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.
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.

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.
level(dB) = \( V_e(\text{dB}) - \text{SNR(\text{dB})} \)  \hspace{1cm} (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;
```

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.
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 (number zone), diffracted, scattering, and direct waves from transceiver to receptor. This phenomenon is known as multipath fading, in which the received signal is intensified or weakened from moment to moment. For this reason, the received signal is corrupted by a 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. \( r_n(t) \) is a continuous wave with carrier frequency \( f_c \) transmitted from the emitter to the receptor through fading multipath channel.

Using the amplitude and phase of received signal, we deduce:

\[
r(t) = R(t) \cos(2 \pi f_c t + \theta(t))
\]  

With:

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

\[
\theta(t) = \theta = \tan^{-1}\left(\frac{y}{x}\right)
\]

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

\[
r(t) = x(t) + jy(t)
\]

\[
= \left[ \sum_{n=1}^{N_1} \frac{\sin(\pi n/N_1) \cos(2 \pi f_d t)}{\sqrt{N_1 + 1} \sqrt{N_1 + 1}} \right] + \left[ \sum_{n=1}^{N_1} \frac{\cos(2 \pi f_d t)}{\sqrt{N_1 + 1} \sqrt{N_1 + 1}} \right]
\]

Where \( N_1 \) is given by:

\[
N_1 = \frac{1}{2} \left( \frac{N}{2} - 1 \right)
\]  

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

```vhdl
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(t(1/(n1+1)))*cos(2*pi*fd*now));
    end loop;
    for n in 1 to 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
```

Figure 11. VHDL-AMS behavioral description of fading multipath channel

Figure 12. Signal fluctuation by a fading simulator

Figure 13. Example of transmitted signal through Multipath Rayleigh Fading channel (f=20 KHz, N1=5, fd=10Hz)

Figure 14. Example of transmitted signal through Multipath Rayleigh Fading channel (f=20 KHz, N1=5, fd=10Hz)

Figure 15. Example of transmitted signal through Multipath Rayleigh Fading and AWGN channels (f=20 KHz, N1=5, fd=100Hz, SNR=10)

Figure 16. Example of transmitted signal through Multipath Rayleigh Fading and AWGN channels (N1=5, f=20 KHz, fd=10Hz, SNR=10)
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 shift. 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: TL $1$ (geom) and TL $2$ (losses) characterizing losses respectively by geometric divergence and absorption phenomena. The expression of transmission losses is given by:

$$\text{TL} = \text{TL}_1 (\text{geom}) + \text{TL}_2 (\text{losses})$$

$$= a.d + 20 \log(d)$$

$$\alpha f_{\text{USE}} = 10 \left( \frac{2692 \times 10^4}{f^2 + 122610^4 + \frac{148110^4}{f^2 + 152210^4}} \right) [\mu \text{dB}]$$

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].

![Figure 17. Example of transmitted signal through Multipath Rayleigh Fading and AWGN channels(N1=5, f=20 KHz, fd=10Hz, SNR=1)](image17.png)

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

<table>
<thead>
<tr>
<th>Range[Km]</th>
<th>Bandwidth[KHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very long</td>
<td>$&gt;20$</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>$\leq 0.1$</td>
</tr>
</tbody>
</table>

![Figure 18. Attenuation vs distance](image18.png)
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]:

\[ \text{SNR} = \text{SL} + \text{TL} + \text{NL} + \text{DI} \]  \hspace{1cm} (13)

Where \( \text{SL} \) is the source level, \( \text{TL} \) is the transmission loss, \( \text{NL} \) is the noise level, and \( \text{DI} \) is the directivity index.

For simplification, we assume that: The directivity index \( \text{DI} \) is zero because we assume omnidirectional hydrophones. We consider an average value for the ambient noise level \( \text{NL} \) 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]:

\[ \text{SL} \,(\text{dB}) = \text{TL} + 90 + 20 \times \log (\text{ve}/\text{vs}) + 90 \]  \hspace{1cm} (14)

The transmitted signal intensity is expressed as

\[ I_t = 10^{\text{SL}/10} \times 0.67 \times 10^{-18} \]  \hspace{1cm} (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 [4]:

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

The table below resumes the corresponding transmits power \( P_t \) needed to achieve a source intensity of \( I_t \) according to a typically frequency equal to 10 KHz and distances.

<table>
<thead>
<tr>
<th>Range (m)</th>
<th>Source level (dB)</th>
<th>Intensity of signal (watt)</th>
<th>Power needed (watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>90</td>
<td>1.64 \times 10^{-12}</td>
<td>9.10^{-6}</td>
</tr>
<tr>
<td>10</td>
<td>110</td>
<td>5.97 \times 10^{-11}</td>
<td>3.75 \times 10^{-6}</td>
</tr>
<tr>
<td>100</td>
<td>130</td>
<td>1.46 \times 10^{-10}</td>
<td>9.17 \times 10^{-6}</td>
</tr>
</tbody>
</table>

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 [23]. 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.

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

<table>
<thead>
<tr>
<th>Authors</th>
<th>Protocols</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smith and all</td>
<td>CSMA/CA</td>
<td>- Performed well in term of latency - Low throughput</td>
</tr>
<tr>
<td>Seaweb 2000 [23]</td>
<td>TDMA-CDMA with MACA style RTS/CTS handshakes</td>
<td>- 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.</td>
</tr>
<tr>
<td>Xie and Gibson 2000 [23]</td>
<td>CDMA</td>
<td>- Problem of Near far - Performed well in shallow water</td>
</tr>
<tr>
<td>Lapierre and all 2001 [23]</td>
<td>CSMA/CD</td>
<td>- Can not be used in a single channel packet radio network - Very difficult to construct a wireless underwater CSMA/CD system full duplex.</td>
</tr>
<tr>
<td>Xie, Garau and Stojanovic 2003 [24]</td>
<td>TDMA/CDMA</td>
<td>- Reduce the length of the TDMA slot, which increases the data rate. - Increase the probability of interference between the adjacent nodes.</td>
</tr>
<tr>
<td>Foo and all 2004 [23]</td>
<td>CDMA/MACA and MACAW</td>
<td>- Worst latency - It performs well in terms of packets received but at extremely high throughput.</td>
</tr>
<tr>
<td>Freitag and all 2005[25]</td>
<td>TDMA with less throughput</td>
<td>A central node controls the network.</td>
</tr>
</tbody>
</table>
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.

References