Alamouti Space Time Coded OFDM for Underwater Acoustic Channels

Baosheng Li[1] and Milica Stojanovic[1]

[1]Dept. of Elec. and Computer Eng., Northeastern University, Boston, MA 02115

***Abstract*—Alamouti space-time coding is investigated in conjunction with OFDM modulation for high-rate underwater acoustic communications over time varying channels. The scheme's diversity gain is exploited using a low-complexity adaptive multichannel receiver. Performance is demonstrated using experimental data transmitted in a 10 kHz bandwidth over a 1 km shallow water channel south of the Martha's Vineyard island in New England. The two-transmitter Alamouti scheme shows the expected improvement over the same-rate single-transmitter scheme.**

I. Introduction

Multicarrier modulation in the form of OFDM is considered as a low-complexity alternative to single-carrier broadband modulation for underwater acoustic communications. Initial results on acoustic OFDM motivated the investigation of multi-input multi-output (MIMO) OFDM techniques, which were applied to obtain the spatial *multiplexing* gain over underwater acoustic channels [1], [2].

The focus of this paper is on the use of MIMO OFDM as a means of obtaining the spatial *diversity* gain over an acoustic channel. The classical Alamouti scheme [3] is used, for which an adaptive receiver is developed to track the time-variation of the channel.

Adaptive channel estimation for space-time block coded (STBC) OFDM systems has been extensively studied for terrestrial communications, e.g. [4]- [8]. STBC for underwater acoustic channels has been considered for both single-carrier systems [9], and multi-carrier systems [10], [11]. Reference [9] discusses a jointly optimized MIMO-DFE with space-time trellis codes. In [10], maximum likelihood detection was considered, while [11] considered iterative equalization and decoding.

In this paper, we focus on multi-carrier MIMO modulation, and investigate an Alamouti OFDM system with adaptive channel estimation and data detection. The proposed receiver explicitly targets both the inherent channel variation and the motion-induced phase offset. The underlying assumption is that the channel and the phase stay fixed over the duration of one OFDM block, but may change from one block to another. Channel estimation and Doppler tracking are based on the block-by-block adaptive method [1]. In its basic form, this method ignores the presence of the Alamouti code. Here, it is adjusted such that Alamouti coding is exploited at the end of every pair of blocks to improve the data detection, and thus provide the channel estimator with improved symbol decisions. Since it provides a new channel/phase estimate for every block, and not only for every pair of blocks, this method is preferred on acoustic channels where block-to-block variation cannot be ignored. The receiver algorithm has been tested using real data, showing an expected performance improvement over the uncoded, single-transmitter scheme.

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The rest of the paper is organized as follows. In Section II, the system model is described. In Section III, the joint channel estimation and data detection schemes are proposed for the adaptive Alamouti OFDM receiver. In Section IV, the experimental results are illustrated. The conclusions are drawn in Section V.

II. System Model

We consider a MIMO system with M_T transmitters and M_R receivers. In the Alamouti OFDM scheme, $M_T = 2$, and two adjacent OFDM blocks, $2n$ and $2n+1$, are used to transmit the following PSK data symbols on the k-th carrier: $d_k(2n)$, $d_k(2n+1)$ from the first transmitter, and $-d_k^*(2n+1)$, $d_k^*(2n)$ from the second transmitter.

If we denote by $A_k^r(2n)$ and $B_k^r(2n)$ the transfer function of the channel observed on the k-th carrier frequency during transmission of block $2n$ from the first and the second transmitter, respectively, to the r-th receiver, and by $\theta_k^t(2n)$ the additional phase distortion caused by the relative motion between the t-th transmitter and the receiver array, the signals received on the k-th carrier during two consecutive OFDM blocks can be represented as

$$y_k^r(2n) = A_k^r(2n)e^{j\theta_k^1(2n)}d_k(2n) - B_k^r(2n)e^{j\theta_k^2(2n)}d_k^*(2n+1) + z_k^r(2n) \quad (1)$$

$$y_k^r(2n+1) = A_k^r(2n+1)e^{j\theta_k^1(2n+1)}d_k(2n+1) + B_k^r(2n+1)e^{j\theta_k^2(2n+1)}d_k^*(2n) + z_k^r(2n+1) \quad (2)$$

where $z_k(2n)$ and $z_k(2n+1)$ are the noise components.

If we now form the vector of all the signals received across M_R elements in two adjacent blocks as

$$\mathbf{y}_k[2n] = \begin{bmatrix} y_k^1(2n) \\ \vdots \\ y_k^{M_R}(2n) \\ --- \\ y_k^{1*}(2n+1) \\ \vdots \\ y_k^{M_R*}(2n+1) \end{bmatrix}, \quad (3)$$

and define the channel matrix

$$\mathbf{C}_k[2n] = \quad (4)$$
$$\begin{bmatrix} A_k^1(2n)e^{j\theta_k^1(2n)} & -B_k^1(2n)e^{j\theta_k^2(2n)} \\ \vdots & \vdots \\ A_k^{M_R}(2n)e^{j\theta_k^1(2n)} & -B_k^{M_R}(2n)e^{j\theta_k^2(2n)} \\ ----- & ----- \\ B_k^{1*}(2n+1)e^{-j\theta_k^2(2n+1)} & A_k^{1*}(2n+1)e^{-j\theta_k^1(2n+1)} \\ \vdots & \vdots \\ B_k^{M_R*}(2n+1)e^{-j\theta_k^2(2n+1)} & A_k^{M_R*}(2n+1)e^{-j\theta_k^1(2n+1)} \end{bmatrix},$$

we obtain a compact representation:

$$\mathbf{y}_k[2n] = \mathbf{C}_k[2n] \begin{bmatrix} d_k(2n) \\ d_k^*(2n+1) \end{bmatrix} + \mathbf{z}_k[2n] \quad (5)$$

III. Receiver Algorithm

The receiver employs the MIMO channel estimation and phase prediction algorithm [1], which provides a new set of estimates for every block. At the end of every *pair* of blocks, Alamouti decoding is performed. The receiver thus operates in two steps, data detection and channel/phase estimation, which we describe below in more detail.

A. Data detection

Assuming that an estimate of the channel matrix, $\hat{\mathbf{C}}_k[2n]$ is available at the beginning of the n-th block pair, the data symbols are estimated as

$$\begin{bmatrix} \hat{d}_k(2n) \\ \hat{d}_k^*(2n+1) \end{bmatrix} = (\hat{\mathbf{C}}_k'[2n]\mathbf{C}_k[2n])^{-1}\hat{\mathbf{C}}_k'[2n]\mathbf{y}_k[2n] \quad (6)$$

Based on these (soft) estimates, symbol decisions are made. If channel coding is employed in addition to the Alamouti mapping, soft decision decoding is employed. The so-obtained symbol decisions $\tilde{d}_k(2n), \tilde{d}_k(2n+1)$ are used to update the existing channel estimate for the next block.

B. Channel estimation and phase prediction

The block-by-block adaptive channel-and-phase estimator [1] is employed ignoring the presence of the Alamouti code, i.e. the symmetry in the channel matrix $\mathbf{C}_k[2n]$. This estimator provides the channel gains $\hat{A}_k^r(m), \hat{B}_k^r(m)$, and the phases $\hat{\theta}_k^t(m)$ for each block m, as well as tentative symbol decisions. At the end of each pair of blocks, the channel and phase estimates are used to construct the matrix $\hat{\mathbf{C}}_k[2n]$, which is in turn used to obtain the refined data symbol estimates (6). In this manner, at every odd time instant $m = 2n+1$, the Alamouti structure is exploited, yielding more reliable symbol decisions for the channel estimator.

The particular details of MIMO channel estimation and phase prediction are given in Ref. [1]. Channel estimation is performed in the impulse response domain, and can be tailored for sparse multipath. Two channel estimation algorithms are described in that reference, one that requires a matrix inversion, and another one that does not. The latter algorithm was used to process the experimental data that we describe in the next section.

IV. Experimental results

The algorithm was tested using real data collected during an experiment that took place south of the Martha's Vineyard island in New England, in October 2008. The transmitter array (4 elements separated by 50 cm) was deployed at a depth of about 10 m with water depth 15 m. The top and the bottom element of the transmitter array (150 cm separation) were used as an Alamouti pair. The receiver array (12 elements, separated by 12 cm) was deployed 1 km away, at a depth of about 11 m. The bandwidth used was 10 kHz, centered at 13.25 kHz. Table I lists the signal parameters.

TABLE I
Signal parameters used in the experiment

Number of subcarriers, K	128, 256, 512, 1024
Subcarrier spacing, Δf [Hz]	78, 39, 19, 10
OFDM block duration, T [ms]	13, 26, 52, 105
Symbols per frame, N_d	16384
Blocks per frame, N	128, 64, 32, 16
Guard interval T_g [ms]	16

Fig. 1 illustrates the performance obtained with the Alamouti space-time coding for a typical data set. This particular data set was a $K = 512$ QPSK frame, recorded at 2:00 am on Oct. 16, 2008. Shown in the figure are the phase estimates for several carriers; the channel responses for all 12 receivers as seen at the end of the frame; the mean squared error (MSE) in time (average over all carriers), and the MSE in frequency (average over all blocks). The uncoded bit error rate (BER) measured over the frame is indicated in the figure together with the various receiver parameters. The use of the BCH(63,10) code resulted in error-free performance.

Fig. 2 and Fig. 3 summarize the performance observed over the course of three days of the experiment (total of 19 transmissions between Oct. 14 and Oct. 16, 2008.). The system performance is measured by the MSE at the detector output for $K = 512$ and $K = 1024$. The performance of the Alamouti scheme is compared to the single-transmitter scheme using the same number of receive elements and the same transmission rate (15 kbps for $K = 512$; 17 kbps for $K = 1024$). We note that Alamouti coding provides the expected diversity gain. The exact amount of gain depends on the ability to accurately track the time-varying channel (as well as on the type of fading, and the amount of correlation between the channels). Table II summarizes the average MSE improvement obtained by the Alamouti scheme. The improvement is given as the average MSE difference, ΔMSE, calculated over all the records between the single-transmitter and the Alamouti scheme. We can also observe that there is a greater improvement for a greater number of carriers K. This may be explained by the fact that a greater K supports a greater time-variation of the channel (longer block duration), and hence leaves more room for improvement.

TABLE II
AVERAGE MSE IMPROVEMENT OBTAINED WITH THE ALAMOUTI SCHEME.

	ΔMSE
$K = 512$	3.2 dB
$K = 1024$	4.0 dB

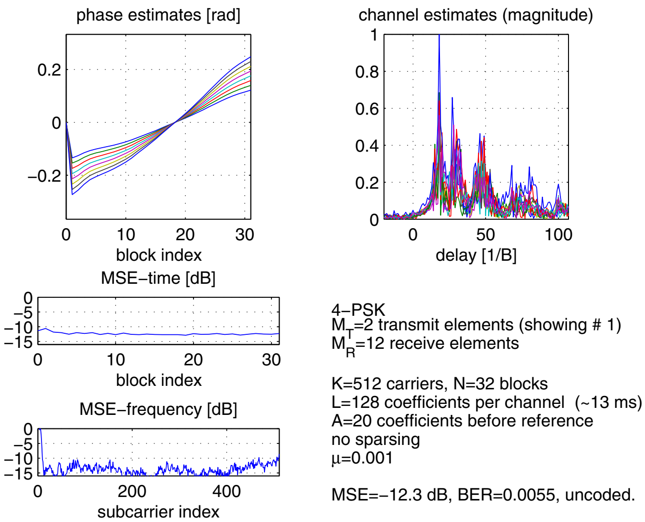

Fig. 1. Signal processing results (10/16/2008, 2:00am, 1 km, SE).

V. CONCLUSION

Multiple-transmitter OFDM provides spatial diversity gain on time-varying channels, provided that the channel can be accurately tracked. To that end, we have coupled the classical Alamouti space-time coding scheme with an adaptive channel estimation and phase prediction method suited for underwater acoustic channels. The technique was demonstrated experimentally over a 1 km long, shallow water channel in the 8-18 kHz acoustic band. Experimental results, obtained by processing the data recorded over the course of three days, show an average performance improvement of about 3 dB over the conventional single-transmitter scheme. Future work will focus on channel estimation schemes that exploit the structure of the Alamouti code to further reduce the computational complexity.

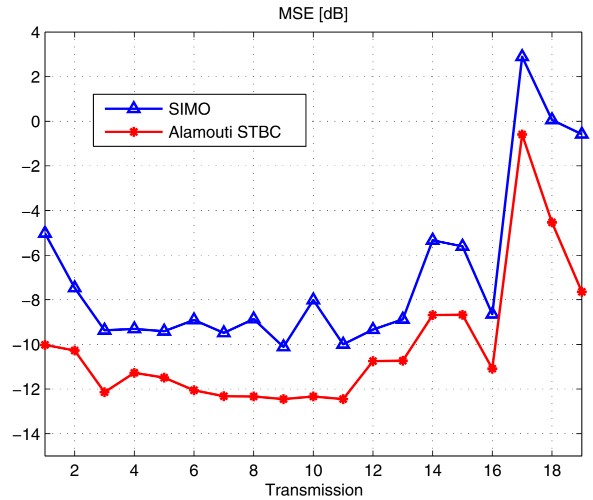

Fig. 2. MSE performance comparison, K=512.

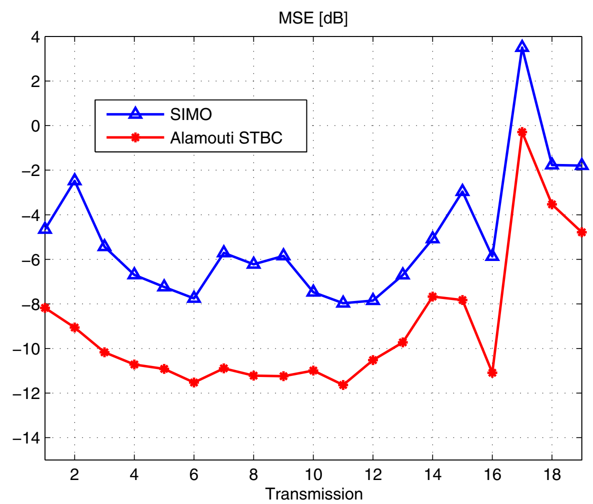

Fig. 3. MSE performance comparison, K=1024.

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