membranes affect more to the signal by reducing the RSSI at about 30 meters. This test leads us to think on other studies such as take measurements in outdoors when it is raining. Or use water containers with membranes to control the coverage.

We have observed that different conductivities generate different effects over the signal propagation.

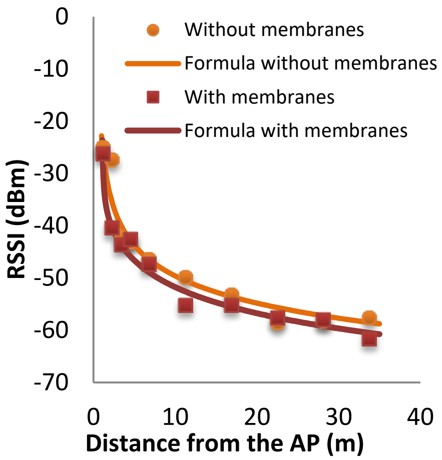

Fig. 7. RSSI value in salty water

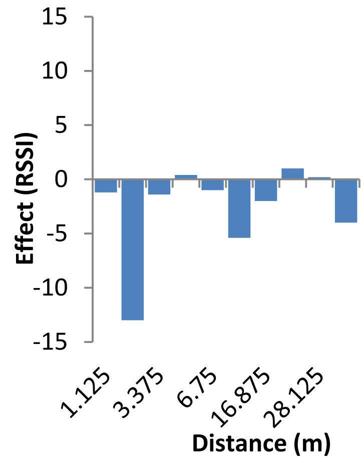

Fig. 8. Changes in salty water

TABLE V
STATISTICAL ANALYSIS IN SALTY WATER.

Distance	RSSI value NM	M	Change	p Value	Effect (p value)
1.125	-25	-26.2	-1.2	0.07	No
2.25	-27.4	-40.4	-13	2E-08	↓RSSI
3.375	-42.2	-43.6	-1.4	0.245	No
4.5	-43	-42.6	0.4	0.374	No
6.75	-46.4	-47.4	-1	0.142	No
11.25	-49.8	-55.2	-5.4	0.019	No
16.875	-53.2	-55.2	-2	0.089	No
22.5	-58.6	-57.6	1	0.0298	No
28.125	-58.2	-58	0.2	0.815	No
33.75	-57.6	-61.6	-4	0.0048	↓RSSI

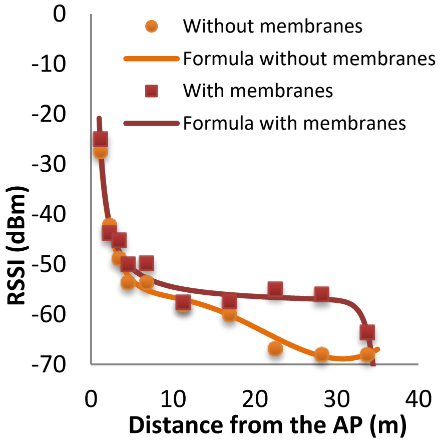

Fig. 9. RSSI values in tap water

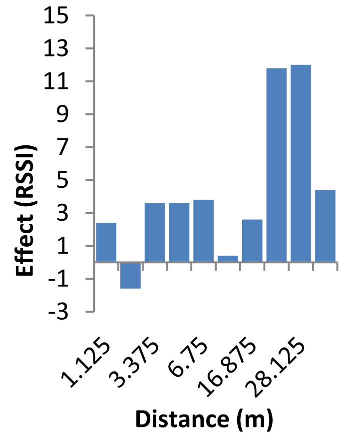

Fig. 10. Changes in tap water

TABLE VI
STATISTICAL ANALYSIS IN TAP WATER.

Distance	RSSI value NM	M	Change	p Value	Effect (p value)
1.125	-27.4	-25	2.4	0.0006	↑ RSSI
2.25	-42.2	-43.8	-1.6	0.077	No
3.375	-48.8	-45.2	3.6	0.0032	↑ RSSI
4.5	-53.6	-50	3.6	0.017	No
6.75	-53.6	-49.8	3.8	0.006	No
11.25	-58	-57.6	0.4	0.648	No
16.875	-60	-57.4	2.6	0.012	No
22.5	-66.8	-55	11.8	0.0002	↑ RSSI
28.125	-68	-56	12	5E-05	↑ RSSI
33.75	-68	-63.6	4.4	0.011	No

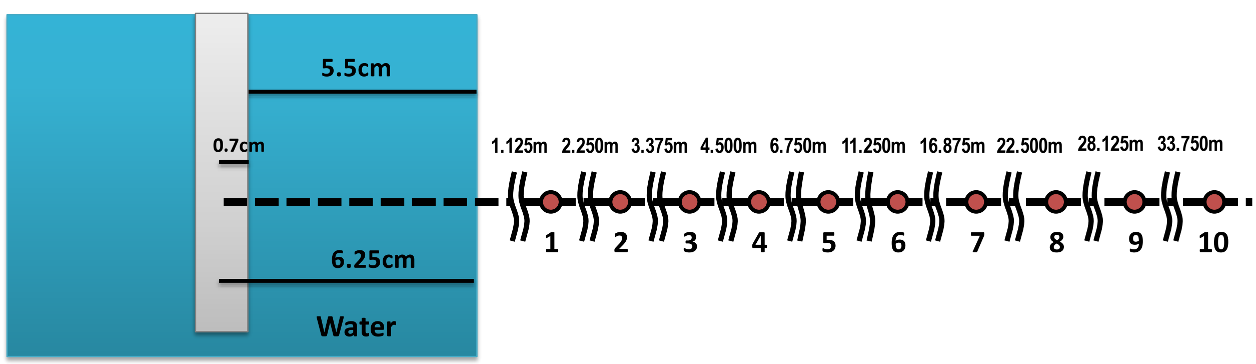

Fig. 13. Test bench when there is water between the antenna and the place to measure the RSSI.

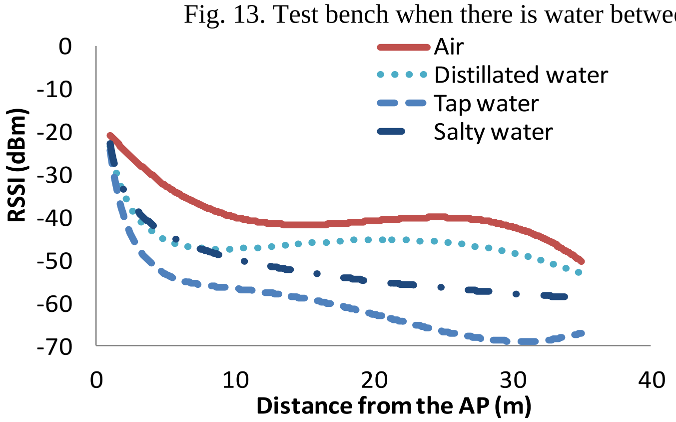

Fig. 11. Changes in RSSI after go over 5.5cm of different environments without membranes.

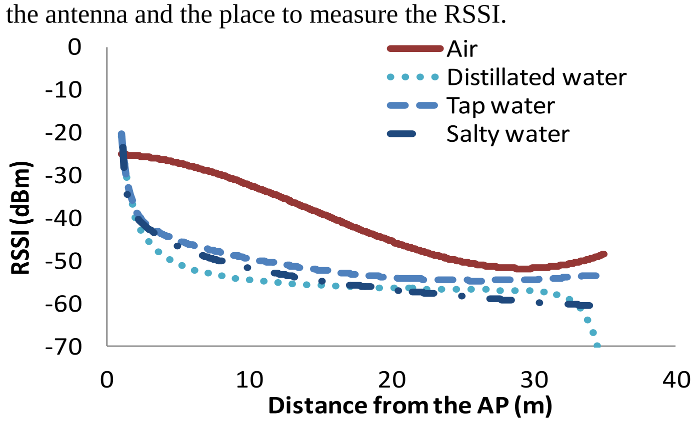

Fig. 12. Changes in RSSI after go over 5.5cm of different environments with membranes.

V. Conclusions and Further Work

In this paper, we have performed an experimental study to analyze how wireless signal propagation is affected by the use of conductive membranes in different environmental conditions

Our results show that each environment generates different alterations and effects on the membranes. This causes changes in RSSI values. This effect also varies as a function of the distance from the AP. The most interesting case is observed in the air. At short distances, the RSSI increases when membranes are used (in some cases, this increment can be up to +14dBm). At higher distances the effect is the opposite. In the rest of cases, we obtained a positive effect in tap water, and a negative effect in distillated water and salty water.

As a future work, we want to test more conductivity values in order to find where the signal has its best results. These new tests will allow us to determine the maximum increments or decrements and if this effect remains constant. Finally, we would like to reproduce these tests in a real underwater environment. The aim of this test would be to improve the wireless signal propagation in underwater environments. Moreover we would like to test if conductive membranes can also be used to control the radio coverage in critical environments such as banks or government buildings.

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