

Analyzing the Behavior of Acoustic Link Models in Underwater Wireless Sensor Networks

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ABSTRACT

In the last years, wireless sensor networks have been proposed for their deployment in underwater environments where a lot of applications like aquaculture, pollution monitoring and offshore exploration would benefit from this technology. Despite having a very similar functionality, Underwater Wireless Sensor Networks (UWSNs) exhibit several architectural differences with respect to the terrestrial ones, which are mainly due to the transmission medium characteristics (sea water) and the signal employed to transmit data (acoustic ultrasound signals). So, the design of appropriate network architecture for UWSNs is seriously hardened by the specific characteristics of the communication system. In this work we analyze several acoustic channel models for their use in underwater wireless sensor network architectures. For that purpose, we have implemented them by using the OPNET Modeler tool in order to perform an evaluation of their behavior under different network scenarios. Finally, some conclusions are drawn showing the impact on UWSN performance of different elements of channel model and particular specific environment conditions

Categories and Subject Descriptors

C.2.1 [Network Architecture and Design].

C.2.2 [Network Protocols].

General Terms

Algorithms, Measurement, Performance, Design.

Keywords

Underwater acoustics, Acoustic channel model, Wireless sensor networks, Network simulation.

1. INTRODUCTION

Wireless networking technologies have experienced a considerably development in the last fifteen years, not only in the standardization areas but also in deployment and commercialization of a bunch of devices, services and

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applications. Among this plethora of wireless products, wireless sensor networks are showing an incredible boom, being one of the technological areas with greater scientific and industrial development pace [1]. Recently, wireless sensor networks have been proposed for their deployment in underwater environments where a lot of applications like aquaculture, pollution monitoring and offshore exploration would benefit from this technology [2].

Despite having a very similar functionality, Underwater Wireless Sensor Networks (UWSNs) exhibit several architectural differences with respect to the terrestrial ones, which are mainly due to the transmission medium characteristics (sea water) and the signal employed to transmit data (acoustic ultrasound signals) [3].

Major challenges in the design of underwater acoustic networks are:

- Battery power is limited and usually it cannot be recharged;
- The available bandwidth is severely limited;
- The channel suffers from long and variable propagation delays, multi-path and fading problems;
- Bit error rates are typically very high;
- Underwater sensors are prone to frequent failures due to fouling, corrosion, etc.

Basically, an UWSN is formed by the cooperation among several nodes that establish and maintain a network through the use of bidirectional acoustic links. Every node is able to send/receive messages from/to other nodes in the network, and also to forward messages to remote destinations in case of multi-hop networks. The most common way to send data in underwater environments is by means of acoustic signals, just like dolphins and whales use to do for communicating between them. Radio frequency signals have serious problems to propagate in sea water as shown in [4], being operative for radio-frequency only at very short ranges (up to 10 meters) and with low-bandwidth modems (tens of Kbps). When using optical signals, the light is strongly scattered and absorbed in underwater scenarios, so only in very clear water conditions (often very deep) does the range go up to 100 meters with high bandwidth modems (several Mbps) and blue-green wavelengths.

Since acoustic signals are mainly used in UWSNs, it is necessary to take into account the main aspects involved in the propagation of acoustic signals in underwater environments, including: (1) the underwater sound propagation speed is around 1500 m/s (5 orders

of magnitude slower than radio signals), being communication links prone to large and variable propagation delays and relatively large motion-induced Doppler effects; (2) phase and magnitude fluctuations lead to higher bit error rates compared with radio channels' behavior, being mandatory the use of forward error correction codes (FEC); (3) as frequency increases, the attenuation observed in the acoustic channel also increases, being this a serious bandwidth constraint; (4) multipath interference in underwater acoustic communications is severe due mainly to the surface waves or vessel activity, being a serious problem to attain good bandwidth efficiency.

In this work, we are going to study and analyze underwater several acoustic link models proposed in the literature in order to understand and evaluate the communications constraints related to the special characteristics of communication medium (ocean) and acoustic signals. We have chosen the OPNET simulation tool to develop the corresponding models. After validating our implementations with the results published by the authors of those models, we have analyzed the contributions that each model has introduced, in order to propose a more detailed one.

The paper is organized as follows: In section 2, we perform a review of related work about underwater acoustic link modeling. In section 3 we describe step-by-step the proposed acoustic model based on the fundamentals of underwater acoustic theory and proposals extracted from other authors. In section 4, we describe the model implementation, network scenarios and the simulation results obtained. And, finally, in section 5 some conclusions and future work are drawn.

2. RELATED WORK

Several works in the literature propose models for an acoustic underwater link taking into account several environment parameters as salinity degree, temperature, depth, environmental noise, etc. with different detail levels. Most of these proposals are validated by means of simulation tools, being some of them publicly available for common simulation tools like NS-2 [5] and Opnet Modeler [5][6]. However, other proposals only give some hints about the complete model, so we have to build the model from scratch and validate it by means of the simulation results provided by authors.

One of the first implemented models was proposed by Sozer et al [9]. They propose a simple physical acoustic model based in the Opnet radio model but using the fundamentals of underwater sound physics found in previous works [7][8]. In this work some parameters like node depth were not considered.

In Coelho [10], a simple physical layer model was proposed to evaluate the performance of UWSN considering two different MAC protocols: a contention based with collision avoidance (CSMA-CA), and a contention free one (ALOHA). The physical layer does not consider any propagation loss, neither the influence of node depth. On the other hand, Leopoldo [11] proposes a more detailed physical layer model based on the Monterrey-Miami Parabolic Equation (MMPE) [13] in order to better predict the underwater acoustic propagation.

One of the most complete models is described in [12], in which features not implemented in the previous works are introduced so

as to calculate the transmission loss, such as (1) variable sound propagation that depends on the environmental conditions, (2) the influence of the waves or wind drift and the objects that can be found in the surroundings (e.g., ship, biologic activity, seafloor shape, etc.).

Most of the works enumerated above, include an upper layer (MAC protocol) and one or more traffic generators in order to verify the correctness of the physical model and also measure its impact on network performance metrics (throughput, end-to-end delay, etc.).

As the result of reviewing and comparing the referred methods, lack of accuracy has been found out when modeling the real world conditions. Obviously, this has a strong influence in the results obtained, leading to serious differences between the different works. The most noteworthy reasons are: (1) do not consider the depth of the nodes, which is an essential factor for calculating the transmission loss; (2) do not consider the movement of the nodes, which is not real in the underwater environment due to the continuous movement of the sea water. Adding mobility to the nodes has an increase of the computational time in calculating the list of reachable nodes all the time of the communication; (3) do not consider that the environmental conditions are very variable. The underwater network is a highly dynamic environment as many features can have an effect on it, like underwater biology (whales, fish banks, etc.), the changing climate of the surface, the sea tides, ship and human activity, etc.

All of these factors should be considered whenever a node tries to make a communication to another node. As in the case of mobility this implies a greater computational load each time we run the simulations, the solution brought to date is to calculate the list of reachable nodes at the beginning of the simulation and assuming that the conditions will not change during the period that the simulation lasts.

So, despite of all the previous works, there is still the need to seek a complete model to simulate and define more realistic scenarios for underwater data communications.

3. UNDERWATER ACOUSTIC LINK MODEL

In this section we summarize the fundamentals of underwater acoustic propagation and, at the same time, we introduce the main blocks of the acoustic link model by reusing or adapting parts of other models, in order to build a more detailed underwater acoustic link model.

The sound, according to the description by Urlick [7], is a regular molecular movement in an elastic substance that propagates to adjacent particles. A sound wave can be considered as the mechanical energy that is transmitted by the source from particle to particle, being propagated through the ocean at the sound speed. The propagation of such waves will refract upwards or downwards in agreement with the changes in salinity, temperature and the pressure has a great impact on the sound speed, ranging from 1450 to 1540 m/s [8].

The transmission loss (TL) is defined as the diminution of the sound intensity through the path from the sender to the receiver.

There have been developed diverse empirical expressions to measure the transmission loss. In [7] [8], the signal transmission loss is defined as:

$$\alpha = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} [\text{dB/Km}]$$

$$SS = 20 \log r$$

$$TL = SS + \alpha r \times 10^{-3} \quad (1)$$

Where f is frequency in kHz, r is the range in meters; SS is the spherical spreading factor and α is the attenuation factor. We will use a more accurate expression for the attenuation factor, the one proposed by Sozer [9]:

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

On the other hand, the Monterrey-Miami Parabolic Equation (MMPE) [13] has been introduced to better predict the underwater acoustic propagation. With the MMPE model, the underwater sound propagation is modeled taking into account the effects of several factors like surface wave activity, seafloor shape and salinity changes. The MMPE model can be considered as an approach to the Helmholtz's equation (wave equation), which is based on a Fourier algorithm.

The obtained coefficients from MMPE approach are used for a more realistic prediction of the transmission loss. It is necessary to be aware that calculating these coefficients has a high computational cost. So, network simulations would require too much time to complete, being necessary to perform simplifications to the way those coefficients are computed. In order to determine the expression for the propagation loss we choose the one based on the MMPE model, introduced in [11]:

$$PL(t) = m(f, s, d_A, d_B) + w(t) + e(t) \quad (3)$$

Where

$PL(t)$: propagation loss while transmitting from node A to node B.

$m()$: propagation loss without random and periodic components; obtained from regression using MMPE data [14].

f : frequency of transmitted acoustic signals (in kHz).

d_A : sender's depth (in meters).

d_B : receiver's depth (in meters).

r : horizontal distance between A and B nodes, called range in MMPE model (in meters).

s : Euclidean distance between A and B nodes (in meters).

$w(t)$: periodic function to approximate signal loss due to wave movement.

$e(t)$: signal loss due to random noise or error.

The $e(t)$ function represents a random term to explain background noise. As the number of sound sources is large and undetermined, this random noise follows a Gaussian distribution [7] and is

modeled to have a maximum of 20dB at the furthest distance [3]. This function is calculated by the following equation:

$$e(t) = 20 \left(\frac{s}{s_{\max}} \right) R_N \quad (4)$$

Where:

$e(t)$: random noise function

s : distance between the sender and receiver (in meters).

s_{\max} : maximum distance (transmission range)

h_w : height of the wave (in meters).

R_N : random number, Gaussian distribution centered in zero and with variance 1.

Taking into consideration the environmental conditions introduced by Harris [12], an improvement has been introduced when calculating $e(t)$, in order to reduce the randomness and introduce more realistic noise sources. Based on [12] we propose that the major factors contributing to the underwater environmental noise are ship activity, wind, turbulence and thermal noise. Notice that in Leopoldo's model [11] the wind and the turbulence is already considered when introducing the wave effect. So, the ship activity and thermal noise sources are added to the physical layer, and as a consequence, we reduce the high degree of randomness of expression (4). So, in order to model the environmental noise, we propose the following expression:

$$N(f) = N_t + N_s$$

$$10 \log N_s(f) = 40 + 2(\text{ship} - 0.5) + 26 \log f - 60 \log(f + 0.03) \quad (5)$$

$$10 \log N_{th}(f) = -15 + 20 \log f$$

Where N_s is the noise due to shipping activity, $ship$ parameter indicates the noise due to ship activity (ranges from 0 to 1) and N_{th} refers to the thermal noise. So, finally, the function $e(t)$ stands as follow:

$$e(t) = 20 \left(\frac{s}{s_{\max}} \right) R_N + N(f) \quad (6)$$

After completely defining the proposed propagation loss, we have also to determine another characteristic parameter of underwater acoustic links: the sound propagation speed. There are several proposals to model the underwater sound propagation speed which is affected by several others like temperature, salinity and depth. For our purpose, we use the expression proposed in [7]:

$$c = 1449 + 4.6 \cdot t + 0.055 \cdot t^2 + 0.003 \cdot t^3 + (1.39 - 0.012 \cdot t)(S - 35) + 0.017 \cdot d \quad (7)$$

Where

t : temperature of water (in Celsius degrees).

S : salinity of water (in parts per million).

d : depth of node (in meters).

On the other hand, we introduce the dynamic calculation of temperature and salinity as a function of the depth of node. In [16] a detailed study about this question was done, showing the temperature value as a function of depth depending on the latitude (low, mid and high) and the season of the year (winter and summer. From [17] we have obtained the salinity values at different node depths.

Table 1. Temperature (°C) as a function of depth and latitude

Depth (m)	Low Lat	Mid Lat Summer	Mid Lat Winter	High Lat
0	28	18	10,2	7,5
125	13	10,2	10,2	0
250	9	10,1	10,1	3,75
375	7,5	10	10	3,5
500	6	8,7	8,7	3,25
625	5,5	7,5	7,5	3
750	5	6,5	6,5	2,75
875	4,5	5,8	5,8	2,5
1000	4,4	5,1	5,1	2,5
1125	4,1	5	5	2,4
1250	3,8	3,8	3,8	2,3
1375	3,2	3,2	3,2	2,1
1500	3,1	3,1	3,1	2
1625	3	3	3	1,8
1750	2,8	2,8	2,8	1,5
1875	2,6	2,6	2,6	1,3
2000	2,5	2,5	2,5	1,25

Table 2. Salinity as a function of depth

Depth (m)	Salinity
0	37,45
50	36,02
100	35,34
500	35,11
1000	34,90
1500	34,05

In Tables 1 and 2, the temperature and salinity values as a function of depth are shown. We will consider them in our model proposal.

4. VALIDATION AND EXPERIMENTAL RESULTS

The implementation of the model described in previous section was mainly based on the models proposed by Coelho [10] and Leopoldo [11] with add-ons from other proposals, like Harris [12] that improves the environmental noise modeling, and [6] that provides a more accurate expression for calculating the sound propagation speed. We employed the OPNET Modeler Release 14.0 PL3 simulation tool to implement the model and defining the network scenarios to perform the corresponding simulation tests.

Firstly, we implemented the original proposals [10] and [11], in order to validate its functional behavior with the simulation results provided by the authors. After that, we introduced some changes in the model (as explained in previous section) in order to perform a global evaluation of our proposed model. For that purpose several network scenarios were defined and, also, we have implemented two simple MAC protocols (upper layers) to analyze the impact of acoustic links model parameters in the UWSN global performance.

4.1 Model Validation

With respect MAC protocols, we will use the Aloha (with explicit ACK) and CSMA-CA (a simple RTS-CTS-DATA-ACK with a contention back-off) versions found in [10] and [11].

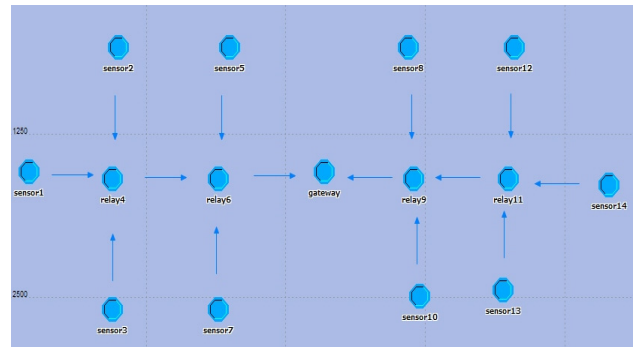


Figure 1. Topology with sensors, relays and one sink node

We defined an UWSN (shown at figure 1) topology with a group of sensor nodes generating background and non-periodic traffic. The relay nodes are responsible to forward the traffic from sensor nodes to the gateway node (also known as sink node), which receives the information from all sensor nodes in order to store and/or retransmit it to the offshore control station. In Table 3, the spatial location of every node is defined. We run every experiment 30 times to obtain reliable results. In Table 4 we summarize the default parameters used in simulations.

To validate the model, we perform several simulation tests from which we show the number of collisions and the average end-to-end delay. The results obtained in our implementation (figures 3 and 5) are very similar to the ones obtained by original author (figures 2 and 4), so we validate our implementation.

Table 3. 3D Position of network nodes

Node	Depth	Pos X	Pos Y
Sensor 1	20	200	1550
Sensor 2	20	1000	600
Sensor 3	25	950	2600
Relay 4	10	950	1600
Sensor 5	25	2000	600
Relay 6	30	1900	1600
Sensor 7	15	1900	2600
Sensor 8	10	3600	600
Relay 9	15	3650	1600
Sensor 10	10	3700	2500
Relay 11	35	4500	1600
Sensor 12	12	4550	600
Sensor 13	5	4450	2450
Sensor 14	14	5400	1650
Gateway	5	2850	1550

Table 4. Default Simulation Parameters

Parameters	Value
Data Frame Payload Size	1024 bits
Packet Time Generation	48,65,80,102,120,144,180,240,360,720
Propagation Threshold	80 dB
Propagation Speed	1500 m/s
Data Rate	1000 bits/s
Node Frequency	20 kHz
waveHeight	4 meters
waveLength	100 meters
wavePeriod	5 seconds

In figures 2 and 3, the behavior of ALOHA and CSMA-CA protocols is the expected one, showing the effectiveness of CSMA-CA in reducing the number of collisions. In figures 4 and 5, CSMA-CA protocol gets better end-to-end delay from low to moderate traffic loads.

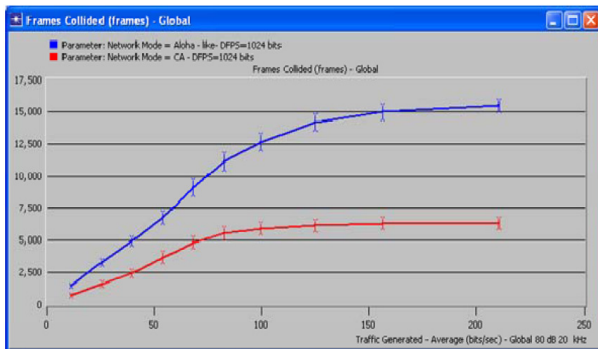


Figure 2. Collisions vs. Load: Results from original authors

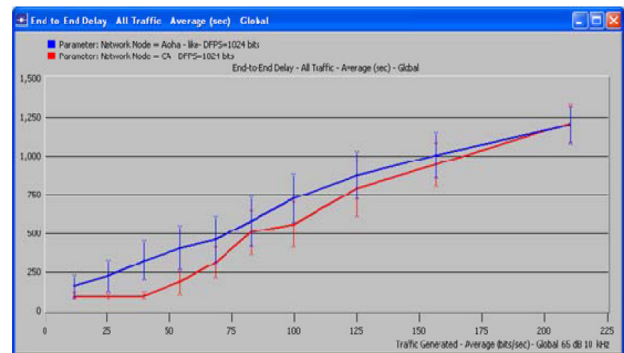


Figure 4. Delay vs. Load: Results from original authors.

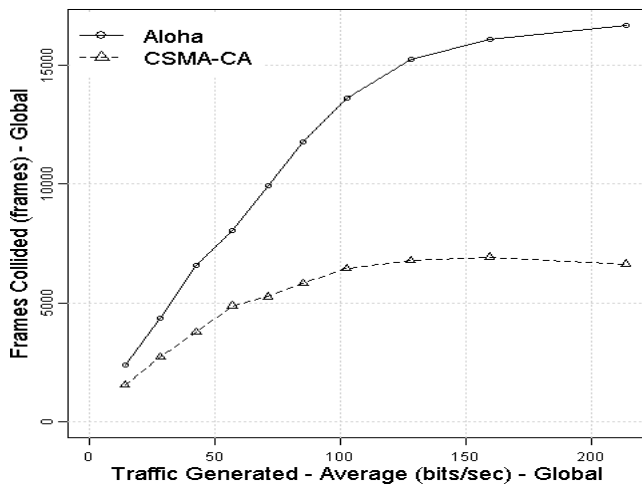


Figure 3. Collisions vs. Load: Our results

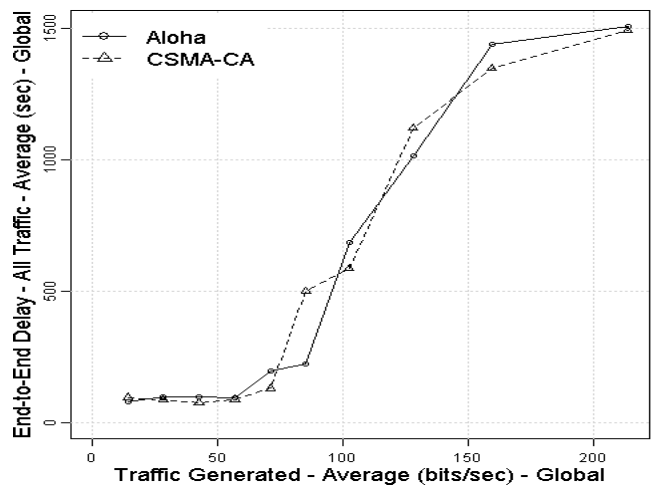


Figure 5. Delay vs. Load: Our results.

4.2 Model Evaluation

4.2.1 Calculation of Sound Propagation Speed

The evaluation of the model begins testing the influence of the physical parameters in the behavior of the model. The first parameter we are going to evaluate is the sound propagation speed based on the expression (7). The simulation is done in a scenario with a point-to-point connection among two nodes at a fixed distance of 1250 meters and with the same depth of 40 meter. The rest of parameters are the ones shown in table 4.

To observe the salinity and temperature influence on the propagation speed, we run several simulations varying those parameters within their operational range. In particular, in this scenario the salinity goes from 32 to 37 ppm and the temperature from 0 to 18 °C. As a summary of this simulation process, the results for the minimum and maximum values are presented in tables 4 and 5.

Table 4. Salinity influence

Salinity	PropSpeed	PropDelay	End to End Delay
32	1537 m/s	0.8107 s	1.9116 s
37	1543 m/s	0.8076 s	1.9147 s

Table 5. Temperature influence

Temperature	PropSpeed	PropDelay	End to End Delay
0	1450 m/s	0.862 s	1.9662 s
18	1550 m/s	0.797 s	1.9013 s

As it can be seen, even comparing the lowest and highest values of salinity and temperature, the effect on the link propagation delay is too little (around 7%) and, hence, the network performance characteristics that depend of this parameter, such as the end-to-end delay will slightly be affected. So, this is one of the main reasons that some authors justify the use of a fixed value of 1500 m/s for the propagation speed. Despite this fact, in the proposed model, we will calculate these parameters to have a more realistic pattern of the underwater acoustic environment.

4.2.2 Depth effect evaluation

We define a point-to-point link among two nodes that keep the same distance. Both nodes move at the same time from the surface to a depth of 300 meters (they always share the same depth) because that is the limit where we can calculate the physical parameters of MMPE model. The traffic load is the one corresponding to a packet time generation of 10 seconds.

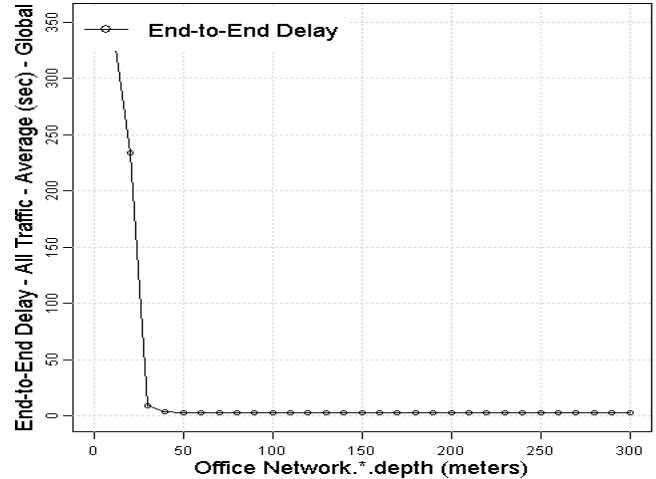


Figure 6. Average End-to-End Delay at different depths

The results are shown at figures 6 and 7. As it can be shown, the average end-to-end delay increases as the node depth decreases. This behavior is mainly due to the wave effect at low depths, where the propagation multipath caused by the surface activity and the wave turbulence effects severely impacts the propagation loss. So, there are a lot of packet losses that lead to retransmissions and, as consequence, the network performance is severely penalized.

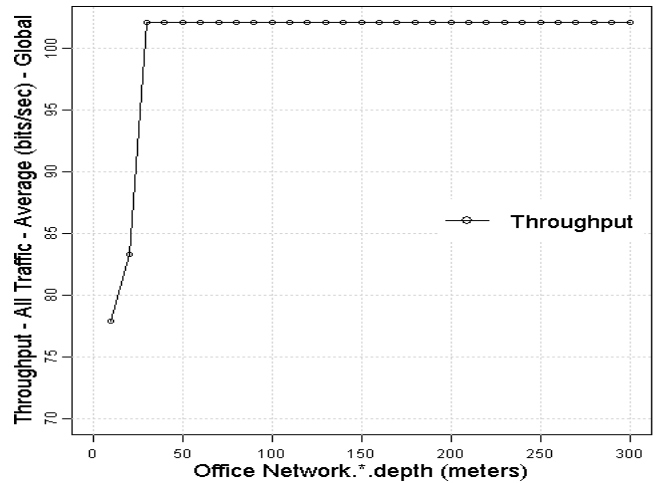


Figure 7. Throughput at different depths

4.2.3 Choosing a depth for wave and ship measurements

Before evaluating the wave and ship effects on the proposed model we need to find a network scenario to properly evaluate these parameters, since at low depths they can not be properly evaluated as shown before.

So, we define again a point-to-point link among two nodes separated at a fixed distance of 1400 meter.

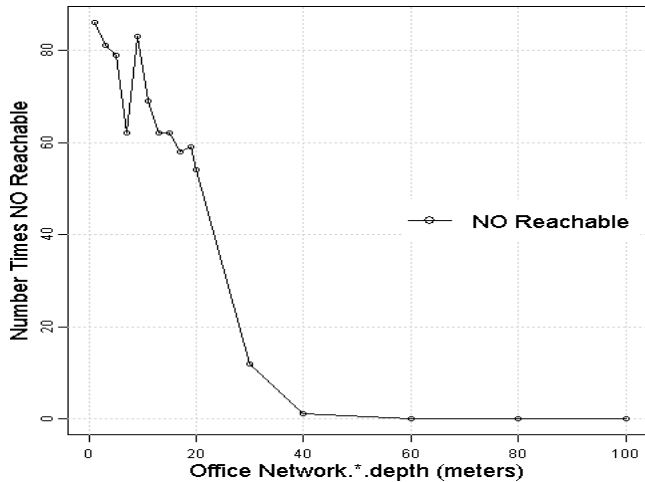


Figure 8. Number of times nodes are reachable vs Depth

In figure 8, we show the reachability graph of both nodes varying their depth from 0 to 300 meters. The graph shows the number of times during the simulation that both nodes were not reachable one from the other. From 0 to 20 meters the wave random effect and the propagation influence in the model could give us not accurately results about the parameters to be evaluated. At 40 meters the nodes are near always reachable at this distance. So the election for the next simulation will fix the node depth at 30 meters.

In figure 9, we show the reachability limits, by defining a scenario where one node moves away from the other and returns back. The distance curve represents the distance among both nodes as a function of time, while the reachability curve indicates if both nodes are reachable (1400 meters) or not (0).

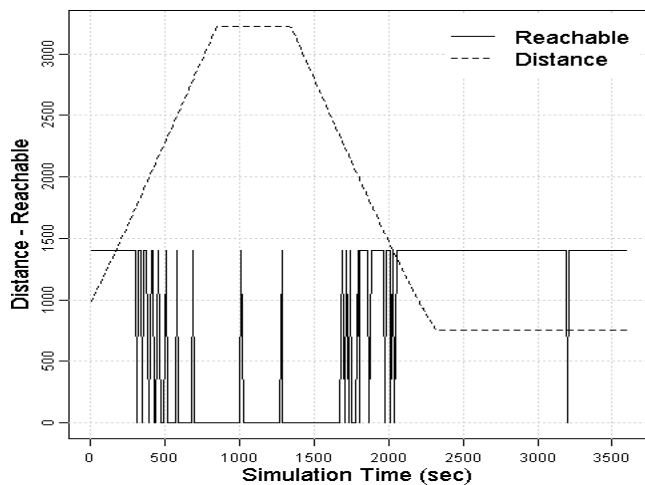


Figure 9. Reachability vs. Distance

As it can be shown, when the distance is above 1400 or 1500 meters the reachability changes from always to sometimes, and at more than 2200 meters, both nodes are considered as unreachable. So, we will also fix the distance among nodes in 1400 meters to evaluate the ship and wave activity.

4.2.4 Wave effect evaluation

Combing the possible values of the characteristics in which a wave is modeled (height, length and period) we evaluate the wave effect by using a range from 0, which represents the minimum values of height (0.5), length (50) and period (1), to 100 that represents the highest values of height (5), length (150), and period (8). In table 6, we show the values that represent the wave activity.

Table 6. Wave activity %

Height	Length	Period	%	Delay
0.5	50	1	0	2.11
2	75	2	25	2.11
3	100	4	50	2.11
4	125	6	75	6.38
5	150	8	100	16.91

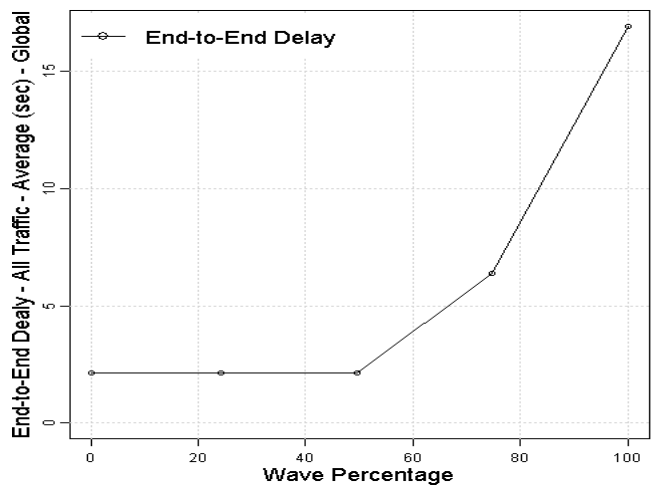


Figure 10. Delay vs. wave activity

In figure 10, we show the average end-to-end delay of a point-to-point link of 1400 meters where both nodes are at the same depth (30 meters) and the packet time generation (traffic load) was set to 20 seconds. The end-to-end delay remains constant up to 50% of wave activity (no effect), but above 50% the end-to-end delay significantly increases.

4.2.5 Ship effect evaluation

Using the same point-to-point link defined in previous section, the ship activity is evaluated in a range from 0 (no ship activity) to 100 (maximum ship activity) in the network. As expected, the throughput falls and the delay increases as the shipping activity approaches to 100 %. In particular, the impact of ship activity on the end-to-end delay is significant above 75% (see figure 11).

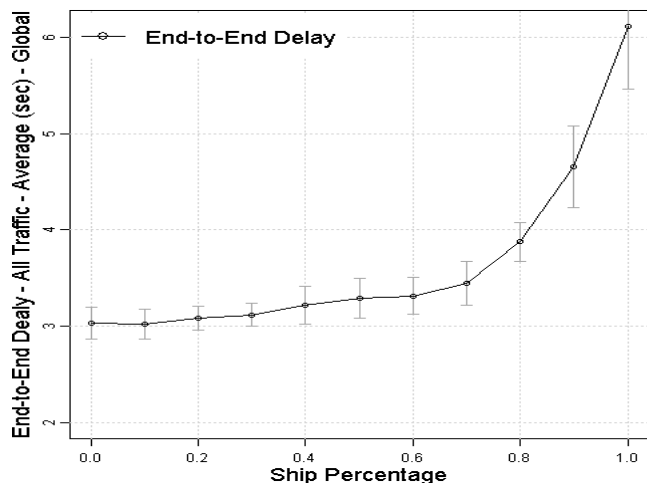


Figure 11. Delay in percentage of the ship activity

5. CONCLUSIONS AND FUTURE WORK

In this paper, we have studied several underwater acoustic communication models in order to define a detailed model that emulates the characteristics of sound propagation in sea water as much realistic as possible. So, we can better define appropriate upper layer architecture for underwater wireless sensor networks as our target application.

On the other hand, we have verified that slight changes in propagation model can significantly affect the final results obtained by simulation. So, we think it is very important to determine a well-defined physical model, so simulation results of the overall network architecture may be useful for the deployment of real underwater sensor networks. In this paper we propose an underwater acoustic model based on the work of other authors in the literature. This model was validated against the original acoustic models by running experiments with the same scenarios and model parameters than those used by their authors. Also, preliminary evaluation results were shown verifying that they are coherent with the ones expected by the proposed model.

As future work, we will continue improving the model and better integrating it with the simulation tool so the dynamic of underwater environment is taken into account during the simulation. This will increase the quality of simulations and it will allow us to study the behavior of higher level protocols in more complex UWSN scenarios including node mobility patterns.

6. ACKNOWLEDGMENTS

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