Underwater Communication via Frequency Shift Keying in Particle Velocity Channels: Experimental Results

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***Abstract* — The commonly-used underwater communication channel is the acoustic pressure channel, which is the scalar component of the acoustic field. In this paper acoustic particle velocity channels, which are vector components of the acoustic field, are used together with the acoustic pressure channel, to increase the transmission rate and also improve the signal-to-noise ratio. The goal of this paper is to provide experimental results on underwater communication via particle velocity channels. Acoustic vector transducers, devices that can excite or measure the vector and scalar components of the acoustic field, are used in our experiments. Here we show how a compact vector transducer can be used either as a multichannel transmitter or a multichannel receiver for underwater communication. Without loss of generality, we have used frequency shift keying as a simple modulation scheme to demonstrate the feasibility of underwater communication in particle velocity channels via vector transducers. We present experimental results on two vector communication system configurations. In the first configuration a compact vector transmitter that excites two particle velocity channels and the pressure channel is used, to triple the transmission rate. One advantage of this setup compared to a fully scalar system which uses an array of three spatially-separated scalar transmitters for tripling the transmission rate is the small size of the vector transmitter. In the second configuration, a compact vector receiver that measures two particle velocity channels and the pressure channel is utilized, to increase the signal-to-noise ratio. Compared to a fully scalar system which uses an array of three spatially-separated scalar receivers, signal-to-noise ratio is significantly increased using a small vector receiver. Overall, our experimental results show the usefulness of particle velocity and vector transducers for underwater communication.**

Keywords — Acoustic communication; Underwater communication; Acoustic particle velocity; Frequency shift keying; Vector sensor; Vector transducer.

I. Introduction

Communication via acoustic particle velocity channels using vector transducers has been recently studied for underwater systems [1][2]. In addition to the acoustic pressure channel [6][7], acoustic particle velocity channels provide extra channels for communication [1][3][8]. To utilize these channels, we use vector transducers which can transmit and receive both pressure and particle velocity signals [1][5][8]. A compact vector transducer can measure or excite acoustic particle velocity and acoustic pressure, all co-located at a single point in space.

Frequency shift keying (FSK) is a traditional method for reliable data transmission in underwater acoustic communication system [6]. In this paper, all signals are transmitted via FSK as a simple scheme, to be able to focus on the new aspects of the proposed system, i.e., particle velocity channels and vector transducers for multichannel underwater communication.

This paper presents underwater experimental results on two vector acoustic communication systems: A 3×1 multiple-input single-output (MISO) system and a 1×3 single-input multiple-output (SIMO) system. The MISO system utilizes the three x-velocity, y-velocity and pressure channels to transmit three independent data streams, so, tripling the transmission rate. On the other hand, the SIMO system benefits from data reception via the three x-velocity, y-velocity and pressure channels, to improve link quality. In both systems, the bit duration is chosen to be long enough so that there is no intersymbol interference (ISI) to mitigate. The rest of the paper is organized as follows. In Section II, experimental feasibility of a 3×1 vector MISO system using a vector transducer transmitter is demonstrated. Experimental data of a 1×3 vector SIMO system having a vector transducer receiver is discussed in Section III, to understand its improved performance compared to a 1×3 fully scalar conventional SIMO system which has three spatially-separated scalar receivers, i.e., regular hydrophones. Concluding remarks are provided in Section IV.

II. The 3×1 MISO System with a Three-Channel Vector Transmitter and One Scalar Receiver

The feasibility of a 3×1 MISO system using a vector transmitter is presented in this section via underwater experiments. The MISO system modulates three independent binary FSK (BFSK) signals on the three x-velocity, y-velocity and pressure channels, to triple the transmission rate.

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A. Experiment setup

Experiments are performed in a large pool. Transmitters and receiver are about 13 meters apart. Our vector transmitter includes a ring transducer [9] with four segments which acts as two orthogonal dipoles [1] [2], to modulate the x and y components of acoustic particle velocity, plus a co-located scalar transducer to modulate the acoustic pressure, as shown in Fig. 1. They are about 30 cm deep in water. The vector transmitter can be considered as two orthogonal dipoles that modulate two independent BFSK signals s_1 and s_2 on x-velocity and y-velocity channels, plus modulating the third BFSK signal s_3 on the co-located pressure channel. This means that three independent data streams are transmitted simultaneously by a three-channel vector transmitter, to triple the data rate. A single scalar hydrophone is used as the receiver. The MISO system equation can be written as

$$r = \begin{bmatrix} p_x & p_y & p \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix} + n. \tag{1}$$

Here r is the received signal, p_x and p_y are the particle velocity channel coefficients in x and y directions, respectively, p is the pressure channel coefficient, s_1, s_2 and s_3 are three independent BFSK modulated signals, and n represents noise at the receiver.

Fig. 1. Vector transmitter of the MISO system includes a ring transducer (left) with four segments which acts as two orthogonal dipoles [1] [2] for two independent data streams, plus a nearly co-located scalar transducer (right) for the third data stream. The transducers are at the same depth and there is no spacing between them.

The resonance frequency for the ring transducer is 20.41 kHz when used as two dipoles. Since BFSK is used for signal modulation, two frequencies are assigned to represent 0's and 1's for each data stream. These frequencies are 20.2, 20.3, 20.4, 20.5, 20.6 and 20.7 kHz for simultaneous transmission of three independent data streams. Sampling rate at both the transmit and receive sides are fixed at 100k samples/sec. To avoid ISI, bit duration T_b is set to 0.1 sec., to be much longer than the delay spread caused by multipath propagation. In each experiment, 6000 bits are split into three equal-length data streams and transmitted simultaneously. The receiver records not only the signal transmission, but also the noise before and after the transmission. Block diagram of the non-coherent BFSK demodulator [10] that we used for three data streams is shown in Fig. 2.

B. Experimental results

Table I presents the bit error rate (BER) of the MISO system for different transmit signal amplitudes. Here the amplitude means the amplitude of the BFSK sine waveform applied to each transmitter. As expected, BER decreases as the signal amplitude is increased.

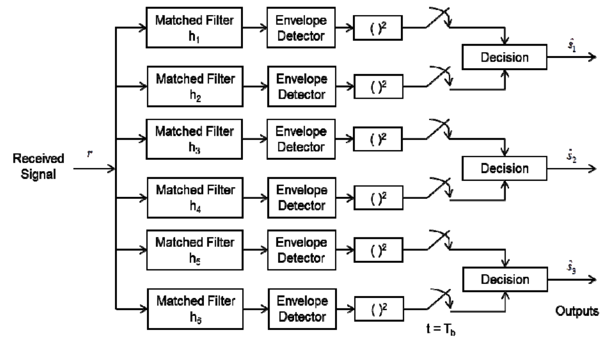

Fig. 2. Block diagram of a non-coherent BFSK demodulator for three independent data streams.

Fig. 3 shows the corresponding spectra of the received signal r in (1), for different transmit signal amplitudes. These spectra also show that the amplitudes at FSK frequencies increase when the same signal amplitude at the transmitter side over two particle velocity and one pressure channels is increased.

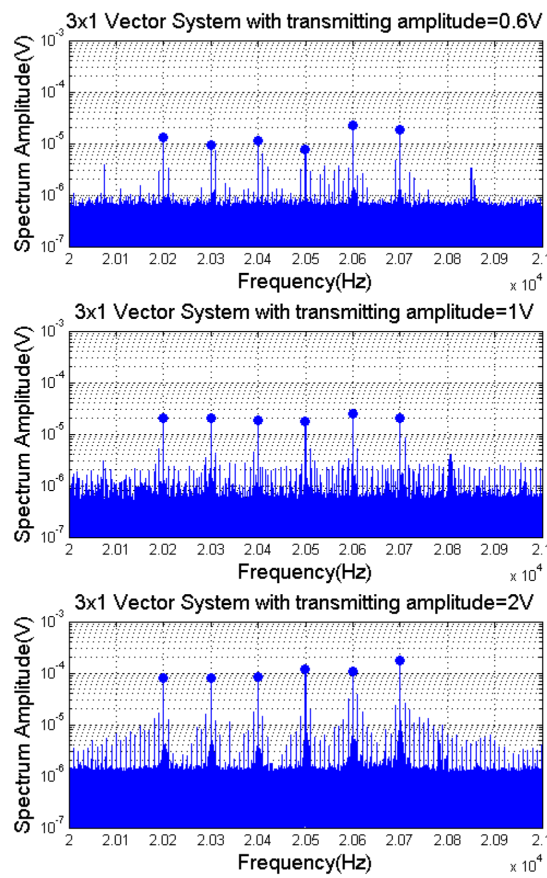

Fig. 3. Spectra of the received signal r in (1) for the 3×1 MISO vector system, for transmit signal amplitudes 0.6 V, 1V and 2 V, respectively.

The table and the spectra both demonstrate the feasibility of using a compact multichannel vector transmitter to simultaneously modulate co-located particle velocity and pressure channels, to increase the transmission rate, instead of using an array of multiple spatially-separated scalar transmitters.

TABLE I. BER PERFORMANCE OF THE MISO SYSTEM FOR DIFFERENT TRANSMIT SIGANL AMPLITUDES

Signal Amplitude (V)	**BER**
0.6	0.1338
1	0.0042
2	0.000011

III. THE 1×3 SIMO SYSTEM WITH ONE SCALAR TRANSMITTER AND A THREE-CHANNEL VECTOR RECEIVER

The advantages of a 1×3 SIMO system using a vector receiver is presented in this section via underwater experiments, compared to a 1×3 fully scalar conventional SIMO system which has three spatially-separated scalar receivers, i.e., regular hydrophones. The SIMO vector system benefits from data reception via the three *x*-velocity, *y*-velocity and pressure channels, to improve link quality. Another advantage is the small size of the receiver, as it measures three co-located channels.

A. Experiment setup

Locations of the SIMO transmitter and receivers are shown in Fig. 4, where the transmitter and receivers are about 13 meters apart. The SIMO system equations can be written as

$$\begin{bmatrix} r \\ r_x \\ r_y \end{bmatrix} = \begin{bmatrix} p \\ p_x \\ p_y \end{bmatrix} s + \begin{bmatrix} n \\ n_x \\ n_y \end{bmatrix}. \tag{2}$$

Here r, r_x and r_y are the received pressure, *x*-velocity and *y*-velocity signals, respectively, p is the pressure channel coefficient, p_x and p_y are the particle velocity channel coefficients in *x* and *y* directions, respectively, s is the BFSK modulated signal, n is the pressure noise, and n_x and n_y represent particle velocity noises in x and y directions, respectively.

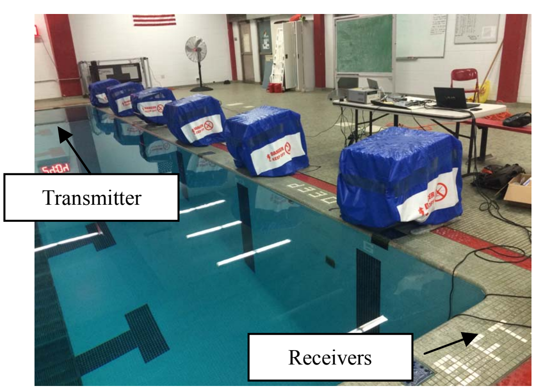

Fig. 4. Locations of the transmitter and the receivers in the pool.

The frequencies 20.2 kHz and 20.3 kHz are used to represent 0's and 1's, respectively, in the BFSK signal. Sampling rate at both the transmit and receive sides are fixed at 100k samples/sec., and we have $T_b = 0.1$ sec for the bit duration.

The block diagram of the multichannel receiver is shown in Fig. 5, which is a non-coherent BFSK demodulator with equal gain combining [10][11]. The receiver combines the measured particle velocity and pressure signals.

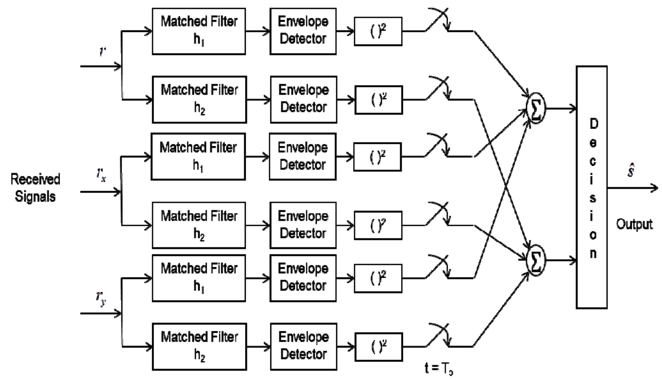

Fig. 5. Block diagram of a non-coherent BFSK demodulator with a three-channel equal gain combiner.

B. Experimental results

Noise characteristics of a vector communication receiver are discussed in [3], including smaller particle velocity noise powers. To look into this matter using experimental data, in Fig. 6 we present measured noise powers in all channels of the 1×3 SIMO vector system, as well as a benchmark 1×3 fully scalar conventional SIMO system which has three spatially-separated scalar receivers, i.e., hydrophones. We observe that in the vector system, the two velocity noise powers are much smaller than the pressure noise power (Fig. 6, top panel). Additionally, pressure noise powers in the fully scalar system are all high (Fig. 6, bottom panel). Different noise level for the 3rd pressure channel of the scalar system, CH3 in Fig. 6, bottom panel, could be because the first two scalar receivers in the scalar system, CH1 and CH2, are exactly the same, whereas the 3rd scalar receiver is different. Therefore, the receive voltage response (RVR) of the 3rd scalar receiver might be different from the first two scalar receivers.

The transmit signal amplitude in both vector and scalar systems is considered to be 0.6 V. Since velocity and pressure channels can have different signal and noise powers, to study the received signal-to-noise ratio (SNR) in each system as a measure of link quality, we define the received average SNR per channel as follows [3]

$$\rho = \left(\Omega_p / \Omega_n + \Omega_p^x / \Omega_n^x + \Omega_p^y / \Omega_n^y \right) \Big/ 3 , \tag{3}$$

where Ω_p, Ω_p^x and Ω_p^y are the signal powers in the pressure, *x*-velocity and *y*-velocity channels, respectively, and Ω_n, Ω_n^x and Ω_n^y are the corresponding noise powers. To measure SNR in each channel, multiple signal transmissions are made, and each is 75 sec. long. Fig. 7 shows multiple measurements of individual SNRs, i.e., $10\log_{10}(\Omega_p / \Omega_n)$, $10\log_{10}(\Omega_p^x / \Omega_n^x)$ and $10\log_{10}(\Omega_p^y / \Omega_n^y)$ as well as the average SNR per channel $10\log_{10}(\rho)$, for both systems.

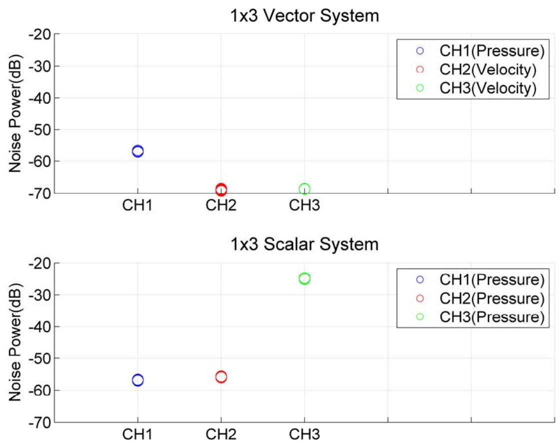

Fig. 6. Measured noise powers in all channels of the 1×3 SIMO vector system (top), as well as measured noise powers in all channels of the benchmark 1×3 SIMO fully scalar conventional system (bottom).

We observe in Fig. 7, top panel, that in the vector system, the two velocity SNRs in CH2 and CH3 are about 10 dB higher than the pressure SNR in CH1. Additionally, comparison of the two systems in Fig. 7 reveals that the average SNR ρ of the vector system is about 10 dB higher than the average SNR of the fully scalar conventional system.

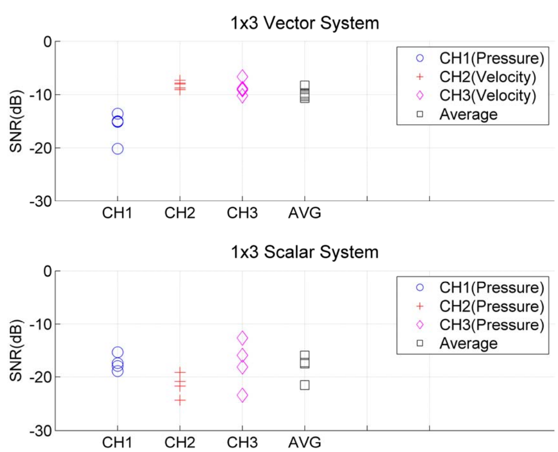

Fig. 7. Measured individual and average received SNRs for the 1×3 SIMO vector system (top) and the benchmark 1×3 SIMO fully scalar conventional system (bottom).

We also observe in Fig. 7 that for repeated similar transmissions, measured SNRs in velocity channels are more stable, compared to SNRs in pressure channels which exhibit higher variance. This might be related to the directional beam pattern of acoustic dipoles [12] which generate velocity signals in our vector receiver system, whereas scalar sensors in the fully scalar receiver system which generate pressure signals have omni-directional beam patterns.

IV. Conclusion

In this paper, feasibility and advantages of underwater communication using acoustic vector transducers are studied via experiments. These transducers utilize acoustic particle velocity channels. We have demonstrated that using a multichannel compact vector transducer transmitter, multiple independent data streams can be simultaneously transmitted, to increase the transmission rate and achieve high speed communication. We have also shown that upon using a multichannel compact vector transducer communication receiver, significant SNR improvement can be obtained, compared to a conventional communication receive array, composed of spatially-separated scalar sensors. Small size of vector transducers makes them particularly suitable for small platforms and underwater sensor networks with small transceivers.

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