Modeling and Simulation of Intermittent Acoustic Communications between Autonomous Underwater Vehicles

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***Abstract*— This paper aims at improving the realism of simulated communications between autonomous underwater vehicles (AUV) in an existing software package that allows the simulation of the execution of coordinated missions involving multiple AUV (NetMar$_{SyS}$ Simulator).**

Currently, the communication model implemented in NetMar$_{SyS}$ is oversimplified as important underwater acoustic channel characteristics are not considered, such as: sound speed profile; multipath channel; bathymetric profile. Therefore, the starting point of this work will be embedding code on NetMar$_{SyS}$ to modulate the acoustic propagation in the underwater environment.

Firstly, a deterministic channel model obtained using an acoustic propagation simulator based on ray tracing (Bellhop) will be considered. Next, the deterministic model will be combined with an empirical model derived from real data collected at sea, which will reflect the channel's dynamic behavior. Lastly, from the acoustic propagation model, important characteristics of the point-to-point link between multiple AUV will be extrapolated, namely the maximum transmission rate that can be supported by the acoustic channel. In order to calculate the maximum transmission rate, methods based on realistic assumptions that constitute the current state of the art to calculate the channel capacity, which allow the inclusion of the stochastic channel behavior, will be employed. The decision criterion for success/failure in the delivery of synchronization messages exchanged between AUV will be based on the computed channel capacity.

***Index Terms*— Underwater autonomous vehicles, underwater acoustic communications, underwater acoustic propagation, channel modeling, channel capacity**

I. Introduction

OVER the last years, the development of control strategies involving multiple autonomous underwater vehicles (AUV) has awakened the interest of the scientific community since these vehicles have the potential to extend the intervention capabilities beyond the current reach significantly help humans in underwater activities involving high risk. To perform this type of challenging missions, advanced cooperative motion control plays a key role. However, the underwater acoustic communication channel is recognized as one of the harshest environments for data communication. Although some known results give an idea of the impact of communication failures in the overall system performance, the underlying models are not well adapted to the specificities of underwater acoustic channels such as the relatively small speed of sound, the strong distortion due to multipath and reduced available bandwidth. Therefore, it must be recognized that any channel model needs to be adaptable so that the model can simulate the channel dynamics to be able to fully analyze the performance of underwater networks. Depending on their degree of completeness and accuracy, these models can highly increase the probability of field trial success and thus reduce the cost of overall system development.

A propagation channel can be usually modeled as a linear random time-varying system entirely defined by its impulse response $h(\tau, t)$, so that the input $x(t)$ and the output $y(t)$ of this system satisfy [1]

$$y(t) = \int_{-\infty}^{+\infty} h(\tau, t) x(t-\tau) d\tau \qquad (1)$$

In order to include a realistic characterization of the underwater environment reflecting its stochastic behavior, often it is important to consider heuristic assumptions to model the channel impulse response.

This paper proposes a heuristic assumption for the channel model based on statistical characterization, aiming at obtaining the range of transmission rates that allow reliable exchange of synchronization messages between multiple AUV, which, according to [2], [3], is strongly dependent on the degree of knowledge of the channel. Channel capacity has been used as a benchmark for determining the maximum data rate and bandwidth of the channel. However, unlike the capacity of the radio channel, previous attempts used to determine the capacity equations of the UAC were not realistic since they neglected some critical characteristics of the channel ([4], [5], [6], [7]) as they considered that the channels have a deterministic behavior in which, for each channel realization, its stochastic behavior is not considered; no limitations are imposed on the transmission equipment by assuming that the peak power of the input symbols is unlimited. Therefore, this paper will employ methods based on realistic assumptions that constitute the current state of the art ([8] [9] [10]), which allow the inclusion in their equations of the stochastic channel behavior and consider that [11]:

- Both the peak and the average power of the transmitted symbols are limited;
- The channel is doubly dispersive, i.e., it exhibits dispersion both in the time domain (due to the relative motion of the vehicles causing Doppler shifts) and

frequency domain (which is related to the dispersion of the signal due to multipath effects of the channel);

- The channel is non-coherent, i.e. neither the transmitter nor the receiver knows the current realization of the channel but both know the channel distribution.

To simplify the statistical description of the channel impulse response, the wide-sense stationary uncorrelated scattering (WSSUS) assumption will be considered [1]. This assumption states that for different path delays the scatterers are uncorrelated (US) and for small scale observations where no significant changes occur in the propagation scenario, the fluctuations of the impulse response are considered as stationary (WSS).

II. CHANNEL MODELING

A. CALCOM'10 Sea trial

The statistical characterization of the channel model derived in this paper relies on the analysis of experimental data collected at sea during the CALCOM'10 sea trial. This data was collected in the south coast of Portugal (12 nautical miles from Vilamoura) in June 2010 with the aim of collecting real calibration data to be used on tomographic studies and transmit signals on different frequency bands in order to analyze the performance of underwater communication systems. The working area was chosen so that the trial would take place in a shallow water environment and with a constant depth (about 100 meters).

The data packets used in this paper, sent by a single emission source towed by a boat, had the duration of 2.5 seconds and consisted of signals with PSK modulation with center frequency of 5.5 kHz and bandwidth of 4.5 kHz [12]. The acoustic system used to gather the data was composed of two Acoustic Oceanographic Buoys, one with 8 vertical hydrophones and the second one with 16 hydrophones, which were equally spaced 4 meters apart and the first one was positioned at 6.3 meters from the surface. Fig. 1 represents the measured impulse responses that reached each one of the 16 hydrophones for a given instant of time, t. Statistical characterization will focus on the data collected by hydrophone No. 8 of the total 16.

Fig. 2 represents the time evolution of gain estimates of the impulse responses that reached hydrophone No. 8, in which it is possible to identify the five responses that arrived at the receiver with the highest energy, where the strongest one corresponds to the direct path.

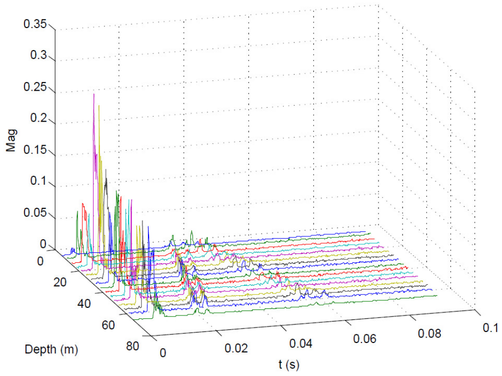

Fig. 1. Channel impulse responses that reached each of the 16 hydrophones for a given instant of time $\boldsymbol{t}$.

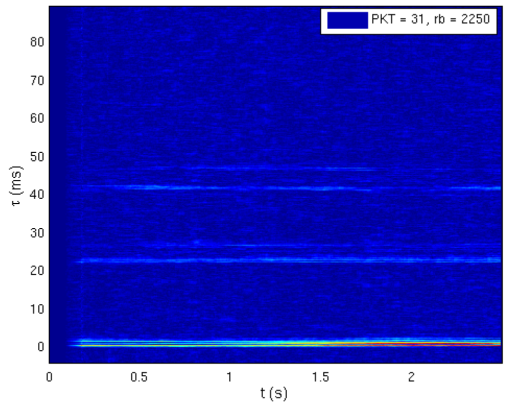

Fig. 2. Evolution over time of the impulse responses gains estimates that reached hydrophone No. 8.

B. Characterization of the Channel Model

This paper applies the methodology used in [12], which considers an empirical model to characterize the underwater channel based on real data collected at sea based on the hypothesis that the channel impulse response for each path of the acoustic signal, $h(\tau, t)$, can be given by:

$$h_l(t) = d_l(t) + w_l(t) \qquad (2)$$

Where,

- $d_l(t)$ is the slow component of the impulse response that follows the trend of the dynamic behavior of the channel response and can be compared to the slow fading that occurs in radio channels caused by shadowing and losses along the path of the acoustic wave;
- $w_l(t)$ is the fast component of the impulse response associated to the random behavior of the underwater environment and can be compared to the fast fading of the radio channel caused by the relative motion of the transmitter and receiver, the multipath and the spreading of the acoustic beam.

To validate the abovementioned hypothesis for the channel characterization, the slow component of the channel impulse response will be isolated from the fast component using the Empirical Mode Decomposition (EMD) algorithm [13].

C. *Empirical Mode Decomposition*

The EMD proposed in [13] is a signal decomposition algorithm based on the assumption that all signals are composed of the sum of several elementary components called by Intrinsic Mode Functions (IMF).

Each IMF is an oscillation signal with the same number of zeros and extreme values and that can have a variable frequency and amplitude over time. Furthermore, at any instant of time, the mean value of the envelope defined by the local maxima extreme values and the envelope defined by the local minima extreme values is zero. Thus, with the use of EMD it is possible to represent each path of the underwater acoustic channel by

$$h_l(t) = \sum_{i=1}^{n} m_{l,i}(t) + r_l(t) \quad (3)$$

Where $m_{l,i}(t)$ represents each of n IMFs wherein the impulse response $h_l(t)$ is decomposed and $r_l(t)$ is the decomposition residue.

Although this method was initially limited to real-valued time series, this paper uses its extension to bivariate (or complex-valued) time series proposed in [14].

To validate the hypothesis assumed in equation (2), the EMD will be applied to the five strongest taps identified in Fig. 2. To separate the slow component from the fast component of the impulse response, the Matlab code available at http://perso.telecom- bretagne.eu/fxsocheleau/software [12] was used, such that

$$h_l(t) = \underbrace{\sum_{i=1}^{S_l-1} m_{l,i}(t)}_{d_l(t)} + \underbrace{\sum_{i=S_l}^{n} m_{l,i}(t) + r_l(t)}_{w_l(t)} \quad (4)$$

Where S_l is the decomposition order leading to the separation of the two components.

After the application of EMD to each of the five taps, similar results were obtained. Fig. 3 illustrates the result of the EMD filtering applied to the direct tap. From this Figure it is possible to verify that the $w_l(t)$ component shows major variations in amplitude over time as compared to the $d_l(t)$ component and to conclude that, contrarily to $d_l(t)$, the samples of $w_l(t)$ are approximately uncorrelated.

From the power spectrum of both components ($d_l(t)$ and $w_l(t)$) it was possible to conclude that the spectrum of the fast component is much wider than the spectrum of the slow component, which suggests that $w_l(t)$ can be regarded as white Gaussian noise. Thus, it will be considered that the dynamic behavior of the underwater acoustic channel can be characterized only by the slow component of the channel.

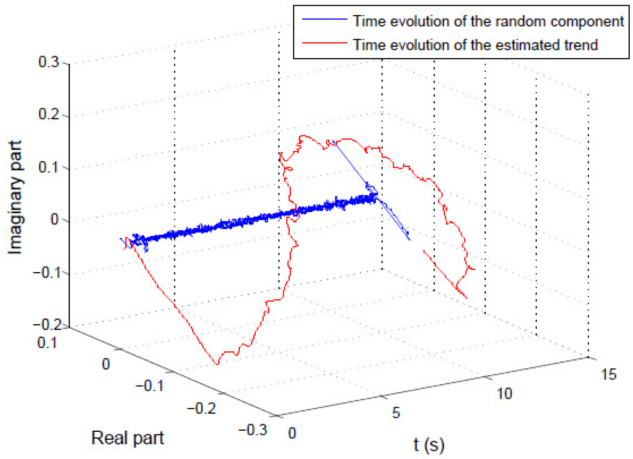

Fig. 3. Illustration of EMD filtering applied to a real channel tap: Separation of the trend (red line) and the random component (blue line).

D. *Statistical characterization of the slow component of the impulse response*

This paper will use a data driven analysis using an order p Auto-Regressive parametric model derived from real data (collected at CALCOM'10) to statistically characterize the dynamic behavior of the channel impulse response. This dynamic behavior will be combined in the channel impulse response.

The order p of the Auto-Regressive model will be obtained taking into account a complexity *versus* accuracy criterion, since the higher the chosen order is the more accurate the model will be but, on the other hand, the number of poles will also be higher. In order to define an appropriate order, Akaike's Information Criterion [15] will be applied using an AIC Matlab tool for each of five channel taps. It was verified that for each of the five taps the results are similar (Fig. 4).

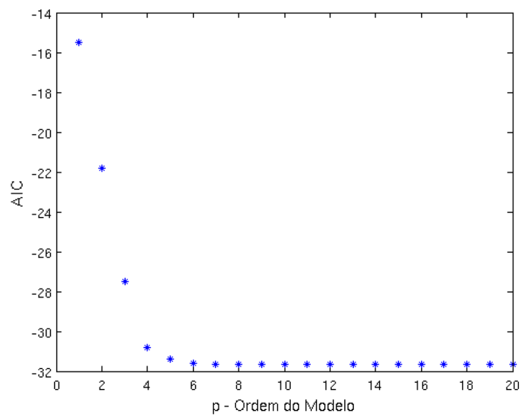

Fig. 4. Result of the AIC command applied to the direct channel path.

From this Figure it is possible to consider that, from the order $p = 6$ onwards, there is no gain in choosing a higher order. Therefore, this will be the order adopted in this paper.

For each of the five taps and in order to obtain the statistical model, the distribution of poles obtained through the AR model will be analyzed in the complex Z plane. From visual inspection it was verified that the distribution of poles is similar for each tap and its behavior appears to be an integrator. Therefore, the transfer function of the channel can be defined by an p order AR model given by

$$G(Z) = \frac{1}{1 - \sum_{i=1}^{p} \alpha_i Z^{-i}} \quad (5)$$

With spectral power density given by

$$P_{AR}(f) = \frac{\sigma_\epsilon^2}{|1 - \sum_{n=1}^{p} \alpha_n e^{-j2\pi f n}|^2} \quad (6)$$

Due to the similarity of the empirical distribution of poles between the five taps analyzed in the Z complex plane, and given that a WSSUS channel is considered, the same statistical model for all taps will be assumed below to reduce the complexity of the analysis.

E. Simulation channel model

The underwater acoustic channel can usually be modeled as a linear random time-varying system entirely defined by its impulse response $h(t,\tau)$:

$$h(t,\tau) = \sum_{n=1}^{L} a_n e^{-jw_c\tau_n} \delta(t - \tau_n) \quad (7)$$

In order to consider a realistic impulse response, and since that will be influenced by the position of the emitter and receiver, the amplitudes (a_n) and delays (τ_n) present in equation (7) will be obtained using the output parameters of the Bellhop acoustic propagation model. The main input file to Bellhop (environmental file) will be created using the results of a software program named OceanDB, developed at ISR/IST, which retrieves a sound speed profile and the bathymetric profile from several public databases given the source and receiver coordinates [17]. Considering the frequency Doppler shift caused by the relative motion of the transmitter and receiver, equation (7) will be given by

$$h(t,\tau) = \sum_{n=1}^{L} a_n e^{-jw_c\tau_n} e^{j\upsilon_n(t-\tau_n)} \delta(t - \tau_n) \quad (8)$$

F. The dynamic behavior of the slow component of the time-varying impulse response

Although the Bellhop model allows the calculation of channel impulse responses, these have a static and deterministic behavior since in the simulation the obtained amplitudes and delays do not take into account the real variations of the channel over time. Therefore, in order to take into account the dynamic behavior of the channel impulse response in the simulations, the statistical characterization obtained from the AR model (Section D) can be combined with equation (7), resulting in

$$h(t,\tau) = \sum_{n=1}^{L} a'_n(t) e^{-jw_c\tau_n} \delta(t - \tau_n) \quad (9)$$

Where, in the time domain

$$a'_n(t) = \eta a_n + (1-\eta) AR(t) \quad (10)$$

With η, whose value is between 0 and 1, representing the distribution of the total power of the channel (P_{Total}) by a dynamic component (P_f) and the deterministic component (P_d) of the impulse response associated to each tap L, where

$$P_{Total} = P_f + P_d = |a_i|^2 \quad (11)$$

And the spectral power density, taking into account with Doppler shift, f_l, is given by

$$P_{AR}(f - f_l) = \frac{\sigma_l^2}{|A_l(f - f_l)|^2} \quad (12)$$

G. Statistical channel model

As discussed in the introduction, underwater acoustic channels are random time-variant systems whose impulse responses are stochastic processes. Therefore, it is necessary to know the joint statistical description to be able to characterize the underwater acoustic channel. Given the considered hypothesis that the channel is WSSUS, the taps are uncorrelated and the joint statistical description of the stochastic behavior can be provided by a Scattering Function of the underwater channel.

By definition, the Scattering Function is the Fourier Transform of the autocorrelation function $R_h(\Delta t,\tau)$, of the $h(t,\tau)$,

$$S_h(\upsilon,\tau) = \int_{-\infty}^{+\infty} R_h(\Delta t,\tau)\, e^{-j2\pi\upsilon\Delta t} d\Delta t \quad (13)$$

Where υ is the Doppler frequency and $R_h(\Delta t,\tau)$ is given by

$$R_h(\Delta t,\tau) = \begin{cases} 0, & se\ \tau_i \neq \tau_j \\ E[h(t,\tau_1)h^*(t+\Delta t,\tau_1)], & c.c. \end{cases} \quad (14)$$

The Scattering Function equation represents the energy dispersal of the channel in the direction of the delay (delay spread) and frequency (Doppler spread). Thus, it provides a measure of the power output as a function of the channel path delay (due to multipath) and the Doppler frequency (due to the motion of the underwater vehicle and to the variations of the underwater medium over time, such as the effect of the waves).

According to [1], from the channel Scattering Function it is possible to calculate the Doppler power spectrum and Delay power spectrum, which are obtained by integrating the Scattering Function with respect to delay and Doppler, respectively,

$$S_{\upsilon}(\upsilon) = \int_{-\infty}^{+\infty} S_h(\upsilon, \tau)\, d\tau \quad (15)$$

$$S_{\tau}(\tau) = \int_{-\infty}^{+\infty} S_h(\upsilon, \tau)\, d\upsilon \quad (16)$$

Therefore, the Doppler power spectrum can be interpreted as the projection of the Scattering Function in the Doppler frequency axis, whereas the delay power spectrum is the projection of the Scattering Function in the delay axis.

In this paper, in order to describe the underwater channel variations over time, only the Doppler power spectrum of the channel will be used. The equation that will be considered in this paper will be derived from the channel model results obtained on the previous sections.

By definition, for each τ, the Scattering Function of each tap is given by the Power Spectrum of the channel gains along the Doppler axis. Therefore this paper will consider that the Doppler Power Spectrum $S_{\upsilon}(\upsilon)$ of the channel is given by the spectral power density of the stochastic behavior over time that was modeled by the AR model, i.e.,

$$S_{\upsilon}(\upsilon) = \sum_{l=1}^{L} \frac{\sigma_l^2}{|A_l(f - \frac{\upsilon_l}{2\pi})|^2} \quad (17)$$

III. CHANNEL CAPACITY

The acoustic communication channel capacity determines the maximum data rate that can be supported (theoretically) by an acoustic channel for a given source power and source/receiver configuration. The Shannon channel capacity [16] represents the theoretical upper bound of the maximum rate of data transmission at an arbitrarily small bit error rate that is dependent on bandwidth and SNR of the channel.

To implement underwater acoustic wireless communication systems, techniques based on well known and widely studied results of radio communication were initially developed. However, due to the harsh propagation conditions of the underwater medium, these systems exhibit a relatively low transmission rate. Furthermore, the acoustic channels impose many constraints that affect the design of UW communication systems. These are characterized by a path loss that depends on both the transmission distance and the signal frequency. The signal frequency determines the absorption loss, which increases with distance as well, eventually imposing a limit on the available bandwidth [17].

An efficient real-time wireless communication between AUVs requires sending and receiving information in due time and free of errors.

In order to simulate the communication between AUVs on $\text{NetMar}_{\text{SyS}}$, and the effects of the failures in the data exchanged, this paper will rely on the UW capacity model given in [11] for a single source-receiver pair based on some of the most realistic assumptions currently available. In these results, the channel is assumed to be time invariant for some time interval (WSSUS) and the ambient noise of the channel is assumed to be Gaussian.

Since the exact channel capacity based on realistic assumptions is still unknown in closed form, [11] proposed upper and lower bounds for the channel capacity, which in this paper will bracket the maximum transmission rate that theoretically guarantees error-free exchange of information between underwater vehicles. These bounds, which take into account the stochastic behavior of the channel over time through the Doppler Power Spectrum, will be used as a decision criterion for the delivery of synchronization messages exchanged between the AUVs.

A. *Capacity bounds*

In [11] two bounds for the Channel Capacity were proposed:

- *Ideal assumption*

This bound corresponds to the ideal case of obtaining the capacity value assuming that the channel does not have variations over time or it is possible to follow the channel variations using adaptive receivers that can estimate the characteristics of the underwater channel perfectly. It is also assumed that the receiver knows each channel realization and there is a constraint on the peak power of the input symbols. The equation for the upper bound, designated as coherent capacity, is given by

$$C^{coh} = \lim_{N\to\infty} \frac{1}{N} \mathrm{E_H}\left\{\log\det\left(\mathrm{I_N} + \frac{\Omega_x^2}{\beta\sigma_w^2}\mathrm{HH^T}\right)\right\} \quad (18)$$

Where, Ω_x^2/β is the average power of the transmitted signal and σ_w^2 is the power associated to the ambient noise that it is assumed to be Gaussian. H is the convolution matrix of the impulse responses of the channel.

- *Realistic assumption*

A lower bound was proposed assuming that the peak power of the input symbols is constrained and the equation takes into account the dynamic behavior of the underwater channel through the inclusion of the Doppler power spectrum. Therefore, the lower bound of non-coherent capacity will be given by the difference of two terms:

$$L_{peak}^{DS} = \lim_{N\to\infty} \frac{1}{N} \mathrm{E_H}\left\{\log\det\left(\mathrm{I_N} + \lambda\frac{\Omega_x^2}{\beta\sigma_w^2}\mathrm{HH^T}\right)\right\} - \int_{-1/2}^{1/2} \log\left(1 + \frac{\Omega_x^2\Xi_H^2}{\beta\sigma_w^2} S_H(\upsilon)\right) d\upsilon \quad (19)$$

This limit can be interpreted as a pessimistic assumption for the capacity value and is given by the difference of two terms:

- The first term is the coherent capacity of the channel (equation (18)), with the inclusion of a weighting factor of SNR expressed by λ.
- The second term is a penalty term corresponding to the capacity loss induced by the channel uncertainty

and taking into account the dynamic channel behavior through the inclusion of the Doppler Spectrum.

From the equation,

- Ξ_H^2 is the sum of the power associated to each path of the acoustic wave and is given by

$$\Xi_H^2 = \sum_{k=0}^{L-1} \sigma_h^2(k) \qquad (20)$$

Where $\sigma_h^2(k)$ represents each element of the covariance matrix main diagonal, $R_H(k)$, of the channel impulse responses.

By entering into account with assumption (2), the power of each tap is given by the sum of the slow power component with the fast power component of the channel impulse response. However, since the power of the fast component is almost zero (Gaussian white noise), Ξ_H^2 can be given by just the sum of the power of the dynamic channel behavior over time for each channel impulse response.

- λ is a weighting factor given by

$$\lambda = \begin{cases} \frac{2\beta}{\pi e}, & 1 \le \beta \le 3 \\ \frac{e^{\gamma\Omega_x^2/\beta}\beta}{\pi e K^2 \Omega_x^2}, & \beta > 3 \end{cases} \qquad (21)$$

Where K and γ are the solution of the following system of equations

$$\int_{-\frac{\Omega_x^2}{2}}^{\frac{\Omega_x^2}{2}} K e^{-\gamma u^2} du = 1 \qquad (22)$$

$$\int_{-\frac{\Omega_x^2}{2}}^{\frac{\Omega_x^2}{2}} u^2 K e^{-\gamma u^2} du = \frac{\Omega_x^2}{2\beta}$$

Which can be solved numerically.

- $S_\upsilon(\upsilon)$ is the Doppler power spectrum that will be given by equation (17).

IV. NETMAR$_{SYS}$ SIMULATOR

A. Simulator Description

The Networked Marine Systems Simulator (NetMar$_{SyS}$) is a software suite developed at IST/ISR aimed at simulating different types of cooperative missions involving a variable number of heterogeneous marine craft [21]. The high level of detail with which the environment can be modeled allows taking into account both the effect of water currents on the vehicle dynamics as well as the delays and environmental noise affecting underwater communications. The simulation kernel developed so far paves the way for future developments aiming at incorporating more sophisticated acoustic communication models and communication protocols, together with interfaces allowing seamless distributed software and hardware-in-the-loop simulation. The detailed description of the NetMar$_{SyS}$ simulator can be found in [21].

The aim of this paper is to improve the realism of communication between AUVs in this simulator since currently the communication model is oversimplified inasmuch as important acoustic channel characteristics are not considered, such as the speed of sound profile (SSP), the multipath channel and the bathymetric profile. Consequently, this paper proposes the inclusion on NetMar$_{SyS}$ of:

- A realistic propagation model that will include the physical characteristics of the underwater acoustic channel (multipath, ssp and bathymetric profile) and that considers in the channel impulse response the Doppler shift caused by the relative motion of underwater vehicles.
- The channel capacity bounds to be used as a decision criterion for the defining the reliability of exchanged messages between vehicles, and that takes into account the dynamic behavior of the channel through the Doppler power spectrum.

Therefore, considering the position of vehicles over the simulation time, the NetMar$_{SyS}$ channel properties were adapted in order to:

- Invoke the OceanDB software that will obtain bathymetric and SSP between two vehicles for each time instant t of the simulation.
- Create the main input Bellhop file (environmental file) that receives as input parameters:
  - Bathymetric and speed of sound profile from OceanDB;
  - Depths associated to the OceanDB SSP;
  - Vehicle depths;
  - Range between vehicles at each instant of the simulation.
- Invoke the Bellhop acoustic propagation model that will give as outputs the amplitudes and delays to be integrated into the channel impulse response.
- Calculate the bounds of channel capacity that will result in the delivery or failure of messages exchanged between AUVs.

B. Communication model

At the current stage, a simplified model is incorporated in NetMar$_{SyS}$, in which a message is declared to be received at a certain time if a uniformly distributed random variable X is greater in value than a threshold n (see Fig. 5). The value of n is a function of the message length, distance between the vehicles, and their specific positions in the area of operation.

In particular, it is possible to define spatial areas in which communication is affected by a higher noise level.

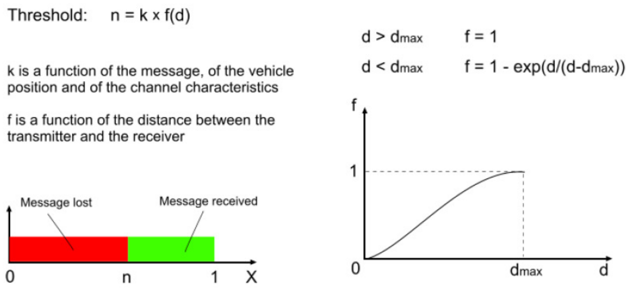

Fig. 5. Communication loss model [21].

In the new version of the $NetMar_{SyS}$ a heuristic metric will be applied based on the error probability inferred from the pessimistic value of the channel capacity (L_{peak}^{DS}) calculated in each instant of simulation and given by equation (23).

$$P_{erro} = exp^{(L_{peak}^{DS}/(L_{peak}^{DS}-C_{th}))} \quad (23)$$

It will be considered that the message is sent with P_{erro} equal to zero whenever the value of L_{peak}^{DS} is greater than or equal to the capacity Threshold value C_{th}. In the cases where the value of L_{peak}^{DS} is lower than C_{th}, successful delivery of the message will occur if, for a given instant of simulation time, a uniformly distributed random variable X is greater in value than P_{erro}. In short,

$$\begin{cases} P_{erro} = 0, & L_{peak}^{DS} \geq C_{th} \\ P_{erro} = exp^{(L_{peak}^{DS}/(L_{peak}^{DS}-C_{th}))}, & L_{peak}^{DS} < C_{th} \end{cases}$$

V. Results

With the aim to analyse the variation of the channel capacity with the variation of the physical characteristics of the underwater medium (namely, different speed sound and bathymetric profiles) two missions were simulated in different areas:

- Sesimbra coast, considered as a region of shallow waters;
- Atlantic Ocean, characterized by a region of deep water.

The simulations were performed considering that the vehicles are positioned at a depth of 10 meters and have a distance between them of 1 kilometer at the beginning of the simulations. The characteristics of the transmission signal used are described in *Table 1*.

Table 1: Characteristics of the transmission signal.

Transmission Power (dB re 1 μPa @ 1 m)	120
Central frequency (kHz)	10
Bandwidth (kHz)	4
Rolloff	0,3

In [21] another simulation is included for the Atlantic Ocean considering that the vehicles are positioned at 20 meters depth. This increase in the depth of the vehicles allowed to analyze if the variation of the position of vehicles in the direction of the lower speed of sound values influences the values obtained for the maximum transmission rate.

Simulation results include values for the ideal channel capacity ((18)) and realistic channel capacity ((19)), where the latter permits to analyse the loss in maximum transmission rate with the inclusion of the stochastic behavior of the channel and the Doppler frequency due to relative motion of the vehicles.
In order to obtain higher error probability rates, the chosen Threshold value C_{th} used in the new decision criterion for the delivery of synchronization messages exchanged between the AUVs, is 70 kbps. In practice, the Threshold value should be set to about 50 kbps.

Hereunder, it will be presented in the Fig. 6 to Fig. 14 the results of the simulations performed in each of the areas referred above.

- Atlantic Ocean
  - GPS coordinates: 39,650222, longitude: -14.704959
  - UTM Zone: 28S
  - Vehicles depths: 10 meters
  - Bathymetry of the ocean: constant and equal to 5378 meters

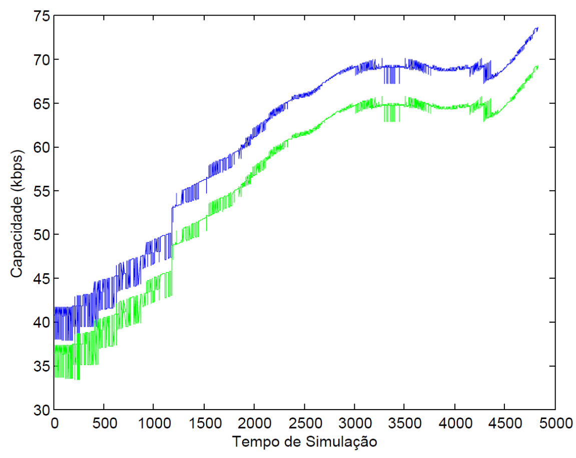

Fig. 6: Values of the coherent channel capacity (in blue) and the lower limit of the channel capacity (in green) at each instant of simulation.

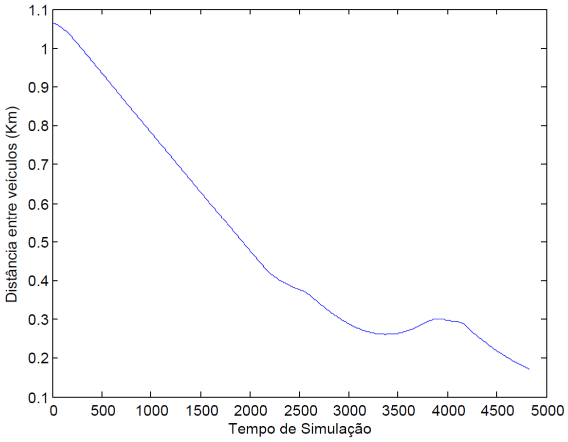

Fig. 7: Distance between the AUVs at each instant of the simulation.

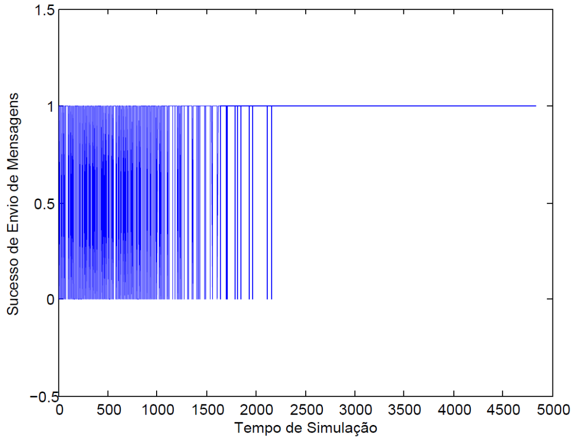

Fig. 8: Messages sent by vehicles at each instant of the simulation - 0 means that the message was not sent and 1 represents the successful delivery. The success rate of transmission obtained is 93.3609%.

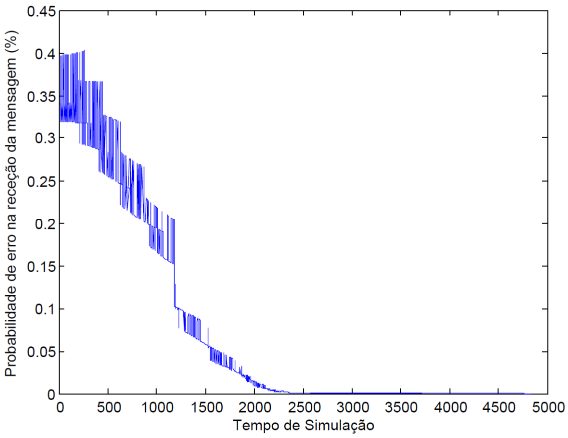

Fig. 9: Probability of error at reception of the message at each instant of the simulation when $L_{peak}^{DS} < C_{th}$.

- Sesimbra coast
  - GPS coordinates: latitude: 38,415938, longitude: -9.124489
  - UTM Zone: 29S
  - Vehicles depths: 10 meters
  - Bathymetry of the ocean: see Fig. 14.

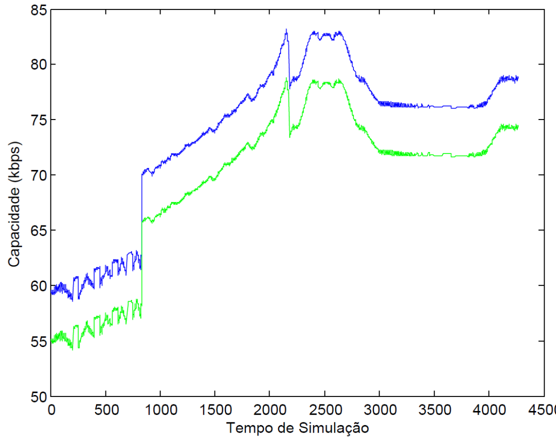

Fig. 10: Values of the coherent channel capacity (in blue) and the lower limit of the channel capacity (in green) at each instant of simulation.

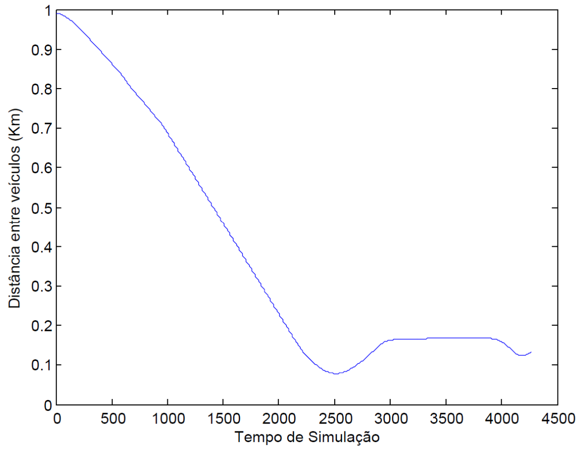

Fig. 11: Distance between the AUVs at each instant of the simulation.

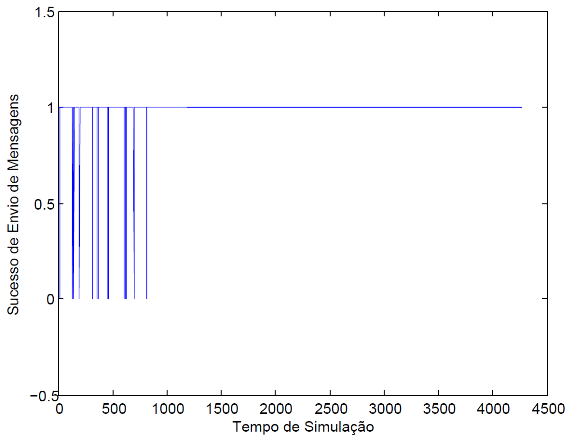

Fig. 12: Messages sent by vehicles at each instant of the simulation - 0 means that the message was not sent and 1 represents the successful delivery. The success rate of transmission obtained is 99.6485%.

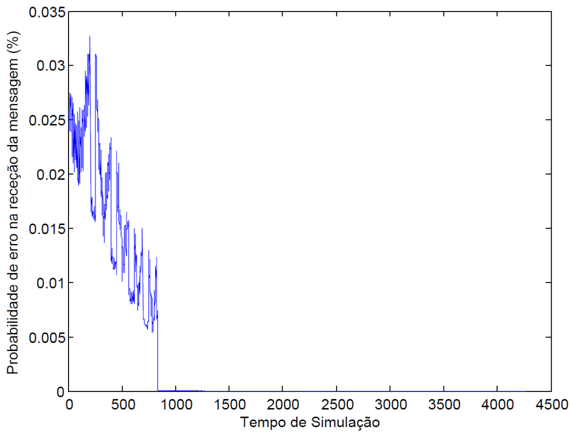

Fig. 13: Probability of error at reception of the message at each instant of the simulation when $L_{peak}^{DS} < C_{th}$.

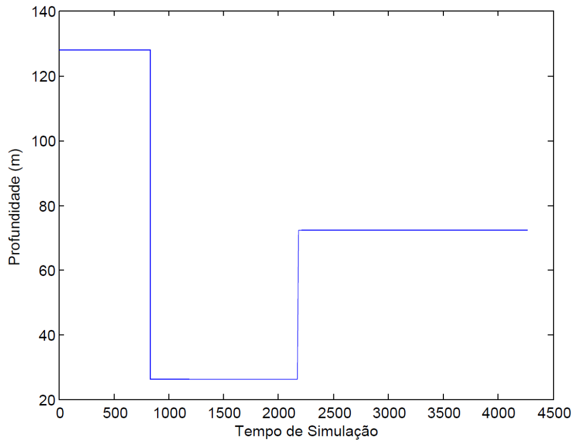

Fig. 14: Bathymetric profile at each instant of the simulation.

From the results, it is possible to conclude that the channel capacity is strongly dependent of the distance between vehicles and the degree of knowledge of the channel. Changing the simulation scenario from deep water to shallow water, at one kilometer distance, the channel capacity increase from 35 kbps to 55kbps, which means an increase of 20 kbps of the maximum transmission rate. It is also possible to verify that the maximum value of the channel capacity is obtained at lower depths (depth of 28 meters in Sesimbra - Fig. 14).

From Fig. 6, Fig. 7 and Fig. 10, Fig. 11 it is possible to verify that the behavior of the maximum transmission rate is inversely proportional to the distance between vehicles in each instant of the simulation.

Fig. 6 and Fig. 10 highlight how the stochastic behavior of the channel yields more realistic channel capacity values. However, the fact that the simulator imposes almost constant speeds of the vehicles along most of the simulation, results in a channel capacity curve that is almost parallel to the curve of the coherent channel capacity since the change in Doppler frequency is practically zero. Therefore, in order to get richer results it is necessary to impose higher variations in the relative speed of the vehicles.

In the simulation results it was verified that the error probability decreases as the maximum transmission rate increases.

Lastly, from Fig. 8 and Fig. 11 successful delivery rates of 93,3609% and 96,9390%, respectively, were calculated. Considering the same scenario of the simulations in the original version of the simulator, the successful delivery rate of the messages decrease to 0,6268% and 1,5775% for the Atlantic Ocean and Sesimbra coast, respectively. From these values it is possible to conclude that the simplistic metrics used in the original version of the simulator penalized the decision of sending synchronization messages between vehicles.

VI. CONCLUSION

This work aimed at improving the realism of communication between autonomous underwater vehicles from NetMar$_{SyS}$ Simulator, since important underwater acoustic channel characteristics are not considered, such as: speed of sound profile, multipath channel and bathymetric profile.

Therefore, the starting point of this work was to get the deterministic channel model using a Bellhop acoustic propagation simulator that takes into account relevant physical characteristics of the underwater acoustic channel.

In order to reflect the stochastic behavior of the underwater channel, the deterministic channel model was combined with an auto-regressive parametric model derived from real data, whose behavior is described by the Doppler Power Spectrum of the channel, that accommodates the frequency Doppler shift caused by the relative motion of the vehicles as well as the dynamic behavior of the channel that occurs over time.

Lastly, from the acoustic propagation model the maximum transmission rate of the channel was obtained, through state-of-the-art results for channel capacity channel capacity that take into account the stochastic channel behavior and the constrained peak power of the input symbols. Lastly, from these channel capacity values new decision criteria for the delivery of synchronization messages exchanged between AUV were derived.

In the simulations performed after the implementation of all the abovementioned considerations, it was verified that the value of the channel capacity is strongly dependent of the:

- Distance between the transmitter and receiver vehicles: the behavior of the maximum transmission rate is inversely proportional to the distance of vehicles in each instant of the simulation;
- Degree of knowledge of the channel, namely, the bathymetry and speed of sound profile of the chosen area for simulations: increasing the ocean depth decreases the maximum transmission rates.

As the maximum transmission rate of the channel is dependent of the distance, thus, the transmission power should be adjusted according to the desired distance used for simulations and entering at the same time into account with the physical characteristics of the channel in the area where the simulations will be performed.

Entering into account with the stochastic behavior of the channel allowed to obtain more realistic channel capacity values, that reflect the losses in the maximum transmission rate caused by the randomness of the underwater acoustic medium.

In the simulations performed it was verified that the error probability at sending messages decreases with the increasing of the maximum transmission rate. This behavior is in agreement with the equation of the error probability ((23)), since with the decrease of the distance between vehicles at each instant of simulation, the value of the capacity channel it will be closer to the chosen capacity Threshold value, making the probability of error tend to zero. As mentioned before, with the decrease of the Threshold value the error probability in sending synchronization messages between vehicles will also decrease. In practice, the Threshold value should be set to about 50 kbps, which indicates that transmission errors will only occur if the value of the maximum transmission rate drops below this value.

Comparatively to the previous version of the simulator, the results obtained from the simulations considering the same scenarios of propagation show that the success rate of sending messages between vehicles improved. This result indicates that the previously simplified model implemented in $\text{NetMar}_{\text{SyS}}$, which only entered into consideration with the length of the message, the maximum distance between vehicles (considered 200 meters) and a random definition of shadow areas in the space defined to perform the simulation, was overly pessimistic. The results obtained in the new version of the simulator shown that it is possibly to send successfully messages at a distance of 1 km between vehicles.

REFERENCES

[1] P. A. Bello, "Characterization of randomly time-variant linear channels," *IEEE Transactions in Communications Systems,* vol. 11, n.º 4, 1963.

[2] Biglieri, E.; Proakis, J. G.; Shamai, S.;, "Fading channels: Information-theoretic and communication aspects," *IEEE Transactions Information Theory,* pp. 2619-2693, 1998.

[3] A. Goldsmith, Wireless Communications, Cambridge University Press, 2005.

[4] Polprasert, C.; Ritcey , J.; Stojanovic, M. ;, "Capacity of OFDM Systems Over Fading Underwater Acoustic Channels," *IEEE Journal of Oceanic Engineering,* pp. 514 - 524, 2011.

[5] Ophir, N. ; Tabrikian , J. ; Messer, H. ;, "Capacity Analysis of Ocean Channels," *Fourth IEEE Workshop on Sensor Array and Multichannel Processing,* pp. 646 - 650, 2006.

[6] H. Leinhos, "Capacity calculations for rapidly fading communications channels," *IEEE Journal of Oceanic Engineering,* pp. 137 - 142, 1996.

[7] A. Radosevic, J. Proakis e M. Stojanovic, "Statistical characterization and capacity of shallow water acoustic channels," *EEE OCEANS 2009 Conference,* pp. 1-8, 2009.

[8] S. Sethuraman, L. Wang, B. Hajek e A. Lapidoth, "Low-SNR Capacity of Noncoherent Fading Channels," *IEEE Transactions on Information Theory,* p. 1555–1574, 2009.

[9] V. Sethuraman e B. Hajek, "Capacity per unit energy of fading channels with a peak constraint," *IEEE Transactions on Information Theory,* 2005.

[10] G. Durisi, U. G. Schuster, H. Bölcskei e S. Sham, "Noncoherent capacity of ununderspread fading channels," *IEEE Transactions on Information Theory,* 2010b.

[11] J. M. Passerieux, X. F. Socheleau e C. Laot, "On the Capacity of the Underwater acoustic Communication Channel under Realistic Assumptions," *Proceedings of the IEEE European Wireless,* pp. 1-6, 2011.

[12] J. Gomes, "Overview of ISR/IST communications signals in CALCOM'10," Institute for Systems and Robotics, Instituto Superior Técnico, Lisbon, Portugal, 2011.

[13] Socheleau, F. X. ; Laot, C. ; Passerieux, J. M. ;, "Stochastic Replay of Non-WSSUS Underwater Acoustic Communication Channels Recorded at Sea," *EEE Transactions on Signal Processing,* vol. 59, p. 4838–4849, 2011.

[14] Huang, Norden E. ;, "The empirical mode decomposition and Hilbert spectrum for nonlinear and non-stationary time series analysis," *Proceedings of the Royal Society of London,* pp. 903-995, 1998.

[15] Rilling, G. ; Flandrin, P. ; Goncalves, P. ; Lilly, J. M. ;, "Bivariate Empirical Mode Decomposition," *IEEE Signal Processing Letters,* pp. 936 - 939, 2007.

[16] H. Akaike, "A new look at the statistical model identification," *IEEE Transactions on Automatic Control ,* p. 716–723, 1974.

[17] P. Ferrão, "Generation of environmental scenarious for simulation of underwater acoustic propagation," Instituto Superior Técnico.

[18] C. Shannon, "A Mathematical Theory of Communication," *The Bell System Technical Journal,* pp. 379–423, 623–656, 1948.

[19] M. Stojanovic, "On the Relationship Between Capacity and Distance in an Underwater Acoustic Communication Channel," *ACM SIGMOBILE Mobile Computing and Communications Review (MC2R),* pp. 64-43, 2007.

[20] F. Vanni, A. Aguiar e A. Pascoal, "Networked Marine Systems Simulator," Instituto Superior Técnico , 2008.

[21] F. Mesquita, "Cooperation among Underwater Autonomous Vehicles with Intermittent Acoustic Communications," Master Thesis, Instututo Superior Técnico, 2014.

[22] E. Biglieri, J. G. Proakis e S. Shamai, "Fading channels : Information-theoretic and communication aspects," *IEEE Transactions Information Theory,* p. 2619–2692, 1998.

[23] F. X. Socheleau, "Communications acoustiques sous-marines sur canal fortement dispersif en temps et en fréquence: point de vue de la théorie de l'information," PhD Thesis, Département Signal et Communications, Université européenne de Bretagne, 2011.