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Modelling and Simulation of Underwater Acoustics Communication based on Stateflow and Simulink Models

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Abstract: In an Underwater Acoustics (UWA) communications system, the channel presents two major differences compared to a radio communication system (wireless air channel): the propagation velocity (~1500m/s) and the path loss of the acoustic signal (propagation). The object of this paper is focused on the modelling and the simulation of the physical layer characteristics (physical layer) and communication protocol unit (Medium Access Control sub-layer) of the UWA communication systems with the stateflow and the simulink simulation tools. The elaborated model allows the student of the acoustic signals attenuation by evaluating the range (reached distances), the possible data rate and the energy consumption for an optimization of the emission power. The proposed medium access control protocol ensures reliable transfer between a source and a destination aquatic node.
Key words: Local Area Networks, Simulation, Underwater Acoustics, Wireless.

1 Introduction

At the frequencies classically used in underwater environments (acoustic waves), the section of water behaves like a waveguide, where the sound energy is perfectly considered at the time of the interactions with the borders of the guide: surface and sea-beds. The acoustic waves are not the only means for underwater wireless transmission, but it is only provide the best characteristics. Indeed, the aquatic environment is relatively opaque with the electromagnetic waves which are quickly attenuated and, which requires large antennas for emission/reception and of the very high powers of emission power. Optical waves are not undergoing significant attenuation, but they are affected by dispersion during the transmission and by consequence, they require a precision raised while directing the narrow laser beams.

To optimize and to improve the quality of transmission (signal relationship on noise S/N, InterSymbols Interference ISI, emission powers, binary speed) in an underwater channel, several techniques of modulation, coding, compression and spectrum utilisation are used, such as HADAMARD coding HADAMARD, MFSK modulations MFSK (Multiple Frequency Shift Keying), PSK (Phase Keying Shift) modulations and Spread Spectrum SS (Bouzoualegh & al., 2003) and (Kilfoyle & al 2000).

This paper presents a functional model for underwater wireless communication systems. It is divided into three parts. The first part describes the principal characteristics of underwater wireless communications. The second part presents necessary modelling to simulate the physical characteristics of the underwater wireless channel. The third part is about results of simulations and comments. Other results about MAC layer and different perspectives are evoked in the conclusion.

2 Underwater Wireless Communication

2.1 Availability of bandwidth

As in each wireless communication systems, the bandwidth allocation is a significant factor to determine the system efficiency. In the case of UWA communication systems, these resources are severely limited (attenuation, frequency band, binary speed). The attenuation level depends on the distance and the the transmission frequency of the acoustic signals (Edelmann & al., 1996). For example, the long distances underwater communications systems (a few tens of kilometres) are limited to frequencies of a few KHz; with frequencies of a few tens of KHz can be reached distances of a few kilometres; on the other hand, the UWA communication systems operating on distances of a few meters can be limited to a few hundred KHz.

The bandwidth employed in UWA systems requires also a considerable attention on the data redundancy during the construction of the frames. In addition to limitation of resources, in UWA communication systems, the channel has variable characteristics according to time and strongly depends on the distance between the emitter and the receiver (Bouzoualegh & al., 2003).

The UWA communication systems undergo also many effects like diffraction on the waves and the rocks, salinity effect of the medium on the propagation conditions, the loss energy by diffusion in volume, the strong levels of noise, effect thermo-cline for systems whose communication is done vertically (on a some levels of difference in temperature, the water layer behaves like reflectors) (Berkhovskikh & al 1982).

Surface and sea-bed induce propagation by multiple ways which is a major defect of the wireless communication systems: a multitude of signals arrives at the receiver which must then reconstitute the initial signal. The multiple ways generates an ISI (Inter Symbol Interference) on the received acoustic signal. To solve the effect of this phenomenon, the Multi Carrier Modulation (MCM), the MFSK, HADAMARD coding and MFSK HADAMARD are used (Scussel & al., 1998), (Bouzoualegh & al., 2003).

2.2 Underwater acoustics waves propagation

With the difference of digital communications through radio channels where the data are transmitted by the means of the electromagnetic waves, the speed of the radio signals in free space is 3×10^8 m/s. The acoustic waves are used for the data transmission in aquatic environments. The propagation velocity of the acoustic waves depends on the local temperature, salinity and pressure in the medium; these three factors vary considerably according with the depth (Stewart & al 1992). The propagation velocity is considered constant in the UWA communication systems where the propagation is horizontal or semi horizontal (less depth variation). Under normal conditions of temperature, salinity and pressure, the propagation velocity of the acoustic signals is 1500 m/s; this is very small compared to a propagation velocity of the radio signals in free space (ratio of 1/200000).

In practice case, the sound waves are not propagated across the discontinuous interfaces of two underwater layers (abrupt variation of the propagation speed). If the variation speeds for temperature, salinity and the pressure are continuous in the medium, for two underwater layers (samples of the medium) in any link position between two communicating nodes, the direction of propagation in the medium changes according to the Snell law which is given by the following formula (1).

$$\frac{\sin\phi_1}{v_1} = \frac{\sin\phi_2}{v_2} \qquad (1)$$

ϕ and v are respectively the speeds of propagation and the angles of inclination compared to the a normal of interfacing between the two underwater layers (directions of propagation) as shown in the figure I.

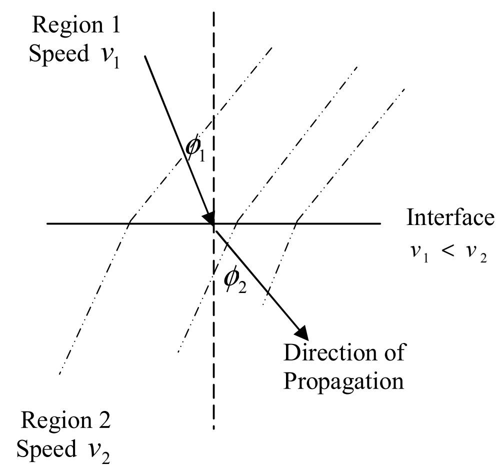

Figure I. *Acoustic wave's refraction across an interface between two regions corresponding to two different speeds of propagation*

The low propagation velocity (speed) in underwater environment generates an increase in the transmission latency (times of transit from beginning to end), which limits the real time applications and reduces considerably the load of the traffic on the network (for example during exchange of requests for the detection of the errors and the retransmission of the erroneous packages in protocol ARQ (Automatic Repeat request)). If a two communicating nodes are mobile, the wave length at the reception differs with that from the emission (Doppler Effect); this variation depends on speeds (propagation and displacement of nodes). For a radio communication system, this variation is often negligible. But for UWA communication systems, the wave length variation at the reception is not negligible what requires its compensation (Sharif 2000).

2.3 Propagation model and energy consumption

The provisioning of energy is a major constraint in UWA systems. This constraint is due to the difficulties encountered to change the batteries of underwater stations. The change of the underwater stations batteries requires the recovery of equipment; this operation takes a significant time, stalls the system, and is expensive.

Two solutions are possible to optimize the energy consumption: the first is physical (empirical), it is based on the modelling of acoustic propagation underwater. For that, theoretical study of the propagation in underwater environments is necessary to evaluate the capacity of such acoustic transmission system and to determine the behaviour of the model according to various parameters. The second solution, is a formal architecture, it consists in reducing the number of retransmissions to be managed, the deactivation of the stations except transactions, to optimize the MAC sub-layer and to propose a protocol of dedicated routing which deals with a low propagation velocity in the case of network interconnection.

To evaluate energy consumption for transmission in underwater environments, one needs to determine the energy needed for the transmission of one packet of data with duration T_P between two underwater stations separated from the distance x. It is supposed that the threshold of reception required is P_0. The emission power required to transmit a bit of data is given by the following formula (2).

$$P_E = P_0 \times A(x) \quad (2)$$

$A(x)$: is the attenuation (underwater path loss) (Berkhovskikh & al 1982). This is given by the formula (3).

$$A(x) = x^k a^x \quad (3)$$
$$a = \exp\ g(f)/10$$

$g(f)$ is the absorption coefficient (dB/km) in function of a frequency range f . This is given by the formula (4).

$$\mathrm{g(f)} = \left(\frac{0.11\mathrm{f}^2}{1+\mathrm{f}^2}\right) + \left(\frac{44\mathrm{f}^2}{4100+\mathrm{f}^2}\right) + 2.75 \times 10^{-4} + 0.003 \quad (4)$$

For transmitting the packet of data with duration T_P from one station to other, the total energy consumed at a distance x is given by the formula (5).

$$E = P_E T_P = P_0 T_P A(x) \quad (5)$$

2.4. Medium Access Protocol

In any communication network system, the major problem consists in knowing which one has the right to emit at a given time. Several medium access protocols are proposed and validated to solve this problem (ALOHA, CSMA, CSMA/CD …). These protocols beings used to indicate the next node which will be authorized to send its information on the network. In the UWA communication systems, the channel has very limited resources. Indeed the medium access protocol for UWA is the meaner to manage very efficiently the shared medium between multiple nodes. In the radio communication networks, several protocols are proposed and validated (Escudero & al., 1999). On the other hand, for UWA networks, only the CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) protocols appear efficient and adapted (Stojanovic & al., 2000).

In the basic CSMA/CA, when no activity is detected on the channel (idle medium), the station waits for an interframe space IFS and senses the medium again; if the medium remains free, the station emits a data packet over the channel. If the medium is busy, the station waits for a random time before actuating the described above for transmitting the data packet. Several methods are proposed to listen to the medium as shown in figure II:

- First is the *1-Persistent*: if the medium is busy, the station continues to listen until the medium becomes idle, and then transmits after IFS.
- Second is the *0-Persistent* (non persistent): if the medium is busy, the station waits a random amount of time and repeats the listening of the medium. The station tries again if the medium still busy.
- Third is the *P-Persistent*: the P-Persistent ($0 \leq P \leq 1$) associates the best of the 0-Persistent and the 1-Persistent to optimize and reduce the probability of collision.

The CSMA/CA protocol can be associated with the RTS/CTS option to resolve the hidden node problem illustrated in figure III. Upon the receipt of the data packet from layer 3, the layer 2 sends to the destination node the RTS command (Request to Send) to signal and to request permission to transmit its data packet. The destination node sends back the CTS (Clear to Send) command like answer to the RTS. As soon as it receives the CTS, it begins the transmission of data packet.

The RTS and CTS packet carry in their fields a special notification indicating the duration of the complete transmission cycle NAV (Network Allocation Vector), which includes the RTS, the CTS, the data frame and the acknowledgment ACK like shown in figure IV. This allows the neighbours communicating entities having started the RTS/CTS mechanism to know the time being reserved for the transmission in progress. This provides positive control over the use of the shared medium and minimizes collisions among hidden nodes (figure III). The collisions between two data packets take more time and more serious than a collision between two short control packets (RTS/CTS) or between a control packet and a data packet.

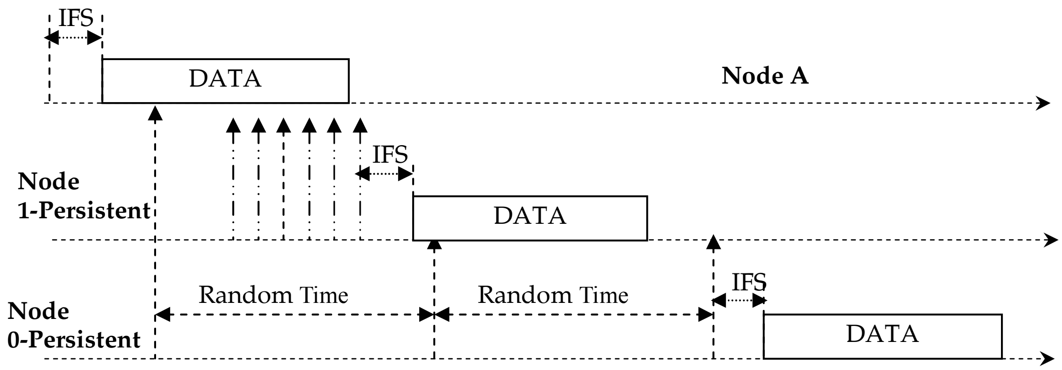

Figure II. *Non Persistent and the 1-Persistent CSMA/CA Protocols*

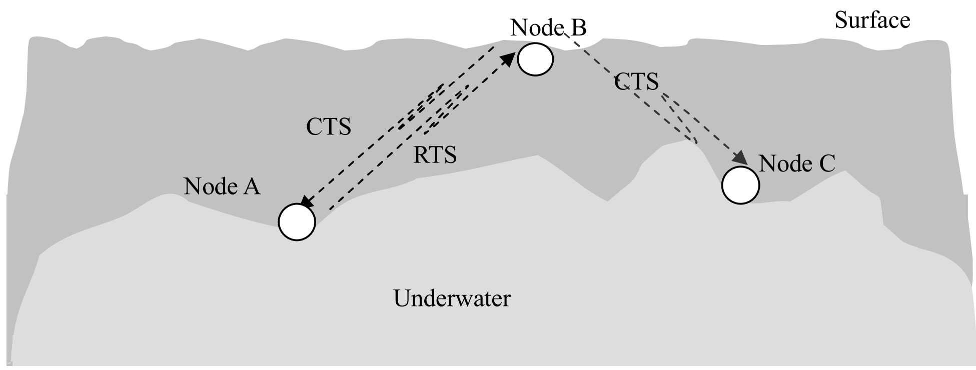

Figure III. *Underwater Hidden Node Problem*

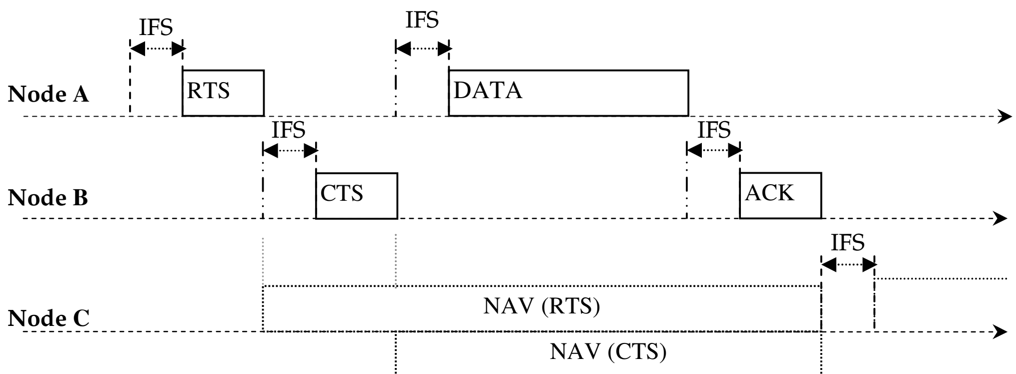

Figure IV. *The RTS/CTS Protocol*

During this time (NAV) all the nodes which receive the CTS command defer their transmission to avoid the collision. If the node source does not receive the CTS of the receiver during a predetermined time interval, it repeats the RTS. After N retransmissions, the source decides to break the connection and returns to a low power mode.

The transaction of data between communicating nodes occurs as result of the exchange of the RTS, CTS, DATA and ACK packets like shown in figure IV. The acknowledgment ACK is used to inform the source that the packet is received correctly. If the source not receives the ACK of its packet during a predetermined time, it repeats the transmission of DATA packets. After K retransmissions, the connection is broken.

3 Modeling and simulation

To simulate the model, we have used Stateflow and Simulink software, because this software is well adapted to modelling and simulating the physical layer of UWA communication system. Stateflow/Simulink is an interactive tool used for the simulation, analysis, and the modelling of continuous and discrete time dynamic systems. It makes it possible to build a diagram block, to simulate the behaviour of the system, to evaluate its performances and to refine the design. It enables the development of precise simulation models.

To simulate our contribution in this work, first we have modelled with Simulink our own model starting from the theoretical equations of path loss in underwater channel (equations connecting energy consumption, frequency and distance). The subsystem is created with the Matlab functions and the Toolbox communication functions like shown in figure V. Indeed, Matlab-Simulink does not contain the functionalities properly intended for the underwater networks.

Our proposed underwater acoustic communication system for short distances is based on the use of PSK modulation (Phase Shift Keying) and HADAMARD coding to achieve the high bandwidth efficiency. Figure VI shows the system block diagram of the transmitter (coding, modulation and underwater channel path loss). The HADAMARD coding provides a significant decrease in the BER (Bit Error Rate) for increasing the level of the SNR (Signal to Noise Ratio for each bit of data), the BER depends on the channel length. The PSK modulation appears efficient to achieve the high binary speed; indeed it provides efficient means to improve the performances in the underwater band limited channel (bandwidth limited). In our simulation, the channel is represented with a multipath fading channel (added noise to the useful signal and multipath rayleigh fading channel) and the underwater path loss block shown in figure VI. The data encoding as illustrated in figure VII is composed with a general CRC generator (Cyclic Redundancy Check), convolutional encoder and HADAMARD code Generator.

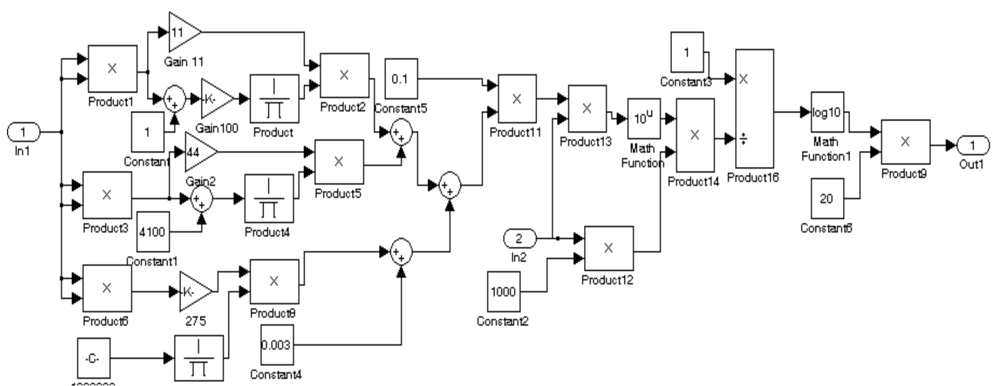

Figure V. *Underwater acoustic signal path loss modelled under Simulink*

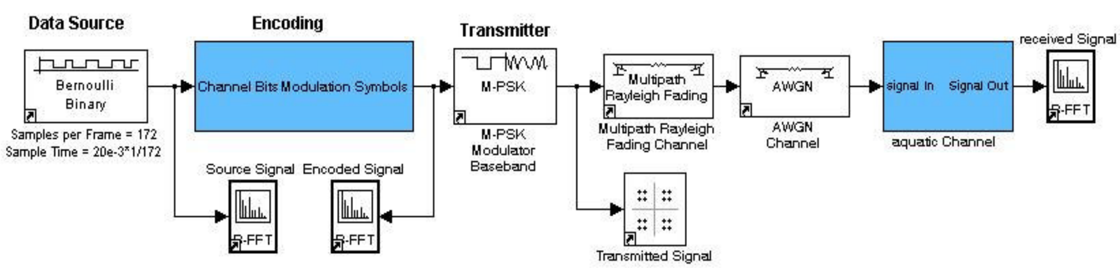

Figure VI. *Block Diagram of the Aquatic Transmitter*

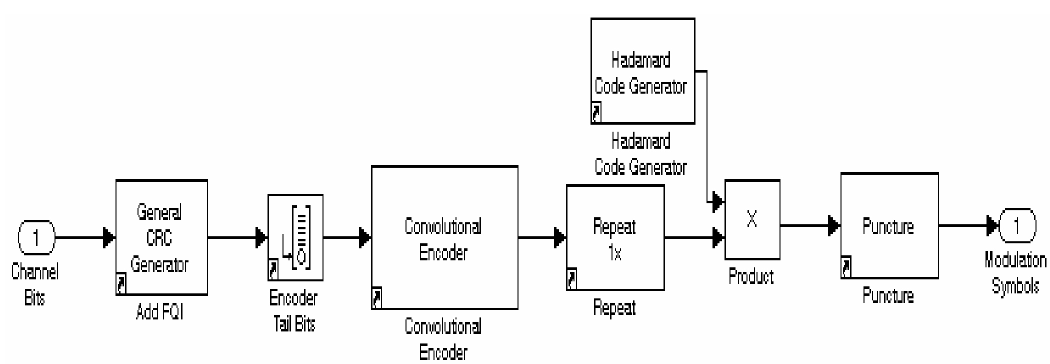

Figure VII. *Block Diagram for the Transmitter Encoder*

For modelling the medium access control protocol, Stateflow and Simulink tools from the Matlab environment facilitate the development of complex models that include data and signal processing functions, as well as protocol finite state machine modules. These models are not represented in this paper.

4 Simulation Result and Comments

We have directed our work of simulation towards the study of path loss and by consequence the energy consumption in a UWA point-to-point communication system. We took into account different possible cases. Figure VIII presents the standardized energy ($E / P_0 T_P$) to transmit one bit of data between two underwater nodes, for various values of energy spreading factor and according to the distance between the two underwater nodes (frequency of 10kHz). The path loss variation is directly proportional to the distance between the two communicating nodes and the k factor.

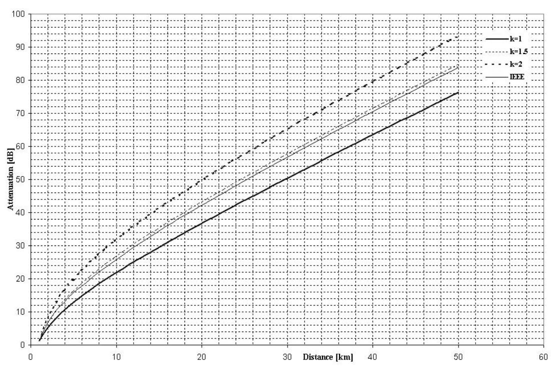

Figure VIII. *Normalized energy needed to transmit one bit with respect to the distance*

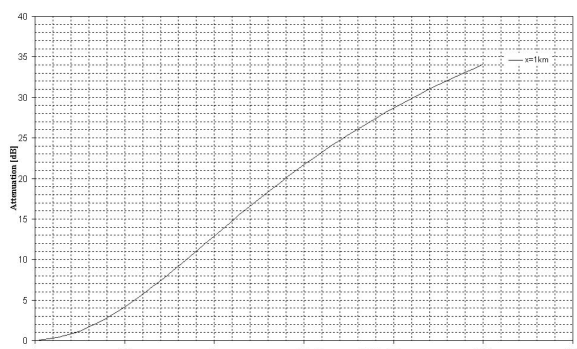

Figure IX. *Normalized energy needed to transmit one bit with respect to the frequency*

Figure IX presents the standardized energy ($E / P_0 T_P$) according to the frequency of transmission to transmit one bit of data at the distance of 1 km and for a spherical spreading of energy ($k = 1$). Between 1 and 100 kHz, there is a difference of 34dB for the same distances and in the same conditions of propagation. A compromise between the possible binary rates and the frequency of transmission must be considered (finding the middle ground). Our model will then bring a decision making aid.

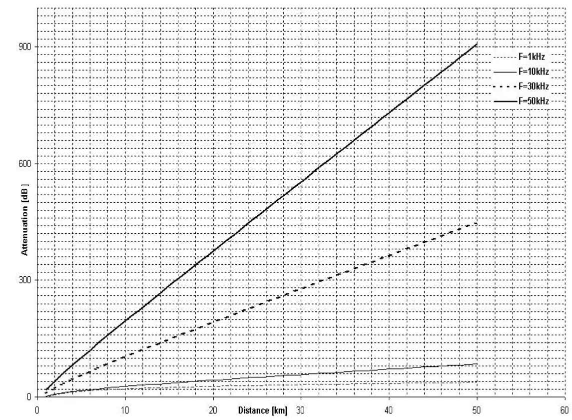

Figure X. *Normalized energy needed to transmit one bit with respect to distance and frequency*

Figure X shows the path loss graph according to the distance and the frequency. For the short distances (distances lower 5 km), the path loss difference for various frequencies is not significant, but for the large distances, this difference is very significant (for a distance of 50 km, the path loss is 40dB for F=1 kHz and it is the 900dB for F=100 kHz).

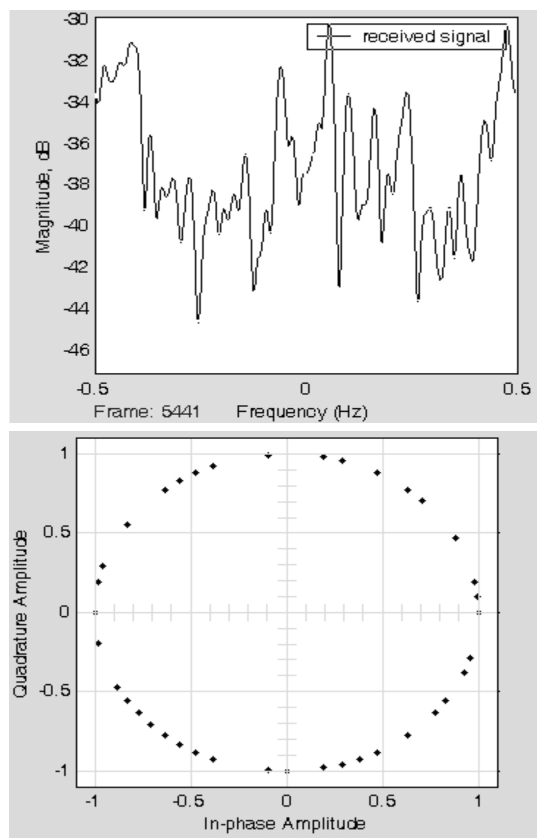

Figure XI. *Received Signal and Scatter Plot for 64-PSK modulator base band Signal*

Figure XI show the underwater channel response (channel represented with multipath fading and underwater path loss): first the scatter plot of the received signal and second the scatter plot of the M-PSK modulator base band Signal.

5 Conclusion

Our contribution consists in the proposition, modelling and validation of protocol architecture for the underwater acoustic local area networks. The firsts results of the simulations obtained with Stateflow and Simulink are in conformity with some results of simulations obtained by the IEEE Oceanic with OPNET simulator (Stojanovic & al., 2000), (Sozer & al., 1999). It is observed that the consumption in energy increases according to the factor k, the distance and the frequency. In a second stage we want to implement an emitter/receiver prototype for compare practical measurements to our simulation results.

We have also modeled the MAC layer with Stateflow and Simulink tool, the different results of simulations are not detailed in this paper. Our model of Media Access Control protocol is more adapted to aquatic environments for the collisions avoidance between underwater nodes. Moreover, our future work will contribute to propose and validate a complete formal architecture dedicated for the underwater acoustic local area networks UWALAN, while basing itself on the results obtained for the physical layer and MAC layer which solves the constraints of energy consumption and optimized medium access control.

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