SSFB: Signal-Space-Frequency Beamforming for Underwater Acoustic Video Transmission

Mehdi Rahmati and Dario Pompili
Department of Electrical and Computer Engineering, Rutgers University–New Brunswick, NJ, USA
E-mails: {mehdi.rahmati, pompili}@rutgers.edu

Abstract— Transmitting large amounts of data such as videos underwater is an important yet challenging problem in the harsh underwater environment in which radio-frequency waves are absorbed for distances above a few tens of meters, optical waves require narrow laser beams and suffer from scattering and ocean wave motion, and acoustic waves—while being able to propagate up to several tens of kilometers—lead to a communication channel that is very dynamic, prone to fading, spectrum limited with passband bandwidths of only a few tens of kHz, and affected by non-Gaussian noise. Notwithstanding these challenges, a hybrid solution that is capable of transmitting at high data rates underwater via acoustic waves at short/medium distances is proposed. The solution introduces a novel signaling method, called Signal-Space-Frequency Beamforming (SSFB), for a multiple antenna array where each antenna consists of Uniform Circular Array (UCA) hydrophones mounted on an underwater vehicle to steer the beam in both azimuth and elevation planes; then, an array of Acoustic Vector Sensors (AVS)—hydrophones that are able to capture the acoustic particle velocity/direction of arrival in addition to measuring regular scalar pressure—are mounted on the surface buoy. Detection is performed based on the beam spatial separation and direction of arrival angles’ estimation. Simulation results confirm that this solution outperforms state-of-the-art underwater acoustic transmission techniques, whose data rates are limited only to few tens of kbps.

Index Terms—Acoustic vector sensors; underwater transmission; underwater wireless networks; multimedia transmission.

I. INTRODUCTION

Overview: Underwater networks enable a wide range of applications such as oceanographic data gathering, pollution monitoring, disaster prevention, and assisted navigation—just to name a few—in which mostly scalar values are sensed from the environment and transmitted to an onshore or surface station. However, many futuristic time-critical applications such as multimedia coastal and tactical surveillance, offshore exploration, sea floor mapping, submarine volcanism and hydrothermal vent studies require multimedia data to be retrieved, processed reliably in real time while it is being transmitted for video acquisition and classification [1].

For many of these futuristic applications, transmitting reliably videos underwater is a challenging problem in the environment in which Radio-Frequency (RF) waves are absorbed for distances above a few tens of meters, optical waves require narrow laser beams and suffer from scattering and ocean wave motion, and acoustic waves—while being able to propagate up to several tens of kilometers—lead to a communication channel that is very dynamic, prone to fading, spectrum limited with passband bandwidths of only a few tens of kHz due to high transmission loss at frequencies above 50 kHz, and affected by non-Gaussian noise [2].

In most cases Autonomous/Remotely Operated Underwater Vehicles (AUVs/ROVs) are key enabling instruments to support such futuristic applications as they can be equipped with cameras. However, current underwater vehicles are often tethered to the supporting ship by a high-data-rate fiber cable or have to surface periodically to communicate with a remote onshore station via terrestrial RF waves. Tethering is a serious limitation for the development of underwater systems for multimedia applications involving one or more underwater vehicles as it constrains severely the maneuverability and range of the vehicles, which run the risk to get tangled and compromise their mission. Resurfacing periodically, on the other hand, does not guarantee interactivity, which is key in real-time applications, and leads to energy/time inefficiencies.

Challenges: Although acoustic communication is the typical physical-layer technology underwater for distances above a hundred meters, yet, achieving high data rates for video transmission through the acoustic channel is hard to accomplish as acoustic waves suffer from attenuation, limited bandwidth, Doppler spreading, high propagation delay, and time-varying propagation characteristics [2], [3]. For these reasons, state-of-the-art acoustic communication solutions are still mostly focusing on enabling delay-tolerant, low-bandwidth/low-data-rate transmission or at best low-quality/low-resolution multimedia streaming in the order of few tens of kbps.

To achieve higher data rates in the bandwidth-limited underwater acoustic channel, several techniques should be combined together. For example, signal beamforming along with multiple antenna arrays [4] could achieve this goal; however, the main challenge is the position uncertainty of the users, which leads to inaccuracies in the estimation of beam angles—a key piece of information in beamforming—and therefore to overall performance degradation. The problem becomes even worse over time if the vehicle remains underwater for long because of the accumulation of its position error, which leads to non-negligible drifts in the vehicle’s position estimation, as attested by many works on underwater localization [51–7].

State of the Art: Over the past few years, researchers have come up with advancements in sensor technology that seem quite promising to overcome the limitations of traditional scalar hydrophones, which detect the acoustic pressure without any directional sensitivity. For example, Acoustic Vector Sensor (AVS) array consists of hydrophones that are able to...
capture the acoustic particle velocity/angle of arrival [8] in addition to measuring regular scalar pressure. This interesting characteristic can be used in determining the position of an acoustic source. Source localization using an array of AVSs is performed in [9] for multipath scenarios. This device can be exploited in a broad range of environments and is constructed using a variety of mechanical, optical, and micro-electromechanical (MEMS) technologies [10].

Contributions: In this paper, we exploit the potential of this recent sensor technology and present a novel AVS-based method to increase the effective data rate of underwater acoustic communications, i.e., to support reliable and high-data-rate video transmissions (in the order of hundreds of Kbps at the operating ranges of the application of interest, i.e., up to a few kilometers). To achieve this goal, we propose a novel signaling method, called Signal-Space-Frequency Beamforming (SSFB), that makes use of multiple domains to leverage the benefits of AVS. A novel arrangement for the vehicle’s antenna is presented, while the surface buoy (receiver) is equipped with AVS hydrophones and detects the signal based on the estimated direction of arrival angles. In addition to modulation, each antenna in a multiple antenna structure and also each subcarrier in Orthogonal Frequency Division Multiplexing (OFDM) system participate in the data rate increase, while inter-antenna-interference is avoided by a Non-Contiguous OFDM (NC-OFDM) technique specifically designed for this system to support video transmission.

Paper Outline: In Sect. II we discuss the related work and position our solution w.r.t. the literature. In Sect. III, we introduce a novel architecture for the system to support our solution. In Sect. IV, we present the basics of our method. Then, in Sect. V, we discuss the simulation setup and present the performance results. Finally, in Sect. VI, we draw the main conclusions and discuss future work.

II. RELATED WORK

The first image transmission via acoustic waves occurred in Japan, where the system [11] demonstrated the transmission over a vertical path with a low frame rate. Low-bit-rate video compression is another solution investigated in the literature to combat the limitations of underwater acoustic channels. The authors in [12] presented an algorithm based on the use of data compression/coding implemented and tested over a 10 m vertical channel with 60–90 kHz bandwidth. The feasibility of video transmission over short-length links was investigated in [13], [14], where MPEG-4 video compression and a wavelet-based transmission method were tested on coded OFDM. A joint optical/acoustic solution was presented in [15], which integrates high-data-rate and low-latency capabilities of optical communications in short transmission ranges with long-distance traveling of acoustics. Another acoustic/optical solution for video streaming was presented in [16], where the acoustic mode is used as backup in case of optical channel failure. Notice that, while optical-based techniques can support high data rates, all the optical solutions reported so far can only transmit at distances below ∼ 50 m due to scattering and laser-pointing-related issues. A software-defined underwater acoustic platform that supports higher data rates and provides flexibility and scalability for future underwater applications was discussed in [17].

However, despite all these works, the problem of robust video transmission is still unsolved, and achieving high video quality is still a challenge when we consider the limited available bandwidth along with the harsh characteristics of the underwater acoustic channel, which calls for novel high-spectral-efficiency methods. Recently, Non-Contiguous OFDM (NC-OFDM) has attracted the attention of researchers [18] due to its dynamic spectrum access and effective use of spectrum as a scarce resource, which increases the spectral efficiency of conventional OFDM while avoiding interference with other users, especially in cognitive radios and frequency-selective channels. The authors in [19] have suggested Index Modulation (IM) as an effective technique for Fifth Generation (5G) wireless networks, in which the indices of the OFDM blocks convey additional information bits. IM can be applied to several modulation schemes such as Spatial Modulation (SM) [20] in order to achieve higher data rates.

Hydroflown sensor [10] is a MEMS-based hydrophone set that is able to measure particle velocity and Angle of Arrival (AoA) [21]. Several algorithms have been proposed for AoA estimation for acoustic vector sensors. Maximum likelihood (ML), as a conventional method, maximizes the likelihood of the received signal from a particular angle. Multiple Signal Classification (MUSIC) [22] is an adaptive eigen-structure-based method that considers the noise subspace, while the signal subspace is considered in the Estimation of Signal Parameters via Rotational Invariance Technique (ESPRIT) [23], which assumes a displacement invariance for sensors. Matrix Pencil (MP) is similar to ESPRIT but, instead of estimating the correlation matrix, it exploits the spatial samples of the data based on a snapshot-by-snapshot basis, and therefore performs well in non-stationary environments [24].

Despite all these efforts, there are still open problems in signal processing and in the hardware needed to support real-time processing. Considering the characteristics of the underwater acoustic channel, direction-of-arrival estimation might be complicated since the position information of a vehicle is not accurate underwater. Although a vehicle may surface periodically to synchronize itself using Global Positioning System (GPS), which does not work underwater, self-inaccuracies in position estimation increases over time; also, the effect of drifting in ocean currents on the vehicle causes more uncertainties in the position, which leads to error in the angle-of-arrival estimation of the vehicle. These errors will lead to distortion in the video quality at the receiver, which translates to a low Quality of Service (QoS) for the user.

III. SYSTEM ARCHITECTURE

System Assumptions: Let us assume that the transmission occurs at short/medium ranges—up to a few kilometers—and that the direct beams are dominant over the reflected ones from the ocean surface/bottom, so that the receiver is not
severely affected by multipath. For farther distances—above a few kilometers—and based on the Sound Speed Profile (SSP), the acoustic rays bend towards the region of lower acoustic speed (“laziness law”). This effect changes the Angles of Departure/Arrival (AoD/AoA) and their estimations. Using the Bellhop model [25] and considering a typical deep-water case, Fig. 1 illustrates the SSP (left) and the acoustic ray tracing (right) in the underwater channel for a sample source at a depth of 1 km and temperature of 39°F. The bending effect can be observed by going above a few kilometers; however, staying within a short/medium range, such bending is not notable, which explains the philosophy behind our signaling method in which the vehicle is steered via beamforming. Moreover, propagation delays in acoustic links are five orders of magnitude larger than in terrestrial RF links, so short/medium ranges are more appropriate for video transmission applications.

Model Descriptions: As in Fig. 2, the model consists of an anchored buoy and a vehicle traveling at a fairly smooth and constant horizontal speed ranging between 0.25 to 0.5 m/s to capture data/video. Buoy and vehicle exchange control messages during the communication setup process. To avoid any interference with the data exchange process, we establish a separate control channel via Frequency Division Duplex (FDD); this will not have much impact on the overall data rate and bandwidth of the system as only a few bits per message are used. In this paper, downlink \((BV)\) defines the direction of acoustic communications from the surface buoy, \(B\), to the vehicle, \(V\); whereas uplink \((VB)\) represents data transmission in the opposite direction.

Several transducers are installed on a vertical bar at the buoy’s side starting from the depth of \(h_r\) with antenna spacing of \(d_h\)—more than half of the wavelength to avoid spatial correlation. An acoustic vector sensor array is embedded on the bar, which gives us the measured scalar pressure and the beam’s direction of arrival, in both the azimuth and elevation planes. The scalar response of the pressure sensor, which is omni-directional, is added to the responses of the vector sensors, which measure particle velocity and output the information about the beam’s direction of arrival. The sensitivity, the Directivity Factor \((D_f)\), and the Directivity Index \((DI)\) of these sensors depend on both the technology and the environment under study at a given range \(r\), where

\[
DI = 10 \log \frac{D_f}{D_{ref}},
\]

in which \(D_{ref}\) is the omni-directional reference intensity and \(D_f(\phi, \theta)\) can be defined as the ratio of the maximum acoustic intensity to the averaged intensity in all directions [26]. Plane wave is represented by \(\phi \in [-\pi, \pi]\) and \(\theta \in [-\pi/2, \pi/2]\) as the azimuth and elevation angles, respectively. The vehicle is equipped with one vector sensor for localization and control purposes in the downlink, and with multiple transmit antennae for sending data via its circular arranged acoustic transmitters capable of performing beamforming for the uplink communications. As a result, differently from the conventional linear arrangement, beamforming and direction-of-arrival estimation are performed in both azimuth and elevation planes.

As the array’s elements can be placed according to different shapes (linear, circular, or rectangular), Uniform Circular Array (UCA) [27], [28] is exploited to leverage its higher performance compared with a Uniform Linear Array (ULA). Since the mobility of the vehicle might change the estimation of angles and, as a result, decrease the reliability of the reception, in this paper, as an alternative configuration for the linear placement and linear array, a circular arrangement and UCA with \(D > \lambda\) are proposed. \(D\) and \(\lambda\) represent the circle’s diameter and the acoustic wavelength, respectively. Interestingly, the circular array can form the beam of \(2\pi\) in azimuth plane and \(\pi\) in elevation plane with little change in either the beamwidth or the sidelobe level [28].

In Fig. 3, DIs of UCA and ULA are compared, where DI accounts for the spatial gain in energy as a result of using directive antenna to the same antenna without directivity [26]. It confirms that UCA is a better choice to combat the channel attenuation, especially at the higher acoustic frequencies.

IV. SSFB: PROPOSED SIGNALING METHOD

To take advantage of AVS, the vehicle’s exact location should be determined. If the ocean currents are assumed unknown, the vehicle’s drifting in the horizontal plane is identically and independently distributed (i.i.d.) and follows a normal distribution, which makes the horizontal projection
of its confidence a circular region. Regarding the vehicle’s movement along its trajectory, there is an uncertainty in the position of the vehicle. This uncertainty region is shown to be a cylinder [7], [29], as in Fig. 2. First, in Sect. IV-A, in order to determine the angles of departure/arrival, we study the uncertainty region and present the proposed protocol. We create spatial pipes towards the vehicle via beamforming based on the uncertainty region and its corresponding angles. Then, based on the estimated angles, the data will be transmitted via the proposed uplink signaling, i.e., SSFB. Afterwards, in Sect. IV-B, the receiver design and the discussion on the data rate compared with other methods are presented.

A. Vehicle Steering Protocol

The procedure is divided into six steps as shown in Fig. 4.

Steps 1 & 2—Vehicle’s Location Uncertainty Estimation: We aim at estimating the location of vehicle given the inherent position uncertainty of objects underwater. The process starts by the buoy’s request command and at the same time setting timer 1 until all the required location samples are gathered. Upon receiving this message and every Δₜ seconds, vehicle V samples its current estimated location loc(Vₙ), n = 1, ..., Nₛ, via Dead reckoning, where Nₛ is the total number of required samples. Timer 1 stops after τ₁ = Nₛ Δₜ + tₚ + tₜ, where tₚ is the time due to the propagation delays and tₜ stands for the distance-based transmission delays in short/medium ranges. There are internal- and external-uncertainties [7] in the trajectory and location estimation of the vehicle, which are considered in the next step.

Step 3—Coarse Buoy’s AoD Estimation: Using Nₛ vehicle’s location samples gathered at the buoy, locations are converted to steering angles θₙ and φₙ, n = 1, ..., Nₛ, in azimuth and elevation planes to estimate the angular uncertainty region of the vehicle via the method introduced in [29]. Let us perform the analysis for one of the planes, i.e., random variable θ with mean value μ and standard deviation σ. The estimation with mean value θ₀ and standard deviation σ₀ can be derived as, θ₀ = ∑ Nₛ n=1 θₙ/Nₛ, and σ₀ = √ 1/(Nₛ−1) ∑ Nₛ n=1 (θₙ − θ₀)²/2. The buoy’s beamwidth is chosen in such a way that it is equal to the confidence interval [30] of θ₂ [29], i.e.,

\[ \Pr(θ₂^(B) ≤ θ₀ ≤ θ₂^(B)) ≥ 1 − α, \] (1)

where θ₂^(B) represents the probability function, θ₂^(B) and θ₂^(B) are the lower and upper angular boundaries at buoy B pointing at the bottom and top of the uncertainty region, 1 − α is the confidence degree [30], and TNₛ−1,α/2 is the student’s t-distribution critical value with Nₛ − 1 degrees of freedom. The buoy forms its estimated Half Power Beam Width \( \tilde{W}_θ^{(BV)} \), in the interval of ±TNₛ−1,α/2 σ₀/√Nₛ around θ₀, as \( \tilde{W}_θ^{(BV)} = θ₂^(B) − θ₁^(B) \), while AoD from buoy towards vehicle is calculated as θ₁^(B) = θ₂. Similarly, it can be concluded that \( \tilde{W}_φ^{(BV)} = φ₂^(B) − φ₁^(B) \) and \( \tilde{φ} = φ₂ - φ₁ \). If this calculation takes t₂ seconds, then timer 2 stops after τ₂ = τ₁ + t₁ + t₂, when the estimation is sent to the buoy.

Step 4—Fine Steering Estimation Using AVS: The angular estimation extracted via the vehicle’s vector sensor is fed to vehicle’s beamformers and is simultaneously reported to the buoy to be used as reference in its tracker. Tuning the antenna from vehicle to buoy (i.e., \( W_φ^{(BV)} \), \( Γ_θ \), \( W_θ^{(BV)} \), and \( Γ_φ \) as depicted in Fig. 5) is performed via the angles measured at vehicle’s vector sensor, and is refined based on the prior coarse estimations, i.e., \( W_φ^{(BV)} \), \( Γ_θ \), \( W_θ^{(BV)} \), and \( Γ_φ \), and the trajectory vector. Several methods were suggested for AoA estimation in the literature, ranging from correlation [24] and ML [31] to MUSIC [22] and ESPRIT [23], based on the assumptions and characteristics of the used elements. Generally, AoA estimation at the vehicle can be written as,

\[ y(V)(t) = A(V)φ(V) + x(V)(t) + z(t), \] (3)

where y(V)(t) is the signal at the vehicle’s antenna, x(V)(t) is the channel affected vector of signals from buoy to vehicle x(buoy)(t), z(t) is the underwater noise vector with the
covariance matrix $\mathbf{Q}_z$, and $\mathbf{A}^{(V)}$ is the steering vector at the vehicle as a function of unknown parameter $\psi^{(V)}$. In our case, $\psi^{(V)} = [\hat{\theta}^{(V)}, \hat{\phi}^{(V)}]$, with unknown arriving angles and the estimated angles of $\hat{\theta}^{(V)}$ and $\hat{\phi}^{(V)}$ are geometrically proportional to $\hat{\theta}^{(B)}$ and $\hat{\phi}^{(B)}$ at the buoy. Regarding the coarse estimation, the angles can be bounded as,

$$\frac{-\ln(1)}{2} < \hat{\theta}^{(B)} < \frac{-\ln(2)}{2},$$

$$\frac{-\ln(1)}{2} < \hat{\phi}^{(B)} < \frac{-\ln(2)}{2}.$$  

The scanning range in (4) is now narrower by the half power beamwidth instead of the whole angular range. Estimation variance is lower bounded by the Cramer-Rao Bound (CRB) and upper bounded by the variance of the coarse estimation. We describe the equation for azimuth plane as,

$$y^{(V)}(t, \theta, \phi) = y^{(V)}(t, \hat{\theta}, \hat{\phi}) + z(t),$$

where $y^{(V)}$ is the received signal as a function of AoA and $r$ stands for the effect of underwater acoustic channel on the signal. The transmitted signal can be written as follows,

$$r_k^{(V)}(t, \theta, \phi) = r_k^{(V)}(t, \theta, \phi) + z(t).$$

In (8), $\mathbf{F}^{(V)}$ stands for the beamforming vector determined by the array antenna. We utilize UCA to steer the beam towards the desired antenna, so the $\varpi - \theta$ element of the beamformer in UCA with the angle of $\varpi$ w.r.t. the x-axis is calculated via (9), as in [27].

$$\text{exp} \left( \frac{2\pi}{\lambda} \left\{ \frac{D_n}{2} \sin(\theta^{(V)}) \cos(\varpi^{(V)} - \varpi) \right\} \right),$$

where $\lambda$ is the wavelength of the signal and $D_n$ is the diameter of UCA. $s_k(t)$ is the transmitted OFDM frame of the $k - \theta$ antenna-set as follows.

$$s_k(t) = \sum_{\xi=0}^{N_c-1} X^{(k)}(\xi) \text{exp}(j2\pi f_s t), \quad X^{(k)}(\xi) \in \{ \delta_\xi e^{j\beta}, 0 \}.$$  

Total number of subcarriers is shown by $N_C$ while $f_s = \xi f_s$ represents the subcarrier frequency. Choosing $f_s = 1/(N_C T_s)$, where $T_s$ is the sampling interval, leads to orthogonality among different subcarriers in OFDM. $X_\xi$ can be either a data/pilot subcarrier or a null subcarrier. $\delta_\xi$ and $\beta_\xi$ stand for the amplitude and the phase of the desired constellation point, respectively. Note that the data/pilot subcarriers of each antenna are overlapped with the null subcarriers of other antennae, so all the antennae can transmit simultaneously without any
is bits define the appropriate
is created. Data stream is made
bits \( M \)
frames. The
\( + \log_2(b) \in 1 \) otherwise.
stands for the reference angles vector
\( = \), is the number of elements in antenna set
\( (14) \)
\( - \) matrix of estimated frames
\( = 1 \) \( q \) \( - \) estimate of the transmitted signal
as follows,
\( \tilde{N}_1 \) from set
\( \) is the vector of estimated angles at the
\( \) is the designated antennae in each set and in every transmission course exploits a portion of subcarriers in the NC-OFDM; (b) Receiver block diagram
in which the received frames are treated. Subcarrier index and subcarrier index extraction is shown as a matrix of frames, before detection is performed.

Fig. 6. (a) Transmitter signaling blocks for the proposed SSFB method. The designation table shows how data bits are grouped for transmission. Each one of the \( N \) implemented antennas in each set and in every previous round of transmission.

We assume that each block of \( N \log_2 N + \log_2 M \) bits consists of segments of \( n + m \)-bits; the first \( n=\log_2 N \) bits define the transmitting antenna in every set containing \( N \) antennas, while the last \( m=\log_2 M \) bits define the appropriate transmitted signal regarding the chosen modulation scheme of order \( M \). Designation table assigns the bits to the appropriate antenna and constellation point. Frequency designation is performed via transmitting signals of different antennas on the orthogonal subcarriers of \( N \) NC-OFDM frames. The \( \xi \) \(-\)subcarrier of the corresponding antenna’s NC-OFDM frame and the other subcarriers in this frame are switched off.

\[
\xi_{fs} = \begin{cases} 
\Xi_i, & b_i, i \in [\{\xi+1\}n + \xi m + 1 \ldots (\xi + 1)(n + m)], \\
0, & \text{otherwise.} 
\end{cases} 
\]

Accordingly, every single antenna utilizes the unoccupied portions of the spectrum of other antennae. Note that unlike conventional Spatial Modulation (SM) [20], in which each symbol is sent via different antenna and so a very fast antenna switching is required, our proposed method first forms a complete frame of desired subcarriers for each antenna and then sends it at once. This feature is essential since fast switching signal transmission is not practical underwater because of the long propagation delay of the acoustic channel. In our method, all \( N \) implemented antennae are active and the subcarriers are being used efficiently; however, for each transmission, only one antenna transmits in each subcarrier.

B. AVS-based Receiver and Rate Comparison

Figure 6(b) describes the receiver of the system at the buoy, while AVS gives us an estimate to decide on the desired antenna \( q \) from set \( k \) as follows,

\[
\tilde{q} = \arg \min_{q \in \{1, \ldots, N_k\}} \left\| \left[ \tilde{\theta}^{(B)}_{ki}, \tilde{\phi}^{(B)}_{ki} \right] - \left[ \tilde{\theta}_{op}^{(B)}, \tilde{\phi}_{op}^{(B)} \right] \right\|^2, 
\]

where \( \left[ \tilde{\theta}^{(B)}_{ki}, \tilde{\phi}^{(B)}_{ki} \right] \) is the vector of estimated angles at the buoy and \( \left[ \tilde{\theta}_{op}^{(B)}, \tilde{\phi}_{op}^{(B)} \right] \) stands for the reference angles vector including all the antennae in every previously estimated set. To describe how AVS estimation error leads to the error in the detection, assume the angular decision on \( q \) is made in the region of \( \{ \tilde{\theta}^{(B)}, \tilde{\phi}^{(B)} \} : -\pi/N_k < \tilde{\theta}^{(B)} < \pi/N_k \), with Probability Density Function (PDF) of \( P_{\theta,\phi}(\theta, \phi) \), the error probability, \( P_e \), can be calculated as,

\[
P_e = 1 - \int_{-\pi/N_k}^{\pi/N_k} P_{\theta,\phi}(\theta^{(B)}, \phi^{(B)}) d\theta d\phi,
\]

where \( N_k \) is the number of elements in antenna set \( k \).

An OFDM frame consists of a preamble—for synchronization and Doppler estimation—and of data blocks. Let us define \( \tilde{y}^{(B)}(t) \) as the estimated received signal after antenna decision. NC-OFDM receiver performs Fast Fourier Transform (FFT) to detect data subcarriers.

\[
\tilde{Y}^{(k)}(\xi) = \frac{1}{T_s} \int \tilde{y}^{(B)}(t) e^{-j2\pi f_{fs} t} dt,
\]

where \( \tilde{Y}^{(k)}(\xi) \) is an estimate of the transmitted signal \( X^{(k)}(\xi) \) at the receiver. Following NC-OFDM receiver block, data subcarrier extraction block makes an \( N \times N_C \) matrix of estimated frames.
and the others should be null. The non-zero data of row element in each column contains data above the noise level. In the case of perfect frequency synchronization, only one column is considered; (c) Throughput of the system with different antenna sets versus variable number of subcarriers compared with OFDM-IM. Four transmitter antennae with QPSK modulation are used.

We assume a channel with a number of sparse and separable paths, in which the first path is the strongest part of signal. To extract the channel characteristics for our simulations, the channel was exploited from Kauai Acomms MURI (KAM08) experiment at the western coast of Kauai, HI, USA [35] where an anchored vertical hydrophone array with 3.75 m inter-element spacing at the depth of 96 m communicates with a source towed by a surface ship. The channel bandwidth is 25 kHz and the sampling rate is 50 kHz. Figures 7(a)-(b) show the normalized delay profile and the phase response of the channel, respectively. An Underwater colored ambient noise, leading to a $SNR \in [0, 30]$ dB, is considered as the background additive noise. Initially, we assume 512 subcarriers are present in every NC-OFDM frame. The proposed system contains an inherent zero padding by nulling the other interfering antennae. The recorded video which will be sent during the simulation is an MP4 RGB-24 video with the duration of 5.2 s and frame resolution $240 \times 320$. Transmission starts with an initial delay of $\tau_1 + \tau_2$ seconds, as explained in Fig. 4.

Results and Discussions: Fig. 8(a) shows the performance in which the $\tilde{q}$-th antenna frame is placed in the $q$-th row. In the case of perfect frequency synchronization, only one element in each column contains data above the noise level and the others should be null. The non-zero data of row $q$ and column $\xi + 1$, \(i.e., \tilde{\Xi}_{q,\xi+1}\) is demodulated in the next block and determines the output frame, using the designation table.

\[
\begin{align*}
\tilde{\Xi}_{q,\xi+1} & \rightarrow b_i, \quad i \in [(\xi + 1)n + \xi m + 1 \ldots (\xi + 1)(n + m)], \\
q & \rightarrow a_i, \quad i \in [(\xi + 1)n + 1 \ldots (\xi + 1)n + \xi m].
\end{align*}
\]

(15)

Rate Comparison: While conventional SM transmits $\log_2 N + \log_2 M$ bits per transmission (bpt), Multiple Active SM (MA-SM), an extended version of SM, transmits $\log_2 \left(\frac{N}{i}\right) + N_i \log_2 M$ bpt from $N_i$ active antennae [19], where $\lfloor \cdot \rfloor$ rounds to the nearest lower integer. OFDM-IM can transmit $\lfloor \log_2 \left(\frac{N}{G}\right) \rfloor + K \log_2 M$ Gbps, where $G \times N = N_G$. Here, $G$ stands for the number of groups, and $N_G$ shows the number of subcarriers in each group. The number of transmitted bits in each transmission course (for $I_B$ sets of antenna at the buoy) for our proposed system is calculated as,

\[
R = I_B N_G (\log_2 N + \log_2 M).
\]

(16)

V. PERFORMANCE EVALUATION

Simulation Settings: We consider a short/medium range transmission (less than 2 km), in which the anchored buoy has an attached bar with installed hydrophones and the vehicle can move with a smooth and almost constant horizontal speed on the other side, as depicted in Fig. 2. Two sets of circular antennae are on the vehicle, each one contains four UCAs while two separate vector sensors are on the buoy. To avoid spatial correlation between antennae, we need to keep the minimum distance between adjacent elements more than $\lambda/2$.

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V. PERFORMANCE EVALUATION

Simulation Settings: We consider a short/medium range transmission (less than 2 km), in which the anchored buoy has an attached bar with installed hydrophones and the vehicle can move with a smooth and almost constant horizontal speed on the other side, as depicted in Fig. 2. Two sets of circular antennae are on the vehicle, each one contains four UCAs while two separate vector sensors are on the buoy. To avoid spatial correlation between antennae, we need to keep the minimum distance between adjacent elements more than $\lambda/2$.
of the proposed system with different modulation orders whereas its BER in the lower SNRs is not satisfactory, regardless of the modulation order. The reason is that null subcarriers are covered by the background noise and so their energy level is comparable with the data subcarriers; therefore, the receiver fails in the process of data subcarrier extraction. The throughput of the system is plotted in Fig. 8(b) in terms of number of bits per transmission course (bpt). Considering these two figures and due to the throughput-BER tradeoff, the most proper modulation scheme is chosen. Therefore, SVC adaptively changes the rate for the next round of transmission. Figure 8(c) compares SSFB with the conventional OFDM-based methods. The proposed solution outperforms other techniques in terms of bit error rate, especially in higher SNRs.

Figure 9(a) confirms that the average Bits Per Symbol (BPS) of SSFB is higher than of SISO- and MIMO-OFDM, when similar modulation order is used for all of them. Moreover, it is observed that SSFB can result in the same BPS values as SISO- and MIMO-OFDM, by using a lower modulation order with the lower error rate. Figure 9(b) confirms that SSFB outperforms the conventional methods in terms of throughput.

Regarding conventional SM, SSFB has a considerable data rate, while it covers the fast antenna switching problem of SM by forming the frames prior to transmission. SSFB rate is around double in comparison with OFDM-IM. In Fig. 9(c), SSFB throughput is compared with OFDM-IM for different number of subcarriers and antenna sets. The bpt of 4 antennas with 512 subcarriers equals using two antenna sets with 1024 subcarriers. Therefore, the later one is preferred regarding its lower probability of antenna beam interference.

Figure 10(a) shows that SSFB is less vulnerable to Doppler shift than SISO- and MIMO-OFDM, especially in higher SNRs. Figure 10(b) investigates the effect of horizontal buoy-vehicle distance on the transmission rate. In Fig. 10(c), we study the situation in which antenna decision making at the receiver is not successful due to the vehicle’s drifts. Under severe drifts, the receiver suffers from error in AoA estimation and antenna decision, which leads to higher error rate. This error is fed back to the SVC encoder to be considered while making decision on the layer to be sent for the next round of transmission. Meanwhile the angular calculation process is restarted, as explained in Fig. 4.

In Fig. 11(a), the array response of UCA is plotted; and Fig. 11(b) shows the result of applying the designed beamformer to the UCA. It demonstrates that it could follow the original signal while focusing energy on a specific direction. Figure 11(c) confirms that AoA estimator is successful in separating two signals arrived at 30 and 65 degrees.

Simulated video transmissions through SSFB is shown for two frames in Figs. 12(a) and (b). In the first scenario, we assume that the vehicle has the least drift. AoA estimation and the antenna decision are performed successfully. This result is reflected in Figs. 12(c) and (d). Figures 12(e) and (f) represents the second scenario, in which vehicle experiences AoA estimation and antenna decision error. Frames can not be recovered when the amount of AoA estimation error increases significantly. In this case, the error is fed back and the encoder changes the compression for the next round of its operation.

VI. CONCLUSIONS AND FUTURE WORK

We designed an Acoustic Vector Sensor (AVS)-based solution, called Signal-Space-Frequency Beamforming (SSFB), to transmit underwater videos at high data rates using acoustic waves for short/medium distances. The receiver (buoy) was equipped with AVS—hydrophones that measures acoustic particle velocity in addition to scalar pressure—in a multiple-
antenna-array configuration, while the transmitter (vehicle) was equipped with a circular array of transducers. Data was modulated and transmitted via NC-OFDM, and detected via beam’s angle of arrival at the receiver (buoy). Simulations showed that video transmission rates can enable applications such as coastal and tactical surveillance, which require multimedia acquisition and classification.

Work is underway towards an implementation on software-defined acoustic modems for field testing and experimental validation. A non-trivial, yet interesting, extension of this work would involve using several vehicles as mobile transceivers in a coordinated spatially-separated mission.

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