Behavioral Modeling and Simulation of Underwater Channel

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Abstract— The Ocean is a dynamic and complex environment; it is a very complicated transmission channel that can change rapidly with the environmental conditions. Hence, to avoid failure of underwater monitoring missions, it's crucial to predict the behavior of underwater acoustic channel. In this paper, several fundamental key aspects of underwater acoustic channel are investigated. A model characterizing the underwater acoustic channel is introduced, and how underwater channel can be simulated is discussed. In addition, this paper describes a methodology for top-down design, modeling, and simulation of underwater channel using hardware description language VHDL-AMS.
The following analysis may provide precious guidelines for the design of underwater communication systems.

Index Terms—underwater communication, underwater channel model, behavior modeling acoustic signal, VHDL-AMS language.

1 Introduction

Sound waves are of great interest for transmission of information in water, so the greatest application of sound in underwater has been associated with detecting tracking, classifying submarine, pollution monitoring, disaster prevention, assisted navigation, and tactical surveillance [1][2]. It's customary to apply the name of underwater Acoustic Sensor Networks (UW-ASN's) to this phase of underwater acoustics. In fact, UW-ASN's consists of sensors and autonomous underwater vehicles deployed as said previously to perform well collaborative monitoring tasks. In approaching this problem and to ensure best underwater communication performance in mobile acoustic, where link conditions vary with time [3], it has been necessary to develop means for efficient conversion of electrical power into underwater sound and systems that are capable of detecting weak signals in the presence of noise. Of equal importance has been the study of underwater phenomena that affect the transmission of sound.

It is well known in underwater channel that low available bandwidth, highly varying multipath, large propagation delays, noise, physical channel properties variation, and high power consumption restrict the efficiency of underwater wireless acoustic systems [4]. The transmission of a reliable underwater acoustic signal, with the least distortions and the minimum emission power is of great interest for the design of underwater wireless acoustic networks while always taking into account the unfavorable conditions of the underwater environment. As well as the problems encountered when providing the system with energy, knowing that in underwater we can not exploit solar energy [4]. The oceans are so complicated that it is usually necessary either to be satisfied with simple analytical models or to rely on complex computer models for calculating transmission loss in any realistic situation.

In this paper, underwater channel behavior is investigated under a wide range of parameters like distance, frequency, and average signal to noise ratio. The analysis we present may provide precious guidelines for the design of energy–efficient and baseband polling algorithms for underwater communication systems.

2 Virtual prototyping of underwater channel model

For the advances in underwater acoustic communication and progress in underwater acoustic modem we need a behavior modeling of the physical communication underwater channel taking into account its most important properties.

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2.1 System conceptualization
The aquatic channel presents a big variety of the propagation medium for the acoustic waves [5] [6]. Thus, in this part we present an overview of underwater channel model manifestations. In this context, the transmission support is assimilated to a Gaussian channel to put in consideration the white Gaussian noise, in cascade with a Multi path fading channel, to take account of multi path effects that represent a major constraint in the underwater communication, and finally a module that represent the path losses introduced by the aquatic environment. The path losses represent the losses due to absorption, scattering, and geometrical effects like diffractions, and reflections [7]. These path losses are the principal factors determining the available bandwidth range and signal to noise ratio [8]. The mechanisms of multipath formation in the underwater channel are different in terrestrial channel. In fact there are several typical ways of multipath propagation water that depend essentially on depth and range communication.

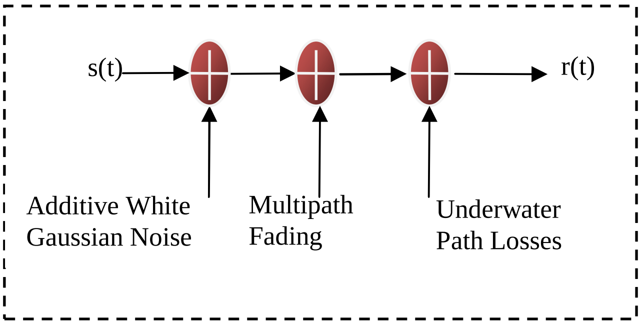

Figure1 . Conceptualization of an underwater channel

2.2 VHDL-AMS implementation of adjustable Additive white Gaussian noise (AWGN) channel
In each wireless communication systems, additive white Gaussian noise (AWGN) is often used as a model of noise. AWGN channel is actually a mathematical model that represents physical phenomena in which the only impairment is the linear addition of white noise with a constant spectral density (expressed as Watts per Hertz of bandwidth) and a Gaussian distribution of amplitude[9]. In underwater channel Gaussian, noise comes from many sources such as the thermal vibrations of atoms in transducer (referred to thermal noise), the agitation of the local sea surface, shipping, biological noise, ocean turbulence, seismic noise, phenomena of structural relaxation and agitation of water molecules.

Modeling AWGN channel needs to construct a mathematical model for the modulated signal. As represented in figure 2, the transmitted signal is corrupted by the addition of white Gaussian noise.

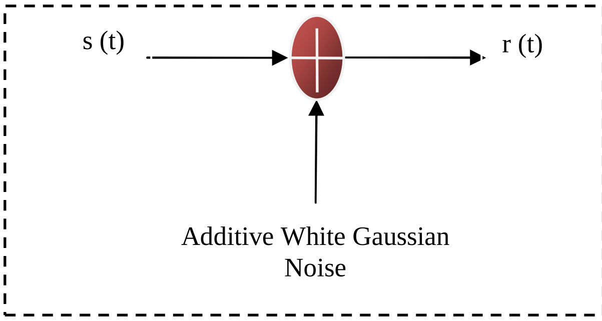

Figure2 . Example of an AWGN channel

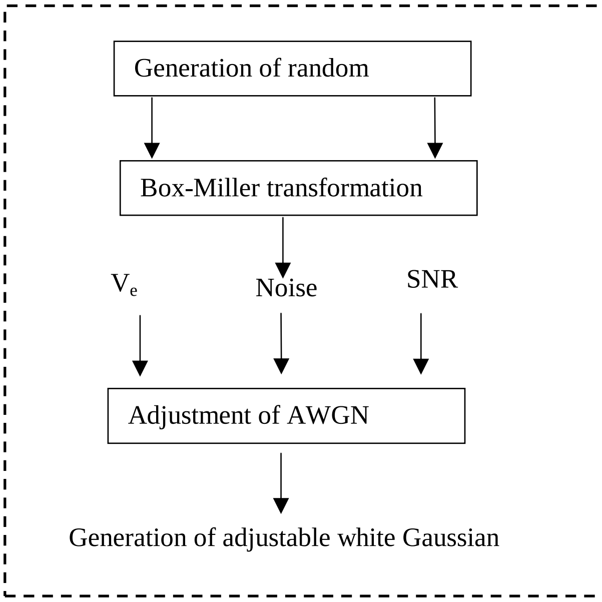

Figure3 . Intern structure of the AWGN channel

Libraries of noise in VHDL-AMS are practically inexistent. Therefore to simulate AWGN channel in VHDL_AMS we built a random function that generates a random variable (Rand1, Rand2). The noise signal is calculated using the Box-Muller [10] method, permitting to transform two definite variables by a uniform distribution in a variable based on a normal law:

$$X = \sqrt{-2\,\mathbf{ln(}\,\mathrm{Rand}_{1}\,\mathbf{)}}\,\mathbf{.\,cos(}\,2\pi\,\mathrm{Rand}_{2}\,\mathbf{)} \quad (1)$$

he implementation of AWGN on VHDL-AMS is described on figure 3 in which the generation of the noise white Gaussian takes place in three steps. The first step permits to describe the two random variables Rand1 and Rand2. Then, we use a function that returns a pseudo - random number based on a uniform distribution in the interval [0.0, 1.0]. In the second step these variables are used by the equation (1) of box Muller to generate noise.

The third step consists in the adjustment of additive white noise that depends on SNR and the input signal.

$$\mathrm{Noise\_generator} = 10^{\left(\mathrm{level}/20\right)} \times \mathrm{Noise} \quad (2)$$

With:

$$\text{level}(\text{dB}) = V_e(\text{dB}) - \text{SNR}(\text{dB}) \quad (3)$$

```
entity random is
  generic (ts : real := 0.0);
  port (quantity max : in real :=
1.0;
     quantity min : in real :=
-1.0;
     quantity val : out real);
end entity random;
architecture behav of random is
 quantity temp_val : real := 0.0;
begin
 temp_val == ((max - min) *
random(1.0) + min);
 val == temp_val'zoh(ts);
end behav;
```

Figure4 . code source for generating random variable

```
noise_calc : process (awgn)
-- seeds for random function call
variable s1 : integer := seed1;
variable s2 : integer := seed2;
-- random variables
variable x1,x2 : real;
begin
-- create two random variables
random (s1,s2,x1);
random(s1,s2,x2);
-- create Gaussian variable using
-- Box-Muller method
awgn<=SQRT(2.0*LOG(x1))*COS(MATH
_2_PI*x2)
after hmin;
end process noise_calc;
```

Figure5 . VHDL-AMS behavioral description of White Gaussian Generator

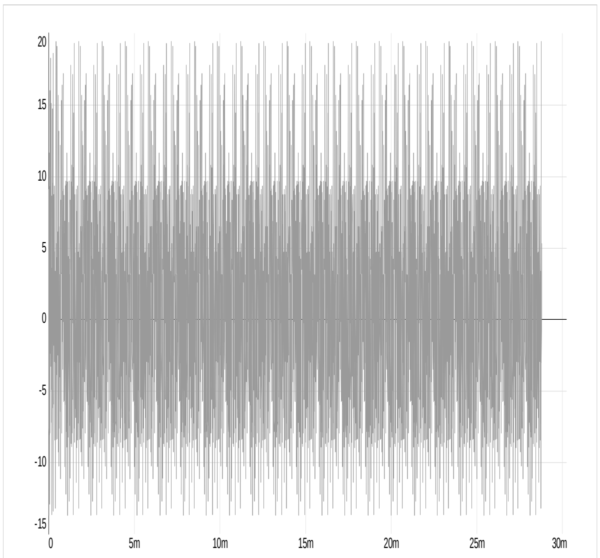

Figure6 . Example of additive white Gaussian noise

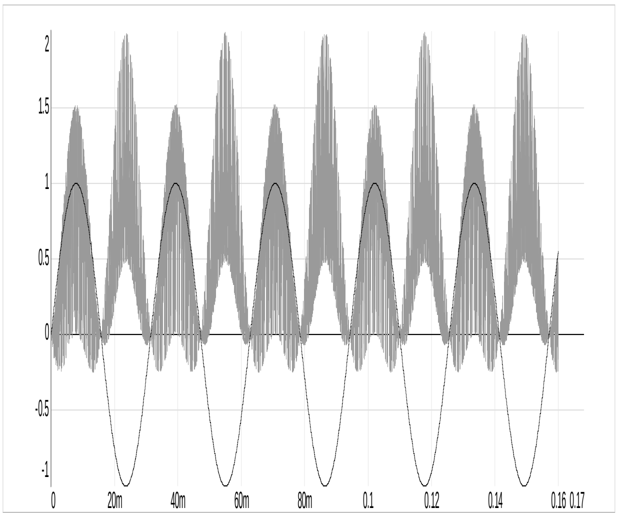

Figure7 . Example of transmitted signal through AWGN channel for SNR(dB)=1

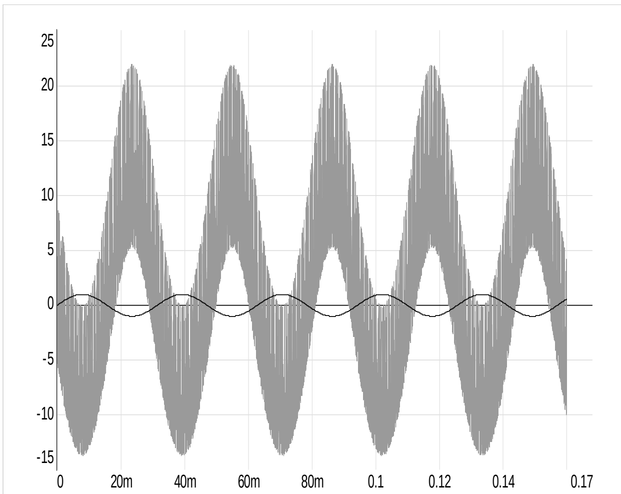

Figure8 . Example of transmitted signal through AWGN channel for SNR(dB)=15

Figure 5, 6 and 7 illustrate the effect of the AWGN channel on the transmitted signal.

2.3 VHDL-AMS Implementation of Multipath Rayleigh Fading channel

The most important phenomenon that alters acoustic signal in the ocean is multipath fading [11] resulting from the presence of surface reflection and spatial variations in sound speed that depend on temperature, salinity, and depth.

Multi path occurs when the signal reaches the receiver through multiple paths. As a result, the receiver observes the same signal at different points in time and at different signal strengths, having Rayleigh distributed amplitudes. It will be up to the receiver to decide which signals to use and which to discard.

Fading refers to the rapid change in received signal strength over a small travel distance or time interval.

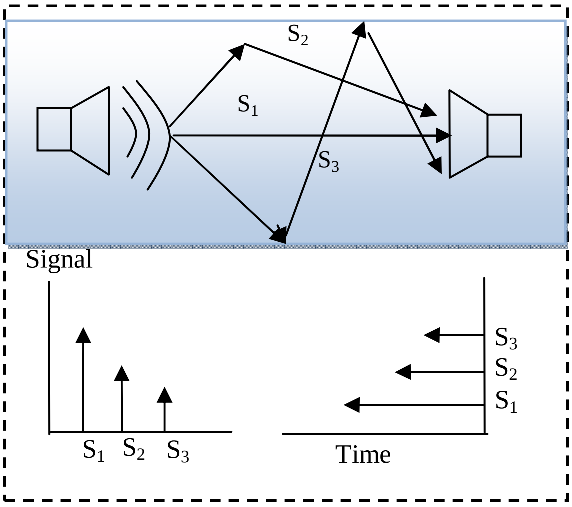

Figure9 . The configuration of multipath fading underwater channel

The general characteristics of acoustic wave propagation in underwater channel are shown in figure 7.The acoustic wave transmitted from underwater transceiver radiates in all directions. These waves, including reflected waves that are reflected off of various underwater obstacles and variations physics parameters(umber zone),diffracted, scattering, and direct waves from transceiver to receptor.

This phenomenon knows as multipath fading, in which the received signal is intensified or weakened from moment to moment. For thus the received signal is corrupted by high level of error [12]. A compensation of this multipath fading needs a prediction of channel behaviors to ensure the best underwater transmission.

This subsection presents a mathematical model and explains a vhdl_ams programming method for simulation of multipath Rayleigh fading channel.

rn(t) is a continuous wave with carrier frequency fc transmitted from the emitter to the receptor through fading multipath channel.

$$r_n(t) = \text{real}\left[e_n(t)\,\mathbf{exp}\ j(2.\pi.f_{c.})\right] \qquad (4)$$

In witch:

$$e_n(t) = R_n(t)\,\mathbf{exp}\ j\left(-\frac{2.\pi.(L_n - v.t.\mathbf{cos}\ \theta_n)}{\lambda} + \varphi_n\right) \qquad (5)$$

$$= x_n(t) + y_n(t)$$

In which Rn(t) and φn(t) are the envelope and phase of nth incoming wave, xn(t) and yn(t) are the in phase and quadrature phase factors of en(t).

In other hand the carrier frequency of nth incoming wave is shifted by v.cosθn/λ (Hz) representing the Doppler Effect (Hz).

The received signal r (t) is the average addition of n incoming waves.

$$r(t) = \sum_{n=1}^{N} r_n(t) \qquad (6)$$

$$= \sum_{n=1}^{N} x_n(t)\,\mathbf{cos}\ 2.\pi.f_c.t - \sum_{n=1}^{N} y_n(t)\,\mathbf{sin}\ 2.\pi.f_c.t$$

$$= x(t)\,\mathbf{cos}\ 2.\pi.f_c.t - y(t)\,\mathbf{sin}\ 2.\pi.f_c.t$$

Using the amplitude and phase of received signal we deduct:

$$r(t) = R(t)\cos(2.\pi.f_c.t + \theta(t)) \qquad (7)$$

With:

$$R(t) = R = \sqrt{x^2 + y^2} \qquad (8)$$

$$\theta(t) = \theta = \mathbf{tan}^{-1}\left[{}^{y}\!/_{x}\right]$$

The expressions for simulation of multipath Rayleigh fading channel are dedicated of jack model [13]in which the complex fading fluctuation is equivalent to low pass system. Jakes popularized a model for Rayleigh fading based on summing sinusoids [14].

$$r(t) = x(t) + j.y(t) \qquad (9)$$

$$= \left[\sqrt{\frac{2}{N_1+1}}\sum_{n=1}^{N} \begin{matrix}\mathbf{sin}(\frac{\pi.n}{N_1})\,\mathbf{cos}\left\{2.\pi.f_d\ \mathbf{cos}(\frac{2.\pi.n}{N_1})t\right\} \\ + \frac{1}{\sqrt{N_1+1}}\mathbf{cos}(2.\pi.f_d.t)\end{matrix}\right] +$$

$$\sqrt{\frac{2}{N_1}}\sum_{n=1}^{N}\mathbf{sin}(\frac{\pi.n}{N_1})\,\mathbf{cos}\left\{2.\pi.f_d\ \mathbf{cos}(\frac{2.\pi.n}{N_1})t\right\}$$

Where N1 is given by:

$$N_1 = \frac{1}{2}\left(\frac{N}{2} - 1\right) \qquad (10)$$

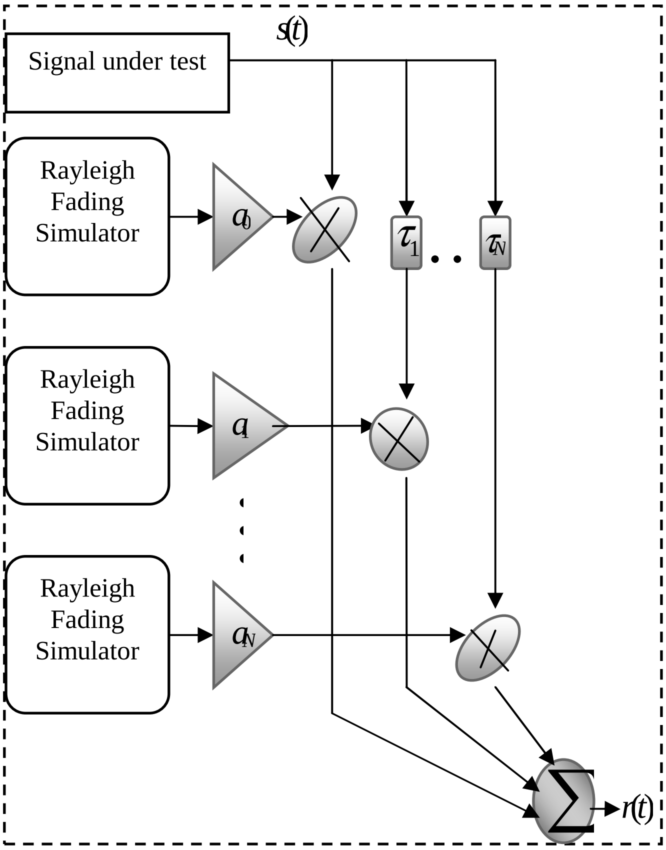

Figure10 . The flowchart to obtain the multipath Rayleigh fading channel

Next, we describe the operation of the multipath fading simulator. As shown to figure 8 the input signal is delayed. Then Rayleigh fading is added to the delayed signals. Finally all signals are added afterwards. As a result, the output signal taken from the multipath Rayleigh fading is obtained.

```
procedural is
variable n,x,y,fd: real;
begin
for n in 1 to 100 loop
x:=x+sqrt(2/(1+n1))*sin(pi*n/n1)c
os(2*pi*f*cos(2*pi*n/n1)*now)+sqr
t(1/(n1+1))*cos(2*pi*fd*now) ;
 end loop;
for n in& t 100 loop
y:=y+sqrt(2/n1)*sin(pi*n/n1)cos(2
*pi*fd*cos(2*pi*n/n1)*now) ;
 end loop;
end procedural
```

Figure11 . VHDL-AMS behavioral description of fading multipath channel

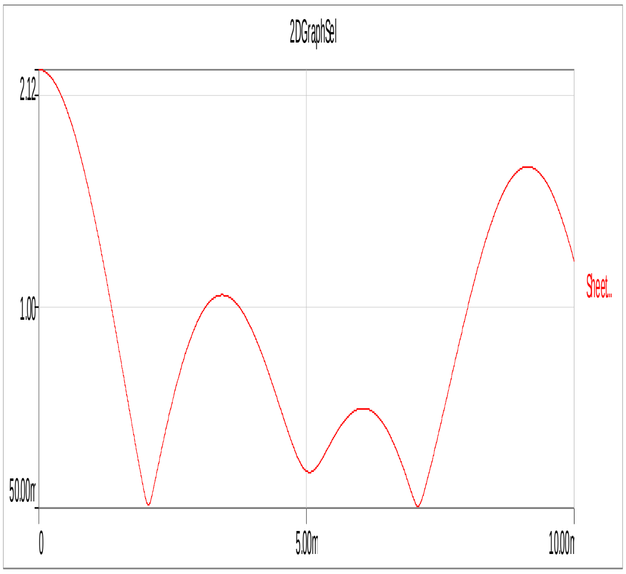

Figure12 . Signal fluctuation by a fading simulator

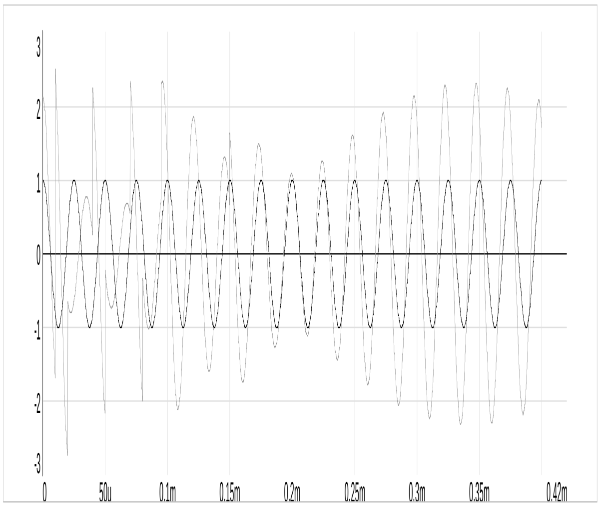

Figure13 . Example of transmitted signal through Multipath Rayleigh Fading channel(f=20 KHz, N1=5, fd=100Hz)

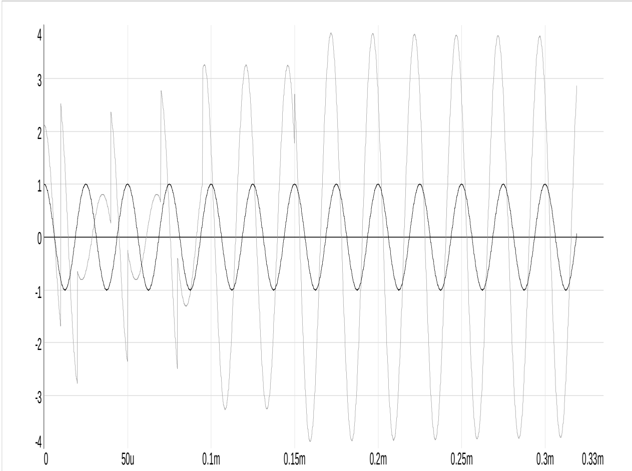

Figure14 . Example of transmitted signal through Multipath Rayleigh Fading channel(f=20 KHz, N1=5, fd=10Hz)

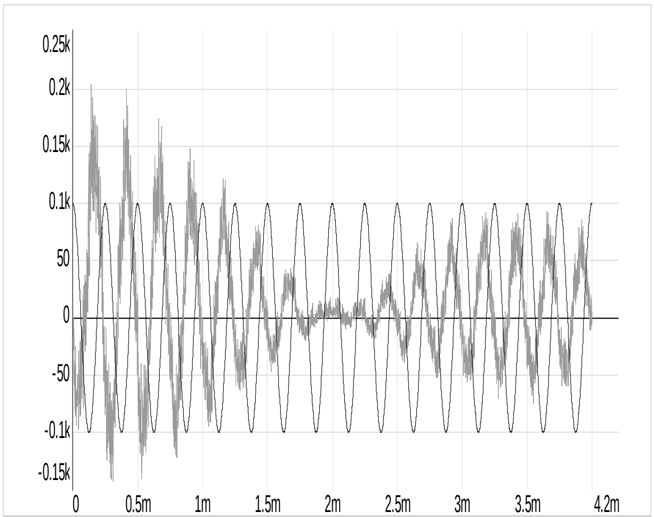

Figure15 . Example of transmitted signal through Multipath Rayleigh Fading and AWGN channels (f=20 KHz, N1=5, fd=100Hz, SNR=10)

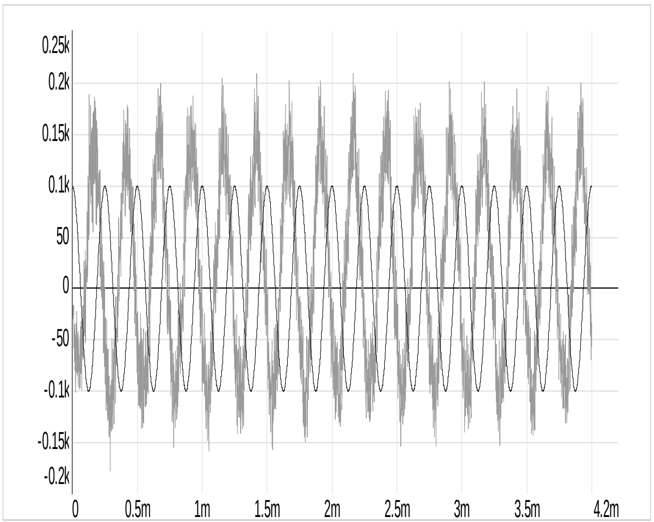

Figure16 . Example of transmitted signal through Multipath Rayleigh Fading and AWGN channels(N1=5, f=20 KHz, fd=10Hz, SNR=10)

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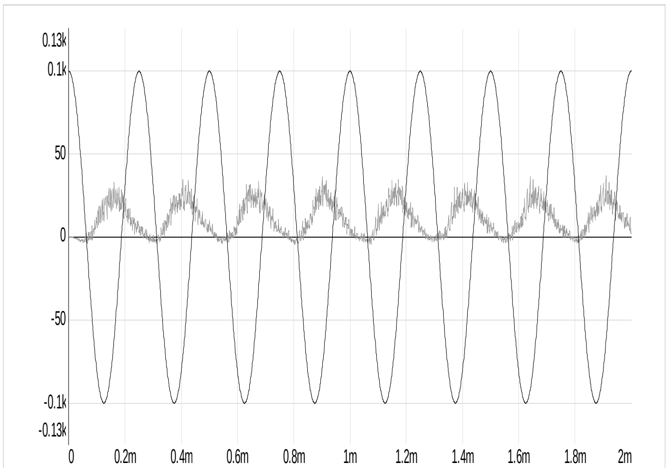

Figure17 . Example of transmitted signal through Multipath Rayleigh Fading and AWGN channels(N1=5, f=20 KHz, fd=10Hz, SNR=1)

The impact of flat fading and Gaussian noise on transmitted signal is shown in Figure.12, 13, 14, 15. It is clear that the received signal will suffer a rapid fluctuation in the amplitude and a phase shifts, Figure.11 shows the effect of the change in the frequency of the received signal. This apparent frequency change is called Doppler shift f_d. These simulations are in concordance with MATLAB resultants.

2.4 VHDL-AMS Implementation of underwater path loss

Adding an attenuation block in underwater channel is necessary to model transmission losses. It is very difficult to establish a mathematical model that takes account of all the parameters of the aquatic environment since this last is a dynamic and very complex environment [3]. We recall that these parameters essentially depend on the seafloor, of the surface of ocean, of bubbles of air, fishes, planktons and the thermal structure. They all contribute to the scattering of the acoustic wave. According to Coppens [6], we can divide the transmission loss into two parts: TL1 (geom) and TL2 (losses) characterizing losses respectively by geometric divergence and absorption phenomena. The expression of transmission losses is given by:

$$TL = TL_1(\text{geom}) + TL_2(\text{losses}) \qquad (11)$$

$$= a.d + 20\,\mathbf{log}(d)$$

$$a(f)_{(dB/m)} = f^2\left(2{,}692.10^{-13} + \frac{7{,}858.10^{-2}}{f^2+1{,}226.10^{10}} + \frac{1{,}481.10^{-4}}{f^2+1{,}522.10^{6}}\right) + 0.001 \qquad (12)$$

The principle of simulation achieved under VHDL-AMS consists in the modeling of the weakening in an aquatic environment. We take account of the optimal parameters for best under water communication as frequency and distance. The figure below shows the attenuation of acoustic signal waves travelling aquatic medium for different array of frequency and distance [15].

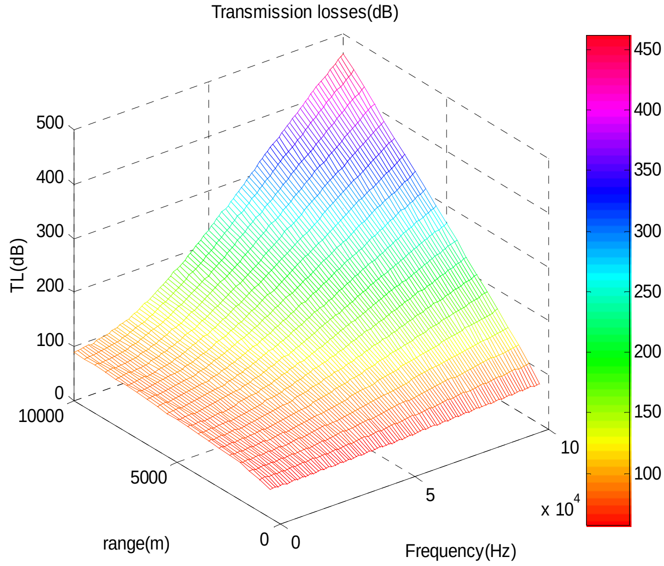

Figure18 . Attenuation vs distance

Table.1 resumes the optimal frequency and distances needed for efficient underwater communication.

TABLE I. AVAILABLE BANDWIDTH FOR DIFFERENT RANGES IN UWA CHANNELS

	Range[Km]	Bandwidth[KHz]
Very long	20≥	≤10
Long	5-20	5-10
Medium	1-5	≈20
short	0.1-1	20-50
Very Short	≤0.1	≥100

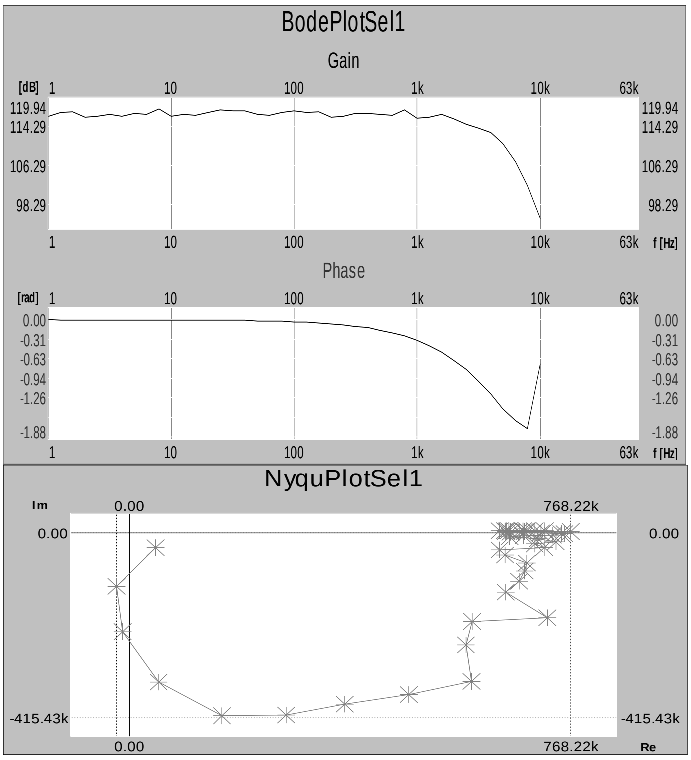

Figure1 . Bode and Nyquist plot of underwater channel

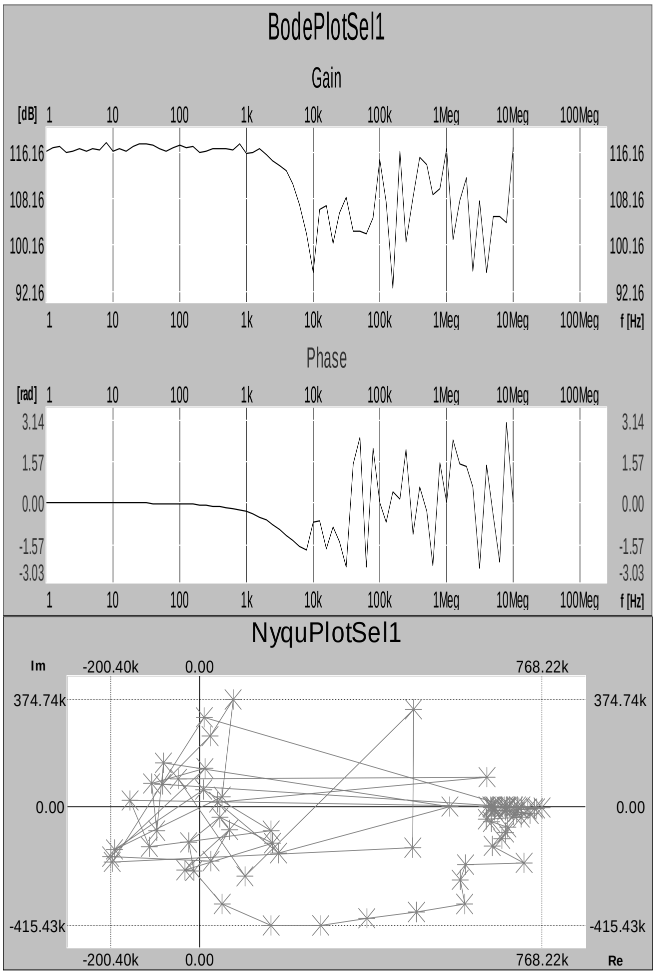

Figure19 . Bode and Nyquist plot of underwater channel

The following curves show that the aquatic channel behaves like a low pass filter. In fact, for frequencies inferior to 10 KHz, there is less attenuation of the signal and the system is stable. For high frequencies, we notice an attenuation of the signal and the system becomes unstable. This instability is due to many factors including chemical and geometrical effects like the phenomenon of structural relaxation that appears essentially in high frequency [6], multipath propagation including reflections from the surface and bottom of the sea.

For the high frequencies λ (C/F) decreases (compared to the dimension of the underwater channel) the wave undergoes several reflections. Therefore the phenomenon of multipath becomes one factor troubling the wireless underwater communication.

However it is possible in idealized conditions to predict and compute precise values for the transmission loss associated to realistic application like essentially identification of ships or baleens.

3 ENERGY EFFICIENCY

3.1 Communication Energy

Occasional outages from poor propagation or elevated noise levels can disrupt wireless underwater links [16].Ultimately, the available energy supply dictates service life; and battery-limited nodes must be energy conserving. For thus we need to estimate the battery life of sensor nodes which has implications on the usefulness, topology and range of the network.

In this subsection we showed an overview of the underwater channel effect on the transmitted signal. Here we are interested to evaluate the power of received signal through variety of range and frequency. We can express the source level SL intensity as [5]:

$$SNR = SL + TL + NL + DI \qquad (13)$$

Where SL is the source level, TL is the transmission loss, NL is the noise level, and DI is the directivity index.

For simplification, we assume that: The directivity index DI is zero because we assume omnidirectional hydrophones. We consider an average value for the ambient noise level NL to be 70 dB as a representative shallow water case. We also consider a target SNR of 20 dB at the receiver.

We can express the source level SL intensity as [5]:

$$SL\ (dB) = TL + 90 = 20*\log(ve/vs) + 90 \qquad (14)$$

The transmitted signal intensity is expressed as

$$It = 10^{SL/10} * 0.67 * 10^{-18} \qquad (15)$$

Finally, the transmitter power Pt needed to achieve an intensity I_t at a fixed distance from the source in the direction of the receiver is expressed as [4]:

$$Pt = 2*\pi*d*h*It \qquad (16)$$

The table below resumes the corresponding transmits power Pt needed to achieve a source intensity of It according to a typically frequency equal to 10 KHz and distances.

TABLE II : TRANSMIT POWER NEEDED VS DISTANCES

Range (m)	Source level (dB)	Intensity of signal (watt)	Power needed (watt)
1	90	$1,64.10^{-12}$	9.10^{-9}
10	110	$5,97.10^{-11}$	3.75110^{-6}
100	130	$1,46.10^{-10}$	9.1710^{-6}

According to this table for shorter ranges the transmit power can be lower, potentially as low as 1W. These result are in accord with the result given by L.Freitag[17].

3.2 MAC Energy Costs

Underwater MAC protocols are another way of energy saving. In fact, Energy consumption is the main criterion for our MAC protocol design. In this subsection, we present the main several ways addressing the problem of energy wasting:

- Collisions: if two nodes transmit at the same time and interfere with each other's transmission, packets are corrupted. Hence, the energy used during transmission and reception is wasted.

- Handshaking: most protocols use control packets like RTS/CTS mechanism in order to avoid packet collisions; these does not contains application data. The energy used for transmitting and receiving these packets is operating cost energy.
- Overhearing: underwater channel is a shared medium; so a node may receive packets that are not destined for it.
- Routing protocols: In underwater networks, node links are in rapid changes due to the complexity of underwater channel. So the avoidance of long-lived routing loops in underwater networks is a way of saving energy.

3.3 Choice of underwater MAC protocols

Several MAC protocols have been proposed recently that attempt to provide sufficient operation and energy efficiency .Most proposals have focused on random access techniques, but some have used a fully synchronized approach. So the Seaweb [18] project (real application of the aquatic networks), use FDMA as an access technique which is not efficient because of the selectivity in frequency and the limited underwater bandwidth. More recent Seaweb [18] experiments have used hybrid TDMA/CDMA clusters with MACA-style RTS/CTS/DATA handshakes. This method of access is adequate for the stationary networks and not for the mobile networks or other networks that change quickly during the time. One of the most promising access methods is the CDMA, she has been evoked by Xie and Gibson in 2000 [19]. The met problem of CDMA is Near Far. In aquatic networks the method of CDMA access appears most promising, in which propagation delays will be reduced. The adaptation of MACA to the aquatic network looks to continue with Sözer and all [17] while adding the WAIT command in order to reduce collisions and to increase the efficiency of power. In 2006, M.Stojanovic [20] proposes a specific access method to the aquatic environment inspired from FAMA, that is called slotted FAMA whose principle is to give out every packet (RTS, CT, DATED or ACK) in the beginning of time slot to eliminate the asynchronous nature aspect of protocols and to eliminate collisions. Açar and Adams [18] studied in 2006 the TDMA centralized with control of power and adaptive debit. In 2007 M.Stojanovic, purpose UWAN-MAC, Distance Aware Collision Avoidance Protocol DACAP [21], which is scalable to the changing number of nodes and the coverage area of the network.

following table shows a characteristics survey of the main protocols for underwater communications:

Authors	Protocols	Characteristics
Smith and all (1997) [22]	CSMA/CA	-Performed well in term of latency -Low throughput
Seaweb'98 99 [23]	FDMA	- Improved performance on term of frequency-selectivity. - Not flexible and very inefficient in bursty traffic (due to limited bandwidth).
Seaweb 2000 [23]	TDMA-CDMA with MACA style RTS/CTS handshakes	- Evolution of seaweb spreading, improvement of the physical layer and the MAC layer. -Performed well in stationary and static nodes, but not in high dynamics network.
Xie and Gibson 2000[23]	CDMA	-Problem of Near far -Performed well in shallow water
Lapierre and all 2001 [23]	CSMA/CD	-Can not be used in a single channel packet radio network -Very difficult to construct a wireless underwater CSMA/CD system full duplex.
Salvà Garau and Stojanovic 2003 [24]	TDMA/CDMA	-Reduce the length of the TDMA slot, which increases the data rate. -Increase the probability of interference between the adjacent nudes.
Foo and all 2004 [23]	CDMA/MACA and MACAW	-Worst latency -It performs well in terms of packets received but at extremely high throughput.
Freitag and all 2005[25]	TDMA with less throughput	A central nude controls the network.
Molins and Stojanovic 2006[20]	Slotted FAMA	Limit the delay of propagation by addition of time slots.
Açar and Adams 2006 [23]	Centralized TDMA	Controlled power and adaptive throughput.

Rodoplu and Park 2006 [26]	UWAN-MAC	Adaptation of the S-MAC (MAC sleeping) in order to save the energy in the case of delayed aquatic sensors networks.
Borja Peleato and Milica Stojanovic 2007[27]	DACAP (Distance Aware Collision Avoidance Protocol)	Scalable to the changing number of nodes and the coverage area of the network.

4 Conclusion

This paper has described underwater channel model that can be used as the bases for testing the performance of several underwater communication systems. Also in this paper for saving energy a distributed Medium Access Control (MAC) protocols and access techniques for UW-ASNs are analyzed. In future works, we will describe the performance of digital modulation techniques. We will also investigate the performance coding in tracking the channel.

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