On an Orthogonal Space-Time-Polarization Block Code

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Abstract— **Over the past several years, diversity methods such as space, time, and polarization diversity have been successfully implemented in wireless communications systems. Orthogonal space-time block codes efficiently combine space and time diversity, and they have been studied in detail. Polarization diversity has also been studied, however it is usually considered in a simple concatenation with other coding methods. In this paper, an efficient method for incorporating polarization diversity with space and time diversity is studied. The simple yet highly efficient technique is based on extending orthogonal space-time block codes into the quaternion domain and utilizing a description of the dual-polarized signal by means of quaternions. The resulting orthogonal space-time-polarization block codes have given promising results in simulations. In the example described in this paper, the achievable performance gain for two transmit and one receive antennas is approximately 6 dB at a bit error rate of 10^{-4} when compared with the Alamouti code.**

Index Terms—**polarization diversity, space-time processing, quaternions, block codes**

I. Introduction

Orthogonal space-time block codes (OSTBCs) based on complex orthogonal designs were introduced as an effective way to combine space and time diversity using multiple transmit and (optionally) multiple receive antennas [1, 2]. The additional transmit antennas allow for transmission channels that experience independent Rayleigh fading, and the orthogonality of the columns in the underlying design allows for a simple maximum likelihood (ML) decoding algorithm based only on linear processing at the receiver [1]. However, for more than two transmit antennas, it is impossible to achieve full rate for complex signal constellations, so any gains must be weighed against this reduction in rate [3]. Alternatively, the orthogonality condition can be sacrificed, but this results in a significant increase in receiver complexity, and in general, no means of a decoupled ML decoding method [4].

Recently, the demand for high rates in mobile communications has raised interest in applying polarization diversity, often together with other forms of diversity [5,6]. Polarization diversity is a technique where information is transmitted and received simultaneously on orthogonally polarized waves with fade-independent propagation characteristics. It has been shown [5,6] that it can significantly add to the performance improvements offered by other diversity techniques and be nearly as effective as spatial diversity for base station antennas, without a noticeable increase in their dimensions.

Some efforts to utilize polarization diversity jointly with OSTBCs have been previously described [7], but these were limited to the use of conventional complex OSTBCs without attempting to introduce a code specially designed to jointly utilize all three diversity techniques. In this paper, we propose to design orthogonal space-time-polarization block codes (OSTPBCs) based on recently defined orthogonal designs with quaternion elements [8]. Quaternions were used in the past to construct complex OSTBCs, e.g. [9], but the technique presented in this paper is significantly different as our approach does not involve non-linear processing as the one presented in [9]. It should be noted that the similar performance gains can be achieved using conventional OSTBCs but at the expense of significant increase in the receiver dimensions due to antenna spacing requirements.

II. Quaternion Orthogonal Designs

In this section, we provide an overview of quaternion orthogonal designs, which will be the building blocks for our proposed space-time-polarization block codes. As quaternion orthogonal designs are a generalization of complex orthogonal designs, and as these complex designs will be used later in this paper, we begin by reviewing complex orthogonal designs.

Complex orthogonal designs and their various generalizations have been successfully applied in wireless communications systems. The following generalization provided by Tarokh *et al* [1] has been particularly useful:

Defn 1: A *generalized complex orthogonal design* **G** is a p x n matrix whose entries are from $\{0, z_1, z_2, \ldots, z_u, z_1^*, z_2^*, \ldots, z_u^*\}$ including possible multiplications by the complex number i, such that

$$\mathbf{G}^H\mathbf{G} = \left(\sum_{l=1}^{\mathbf{u}} \boldsymbol{\lambda}_l \mid z_l \mid^2\right)\mathbf{I_n}$$

where H indicates the Hermitian transpose, $\mathbf{I}_n$ is the $n \times n$ identity matrix, and λ_l is the positive number of times the variable z_l appears in each column.

More recently, orthogonal designs over the quaternion domain have been studied [8]. The noncommutative quaternions, invented by Hamilton in 1843, can be viewed as a generalization of the complex numbers. The quaternion elements Q = $\{\pm 1, \pm i, \pm j, \pm k\}$ satisfy $i^2 = j^2 = k^2 = ijk = -1$. Given a quaternion variable $s = x_1 + y_1 i + x_2 j + y_2 k$ where x_1, y_1, x_2, y_2 are real variables, the quaternion conjugate s^Q is defined analogously to the complex conjugate so that

$$\begin{aligned} s^Q &= (x_1 + y_1 i + x_2 j + y_2 k)^Q \\ &= x_1 - y_1 i - x_2 j - y_2 k \end{aligned} \quad . \tag{1}$$

We note that for a complex variable z, we have $zj = jz^*$, where z^* is the complex conjugate of z. It follows that $s^Q s = |s|^2 = |z_1|^2 + |z_2|^2 = x_1^2 + y_1^2 + x_2^2 + y_2^2$. For matrices of quaternion numbers or variables, the quaternion transform is analogous to the Hermitian transform for complex matrices: For a quaternion matrix $\mathbf{S} = [s_{lm}]$, we define the quaternion transform as $\mathbf{S}^Q = [s^Q_{ml}]$. This leads to the following definition of quaternion orthogonal designs [8], which is clearly a generalization of Defn 1:

Defn 2: A *quaternion orthogonal design* (QOD) **D** on quaternion variables $s_1, s_2, \ldots, s_u$ is a $p \times n$ matrix with entries from the set $\{0, s_1, s_2, \ldots, s_u, s_1^Q, s_2^Q, \ldots, s_u^Q\}$ including possible multiplications on the left and/or right by quaternion elements $q \in Q$ satisfying

$$\mathbf{D}^Q\mathbf{D} = \left(\sum_{l=1}^{u} \lambda_l \mid s_l \mid^2\right)\mathbf{I}_n \ ,$$

where λ_l is the positive number of times the variable s_l appears in each column.

Several construction methods for obtaining QODs over quaternion variables, as well as for QODs over real and complex variables, have been introduced [8, 10]. One of these construction methods will be utilized below in Section V. Previously, the application of QODs as orthogonal space-time-polarization block codes has been briefly described [8], and this current paper expands upon the authors' recent conference paper on this application [11].

III. Quaternionic Representation of Dual Polarized Signals

Quaternions are very well suited to describe rotations and sequences of rotations and were used by Isayeva and Sarytchev [12] to describe dual-polarized radio signals, whereby two complex signals are rotated one against another by 90 degrees on the polarization plane. Using that approach, two complex signals

$$z_1 = x_1 + y_1 i \quad \text{and} \quad z_2 = x_2 + y_2 i \tag{2}$$

being orthogonal to each other on a polarization plane form a quaternion number

$$s = z_1 + z_2 j = x_1 + y_1 i + x_2 j + y_2 k$$

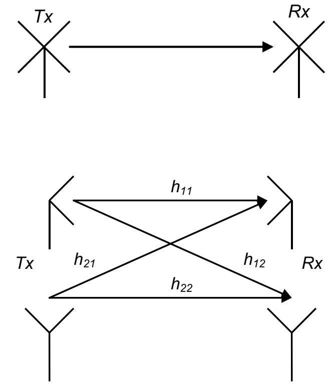

Fig. 1. Schematic diagram of a channel utilizing dual-polarized antennas and its model (below) with the horizontally and vertically polarized antennas considered separately; the channel gains are complex numbers.

A rotation s_φ of the signal s on a polarization plane by an angle of φ can be simply represented in the quaternion notation as:

$$\begin{aligned} s_\varphi &= s e^{j\varphi} = (z_1 + z_2 j) e^{j\varphi} \\ &= (z_1 + z_2 j)[\cos(\varphi) + j\sin(\varphi)] \end{aligned} \quad . \tag{3}$$

Similarly, any change to the polarization bases, *e.g.*, due to differences between transmit and receive antenna alignments, can be easily represented in the quaternion notation, as long as the polarization bases are orthogonal [12].

IV. Diversity Gain in Dual-polarized Channels

The mechanism of a diversity gain for OSTBCs relies on providing extra transmission channels that experience independent Rayleigh fading through the use of additional transmit antennas [13]. This can be also achieved using dual-polarized antennas (*e.g.*, antennas having both vertical and horizontal polarizations). Even a case involving just 1 transmit and 1 receive antenna results in 4 sub-channels, each characterized by its own complex gain (see Fig. 1), much the same as in case of a 2-input 2-output MIMO system [14].

Mathematically, the channel between transmitter and receiver is in such a case described by a channel gain matrix **H**:

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}, \qquad (4)$$

where h_{11} and h_{22} are complex channel gains for signals received with the same polarization as they were transmitted, and h_{12} and h_{21} are complex channel gains for a cross-polar scatter, *i.e.,* signals received with different polarization from that at which it was transmitted due to scatter, reflections and polarization twist between the transmit and receive antennas.

Introducing representation of a quaternion variable $s = z_1 + z_2 j$ as $s = [z_1, z_2]$, transmission of the signal through a channel between a dual-polarized transmit and a dual-polarized receive antennas can be modeled as a product $s\mathbf{H}$. Hence the received quaternion signal r is given by:

$$\begin{aligned} r &= s\mathbf{H} + n \\ &= [z_1, z_2]\mathbf{H} + [n_1, n_2] \\ &= [z_1 h_{11} + z_2 h_{21}, z_1 h_{12} + z_2 h_{22}] + [n_1, n_2] \\ &= (z_1 h_{11} + z_2 h_{21}) + (z_1 h_{12} + z_2 h_{22}) j + n_1 + n_2 j \end{aligned}, \qquad (5)$$

where n_1, n_2 are complex additive White Gaussian noises being the independent identically distributed (i.i.d.) zero-mean two dimensional Gaussian random variables with identical variance per dimension. The exact value of the variance depends on the value of a signal-to-noise ratio (SNR) at the receiver.

This consideration can be extended to the scenarios with multiple transmit and/or receive antennas [8], like the scenario considered in Fig. 2.

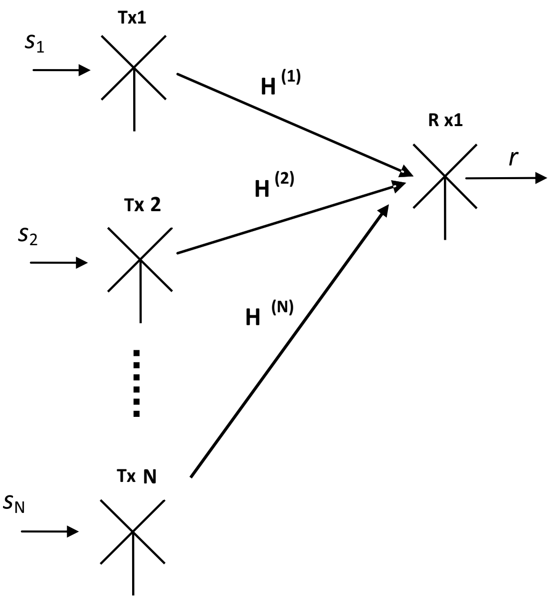

Fig. 2. A transmission system utilizing N dual-polarized transmit antennas Tx1, …, TxN, and a single receive dual-polarized antenna.

For example, for the scenario considered there, the received signal r can be modeled as a quaternionic variable given by:

$$r = [s_1 \quad s_2 \quad \cdots \quad s_N] \begin{bmatrix} \mathbf{H}^{(1)} \\ \mathbf{H}^{(2)} \\ \vdots \\ \mathbf{H}^{(N)} \end{bmatrix} + [n_1 \quad n_2], \qquad (6)$$

where $s_1, s_2, \ldots, s_N$ are the input signal symbols applied to the transmit antennas Tx1, Tx2, …, TxN,

$$s_m \mathbf{H}^{(m)} = [z_{m1} \quad z_{m2}]\mathbf{H}^{(m)},$$

$$s_m = z_{m1} + z_{m2} j,$$

and matrices $\mathbf{H}^{(m)}$; $m = 1, 2, \ldots, N$, are all of the structure defined by Eqn. (4).

V. Orthogonal Space-Time-Polarization Block Codes

Orthogonal space-time block codes (OSTBCs) jointly utilize space and time diversities and allow for a decoupled maximum likelihood (ML) decoding at the receiver [1]. To jointly utilize space, time, and polarization diversities, we propose here orthogonal space-time-polarization block codes (OSTPBCs). Such codes can be derived from the quaternion orthogonal designs defined in Section II.

Of the various techniques recently presented to construct QODs [8, 10], one of the simplest techniques is based on *symmetric-paired designs:* Two complex orthogonal designs **A** and **B** are said to be *symmetric-paired designs* if $\mathbf{A}\mathbf{B}^H$ is symmetric and/or $\mathbf{A}^H\mathbf{B}$ is symmetric [8]. This condition is similar to that required of complex amicable designs [8]. It has been shown [8] that if the complex orthogonal designs **A** and **B** are *symmetric-paired designs,* then

$$\mathbf{A} + \mathbf{B}j \qquad (7)$$

is a QOD.

Consider now two CODs of order 2

$$\mathbf{A} = \begin{bmatrix} z_1 & z_2 \\ -z_2^* & z_1^* \end{bmatrix} \text{ and } \mathbf{B} = \begin{bmatrix} z_2 & z_1 \\ z_1^* & -z_2^* \end{bmatrix}, \qquad (8)$$

which are two Alamouti [11] OSTBCs, one of them (**B**) having switched columns. Since we have

$$\mathbf{A}^H\mathbf{B} = \begin{bmatrix} z_1^* z_2 - z_2 z_1^* & z_1^* z_1 + z_2 z_2^* \\ z_2^* z_2 + z_1 z_1^* & z_2^* z_1 - z_1 z_2^* \end{bmatrix} \qquad (9)$$

then $\mathbf{A}^H\mathbf{B}$ is clearly symmetric and the design

$$\mathbf{Q}_1 = \mathbf{A} + \mathbf{B}j = \begin{bmatrix} z_1 + z_2 j & z_2 + z_1 j \\ -z_2^* + z_1^* j & z_1^* - z_2^* j \end{bmatrix} \qquad (10)$$

is a QOD. Introducing now a quaternion variable

$$a = z_1 + z_2 j$$

$\mathbf{Q}_1$ can be expressed as:

$$\mathbf{Q}_1 = \begin{bmatrix} a & -iak \\ ja & -kak \end{bmatrix}, \qquad (11)$$

and can be considered as a QOD on the one quaternion variable a. The orthogonality can be easily checked, as

$$\mathbf{Q}_1^Q\mathbf{Q}_1 = \begin{bmatrix} a^Q & -a^Qj \\ -ka^Qi & -ka^Qk \end{bmatrix}\begin{bmatrix} a & -iak \\ ja & -kak \end{bmatrix}. \quad (12)$$

Because for two quaternion variables b and c [7]:

$$(bc)^Q = c^Q b^Q \quad (13)$$

Eqn. (12) can be expanded to:

$$\mathbf{Q}_1^Q\mathbf{Q}_1 = \quad (14)$$

$$\begin{bmatrix} a^Qa - a^Qjja & a^Q(-i)ak + a^Qjkak \\ -ka^Qia - ka^Qkja & -ka^Qi(-i)ak - ka^Qk(-k)ak \end{bmatrix}.$$

From the definition of a quaternion, we have:

$$ijk = -1 .$$

Hence

$$jk = i \quad \text{and} \quad kj = -i .$$

Substituting the latest results into (14) and utilizing the principles of the arithmetic of quaternions, yields:

$$\mathbf{Q}_1^Q\mathbf{Q}_1 = \begin{bmatrix} 2|a|^2 & 0 \\ 0 & 2|a|^2 \end{bmatrix} = 2|a|^2\mathbf{I}_{2\times 2} \quad (15)$$

Using the same notation as in (5), $\mathbf{Q}_1$ can be expressed as:

$$\mathbf{Q}_1 = \begin{bmatrix} z_1 & z_2 & z_2 & z_1 \\ -z_2^* & z_1^* & z_1^* & -z_2^* \end{bmatrix} \quad (16)$$

where odd columns represent signals transmitted through one polarization and even columns represent signals transmitted through the polarization orthogonal to the first one.

For a single receive dual-polarized antenna, the channels between dual-polarized transmit antennas Tx1 and Tx2, and the dual-polarized receive antenna Rx1 are described by their own channel gain matrices, $\mathbf{H}^{(1)} = [h_{mn}^{(1)}]_{2\times 2}$ and $\mathbf{H}^{(2)} = [h_{mn}^{(2)}]_{2\times 2}$, respectively. The received signal vector $\mathbf{R}$ is given by

$$\begin{aligned}\mathbf{R} &= \mathbf{Q}_1\begin{bmatrix}\mathbf{H}^{(1)} \\ \mathbf{H}^{(2)}\end{bmatrix} + \begin{bmatrix} n_{11} & n_{12} \\ n_{21} & n_{22}\end{bmatrix} \\ &= \begin{bmatrix} z_1h_{11}^{(1)} + z_2h_{21}^{(1)} + z_2h_{11}^{(2)} + z_1h_{21}^{(2)} \\ -z_2^*h_{11}^{(1)} + z_1^*h_{21}^{(1)} + z_1^*h_{11}^{(2)} - z_2^*h_{21}^{(2)} \end{bmatrix} \\ &+ \begin{bmatrix} z_1h_{12}^{(1)} + z_2h_{22}^{(1)} + z_2h_{12}^{(2)} + z_1h_{22}^{(2)} \\ -z_2^*h_{12}^{(1)} + z_1^*h_{22}^{(1)} + z_1^*h_{12}^{(2)} - z_2^*h_{22}^{(2)} \end{bmatrix} j + \begin{bmatrix} n_{11} \\ n_{21}\end{bmatrix} + \begin{bmatrix} n_{12} \\ n_{22}\end{bmatrix} j\end{aligned} \quad (17)$$

where n_{ml}; m, l = 1, 2 represent complex noises being the independent identically distributed (i.i.d.) zero-mean two dimensional Gaussian random variables with identical variance per dimension.

Assuming perfect channel knowledge at the receiver, *i.e.* assuming that matrices $\mathbf{H}^{(1)}$ and $\mathbf{H}^{(2)}$ are known and constant for some reasonable time, as in the case of slow or block fading channels [14], the ML decoding means finding a pair of elements z_1 and z_2 of the complex signal constellation $\mathbf{Z}$ that minimizes the following metric:

$$\begin{aligned}&\left\|\mathbf{R} - \mathbf{Q}_1\begin{bmatrix}\mathbf{H}^{(1)} \\ \mathbf{H}^{(2)}\end{bmatrix}\right\| = \\ &= |r_1 - z_1h_{11}^{(1)} - z_2h_{21}^{(1)} - z_2h_{11}^{(2)} - z_1h_{21}^{(2)} \\ &\quad - z_1h_{12}^{(1)}j - z_2h_{22}^{(1)}j - z_2h_{12}^{(2)}j - z_1h_{22}^{(2)}j|^2 \\ &\quad + |r_2 + z_2^*h_{11}^{(1)} - z_1^*h_{21}^{(1)} - z_1^*h_{11}^{(2)} + z_2^*h_{21}^{(2)} \\ &\quad + z_2^*h_{12}^{(1)}j - z_1^*h_{22}^{(1)}j - z_1^*h_{12}^{(2)}j + z_2^*h_{22}^{(2)}j|^2\end{aligned} \quad (18)$$

where r_1 and r_2 are the elements of the receive vector **R.**

Utilizing the principles of quaternionic arithmetic given in Section II, the decoding rule can be simplified and proven to be decoupled. The resulting decoding statistics for z_1 is:

$$\begin{aligned}&\min_{z_1\in Z} |z_1|^2 (|g_1|^2 + |g_2|^2 + |g_3|^2 + |g_4|^2) \\ &\quad - 2\,\mathrm{Re}\{r_1^Q z_1(g_1 + g_2 j) + r_2^Q z_1^*(g_3 + g_4 j)\}\end{aligned} \quad (19)$$

and for z_2 it is:

$$\begin{aligned}&\min_{z_2\in Z} |z_2|^2 (|g_1|^2 + |g_2|^2 + |g_3|^2 + |g_4|^2) \\ &\quad - 2\,\mathrm{Re}\{r_1^Q z_2(g_3 + g_4 j) - r_2^Q z_2^*(g_1 + g_2 j)\}\end{aligned} \quad (20)$$

where

$$g_1 = h_{11}^{(1)} + h_{21}^{(2)}, \quad g_2 = h_{12}^{(1)} + h_{22}^{(2)},$$
$$g_3 = h_{21}^{(1)} + h_{11}^{(2)}, \quad g_4 = h_{22}^{(1)} + h_{12}^{(2)}$$

VI. Simulation Results

To assess performance gain that can be achieved using the developed OSTPBC for 2 transmit and a single receive dual-polarized antennas, the system was implemented using MATLAB. The following conditions were assumed:

- The QPSK {π/4, 3π/4, 5π/4, 7π/4} signal constellation was applied, and the code based on $\mathbf{Q}_1$ was used (OSTPBC).
- Total transmitted power in both polarizations and through both antennas was equal to 1 and equally distributed per antenna and per polarization.
- Channel coefficient matrices, $\mathbf{H}^{(1)}$ and $\mathbf{H}^{(2)}$ were assumed known at the receiver and kept constant for 1024 data bits (the block fading scenario).
- In the dynamic indoor scenario, variances of channel coefficients can change randomly due to changing scattering conditions. Hence we only assumed that the sum of variances of all the coefficients was equal to 1 and that the variance of real and imaginary part of a particular coefficient was identical. The variances were then drawn randomly, every time the new set of coefficients was drawn.
- The channel coefficients were generated as random complex Gaussian i.i.d. variables.
- The additive noise was assumed to be AWGN added uniformly for each polarization and each

real/imaginary component (a quaternion zero-mean Gaussian variable).

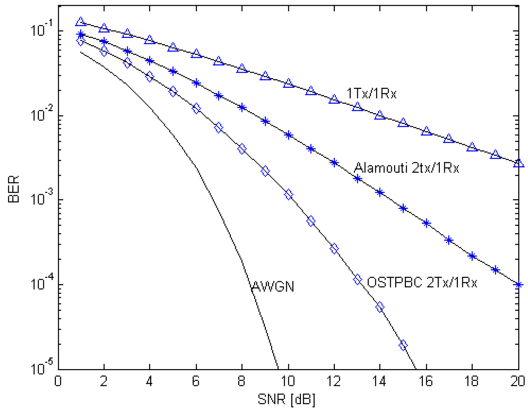

Fig. 3. Bit-error-rate (BER) performance of the developed scheme (OSTPBC) combined with QPSK modulation in a slow flat Rayleigh fading channel experiencing random cross-polar scatter compared with the Alamouti's scheme and a single transmit/single receive antenna system.

To compare the performance achieved, we also simulated a single polarization, single transmit – single receive system experiencing slow Rayleigh fading, and a single polarization Alamouti systems with two transmit and one receive (2Tx/1Rx) antennas and with 4Tx/2Rx configuration [2]. The simulation parameters were adjusted for those systems to ensure consistency of the conditions. The simulation results are presented in Fig. 3, where we have also drawn the curve representing performance of QPSK in the AWGN channel. It is clearly visible that the proposed OSTPBC performs very robustly in a realistic indoor environment and significantly outperforms the 2Tx/1Rx Alamouti system and performs exactly the same as 4Tx/2Rx Alamouti scheme. This is due to the fact that the proposed OSTPBC is equivalent to the 4Tx/2Rx Alamouti scheme. The benefit of the proposed scheme follows from the fact that its physical dimensions are similar to the system using 2Tx/1Rx Alamouti OSTBC with the performance of the 4Tx/2Rx code. For a fair comparison, the average total received power in all systems before adding noise was set to 1, and we used the same SNR normalization as used in [2].

In addition, the 2Tx/1Rx Alamouti scheme is susceptible to the cross-polar scatter unless antennas capturing energy from both polarizations are used with the dimensions fully comparable to antenna system of the proposed scheme.

VII. Conclusions

In this paper, we proposed a method to jointly utilize space, time, and polarization diversities by introducing the concept of orthogonal space-time-polarization block codes (OSTPBCs). The given example performs very well in an environment characterized by block or slow Rayleigh fading combined with slowly changing cross-polar scatter. The use of quaternionic arithmetic to design OSTPBCs and to perform decoding opens new possibilities for increasing the total diversity gain and improving system performance in harsh radio environments without increasing dimensions of antenna system. In the paper, we considered a very simple channel model. More realistic channel models taking to account possibility of correlation between polarizations need to be considered as well. Future research efforts will be devoted to designing maximum rate, full diversity OSTPBCs for two and more transmit antennas.

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