Deep Underwater Compatible Wi-Fi Antenna Development

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***Abstract*— In the context of future scientific oceanic observatories, this work concerns the development of a UHF radio antenna compatible with deep underwater transmissions. It aims to allow rapid transmission of large size files and real-time video. The solution under development is based on a radiating excitation isolated from the sea water by a buffer. The system presents several advantages: lack of sensitivity to sea water variability, robustness to axial rotation and to alignment between emitter and receiver, and ease of integration into classic underwater equipment. First measurements on a simple prototype present a bandwidth of 70 MHz around 2.4 GHz, appropriate for Wi-Fi communications.**

Index Terms*— Underwater antenna, Underwater Wi-Fi, antenna buffer, electrical properties of the sea water, oceanic observatory communications, deep underwater communications.

I. INTRODUCTION

Underwater scientific observatories are deployed in several international projects. For instance concerning Europe, a network of such observatories is present in ESONET, a proposed subsea component of the European GMES (Global Monitoring for Environment and Security) to provide strategic long-term monitoring capability in geophysics, chemistry, biochemistry, oceanography, biology and fisheries. In North America,NEPTUNE (Northeast Pacific Time-Series Undersea Networked Experiments) is another example whose initial objective was the feasibility study of the design featuring a cable encircling and crossing the Juan de Fuca tectonic plate. ARENA is a submarine-cabled seafloor observatory open project in Japan with the aim of providing an interdisciplinary infrastructure for scientific research and observations. Due to the well-known high attenuation of radiowaves in sea water, the use of radio transmission is not common in such contexts. But some work has been carried out by the Swedish Defence Research Agency (FOI), which has recently developed a brand-new technology for underwater communications and for applications such as monitoring climate change, detecting oil spills and communicating with divers. WFS in England is also a leading company in underwater radio technology.

The development of underwater observatories will benefit from new data transmission capabilities to enable large file exchanges between autonomous entities and fixed platforms, or interactive video transfers. Current existing solutions are based on different principles with specific limitations. Acoustic waves are often used in this context, but data rate is still limited. Temporary mechanical connections are very efficient but, notably, they have to deal with sealing problems; this results in costly and still failure-prone solutions in deep water. Laser optical systems benefit from wide bandwidths, but necessitate good alignments between the emitter and receiver; they are also sensitive to electromagnetic diffusion due to the impurities in the water. Thus they are costly as well.

The work under development is ongoing within the perspective of responding to these needs over short distances, also for deep underwater observatories, thanks to the support of the French "Europôle Mer Bretagne" program (axis 5: Complex systems for observation, measures and intervention). After a review of the sea water electrical characteristics necessary for electromagnetic antenna study, we compare two selected models from the scientific literature and point out differences which lead to some uncertainties concerning the expected reachable range. Then we present the design of an original radio antenna adaptable to the common UHF WLAN standards. Initial experimental results with a simple prototype are presented at 2.4 GHz.

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 εs, asymptotic ε_∞, and relaxation time τ.

In the published literature, simple, useful, fairly accurate empirical formulas are proposed for these parameters [1], 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 [2] 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 [1] and rigorous [2]) could induce a significant impact on the attenuation assessment in seawater for electromagnetic waves at around the 2.4-GHz frequency.

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

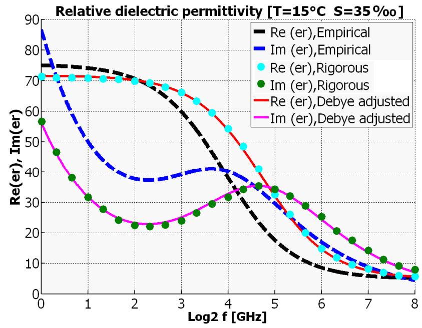

Figure 1. Dielectric permittivity of seawater

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 of radio waves 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. ONGOING STUDY OF THE UNDERWATER ANTENNA

A. *Specification of constraints and objectives*

In underwater conditions there is a need for fast wireless transmission of large computer video files, or even real-time video, using an antenna system integrated in underwater mobile module equipment.

Another important requirement is the competitive cost with respect to actual solutions (acoustic, laser, temporary mechanical connections). Moreover, special care has to be taken concerning bio-pollution and hydrostatic pressure, bearing in mind that the oceanic trenches are a part of the objectives of operational implementation.

As presented above, the electrical properties of seawater will change according to the local conditions. Possible instability in the relative positions of the transmitter and the receiver will also have to be considered to prevent any failures in data transmission.

B. *Antenna solution for transmission*

In the context of radio transmissions through biological tissues, solutions combining radiating elements and element protection (buffer) have been successfully developed [3-5]. Cavity-enclosed microstrip patch antennas have also gained considerable interest from antenna designers, due to their miniature configuration and isolation from surroundings [6]. In this way, the additional use of circular polarization was first suggested to overcome any constraints regarding the azimuthal alignment between transmitter and receiver. But the usual shapes of underwater equipment led us to consider a more appropriate cylindrical buffer.

The study of Eigen modes in this buffer demonstrates that the resonant frequency of the TM010 mode does not depend on the height and results in an azimuthal symmetry; thus its selection for radiation excitation obviates the complexification added for generating a circular polarization, while maintaining the advantages of lack of constraint concerning azimuthal alignment. In Fig. 2, we present a general description of the antenna system.

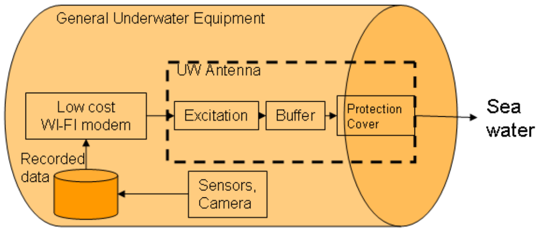

Figure 2. Antenna System Schematic and general underwater equipment

By considering on the one hand the shapes of the buffer and its excitation, and on the other hand the electrical properties of the materials, we conducted electromagnetic simulations to predict and optimize the antenna performance. The simulations were carried out by using ANSYS-ANSOFT/HFSS ® software (implementing the finite element numerical method FEM).

C. Antenna adaptation performance

With the goal of comparing simulations with experimental results using a simple prototype based on a tin can, we first tuned an antenna system with a buffer for which the radius involves a resonant frequency of 2.359 GHz.

Corresponding simulation results are shown in Fig. 3. We observe that in the presence of air around the antenna system instead of sea water, the operating frequency is shifted to a higher frequency of 2.642 GHz. However, the change in the adaptation level, due to the different corresponding impedances, is not very important. This is a useful property for simplifying manipulations when tuning the excitation during measurements, because the first manipulations were done simply in the air, but not in the sea water.

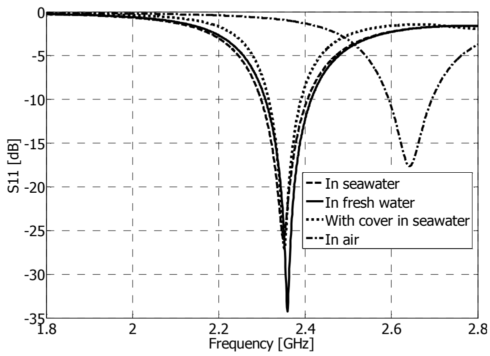

Figure 3. Input reflection coeffcient for the antenna in various conditions

We also notice that the curves predicted for both the sea water and the fresh water are very close to each other, with a very good adaptation level. This confirms the insensivity of the local sea conditions to the frequency operation for this antenna.

We have also simulated the presence of a glass cover that will be necessary to separate water from the antenna excitation. We can see that no change appears to either the operating frequency or the adaptation level, but we notice a slight reduction of the antenna bandwidth from 100 MHz to 70 MHz (for a 10 dB level) due to the permittivity of the glass. Indeed it introduces supplementary phase rotations with frequency in comparison with the air, which impacts the frequency behaviour more rapidly. Also, we have observed that higher resonant modes are shifted to lower frequencies with the presence of the glass, but these effects appear only at 3 GHz and are not visible in Fig. 3. Due to the frequency range concerned, this effect should no longer affect the functioning of the antenna.

Table III synthesizes the various levels of performance concerning the adaptation simulation results.

TABLE II. S11 PARAMETER SIMULATED

Res.Freq.	GHz	S11 (dB)	BW (%)
Simulated In air	2.642	-17.66	3.9
Simulated In fresh water	2.352	-27.06	4.5
Simulated In seawater	2.349	-25.98	4.6
Simulated with cover	2.359	-34.29	3.2

D. Antenna transmission performance

Using the antenna model tuned for the best adaptation performance as presented above, we have been able to simulate the transmission performance for a wireless link in the water as a function of the frequency and water conditions.

Firstly, in Fig. 4 we present the corresponding transmission results (S21 parameter in dB) in fresh water, considering a standard temperature condition. As expected, the transmission level decreases with the distance. For a given distance, we verify that the maximum of the transmission is very close to the operating frequency where the antenna is adapted. The small difference between the operating frequency and the maximum transmission frequency is mainly due to the increase of the attenuation with the frequency. The same reason explains why this effect is more visible and why the transmission curve becomes less symmetric when the distance between the antennas is increased. Due to the iterative meshing process used by HFSS, special care must be taken concerning the best values used for the HFSS calculation parameters, in order to obtain correct results for greater distances.

In Fig. 5 below, the curves are obtained from simulations in which the propagation medium is sea water, and in which the effects of standard temperature and salinity are studied. As explained in the previous paragraph, there is no difference in the adaptation performance (S11 in dB) between the two situations. Considering the transmission, the general shape of the curves is the same in Fig. 4 and Fig. 5, but the level is much lower for the sea water case and the dissymmetry around operating frequency is increased. This is obviously due to the increase of the loss due to salinity.

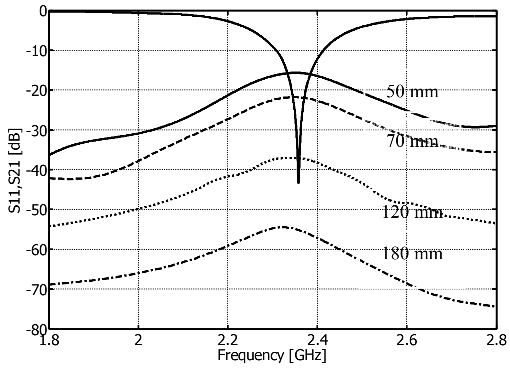

Figure 4. Fresh water case : simulation of the adaptation and transmission for different inter-antenna separation distances

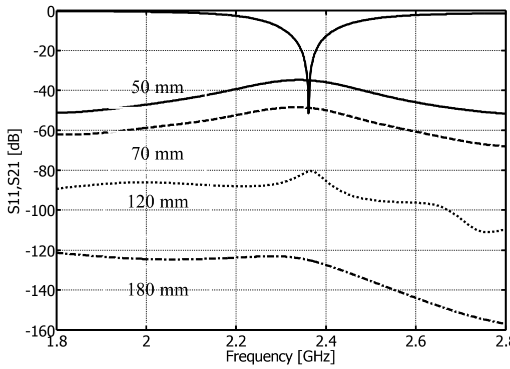

Figure 5. Sea water case : simulation of the adaptation and transmission for different inter-antenna separation distances.

One can note that in both fresh water and sea water, no coupling appears between the antennas despite the short distances considered. The reason is the amount of loss in both cases.

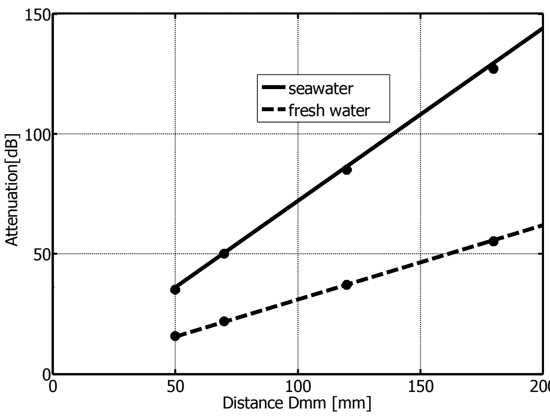

Figure 6. Budget link in fresh water and sea water as a function of the distance Dmm (in millimeters). Markers indicate the computed values.

We have synthesized the levels of transmission performance in Fig 6. The interpolation in the first 50 mm range is not significant because it concerns the near field region of the antenna. We can verify the linear dependency of the attenuation in dB with the separation distance (Dmm) between the antennas. The slope of the lines interpolating the curves are in exact conformity with the attenuation calculation of EM wave in such media derived from the analytical expression (2), as presented before. Also it appears that a distance of 15 cm should be reachable for a standard Wi-Fi system with an output power of only 100 mW.

The reflection coefficient of a preliminary simple antenna prototype based on the use of a standard tin can was measured with an Agilent 8714ET 300 kHz – 3000 MHz RF Network Analyzer. The latter was accurately calibrated by using a short-open-load method.

An experimental adjustment of the excitation element makes it possible to obtain a return loss (S11) with a very good performance, close to -25 dB at the resonant frequency. Then we verified that the water level variations in the buffer do not shift the working frequency of 2.355 GHz and a -10 dB fractional bandwidth superior to 70 MHz (Fig.7). That was expected, because the antenna operating frequency is related to the buffer radius, not the sea conditions or height buffer.

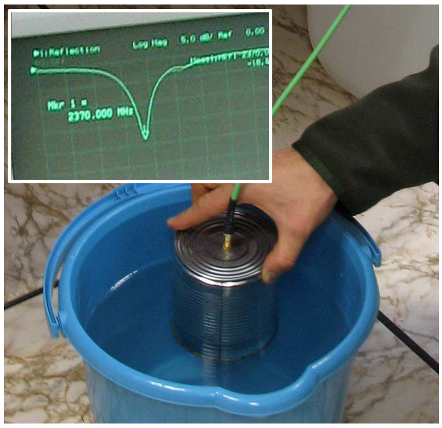

Figure 7. Measurements on a preliminary prototype at 2.4 GHz

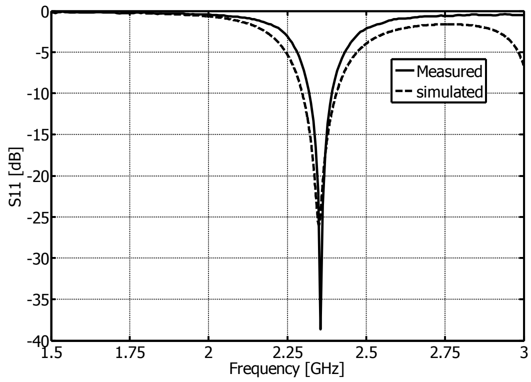

Figure 8. S11 Experimental and simulation comparison for the input reflection coefficient.

In Fig. 8, we compare simulated and measured input with respect to the reflection coefficient for the antenna. A very good correspondence for the frequency is obtained at 2.349 GHz. A slight reduction of the bandwidth appears for the measured case, due the difference in modelling of the excitation and manufacturing. The frequency is tuned experimentally during measurements

IV. CONCLUSION

A preliminary prototype of an underwater radio antenna at 2.4 GHz has been developed. The experimental measurements confirm certain specific properties selected for applications in various seawater conditions (temperature, salinity, depth...). Notably, it was not necessary to develop a circular polarization excitation to suppress any azimuthal alignment constraints between the transmitter and the receiver. Simulations for the transmission were carried out. The experimental study of the transmission in progress will make it possible to verify the hypothesis of the medium modelling and evaluate the experimental reachable distance for an underwater radiocommunication. It is expected to be about 10 to 15 cm with a common wireless Wi-Fi system. We are now improving the buffer excitation and manufacturing a more advanced prototype in order to confirm the different transmission simulation results.

REFERENCES

[1] A.Stogryn, “Equations for calculating the Dielectric Constant of saline water”, IEEE Trans on Microwave Theory and Techniques, August 1971, pp 733-736

[2] R. Somaraju, J. Trumpf. ‘Frequency, Temperature and Salinity Variation of the Permittivity of Seawater’’, Antennas and Propagation, IEEE Transactions on Volume 54, Issue 11, Part 2, Nov. 2006, pp 3441 - 3448

[3] J. Kim, Y. Rahmat-Samii “Implanted Antennas Inside a Human Body: Simulations, Designs, and Characterizations”, IEEE Transactions on Microwave Theory and Techniques, Vol. 52, No. 8, August 2004, pp 1934-1943.

[4] Tutku Karacolak, , Aaron Z. Hood, Erdem Topsakal, , “Design of a Dual-Band Implantable Antenna and Development of Skin Mimicking Gels for Continuous Glucose Monitoring”, IEEE Transactions on Microwave Theory and Techniques, vol. 56, No. 4, April 2008.

[5] Gareth A. Conway and William G. Scanlon, “Antennas for Over-Body-Surface Communication at 2.45 GHz”, IEEE Transactions on Antennas and Propagation, vol. 57, No. 4, April 2009.

[6] Karmakar, N.; Singh, M, “Investigations into a circular patch antenna in a cylindrical cavity enclosure” Singapore ICCS'94. Conference Proceedings, Vol.2, 1994, pp 446 – 450.