2.4 GHz Radio Transmission Measurements in a Basin filled with Sea Water

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I. INTRODUCTION

Underwater observatories contribute to scientific studies related to the interactions in the geosphere, biosphere and hydrosphere. They also participate in major natural risk prevention by monitoring underwater volcanoes or tsunamis. The European ESONET – EMSO network and NEPTUNE in Canada are among the most well-known of these observatories. Their recorded data (salinity, temperatures, hydrothermal winds, etc.) are used in several important applications, like global warming forecasts. The continuous improvement of their observation capabilities has led to a continuous increase in the amount of data they collect. Underwater wireless transmissions are concerned as well, notably between autonomous underwater vehicles (AUVs) or remotely operated vehicles (ROVs) and fixed sensor networks or seabed units.

Data transmission using acoustic waves is often a good solution in fresh or salt water. Their low attenuation enables long transmission ranges. In favourable conditions, the acoustic data rate can exceed 100 Kbits/s. Optical systems enable an important increase in this data rate, up to several meters. But water turbidity, positioning constraints, progressive lens masking by bio-fouling and the need for a clear link all limit their application capabilities.

Due to electrical conductivity and dielectric losses, radio waves are highly attenuated in water. Attenuation increases with both frequency and salinity. However, they have been successfully used in the HF or VHF bands when considering the best trade-off between a limited transmission range (from 1 to 10 meters), a high data rate (superior to 1 Mbit/s) and cost [1][2]. The idea of adapting wireless air telecommunication standard equipment to the water medium has also become attractive.

With the support of the Europole Mer Research Consortium (research axis 5), we have developed an underwater radio antenna for these applications. It is compatible with the 2.4 GHz Wi-Fi radio standard and low cost when considering the underwater context [3]. In section II, we recall the electrical characteristics of sea water and radio wave attenuation calculation in this medium. Characteristics of the antenna are briefly recalled in section III-A. In section III-B, we present the measurements for the antennas in a wide general purpose experimental basin filled with fresh water. In section III-c, the measurements are done in a basin specifically built for these experiments and filled with sea water.

II. EM MODELING OF THE SEAWATER

A. *Electromagnetic model of the seawater*

In the liquid state, the evolution of the relative dielectric permittivity ε_r of the water according to the frequency yields to a first-order Debye equation, eq (1), well matched to the expression of the characteristic relaxation phenomenon related to underlying polarization mechanisms. For seawater, salinity is due to the presence of various ionic components. It induces conductivity σ (S/m), depending on location, depth, temperature, etc.

$$\varepsilon_r = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 - i2\pi\tau f} + i\frac{\sigma}{2\pi\varepsilon_0 f} \qquad (1)$$

The typical parameters of the model are the static permittivities ε_s, asymptotic ε_∞, and relaxation time τ.

In the published literature, simple, useful, fairly accurate empirical formulas are proposed for these parameters [4], based on salinity or normality (‰), temperature (° C) and frequency (Hz). These expressions were obtained from tabulated values from aqueous solutions of sodium chloride (NaCl) for varying normalities, which is representative of seawater since cumulative concentrations of chloride ions and sodium represent more than 85% of ionic constituents.

Moreover, a rigorous model based on the electrophysiology of seawater [5] demonstrates an excellent correspondence between simulations and measurements. Unfortunately, the calculation of the rigorous model involves substantial experimental characterization, thus considerably reducing the possibilities for use.

By evaluating the equations of the empirical model, we calculated that for standard underwater conditions, variations of predictions between the two models (empirical [4] and rigorous [5]) could induce a significant impact on the attenuation assessment in seawater for electromagnetic waves at around the frequency of 2.4 GHz.

Fig.1 shows a graph comparing the response of ε_r as a function of the frequency, for both the empirical model and the rigorous one, in real and imaginary parts, at 15 ° C and 35‰ salinity (oceanic average).

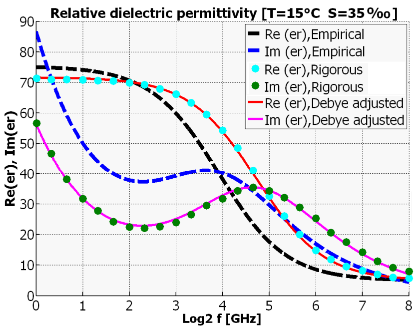

Fig. 1. Dielectric permittivity of shallow or deep seawater

Furthermore, Fig. 1 also demonstrates that the empirical model can be adjusted to obtain an excellent correspondence with the rigorous one, by modifying the parameters according to TABLE I

TABLE I. COMPARISON OF EMPIRICAL AND ADJUSTED PARAMETERS FOR THE DEBYE MODEL

	ε_s	ε_∞	τ (ps)
Empirical model	75.258	4.9	65.84
Adjusted model	71.615	4.9	37.50
Variation	4.8 %	0 %	43.1 %

B. Attenuation

The expression of the linear attenuation α (m^{-1}) for the plane wave in a medium is calculated from the homogeneous Helmholtz equation. It leads to:

$$\alpha = \omega\sqrt{\mu\varepsilon'}\left[\frac{1}{2}\left(\sqrt{1+\tan^2(\delta)}-1\right)\right]^{1/2} \quad (2)$$

where ε' is the real part of the dielectric permittivity and tan(δ) the loss tangent which integrates the conductivity contribution. Considering the frequency at 2.4 GHz, the attenuation assessment differs significantly depending on the origin of the values used for the permittivity calculation. While the rigorous model predicts an attenuation of 7.2 dB / cm, the empirical model provides an additional 4 dB / cm, due to a significant difference in the imaginary parts. Finally this is due to the differences in "τ" relaxation time, as shown in TABLE I. We note, however, that in the case presented, the real parts of the models are almost identical for that frequency.

In conclusion to this section, significant uncertainties remain in the theoretical evaluation of the attenuation at 2.4 GHz according to the different models compared.

Moreover, special care will have to be taken with respect to the sensitivity of the antenna's performances, due to the variability of the natural electrical properties of sea water with respect to various local conditions.

III. EXPERIMENTATION

A. Antenna description

Sea water presents variable electrical characteristics depending on the temperature, hydrostatic pressure, chemical composition, density of suspended particles in the medium, and the underwater flora and fauna that progressively hang on the outer surfaces of the equipment (bio-fouling). Water currents may also lead to difficulties in stabilizing the AUVs or ROVs. The antenna was developed in order to take into account most of these constraints. It benefits from a cylindrical shape that facilitates its integration on underwater instrumentation platforms. A radiating aperture is situated on the surface of a dielectric cover that prevents the water from entering the antenna. A specific probe is used in the cavity to select the illumination of the radiating aperture. The relevant mode presents a radial symmetry which suppresses any constraint concerning the rotation of the emitter and receiver relatively to the alignment axis. Such a solution is much simpler than the design of a circularly polarised antenna from which the same rotation insensitivity property should be obtained. Two prototypes have been manufactured from stainless steel (inner radius of 47.03 mm and a height of 200 mm). PVC material is used for the cover (Er= 3, thickness of 40 mm). Each prototype combines two cavities; they have approximately the same height. The front cavity is the radiator part, while the back one enables the connection of the excitation probe to a waterproof coaxial connector (Seacon SCE-DS-0010 50 Ohm).

B. Measurements in a basin filled with fresh water

The freshwater pool is largely oversized for the purposes of this study (length 4m, width 2.5m, 2m depth). Each antenna is immersed in 40 cm of depth (Fig. 2), attached by flanges and a vertical arm to a gantry above the pool which is mobile in translation along the two horizontal axes. This allows horizontal alignment and precise control of the separation distance between the antennas. The vertical alignment is performed when installed in the basin. The rotation of one of the arms about its vertical axis may be driven by stepper motor and a computer with a resolution of 0.1 °. It is then possible to determine precisely the angular characteristics of the radiation from transmission measurements. 4 temperature sensors programmed to record every minute during a manipulation did not show a significant variation within the same series of measurements on a scale ranging from 18 ° C to 20 ° C. Control by salinometer performed on three water samples confirmed the negligible conductivity of the water. In fact, the average measurements was 831 µS/cm. The antennas were connected to an analyzer HP 8753ES Vector Network 30 kHz - 6000 MHz, Pout = 10 dBm, RBW = 10 Hz filter. The calibration is performed using the SOLT method, the nearest to the excitation probes just at the entrance of the radiating cavity.

Fig. 2. Transmission measurement between the antennas in freshwater basin

The excitation of each antenna was adjusted to optimize adaptation to the nominal frequency of 2.46 GHz, close to the Wi-Fi middle band (2410-2484 GHz). The measurement results in reflection and transmission are shown in Fig. 3, the antennas being aligned in the best "visually" and located at distances between antenna apertures varying in steps of 5 cm.

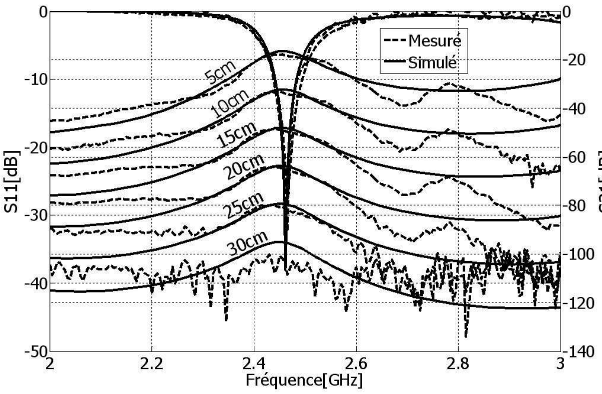

Fig. 3. S11 et S21 measuerments compared to EM simulations

Respective reflexion bandwidths are 53.9 MHz@10dB and 46.6 MHz@10dB, depending on the considered antenna. Around the nominal frequency and up to 25 cm for the separation distance, there is a very good agreement between measurement and electromagnetic simulation using finite element method (FEM). During simulations, the dielectric permittivity of water is calculated from the empirical model from Stogryn referenced above, taking into account the variations on the frequency band considered. The attenuation with the distance is extracted from measurements (3.1 dB / cm @ 2.46 GHz). It is very close to that of a plane wave in the same medium (3.2 dB / cm @ 2.46 GHz), depending on model of Stogryn. This is explained by the fact that the aperture size of the antennas is large compared firstly to the wavelength in the water and secondly the distance between the antennas. The far field distance at 2.46 GHz is 1.3 m in water, the transmission is only possible in the near-field Rayleigh zone for these frequencies.

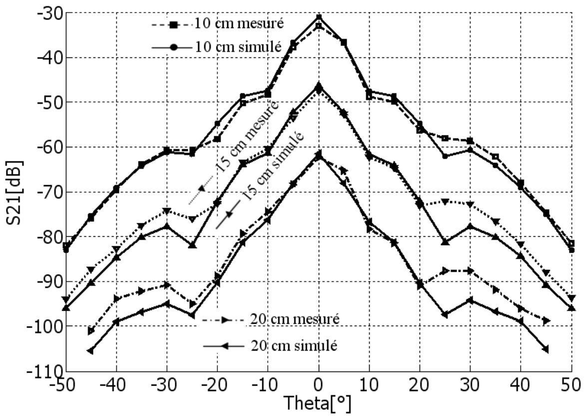

Fig. 4. Transmission depending on azimuth angular position of the antennas, for 10, 15 and 20 cm separation distances

When turning about its longitudinal axis the vertical arm holding one of the antennas, the measurements reported in Fig. 4 show at 2.46 GHz the azimuthal angular distribution of radiation as a function of the separation distance. Angle 0 ° corresponds to the case in which the antennas are aligned. The separation distances range from 10 cm to 20 cm. A very good correspondence is observed between measurements and simulations, especially as the separation distance is small (10 cm). For this distance, a transmission loss of 3 dB appears to + / - 5 °. One can also note sidelobes with levels 18 dB @ +/-15 ° and 25 dB @ +/- 30 °. It is observed that for distances between 10 cm to 30 cm , the general shape of the curve varies little but the presence of sidelobes is reinforced with respect to the maximum of the curve.

C. Measurements in a basin filled with sea water

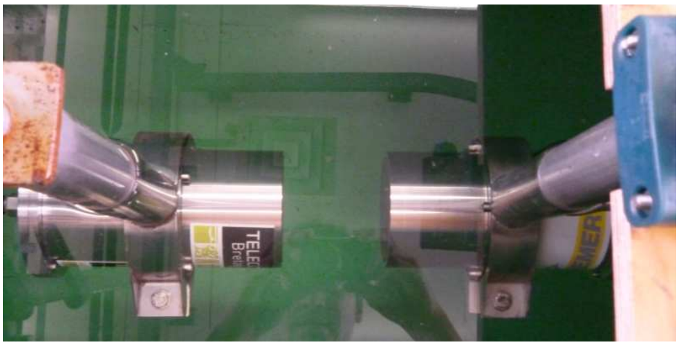

Fig. 5. The two antennas immersed in the basin filled with sea water

The dimensions of this basin are L=2m X W=1m X H=1m. The antennas are located very close to 15 cm below the water surface. These dimensions are large enough to prevent any parasitic reflection from the sea interfaces with air or basin. Indeed the expected attenuation here is about 10 dB/cm in the sea water [3]. Each one of the submerged antennas is maintained by a flange attached to a vertical metallic arm. One of the arms can be horizontally translated in order to tune the separation distance of the antennas between 0 and 20 cm. Horizontal and vertical alignments are done carefully during the mounting of the antennas in the basin. The rotation of one of the antennas around the axis of its associated vertical arm makes it possible to measure the radiating angular characteristics. A thermometer monitors the water temperature in the basin: one temperature sample is taken at the beginning of a measurement series, another one at the end. No temperature change was observed during one continuous series of the measurements. Also several series of measures were carried out in order to highlight the general sensitivity of the measurement system to the conditions of manipulations. A network analyser HP 8753ES 30 kHz – 6000 MHz, Pout=10 dBm, RBW filter=10 Hz was used for reflection and transmission measurements. SOLT calibration was done as close as possible to the input of the antenna excitation probes.

Each antenna excitation probe was adjusted to optimize the return loss (33 dB) at the nominal frequency of 2.455 GHz, close to the center of the Wi-Fi band as in the fresh water basin. The measurement results for the reflection (S_{11dB}) and the transmission (S_{21dB}) are presented in the Fig. 6 for the aligned antennas. The measured reflection bandwidths (for a return loss of 10 dB) are close to 58 MHz for both antennas. This value is much superior to a 20 MHz Wi-Fi elementary channel. The different transmission curves correspond to separation distances varying by 5 cm steps from 3 to 10 cm.

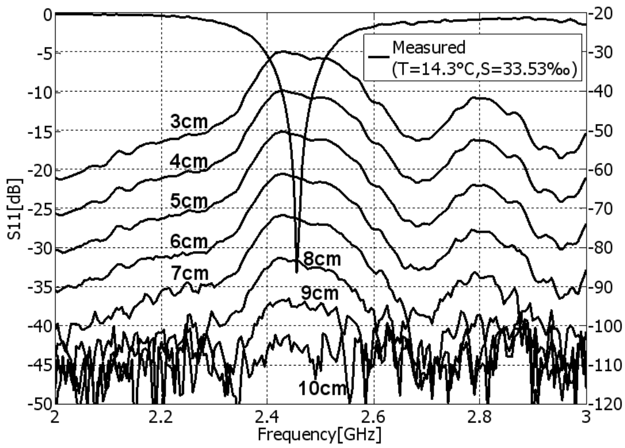

Fig. 6. Reflection (S11[dB]) and transmission (S21[dB]) sea water measurements for several antennas separation distances

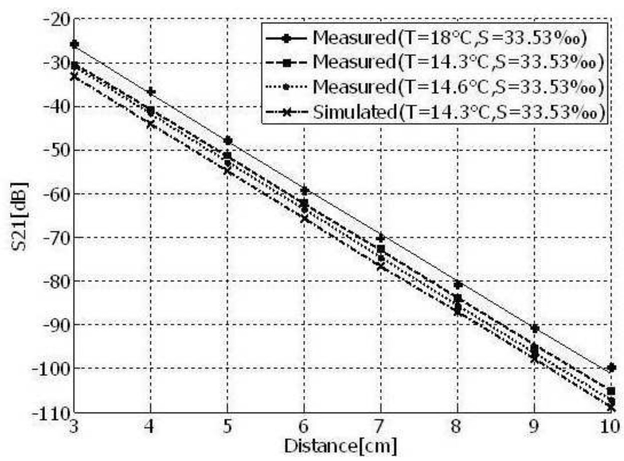

Fig. 7. Sea water transmission (S21[dB]) at nominal frequency vs separation distance for different measurements series compared to EM simulation.

We have reported in Fig. 7 the evolution of the transmission coefficient at the nominal frequency for different separation distances and different series of measurements. We have added the simulation results obtained from finite element electromagnetic simulations (Ansoft/HFSS CAD software). The dielectric permittivity is obtained from adjusted Stogryn empirical model [4] and we take into account its frequency dependency during the simulations. We can see that the attenuation in dB is quite linear for these short separation distances. Due to the very high losses, the transmission is only possible in the Rayleigh near field region of the antennas. Also the slopes are very close to each other whatever the measurement series or simulation, and correspond quite well to adjusted Stogryn model.

IV. CONCLUSION

Measurements of scattering parameter around 2.4 GHz have been presented for dedicated aligned immersed antennas in two experimental basins, one filled with fresh, the other with sea water. The measurements demonstrate transmission capabilities of these low cost antennas to support 54 Mb/s Wi-Fi underwater communications over short distances (25 cm in fresh water, 10 cm in sea water), using low emission power (10 dBm) and standards Wi-Fi modems. When salinity of water is changed from 0 (fresh) to 4 S/m (sea), only the range of transmission is affected, not the functioning of the developed antennas [3]. Moreover experiments confirmed that for a given separation distance, the rotation of one antenna around the transmission axis does not impact the signal level received (polarisation alignment unnecessary). Variation of reception due to misalignment is also reported in the case of fresh water. Otherwise multiplying the emitting power by a factor 10 will increase the range by about only 3,5 cm in fresh water and 1 cm in sea water (2.4 GHz, 20°C).

Impact of bio pollution on antenna performances as well as their integration in real underwater systems should now be considered, as well as the extension of their application areas. Their compactness and bandwidth can be further improved.

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