PARTICLE VELOCITY UNDERWATER DATA COMMUNICATION: PHYSICS, CHANNELS, SYSTEM AND EXPERIMENTS

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Abstract

The largely unexplored underwater world has strong and multi-faceted ties with our lives. There are numerous ocean-related areas and applications such as oceanography, climate, pollution and environmental monitoring that have created increasing demand for wireless acoustic data communication among underwater sensors, platforms and autonomous vehicles. Contrary to wireless transmission in air, electromagnetic waves are strongly attenuated in water, whereas acoustic waves are proper carriers of information in water, since compared to electromagnetic waves, they typically incur less attenuation in water. However, the underwater bandwidth is usually highly limited. Here, we demonstrate that it is possible to multiplex multiple data streams over acoustic particle velocity field components using a proposed compact vector transmitter and over the same bandwidth. In existing underwater communication systems, data are conventionally modulated on acoustic pressure, i.e., scalar component of the acoustic field, using one scalar transmitter. Arrays of several spatially-separated scalar transmitters are also used, to transmit multiple data streams simultaneously. However, given the large size of an equipment carrying an array of several transmitters, many modern underwater platforms such as autonomous underwater vehicles cannot use multiple transmitters. Our experimental results demonstrate that using the developed vector transmitter, together with the proposed physics-based particle velocity modulation method over co-located underwater vector field components, multiple data streams can be concurrently transmitted, without requiring additional bandwidth. Using our findings, small size underwater acoustic systems, modems and equipment can be built that benefit from the acoustic vector field components.

Index Terms

Underwater acoustic communication; acoustic particle velocity; data multiplexing.

I. INTRODUCTION

About three quarters of the earth surface is covered with water that overlays many resources upon which our lives depend. Wireless underwater data communication among underwater sensors, deep-water instruments, autonomous underwater vehicles and surface ships is of high importance in many applications. The applications include oceanography, climate, environmental and pollution monitoring, hydrography and aquatic studies, with diverse end users ranging from scientific research and development to homeland security, and oil and gas scientists and engineers. The underwater acoustic bandwidth is typically limited. One remedy is to simultaneously transmit multiple data streams over the available bandwidth, i.e., data multiplexing. Data multiplexing in wireless systems utilizing electromagnetic waves was first invented using multiple individual transmitters (multiple antennas) [1]. Using certain properties of electromagnetic waves, polarization multiplexing and orbital angular momentum multiplexing were also discovered for data multiplexing in wireless terrestrial systems. Code division multiple access is another method for transmitting information using the same bandwidth. Given the strong attenuation of electromagnetic waves in underwater environments, acoustic waves are proper carriers of information in underwater communication systems, since compared to electromagnetic waves, they typically incur less attenuation in water. In existing underwater systems, data are modulated on acoustic pressure, which is the scalar component of the acoustic field, using one scalar transmitter. The use of multiple individual scalar transmitters for multiple-input multiple-output (MIMO) underwater communication is also extensively studied, e.g., [2]-[4] and references therein. However, given the large size of a communication modem carrying several transmitters, underwater platforms such as medium and small autonomous and unmanned underwater vehicles may not have the option of communicating via multiple transmitters.

In this paper, we propose and experimentally demonstrate that upon utilizing the unique physics of underwater acoustics, it is feasible to multiplex several data streams from a single transmitter. The key idea is to devise a method which benefits from the vector nature of the underwater acoustic field for data multiplexing. In this paper, we present a method and implement a system accordingly, to modulate multiple data streams on underwater acoustic particle velocity components, with particle velocity being the aforementioned vector field to explore. The fundamental difference between the introduced approach and other underwater acoustic communication methods and systems is that they modulate data on the acoustic pressure, which is the scalar component of the acoustic field. Underwater acoustic vector field components were proposed to be used in communication receivers and for multi-channel equalization [5]. Afterwards, theoretical foundation of particle velocity data multiplexing was introduced [6]. Signal processing applications of vector sensors are focused on other topics such as source localization, direction of arrival estimation and beamforming, e.g., [7]-[9] and references therein.

The rest of this paper is organized as follows. Section II presents the proposed concept of data modulation over the underwater acoustic particle velocity channels, the definitions and equations for such channels, and also implementation methods to communicate through these channels. Details of the developed particle velocity communication systems and the experimental results are provided in Section III. At the end, some concluding remarks are presented in Section IV.

II. UNDERWATER ACOUSTIC PARTICLE VELOCITY CHANNELS AND DATA MODULATION

A. Basic Concepts

Acoustic particle velocity is a vector quantity whose magnitude in each axis is the spatial gradient of acoustic pressure in that direction [10]. To modulate data on a specific acoustic particle velocity component, for example, the *x*-axis component, we propose to acoustically induce data into water at the transmit side such that from the viewpoint of the receive end, the spatial gradient of the acoustic pressure along the *x* axis becomes convolved with the data.

To explain the proposed particle velocity modulation method, we use dipoles. Consider two dipoles along the *x* and *y* axes (Fig. 1a), each composed of two closely spaced scalar transmitters. To modulate a signal or data stream s_1 on the *x*-dipole, we propose the poles A and B (Fig. 1a) to transmit s_1 and $-s_1$, respectively. To understand why this proposed method modulates s_1 on the *x* particle velocity component, let h_{Aq} and h_{Bq} represent the acoustic pressure channel impulse responses between A and B and a scalar receiver q, respectively (Fig. 1a). Therefore, the received signal can be written as a superposition of the convolution of s_1 and $-s_1$ with h_{Aq} and h_{Bq}, respectively, i.e., $r = h_{\mathrm{Aq}} \oplus s_1 + h_{\mathrm{Bq}} \oplus (-s_1) = (h_{\mathrm{Aq}} - h_{\mathrm{Bq}}) \oplus s_1$, where $\oplus$ is the convolution. On the other hand, $h_{\mathrm{q}}^{x} = \partial h_{\mathrm{oq}} / \partial x$ is the *x* component of the acoustic particle velocity impulse response, i.e., the spatial gradient of h_{oq}, where h_{oq} is acoustic pressure channel impulse response between the point "o" (Fig. 1a) and the scalar receiver q. Given the small spacing d_{AB} between A and B, finite difference representation of the spatial gradient results in $h_{\mathrm{q}}^{x} = \partial h_{\mathrm{oq}} / \partial x \approx (h_{\mathrm{Aq}} - h_{\mathrm{Bq}}) / d_{\mathrm{AB}}$, that is, h_{q}^{x} is proportional to $h_{\mathrm{Aq}} - h_{\mathrm{Bq}}$. By substituting this into the received signal equation we obtain $r = h_{\mathrm{q}}^{x} \oplus s_1$, where the proportionality constant is considered to be 1, just to simplify the notation in the subsequent equations. This is a key result which demonstrates that upon using the proposed method, the signal or data stream s_1 is indeed modulated on the *x* particle velocity channel h_{q}^{x}. Similarly, a second signal or data stream s_2 can be simultaneously modulated on the *y* particle velocity channel h_{q}^{y} (These particle velocity vector channels are not orthogonal at the receiver side, even when signals are received by an aligned vector receiver). Some graphical illustrations of these particle velocity channels are presented in the next subsection, followed by experimental measurements of such channels discussed in Section III.

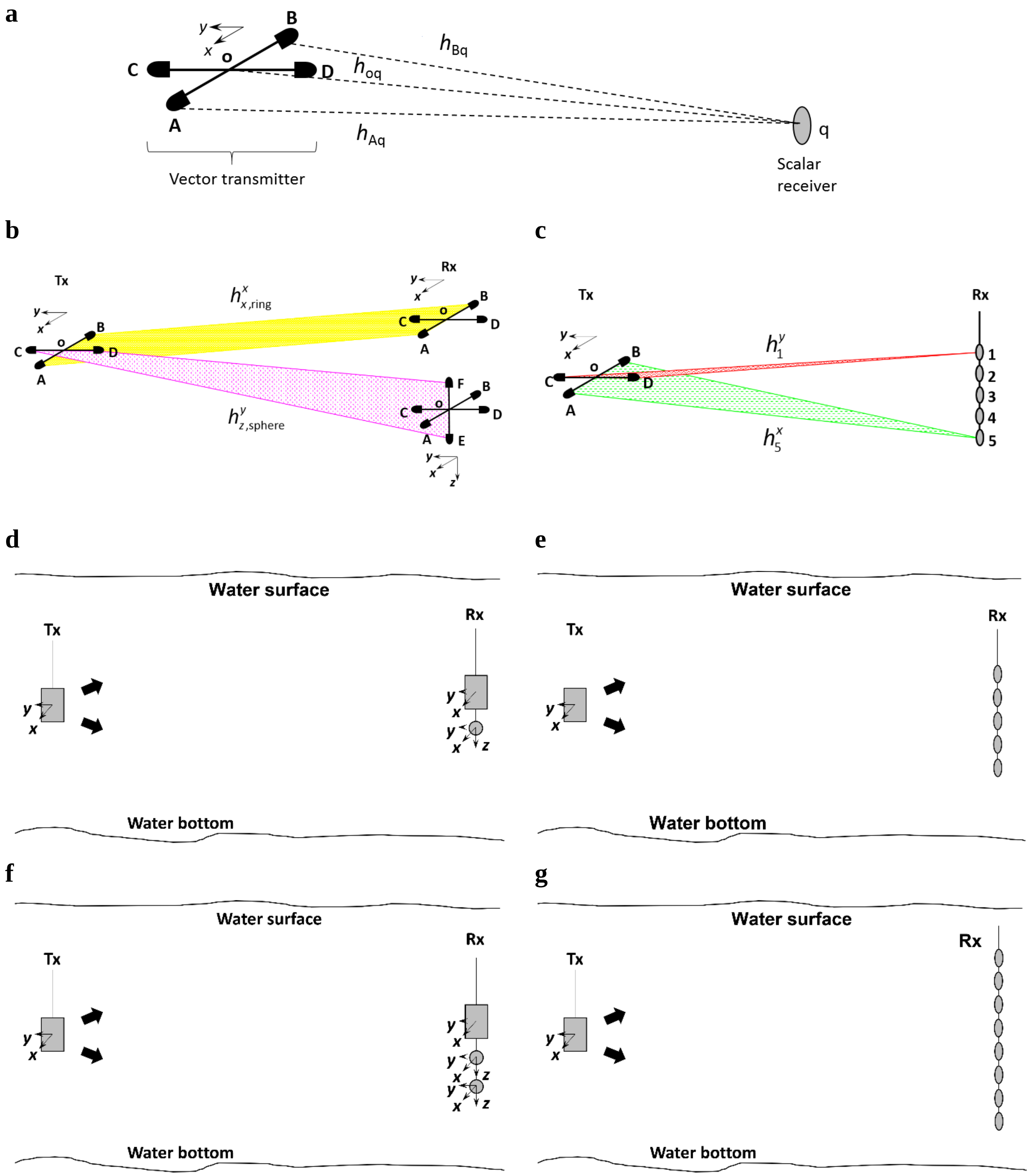

Fig. 1. The proposed particle velocity double data multiplexing system for underwater acoustic communication via one vector transmitter and various number of vector or scalar receivers. a, Schematic representation of the proposed vector transmitter for particle velocity data multiplexing. There are two dipoles along the *x* and *y* axes. **b,** Illustration of two out of ten vector particle velocity-related communication channels in the proposed fully-vector system: Two transmitting dipoles, two receiving dipoles and three receiving dipoles (a 2×5 system).

Fig. 1. (continued) c, Illustration of two out of ten semi-vector particle velocity-related communication channels in the proposed semi-vector system: Two transmitting dipoles, and five receiving scalar hydrophones (a 2×5 system). **d,** The proposed fully-vector underwater communication system, a 2×5 system, implemented with one ring vector transmitter acting as two dipoles (Fig. 1b, left), one ring vector receiver (two dipoles, Fig. 1b, right) and one sphere vector receiver (three dipoles, Fig. 1b, right). **e,** The proposed semi-vector underwater communication system implemented with one ring vector transmitter acting as two dipoles (Fig. 1c, left) and five hydrophone scalar receivers, a 2×5 system, considered for comparison. **f,** A fully-vector system with one ring vector transmitter, one ring vector receiver and two sphere vector receivers (a 2×8 system). **g,** A semi-vector system with one ring vector transmitter and eight hydrophone scalar receivers, a 2×8 system, considered for comparison.

Overall, the proposed idea represents particle velocity multiplexing of two data streams. Since the transmitter (Fig. 1a) modulates data on *x* and *y* components of a vector quantity, i.e., the acoustic particle velocity, we call it a vector transmitter. In principle, a third dipole can be added along the *z* axis, to modulate a third signal or data stream s_3 on the *z* particle velocity. However, as explained later, we devise a specific triple data multiplexing method that still uses the vector transmitter as is (Fig. 1a), without adding a third dipole.

B. Various Underwater Acoustic Particle Velocity Channels

Using the proposed vector transmitter composed of two dipoles (Fig. 1a), we propose two-dipole and three-dipole vector receivers (Fig. 1b), and an array of five spatially-separated hydrophone scalar receivers (Fig. 1c) for comparison purposes (practical implementations of the vector transmitter using a ring device and the vector receivers using ring and sphere devices are discussed at the end of this subsection). There are 10 particle velocity-based communication channels in each system (Fig. 1b, 1c). To name all these channels originating from the vector transmitter, we use superscripts to indicate the transmitting dipoles, and subscripts to identify the receiving dipoles and scalar hydrophones (Fig. 1b, 1c). For example, $h^{y}_{z,\text{sphere}}$ is the communication channel when a *y*-dipole transmits and *z*-dipole of a sphere receives (Fig. 1b). As two further examples, h^{x}_{5} represents impulse response of an *x* particle velocity channel between a transmitting *x*-dipole and hydrophone number 5 of a receiving scalar array (Fig. 1c), whereas h^{y}_{1} represents impulse response of a *y* particle velocity channel between a transmitting *y*-dipole and hydrophone number 1 of the same receiving scalar array (Fig. 1c). In what follows, the complete set of all the underwater acoustic particle velocity-based channels and signals are presented in Equations (1)-(6).

In the semi-vector system (Fig. 1c), h_{q}^{i}, $i = x, y$, represents the impulse response of the i particle velocity channel between the transmitting i-dipole and hydrophone number q of the receiving scalar array. As demonstrated in the previous subsection, we have $h_{\mathrm{q}}^{i} = \partial h_{\mathrm{oq}} / \partial i$, i.e., it is the spatial gradient of the acoustic pressure channel impulse response between the center of the transmitting dipoles and the scalar receiver q.

With the signals or data streams s_1 and s_2 concurrently modulated on the x-dipole and y-dipole, respectively, using the method presented in the previous subsection, equation for the signal received by the scalar receiver q in Fig. 1c, the semi-vector system, can be written as:

$$r_{\mathrm{q}} = h_{\mathrm{q}}^{x} \oplus s_1 + h_{\mathrm{q}}^{y} \oplus s_2 + n_{\mathrm{q}}, \;\; \mathrm{q} = 1, \ldots, 5 . \tag{1}$$

In the above equation, $\oplus$ is the convolution and n_{q} is the ambient acoustic pressure noise at the scalar receiver q. Two of the above ten channels in Equation (1), h_5^{x} and h_1^{y}, are graphically illustrated in Fig. 1c as some representative examples.

In the fully-vector system (Fig. 1b), we have these two sets of channels: $h_{\kappa,\mathrm{ring}}^{i}$, $i = x, y$, $\kappa = x, y$, and $h_{\ell,\mathrm{sphere}}^{i}$, $i = x, y$, $\ell = x, y, z$, where the superscripts specify the transmitting dipoles and the subscripts refer to the receiving dipoles. More specifically, $h_{\kappa,\mathrm{ring}}^{i}$ is the communication channel impulse response when the i-dipole transmits and the κ-dipole of a ring receives. Additionally, $h_{\ell,\mathrm{sphere}}^{i}$ is the communication channel impulse response when the i-dipole transmits and the ℓ-dipole of a sphere receives. Upon expanding the approach presented in the previous subsection, $h_{\kappa,\mathrm{ring}}^{i}$ and $h_{\ell,\mathrm{sphere}}^{i}$ can be shown to be the second spatial gradients of the acoustic pressure channel impulse responses between the centers of the transmitting and receiving dipoles.

By modulating the signals or data streams s_1 and s_2 simultaneously on the x-dipole and y-dipole, respectively, using the method introduced in the previous subsection, equations in the fully-vector system (Fig. 1b) for the signals received by receiving dipoles can be written as:

$$r_{x,\text{ring}} = h^{x}_{x,\text{ring}} \oplus s_1 + h^{y}_{x,\text{ring}} \oplus s_2 + n_{x,\text{ring}}\,, \tag{2}$$

$$r_{y,\text{ring}} = h^{x}_{y,\text{ring}} \oplus s_1 + h^{y}_{y,\text{ring}} \oplus s_2 + n_{y,\text{ring}}\,, \tag{3}$$

$$r_{x,\text{sphere}} = h^{x}_{x,\text{sphere}} \oplus s_1 + h^{y}_{x,\text{sphere}} \oplus s_2 + n_{x,\text{sphere}}\,, \tag{4}$$

$$r_{y,\text{sphere}} = h^{x}_{y,\text{sphere}} \oplus s_1 + h^{y}_{y,\text{sphere}} \oplus s_2 + n_{y,\text{sphere}}\,, \tag{5}$$

$$r_{z,\text{sphere}} = h^{x}_{z,\text{sphere}} \oplus s_1 + h^{y}_{z,\text{sphere}} \oplus s_2 + n_{z,\text{sphere}}\,. \tag{6}$$

In the above equations, $r_{\kappa,\text{ring}}$, $\kappa = x, y$, is the signal received by the κ-dipole of the ring vector receiver, whereas $r_{\ell,\text{sphere}}$, $\ell = x, y, z$, is the signal received by the ℓ-dipole of the sphere vector receiver. Additionally, $n_{\kappa,\text{ring}}$, $\kappa = x, y$, and $n_{\ell,\text{sphere}}$, $\ell = x, y, z$, are the ambient acoustic particle velocity noise at the κ-dipole and ℓ-dipole of the ring and sphere vector receivers, respectively. As some examples, two out of the above ten channels, $h^{x}_{x,\text{ring}}$ in Equation (2) and $h^{y}_{z,\text{sphere}}$ in Equation (6), are graphically shown in Fig. 1b.

To implement the proposed vector transmitter, we note that a dipole can be built using a ring with two electrodes [11]. To build the proposed vector transmitter having two dipoles (Fig. 1a, 1b, 1c), we use a ring with four electrodes. Receivers include an identical ring (Fig. 1d, right), which measures the *x* and *y* particle velocity components, as well as a sphere [12] (Fig. 1d, right), acting as a three-dipole receiver, measuring the *x*, *y* and *z* particle velocity components. These two are our proposed and custom-made vector receivers. As a reference for comparison, we also use an array of spatially-separated scalar receivers (Fig. 1e, right), which are regular hydrophones that measure the acoustic pressure. Since the ring and sphere vector receivers (Fig. 1d) provide 5 receiving channels, 5 hydrophones are considered in the scalar array receiver accordingly (Fig. 1e). We use our custom-made vector devices to implement Fig. 1d and 1e system configurations in underwater experiments. An important advantage of a vector receiver such as a sphere over an array of spatially-separated scalar receivers is its compact size, as it measures multiple particle velocity components at a single point in space. This is particularly important for modern medium and small underwater platforms and modems.

III. Underwater Particle Velocity Communication System and Experiments

A. The System

The vector orthogonal frequency division multiplexing (OFDM) system implemented for the experiments has several functional blocks (Fig. 2). After coding each source binary data stream using a convolutional encoder, they are mapped to quadrature phase shift keying (QPSK) constellation points (other coding techniques and constellations can be used as well). Then pilot tones - pilot subcarriers - are added for channel estimation, followed by inverse fast Fourier transform (IFFT). The multi-channel digital-to-analog converter (DAC) converts the data to the analog OFDM signals $s_1(t)$ and $s_2(t)$ for double data multiplexing, or $s_1(t)$, $s_2(t)$ and $s_3(t)$ for triple data multiplexing. Using the proposed particle velocity modulation methods presented earlier in this paper, the OFDM signals are applied to the vector transmitter as follows: for double data multiplexing, $s_1(t)$ and $-s_1(t)$ are applied to the poles A and B (Fig. 2, the Vector Transmitter

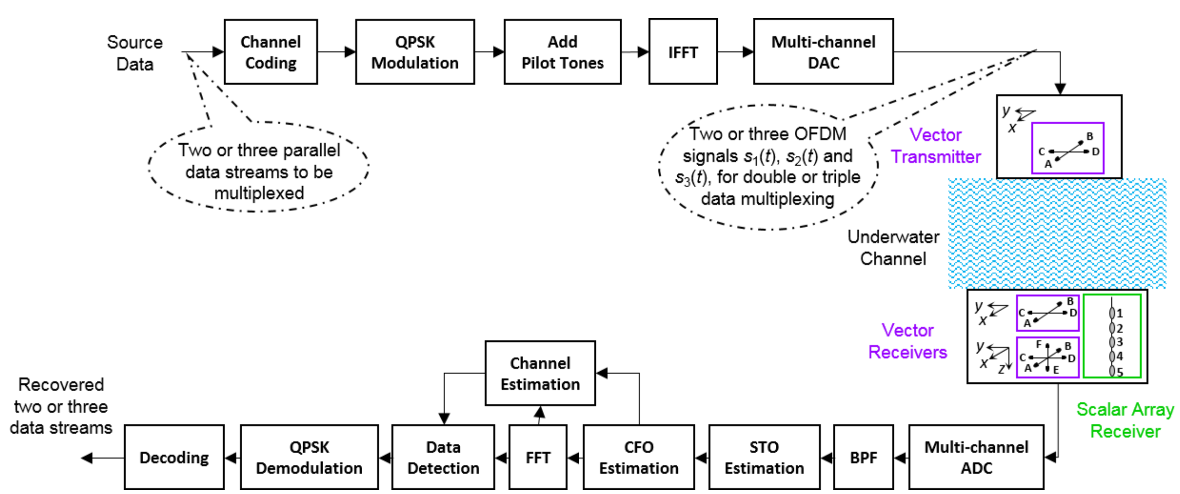

Fig. 2. Block diagram of the implemented vector OFDM system in underwater communication experiments, for double or triple data multiplexing over a given bandwidth, using one vector transmitter. The abbreviations in some blocks are: QPSK (quadrature phase shift keying), IFFT (inverse fast Fourier transform), DAC (digital-to-analog converter), ADC (analog-to-digital converter), BPF (bandpass filter), STO (symbol timing offset), and CFO (carrier frequency offset). The data detection block includes the MMSE separation algorithm. The vector transmitter and receivers and the scalar array receiver correspond to Fig. 1b and 1c.

block), respectively, whereas $s_2(t)$ and $-s_2(t)$ are applied to the poles C and D, respectively; and for triple data multiplexing, $s_1(t)+s_3(t)$ and $-s_1(t)-s_3(t)$ are applied to the poles A and B, respectively, while $s_2(t)+s_3(t)$ and $-s_2(t)-s_3(t)$ are applied to the poles C and D, respectively. To understand this process, note that as explained in Subsection II.A, applying s_1 and $-s_1$ to the poles A and B in Fig. 1a, respectively, induces the signal $r_{\text{due to } s_1} = h_{\text{q}}^x \oplus s_1$ at the receiver. Similarly, applying s_2 and $-s_2$ to the poles C and D, respectively, induces the signal $r_{\text{due to } s_2} = h_{\text{q}}^y \oplus s_2$ at the receiver. With regard to the s_3 signal, the proposed method applies s_3 to the poles A and C, and $-s_3$ to the poles B and D, respectively. This results in:

$$\begin{aligned} r_{\text{due to } s_3} &= h_{\text{Aq}} \oplus s_3 + h_{\text{Cq}} \oplus s_3 + h_{\text{Bq}} \oplus (-s_3) + h_{\text{Dq}} \oplus (-s_3) \\ &= (h_{\text{Aq}} + h_{\text{Cq}}) \oplus s_3 + (h_{\text{Bq}} + h_{\text{Dq}}) \oplus (-s_3). \end{aligned} \tag{7}$$

Given the small spacing between the adjacent poles A and C, one can consider them together as a single pole AC and can also define $h_{\text{ACq}} = h_{\text{Aq}} + h_{\text{Cq}}$. Similarly, we consider the adjacent poles B and D together as a single pole BD and also define $h_{\text{BDq}} = h_{\text{Bq}} + h_{\text{Dq}}$. Subsequently, Equation (7) can be written as:

$$r_{\text{due to } s_3} = h_{\text{ACq}} \oplus s_3 + h_{\text{BDq}} \oplus (-s_3). \tag{8}$$

If we envision a third dipole whose first pole is AC and its second pole is BD, then (8) indicates that according to the proposed method, s_3 and $-s_3$ are applied to the poles AC and BD, respectively. Moreover, (8) exhibits the convolution of s_3 with $h_{\text{ACq}} - h_{\text{BDq}}$, which can be considered as the finite difference representation of the spatial gradient of the acoustic pressure channel impulse response, along the 45$^{\text{o}}$ axis in the x-y plane. Superposition of r due to s_1, s_2 and s_3 results in $r_{\text{due to } s_1 \text{ and } s_2 \text{ and } s_3} = r_{\text{due to } s_1} + r_{\text{due to } s_2} + r_{\text{due to } s_3}$ as the overall received signal.

The signals received by vector receivers and a scalar array of one wavelength λ-spaced hydrophones are collected by a multi-channel analog-to-digital converter (ADC), followed by bandpass filter (BPF) to remove out-of-band noise. To estimate symbol timing offset (STO), we use a filter matched to the chirp signal included at the beginning of each transmitted frame that consists of fifty OFDM blocks. Carrier frequency offset (CFO) and channel responses are estimated using null and pilot tones, respectively [13]. After performing fast Fourier transform (FFT), data on OFDM tones are detected using the minimum mean square error (MMSE) method [14], and then converted back to binary data streams using the QPSK demodulator, followed by the Viterbi decoding algorithm. OFDM parameters of the system are 1024 tones over the bandwidth from 18.4 kHz to 22.4 kHz, which include 256 pilot tones for channel estimation and 96 null tones for noise power estimation and CFO estimation. Each transmission trial (frame) contains 50 OFDM blocks, each OFDM block length is 256 msec, with 25 msec guard time intervals between each two consecutive OFDM blocks in one frame.

B. Experimental Results

Using the OFDM pilot tones and a least squares technique, we measured impulse responses (Fig. 3) of all the 10 vector particle velocity-based communication channels in the proposed fully-vector system (Fig. 1d), from 18.4 kHz to 22.4 kHz. Initial experiments were conducted in shallow waters off Woods Hole, MA (further experiments conducted in other locations are discussed later in the paper). The single vector transmitter and the receivers were placed 15 m below the water surface, with the receivers maintained at one location. For the transmitter location we examined various distances from the receivers. Since our initial power amplifiers were not strong enough, the longest range for our initial tests turned out to be about 26 m. At this range, average signal-to-noise ratios (SNRs) were below 9 dB, and sometimes were as low as about 6 dB. However, still we could demodulate the data, to demonstrate the feasibility of particle velocity data multiplexing using one vector transmitter. Experimental results for several longer transmission ranges are presented afterwards.

Average bit error rate (BER) of the 2×5 fully-vector system is 9.2E-3 (Fig. 1d), obtained by averaging over five trials, and each trial includes transmission of fifty OFDM blocks per each of the two data streams. The average SNR is 7.5 dB. As a reference, average BER of the 2×5 semi-vector system is 11E-3 (Fig. 1e), with an average SNR of 8.9 dB. With slightly better performance, key advantage of the vector receiver is its compact size, as it does not use an array of spatially-separated scalar receivers. Nevertheless, both systems demonstrate the feasibility of demodulating two data streams, multiplexed and transmitted by one vector transmitter over the same bandwidth. Since typically more receivers are needed to decrease BER [15], we add a three-channel sphere vector receiver (Fig. 1f), which reduces the average BER by about an order of magnitude, from 9.2E-3 to 0.71E-3. This comes from having more OFDM blocks demodulated with zero BER (Fig. 4). Similarly, by adding three hydrophone scalar receivers (Fig. 1g), the average BER decreases by about an order of magnitude, from 11E-3 to 0.8E-3. This BER reduction again shows that the

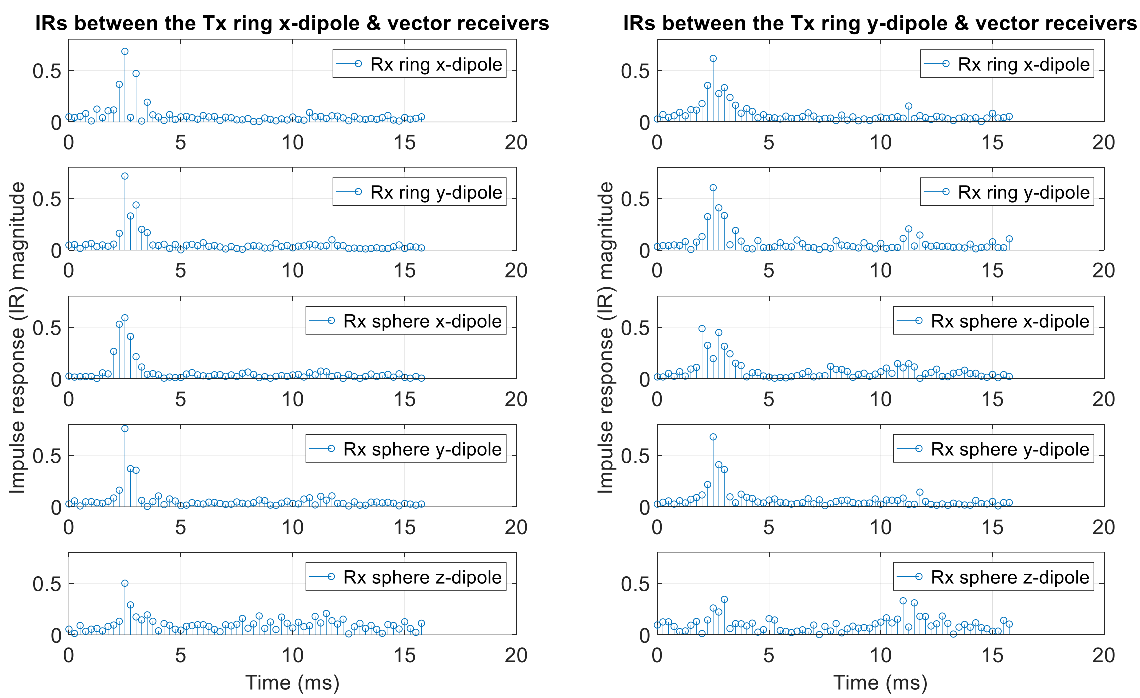

Fig. 3. Magnitudes of measured impulse responses of all the 10 vector particle velocity-related communication channels in the proposed fully-vector system (Fig. 1d), over one OFDM block. In the system we have one ring vector transmitter, one ring vector receiver and one sphere vector receiver. Tx and Rx in the above figures stand for transmitter and receiver, respectively. The Tx ring has two dipoles, *x*-dipole and *y*-dipole, the Rx ring similarly has two dipoles, *x*-dipole and *y*-dipole, and the Rx sphere has three dipoles, *x*-dipole, *y*-dipole and *z*-dipole. Figures in the left column are measured impulse response (IR) magnitudes of the channels between the Tx ring *x*-dipole and the dipoles of the Rx ring and Rx sphere, whereas figures in the right column are measured IR magnitudes of the channels between the Tx ring *y*-dipole and the dipoles of the Rx ring and Rx sphere.

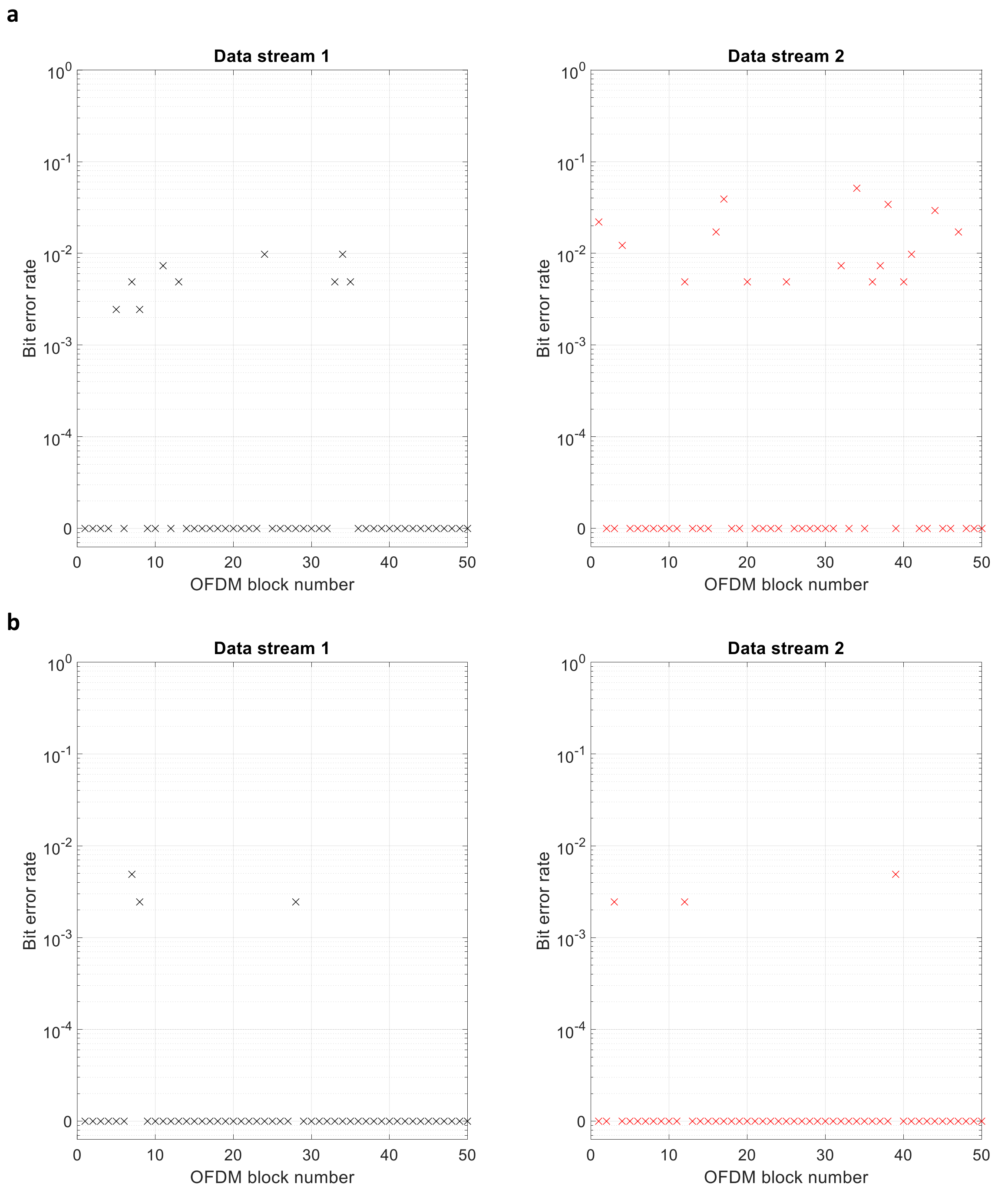

Fig. 4. Bit error rates (BERs) of OFDM blocks in two data streams multiplexed by the vector transmitter in the proposed fully-vector system with different number of vector receivers (Fig. 1d and Fig. 1f). a, BERs with one ring vector receiver and one sphere vector receiver, providing five receive channels (the 2×5 system in Fig. 1d). **b,** BERs with one ring vector receiver and two sphere vector receivers, providing eight receive channels (the 2×8 system in Fig. 1f). We observe that by using one additional vector receiver, many more OFDM blocks are demodulated with zero BER.

developed vector transmitter can work with both vector and scalar receivers. To study the effect oof higher SNRs, and since our initial power amplifiers were not strong enough, we had to reduce the range in some experiments, to increase SNR. In the 2×5 fully-vector system (Fig. 1d), average SNR is increased from 7.5 dB at the original longer range to 18 dB at 9 m, resulting in a two order of magnitude BER reduction from 9.2E-3 to 0.07E-3.

With the increased SNR at the shorter range, now we can examine the system performance with smaller number of receive channels. With a three-channel sphere vector receiver, the 2×3 system (Fig. 5a) exhibits an average BER of 0.039E-3. This is obtained using a maximum likelihood (ML) detector, as the MMSE detector provides a higher BER due to the small number of receive channels, which is three here. A sphere decoder can be used instead, which offers near ML performance, with less computational complexity. To see how far we can go in terms of reducing the number of receive channels, now we use a ring receiver. With a two-channel ring vector receiver, the 2×2 system (Fig. 5b) provides an average BER of 0.23E-3. Comparison of some typically-observed OFDM blocks BERs for the 2×3 and 2×2 fully-vector systems (Fig. 6) reveals that the ring vector receiver exhibits few more OFDM blocks with non-zero BERs than the sphere vector receiver.

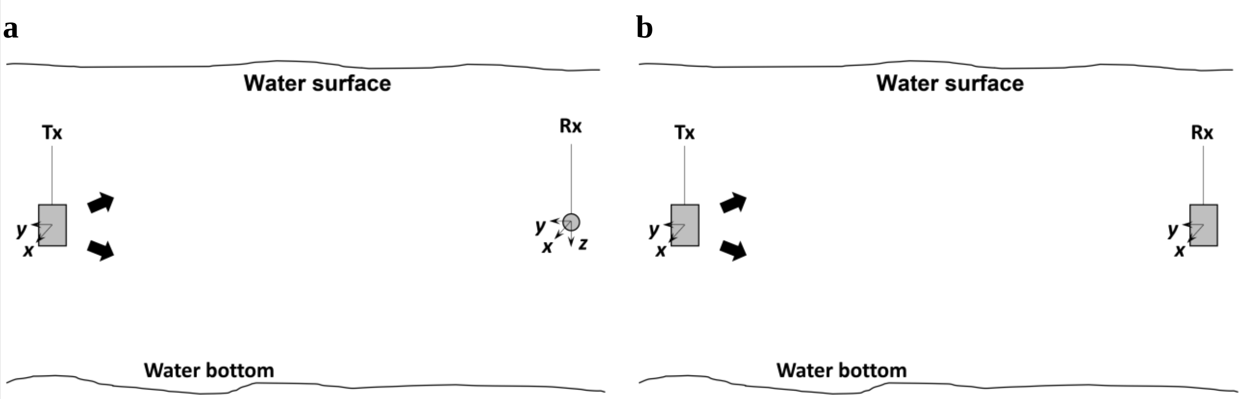

Fig. 5. The proposed particle velocity *double* data multiplexing system for underwater acoustic communication via one vector transmitter and a three-channel or two-channel vector receiver. a, A fully-vector underwater communication system with one ring vector transmitter and one sphere vector receiver, providing three receive channels, a 2×3 system. b, A fully-vector underwater communication system with one ring vector transmitter and one ring vector receiver, providing two receive channels, a 2×2 system.

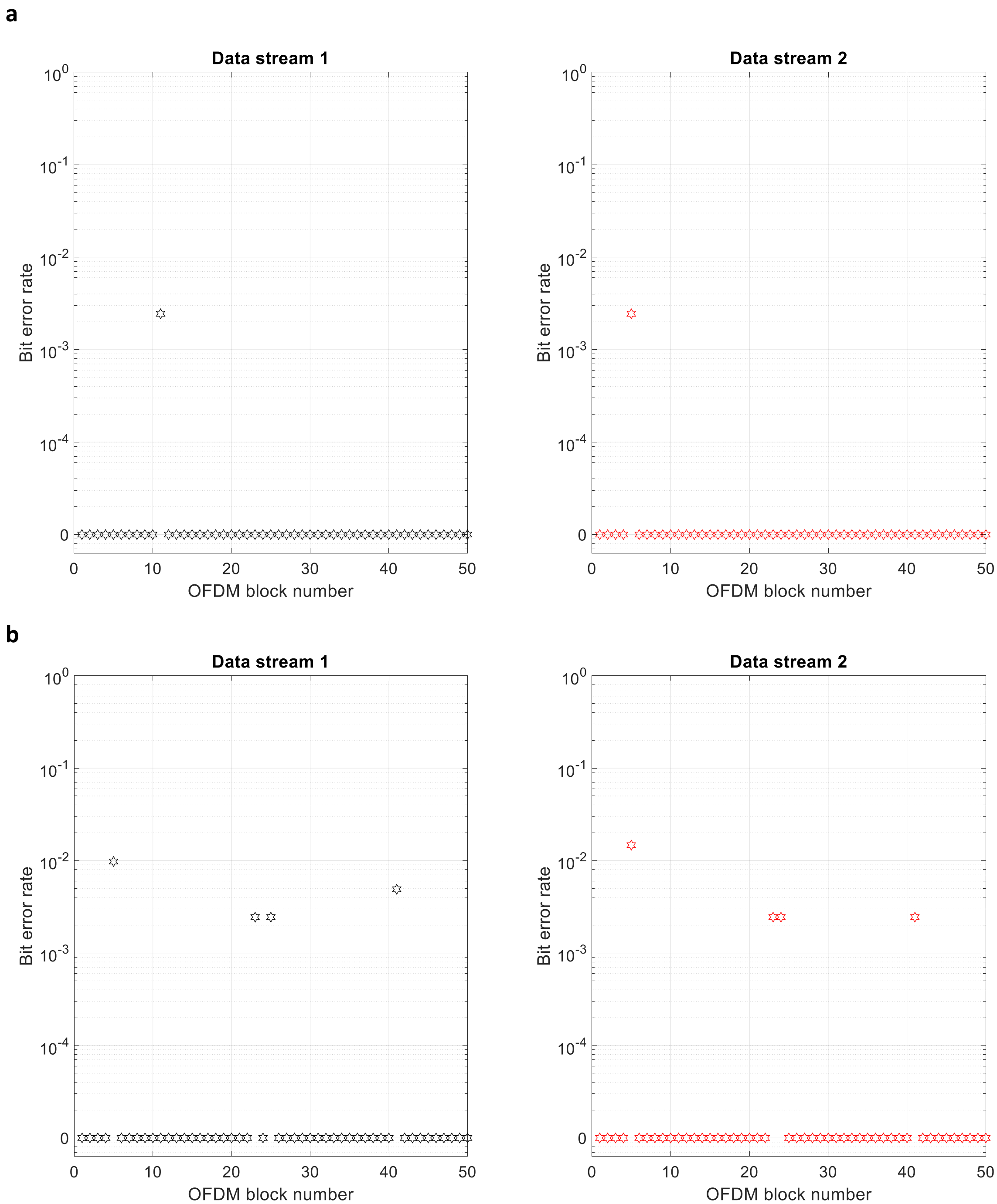

Fig. 6. Bit error rates (BERs) of OFDM blocks in two data streams multiplexed by the vector transmitter in the proposed fully-vector system with a three-channel or two-channel vector receiver (Fig. 5a and Fig. 5b). a, BERs with one sphere vector receiver, providing three receive channels (the 2×3 system in Fig. 5a). **b,** BERs with one ring vector receiver, providing two receive channels (the 2×2 system in Fig. 5b). We observe few more OFDM blocks with non-zero BERs, when using a vector receiver with less number of channels.

To multiplex and transmit three signals or data streams s_1, s_2 and s_3 from the same vector transmitter (Fig. 1a), we propose to modulate them on the *x* and *y* components of acoustic particle velocity as follows: the poles A and B (Fig. 1a) transmit $s_1 + s_3$ and $-s_1 - s_3$, respectively, and the poles C and D (Fig. 1a) transmit $s_2 + s_3$ and $-s_2 - s_3$, respectively. The rationale behind this modulation method is that we envision a third dipole whose first pole is composed of A and C, and its second pole consists of B and D. This third dipole allows to modulate the extra signal or data stream s_3, in addition to s_1 and s_2. To implement the method, we present a system (Fig. 7) which consists of one vector transmitter and three vector receivers. The average BER of this system is 0.2E-3, obtained using an ML detector. Examination of some typically-observed OFDM blocks BERs for the three multiplexed data streams (Fig. 8) demonstrates that most of the OFDM blocks are demodulated with no error. Motivated by the specific way we modulate s_3 together with s_1 and s_2, we have also developed a computationally inexpensive successive interference cancellation algorithm combined with MMSE detection, which offers a trade-off between system performance and complexity, a matter of interest in some applications. Another option is a computationally-inexpensive near-ML sphere decoding detection algorithm.

After the initial experiments and to extend the transmission range, we have also built a 2×4 system with stronger power amplifiers, where the vector transmitter transmits two data streams simultaneously. The first set of experiments with this system is conducted in a harbor in Sandwich,

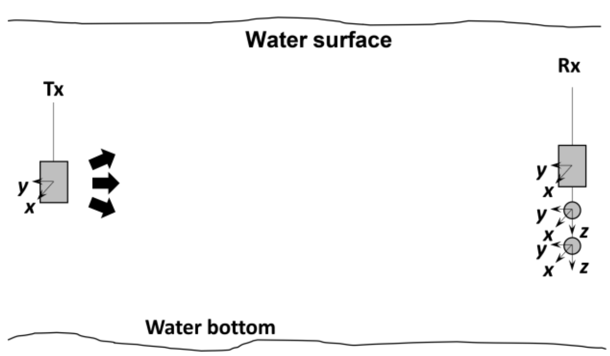

Fig. 7. The proposed particle velocity *triple* data multiplexing system for underwater acoustic communication via one vector transmitter and an eight-channel vector receiver. A fully-vector underwater communication system with one ring vector transmitter, one ring vector receiver and two sphere vector receivers, a 3×8 system.

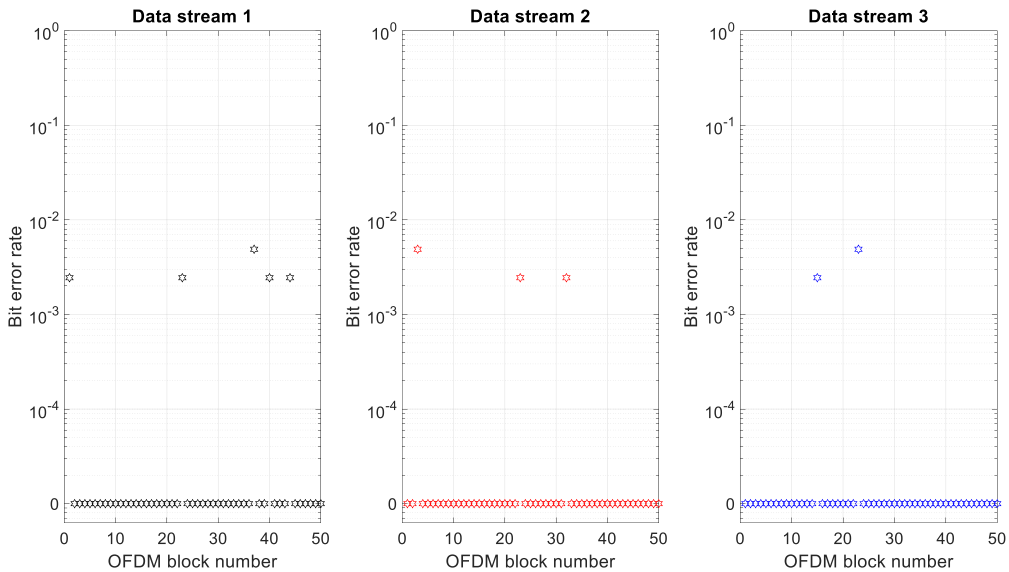

Fig. 8. Bit error rates (BERs) of OFDM blocks in three data streams multiplexed by the proposed vector transmitter and demodulated by an eight-channel vector receiver (Fig. 7). BERs with one ring vector transmitter, one ring vector receiver and two sphere vector receivers, providing eight receive channels (the 3×8 system in Fig. 7). Most of the OFDM blocks are demodulated with zero BER.

MA, over 130 m along the harbor length. With average SNR of 13.7 dB, the average BER is 0.075%. The second set of experiments using this system is conducted at a much larger range, 800 m, in a lake in Mt. Arlington, NJ. Given the increased communication range, average SNR and BER are changed to 7.8 dB and 5%, respectively. These are changes that can typically occur upon range increase. Overall and compared to the 26 m range in the initial experiments conducted using the initial 2×4 system having weak amplifiers, resulting in average SNR and BER of 8.8 dB and 3.8%, respectively, we observe that the stronger amplifiers allow for particle velocity data multiplexing over much longer communication ranges.

At the end and in Table I, we provide a summary of various implemented systems in the paper, Additionally, our custom-made vector and scalar devices to implement Fig. 1d and 1e system configurations in underwater communication experiments are shown in Fig. 9. Upon adding or removing some devices on the receiver side, other system configurations (Fig. 1f, 1g, 5a, 5b, and 7) for various other underwater communication experiments are implemented as well.

TABLE I. A SUMMARY OF VARIOUS PROPOSED PARTICLE VELOCITY UNDERWATER COMMUNICATION SYSTEMS IMPLEMENTED IN THE PAPER

System Type	System Size	System Description
Fully-vector system	2×5	Two transmitting dipoles and five receiving dipoles
Semi-vector system	2×5	Two transmitting dipoles and five receiving scalar hydrophones
Fully-vector system	2×8	Two transmitting dipoles and eight receiving dipoles
Semi-vector system	2×8	Two transmitting dipoles and eight receiving scalar hydrophones
Fully-vector system	2×3	Two transmitting dipoles and three receiving dipoles
Fully-vector system	2×2	Two transmitting dipoles and two receiving dipoles
Fully-vector system	3×8	Three transmitting dipoles and eight receiving dipoles
Semi-vector system	2×4	Two transmitting dipoles, two receiving dipoles and two receiving scalar hydrophones

IV. CONCLUSION

In this paper, physics-based communication concepts for multiplexing multiple data streams over the same bandwidth, using underwater acoustic particle velocity field components, are introduced and examined through experiments. First, basic concepts of how data can be modulated over the underwater acoustic particle velocity channels are introduced, followed by presenting the definitions and equations for various particle velocity channels. All these channels are estimated using pilot tones of a developed vector OFDM system. The experimental results correspond to several distinct implemented systems, that are basically the introduced fully-vector and semi-vector systems with various configurations of vector and scalar devices. The results

a **b**

Fig. 9. Custom-made vector and scalar devices to implement Fig. 1d and 1e system configurations in underwater communication experiments. a, The ring vector transmitter to multiplex two or three data streams. **b,** A similar ring device used as the ring vector receiver, the sphere vector receiver, and the scalar array receiver composed of five hydrophones. By adding or removing some devices on the receive side, we implement other system configurations (Fig. 1f, 1g, 5a, 5b, and 7) for various other underwater communication experiments.

indicate that using one vector transmitter and over the same bandwidth, particle velocity multiplexing of two or three data streams is feasible. This approach can be useful in systems and platforms that have size constraints and intend to increase their usage of the limited available bandwidth.

APPENDIX

Given the similarities between the proposed approach and MIMO communications, similar techniques can be used to separate the channels and detect the data. The advantage of the proposed approach is its compact way of building MIMO channels. Here we first show how the data transmitted on the OFDM data subcarriers - data tones - are separated and detected using the minimum mean square error (MMSE) algorithm. The system model with N_{rx} receivers and N_{tx} transmitters can be written as:

$$\mathbf{R} = \mathbf{HS} + \mathbf{N}. \tag{A1}$$

In the above equation for the OFDM data subcarrier frequency f_d, $\mathbf{R} = [R_1(f_d) \cdots R_{\mathrm{N_{rx}}}(f_d)]^T$ is the received signal vector, ^{T} represents the transpose, $\mathbf{S} = [S_1(f_d) \cdots S_{\mathrm{N_{tx}}}(f_d)]^T$ is the transmitted symbol vector, $\mathbf{N} = [N_1(f_d) \cdots N_{\mathrm{N_{rx}}}(f_d)]^T$ is the noise vector and $\mathbf{H}$ is the $\mathrm{N_{rx}} \times \mathrm{N_{tx}}$ channel matrix:

$$\mathbf{H} = \begin{bmatrix} H_{11}(f_d) & \cdots & H_{1\mathrm{N_{tx}}}(f_d) \\ \vdots & \ddots & \vdots \\ H_{\mathrm{N_{rx}}1}(f_d) & \cdots & H_{\mathrm{N_{rx}}\mathrm{N_{tx}}}(f_d) \end{bmatrix}. \tag{A2}$$

To recover the transmitted data symbols in $\mathbf{S}$ at each f_d from the associated received signal vector $\mathbf{R}$ in Equation (A1), an MMSE method [14] is used:

$$\hat{\mathbf{S}} = \hat{\mathbf{H}}^\dagger (\hat{\mathbf{H}}\hat{\mathbf{H}}^\dagger + \hat{\mathbf{\Sigma}})^{-1} \mathbf{R}, \tag{A3}$$

$$\hat{\mathbf{\Sigma}} = \begin{bmatrix} \hat{\sigma}_1^2 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \hat{\sigma}_{\mathrm{N_{rx}}}^2 \end{bmatrix}. \tag{A4}$$

Here $\hat{\mathbf{S}}$ is the estimated symbol vector, $\hat{\mathbf{H}}$ is the estimated channel matrix obtained using a least squares method [4], † denotes the transpose conjugate, and $\hat{\mathbf{\Sigma}}$ is a matrix composed of the noise variances that are estimated using the null subcarriers at the receivers [4].

With regard to using the pilot tones for channel separation, we note that the pilot tones are the subcarrier frequencies reserved for transmitting the pilot symbols. In this paper, the pilot symbols are considered to be the QPSK constellation points. The strategy to use the pilot tones to assist in channel separation is to assign non-overlapping groups of pilot tones to different transmitters, such that each transmitter has its own specific pilot tones that are different from the pilot tones of other transmitters [4]. More specifically, the pilot tone positions for the m-th transmitter are determined as follows:

$$(m-1)(J/J_p) + (u-1)(J/J_p)\mathrm{N_{tx}} + 2, \quad m = 1, \ldots, \mathrm{N_{tx}},\ u = 1, \ldots, J_p/\mathrm{N_{tx}}, \tag{A5}$$

where $J = 1024$ is the number of all the tones and $J_p = 256$ is the number of pilot tones. Using Equation (A5), each receiver knows where the distinct pilot tones specifically and separately allocated to different transmitters are located.

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