Coherence as a criterion for multichannel combining low SNR communications in an upwelling environment

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***Abstract*—This paper presents a study on the impact of temporal (TCOH) and spatial (SCOH) coherence over low SNR communications in an environment with intense upwelling and demonstrates how to use coherence as a criterion to perform multichannel combining. Using low power signals collected in a shallow water experiment, from two independent and different geometry arrays with four hydrophones each, temporal coherence was estimated. Signals whose TCOH was above a threshold were averaged and SCOH between channels were estimated. Bit error rate results showed that SCOH can be used as a criterion to discard noisy and high multipath channels. Multichannel combination based on SCOH indicated that the use of the arrays can increase the processing gain, even if the sensors are just a few wavelengths from each other. Moreover, longer averaging times provided lower BER but reduced the effective bit rate.**

***Index Terms*—Coherence, Underwater communications**

I. Introduction

Establishing low signal-to-noise ratio (SNR) communications is a challenging task as the ocean is a complex and time-varying propagation medium. In an upwelling shallow water environment, signals fluctuate rapidly with time due to short time scale oceanographic phenomena [1] that cause a severe multipath, reducing the communication system performance. Furthermore, in the vicinity of rocky shores and busy harbors, high noise levels may hamper efforts to recover acceptable SNR of weak communication signals. To improve the system reliability, the SNR at the receiver must be increased, which can be achieved by temporal and spatial coherent averaging of signals recorded by several receivers. Therefore, much effort has been dedicated to measure and understand coherence in shallow water. Coherence (COH) describes the rate of the signal fluctuation, in time or space. Defined as a statistical measure of the change of a waveform, coherence depends on both amplitude and phase of the signal [2] [3]. In this work, "instantaneous" coherence, covering short periods (seconds), will be used to express the rate of the low SNR signal fluctuation in time and space, influencing the time of integration and therefore the effective bit rate of the communication system.

Previous work reported in the literature measured both temporal and spatial coherence in shallow water for different reasons. In [2], DeFerrari studied the propagating modes decorrelation of low-frequency broadband transmissions in shallow water, at a range of 10 km, and compared results to those of a numerical model. In [3], Yang measured temporal coherence in three shallow water sites with low to high internal wave activity using signals with frequencies from 1.5 to 20kHz, in a range up to 42 km. Therefore, an analysis was conducted on the relationship between coherence, source frequency, range, and sound speed profile.

In this study, the main goal is to understand the impact of both temporal (TCOH) and spatial coherence (SCOH) on low SNR communications in an upwelling channel and how to use coherence as a criterion to perform multichannel combining. Data presented here are a small subset from the BioCom'19 experiment [4], performed in a shallow water site, in Cabo Frio Island Bay. During the experiment, several superimposed training broadband signals [5] with a central frequency of 7.5 kHz and a bandwidth of 3 kHz were transmitted and recorded by a linear and a pyramidal array with four hydrophones each. All four channels of each array are analyzed independently and processed using a Wiener filter to mitigate multipath. Then, based on estimated TCOH and SCOH, channels are combined to improve the gain of the array. Assuming that noise is uncorrelated between channels, coherent averaging of several sequences increases the SNR and thus, reduces the bit error rate (BER). All coherence estimates are matched to the BER to understand implications over receiver performance. Both arrays are also compared to determine the advantages of their variable geometry.

II. Coherence and multichannel combining

Coherence measures, in a statistical sense, the difference in waveform and expresses the rate of signal fluctuation, in a time or space interval [3]. Dependent on the amplitude and phase of the signals, coherence is estimated by the autocorrelation of the signals separated by a delay-time (temporal coherence) or distance intervals along an array of sensors (spatial coherence), normalized by the power of the signals as given by

$$COH(t,\tau) = \frac{\left\langle |p^*(t)p(t+\tau)|^2 \right\rangle}{\langle p^*(t)p(t)\rangle \langle p^*(t+\tau)p(t+\tau)\rangle} \qquad (1)$$

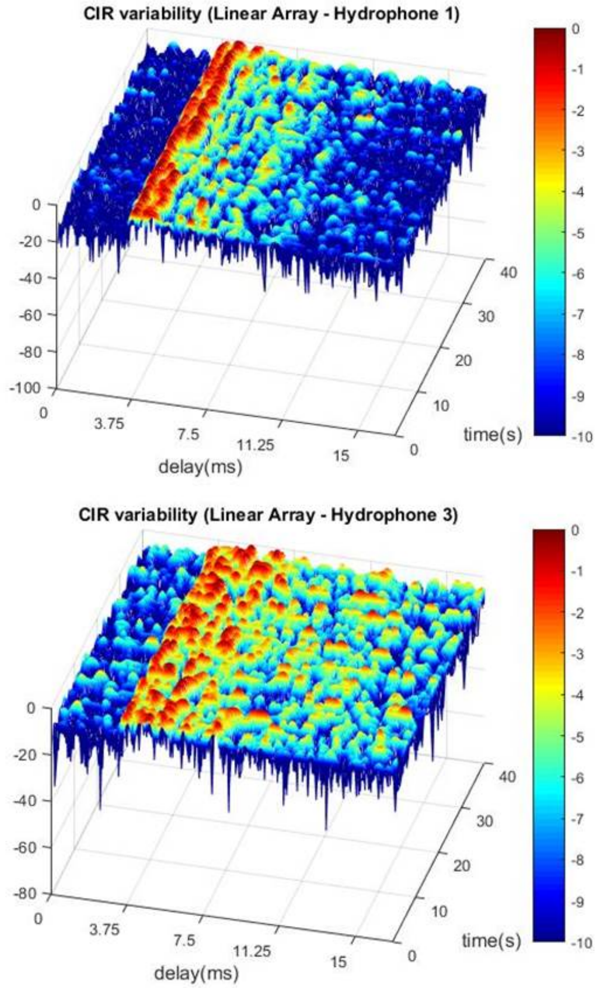

Fig. 1. CIR variability in time, estimated using 50 bitstreams (Fc:7.5 kHz, BW: 3 kHz). Data were recorded by hydrophone #1 (top plot) and #3 (bottom plot) of the vertical linear array, installed at 1.5 m and 4.5 m above the bottom in approximately 8 m water depth.

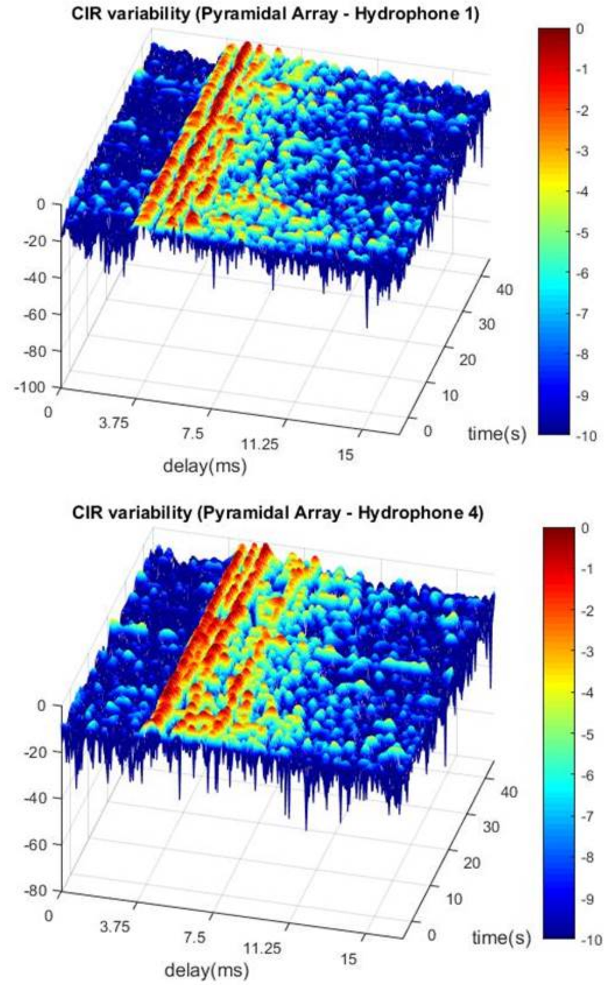

Fig. 2. CIR variability in time, estimated using 50 bitstreams (Fc:7.5 kHz, BW: 3 kHz). Data were recorded by hydrophone #1 (top plot) and #4 (bottom plot), installed at the top (1m above the bottom) and at the base of the pyramidal array.

where p(t) is a channel impulse response obtained after matched filter pulse compression of the received signals, τ is the lag time, $\langle\rangle$ denotes ensemble average over time t and * denotes complex conjugate.

Based on data from the BioCom'19 experiment, performed in a shallow water site, in Cabo Frio Island Bay (Brazil) from Jan14-18, 2019, both TCOH and SCOH were estimated. The test site is a challenging environment due to the upwelling phenomena in the region of Cabo Frio Island, which influences ocean temperature stratification and therefore, the sound wave propagation. Short-term drastic temperature changes of about 10 degrees Celsius in a few hours were observed [4]. Furthermore, the proximity to the city harbor and to the rocky shores with a substantial coverage of soniferous invertebrates [6] added broadband impulsive noise to the recorded signals.

During the experiment, consecutive broadband bitstreams y(t) composed of a long m-sequence superimposed to the data were transmitted [5]. Used as a probe, m-sequences are orthogonal codes which provide an impulse-like autocorrelation with a peak-to-sidelobe ratio of 10logN, where N=2047 is the number of symbols in the bitstream. The transmissions were set up with a central frequency of 7.5 kHz, bandwidth of 3 kHz, and emitted from an omnidirectional acoustic source located at mid-water in a 4 m deep water column. To explore channel temporal diversity, each 2047 bit-long bitstream was transmitted 50 times per minute, repeated every five minutes. To explore channel spatial diversity, two arrays of four hydrophones each were installed 1.6 km away from the source. In one of the arrays, the hydrophones were located at the vertices of a pyramidal structure with a 1m side, posed in the bottom. The other was a vertical line array spanning 4.5 m of an 8 m water column.

A. Temporal Coherence

For the signals recorded in each channel of both arrays, a Fast Hadamard Transform (FHT) [7] was used to estimate the channel impulse responses (CIR) through m-sequence crosscorrelation. Before estimating COH, an arbitrarily defined section of 100 ms of each CIR $p(t)$ including all the dominant multipath arrivals was selected. In a low SNR environment, time-gating the CIR can avoid the inclusion of excessive noise in the calculations of COH, improving results. Based on these time-gated $p(t)$ and choosing the first CIR $p_{1^{Ref}}(t)$ as the reference, TCOH of bitstreams arriving at later times can be calculated using (1). As shown in Fig. 1 and 2, the channel presents a long time delay spread, with multiple arrivals of high energy in both arrays. This multipath severely degrades coherence (Fig. 4 and 5 (top plot)). In diagram of Fig. 3, the received signals $y_Z(t + Z\tau)$ were processed with an inverse Wiener filter to mitigate multipath. Using filtered $g_Z(t+Z\tau)$, TCOH was recalculated improving results (Fig. 4 and 5 (bottom plot)). When the resulting TCOH, estimated over the filtered sequences, was above a given threshold, the respective bitstreams were coherently averaged. The averaged bitstream $s_{ave}(t)$ represents the channel in the SCOH calculations.

B. Spatial Coherence

SCOH between different channels of the same array can also be determined using (1), replacing time $(t + \tau)$ for the hydrophone spacing (η). SCOH was calculated using the averaged bitstream $s_{ave}(t)$, formed by Z sequences $s_Z(t+Z\tau)$ whose TCOH were above a certain threshold. For each channel, the CIR $p_{ave}(\eta)$ was estimated by matched filtering the averaged signal $s_{ave}(t)$ with the transmitted bitstream replica $r(t)$. After time-gating $p_{ave}(\eta)$ from all four channels, these sequences were aligned in time to correct the misalignment of the wavefront and the array. As the phase shifts related to the position in the array were reduced, SCOH were estimated between two channels choosing any CIR $p_{ave}(\eta)$ as the reference.

C. Multichannel combining

The SCOH above a certain threshold is the criteria to perform multichannel combining. Previous work [3] showed that a coherence of approximately 0.8 was required to process communication signals. However, improvement was achieved combining sequences in which TCOH and SCOH were above a lower threshold, placed at 0.6. Therefore, the averaged bitstreams of all channels were combined to improve the gain of the array. But if SCOH was below the threshold, the channel was discarded as it degraded the combined result.

III. COMMUNICATION PERFORMANCE RESULTS

Data presented here are a small subset from those recorded during BioCom'19 on JAN17, 2019 - 11 a.m by the vertical linear and pyramidal arrays. Fig. 1 shows the evolution of CIR for the vertical linear array, from bitstreams recorded by hydrophone #1 and hydrophone #3, installed 1.5 m and 4.5 m above the bottom in approximately 8 m water depth, respectively. One can observe that signals recorded on hydrophone #3 show a severe multipath and an in-band higher noise level compared to hydrophone #1. Using 50 sequences, the average SNR were SNR$_{ave}$Ch#1= -0.77 dB and SNR$_{ave}$Ch#3= -2.41 dB, but SNR fluctuates according to the number of sequences used in the calculations. Therefore, signals decorrelate in time much faster in channel #3 than in channel #1. TCOH for channel #3 is shown in Fig. 4, before and after the Wiener filter. Using the threshold (dashed line) as a reference, one can observe that the instantaneous TCOH exhibits a high degree of fluctuation. The large variance may be related to the upwelling oceanographic processes in the region of the experiment that affects the propagation conditions. These results of TCOH impact directly over SCOH and data retrieval. Table I shows SCOH, BER and SNR for several combinations of channels based on TCOH estimated previously. All SCOH estimations including channel #3 were below the 0.6 threshold and the corresponding BER were deeply degraded. Therefore, channel #3 was discarded and the combination of channels #1,2 and 4 retrieved the transmitted data with a lower BER.

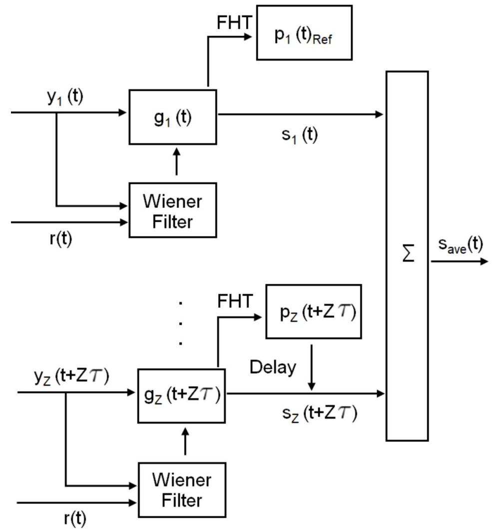

Fig. 3. Diagram of Wiener filtering, CIR estimation using Hadamard transform and coherent averaging of sequences whose TCOH was above the 0.6 threshold.

Fig 2 shows the evolution of CIR for the pyramidal array. Hydrophone #1 was placed at the top of the pyramid and #4 was posed in the bottom over the base of the array. As this array had all four hydrophones just a few wavelengths from each other, one could expect that the signals in the channels were similar and noise correlated. However, comparing channels in Fig. 2, one can observe that both noise levels and multipath were different in time and space. Averaging 50 sequences, the SNR$_{ave}$Ch#1= -1.27 dB and SNR$_{ave}$Ch#4= -1.64 dB. Also, both channels present several arrivals of high amplitude, but channel #4 presents a strong and much-delayed multipath at 7.5 ms which complicated data retrieval. The combination of a severe multipath and a high impulsive noise in the band deeply degraded TCOH, especially for channel #4 (Fig. 5 (top plot)). Even after filtering the bitstreams, most of the recalculated TCOH continued lower than the 0.6 threshold (Fig. 5 (bottom plot)). Table II shows SCOH, BER, and SNR for combinations of the channels of the pyramidal array. Based

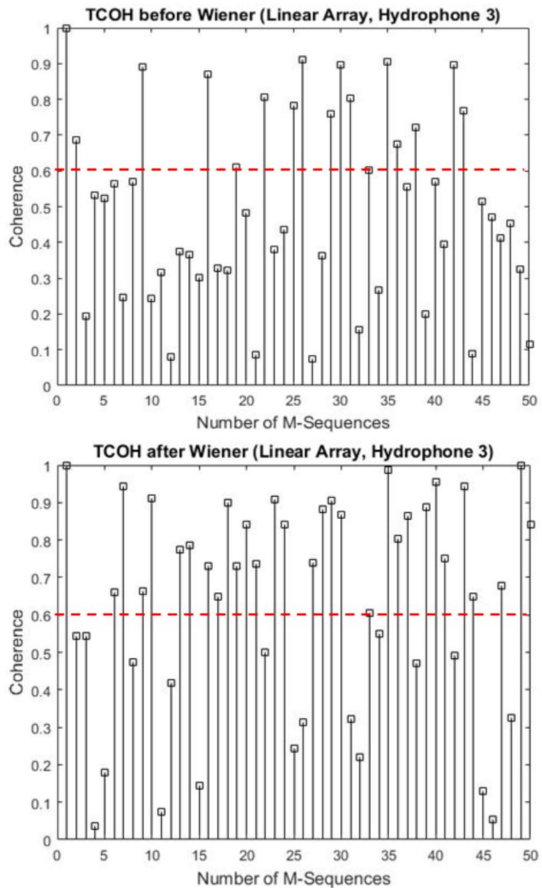

Fig. 4. Temporal coherence before (top plot) and after Wiener filter (bottom plot) of bitstreams recorded by hydrophone #3 of the vertical linear array. Dashed line in red, at 0.6, marks the threshold for TCOH

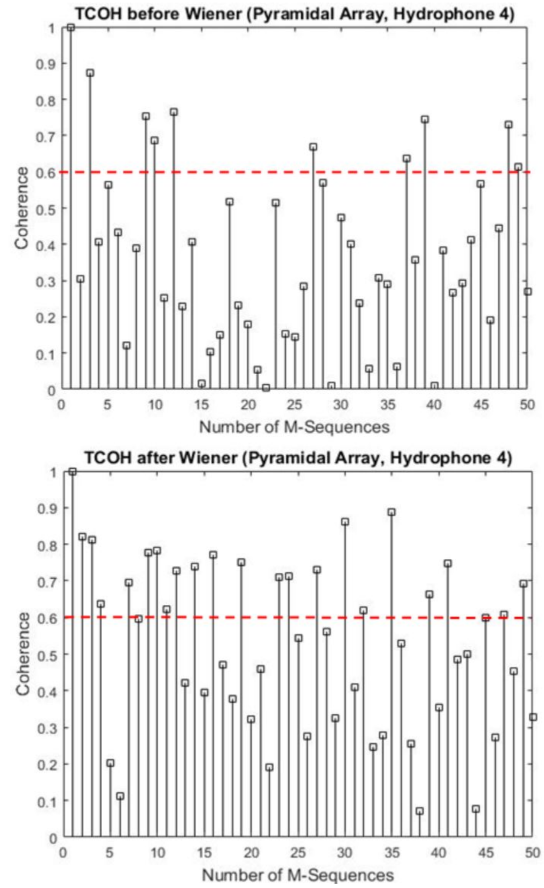

Fig. 5. Temporal coherence before (top plot) and after Wiener filter (bottom plot) of bitstreams recorded by hydrophone #4 from pyramidal array. Dashed line in red, at 0.6, marks the threshold for TCOH

on SCOH estimations, the channel to be discarded was the #4. In a low SNR environment, repetition of the same signal is used as an error correction tool. In general, longer averaging times provide lower BER but reduce the effective bit rate. Averaging over 10 bitstreams, approximately 10 seconds, the effective bit rate was 48 bps against 24 bps for 20 sequences. Defining an optimum averaging time was a hard task due to signal fluctuations in time and channel noise levels. But the use of the array increased the processing gain, even if the sensors were just a few wavelengths from each other. Even not taking advantage of spatial diversity along the water column as the vertical linear array, the pyramidal array still provided low BER.

IV. Conclusions

In this paper, we performed an analysis of the impact of temporal and spatial coherence over low SNR communications in an upwelling environment. Furthermore, we defined a criteria to perform multichannel combining based on spatial coherence. Using low power data from two different geometry arrays, temporal coherence was estimated before and after equalization to show the impact of multipath over data retrieval. The results indicate that TCOH and SCOH can be used as a criterion to combine consecutive signals and multiple channels of the arrays. Sequences whose TCOH were above the threshold were coherent averaged. SCOH between the channels were estimated and compared in terms of BER. In both cases, the achieved BER was in agreement with the evolution of SCOH. The lower the SCOH, the higher the BER. Improving knowledge about the use of low SNR communication signals associated with a linear and pyramidal array in this challenging environment can not only reduce the integration time, increasing the bit rate but also can save power, and reduce acoustic pollution. Future work will explore passive time-reversal techniques to mitigate multipath, increasing coherence and the effective bit rate as less sequences are averaged to obtain the transmitted data.

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TABLE I

VERTICAL ARRAY: SCOH[1],BER AND SNR FROM MULTICHANNEL COMBINING, AVERAGING 10 AND 20 BITSTREAMS (48 AND 24 BPS)[2]

	10 bitstreams (48 bps)			20 bitstreams (24 bps)		
Channels	SCOH	BER %	SNR	SCOH	BER %	SNR
1/2	0.61	1.2	-3.7	0.91	1.8	-3.4
1/3	0.30	34.2	-9.9	0.54	9.6	-10.2
1/4	0.70	0.8	-0.4	0.75	1.2	-0.3
2/3	0.29	34.5	-5.3	0.39	15.2	-11.5
2/4	0.82	1.8	+0.5	0.95	4.3	+0.5
3/4	0.42	19.5	-1.2	0.21	18.5	-1.1
1/2/3/4		5.8	-2.2		3.5	-1.8
1/2 and 4		2.4	-1.8		1.5	-0.6

[1] SCOH: Spatial coherence

[2] The effective bit rate is related to the number of the averaged bitstreams

TABLE II

PYRAMIDAL ARRAY: SCOH[1],BER AND SNR FROM MULTICHANNEL COMBINING, AVERAGING 10 AND 20 BITSTREAMS (48 AND 24 BPS)[2]

	10 bitstreams (48 bps)			20 bitstreams (24 bps)		
Channels	SCOH	BER %	SNR	SCOH	BER %	SNR
1/2	0.62	6.2	-5.1	0.73	0.2	-3.4
1/3	0.69	4.3	-4.2	0.64	2.7	-2.8
1/4	0.44	10.7	-3.9	0.49	0.3	-2.5
2/3	0.71	5.1	-6.1	0.67	4.3	-4.2
2/4	0.56	12.2	-5.8	0.54	1.2	3.9
3/4	0.51	9.2	-4.8	0.59	6.8	-3.2
1/2/3/4		7.3	-5.1		4.4	-3.7
1/2 and 3		3.3	-4.2		0.5	-2.8

[1] SCOH: Spatial coherence

[2] The effective bit rate is related to the number of the averaged bitstreams

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REFERENCES

[1] L. Calado, O. Rodriguez, G. Codato, and F. Xavier, "Upwelling regime off the cabo frio region in brazil and impact on acoustic propagation," *J. Acoust. Soc. Am.*, vol. 143, no. 3, p. 174, 2018.

[2] H. A. DeFerrari, "Observations of low-frequency temporal and spatial coherence in shallow water," *J. Acoust. Soc. Am.*, vol. 125, EL45, no. 1, 2009.

[3] T. C. Yang, "Measurements of temporal coherence of sound transmissions through shallow water," *J. Acoust. Soc. Am.*, vol. 120, no. 5, pp. 2595–2614, 2006.

[4] F. B. Louza, J. Osowsky, F. C. Xavier, E. E. Vale, L. P. Maia, R. P. Vio, M. V. S. Simões, V. Barroso, and S. M. Jesus, "Communications and biological monitoring experiment in an upwelling environment at cabo frio island bay," in *OCEANS 2019 - Marseille*, 2019, pp. 1–7.

[5] F. B. Louza and H. A. DeFerrari, "Superimposed training low probability of detection underwater communications," *J. Acoust. Soc. Am.*, (in press).

[6] E. L. Ferreira, J. E. A. Goncalves, and R. Coutinho, "Community structure of fishes and habitat complexity on a tropical rocky shore," *Environ. Biol. Fishes*, vol. 61, p. 353–369, 2001.

[7] A. Lempel and M. Cohn, "On fast m-sequence transform," *IEEE Trans. Inf. Theory*, vol. 23, no. 1, p. 135–137, 1977.