MIMO-OFDM for the Internet of Underwater Things

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Abstract: *To meet the rising need for underwater research, a platform with higher data rates, more reliable performance, and hardware and software flexibility is required. OFDM is a low-complexity alternative to single-carrier transmission for optimizing the utilization of the available bandwidth. On the other hand, MIMO techniques may significantly boost the narrow band channel capacity. MIMO-OFDM is thus the preferred method for high-data-rate transmissions across underwater acoustic channels. In this work, a new MIMO-OFDM transceiver configuration is suggested. We show a prototype of a 2x2 MIMO-OFDM transceiver node for the Internet of Underwater Things (IoUT), which intends to build a new generation of programmable and portable platforms a networking testbed with real-time processing and reconfiguration. The suggested receiver operates on a block-by-block basis, using pilot subcarriers for channel estimation to prevent matrix inversion and accommodate the hardware's limited resources. We also use space-frequency block coding (SFBC) for transmission diversity. In addition, null-carrier based Doppler compensation enables high-resolution uniform Doppler drifting. We assess the performance of MIMO-OFDM with 8192 subcarriers in Boston Harbor's open water region. TX and RX transducers are separated by 2 meters at a depth of 4 meters. The transmission employs a 125 kHz bandwidth and a 125 kHz carrier frequency. We show that the suggested MIMO-OFDM IUoT prototype can support data speeds of up to 600kbit/s with 16QAM modulation.*

Keywords: *MIMO, OFDM, Internet of Underwater Things*

1. INTRODUCTION

Underwater acoustic communications, which are fundamentally bandwidth limited, are inclined to multiple-input multiple-output (MIMO) systems as they can significantly improve spectral efficiency through simultaneous transmissions over multiple transmitters. Orthogonal frequency division multiplexing (OFDM) is also being studied as a low-complexity alternative to single-carrier modulation for the next generation of acoustic modems. The objective of making effective use of the available acoustic bandwidth compels the design of the system to include a significant number of carriers and MIMO configurations.

The combination of MIMO and OFDM is a tempting low-complexity solution for bandwidth-efficient communications over frequency selective and bandwidth limited UWA channels. It combines the benefits of spatially de-correlated acoustic channel with the frequency diversity that exists due to delay-spread, and results in considerable capacity improvement. Thus coherent MIMO-OFDM systems have been considered ideal choice for the dynamic and extremely band limited UWA channels [1–4]. [1] exploited two forms of diversities. One was frequency diversity using coded OFDM (COFDM), which took advantage of the frequency selectivity inherent to channels with multipath propagation, and the second was spatial diversity using MIMO, which utilized multiple transducers to increase the system's potential capacity. [2] and [3] present a block-by-block architecture that is non-adaptive and demonstrates experimental results on the viability of MIMO-OFDM transmissions over UWA channels. In [4], in an OFDM system with two transmitters, experimental results were provided for both coherent and differential configurations.

Fast growing underwater applications, such as environmental monitoring, resource exploration, disaster prevention, etc., require flexibility and real-time features for the efficient communication of small, low-power devices with limited processing capabilities. To that end, Internet of Underwater Things (IoUT) are realised to establish a smart network to provide a set of features such as low power consumption, and low-cost hardware. Recent projects have been developed for the IoUT to reap the full potential, however, the data rates cannot reach the demand for high speed transmission applications, such as real-time underwater video streaming. The JANUS project [5] allows a packet size of 56-bits and employs Frequency-Hopped Binary Frequency Shift Keying (FH-BFSK) that can achieve 10 km for underwater transmission at 80 bps.SUNRISE project [6] is an open software-defined architecture modem and protocol stack that facilitates open collaborative research developments over a variety of applications and environments. In [7], SISO-OFDM and MIMO-OFDM underwater acoustic communication system have been developed based on the floating-point TMS320C6713 DSP development kit.

In this paper, we address these limitations by further investigate our previous work on SEANet IoUT [8], to a platform support even higher data rate by deploying MIMO-OFDM to the PHY layer. First, we present the MIMO-OFDM transceiver design that is compatible with the SEANet modem, as well as space-frequency block coding (SFBC) and Doppler compensation that can further enhance the performance. Second, we introduce the hardware and software implementation of the MIMO-OFDM. Moreover, we demonstrate data rates of 596 kbit/s achieved at sea over short horizontal links for 2 by 2 MIMO with 16QAM coding.

The remainder of this article is organized as follows. In Section 3, we present the design of the MIMO-OFDM transceiver. In Section 3, we introduce the implementation of the platform. In Section 4 we present performance evaluation results. Finally, we draw conclusions in Section 5.

2. MIMO-OFDM TRANSCEIVER DESIGN

In this section, we focus on the transmission and reception schemes applied in the Physical Layer transceiver for two transmitters and two receivers MIMO-OFDM communication. We apply spatial multiplexing of independent data streams. Each antenna transmits with N subcarriers, among which are $N/4$ pilots and $3N/4$ data symbols.

2.1. MIMO-OFDM CHANNEL ESTIMATION

Let $\mathbf{X}[k] = (X_1[k], X_2[k])^T, k = 0, 1, ..., N-1$ be the data symbol at the kth transmitted subcarrier,
$\mathbf{H}[k] = \begin{pmatrix} H_{11}[k] & H_{12}[k] \\ H_{21}[k] & H_{22}[k] \end{pmatrix}$ is the channel impulse response matrix in frequency domain, and $H_{ij}[k]$ indicates the impulse response of the channel between transmitter i and receiver j. Then the FFT output of the received signal can be expressed as

$$\mathbf{Y}[k] = \begin{pmatrix} Y_1[k] \\ Y_2[k] \end{pmatrix} = \mathbf{H}[k]\mathbf{X}[k] + \mathbf{W}[k], \tag{1}$$

where $\mathbf{W}[k] = (W_1[k], W_2[k])^T$ denotes the additive noise.

Here we introduce a method of channel estimation for MIMO-OFDM based on pilots and the Alamouti algorithm [9]. In [9], the 2×2 MIMO system transmits x_1, x_2 in two adjacent time slots from one antenna and $-x_2^*, x_1^*$ from the other one, where "*" indicates the conjugate of a complex value, so-called Space Time Block Coding (STBC). In our design, we set two pilots to adjacent subcarriers to inherit the property, which is Space-Frequency Block Code (SFBC), accordingly. In the later session of this paper, SFBC can also be applied to data subcarriers to obtain transmission diversity.

For each OFDM block, the two pilots are allocated to every eight subcarriers. Let $X_1[8k] = p_1, X_1[8k+1] = p_2$. As a result of SFBC, $X_2[8k] = -p_2^*, X_2[8k+1] = p_1^*$. For a channel without drastic change, We assume that the estimated channel $\hat{H}_{ij}[8k] \approx \hat{H}_{ij}[8k+1]$. Consider (1), the received pilot subcarriers can be denoted as

$$\begin{pmatrix} Y_1[8k] & Y_1[8k+1] \\ Y_2[8k] & Y_2[8k+1] \end{pmatrix} \approx \hat{\mathbf{H}}[8k] \begin{pmatrix} p_1 & p_2 \\ -p_2^* & p_1^* \end{pmatrix} \tag{2}$$

By solving the equations (3), we can estimate the channel as

$$\hat{\mathbf{H}}[8k] \approx \frac{1}{E_p} \begin{pmatrix} Y_1[8k] & Y_1[8k+1] \\ Y_2[8k] & Y_2[8k+1] \end{pmatrix} \begin{pmatrix} p_1^* & -p_2 \\ p_2^* & p_1 \end{pmatrix} \tag{3}$$

where $E_p = |p_1|^2 + |p_2|^2$. Hence, we estimated the channel matrices $\mathbf{H}[8k]$. We can construct the rest of channel matrices $\mathbf{H}[8k+l], l = 2, 3, ..., 7$ with difference approaches. In practice, we apply linear interpolation in the implementation, that is

$$\hat{\mathbf{H}}[8k+l] = \left(1 - \frac{l-1}{7}\right) \hat{\mathbf{H}}[8k] + \frac{l-1}{7} \hat{\mathbf{H}}[8k+8] \tag{4}$$

Here we define $\hat{H}[N] = \hat{H}[0]$ as the spectrum is periodic. Hence, we can apply the zero-force

(ZF) method to estimate the signal

$$\hat{\mathbf{X}[k]} = \hat{\mathbf{H}}^{-1}[k]\mathbf{Y}[k] \tag{5}$$

2.2. SFBC IN MIMO-OFDM

In addition to the pilots, SFBC can also be applied to the data subcarriers in a similar pattern. The use of Alamouti codes for transmit diversity enhancement on UWA channels has been studied primarily in the context of coherent detection. SFBC implies to the encoding of OFDM carriers. Due to the time-dependent characteristics of UWA channels, SFBC is considered more appropriate for use in these channels. Moreover, it can outperform the traditional coherent detection on highly time-varying channels, where channel estimation suffers from errors [10].

Specifically, when $X\left[8k+m\right] = (x_1, x_2)^T, m = 2, 4, 6$, we map its following subcarrier $\mathbf{X}\left[8k+m+1\right] = (-x_2^*, x_1^*)^T$. Thus, assuming that $\hat{H}_{ij}[8k+m] \approx \hat{H}_{ij}[8k+m+1]$, after the procedure of channel estimation, the received signal can be denoted.

2.3. DOPPLER COMPENSATION FOR UNDERWATER OFDM

The Doppler shift caused by channel variation is characterized as a carrier frequency offset (CFO) between the transmitter and receiver. We compensate the CFO on the OFDM block for each provisional CFO ϵ and analyze the FFT output on the null subcarriers. An approximate estimate of ϵ can be obtained via a 1-D search for the minimum of the total energy of the null subcarriers, which can be denoted as a cost function $J(\epsilon)$.

Due to the complexity of the design, we assume that the differences of the Doppler shift between the TX-RX pairs are negligible. As a result, the Doppler shift estimation is only obtained from one of the TX-RX pair and all the channels are compensated based on this estimation.

3. SYSTEM IMPLEMENTATION

In this section, we describe and evaluate the integration of a custom software-defined IoUT platform, the SEANet modem [8], to accommodate our MIMO-OFDM design.

3.1. HARDWARE IMPLEMENTATION

The hardware of the SEANet IoUT prototype is comprised of a main module that includes a Microzed development board.Microzed is equipped with a Zynq Z-7020 SoC that combines a dual-core ARM Cortex-A9-based Processing System (PS) and a Xilinx Programmable Logic (PL) on the same processor. The converter module consists of an LTC 1740CG ADC with 14-bit parallel outputs and 6M sample/s and an LTC 1668 DAC with 12-bit parallel inputs and 50Msample/s. The power amplifier is a Mini-Circuits ZHL-6A-S+ high voltage amplifier with a maximum gain of 25 dB. The Teledyne RESON EC6081 preamplifier module interfaces with the transducer's received signal and consists of multistage amplifiers and a series of filters.

3.2. SOFTWARE IMPLEMENTATION

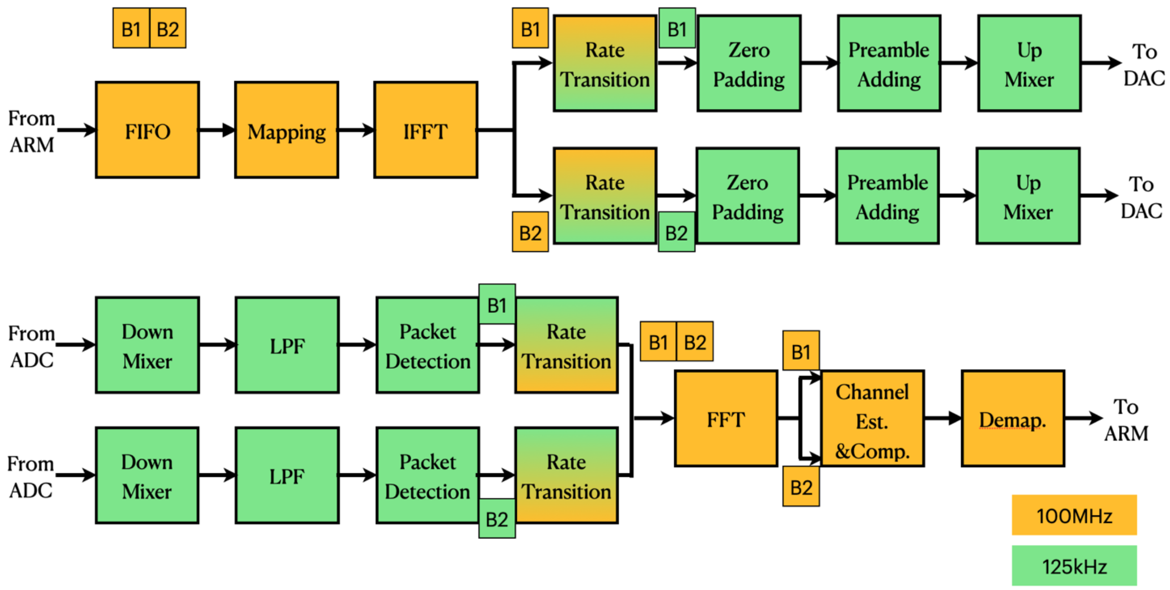

Figure 1: Software Implementation Block Design

The block-level representation of the programmable logic used to implement the proposed MIMO-OFDM transceiver is shown in 1. The ARM processor sends information bits to the transmitter chain. According to the designated modulation scheme, the bits of input information are mapped to symbols with different modulation schemes, such as BPSK, QPSk etc. The generated symbols are then assigned to various subcarriers, along with pilot and null subcarriers. The OFDM symbols are then transmitted to the IFFT block for time-domain. The output of the IFFT block is then transmitted to the zero-padding block, which generates ZP-OFDM symbols. Later, the formed ZP-OFDM symbols are translated into packets that consists of a preamble (PN sequence) and ZP-OFDM symbols. The packets are converted to the passband by the upmixer and sent to the DAC.

The receiver acquires the signal from ADC. Through a down-mixer block, the detected packets are eventually converted to baseband signals. A low-pass filter (LPF) is then applied to the baseband signals to eradicate higher frequency band. The PN sequence is detected by auto-correlation to achieve time synchronization (packet). After taking the FFT of each OFDM symbol and translating it into the frequency domain, each OFDM symbol is passed through blocks that perform Doppler compensation based on null subcarriers, pilot-based channel estimation and demapping. The final data packets are transferred to the ARM.

To further accelate the proessing time on the FPGA, the frequency domain processing operates at the base clock of the FPGA (100MHz), while the time domain processing operates at 125kHz sample rate. Also, the frequency domain processing are done in a serialized pattern in order to save the utilization of the FPGA resources, as the much faster processing in frequency domain guarantees a short processing delay that is shorter than the guard interval between the OFDM symbols.

4. PERFORMANCE EVALUATION

Using the platform, we have conducted preliminary experiments at sea. In these experiments, we demonstrated reconfigurable high-rate communication capabilities. The experiments were performed at a boat dock in the Charlestown neighborhood of Boston, Massachusetts. The dock is located between a marina and a wharf, and it is open to Boston Harbor. We evaluate the performance of MIMO-OFDM with 8192 subcarriers. The TX and RX transducers are separated by 2 meters at a depth of 4 meters. The signal obtains a bandwidth of $B = 125$ kHz and a carrier frequency of $fc = 125$ kHz.

We show the performance of the 2×2 MIMO-OFDM with BPSK, QPSK and 16QAM modulation. We also compare these modulations with SFBC as well as SISO. The data rates of varies transmission schemes are shown in Table 1.

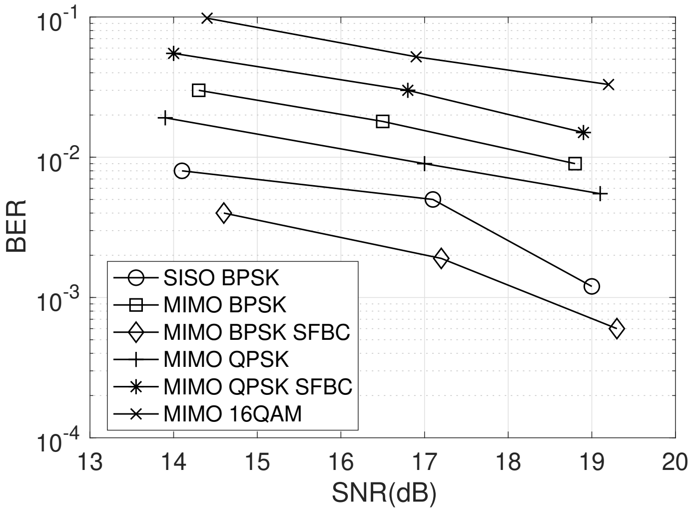

Figure 2: BER performance versus SNR.

$Tx \times Rx$	Modulation	SFBC	Data Rate/kbit/s
1×1	BPSK	N/A	74
2×2	BPSK	No	148
2×2	BPSK	Yes	74
2×2	QPSK	No	296
2×2	QPSK	Yes	148
2×2	16 QAM	No	592

Table 1: Table to test captions and labels.

Fig.2 shows the BER as a function of the received SNR. We observe that the proposed MIMO-OFDM IUoT prototype can reach up to aroung 600kbit/s data rate. The experiments also demonstrate that SFBC in MIMO-OFDM outperforms that without SFBC when the transmission are at the same transmission rate.

5. CONCLUSION

In this paper, we propose a prototype for Internet of Underwater things that supports MIMO-OFDM configuration. We present the transceiver design of the MIMO-OFDM system. We also discuss the hardware and software implementaiton of the prototype. The sea experiments show that we can reach up to 600kbit/s data rate with 2×2 MIMO at the bandwidth of 125 kHz.

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