VHDL-AMS Modelling 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 is crucial to predict the behavior of underwater acoustic channel. In this paper, several fundamental keys 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, modelling, and simulation of underwater channel using hardware description language VHDL-AMS. The following analysis may provide precious guidelines for the design and energy efficiency of underwater communication systems.

Key words: Index Terms— underwater communication, underwater channel model, VHDL-AMS modelling, acoustic signal, energy efficiency

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 (Akyildiz and Melodia, 2005; Jurdak et al., 2004). For thus it’s customary to apply the name of underwater Acoustic Sensor Networks (UW-ASN’s). In fact, UW-ASN’s consists of sensors and autonomous underwater vehicles deployed 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 (Hong et al., 2006), it has been necessary to survey the 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 (Pompili, 2007). 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 (Pompili, 2007). 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. This analysis may provide precious guidelines for the design of energy-efficient and baseband polling algorithms for underwater communication systems. The remainder of this document is organized as follows: In section II, we have presented a virtual prototyping of underwater channel model and we have drawn the main conclusions. In section III, we have provided solution for underwater energy efficiency.

Virtual Prototyping of Underwater Channel Model:

For the advances in underwater acoustic communication and progress in underwater acoustic modem a behavior modeling of the physical communication underwater channel taking into account it’s most important properties is needed.
System Conceptualization:
The aquatic channel presents a big variety of the propagation medium for the acoustic waves (Urick, 1986; Coppens et al., 1980). Thus, in this part we have presented an overview of underwater channel model manifestations. In this context, as showing in figure 1 the transmission support is assumed as a Gaussian channel to make 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 (Ahcene et al., 2005). These path losses are the main factors determining the available bandwidth range and signal to noise ratio (Nasri et al., 2008). The mechanisms of multipath formation in the underwater channel are different from terrestrial one.

VHDL-AMS implementation of adjustable Additive Gaussian noise (AGN) channel:
In wireless communication systems, additive Gaussian noise (AGN) is often used. AGN channel is actually a mathematical model that represents physical phenomena in which the only impairment is the linear addition of noise with a constant spectral density and a Gaussian distribution of amplitude (Box and Muller, 1958). In a Gaussian underwater channel, 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 an AGN 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 Gaussian noise.

Libraries of noise in VHDL-AMS are practically inexistent. Therefore to simulate an AGN channel in VHDL-AMS we have built a random function that generates a random variable (Rand1, Rand2). The noise signal is calculated using the Box-Miller (Berkhovskikh and Lysanoy, 1982) method, permitting to transform two definite variables by a uniform distribution in a variable based on a normal law:

\[ X = \sqrt{-2 \ln(Rand_1)} \cos(2 \pi Rand_2) \]  

(1)

The implementation of AGN on VHDL-AMS is described in figure 3 in which the generation of the Gaussian noise 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 Gaussian noise that depends on SNR and the input signal:

\[ \text{Noise\_generator} = 10^{\text{level}(dB)/10} \times \text{Noise} \]

(2)

With:

\[ \text{level}(dB) = V_r(dB) - \text{SNR}(dB) \]

(3)

VHDL-AMS Implementation of a Multipath Rayleigh Fading channel:
The most important phenomenon that alters acoustic signal in the ocean is multipath fading resulting from the presence of surface reflection and spatial variations in sound speed that depend on temperature, salinity, and depth (Win and Scholtz, 2005).

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 with 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.

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 by 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 (Jakes, 1994). 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.

$r_n(t)$ is a continuous wave with carrier frequency $f_c$ transmitted from the emitter to the receiver through fading multipath channel.

$$r_n(t) = \text{real}\left[e_n(t)\exp\left(j2\pi f_c t\right)\right]$$  \hspace{2cm} (4)

In which:

$$e_n(t) = R_n(t)\exp\left(-\frac{2\pi(n\cdot f_c - v\cdot t\cdot \cos \theta_n)}{\lambda}\right) + \varphi_n = x_n(t) + jy_n(t)$$  \hspace{2cm} (5)

In which $R_n(t)$ and $\varphi_n(t)$ are the envelope and phase of the $n$th incoming wave. $x_n(t)$ and $y_n(t)$ are the in-phase and quadrature phase factors of $e_n(t)$.

In other hand the carrier frequency of the $n$th incoming wave is shifted by $v\cdot \cos \theta / \lambda$ (Hz) representing the Doppler Effect.

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

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

$$= x(t)\cos(2\pi f_c t) - y(t)\sin(2\pi f_c t)$$

Using the amplitude and phase of the received signal we deduct:

$$r(t) = R(t)\cos(2\pi f_c t + \theta(t))$$  \hspace{2cm} (7)

With:

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

$$\theta(t) = \tan^{-1}\left(\frac{y}{x}\right)$$  \hspace{2cm} (8)

The simulation of multipath Rayleigh fading channel is based on jack model (Kandangath, 2003) in which the complex fading fluctuation is equivalent to low pass system. Jakes present a model for Rayleigh fading based on summing of received sinusoids (Adellaoui, 2006).

$$r(t) = x(f(t)) + jy(f(t)) = \left[\sin\left(\frac{\pi\cdot N}{N_1}\right)\cos\left(2\pi f_c t + \frac{2\pi\cdot N}{N_1}\right)\right] + \left[\sqrt{\frac{2}{N_1+1}}\sum_{n=1}^{N}\sin\left(\frac{\pi\cdot N}{N_1}\right)\cos\left(2\pi f_c t + \frac{2\pi\cdot N}{N_1}\right)\right]$$

Where $N_1$ is given by:

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

Next, we describe the operation of the multipath fading simulator. As shown in figure 10 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.

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 $f_d$.  

3866
Fig. 1: Conceptualization of an underwater channel

Fig. 2: Example of an AGN channel

Fig. 3: Internal structure of the AGN channel

Fig. 4: Source code for generating random variable

```plaintext
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;
begnin
temp_val = ((max - min) * random(1.0) + min);
val = temp_val*zoh(ts);
end behav;
```
Fig. 5: VHDL-AMS behavioral description of Gaussian Generator

```
noise_calc : process (agn)
  -- 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;
```

Fig. 6: Example of transmitted signal through AGN channel for SNR(dB)=1

Fig. 7: The configuration of multipath fading in underwater channel
Fig. 8: The flowchart to obtain the multipath Rayleigh fading channel

![Flowchart](image_url)

```
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)*cos(2*pi*f*cos(2*pi*n/n1)*now)+sqrt(1/(n1-1))*cos(2*pi*f+now);
  end loop;
for n in 1 to 10 loop
  y=y+sqrt(2/n1)*sin(pi*n/n1)*cos(2*pi*f*cos(2*pi*n/n1)*now);
  end loop;
end procedural
```

Fig. 9: VHDL-AMS behavioral description of fading multipath channel

Fig. 10: Signal fluctuation by a fading simulator
Fig. 11: Example of transmitted signal through Multipath Rayleigh Fading and AGN channels 
(f=20 KHz, N1=5, fd=100Hz, SNR=10)

Fig. 12: Example of transmitted signal through Multipath Rayleigh Fading and AGN channels 
(N1=5, f=20 KHz, fd=10Hz, SNR=10)

Fig. 13: Attenuation vs distance and frequency
VHDL-AMS Implementation of Underwater Path Loss:

Adding an attenuation block to underwater channel is necessary to characterizing transmission losses. So it is very difficult to establish a mathematical model that takes account of all the parameters of the aquatic environment since it is a dynamic and very complex environment (Hong et al., 2006). 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 (Coppens et al., 1980), we can divide the transmission loss into two parts: TL1 (geom) and TL2 (absorp) characterizing losses respectively by geometric divergence and absorption phenomena. The expression of transmission losses is given by:

$$TL = TL_1(geom) + TL_2(absorp) = a(f)\cdot d + 20 \log(d)$$

$$a(f)_absorp = f^2 \left(2,6920^{-4} + \frac{7,85810^2}{f^2} + 1,22610^4 + \frac{1,48110^4}{f^2} + 1,52210^4\right) + 0.001$$

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 (Nasri et al., 2008).

Table 1: Available Bandwidth for Different Ranges in Underwater Channels

<table>
<thead>
<tr>
<th>Range</th>
<th>Bandwidth[khz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Long</td>
<td>≤10</td>
</tr>
<tr>
<td>Long</td>
<td>5-20</td>
</tr>
<tr>
<td>Medium</td>
<td>1-5</td>
</tr>
<tr>
<td>Short</td>
<td>0.1-1</td>
</tr>
<tr>
<td>Very Short</td>
<td>≥20</td>
</tr>
</tbody>
</table>

Figure 14 and figure 15 shows the gain and phase of a frequency response of underwater channel to determine the stability of the system. So according to these curves the aquatic channel behaves like a low pass filter. In fact, for low frequency, 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 (Coppens et al., 1980) and multipath propagation including reflections from the surface and bottom of the sea.

For the high frequencies λ=C/F (Celerity/frequency) decreases (compared to the dimension of the underwater channel) so the acoustic waves 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.

Energy Efficiency:

Communication Energy:

Occasional outages from poor propagation or elevated noise levels can disrupt wireless underwater links. Ultimately, the available energy 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 transmitted power signal needed through variety of range and frequency. Without loss of generality, we assume that the size of data packets is 1 Kbit and the bandwidth of each acoustic channel is 1 KHz. Thus, the available bit rate is 1 Kbit/sec. We can express the source level SL intensity as (Urick, 1983):

$$SNR = SL - TL - NL + DI$$

Where SL is the source level, TL is the transmission loss, NL is the noise level, and DI is the directivity index.
Fig. 14: Bode and Nyquist plot of underwater channel

For simplification, we assume that: The directivity index DI is zero because we assume unidirectional transducer. 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 (Urick, 1983):

\[ SL(dB) = TL + 90 = 20 \log(\nu_0 / \nu_1) + 90 \]  \hspace{1cm} (14)

The transmitted signal intensity is expressed as

\[ It = 10^{SL/10} \times 0.67 \times 10^{18} \]  \hspace{1cm} (15)

Finally, the transmitter power Pt needed to achieve an intensity It at a fixed distance from the source in the direction of the receiver is expressed as (Pompili, 2007):

\[ P_t = 2 \pi f d^2 h \times It \]  \hspace{1cm} (16)

Figure 16 shows transmission power needed with desired distance and frequency. In this simulation we deduct that the puissance needed is directly proportional to the distance between the two communicating nodes and the transmission power difference from various frequency is significant:

For the low frequency (less than 20 KHz) the power needed to transmit one packet from a distance varying from 1 to 1 000m is less than 5 pico-watts. But for high frequency the puissance needed become more interesting. For energy efficiency we limit to low frequency.
Fig. 15: Bode and Nyquist plot of underwater channel

Fig. 16: Transmitted power signal needed vs frequency and distance
For simplification, we assume that: The directivity index DI is zero because we assume unidirectional transducer. 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 SI intensity as (Urick, 1983):

\[ \text{SI} = 10 \log(\rho e / \nu') + 90 \]

(14)

The transmitted signal intensity is expressed as

\[ I_t = 10^{\text{SI}/10} \times 0.67 \times 10^{18} \]

(15)

Finally, the transmitter power \( P_t \) needed to achieve an intensity \( I_t \) at a fixed distance from the source in the direction of the receiver is expressed as (Pompili, 2007):

\[ P_t = 2 \times \pi \times d^2 \times I_t \]

(16)

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**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.

**Conclusion:**

The paper describes a methodology for the behavioral modelling and simulation of underwater channel. It deals with multipath fading, path losses and Gaussian noise in underwater environment. The presented model can be used as the basis for testing the performance of several underwater communication systems. Also in this paper solutions for saving energy are presented that undergoes distributed Medium Access Control (MAC) protocols solution and energetic solution. In future work, we will describe the performance of digital modulation techniques. We will also investigate the performance coding in tracking the channel.

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3874
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