A Multipath Fading Channel Model for Underwater Shallow Acoustic Communications

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Abstract— **In these last years, many studies have focalized on the design of reliable under water acoustic communication systems. However, the ocean acoustic communication channel exhibits strong amplitude and phase fluctuations and the phenomena of diffraction, refraction and reflection. Due to the complexity of environment, the motions of transducers, sea surface, etc., the underwater acoustic signals exhibit random temporal and spatial frequency fluctuations in both amplitude and phase. These highly space, time and frequency dependent features introduce numerous obstacles for any attempts to establish reliable and long-range underwater acoustic communications. Therefore, it is very important to model a so complex channel. In this paper, we propose a new multipath channel model for shallow underwater acoustic communications. In particular, our model takes into account the effects due to spreading loss, scattering and reflections.**

***Index Terms*—Underwater communications, Acoustic channel, underwater reflections, sound intensity loss.**

I. INTRODUCTION

UNDERWATER acoustic (UWA) communications have been used in military applications for a long time. Compared to radio waves, sound has superior propagation characteristics in water, which make it the favorite technology for this specific scenario. However, the shallow-water acoustic channel is different from the radio channels in many aspects. The available bandwidth of the UWA channel is limited and it depends on both range and frequency. The acoustic signals are affected by time-varying multipath, which may create severe inter symbol interference (ISI) and large Doppler shifts and spreads. These characteristics restrict the range and bandwidth for the reliable communications. The propagation speed in the UWA channel is five orders of magnitude lower than the speed of the radio wave. When designing a network protocol, it should be given special attention to these aspects. These highly space, time and frequency dependent features pose numerous obstacles for any attempts to establish reliable and long-range underwater acoustic communications. Therefore, it is very important to model this complex channel. The main goal of this paper is to modeling how environmental conditions affect underwater transmission. For this purpose a mathematical formulation taking into account the effects due to spreading loss, scattering and reflections, was presented. The paper is organized as follows: in Section II related works are described, a brief introduction of underwater sound propagation is presented in Section III, the underwater channel modeling is described in Section IV and Conclusions are summarized in section V.

II. RELATED WORK

In literature, there are several articles dealing with Under Water Acoustic Sensor Networks (UWASNs). On the shallow water acoustic channel, the transmission systems are exposed to some problems including non stationary properties of underwater channel and presence of multiple paths. One of the first works that tried to solve these problems was [1]. In this paper the authors suggest a multicarrier transmission system based on the OFDM principle, whose D.F.T implementation is quite simple. The performance of this transmission was evaluated by simulative experiments carried out in the Ocean sea scenario leading to satisfying results. However, there are no performance evaluations taking into account as noise severely degrades transmitted signal. In our work, instead, great importance to the various noise factors and phenomena of degradation has been given. The benefits of using Orthogonal Frequency Division Multiplexing and coded OFDM for underwater acoustic communications are exposed in [2]. In [3] design criteria and analysis procedures for a practical OFDM underwater communications system are presented. Numerical simulations demonstrate that OFDM technique is robust at the frequency selectivity and time selectivity. Motivated by the success of OFDM in radio channels, Stojanovic et al. in [4] investigate the OFDM use for underwater acoustic channels. In [5], it is provided a reference framework for the classification of underwater acoustic communication systems. It proposes a model for frequency bands allocation, like that used in radio systems. It also defines "superficial" acoustic channel at various depths and evaluates the performance of a range of communications systems developed at the University of Birmingham, UK. In [6], it is reported the description of the underwater channel characteristics in terms of range, bandwidth, and degradation of underwater acoustic signal due to multipath fading and absorption. In addition, coherent/non-coherent modulation schemes are in detail analyzed and methods of signal processing are suggested to compensate multipath. The improvements made in the underwater acoustic telemetry from 1982 until now are examined in [7]. The research challenges include the physical underwater channel, the receiver structure, the submarines network devices and modulation techniques. One of the major limits of the underwater sensor networks is due to the battery life in sensor node. In [8] it is provided a method to estimate battery life and consumption of power of each node in a UWASN. The analysis is based on four independent parameters: distance between two adjacent nodes, carrier frequency,

frequency of data update and number of nodes per cluster. A discussion on the existing network architectures (2-D and 3-D) in underwater environment is reported in [9]. Particular attention is paid to the development of efficient network topologies and future design challenges for each level of the protocol stack. The main differences between the major terrestrial sensor networks and the underwater sensor networks are also here reported. It is also provided a detailed overview about the existing solutions for MAC, network and transport layer protocols. Acoustic short-range communications, MAC layer protocols, synchronization, issue of high latency and scheduling algorithms are described in [10]. Another important issue regards the high level channel modeling. In [11], the authors propose an approach to obtain a high level Markov chain based channel model. However, this approach is related to the physical phenomena taken into account, so an accurate physical model is needed. Since underwater channel characteristics are highly space-time variable, it is not easy to build a physical model in which all phenomena are considered. The goal of this work is to combine the acoustic intensity loss, depth and shallow reflections and propagation delay in a single underwater channel model.

III. OCEAN AS TRANSMISSION MEDIUM

The propagation of sound in a non-uniform medium is described by an equation obtained by linearization of the hydrodynamic equations of an ideal fluid. The starting equations are the Euler equation and the continuity equation from which we obtain the Helmholtz equation which is solved by imposing appropriate boundary conditions, which allow us to obtain a closed solution. One possible solution is the solution of spherical wave, which describes the field emitted by a omni-directional source and it is given by:

$$p = \frac{-j\omega\rho V_0}{4\pi R} exp(jkR) \qquad (1)$$

Another simple and important solution to the hydrodynamic equation is the so-called plane wave solution:

$$p = Aexp\left[j\left(k_x x + k_y y + k_z z\right)\right] \qquad (2)$$

The solution of Helmholtz equation in the form of plane wave is very important because in many cases, especially at sufficiently large distances from the source, the sound wave can be represented as a plane wave, or rather an overlap of plane waves. The variation of the speed sound c in the ocean is relatively small. Normally c assumes values between 1450 and 1540 *m/s*. However, even such small variations of c have a profound effect on the propagation of sound in the ocean. The sound speed can be directly measured or calculated using empirical formulas, if you know the temperature T, salinity S, and the hydrostatic pressure P or the depth z. The accuracy of the most comprehensive empirical formula is comparable to that of modern velocimeter measurements. However, the formulas that offer such accuracy are very complicated. A simple equation, but less accurate, to calculate the speed of sound in water, in *m/s,* is:

$$c=1449.2+4.6T-0.055T^2+0.00029T^3+(1.34-0.010T)(S-35)+0.016z \quad (3)$$

where T is the temperature in °C, S the salinity in *ppm* $[\%_0]$, z the depth in meters and c the speed of sound in m / s.

IV. UNDERWATER MULTIPATH CHANNEL MODEL

A. Acoustic Intensity Loss

The acoustic waves propagate in the ocean are weakened, mainly due to two phenomena, the spreading and absorption ([12],[13]). The losses due to spreading is a measure of the weakening signal due to acoustic wave geometric propagation far away from the source. In acoustics underwater propagation, we can observe two fundamental geometries, spherical geometry and cylindrical geometry. In an infinitely extended and homogeneous medium, the power generated by a source is radiated in all directions, on the surface of a sphere. This type of propagation is called spherical spreading. The losses due to the spreading of spherical type are calculated as:

$$g_{sphere}(r) = \left[\frac{I_0}{I}\right]_{sphere} = \left[\frac{r}{r_0}\right]^2 \qquad (4)$$

In the case of spherical spreading so the intensity decreases with r^2. The cylindrical spreading occurs where the propagation medium is confined between two reflecting planes. The distance between these two levels, i.e. h, must be greater than ten times the wavelength. Losses due to cylindrical spreading is therefore:

$$g_{cylinder}(r) = \left[\frac{I_0}{I}\right] = \left[\frac{r}{r_0}\right] \qquad (5)$$

In our model, the term representing the loss of sound pressure due to spherical spreading along each ray of length D can be written as

$$L_{SS}(D) = \sqrt{\frac{1}{D^2}} = \frac{1}{D} \qquad (6)$$

This term is modified in case of cylindrical spreading. In this case, the intensity of the sound pressure decays linearly with distance then:

$$L_{SS}(D) = \sqrt{\frac{1}{D}} = \frac{1}{\sqrt{D}} \qquad (7)$$

It is easy to derive geometrically the length of each ray. Let us call d_1 the depth at which the source is located, d_2 the receiver depth, h the height of the water column and R the transmission range. The distance covered by direct ray, denoted by D_{00}, is equal to:

$$D_{00} = \sqrt{R^2 + (d_1 - d_2)^2} \qquad (8)$$

Let us call D_{sb} the distance covered by a ray which has its first reflection on the surface, where s represents the surface reflections whereas b takes into account reflections on the seabed:

$$D_{sb} = \sqrt{R^2 + [2bh + d_1 - (-1)^{s-b} d_2]^2} \qquad (9)$$

Instead, D_{bs} is the distance covered by a ray which has its first reflection on the seabed:

$$D_{bs} = \sqrt{R^2 + [2bh - d_1 + (-1)^{b-s} d_2]^2} \qquad (10)$$

When sound is propagated in the ocean, part of its acoustic energy is continuously absorbed, for example, is transformed into heat. This absorption is largely due to the viscosity of the liquid, especially in the frequencies between 100 *Hz* and 100 *kHz.* Another reason for the decay of sound intensity with distance in the ocean is the phenomenon of sound waves scattering due to inhomogeneities of various kinds. Normally, you can only measure the combined effect of both absorption and scattering. We refer to it as the sound attenuation. An experimental formula for calculating the attenuation coefficient β [*dB/km*] at frequencies between 3 *kHz* and 500 *kHz* is:

$$\beta = 8.68 \cdot 10^3 \left(\frac{SAf_Tf^2}{f_T^2+f^2} + \frac{Bf^2}{f_T}\right)(1 - 6.54 \cdot 10^{-4}P) \qquad (11)$$

where $A = 2.34 \cdot 10^{-6}$, $B = 3.38 \cdot 10^{-6}$, S is the salinity [‰], P is the hydrostatic pressure [*Kg/cm*^{2}], f is the acoustic wave frequency [*KHz*], and f_T is the relaxation frequency [*KHz*] that is:

$$f_T = 21.9 \cdot 10^{6-1520/(T+273)} \qquad (12)$$

where T is the temperature [°*C*]. if the temperature varies between 0° and 30°, then f_T varies between 59 e 210 *KHz*.

At frequencies between 100 *Hz* and 3 *kHz*, β is usually computed through Thorp's formula:

$$\beta = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} \qquad (13)$$

where f is the frequency of the sound wave [*kHz*].

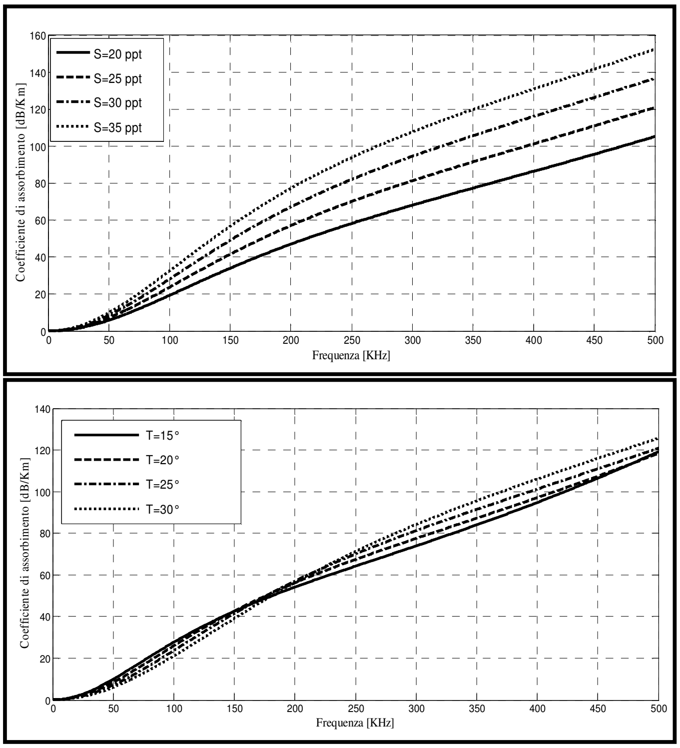

Fig. 1. Absorption coefficient for different values of salinity and temperature.

The sound attenuation at low frequencies is very small. In fact, at a frequency of 100 *Hz* the intensity of the sound wave reaches one-tenth of its initial value after more than 8000 *Km*. No other type of radiation can compete with the low-frequency sound waves to communicate over great distances in oceanic environment. Electromagnetic waves, including also those radiated by the most powerful laser, are almost completely absorbed at distances less than 1 *Km*. The values of salinity, temperature and depth affect the absorption coefficient β and thus the maximum distance of propagation. Fig. 1 shows the trend of β as a function of frequency for different values of salinity and temperature. We can see that the absorption coefficient is strongly influenced by salinity. At frequencies above 200 *kHz* an increase of 5 *ppm* of salinity causes an increase of over 10 *dB/km* in the attenuation coefficient, which however, increases for all frequency values with increasing salinity. On the other hand, the temperature has a very little impact on the value of β. Furthermore, there is not a direct relationship between temperature and attenuation coefficient, but rather, to below 200 *kHz* an increase in temperature causes a decrease in the absorption coefficient while above this threshold, the reverse is true. To obtain the value of the loss factor, the coefficient of absorption, expressed in *dB/km*, must be returned to its natural value. On the basis of this attenuation coefficient, it can be calculated a factor of sound pressure loss at distance D from the source along a ray in this way:

$$L_A(D) = 10^{-[(D/1000)\beta]/20} \qquad (14)$$

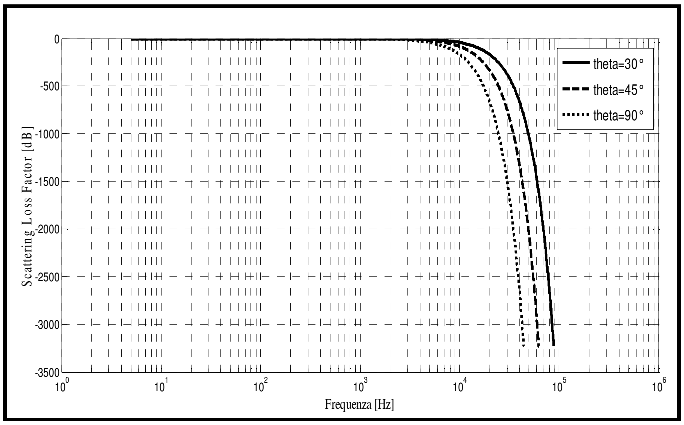

Fig. 2. Reflection coefficient as a function of frequency.

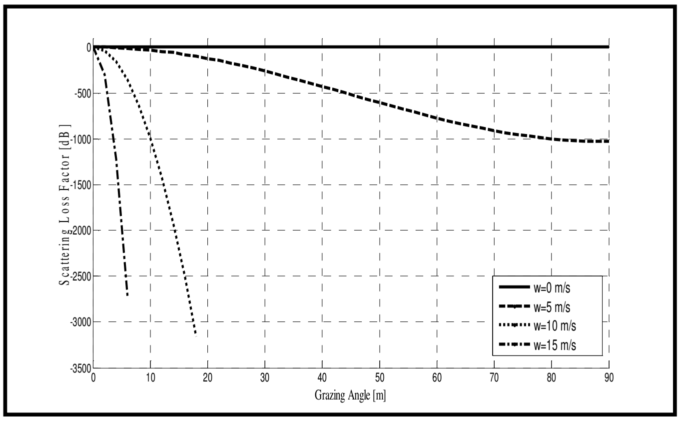

Fig. 3. Loss factor for reflection as a function of the angle of incidence.

B. Depth and Shallow Reflections

When a sound wave propagated in the ocean impacts on a rough surface, it creates a reflected field in which there are coherent and incoherent components. The coherent component is a wave that is propagated in the direction of specular reflection. The sound wave impacting on a rough surface (i.e. sea surface or seabed) is not totally reflected, in fact a portion is lost: the incoherent component of the reflected field takes into account this effect. Therefore, the reflection coefficient is less than unity and decrease with increasing mean square of the height of the imperfections on the surface .The value of σ can be calculated from the spectral density of the provision of ocean waves. This density is often modeled by the Neumann-Pierson wave spectrum. According to this model the value of σ can be approximated as:

$$\sigma \cong \sqrt{0.324 \cdot 10^{-5} \cdot v_w^5} \quad (15)$$

where v_w is the wind speed in *m/s*. Now, we can define the reflection coefficient of a not perfectly smooth surface as:

$$L_{SR} = R(\theta) e^{-p^2} \quad (16)$$

where *R(θ)* is the ideal reflection coefficient, i.e. without considering the effect of surface roughness, and its value is 1.

Fig. 2 shows the coherent reflection coefficient as a function of frequency for various values of the angle of incidence in windy conditions amounting to 5 *m/s*. In Fig. 3, instead, it is shown the trend of the loss factor due to scattering to vary the angle of grazing for different values of wind speed. It may be noted that, except in the ideal case of no wind where the surface behaves as a perfect reflector for each incident angle, if the grazing angle increases, then losses due to reflection increase. The same also happens with increasing wind speed, with a scattering coefficient decreases very rapidly. The effect of the wind makes, therefore, less important the contribution made by the rays that follow the paths that include one or more reflections on the surface. This means a lower intersymbolic interference and therefore the possibility of increasing transmission rate.

If the oceanic surface only reflects the sound waves incident upon it, the seabed reflects and absorbs the waves at the same time. A portion of the acoustic energy incident on the seabed penetrates the soil and this is a major reason that limits the propagation distance of sound at low frequencies. The acoustic parameters of the outermost layer of the sediments that make up the seabed have been studied in a rather complete way and using the experimental data it was concluded that the sound absorption coefficient for a given sediment is proportional to the frequency.

The seabed unlike the surface, does not behave like a perfect reflector but the reflection coefficient depends on the density and the granularity of the particles that form the seabed. In the case of smooth seabed, the reflection coefficient depends on the angle of incidence of the ray on the seabed and it is [7]:

$$L_{BR}(\theta) = \left| \frac{m \cos\theta - \sqrt{n^2 - \sin^2\theta}}{m \cos\theta + \sqrt{n^2 - \sin^2\theta}} \right| \quad (17)$$

where: $m = \frac{\rho_1}{\rho}$ $\qquad n = \frac{c}{c_1}$

where ρ and c represent, respectively the density and speed of sound in seawater, whereas ρ_1 and c_1 represent density and sound speed in the seabed. So, in order to calculate the reflection coefficient for the ocean floor, we must know the angle of incidence θ. Let us call Θ_{sb} the angle of incidence corresponding to the ray D_{sb} and Θ_{bs} the angle of incidence corresponding to the radius D_{bs},we can write:

$$\theta_{sb} = tan^{-1}\left(\frac{R}{2bh + d_1 - (-1)^{s-b} d_2}\right) \quad (18)$$

$$\theta_{bs} = tan^{-1}\left(\frac{R}{2bh - d_1 + (-1)^{b-s} d_2}\right) \quad (19)$$

Even for the seabed should be considered a coherent reflection coefficient, but to obtain the value of the coherence parameter is, in this case, much more complex since it is difficult to determine the characteristics of different types of seabed. Some experimental studies carried out in different sea regions and it has been shown that the reflection of sound is determined by the parameters of the sediment only for relatively low frequencies. Above a few *kHz,* the reliefs on the seabed play a predominant role. The reflection coefficient from a very steep rocky seabed is usually less than that experienced with a muddy seabed or what you get in case of a smooth seabed. Fig. 4 shows the trend of the reflection coefficient as a function of the angle of incidence in the ideal case i.e. in the absence of backscattering.

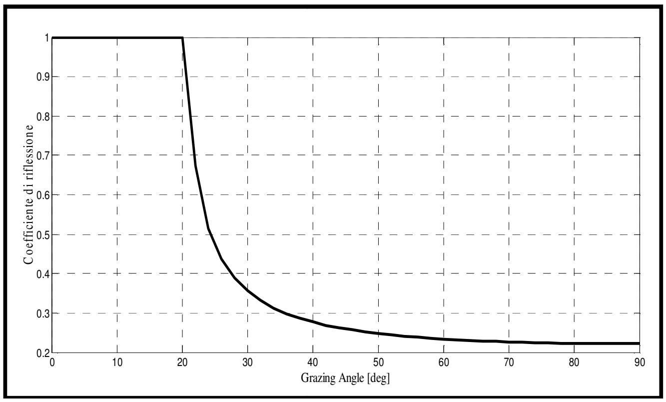

Fig. 4. Reflection coefficient on the seabed to vary the angle of incidence.

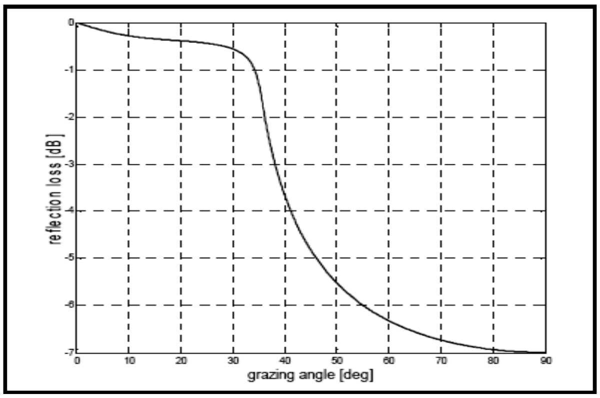

Fig. 5. Losses due to reflections caused by a seabed with coarse sand.

As mentioned above, however, the real reflection coefficient is affected by the backscattering coefficient, which depends on the size of the sediments that make up the seabed as well as the roughness of the seabed itself. In Fig. 5 and Fig. 6 the trend of the reflection loss factor for different type of seabed (coarse and fine sand) are shown. We can see how the various sediments introduce large differences in the values of loss factor.

C. *Propagation Delay*

The delay of each reflected ray with respect to the direct path is related to differences in the lengths of the different paths. Let us call τ_{sb} the propagation delay along the ray length D_{sb} and τ_{bs} the propagation delay along the ray length D_{bs}. We have that:

$$\tau_{sb} = \frac{D_{sb} - D_{00}}{c}; \qquad \tau_{bs} = \frac{D_{bs} - D_{00}}{c} \quad (20)$$

The propagation delays of the secondary rays respect to the direct ray are a very important parameter in the underwater channel and affect system performance because the delayed replicas of the signal arriving at the receiver introduces inter-symbol interference and hence the need to reduce the rate transmission. Fig. 7 shows the delay of the first 4 rays that reach the receiver as a function of transmission range.

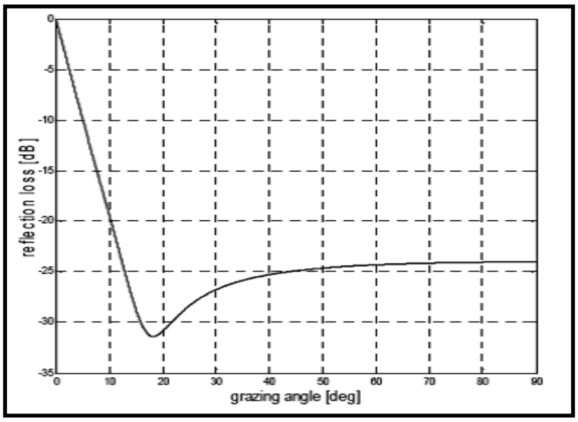

Fig. 6. Losses due to reflections caused by a seabed with fine sand.

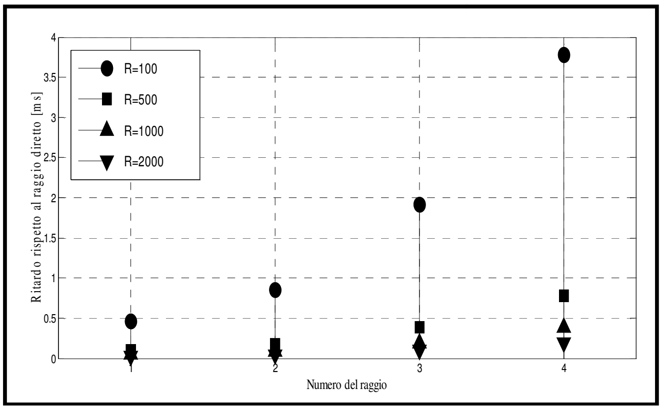

Fig. 7. delay of the first 4 rays that reach the receiver as a function of transmission range.

D. Multipath channel model

In previous subsections, we have listed the mathematical formulations of the phenomena that contribute to the degradation of an acoustic signal propagating in a static channel. Now, we have to relate all the components.

Let us call *x(t)* the signal transmitted through the channel and *y(t)* the corresponding received signal. Ignoring the absolute propagation delay on the direct ray between transmitter and receiver and combining the formulas (8), (9), (10), (14), (16), (17) and (20), we can express *y(t)* as a function of *x(t)* in the following way:

$$y(t) = \frac{L_A(D_{00})}{D_{00}} x(t) + \sum_{s=1}^{\infty}\sum_{b=s-1}^{s} \frac{L_A(D_{sb})(L_{SR})^s(L_{BR}(\theta_{sb}))^b}{D_{sb}} x(t-\tau_{sb}) + \sum_{b=1}^{\infty}\sum_{s=b-1}^{b} \frac{L_A(D_{bs})(L_{SR})^s(L_{BR}(\theta_{bs}))^b}{D_{bs}} x(t-\tau_{bs}) \quad (21)$$

V. CONCLUSIONS

In this paper, the losses due to phenomena of acoustic wave propagation and absorption have been modeled. Furthermore, also the effect of reflections on the surface has been modeled. From the acoustic point of view, the ocean is highly variable: current and turbulence disrupt the horizontally stratified characteristic of sound speed, causing spatial and temporal fluctuations to the sound propagation. In order to reduce this phenomenon, it is needed a prediction of the behavior of the channel to ensure the best possible reception. These effects can lead to transmit signal imperfections, very extreme channel characteristics or receiver frequency shaping. So, in order to partially mitigate these effects it should be needed to employ robust multicarrier transmission technique such us OFDM. The proposed model takes into account the most phenomena affecting underwater communications, however, further research can be carried out in order to predict for example the effect of reflections on different types of surface or the effect of other sources of noise such as biological noise.

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