Communications and Biological Monitoring Experiment in an Upwelling Environment at Cabo Frio Island Bay

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***Abstract*—This work presents the results of an experiment aiming at acoustically characterizing, in a long term, the biological activity and its correlation with the upwelling regime in Cabo Frio Island Bay, and other biotic and abiotic factors. Moreover, to develop a signaling scheme using local bioacoustics characteristics for covert communications and to understand the impact of noise and ocean stratification on broadband communications. Previous long-term soundscape monitoring has identified marine life noise temporal patterns correlated to ocean temperature stratification and to light intensity. This work also shows results obtained with a vector sensor, in an attempt to characterize particle motion due to noise sources in terms of amplitude and directional spectrum, and presents developed communication codes performance, in terms of Bit Error Rate versus Signal to Noise Ratio or Eb/N0.**

Keywords—Underwater Communications, Biological monitoring, Upwelling

I. Introduction

There is a growing interest in underwater soundscape monitoring to comprehend temporal pattern of biological noises and to understand the influence of ocean physical parameters over communications and marine life that has motivated a number of research efforts in the field. Coastal upwelling processes nearby Cabo Frio region in Southeast Brazilian coast influence ocean temperature stratification, sound wave propagation and biological activity [1,2]. Therefore, the joint project “BioCommunications (BIOCOM´19)” between Brazilian Navy Institute of Sea Studies and the University of Algarve-Portugal aims to acoustically characterize, in a long term, the biological activity and its correlation with the upwelling regime and other biotic and abiotic factors. The relationship among abiotic factors and bio-acoustic signature can contribute to a better understanding of rocky shore organisms behavior and to future development of biotechnological applications. Another objective is the development of a signalling scheme, with local bioacoustics noise characteristics, for covert underwater communications. Disguising the signal in the noisy background can reduce the probability of detection by any unfriendly receiver [3].

A long-term monitoring system was installed in the bay of Cabo Frio Island in February 2018 and has been continuously recording biological and human made noise activity, for over one year. Moreover, a shallow water experiment occurred in January 2019, focused on both particle motion using vector sensors and underwater communications. A vector sensor installed in the field estimated the noise field directionality as well as measured noise power levels. Four different signalling codes with specific goals were transmitted across the bay over a propagation path of approximately 1.6 km. Code 1 presents an experimental method for covert communications. Code 3 is related to receiver training and identification of acoustic signals in multiple conditions based on statistics of environmental noise. Codes 2 and 4 aim to check their robustness in this challenging environment. The transmission system was adjusted to change source power level in time, thus allowing to vary the Signal to Noise Ratio (SNR) during the experiment. To check upwelling occurrence, several temperature profiles were taken along the propagation path. Signals attenuation, long channel delay spread due to severe multipath and high noise levels due to recreational vessels traffic are expected to make signal decoding a challenging task.

II. The Biocom´19 Experiment

A. Environmental Description and Setup

BIOCOM’19 experiment took place at a shallow water research site, in Cabo Frio Island Bay, during Jan14-18,2019. Biological soundscape monitoring has been performed continuously over a year, allowing sea trials to focus on simultaneous oceanographic and acoustic characterization. To capture biological noise, a four-hydrophone array, disposed in a pyramidal shape, was placed close to the rocky shore, in an almost flat bottom location. During the experiment, another four-hydrophone linear array was disposed spanning 4.5 m of an 8m water column and a vector sensor were placed approximately 1m above the bottom, both located just a few meters on each side of the pyramid, as shown in the diagram of Fig.1. The recording system was configured with sampling frequency of 52734Hz, a quantization of 24 bits, where each hydrophone has a sensitivity of -174.9 dB re 1V/1microPa and a frequency response between 0.1 and 40 kHz. For communication purposes, an omnidirectional acoustic source, ITC 1001, was located approximately 1.6 km from the receivers, as shown in Fig.2. The source was placed in the middle of the 4m deep water column, hardwired to the transmission system on shore (Fig.1). The bathymetry changes strongly along propagation path. Most part of the path has an almost flat 5m deep bottom. However, in its deepest part, the propagation path crosses the entrance of the bay. Pointing to Southwest/South, the entrance connects the bay to the region off the Cabo Frio Island where upwelling occurs.

In the experiment, several sound speed profiles (SSP) and temperature were collected along track (Fig.2), variably spaced between acoustic source and receivers, reaching depths in the interval 4-20m, during daylight. Such measurements allowed observations of short-term drastic temperature changes of about 10 degrees Celsius in a few hours (Fig.3), possibly due to the upwelling regime occurring off the southern side of the bay rocky shore, and the cold water sipping through the narrow entrance (see Fig.2).

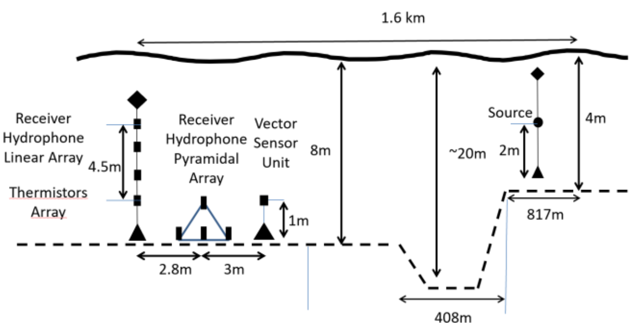

Fig. 1. Diagram of the BioCom'19 experimental setup (not to scale)

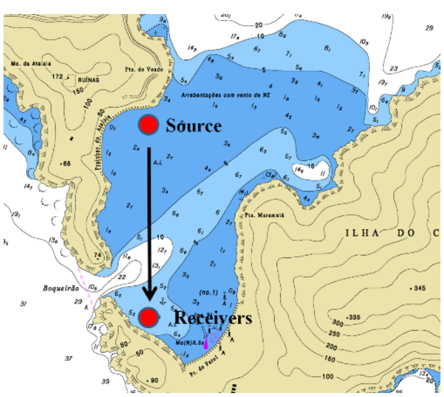

Fig. 2. Position of source, receivers and propagation line across the bay of Cabo Frio Island during the BioCom'19 experiment.

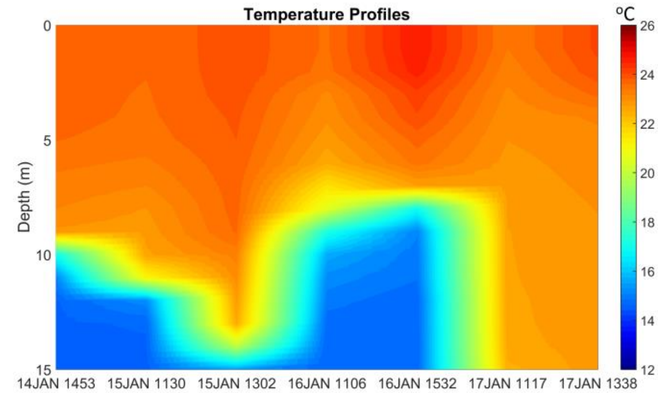

Fig. 3. Temperature profiles collected at the entrance of the bay

B. Communication Signals Setup

Different communication signalling schemes were transmitted in this upwelling environment for specific purposes (Table I). The data block is composed of four codes and several guard time periods with a total duration of 4min20s (Table II). The data block was transmitted once every 5 minutes during the experiment (Fig.4), but with different source power level (SL). The transmission and recording systems were synchronized at minute 45. Therefore, from minute 45 to minute 10 of next hour, the blocks were transmitted with constant SL, to check codes consistency. Next, from minute 15 to 40, the SL was reduced in 1dB after each transmission, to reduce the Signal to Noise Ratio (SNR) and allow some performance analysis.

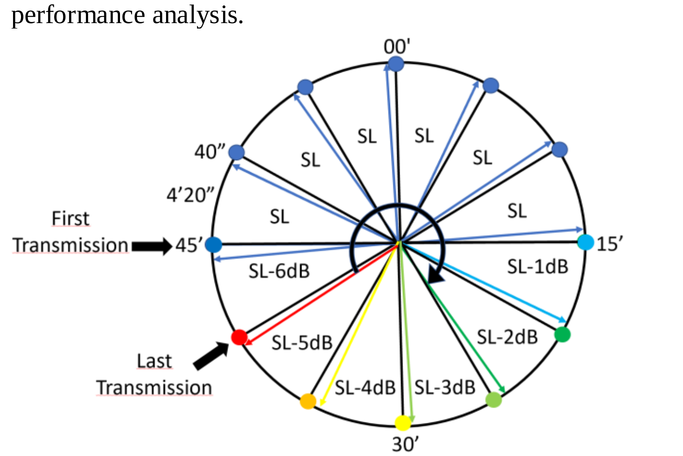

Fig. 4. One-hour diagram of different SL transmissions, once every 5 minutes, during the experiment. First transmission at minute 45 with SL. Last transmission at minute 40 with SL-6dB. Total duration of data block: 4min20s

TABLE I. TRANSMITTED CODES

c	*Modulation*	*Bandwidth (kHz)*
Code 1	BPSK	5-10
Code 2	8-CHSK	4.5-12.2
Code 3	LFM/CW	2-12
Code 4	8-FSK	5-10

BPSK: Binary Phase Shift Keying, CHSK: Chirp Shift Keying, LFM: Linear Frequency Modulation, CW: Continuous Wave, FSK: Frequency Shift Keying

TABLE II. DATA BLOCK

Total duration: 4min20s								
G	C1	G	C2	G	C3	G	C4	G
5 s	60 s	5 s	60 s	5 s	60 s	5 s	20 s	40 s

G: Guard time, C: Code

C. PRELIMINARY RESULTS

B. *Biological Acoustic Monitoring*

Long term acoustic monitoring aiming at characterizing the marine soundscape, its daily pattern and its possible relation with abiotic factors was carried out during the past year. Acoustic data analysis was performed in one hydrophone positioned in the pyramid top, for a period of 82 days, from February 8 to April 30, 2018. The signals were filtered in the band of 1.5-8 kHz, which presents the greater biophony and less anthropogenic noise. Water temperature data were collected with a data logger and acoustic data were analyzed together with environmental data (tide, rain, wind). Upwelling in the region, especially during the spring and summer seasons, brings rich and colder waters to the surface. These conditions motivate the development of a large diversity of marine organisms which contribute to the underwater soundscape. Fig. 5 shows the biological noise power, averaged for 82 days. The noise presents a temporal daily pattern, increasing during night and decreasing in diurnal periods, with peaks in the twilight. This temporal pattern is probably related to the biological activity of the marine invertebrates located in the rocky shore near the hydrophone, a fact already reported by several authors [4]. Furthermore, there is an influence of the upwelling over biological noises. The average noise power is also modulated by water temperature and light intensity. Therefore, noise decreases during upwelling events (lower temperatures) and increases during cloudy periods.

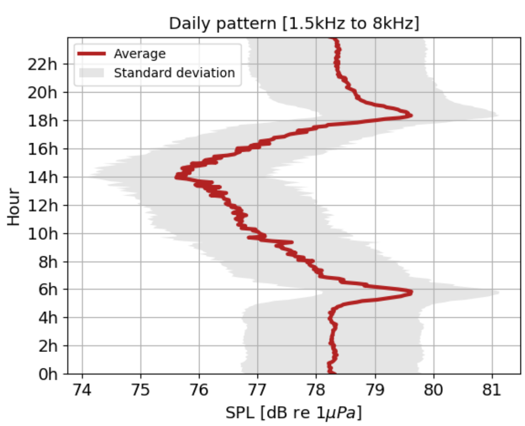

Fig. 5. In red, the biological noise power, averaged for 82 days (local time), in frequency band 1.5-8 kHz. In gray, the standard deviation of the averaged noise.

During the BioCom'19 experiment, a Dual Accelerometer Vector Sensor - version 1 (DAVS1), developed at the University of Algarve, was used for the characterization of bioacoustics activity in terms of particle motion. As DAVS1 is a directional device, its orientation during deployment is important for direction calibration purposes. Vertically installed on a tripod, around 3m from pyramidal hydrophone array (Fig. 1), along a line parallel to the shore rock, DAVS1 axes orientation was setup so that axis z pointed to the rocky shore and axis y pointed at 90 degrees along rocky shore direction (Fig.6-Left). Composed by two tri-axial accelerometers and one hydrophone, the system records both the acoustic pressure and particle accelerations along the three perpendicular axes. The accelerometer #50 was turned to the rocky shore while the #49 pointed to the open bay, in opposite direction (Fig.6-Right). For the time being DAVS1 data analysis were performed over the periods of noise only, after code C4 (see Table II). The LFM sweeps of code C2, below 5 kHz, were used to for synchronizing the noise periods in which both biological noise levels and direction of arrival were estimated. By summing the received noise power for each detected 35 s noise period over each recording day, in the band above 1.5 kHz, one gets the plots shown in Fig.7 for days 14-15Jan. In accordance to data in Fig. 5, preliminary analysis shows a biological signature with noise power peaks timely located before or at sun rise and at or just after sun set. These peaks can also be seen in the particle velocity channels with decreasing clarity from Vz, Vy and Vx. In these plots Vx, Vy and Vz are shown in pressure equivalent units by multiplying each particle velocity component by the acoustic impedance ρc. The levels measured on the z component (pointing to the rocky shore) and on accelerometer #50 are clearly much higher than those obtained for #49, while for the other components the inverse is true. Particle velocity levels are higher than equivalent sound pressure, which characterizes the particle motion field in a rock shore community noise dominated area.

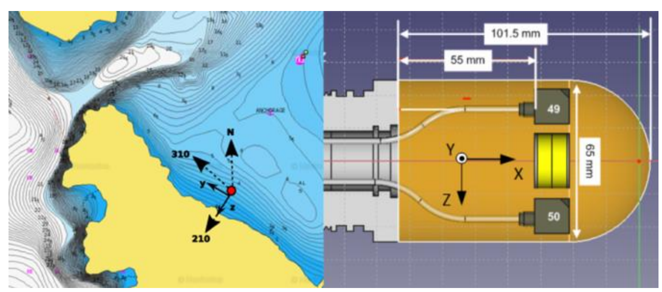

Fig. 6. DAVS1 location and horizontal plane orientation (left) and schematic of internal accelerometer and hydrophone position with axes definition (right).

To extract directional information during the noise only periods, particle velocity pressure like directional components are combined into a single pressure equivalent field in a particular direction. The combination of acoustic pressure P and particle velocity V_p gives a quantity $\widetilde{P}(\omega)$, in the frequency domain, such as (1):

$$\widetilde{P}(\omega, \varphi)= P(\omega)+V_{pz}\sin(\varphi)+ V_{py}\cos(\varphi) \qquad (1)$$

where the steering angle φ is measured relative to axis y in the z-y plane. In Fig. 8, one can observe the estimated directivity using superimposed Vy-Vz channels for forming an angle φ in the horizontal plane, from noise periods for Jan 16-17, for accelerometer #49. Fig.8 shows two-time synchronized plots: on the left is the estimated angle φ, and on the right is the sound pressure level (SPL) in dB identical as those of Fig. 7, but for days 16-17, January. The estimated angle is more or less chaotic throughout the day taking an average value between 50 and 90 degrees, which is into the rock shore direction. During the day 17 January there are strong and possibly close by interferences that deviate the estimated angle.

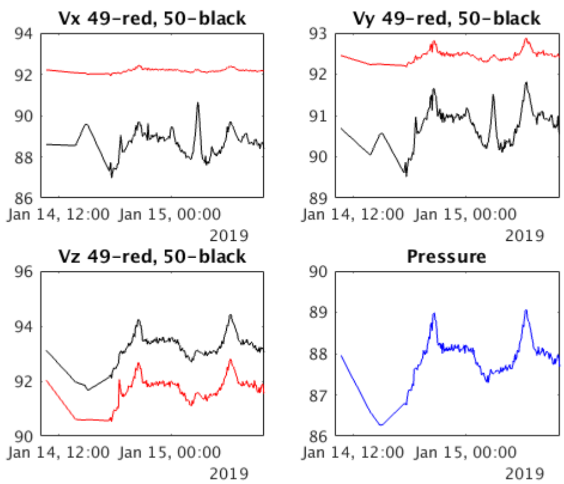

Fig. 7. Received power above 1.5 kHz on the DAVS channels for day January 14-15, 2019

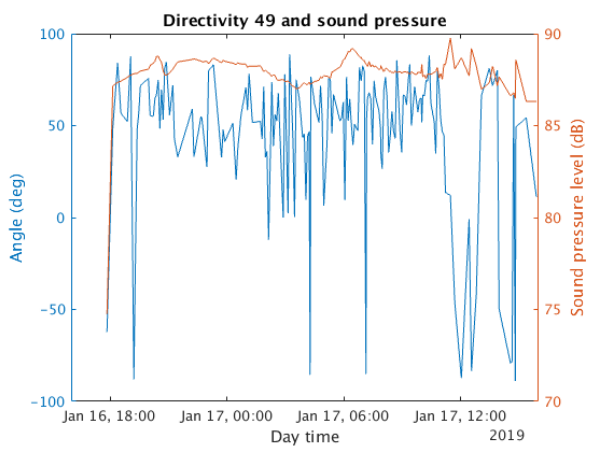

Fig. 8. Estimated directivity superposing Vy-Vz channels – Jan16-17,2019

C. Underwater Acoustic Communications

Codes transmitted in the experiment had different characteristics in both frequency band and modulation (Table I). Previous underwater soundscape monitoring suggested the frequency bands used in the experiment. In the 2-12 kHz band, most codes share part of the spectrum with biological noise (3-6kHz) creating undesired interference. Fig.9 shows two spectrograms in which both the strong broadband biological noise and the four codes spread in frequency and time can be observed. In a low-level source condition (Fig. 9 upper plot), code signals cannot be detected by an unalerted listener. For a high-level source condition (Fig. 9 lower plot), code signals can be easily observed. But, signals below 6 kHz were strongly attenuated during the experiment, possibly due to source transmitting voltage response.

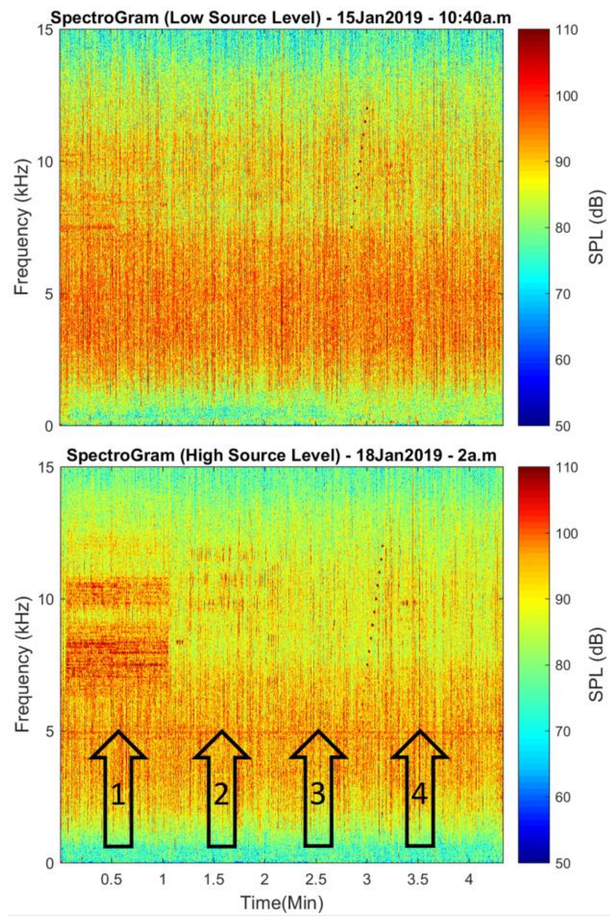

Fig. 9. Spectrograms of the received codes at pyramidal hydrophone array, for two different days during BioCom´19 experiment: on 15January at 10:40 a.m. and on 18 January at 2 a.m. (arrows in lower plot indicate the four received codes)

Code 1 presents an experimental covert or Low Probability of Detection (LPD) signaling scheme which can contribute to minimize underwater acoustic pollution, mitigating noise impacts over marine life. Transmitting a long 2047 bits BPSK m-sequence superimposed to a same length message, the approach estimates the channel impulse response (CIR) and retrieves the message simultaneously. The method uses Fast Hadamard Transforms (FHT) to estimate channel impulse response, through m-sequence cross correlation. FHT CIR peaks, estimated using 2047-bit sequences, are used for soft synchronization. Also, a Wiener filter mitigates intersymbol interference and Hyperslice Cancellation by Coordinate Zeroing (HCC0) [5] removes probe interference to the message [6]. Each 2047-bit sequence carried out four equal data packets containing the same 60 character or 480-bit message. Each data packet is preceded by an m-sequence of 31 bits which is used for hard synchronization purposes, through FHT cross-correlation peaks.

The source transmitted the sequence on a carrier frequency of 7.5 kHz (BW:5 kHz), at a data rate of 1920 bits/s. In this experiment, the method explored both temporal and spatial diversity using the signals received on the pyramidal array only, combining the four channels to minimize fading. The same sequence was repeated 55 times to increase SNR through coherent averaging in time. However, these repetitions reduced the data rate. In this work, received signals were bandpass filtered between 5-10kHz and averaged for 26 and 52 seconds, over 24 and 48 sequences leading to an effective bit rate of 20 and 10bits/s, respectively.

In addition to the noise, severe multipath, probably due to fast changes in sea state and SSP, were observed causing intersymbol interference. Fig. 10 shows the CIR variability in time, for a single transmission, estimated by the method.

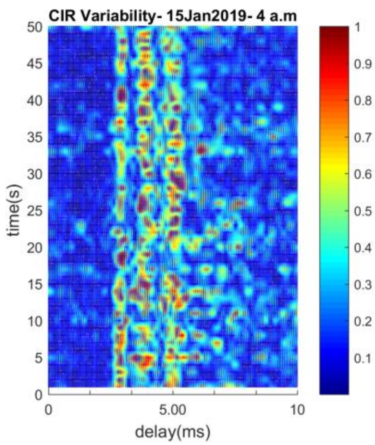

Fig. 10. Channel impulse response variability in time – Jan15,2019 – 4 a.m.

The channel delay spread is approximately 3 ms, therefore much longer than the 0.53 ms bit duration, so the performance degraded. In Fig.10 one can observe three strong arrivals due to multipath which makes receiver synchronization a challenging task. The pyramid was close to the bottom and all four hydrophones were just a meter away from each other, which probably reduced spatial diversity gain.

To estimate Bit Error Rate (BER) and SNR, only signals transmitted in minutes 00 with a constant SL, and in minutes 30, with SL-4dB, were used. As received signals are contaminated with background noise, the SNR in dB is estimated according (2):

$$SNR=10\log_{10}[(S-N)/N] \qquad (2)$$

where S: mean of the signal power of the four channels, averaged over 48 and 24 sequences, related to 10 and 20 bits/s, respectively; N: mean of the noise power of the four channels, for one sequence estimated from the 40s period in the end of the data block.

In Fig. 11, BER is evaluated as a function of in band SNR, for 10 and 20 bits/s. In Fig.12, same results are indexed in time. Fig. 12, upper plot shows BER vs time with most results below 10^{-2}. In Fig. 12 lower plot, lines show the average SNR for both high and low source level transmissions, during minutes 00 and 30, respectively, allowing observation of SNR fluctuation in time. Despite signal fluctuation in this challenging environment, the method has showed consistent in time, pointing to possible future LPD applications (in band SNR<-8dB) [7]. No error correction code was used.

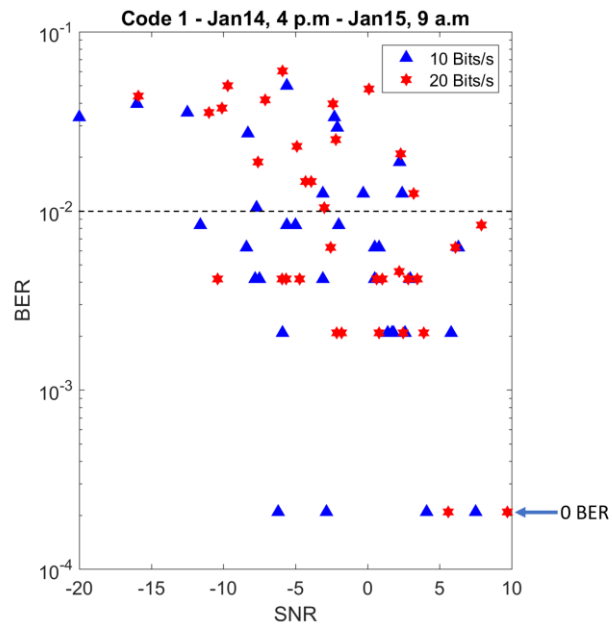

Fig. 11. BER versus SNR, for Code 1. Results from Jan14, 16:00 to Jan15, 09:00. Effective Bit Rate: 10 and 20 bits/s

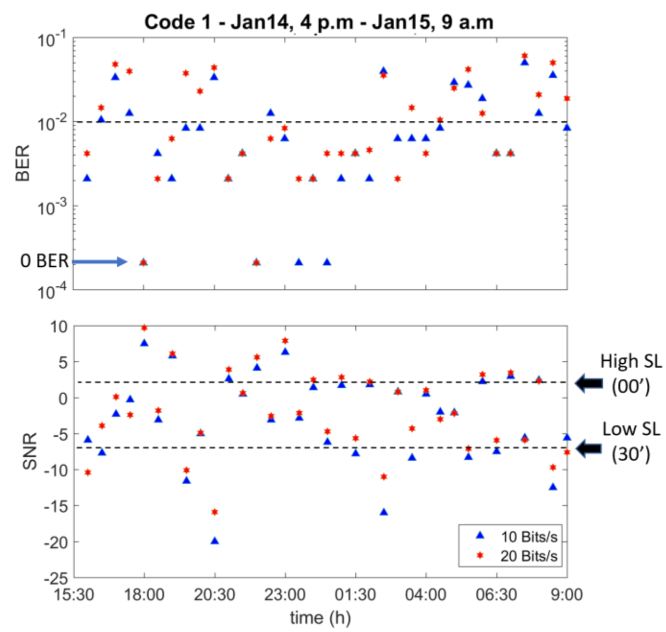

Fig. 12. BER (top) and in band SNR (bottom) versus time from Jan14, 16:00 to Jan15, 09:00. Effective Bit Rate: 10 and 20 bits/s

Code 2 presents a modulation scheme based on an 8-hyperbolic swept frequency chirp, hereafter named HCSK. The main goal was to perform communications in noisy shallow water sharing information from background noise frequency spectrum. A previous analysis of 82 days of background noise recordings was performed to choose best suitable Code 2 band. Transmitted from 4.5-12kHz, the hyperbolic chirps were used in substitution to FSK tones, aiming to enhance detection capability in a matched filter receiver. The symbol rate was 120 sym/s, corresponding to a bit rate of 360 bits/s. To mitigate multipath effects over demodulation, a guard time of 0.033s were inserted between consecutive chirps. The HCSK data are currently being processed and results will be presented in the future.

Code 3 allows for a strategy using Gaussian Mixture Models (GMM), Mel-Frequency Cepstral Coefficients (MFCC) and multiple condition training [8] to identify underwater acoustic signals. The goal of this strategy is to use statistics from environmental noise to identify a desired signal severely corrupted by noise, which is not possible using correlation techniques. The new proposal is used in robust speaker recognition (identification, verification) [9]. During the present experiment, several sequences of 6 chirp types, in the frequency band of 3.75-9kHz, were transmitted to extract MFCC parameters which are used as inputs of a GMM classifier [10]. In addition, a sequence of chirps and CW signals from 2-12kHz were also transmitted to estimate channel transmission loss. The code 3 data are still being processed and results will be presented in the future.

Code 4 employed an 8-FSK modulation with frequency diversity scheme [11], with redundancy, in the frequency band from 5-10 kHz, to check its robustness in this challenging environment. The transmitted message contained a pangram of 81 characters. The symbol rate was 26 sym/s, corresponding to a bit rate of 78 bits/s. Using only audio files from the 4-channel pyramid array, a total of 4156 files were analyzed individually. From those, 1336 files had the transmitted message with errors. To improve results, convolutional code was previously included at transmission and Viterbi algorithm allowed for error correction at the receiver. The correction code used was the Forward Error Corrector Code (FECC). Fig.13 and Fig.14 show the BER versus E_b/N_0, for two distinct cases: before and after the implementation of the correcting code, respectively. Before FECC, just 15 signals were received with 0 errors. There is no coincidence between the mean curve and the theoretical one. However, after FECC, the number of 0 error signals increased from 15 to 630. Both mean and theoretical curves are almost coincident proving FECC efficiency even in this shallow water environment.

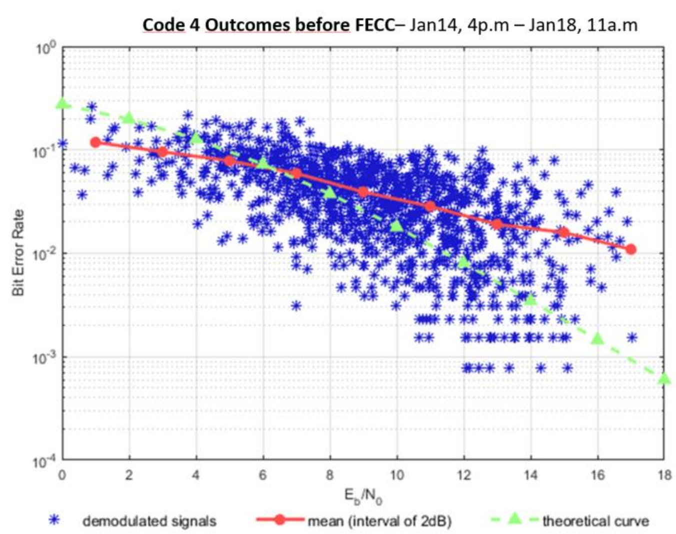

Fig. 13. Results from an 8-FSK modulation, with frequency diversity scheme, with redundancy, before error correction. No coincidence between the mean and theoretical curve. Data from Jan14, 4p.m to Jan18, 11 a.m.

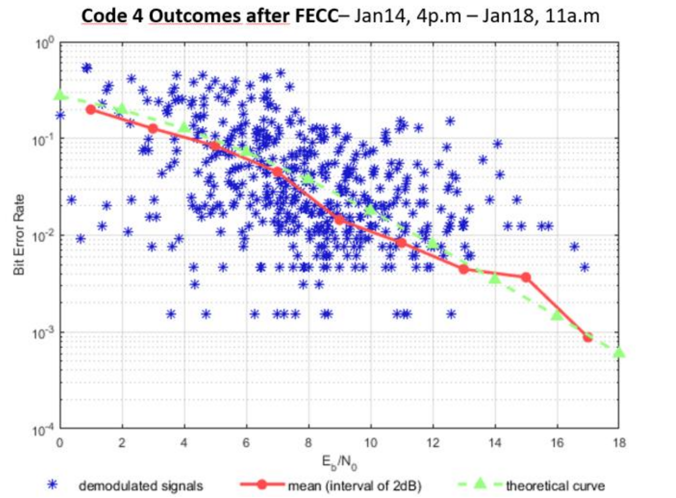

Fig. 14. Results from an 8-FSK modulation, with frequency diversity scheme, with redundancy, after error correction. Mean and theoretical curves almost coincident. Data from Jan14, 4p.m to Jan18, 11 a.m.

III. Conclusions

This work presented some preliminary results from BIOCOM´19 experiment, related to both a long-term biological noise monitoring and experiments related to underwater acoustic communications and particle motion, in an upwelling environment. In addition to the soundscape monitoring system, four signalling schemes were used with specific goals as such covert communications, receiver training and recognition, and performance analysis.

Noise recorded by the pyramidal hydrophone array showed a biological temporal pattern, including intensification in marine life activity during twilights. The same conclusion was obtained through DAVS1, which also provided estimation of noise arrival direction. The combination of these two independent passive systems is promising for soundscape monitoring where both noise power and source localization are of interest.

Communication results point to a complex propagation channel condition during the experiment. Collected SSP showed significant variations during daytime, probably due to the ongoing upwelling regime, supporting conclusions about sound waves refracting to the bottom when travelling over the deepest part of the channel, near the entrance of the bay. Therefore, received signals suffered strong attenuation due to ocean temperature stratification. During daytime, source power level variation in time combined to high biological noise level and noise generated by recreational vessels in the experiment area, contributed to degrade receiver performance. These vessels can emit high energetic noise due to cavitation, auxiliary machinery and other systems related to recreational activities.

However, we speculate that at night anthropogenic noise levels reduced significantly and, probably, the sound speed profiles, not measured, changed to an almost isothermal cold condition, minimizing sound refraction and improving communications. These parameters combined permitted some performance estimation in terms of BERvs.SNR and BERvs.Eb/N0.

Various signalling methods, in frequency band 4-12 kHz, have been tested with the following preliminary results: 1) method based on BPSK modulation, presented an experimental approach for covert communications using Fast Hadamard Transforms and m-sequences. Presenting a frequency spectrum similar to background noise, the low power signal can mitigate impact of high source level over marine life. The method showed consistent in time, dealing with both time varying noise level and oceanographic events. The experimental low probability of detection method provided encouraging preliminary results with several BER<10^{-2} for SNR<-5 dB, for effective bit rates of 10 and 20 bits/s. To improve BER, longer averaging in time, over a greater number of sequences is necessary.; 2) method based on an 8-hyperbolic swept frequency chirp performed communications in noisy shallow water in substitution to FSK tones, aiming to enhance detection in a matched filter. Data are still under analysis. Results to be published in the future; 3) method proposed a new approach to identify underwater acoustic signals, severely corrupted by noise, using statistics, instead of classic correlation techniques. Based on Gaussian Mixture Models and Mel-Frequency Cepstral Coefficients, the method transmitted chirps and CW to check technique performance. Data are being processed. Results to be published in the future; 4) method based on 8-FSK modulation, with redundancy, aimed to check its robustness in this challenging shallow water environment. For signals recorded from Jan14, 4 p.m to Jan18, 11 a.m, results in terms of BER vs. Eb/N0 showed that the Forward Error Correction Code can improve results consistently. From 1336 files, before FECC, only 15 signals had zero error. After FECC, this number increased to 630, proving its efficiency.

Future works, processing of vertical array data and comparison to pyramidal array and DAVS1 could help to better understand the role of both biological noise and upwelling oceanographic factors over communications. Also, further analysis of biological noise can provide information to help existing covert communication signals to improve performance as well as to develop new signaling schemes with local bioacoustics characteristics.

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