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(Article begins on next page)

Analysis of underwater EM propagation for scuba diving communication systems

Andrea Massaccesi¹, Paola Pirinoli¹

¹ Dept. of Electronic and Telecommunications, Politecnico di Torino, Torino, Italy, paola.pirinoli@polito.it

Abstract—In this summary, the feasibility of a wireless communication system to be used by scuba divers in case of danger, adopting radio frequency electromagnetic wave technology, is investigated. Some results on the characterizing feature of the propagation inside the water are reported, together with the principal constraints that the environment introduced on the design of the entire system and of its antenna more specifically.

Index Terms—antenna, underwater propagation.

I. INTRODUCTION

In recent years, diving is becoming an activity largely diffused and in continuous development. However, most divers are people who practice such activity sporadically or for the first time in vacation. The low experience level of these scuba divers has caused an increase in risk of incidents or dangerous situations, and therefore, the use of safety devices, allowing to every scuba diver to communicate in case of danger, can be essential.

Underwater communication is significantly affected by marine environments, noise, limited bandwidth and power resources, severe attenuation, multipath, frequency dispersion and other effects that make underwater communication complex and difficult to control. Despite of these problems, in the last 15 years the interest for wireless sensor network, especially devoted to monitor the marine environment, pushes the researches to investigate the possibility of designing systems for the underwater wireless communication.

Up to now, the most widely proposed technology is based on the propagation of acoustic waves, that provides long transmission ranges (up to 20 km) [1]. However, as mentioned in [2] its performances in shallow water are very poor, because the transmission is affected by turbidity, ambient noise, salinity and pressure gradients; moreover, acoustic waves can have an adverse impact on marine life [3]. In view of these drawbacks, several studies have been conducted in the last 10 years on underwater optical communication, e.g. in [4] and [5]. Despite of their attractive wide bandwidth, optical waves provide good performances only in very clear water. In Wireless Sensor Networks (WSN) applications, the use of optical waves requires tight alignment of nodes, even if some efforts have been made in [6] to try to overcome such a limitation.

A third possibility is represented by the use of radio frequency (RF) electromagnetic (EM) waves, whose most important drawbacks are the short transmission range and the electromagnetic interference (EMI). Some results on the use of

EM wave technology in underwater wireless communication are presented in [7] [8], while in [2] the comparison among underwater acoustic, optical and electromagnetic waves propagation is carried on, pointing out the main benefits and limitations of the three.

The main advantage of a RF signal propagating in water is that it can cross water-to-air or water-to-earth boundaries easily following the path of least resistance, while optical and acoustic waves have a strong attenuation when transmitting through water/air boundary. Secondly, acoustic and optical waves have poor performance where there are turbulence caused by tidal waves or human activities, in opposition to EM propagation, that is less affected by these phenomena. Afterwards, EM waves can work in dirty water conditions, while optical waves are susceptible to particles and marine fouling and they are also immune to acoustic noise. Finally, EM waves have no dramatic effects on marine life. All these features indicate that RF EM wave technology could represent a good alternative in sensor network systems located in shallow waters or near to the coast, i.e. in the situation in which it is possible to take advantage of the RF propagation characteristic mentioned above [2].

However, in case of communications between two or more scuba divers, things are completely different, since it is reasonable to assume that both the transmitter and the receiver are at a depth of at least 10-20 m. Moreover, they are both in movement and finally the devices must have a reduced size and weight. On the other side, such a link presents also some advantages with respect to the one between two underwater sensors, as the reduced distance between two divers, that could be assumed of the order of 10-15 m and the need of a reduced bandwidth, since just an alarm signal or the voice signal have to be transmitted in case of danger. In order to investigate the feasibility of such a communication system it is important to have a quite accurate model for the underwater RF EM propagation. In the next section two different approximated models for the computation of the conductivity σ and the complex permittivity ϵ of the water as a function of temperature, salinity and frequency, are presented. Since on σ and ϵ all the parameters characterizing the propagation in the water depend, it is necessary to test the validity of the considered models: this is done comparing the data obtained by their use with those of a full-wave simulation of a plane wave propagating in water. Some results on these studies are reported in the next section, while in the concluding one the system design specifications derived by this analysis are introduced.

II. UNDERWATER RF EM WAVE PROPAGATION

In order to study the real feasibility of an underwater EM system for communication among scuba divers, it is necessary to properly model the EM propagation in water, a lossy medium whose electromagnetic properties depends essentially on three parameters: salt concentration, frequency and temperature. In nature, water exists in several forms, characterized by a different salinity and temperature. As a result, the electromagnetic properties of the different type of water change drastically and it is not possible to design an EM communication system that works properly in any water condition, but it is necessary its optimization for the particular environment in which it has to be used. Referring to the case of a system for scuba divers, it is reasonable to imagine that it has to work in waters with quite high salinity (seawater), or with low salinity (freshwater); therefore, these two situations will be separately analyzed.

In the papers dealing with underwater EM propagation, different approximated model for computing its main parameters are introduced (see [2] and [8]). In order to properly take into account their dependence from the water features, as temperature and salinity, and from frequency, here two models for the computation of the conductivity σ and the complex permittivity ε have been used. The other quantities, as the attenuation, the phase velocity and the intrinsic impedance, are evaluated from the obtained values for σ and ε .

A. Weyl model

According to the model introduced by Weyl in [9] and modified by Stogryn in [10], the ionic conductivity of saline water as a function of salinity and temperature is defined by the following equations:

$$\sigma(S, T) = \sigma(S, 25) \cdot \exp(-\Delta\beta)$$

$$\Delta = 25 - T$$

$$\beta = 2.033 \cdot 10^{-2} + 1.266 \cdot 10^{-4} \cdot \Delta + 2.464 \cdot 10^{-6} \Delta^2 - S (1.849 \cdot 10^{-5} - 2.551 \cdot 10^{-7} \cdot \Delta + 2.551 \cdot 10^{-8} \Delta^2)$$

and

$$\sigma(S, 25) = S (0.182521 - 1.46192 \cdot 10^{-3} S + 2.09324 \cdot 10^{-5} S^2 - 1.28205 \cdot 10^{-7} S^3)$$

where T is temperature in degrees centigrade ($^{\circ}\text{C}$), S is salinity in parts per thousand (g/kg) and $\sigma(S, 25)$ represents the specific conductivity measured at 25°C .

This model is based on polynomial interpolations of measured data and it can be used for the computation of the freshwater and seawater conductivity.

B. Klein-Swift model

According to this model, introduced by L. A. Klein and C. T. Swift in [11], the complex permittivity could be defined by the Debye expression:

$$\varepsilon(\omega, T, S) = \varepsilon_{\infty} + \frac{\varepsilon_s(S, T) - \varepsilon_{\infty}}{1 - [j\omega\tau(S, T)]^{1-\alpha}} + j \frac{\sigma(S, T)}{\omega \varepsilon_0}$$

where T is the temperature, S the salinity, ε_{∞} is the dielectric constant at infinite frequency, ε_s is the static dielectric constant, τ is the relation time, σ is the conductivity and α is an empirical parameter that describes the distribution of relation times.

In the above equation, the quantities ε_s , τ and σ , are all functions of temperature and salinity. Their dependence is derived from experimental results, utilizing regression fits to the data. The expressions of the terms $\varepsilon_s(S, T)$ and $\tau(S, T)$ are reported in [11], while $\sigma(S, T)$ is defined by Weyl model.

C. Attenuation

The Klein-Swift model and Weyl model have been used for the computation of the quantities characterizing the EM propagation, such as attenuation.

In Fig.1, it is shown the frequency behavior of the p.u.l. attenuation α for different values of σ computed for $T = 20^{\circ}\text{C}$, that is the average temperature in the Mediterranean sea. The value of $\sigma = 5 \text{ S/m}$ almost corresponds to the average salinity of the Mediterranean Sea ($\sigma = 4.78 \text{ S/m}$ for $S = 35 \text{ g/kg}$).

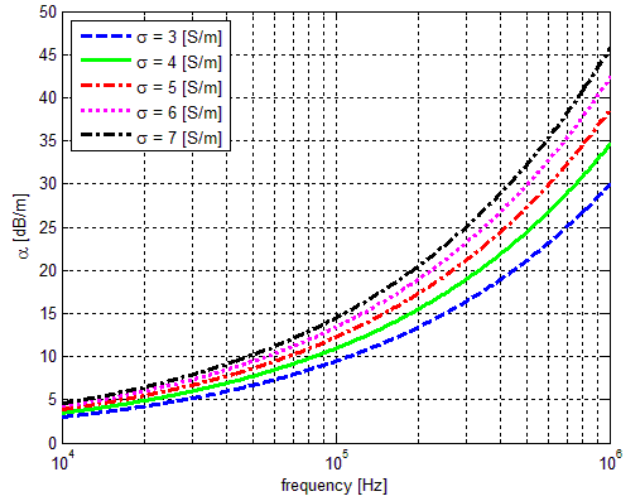


Fig.1 - Frequency behavior of the p.u.l. attenuation for different values of the conductivity σ and for $T = 20^{\circ}\text{C}$.

The curves in Fig.1 confirm that attenuation strongly increases with frequency, and therefore, frequency higher than 100 kHz could not be used, if a transmitter signal would be received at 10-15 m from the source. The attenuation in freshwater is much lower than in seawater. If we consider, for example, a frequency of 100 MHz, the attenuation of a generic freshwater ($\sigma = 0.0164 \text{ S/m}$) is approximately equal to 3 dB/m, while in seawater ($\sigma = 4.78 \text{ S/m}$) is about 362 dB/m. This clearly implies that communication systems for freshwater applications could work at higher frequency, or vice versa that at a fixed frequency the EM signal could reach larger distances in freshwater than in seawater.

D. Models validation

The goodness of the models adopted to evaluate the EM propagation parameters in water has finally been tested simulating with CST Microwave Studio the propagation of a plane wave inside water, for different values of its characteristic parameters and for several frequencies. The curves in Fig. 2 show the variation with the distance from the source of the power density computed adopting the models for seawater ($\sigma = 4.78$ S/m) introduced above and obtained with CST simulations. Both graphs are referred to 10 kHz. At this frequency, the attenuation is about 3.77 dB/m, the wavelength is 14.45 m, the permittivity is $\epsilon = 72.5 + j8.6 \cdot 10^6$ and the intrinsic impedance is $\eta = 0.091 + j0.091 \Omega$. They are practically coincident and this confirms the possibility to use the models introduced above, for characterizing the medium.

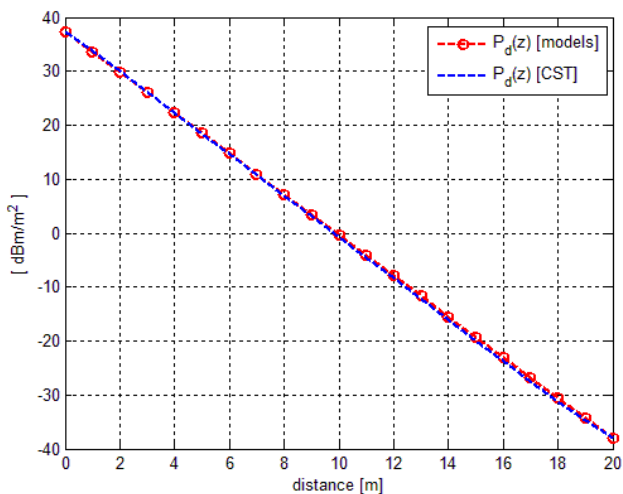


Fig. 2 - Variation of the power density with the distance from the source at $f = 10$ kHz

III. DESIGN SPECIFICATIONS SUMMARY

From the analysis summarized in the previous section, it is finally possible to derive the system design specifications, for both freshwater and seawater. The strong attenuation, especially for this latter, suggests to design a low frequency system; on the other side, decreasing too much the frequency is not possible, since it causes an increase of the size of the antenna and therefore of the entire equipment that has to be carried by the divers. A good compromise seems to be that of working at frequencies in the range 10-100 kHz, in case of seawater, in such a way to have an antenna with size lower than 40 cm. Another critical parameter is the antenna input impedance, that could be very low ($< 1\Omega$) and therefore it requires the design of an efficient matching circuit. For what finally concerns the radiation pattern, it has to be omnidirectional. In freshwater,

lower attenuation values allow to increase the working frequency. The optimal frequency range could be 10 MHz - 3 GHz. The lower limit cannot be exceeded in order to have a small antenna, while the upper bound represents the maximum frequency to reach the desired wireless communication range. A good solution can be the 433 MHz ISM band, where the central frequency is 433.92 MHz. At this frequency the wavelength is reduced ($\lambda = 7.72$ cm), the attenuation is 3 dB/m and the intrinsic impedance of the medium is about $42.11 + j0.18 \Omega$. In order to verify the effective characteristics of an antenna radiating in freshwater, easy configurations, as a dipole or a monopole have been considered. If from a radiation point of view they present patterns similar to those in free-space, a problem arises with the input impedances, that is of the order of 9-14 Ω for the dipole and 4-7 Ω for the monopole. This requires the use of a different type of antenna, as for instance, the folded dipole, that has an input impedance 4 times greater and it is easier to match.

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