Low probability of detection underwater communications using a vector sensor

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***Abstract*—Low probability of detection underwater acoustic communications are required for command and control of mobile underwater platforms performing covert missions. To deal with multipath and increase the signal-to-noise ratio (SNR) at the receiver, this paper presents a study on the low probability of detection communications using a single vector sensor. Compact in size, vector sensors (VS) are suitable for autonomous underwater vehicles, measuring both acoustic pressure and particle velocity, and therefore providing diversity gain. As part of the multidisciplinary EMSO-PT project, an experiment took place off the coast of Algarve/Portugal on Nov 24th, 2021. A single 2D VS was posed on the bottom. Broadband signals were transmitted from several positions, varying both the source-receiver range and the direction of arrival. Recorded noise was added to the signals to reduce the SNR from 0 to -10 dB. A superimposed training passive time-reversal approach was employed for equalization. Coherent communication performance was evaluated. Results show that VS multichannel combining may provide an average SNR and mean squared-error gain of up to 9.4 and 3.1 dB, respectively, compared to the pressure channel.**

***Index Terms*—Low probability of detection, Vector sensor, Underwater communications**

I. Introduction

Low probability of detection (LPD) underwater acoustic communications are an essential requirement for command and control of mobile underwater platforms performing covert missions [1], [2]. Based on low power signals, much weaker than the ambient noise, LPD communications may also extend the operating life of battery-operated autonomous underwater vehicles (AUV) and other submerged network nodes. Furthermore, covert communications may contribute to reducing the environmental noise level, mitigating the impacts of acoustic signals on marine life [1]. The shallow water close to the coastline is a challenging environment for LPD communications, presenting high noise levels due to human and biological activities. Furthermore, the time-varying signal fluctuation, the long multipath spread, and the Doppler shift induced by source-receiver motions also impact signal demodulation [3]. Most common systems for covert communications rely on direct sequence spread spectrum (DSSS) [4], [5], orthogonal frequency-division multiplexing (OFDM) [6], [7] and arrays of pressure sensors to deal with multipath and to increase the signal-to-noise ratio (SNR) through multichannel combining. However, these large-size arrays are not suitable for AUVs. Acoustic vector sensors (VS) are an alternative for hydrophone arrays, being widely employed for sonar applications, such as passive source localization [8], and tracking [9]. Compact in size, the VS measure both the scalar acoustic pressure and the orthogonal particle velocities in a co-located device. However, despite providing diversity gain, just recently the VS started being explored for underwater communications [10]–[12].

This paper presents a study on the VS multichannel combining for LPD communications in shallow water. Based on a superimposed training passive time-reversal (STpTR) approach [13], this study explores both the temporal diversity provided by repetition of the same signal and the spatial diversity given by the pressure and particle velocity channels. To support this work, a VS communication experiment took place off the coast of Algarve/Portugal on Nov 24th, 2021. A single 2D VS mounted on a tripod was deployed on the bottom. An omnidirectional source hanged from a vessel transmitted broadband bitstreams from several positions, varying both the source-receiver range and the direction of arrival. The bitstream has LPD properties, as the message is embedded in the probe [14]. Furthermore, the method employs double synchronization using codes shared between the transmitter and receiver. The bitstreams were acquired in a high SNR. Thus, recorded noise was added to the signals to reduce the in-band SNR from 0 to -10 dB. This work does not investigate the covertness properties from an interceptor perspective which depends on both range to the source and interception techniques [2]. Therefore, an arbitrary threshold of SNR< -8dB at the receiver location is considered for benchmark [15]. Experimental results show the suitability of VS multichannel combining for covert communications, providing an average SNR and mean squared-error gain (MSE) of 9.4 and 3.1 dB, respectively, compared to the pressure channel.

II. Theoretical framework

In this section, the theoretical VS system equations and the superimposed training pTR receiver are briefly presented.

A. Vector sensor data model

Composed by a pressure sensor and particle velocity channels, the VS system equations can be defined as (1).

$$\begin{aligned} y_p &= s * h_p + w_p, \\ y_{v_{x,y,z}} &= s * h_{v_{x,y,z}} + w_{v_{x,y,z}}, \end{aligned} \tag{1}$$

where $y_{p,v_{x,y,z}}$ are the received pressure/pressure equivalent particle velocity signals, s is the transmitted signal,

$h_{p,v_{x,y,z}}$ are the channel impulse responses of respective pressure/particle velocity channels, and $w_{p,v_{x,y,z}}$ is the additive ambient noise, assumed spherically isotropic. Here and throughout this paper, $*$ denotes convolution. Despite all signals $y_{p,v_{x,y,z}}$ are measured at a single point, previous studies have shown that the pressure and particle velocity channels may provide spatial diversity [11], [12]. Therefore, an approach developed for low SNR communications based on both temporal and spatial diversity, using an array of pressure sensors only, may be extended for VS receivers.

B. Superimposed training pTR receiver

In this work, an approach called superimposed training passive time-reversal (STpTR) is employed [13]. The transmitted bitstreams $s(t')$ are composed of a long M-sequence laid over to the data [14], used for channel estimation and soft synchronization. Both the probe and the message are 2047-bit BPSK signals, and their symbol rates are the same. The message is composed of 3 zero-padded bits, and 4 packets of 511 bits, of the same content. Each packet is composed of a short M-sequence of 31 bits, used for hard synchronization, followed by 480 bits of data. The amplitude relation between the probe and the data is 5/4. Therefore, the signal to probe ratio is -1.94 dB, useful to improve covertness. Due to the M-sequence correlation properties, signal detection, soft synchronization, and channel estimation can be improved in a low SNR environment. In this approach, the same bitstream is transmitted several times to explore temporal diversity.

Fig. 1 (a) shows the receiver diagram for each channel. The received bitstreams $y_z(t+z\tau)$ are bandpass filtered, converted to baseband, and Doppler compensated. Then, to deal with multipath, the STpTR convolves each bitstream $y_z(t+z\tau)$ with their own time-reversed CIR $\widehat{h}_z(-t)$ (2).

$$o_z(t') = y_z(t') * \widehat{h}_z(-t') = s(t') * \left[h_z(t') * \widehat{h}_z(-t')\right] \quad (2)$$

where $t' = t + z\tau$ is the z bitstream time slot, and τ is the period. To remove residual intersymbol interference (ISI), an inverse Wiener filter is used [16], [17]. The filtered bitstreams $g_z(t+z\tau)$ are matched filtered with the M-sequence probe $x(k)$. Based on the strongest peak of the cross-correlation results $h_z(t+z\tau)$, the bitstreams $r_z(t+z\tau)$ are synchronized (time-aligned) and coherent averaged, providing a high SNR signal $r_m(k)_{ave}$ and performing error correction, in each m available channel (3).

$$r_m(k)_{ave} = s(t') * \left[\frac{1}{Z}\sum_{z=1}^{Z}\left[w_z(n) * h_z(t') * \widehat{h}_z(-t')\right]\right] \quad (3)$$

where $w_z(n)$ are the Wiener coefficients, and k is the discrete-time index.

Spatial diversity is also explored through multichannel combining shown in Fig. 1 (b). The high SNR averaged bitstream

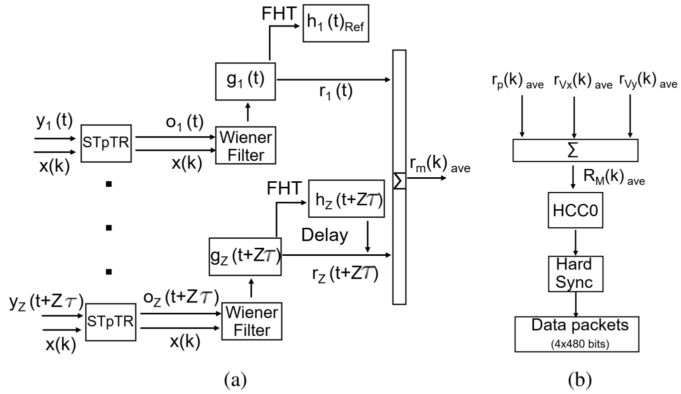

Fig. 1. a) Diagram of STpTR, channel equalization, soft synchronization in time, and temporal coherent averaging of Z bitstreams. b) Diagram of VS multichannel combining, HCC0, hard synchronization and data retrieval.

$r_m(k)_{ave}$ from both pressure and particle velocity channels are combined (4).

$$R_M(k) = s(t') * \left[\frac{1}{MZ}\sum_{m=1}^{M}\sum_{z=1}^{Z} w_z(n) * h_z(t') * \widehat{h}_z(-t')\right] \quad (4)$$

where the term in the brackets may be interpreted as the Q-function [18]–[20], modified by the Wiener coefficients.

Therefore, a high processing gain may be achieved at the VS receiver taking advantage of both temporal and spatial coherent averaging. To eliminate the probe interference to the message, a technique named "Hyperslice Cancellation by Coordinate Zeroing (HCC0) is used [14], [21]. Performing a hard synchronization based on short M-sequences of 31 bits [14], preceding each data packet, the message is retrieved.

III. The EMSO'21 VS experiment

The EMSO'21 VS experiment took place off the coast of Algarve/Portugal on Nov 24th, 2021 (Fig. 2). The experiment deployed a single 2D VS (Geospectrum VS, model 35) that measures both the pressure and the horizontal particle velocities (Vx, Vy), attached at the top of a bottom-mounted tripod. The VS was placed in a 20 m deep water column, approximately 2 m above the bottom. An omnidirectional source (Lubell-916C) hanged from a vessel approximately 7 m below the sea surface, transmitted broadband bitstreams with a central frequency of 7.5 kHz, and bandwidth of 3 kHz, from several locations, varying the source-receiver range and the direction of arrival. The transmissions were performed inside a circular area of a maximum radius of 2.3 km, centered on the VS. Data recorded from transmissions from 4 locations (PT1, PT2, PT3, and PT4) with the vessel just drifting, and another transmission from PT4 with the vessel moving towards the VS are analyzed. Each data file is composed of 55 consecutive bitstreams and a noise-only period of same duration for SNR estimation. The source to VS range was 1900 m (PT1), 2200 m (PT2), 1250 m (PT3), and 1500 m (PT4). Transmissions from PT1, and PT2 were approximately parallel to the coastline, over the isobath of 20 m, in a predominant E-W direction.

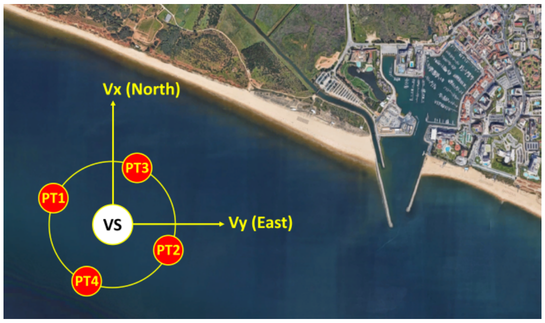

Fig. 2. (Not to scale) Layout of the EMSO'21 VS experiment indicates four points of transmissions (PT1, PT2, PT3, PT4) placed in an approximately circular area of radius 2 km, centered on the VS.

The VS Vy channel was pointing to the East. Transmissions from PT3 and PT4 were approximately perpendicular to the coastline, in a predominant N-S direction. The VS Vx channel was pointing to the North. The bathymetry varied from 15 m (PT3) to 30 m (PT4).

IV. Noise addition, detection and Doppler

The experimental data were received at a high SNR. To simulate a realistic scenario for LPD communications, ambient noise recorded by each channel, at the beginning of the experiment before transmissions, was added to the data files to reduce the in-band input SNR from 0 to -10 dB. After the noise addition, the resulting bitstreams $y_z(t + z\tau)$ were filtered in the transmission frequency band (6-9 kHz). Then, the in-band input SNR (dB) for each channel m was estimated, in time-domain, according to $SNR_m = 10log_{10}\left[(S_m - N_m)/N_m\right]$, where S is the mean power of Z received bitstreams plus added noise, N is the mean power of the combined noise of a period of the same length of S, estimated after each transmission. For multichannel combining, the input SNR of the array was estimated as $SNR_{array} = 10log_{10}\left[\frac{1}{M}\sum_{m=1}^{M}(S_m - N_m)/N_m\right]$.

Assuming that an eavesdropper closer to the receiver location has limited knowledge about the signal, such as the frequency band, conventional detection employs energy detectors. Using the directional information from the Vx channel, Fig. 3 shows the power spectrum density of both the background noise (red) and the transmitted signal (blue), filtered in the band 6-9 kHz. In Fig. 3 (left), the original signal transmitted from PT4, with the vessel in movement, is clearly visible above the noise. However, with an average SNR=-4.7 dB, the signal is barely visible hidden in the noise spectrum (Fig. 3 (right)). The pressure and the Vy channel provide even lower SNR, -9.2 dB, and -7.1 dB, respectively. Therefore, the LPD requirement, at the receiver location, may be assumed, and the system performance evaluated.

Fig. 4 (left) shows the normalized matched filter outputs for comparing detection of the 55 bitstreams transmitted from PT4, with the vessel moving towards the VS, and recorded by the Vx channel. One can also observe that several bitstreams were barely detected. Doppler frequency shift must be estimated and compensated to improve detection in a low

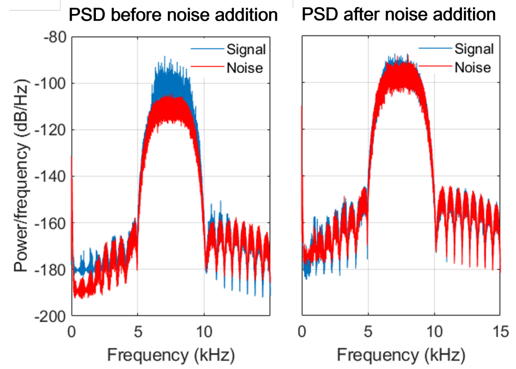

Fig. 3. Power spectral density (PSD) of background noise (red), and the transmitted signals (blue) from PT4 measured by the Vx channel, and filtered in the band 6-9 kHz. Left) PSD before noise addition. Right) PSD after noise addition.

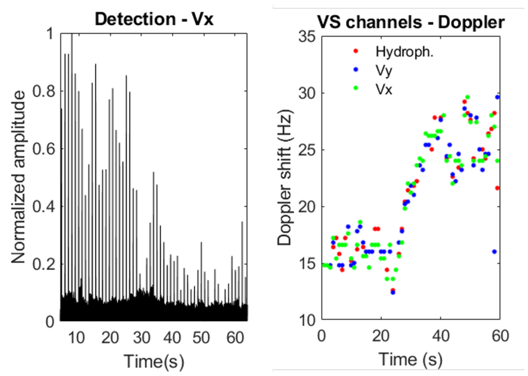

Fig. 4. Left) Matched filter (MF) outputs, used for detection, from 55 Doppler compensated bitstreams transmitted from PT 4 while the vessel was moving towards the VS, and measured by the Vx channel. Right) Doppler shift estimated from the same bitstreams, for all 3 VS channels.

SNR environment. Fig. 4 (right) shows that all VS channels tracked the vessel movement, including a sudden acceleration to increase speed. During the first 25 s, the average Doppler shift was 16 Hz, for a vessel speed of 1.5 knots. The Doppler shift rises to 25 Hz during the acceleration. The last 20 s show a turbulent period faced by the hanging source until the vessel stabilizes the course and speed around 2.4 knots.

V. LPD communication performance

Fig. 5 (left) shows the CIR estimated from signals transmitted from PT4 while the vessel was moving towards the VS, and measured by the Vx channel. The CIR present multiple energetic arrivals and a multipath spread longer than 20 ms. To cope with this challenging environment, the CIR used for pTR were time-gated to 25 ms, in a trial and error process, to include only the most representative arrivals. Fig. 5 (middle) shows the STpTR multipath recombination for the first 10 bitstreams. Fig. 5 (right) shows the normalized Q-function, after summing the 10 previous matched filtered signals. One can observe that the ISI is mitigated as the main lobes add up coherently, while the out-of-phase sidelobes fade away.

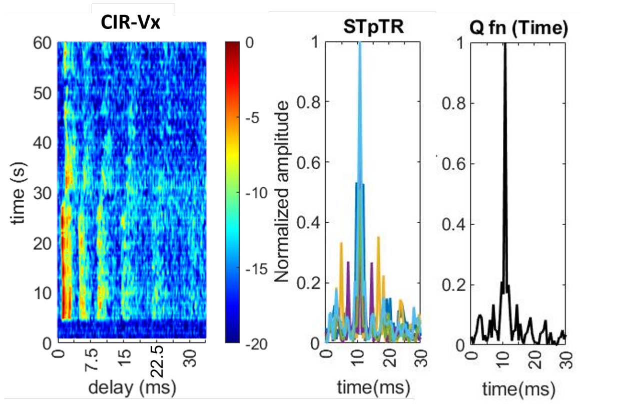

Fig. 5. The 55 channel impulse responses, the STpTR multipath recombination and the Q-function in time, for the first 10 received bitstreams transmitted from PT4 while the vessel was moving towards the VS, and measured by the Vx channel.

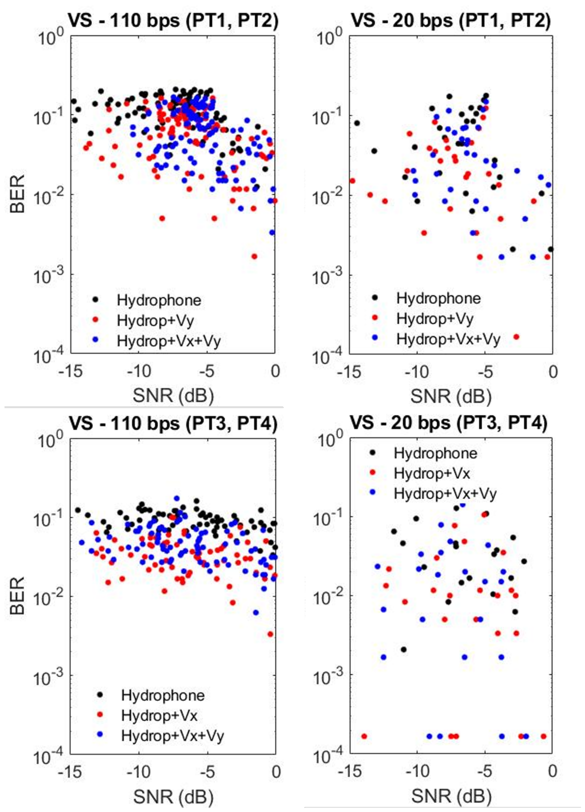

Fig. 6. BER vs. SNR for 3 VS channel combining: hydrophone (black), hydrophone+Vx or hydrophone+Vy (red), and hydrophone+Vx+Vy (blue). Upper row) Results for PT1, and PT2, for 110 bps (left) and 20 bps (right). Lower row) Results for PT3, and PT4 for 110 bps (left) and 20 bps (right).

Fig. 6 (upper row) shows the BER performance from signals transmitted from PT1, and PT2, parallel to the coastline, and predominantly aligned to the Vy channel. The BER were estimated for the hydrophone (pressure sensor), for the hydrophone combined with the Vy, and for all 3 channels (hydrophone+Vx+Vy). Fig. 6 (lower row) shows the BER from signals transmitted from PT3, and PT4 predominantly aligned to the Vx channel, and perpendicular to the coastline. The same comparison is performed, except that the hydrophone is combined with the Vx channel, instead of Vy. To evaluate the system robustness, the BER were estimated using 4 and 22 bitstreams for an effective bit rate of 110 and 20 bps, shown in Fig. 6, left and right, respectively.

In this work, the high noise levels needed to keep covertness, and the severe multipath structure contributed to hampering the demodulation of the received signals. However, Fig. 6 shows that the system achieved BER $< 10^{-2}$, for SNR between 0 and -10 dB, in a possible covert condition at the receiver location, as shown in power spectrum density in Fig. 3 (right). One can observe in Fig. 6 that the combination of the pressure channel to the particle velocity channel approximately aligned to the propagation increased the average input SNR, providing lower BER compared to a single hydrophone. Lower BER were also achieved by averaging a higher number of bitstreams, improving error correction, and therefore, reducing the data rate. However, for any bit rate, the inclusion of the channels perpendicular to the propagation degraded the performance. The LPD benchmark of SNR< -8 dB at the receiver was not defined for directional receivers. Thus, the pressure sensor may be in a LPD condition while the particle velocity channels may have higher SNR, an interesting feature to be explored in LPD communications. To observe the VS multichannel combining performance compared to a single hydrophone, for the highest bit rate of 110 bps, the average SNR and MSE gain are estimated. For PT1, and PT2 (Fig. 6(upper row)), the hydrophone combined with the Vy provided an average SNR and MSE gain equal to 6.9 dB and 2.7 dB. However, for PT3, and PT4 (Fig. 6(lower row)), the hydrophone combined with the Vx channel provided a SNR and MSE gain of 7.6 and 3.1 dB. Combining all 3 channels, the resulting SNR and MSE gain are 9.4 dB and 2.4 dB (PT1, and PT2), and 7.6 and 2.8 dB (PT3, and PT4). In all communication scenarios, the VS multichannel combining outperformed the pressure sensor results.

VI. Conclusions

In this paper, we presented a study on the VS multichannel combining for LPD communications in shallow water. Based on a subset of data from the EMSO'21 VS experiment, a series of signals were transmitted from several points to a single 2D vector sensor. Adding ambient noise to the data to reduce the SNR, the authors analyzed the SNR vs. BER plots for the pressure sensor alone, and the pressure and particle velocity channels combined. Exploring both temporal and spatial diversity, the vector sensor provided promising results for covert communications at the legitimate receiver location, achieving BER $< 10^{-2}$ for SNR < -8 dB. Future work may include beamforming techniques to weight each particle velocity channel according to the direction of arrival. Moreover, it may provide considerations about covertness from an interceptor perspective.

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