Experimental characterization of the mobile underwater acoustic communication channel in shallow water

Caracterização experimental do canal de comunicação móvel acústico submarino em águas rasas

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ABSTRACT
This paper presents the results for the experimental characterization of the mobile underwater acoustic communication channel in shallow water through the statistics of the fading and the time and frequency dispersion parameters. Starting from measurements performed in Forno Bay, Arraial do Cabo, Rio de Janeiro, Brazil, using three hydrophones in the reception side, two CW signals (3 and 6 kHz) and three sequences of LFM chirps in different bands: 2 to 4 kHz, 5 to 7 kHz and 1 to 8 kHz, the mobile sounding was performed in that channel in order to characterize it as in narrowband as in wideband.

Keywords: acoustic communication, delay spread, doppler spread, propagation in shallow water, underwater communication.

RESUMO
Este artigo apresenta os resultados para a caracterização experimental do canal de comunicação acústica submarino em água rasa através das estatísticas de desvanecimento e parâmetros de dispersão no tempo e na frequência. Partindo de medições realizadas na Baía do Forno, Arraial do Cabo, Rio de Janeiro, Brasil, empregando três hidrofones na recepção, dois sinais CW (3 e 6 kHz) e três sequências de chirps LFM em diferentes faixas: 2 a 4 kHz, 5 a 7 kHz and 1 a 8 kHz, a sondagem móvel foi realizada nesse canal a fim de caracterizá-lo tanto em faixa estreita quanto em faixa larga.

Palavras-chave: comunicação acustica, espalhamento de retardo, espalhamento doppler, propagação em agua rasa, comunicação submarina.
1 INTRODUCTION

The underwater acoustic signal presents applications as in oceanographic researches as in autonomous underwater vehicles (AUV) for controlling and monitoring mainly in the petroleum area. Nowadays, an important application is in the underwater acoustic communication, which can be performed with divers and underwater vehicles. The underwater channel, however, is not a good one for propagating a radiofrequency due to strong attenuation in the salty water.

In spite of the low sound speed and its variation with the depth, besides the time-varying multipath propagation mainly due to the reflections on the water surface and on the bottom, it is possible the propagation with acoustic waves in low frequencies, in the kHz band.

Along the last decade, the study in the underwater communication (UWC) has increased and many articles have been published. These articles deal with channel characterization and modeling [1]-[7], channel simulation [8]-[9] or signal modulation techniques [10]-[12]. Other studies [13] have succeed in establishing UWC with relatively high data rates, higher than 2 kbps. However, this can only be achieved in short distances scenarios, approximately 10 meters. However, they work with simulations or experimental results, but these only account for the movement of tides since the reception system is inherently subject to it because the hydrophones are positioned in different depths by cables that are launched from a vessel without displacement. Measurements are, in general, made in fixed points due to the difficulty of measuring in movement. In this context, this paper contributes with experimental results for the signal statistics and dispersion parameters obtained in an underwater acoustic communication channel in which the reception is made in mobility, approximately 2 knots, permitting to characterize the mobile underwater acoustic communication channel. For this, the receivers (hydrophones) were launched from a vessel on the sea and then, the vessel moved while the projector was practically fixed. Another experimental contribution is in the long distance sounded, exceeding 9 km.

This paper consists of five sections. Section II describes the environment and the specifications of the system used in the measurements; Section III describes the probe signals and Section IV presents the results of the narrowband and wideband channel characterization. Section IV provides the results and Section V, the conclusions.
2 ENVIRONMENT AND SETUP SPECIFICATIONS

Measurements were carried out at Forno Bay, Arraial do Cabo, Rio de Janeiro, Brazil. It was a sunny day and the sea was calm. A cable used at the transmission vessel permitted the acoustic source to be launched at 10 meters below the sea surface, maintained practically fixed by a poita. At the reception, an array of three hydrophones was used, and the elements were placed at 5 m, 10 m and 20 m depth via reception cables launched from another vessel, which moved at 2 knots approximately. Figure 1 illustrates the block diagram of the system used for transmitting and receiving the signals and Table I specifies the devices used.

![Block diagram of the sounding system](image)

Table I: Specifications of the Transmitter-Receiver system.

| Device  | Specification          |
|---------|------------------------|
| TX      |                        |
| Laptop  | Dell Inspiron 15       |
| Amplifier | Crown CDi 2000         |
| Impedance Matching | B11-6001           |
| Projector | Lubell LL 1424 HP     |
| RX      |                        |
| Hydrophone | Reson TC 4032        |
| DAQ     | NI USB-6212 BNC       |
| Laptop  | Dell Inspiron 15       |

In the transmission, the probe signal, generated at Matlab® software, follows to a power amplifier, an impedance matching device, finally reaching the projector, responsible for transmitting the acoustic waves in the sea. The signal propagates through the channel and it is received simultaneously and independently by three hydrophones, being acquired at 50,000 samples per second, which are saved in a file for offline processing.
The horizontal distance between the acoustic source and the reception varied from 4.8 km to 9.4 km, from P1 to P7 points marked on Figure 2, which presents an aerial view of the measurement points. The sounding occurred by moving away the projector. Sea depth at the measured points ranged up to 90 m. In each point, the sounding was started in the channel with mobility, and two CW signals and three sequences of LFM chirps were received in sequence as it is specified in the next Section.

Figure 2: Aerial view of the measured points (P1 to P7).

(Source: Google earth).

3 PROBE SIGNAL DESCRIPTION

Both narrowband and wideband analysis of the underwater acoustics communication channel were intended and for these, two sets of signals were generated in software for transmitting in the channel. For the narrowband transmission, two continuous wave (CW) signals were generated: one in 3 kHz and another in 6 kHz, with 40 seconds of duration each, and 35 seconds of silence between them. With them, it is possible to determine the fading statistics of the signal. For wideband analysis, three LFM chirp signals sequences were used. Each sequence had a specific number of chirps, duration and frequency range, as follows:

1. 24 LFM chirp signals; each signal sweeping from 1 to 8 kHz and duration of 20 ms with 250 ms of silence between each chirp;
2. 100 chirp signals; each signal sweeping from 2 to 4 kHz and duration of 20 ms with 250 ms of silence between each chirp;
3. 100 chirp signals; each signal sweeping from 5 to 7 kHz and duration of 20 ms with 250 ms of silence between each chirp.

With these configurations of the chirps, it is possible to estimate important channel parameters, such as delay spread, Doppler spread, coherence time and coherence bandwidth, starting from the power delays profiles (PDPs) obtained from the data processing [14]. The silence interval used was sufficient for accommodating the delays of the received multipath as it is seen in the channel impulse response related to the P2 point and depicted in Figure 3, for a 1-8 kHz LFM chirp. No delays obtained overcame 250 ms, therefore the silence time used was appropriate.

![Figure 3: Example of a measured impulse response at P2.](image)

4 CHANNEL CHARACTERIZATION AND RESULTS

4.1 NARROWBAND CHARACTERIZATION

At each measured point (P1 - P7), the received samples of the demodulated envelope were filtered by a moving average filter [15] in order to obtain the small scale fading besides smoothing the noise. With this fading signal it is possible to find a statistic behavior that best describes its variations. For this experiment, four kinds of distribution were considered: Gauss, Rice, Rayleigh and Nakagami-m [14], defined as:

1. Gauss:

   \[ p(r) = \frac{1}{\sigma_r \sqrt{2\pi}} \exp\left(-\frac{r^2}{2\sigma_r^2}\right) \]  

   (1)
2. Rayleigh:

\[ p(r) = \frac{r}{2\pi\sigma_r^2} \exp\left(-\frac{r^2}{2\sigma_r^2}\right), r > 0 \]  

(2)

3. Rice

\[ p(r) = \frac{r}{\sigma_r^2} \exp\left(-\frac{r^2+a^2}{2\sigma_r^2}\right) I_0\left(\frac{ar}{\sigma_r^2}\right) \]  

(3)

or

\[ p(r) = \frac{2r 10^{10}}{a^2} \exp\left(-\frac{K}{a^2}\right) I_0\left(\frac{2r 10^{10}}{a}\right) \]  

(4)

4. Nakagami-m:

\[ p(r, m, \Omega) = \frac{2}{\Gamma(m)} \left(\frac{m}{\Omega}\right)^m r^{2m-1} e^{-mr^2/\Omega} \]  

(5)

where \( r \) is the envelope of the signal \((r \geq 0)\), \( \sigma_r \) is the standard deviation of the distribution, \( a \) is the amplitude of the direct ray, \( I_0 \) is the modified Bessel function of the first kind and zero order, \( K = a^2/2\sigma^2 \) is the relation of the direct path power \((= a^2)\) and that in the multipath components is equal to \( 2\sigma^2 \), \( \Omega = E[r^2] \), \( \Gamma(m) = \int_0^\infty x^{m-1} e^{-x} \, dx \)

and \( m = \frac{\sigma^2}{E[(r^2-\Omega)^2]} (m \geq 1/2) \).

The best probability density function (pdf) fitted to the data was determined with the minimum mean square error criteria. As conclusion, from the received 3 kHz CW signals, 70% showed the best fitting to the Nakagami-m pdf. The same pattern appears for the 6 kHz CW signals, in which Nakagami-m pdf was the best fit for 63% of valid signal receptions.

It is worth to say that in measurements close to the coast, such as the ones used in [1], the \( m \) parameter of Nakagami pdf was widely variable, ranging from 0.5 to 4.2. The set of measurements treated in the present study, however, were made farther from the coast. Consequently, the \( m \) parameter is much more behaved, ranging from 0.5 to 1.4, meaning that the fading varies around the Rayleigh distribution, since \( 0.5 < m < 1 \) is a channel worse than Rayleigh, \( m = 1 \) is equivalent to a Rayleigh channel and \( m > 1 \) is better than one, therefore, approaching a Rice channel. For \( m >> 1 \), Nakagami tends towards Gauss [14]. This result is quite reasonable, since the region near the coast has greater influence of multipath signals coming from the bottom and the water surface,
besides the coast noise in general. In Figure 4 is an example of fitting for the amplitudes of the received signal in the measured point named P2, at 10 m hydrophone depth, and Nakagami and Rice p.d.f.’s provide good fitting to the data.

Figure 4: PDFs adjusted to the variability signal.

Two significant narrowband parameters are $NR$, the level crossing rate (LCR) and $TR$, the average fade duration (AFD). LCR is defined as the mean number of crossings per second in which the envelope ($r$) of the received signal exceeds a pre-established threshold ($R$), normally chosen as the effective ($r_{rms}$) one, and AFD is the mean duration of fade [14]. Starting from those definitions, their expressions vary depending on the behavior of the channel statistics.

After some development, these LCR and AFD parameters can be calculated for each kind of channel [16] and they are written below:

1. Rayleigh channel:

\[ N_R = \sqrt{2\pi} f_m \rho e^{-\rho^2} \]  \hspace{1cm} (6)

\[ T_R = (e^{\rho^2} - 1)/(\sqrt{2\pi} f_m \rho) \]  \hspace{1cm} (7)

with the following definitions: $\rho = r/r_{rms}$, $r_{rms} = \sqrt{2}\sigma$ and $f_m$ is the maximum Doppler shift (displacement speed/wavelength).
2. Rice channel:

\[ N_r = \sqrt{2\pi(K+1)}f_m \rho e^{-K-(K+1)\rho^2} I_0 \left[ 2\rho \sqrt{K(K+1)} \right] \]  

(8)

\[ T_R = \frac{1 - Q[\sqrt{2K}, \sqrt{2(K+1)\rho^2}]}{\sqrt{2\pi(K+1)}f_m \rho e^{-K-(K+1)\rho^2} I_0 \left[ 2\rho \sqrt{K(K+1)} \right]} \]  

(9)

with \( \sigma_{rms} = \sqrt{\Omega} \) and \( Q \) is the Marcum function [17].

3. Nakagami channel:

\[ N_R = \sqrt{2\pi f_m} \frac{\Gamma(m-\frac{1}{2})}{\Gamma(m)} \rho^{2m-1} e^{-\rho^2} \]  

(10)

\[ T_R = \frac{\Gamma(m, m\rho^2)}{\sqrt{2\pi f_m \rho^{m-\frac{1}{2}}}} \rho^{2m-1} e^{-\rho^2} \]  

(11)

Starting from (6) until (11) and the experimental data, Figure 5 provides the number of crossings versus \( \rho \) calculated for different kind of channels and for the data of the same sector used in Figure 4. The data point to a signal variability in the -20 to 8 dB range approximately, relatively to the effective (RMS) value of the envelope, whereas Figure 6 provides the fade length in wavelengths, \( TR*fm \), which varies from 0.004 to 0.5, in the same range of \( \rho \). Therefore, Nakagami and Rice show good adjustment to the data for the LCR, but Rice shows better for the AFD parameter, in the same range of \( \rho \).
4.2 WIDEBAND CHARACTERIZATION

The received samples of the LFM chirp signals were saved for offline processing. Supposing that \( s(t) \) corresponds to the signal transmitted through a channel and that \( s'(t, \tau) \) refers to the signal that arrives at the reception as a sum of \( N \) multipath of the transmitted signal, whose amplitudes are represented as \( a_i \), delays as \( \tau_i \) and phases as \( \varphi_i \):

\[
s'(t, \tau) = \sum_{i=1}^{N} C_i s(t - \tau_i, \tau)
\] (12)

in which \( C_i = a_i e^{j\varphi_i} \) in (12).

If the received signal is the input of a matched filter, defined as:

\[
h_{FC}(t, \tau) = s(-t, \tau)
\] (13)

therefore, the signal after the matched filter is:

\[
y(t, \tau) = s'(t, \tau) \ast h_{FC}(t, \tau)
\] (14)

Convolving (13) and (14), results for the signal after the matched filter:

\[
y(t, \tau) = \sum_{i=1}^{N} C_i \int_{-\infty}^{\infty} s(\xi - \tau_i, \tau) s(-t + \xi, \tau) d\xi
\] (1)

\[
y(t, \tau) = \sum_{i=1}^{N} C_i R_s(t - \tau_i, \tau)
\] (2)
If \( s(t, \tau) = \delta(t, \tau) \), is an impulsive input, (12) is written by:

\[
s'(t, \tau) = \sum_{i=1}^{N} C_i \delta(t - \tau_i, \tau) \tag{3}
\]

and the output of the channel to the impulsive response is the transfer function of the channel, i.e.:

\[
h(t, \tau) = \sum_{i=1}^{N} C_i \delta(t - \tau_i, \tau) \tag{18}
\]

For impulsive input, \( R_s(t - \tau_i, \tau) = \delta(t - \tau_i, \tau) \) and if it is applied to (16), it results after the matched filter:

\[
y(t, \tau) = \sum_{i=1}^{N} C_i \delta(t - \tau_i, \tau) \tag{19}
\]

Comparing (18) and (19), we conclude that the output of the matched filter in (19) corresponds to the transfer function of the channel in (18) when an impulsive input is used. In short, with a transmitted signal as similar as an impulse it will be possible to achieve the transfer function of a channel, if the received signal passes through a matched filter. Therefore, the absolute value of the power delay profiles (PDPs) for the sounded channel [14] can be calculated as:

\[
P_h(t, \tau) = |h(t, \tau)|^2 \tag{20}
\]

and \( P_h(t, \tau) \) represents the complex power of all multipath arriving at the receiver in the different delays (\( \tau \)) at each time instant (\( t \)).

In light of the explained, via software, the acquired data were filtered by a matched filter in order to obtain the channel impulse response, \( h(t, \tau) \), in delay domain (\( \tau \)), related to each time instant (\( t \)) and so, the PDPs could be calculated.

If the channel can be considered WSSUS (Wide Sense Stationary with Uncorrelated Scattering) [14], the correlation function of the channel, \( P_h(t, \tau) \), can be obtained in other domains simply by Fourier Transform, as depicted in Figure 7. They are: time-frequency (\( t-f \)), Doppler-frequency (\( \mu-f \)) and Doppler-delay (\( \mu-\tau \)). Thus, in
WSSUS channel, the channel function can also be written by: \( T(t,f), S(\mu, \tau) \) or \( H(\mu,f) \) related, respectively, to \( R_T(t,f), P_S(\mu,\tau) \) and \( P_H(\mu,f) \).

Figure 7: Relation between the correlation functions of the WSSUS channels.

By a Fourier transform in time domain and after, in delay domain, the Doppler profiles, \( P_H(\square,f) \), were obtained. Such functions represent the same channel in different domains when it is considered WSSUS. This is true only in small time intervals since the channel presents great variability due to the multipath and the mobility. Then, in these intervals the channel can be said quasi-stationary or slowly time variant, therefore, it is possible to take a unique profile representative of each interval. For the measurements treated in this paper this condition occurred in each measured point showed in Figure 2 (P1 to P7).

From any of the functions in Figure 7, which represent the same channel, dispersion parameters can be calculated and they are: time and frequency parameters. The first are associated to the time dispersion and the frequency selectivity in the wideband signals. The second are related to Doppler scattering mainly due to the mobility of the receiver. In their discrete expressions, the parameters are defined as [14]:

**Mean Delay** \((\bar{\tau})\): Average time of occurrence between replicas of multipath that arrive at the receiver, leaving from the transmitter at the same instant of time:

\[
\bar{\tau} = \frac{\sum_{i=1}^{N-1} \tau_i P_h(\tau_i)}{\sum_{i=0}^{N-1} P_h(\tau_i)}
\]  

where \( N \) is the number of valid multipath in the power delay profile \( P_h(\tau) \) for each time instant \( t \), occurring in the delays of the multipath \( \tau_i \).

**Delay spread** \((\sigma_T)\): Represents the standard deviation of the p.d.f. that characterizes the arrival time of the multipath that arrive at the receiver, coming from the
impulse at $t = 0$. Its estimation is important, since the duration of each symbol must be much longer than the delay spread, in order to prevent intersymbol interference when no equalizers are used.

$$\sigma_T = \sqrt{\frac{\sum_{i=1}^{N-1} (\tau_i - \tau)\tau_i^2 P_h(\tau_i)}{\sum_{i=0}^{N-1} P_h(\tau_i)}}$$  \hspace{1cm} (22)

**Coherence band** ($B_c$): Frequency band in which the correlation between the amplitudes of the spectral components is greater than 90% or considering a less rigid definition, greater than 50%. Since the time scattering of the channel is responsible for the variation in the amplitude of the spectral components of the transmitted signal, the channel coherence band has an inverse relationship with the delay spread. Rappaport [18] have established (23) and (24) for a measured outdoor channel, respectively for 90% and 50% correlation:

$$B_c = \frac{1}{50\sigma_t}$$  \hspace{1cm} (23)

$$B_c = \frac{1}{5\sigma_t}$$  \hspace{1cm} (24)

Although they are often used to calculate the relationship between the coherence band and the delay spread, it does not fit for many environments.

The coherence band is determined from the function $R_T(t_i; t)$, which represents the correlation of the signal in the frequency, over time, and it can be determined from the function of the channel $T(t, f_i)$. This function is the DFFT of $h(t, \tau_i)$ along the delay variable. Shenoi [19] defines the correlation of periodic or non-periodic deterministic functions as (25), as well as, an estimate for non-deterministic signals.

$$[R_T(\Omega)]_p = \sum_{n=1}^{N-P} [T]_n [T]_{n+p}^*$$  \hspace{1cm} (25)

where $[T]_n$ is the vector containing the samples of the function of $T(t,f_i)$, $N$ is the number of discrete samples used in the probing and $p$ is the position index of the correlation vector, ranging from 0 to $N-1$ and representing the spacing between consecutive discrete frequencies ($\Delta f$) of $T(t,f_i)$ function. When $f = 0$ and $p = 0$, the
correlation is maximum and it decreases as the spacing between frequencies increases, in other words, as $p$ increases.

Mean Doppler Shift ($d_D$):

$$d_D = \frac{\sum_{i=1}^{M-1} \mu_i P_H(\mu_i)}{\sum_{i=0}^{M-1} P_H(\mu_i)}$$  \hspace{1cm} (26)$$

In (26), $P_H(\mu)$ is the Doppler profile for some frequency $f$ and it is calculated by the DFFT of $R_T$ in the time domain.

Doppler spread ($\sigma_D$): the standard deviation of the Doppler shift’s pdf, meaning the spectral spread of the rate of variation of the mobile channel, in time domain.

$$\sigma_D = \sqrt{\frac{\sum_{i=1}^{M-1} (\mu_i - d_D)^2 P_H(\mu_i)}{\sum_{i=0}^{M-1} P_H(\mu_i)}}$$  \hspace{1cm} (27)$$

Coherence time ($T_c$): Time interval in which the correlation between the amplitudes of the temporal components is greater than 90% or considering a less rigid definition, greater than 50%. Since the Doppler scattering of the channel is responsible for the variation in the amplitudes of the temporal components of the transmitted signal, the channel coherence time has an inverse relationship with the Doppler spread.

The LFM chirp signals with wider band, i.e., 1 to 8 kHz, were used to determine time dispersion parameters of the sounded channel, such as average delay, delay spread and coherence band [20]. These signals have a better multipath resolution in time domain, equal to 0.14 ms ($1/BW = 1/(7 \text{ kHz})$), providing greater precision for these parameters. Moreover, the silence time of 250 ms was sufficient to accommodate the multipath, therefore, it avoids aliasing in delay. On the other hand, for the frequency dispersion parameters, such as average Doppler, Doppler spread and coherence time, they were determined through the LFM chirp signals with shorter frequency band, 2 to 4 kHz, with a Doppler resolution of 0.037 Hz ($1/[T. \text{ (M-1)}] = 1/[270\text{ ms} \cdot 99 \text{ chirps}]$) and Doppler in the (-1.85,+1.85) Hz band. This guarantees more correct results for the frequency dispersion parameters since the sounding used could only provide Doppler calculated from: $v/\lambda$, where $v$ is the speed of the receiver and $c$ is the mean sound speed in the UWC. For $v \approx 2$ knots, used in the experiments, $c \approx 1500 \text{ m/s}$ and $f = 4 \text{ kHz}$, the limits of Doppler
are ± 1.37 Hz. The other band, 5-7 kHz, would produce Doppler beyond that band, therefore, wrong results would result.

Tables II and III provide the ranges in which vary each dispersion parameter calculated, related to the sequence of LFM chirps specified in section III. The average Doppler is predominantly negative, although it can be positive for some frequencies due to the larger Doppler spread. This means that the multipath generally came from behind while the vessel with the hydrophones moved ahead.

It is important to say that the Doppler shift can cause interference mainly in subcarriers of an OFDM transmission. This subject is treated in [21], taking account frequency, time, and spatial diversity.

| Depth (m) | Average Delay (ms) | Delay Spread (ms) | Coherence Band (Hz) |
|-----------|---------------------|-------------------|---------------------|
| 5         | 82.29 to 99.58      | 64.10 to 80.77    | 12.76 to 17.30      |
| 10        | 74.73 to 101.66     | 60.68 to 87.93    | 9.17 to 13.14       |
| 20        | 69.10 to 91.87      | 65.89 to 78.10    | 10.11 to 15.40      |

| Depth (m) | Average Doppler (Hz) | Doppler Spread (Hz) | Coherence Time (s) |
|-----------|----------------------|---------------------|--------------------|
| 5         | -0.182 to -0.229     | 1.533 to 1.609      | 2.524 to 2.558     |
| 10        | -0.176 to -0.228     | 1.520 to 1.650      | 2.510 to 2.525     |
| 20        | -0.182 to -0.204     | 1.556 to 1.604      | 2.519 to 2.564     |

In Table II, the mean delay and delay spread values confirm that the silence time was sufficient for accommodating multipath along the profile since the duration of the profile was taken as 270 ms. The coherence bandwidth points to low transmission rate if none technique is used for improving it such as equalization [21].

In Table III the average Doppler shows more concentration in smalls values of frequency and the standard deviation is approximately 1.5 Hz. The sounding in three depths was used for observing if spatial diversity would permit good signal amplitudes to be used in a diversity scheme as represented in [21] with OFDM transmission in the same experiment here used in the underwater acoustic communication channel.

Finalizing, the variability statistics of the wideband signal was also verified. For this, the PDPs samples were taken along the time, for each delay, and the fitting of pdf’s was performed and Figure 8 depicts the pdf fitted to the data.
Figure 8: PDF's adjusted to the variability of wideband data.

Again, Nakagami distribution could be fitted to the data, with the factor $m$ increasing from 0.734 to 0.875, respectively for the hydrophone depth decreasing from 40 m to 10 m. Rice and normal distribution also fitted well, and all of them had the log likelyhood practically equal to 61.5. The sounded channel, therefore, behaved as a Nagakami one.

**5 CONCLUSION**

Through measurements in shallow water with mobile reception, the narrowband statistics of the channel shows that the Nakagami distribution presents the best fit for the received signal, with the $m$ parameter varying from 0.5 to 1.4, meaning that it approaches a Rayleigh pdf, typical of a channel with several multipath, but none of them with a strong value. By analyzing the level crossing rate and the average fade duration, it concludes that the received signal has high variability around the effective value, from -20 to 8 dB and Nakagami and Rice fit well to the signal envelope ($r$).

With results of the wideband probing, it is possible to confirm that the average delay and delay spread have close ranges at all depths, with mean values around 90 ms and 75 ms, respectively. For the coherence band, it did not overcome 18 Hz, meaning that techniques must be used in order to improve the transmission rate in this kind of channel.

It was also verified the wideband signal variability. For this, in each delay the signal amplitudes were taken along the time and pdf.'s were fitted to them. Again, Nakagami has confirmed the best fitting. Then, it can be said that the channel behaved like Nakagami one as in narrowband as in wideband.
As aforementioned, the measurements occurred under favorable weather conditions. Meteorological phenomena, as strong wind or heavy rain, will impact the dispersion parameters, especially at 5 meters depth, where the waves and the occurrence of bubbles are stronger. In a general way, without use of appropriate modulation, equalization, diversity and/or bit correction techniques, the probed underwater acoustic channel allows low data transmission rates, no higher than 20 bps (coherence band < 20 Hz).

On the continuity, the simulation of the channel will be studied. A paper dealing with the analysis of modulation techniques allied to spatial, frequency and time diversity, emphasizing the OFDM, in the same sounded channel was already published [21]. The measurements were carried out in the same experiment, but with another probe signals. The hydrophones used in different depth (5, 10 and 20 m) permit to combine the received signals in a spatial diversity. Besides this, the sounding was carried out in two different bands of frequency promoting frequency diversity. Attention was given to the Doppler shifts, obtained in this paper in order to adequately space the subcarriers, and to the delay spread in order to prevent interference between OFDM symbols.
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