Underwater Communication Experiments for Transmitting Multiple Data Streams Using a Vector Acoustic MIMO System: OFDM and FSK Modulations

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***Abstract* — In this paper, we utilize the vector components of the acoustic field in a MIMO setting, to simultaneously transmit multiple independent data streams to increase the communication spectral efficiency in bandlimited underwater channels, while using small-size vector transceivers. In the developed vector MIMO-OFDM system, we use one ring vector transducer to transmit two or three data streams, and two ring vector transducers to transmit four data streams. At the receiver side, we use a sphere vector sensor that provides measurements of the *x*, *y* and *z* components of the acoustic particle velocity, plus six scalar sensors that measure the acoustic pressure – the scalar component of the acoustic field. Additionally, we present a vector MIMO-FSK system that includes one ring vector transmitter and one ring vector receiver. Our results obtained using underwater experiments demonstrate the feasibility of simultaneous transmission and demodulation of multiple data streams using compact vector transceivers, to optimally use the limited bandwidth while using small-size transceivers.**

Keywords—MIMO, OFDM, FSK, Vector Transducer, Vector Sensor, Underwater Communication.

I. INTRODUCTION

The underwater acoustic propagation channel is highly bandlimited. To increase the spectral efficiency of communication systems over the bandlimited underwater channels, spatial multiplexing using multiple-input multiple-output (MIMO) system architectures are considered [1]. In a MIMO system, there are multiple transmit and receive transducers and sensors. Suppose there are N_T transmit transducers. To increase the spectral efficiency via spatial multiplexing, the input data stream is divided into N_T independent blocks, and each block is transmitted from only one transducer, all at the same time and over the same bandwidth. This makes the transmission N_T times faster and therefore more spectrally efficient. At the receiver side, a proper interference cancellation method is needed to recover the concurrently-transmitted N_T data streams using N_R sensors. To mitigate the frequency selectivity of underwater channels, one can use the orthogonal frequency division multiplexing (OFDM) method, combined with the MIMO spatial multiplexing approach [1].

MIMO array size in scalar acoustic underwater communication systems: The concern with the aforementioned MIMO approach for underwater communication is that at each of the transmit and receive sides, multiple spatially-separated scalar transducers and sensors are needed. This means that large arrays of scalar transducers and sensors are required, which typically do not fit into small platforms. Overall, array size can be a main concern in some emerging applications of small unmanned underwater vehicles (UUVs) and other platforms that have size constraints [2].

The proposed vector acoustic MIMO underwater communication system: Our developed concepts of vector transducers and sensors for underwater communication, to benefit from the vector components of the acoustic field, allow for having multichannel and small-size transmitters and receivers. The small size of the proposed vector acoustic system is due to the fact that vector transducers and sensors excite and measure the vector components of the acoustic field all at a single point in space [3]-[5]. Therefore, they can serve as compact multichannel devices. This is different from the existing multichannel arrays that are composed of spatially-separated scalar transducers and sensors.

The rest of this paper is organized as follows. Section II provides an overview of the proposed vector acoustic MIMO-OFDM system that uses vector transducers and sensors, while its experimental results are presented in Section III. Given the usefulness of frequency shift keying (FSK) as a robust and phase-independent method - that is of interest in certain applications, a vector acoustic MIMO-FSK system is proposed in Section IV, followed by its experimental results in the same section. Finally, we draw some conclusions in Section V.

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II. The Vector Acoustic MIMO-OFDM System

In this section, the used vector transducer for transmit data multiplexing has a ring configuration [6], whereas a combination of vector and scalar sensors are used at the receiver side, to examine all the vector and scalar components of the acoustic field for demodulation (Fig. 1). We transmit $N_T = 2$, 3 and 4 data streams simultaneously in several experiments, with $N_R = 9$ measured signals at the receiver side. Therefore, we have 2×9, 3×9 and 4×9 vector acoustic MIMO setups, respectively. To handle the channel frequency selectivity, we combine our vector acoustic systems with OFDM signaling (see Table I for the OFDM parameters).

Table I. The Vector Acoustic MIMO-OFDM System Parameters

Center Frequency	20.4 kHz
Bandwidth	8 kHz
Tone Spacing	7.8 Hz
OFDM Block Length	128 ms
Sampling Frequency	200 ksamples/s
Modulation	QPSK
Number of Tones	1024
Number of Pilot Tones	256
Number of Null Tones	96
Time Guard Interval	25 ms

The pilot and null tones are used for channel estimation, carrier frequency offset (CFO) and signal-to-noise ratio (SNR) estimation [6]. The used channel code is convolutional. For interference cancellation and data detection, minimum mean square error (MMSE) and maximum likelihood (ML) methods are used [6]. In the next section, we present performance results for several vector acoustic MIMO systems using the conducted experiments.

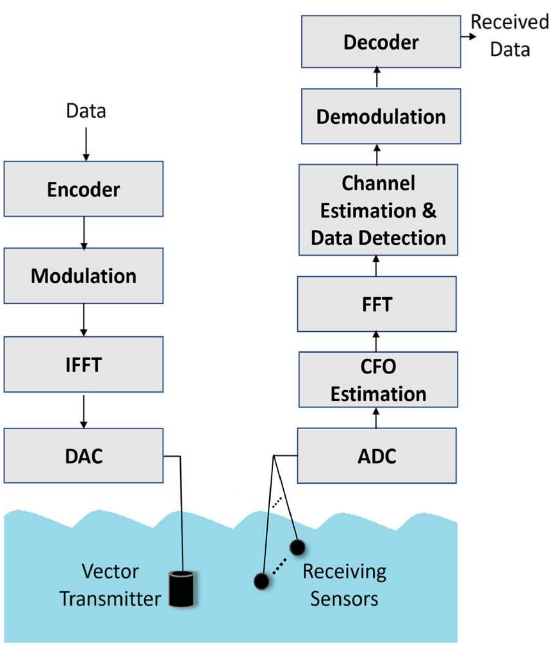

Fig. 1. Block diagram of the proposed and implemented vector acoustic MIMO-OFDM system.

III. Experimental Results for the Vector Acoustic MIMO-OFDM System

Multiple underwater vector acoustic communication experiments are conducted in a large pool using our 2×9, 3×9 and 4×9 system configurations. In the 2×9 and 3×9 tests, *one* ring vector transducer (Fig. 2a) is used to transmit two or three data streams simultaneously. In the 4×9 tests, *two* ring vector transducers are used together, each transmitting two independent data streams simultaneously (this setup allows for a $6{\times}N_R$ system and further data multiplexing, if N_R is increased). At the receiver side, three out of nine measured signals are collected using a three-channel compact sphere vector sensor (Fig. 2b), whereas the rest of the measured signals are collected using six scalar sensors. While in some experiments the transmitter is stationary, in some other experiments we move the transmitter back and forth, to induce some motion and Doppler. Some estimated CFOs for 50 OFDM blocks and various vector and scalar measured signals are shown in Fig. 3 and Fig. 4, for stationary and moving transmitters, respectively. We observe that while the CFOs for the stationary transmitter are stable, they change over a 3.5 Hz interval for the moving transmitter.

In Fig. 5 and Fig. 6, we present the bit error rates (BERs) for each OFDM block for the 2×9 system using one vector transmitter, when the transmitter is stationary or moving, respectively. Additionally, average BER and SNR results for the 50 OFDM blocks included in each data stream in the 2×9 tests are shown in Table II. The BERs are obtained using two different detection methods (MMSE and ML). While we note a decrease in SNR for the moving transmitter in Table II due to the Doppler effect, we still observe low and robust BERs in Fig. 6.

Average BERs and SNRs for 50 OFDM blocks included in each data stream in the 3×9 tests and using one moving vector transmitter are shown in Table III, using the MMSE and ML methods. We observe the feasibility of successful demodulation of three data streams that are simultaneously transmitted by only one vector transducer. Additionally, the BERs of the ML method are typically smaller than the MMSE BERs.

For the 4×9 tests and using two moving vector transmitters, average BERs and SNRs for 50 OFDM blocks included in each data stream are shown in Table IV, using the ML method (since the MMSE method gives higher BERs, due to the increased

(a) (b)

Fig. 2. (a) A ring vector transducer that transmits two or three data streams simultaneously, (b) a three-channel sphere vector sensor that provides three measured signals at the receiver side.

number of transmitted data streams and not having a larger number of receiving sensors). Since DS1 and DS2 are from one vector transducer, while DS3 and DS4 are from the other vector transducer, and given that they are not in the exact same spot, their BERs are not the same. Overall, we observe that the four data streams concurrently transmitted over the same bandwidth can be successfully demodulated.

TABLE II. AVERAGE BERS AND SNRS FOR VECTOR MULTIPLEXING OF TWO DATA STREAMS (DSS)

		SNR (dB)	BER	
			MMSE	ML
Stationary Transmitter	DS1	14.91	0	0
	DS2	13.73	0	0.00015
Moving Transmitter	DS1	10.75	0	0
	DS2	11.53	0	0

TABLE III. AVERAGE BERS AND SNRS FOR VECTOR MULTIPLEXING OF THREE DATA STREAMS (DSS) IN THE PRESENCE OF TRANSMITTER MOTION

	SNR (dB)	BER	
		MMSE	ML
DS1	9.38	0.0133	0.0003
DS2	10.18	0.0074	0.0002
DS3	9.74	0.0069	0.0064

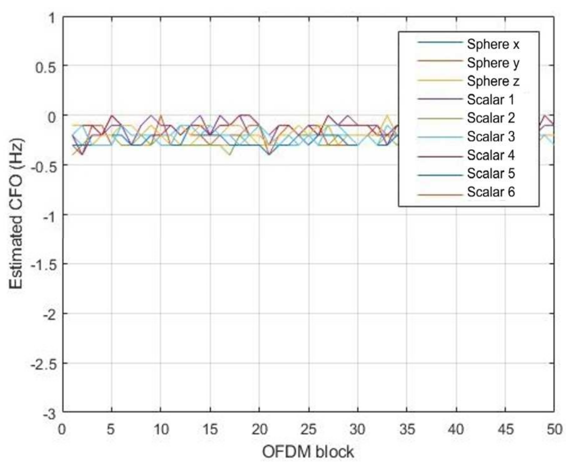

Fig. 3. Estimated CFOs for various vector and scalar measured signals in the MIMO-OFDM system, when the transmitter is stationary.

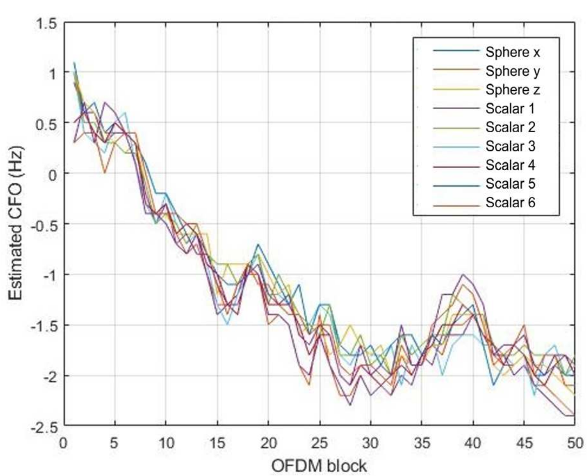

Fig. 4. Estimated CFOs for various vector and scalar measured signals in the MIMO-OFDM system, when the transmitter is moving.

TABLE IV. AVERAGE BERS AND SNRS FOR VECTOR MULTIPLEXING OF FOUR DATA STREAMS (DSS) IN THE PRESENCE OF TRANSMITTER MOTION

	SNR (dB)	BER
		ML
DS1	16.70	0
DS2	15.05	0
DS3	15.76	0.0010
DS4	14.96	0.0049

IV. THE VECTOR ACOUSTIC MIMO-FSK SYSTEM

Frequency shift keying (FSK) has been a useful underwater communication technique, due to the possibility of phase-independent (non-coherent) demodulation [7]. The main drawback of FSK is its low spectral efficiency [8]. However, upon using the vector components of the acoustic field as co-located channels for simultaneous data transmission over the same bandwidth, FSK can provide higher spectral efficiencies. In what follows, we propose and implement a vector acoustic MIMO-FSK signaling method. This signaling scheme is suitable for robust transmission in time-varying underwater channels where channel estimation and tracking are impractical due to the rapid changes in the channel.

To demonstrate the possibility of data multiplexing using one vector transmitter and FSK signaling, we transmit two 4FSK-modulated data streams $s_1(t)$ and $s_2(t)$, one transmitted from the A-B dipole and the other from the C-D dipole (Fig. 7). To implement this two-channel vector transmitter, we use a ring device. Using another ring device as a two-channel vector receiver, we obtain the two signals $r_x(t)$ and $r_y(t)$ (Fig. 7). The ring and the dipoles are explained in [6]. To benefit from this multi-channel signal reception, we use non-coherent equal gain combining [9]. To address channel frequency selectivity, we use frequency hopping, by dividing the 18.4-22.4 kHz bandwidth to distinct hopping groups.

Now we present the experimental results that demonstrate the possibility of data multiplexing using one vector transmitter, together with non-coherent FSK signaling and demodulation. The implemented vector non-coherent FSK system in Fig. 7 includes one ring vector transmitter to multiplex two data streams, and a similar two-channel ring vector receiver. With no channel coding in this feasibility study, average BER is 1.65E-02, obtained by averaging over five trials, and each trial includes transmission of 900 bits per each of the two data streams. The average SNR is 1.2 dB, at a range of 65 m. The vector acoustic

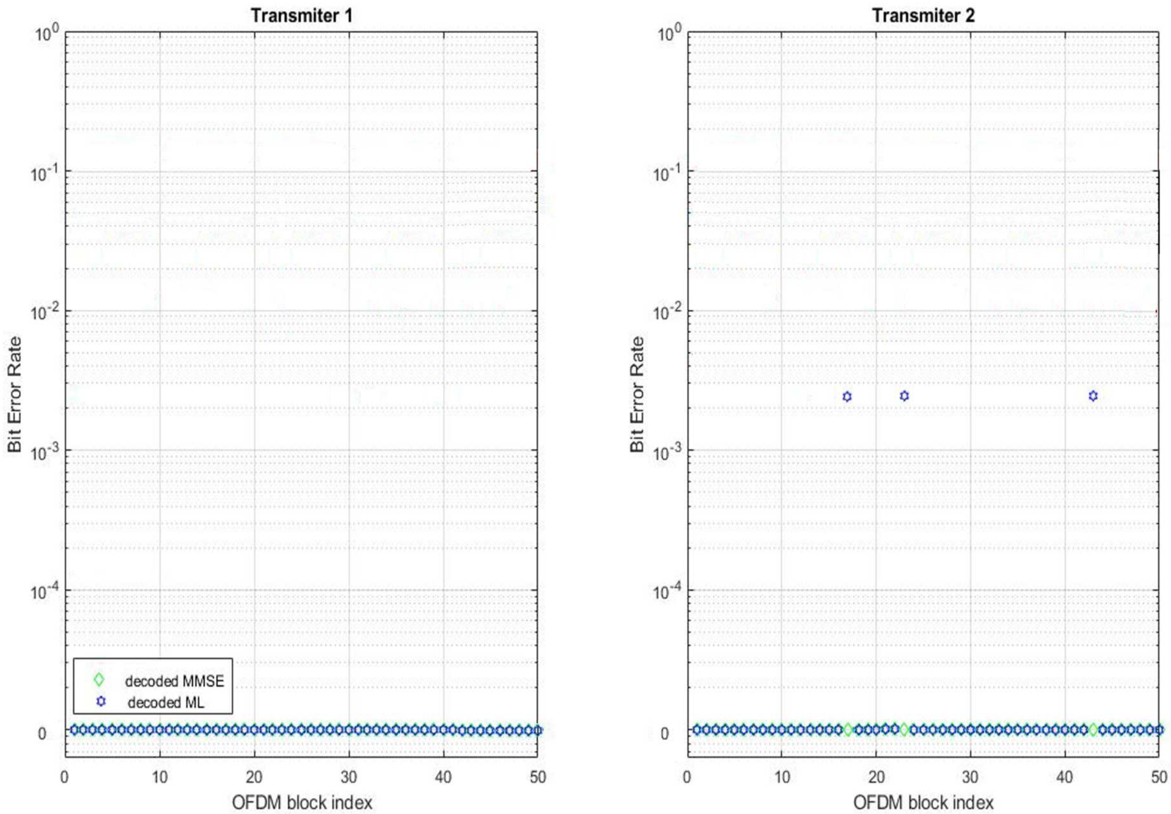

Fig. 5. BER results in the 2×9 MIMO-OFDM system when the vector transmitter is stationary.

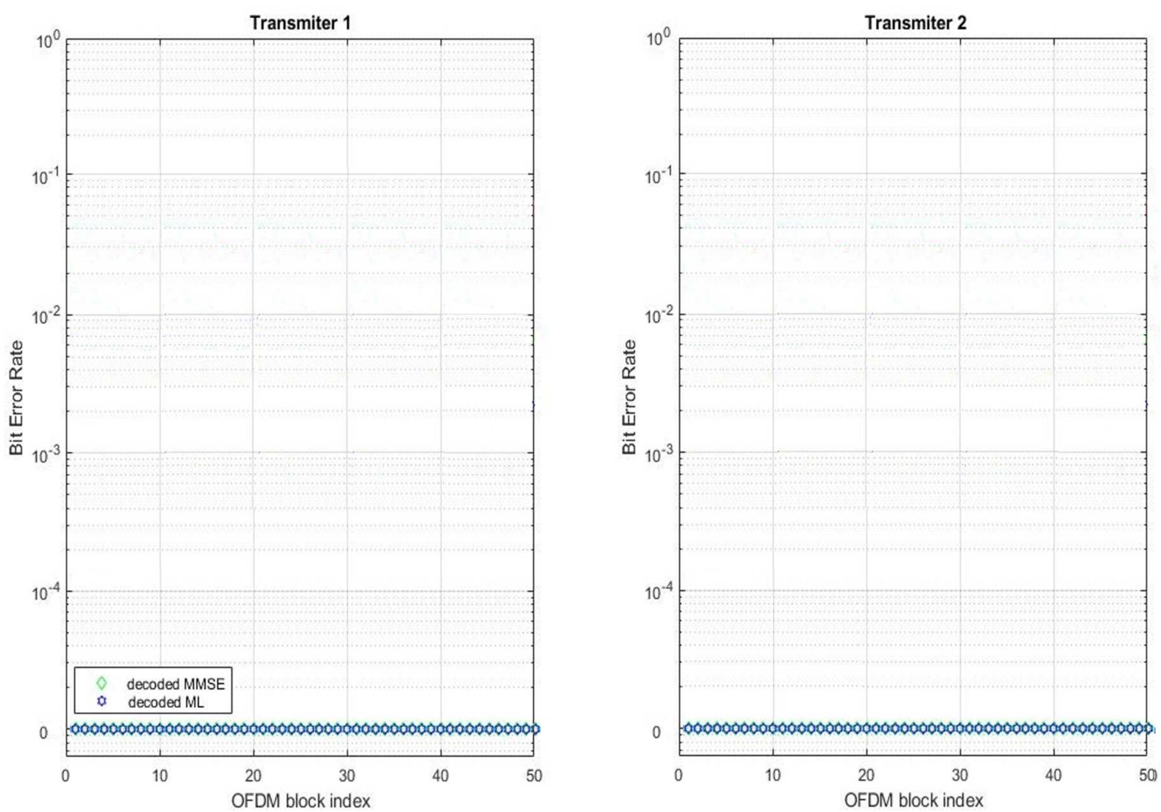

Fig. 6. BER results in the 2×9 MIMO-OFDM system when the vector transmitter is moving.

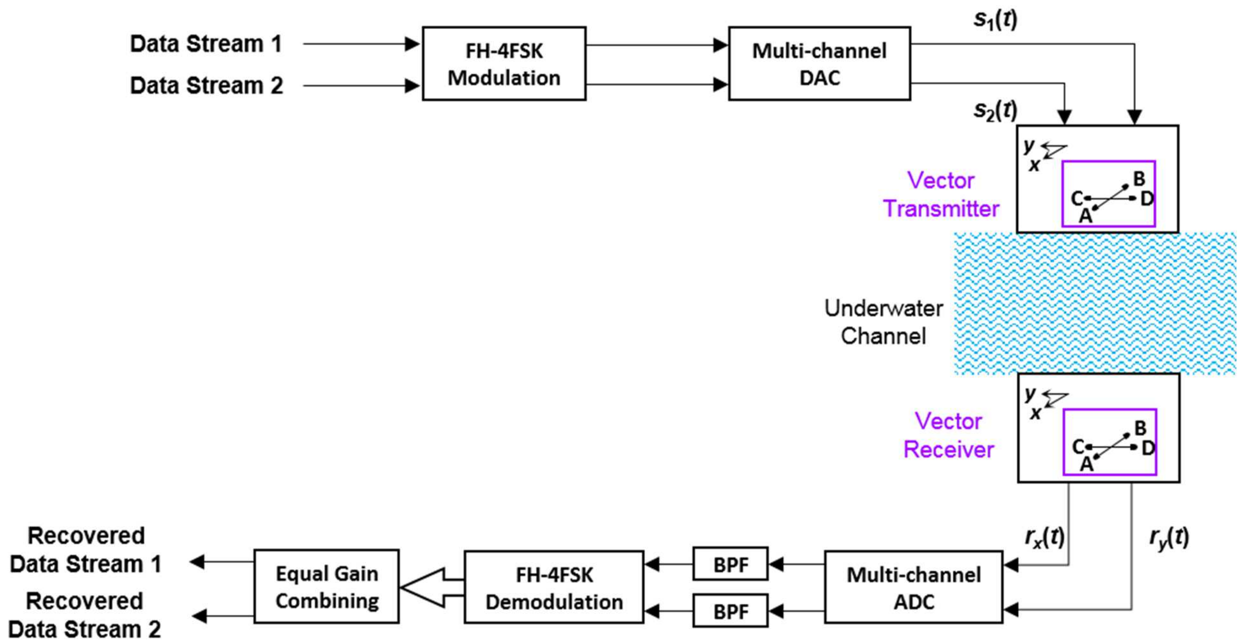

Fig. 7. Block diagram of the implemented vector FSK system in underwater communication experiments, for double data multiplexing over the same bandwidth, using one vector transmitter. Abbreviations in some blocks are: FH (frequency hopping), DAC (digital-to-analog converter), ADC (analog-to-digital converter), and BPF (bandpass filter). The vector transmitter and receiver are two transmit dipoles and two receive dipoles, respectively.

MIMO-FSK experiments are conducted in shallow waters off Woods Hole, MA. The results demonstrate that transmit data multiplexing using one vector transducer is feasible using the power-efficient non-coherent FSK modulation.

V. Conclusion

In this paper, we utilize compact acoustic vector transducers for simultaneously transmitting multiple data streams using OFDM or FSK modulations. Both types of vector and scalar sensors are used for data detection and demodulation, where the vector sensor is a compact three-channel sensor. The introduced vector MIMO-OFDM systems are 2×9, 3×9 and 4×9, and the developed vector MIMO-FSK system is 2×2. Our experimental results demonstrate the viability of underwater transmission and demodulation of multiple independent data streams using compact vector transducers and sensors. These vector acoustic systems allow for optimum utilization of the limited underwater bandwidth, while being compact and therefore suitable for various underwater platforms and applications, specifically those that have size limitations.

While not discussed in the paper, various types of space-time, space-frequency and space-time-frequency codes can be implemented in the proposed underwater vector acoustic MIMO communication systems, to increase the reliability using small-size transmitters and receivers.

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