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Decoding alamouti STBC from received signal power

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Abstract: We present two decoding schemes for Alamouti space-time block codes (STBC) that do not require full knowledge of the received signal. Our schemes are able to decode signals directly from the received signal power, without knowledge of the signal amplitude and phase. This in turn allows for reduced susceptibility to fast fading and lower receiver complexity. Such decoding approach is not possible for the case of conventional Alamouti STBC scheme. It is shown that the proposed First Quadrant Transmission (FQT) is able to deliver the best performance on par with the conventional Alamouti STBC scheme even when the conventional scheme has full knowledge of the received signal. Our recommendations are based on the novel complex to real Alamouti STBC mapper and the sign ambiguity elimination method, both presented in this letter.

Keywords: decoder, Alamouti STBC, MIMO, signal power, wireless communications

Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

It is well known that multiple–input multiple–output (MIMO) system offers significant performance improvement over single antenna system [1, 2, 3]. MIMO is seen as the key technology for high-speed wireless transmission, shown by its adoption into the latest standards [4]. While MIMO has become an active field of research, very little works have been done on exploiting received signal power information for improved usability. We believe that designing MIMO scheme that is capable of utilising received signal power information is highly important as it reduces the dependability on received signal information.

Alamouti space-time block codes (STBC) is highly dependent on the knowledge of the received signal. Our aim is to reduce the dependency. We present two novel methods for decoding Alamouti STBC from power information of the received signal, discarding the need for the knowledge of signal amplitude and phase or real and imaginary components. Note that the amplitude and phase of a signal is just the polar notation for the signal real and imaginary components. The proposed schemes derive estimates of the received signal directly from the received power. The estimates are then used for predicting the transmitted symbols. The proposed schemes significantly lower the amount of information needed for proper decoding, directly increasing Alamouti scheme robustness to interference. Note that conventional coherent systems require actual amplitude and phase information and thus suffer from susceptibility to fast fading and complex receiver circuitry [5]. Direct decoding from received power reduces those weaknesses.

2 Complex to real Alamouti STBC mapper

The received Alamouti signal block matrix equation for two transmit and two receive antennas is given as

$$\mathbf{Y} = \mathbf{HS} + \mathbf{N}$$
$$\begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{bmatrix} + \begin{bmatrix} n_{11} & n_{12} \\ n_{21} & n_{22} \end{bmatrix} \tag{1}$$

where y_{uv} and n_{uv} represents signal and noise at receive antenna u time slot v respectively. h_{mn} is the channel from transmit antenna n to receive antenna m. s_1 is transmitted from antenna one and s_2 is transmitted from antenna two during the first time slot. $-s_2^*$ and s_1^* are transmitted in the second symbol period from antenna one and two respectively. Superscript * represents conjugate transpose operation. In this letter, we present a scheme based on Alamouti two transmit and two receive antennas system. However, the scheme can work with any number of receive antennas. Note that **Y, H, S** and **N** are matrices of complex variables. The power of a complex valued signal y_C is given by

$$p_{y_C} = \left(\sqrt{(\text{real } y_C)^2 + (\text{imaginary } y_C)^2} \right)^2 \tag{2}$$

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Therefore, decoding from signal power information is a challenging task as the exact values of real and imaginary components, together with the amplitude and phase information are not available. The problem is greatly reduced if the complex variables are converted into real variables. The power of a real valued signal y_R is given by

$$p_{y_R} = (y_R)^2 \tag{3}$$

Estimating the received signal y_R would be a square-root operation

$$y_R = \pm\sqrt{p_{y_R}} \tag{4}$$

Now we present the novel complex to real Alamouti STBC transmission mapper. The conversion of complex to real Alamouti STBC signal transmission equation is done by mapping Eq. (1) into

$$\begin{bmatrix} \text{real}\,(y_{11}) & \text{real}\,(y_{21}) \\ \text{imag.}\,(y_{11}) & \text{imag.}\,(y_{21}) \\ \text{real}\,(y_{12}) & \text{real}\,(y_{22}) \\ \text{imag.}\,(y_{12}) & \text{imag.}\,(y_{22}) \end{bmatrix}^{\mathrm{T}} = \begin{bmatrix} \text{real}\,(h_{11}) & \text{real}\,(h_{21}) \\ \text{imag.}\,(h_{11}) & \text{imag.}\,(h_{21}) \\ \text{real}\,(h_{12}) & \text{real}\,(h_{22}) \\ \text{imag.}\,(h_{12}) & \text{imag.}\,(h_{22}) \end{bmatrix}^{\mathrm{T}}$$
$$\times \begin{bmatrix} \text{real}\,(s_1) & -\text{imag.}\,(s_1) & \text{real}\,(s_2) & -\text{imag.}\,(s_2) \\ \text{imag.}\,(s_1) & \text{real}\,(s_1) & \text{imag}\,(s_2) & \text{real}\,(s_2) \\ \text{real}\,(-s_2^*) & -\text{imag.}\,(-s_2^*) & \text{real}\,(s_1^*) & -\text{imag.}\,(s_1^*) \\ \text{imag.}\,(-s_2{}^*) & \text{real}\,(-s_2^*) & \text{imag.}\,(s_1^*) & \text{real}\,(s_1^*) \end{bmatrix}^{\mathrm{T}} + \mathbf{N} \tag{5}$$

where superscript T represents the transpose operation. Note that most practical wireless communication systems transmit complex symbols using a quadrature modulator, i.e., a sine wave carrier and a cosine wave carrier. One carrier is carrying the real component while the other is carrying the imaginary component. Because of the phase difference between the carriers, the real and imaginary components can be separated when the complex signal is being demodulated at the receiver. As such, the individual real and imaginary received signal power can be made available at the receiver. This allows for the value of real and imaginary components of the received signal matrix $\mathbf{Y}$ in Eq. (5) be calculated using square-root operation in Eq. (4). However, the square root operation results in two possible sign values; positive and negative. Selecting the wrong sign will cause decoding error. As such, we present a method to eliminate the sign ambiguity problem for proper decoding.

3 Sign ambiguity elimination

We follow the assumption of the Alamouti scheme where perfect channel state information (CSI) is available at the receiver. Note that CSI refers to the knowledge of channel $\mathbf{H}$ and is different from the knowledge of the received signal y_{uv}. A modified version of phase-shift keying (PSK) is used where all symbol constellations are set to be positive and have uniform amplitudes and

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spacing. This is done by moving the constellations into the first quadrant. We named this approach as first quadrant restriction (FQR). FQR allows for sign estimation of received signal y_{uv} which is being calculated using

$$\begin{aligned}
&\text{sign of real}(y_{11}) = \text{sgn}\left(real\left(h_{11}\right) - imag.\left(h_{11}\right) + real\left(h_{12}\right) - imag.\left(h_{12}\right)\right)\\
&\text{sign of imag.}(y_{11}) = \text{sgn}\left(real\left(h_{11}\right) + imag.\left(h_{11}\right) + real\left(h_{12}\right) + imag.\left(h_{12}\right)\right)\\
&\text{sign of real}(y_{21}) = \text{sgn}\left(real\left(h_{21}\right) - imag.\left(h_{21}\right) + real\left(h_{22}\right) - imag.\left(h_{22}\right)\right)\\
&\text{sign of imag.}(y_{21}) = \text{sgn}\left(real\left(h_{21}\right) + imag.\left(h_{21}\right) + real\left(h_{22}\right) + imag.\left(h_{22}\right)\right)\\
&\text{sign of real}(y_{12}) = \text{sgn}\left(-real\left(h_{11}\right) - imag.\left(h_{11}\right) + real\left(h_{12}\right) + imag.\left(h_{12}\right)\right)\\
&\text{sign of imag.}(y_{12}) = \text{sgn}\left(real\left(h_{11}\right) - imag.\left(h_{11}\right) - real\left(h_{12}\right) + imag.\left(h_{12}\right)\right)\\
&\text{sign of real}(y_{22}) = \text{sgn}\left(-real\left(h_{21}\right) - imag.\left(h_{21}\right) + real\left(h_{22}\right) + imag.\left(h_{22}\right)\right)\\
&\text{sign of imag.}(y_{22}) = \text{sgn}\left(real\left(h_{21}\right) - imag.\left(h_{21}\right) - real\left(h_{22}\right) + imag.\left(h_{22}\right)\right)
\end{aligned} \tag{6}$$

where sgn is the signum function. This method eliminates the sign ambiguity of the received signal. The following equations are used for symbol estimation.

$$\begin{aligned}
\hat{s_1} &= h_{11}^* y_{11} + h_{12} y_{12}^* + h_{21}^* y_{21} + h_{22} y_{22}^*\\
\hat{s_2} &= h_{12}^* y_{11} + h_{11} y_{12}^* + h_{22}^* y_{21} + h_{21} y_{22}^*
\end{aligned} \tag{7}$$

Symbol detection is done using the Maximum-Likelihood (ML) approach where symbol s_i is chosen based on

$$\begin{aligned}
&\left(|h_{11}|^2 + |h_{12}|^2 + |h_{21}|^2 + |h_{22}|^2\right) s_i^2 + d^2\left(\hat{s_a}, s_i\right) \leq\\
&\quad \left(|h_{11}|^2 + |h_{12}|^2 + |h_{21}|^2 + |h_{22}|^2\right) s_j^2 + d^2\left(\hat{s_a}, s_j\right) \quad \forall i \neq j, a \in \{1, 2\}
\end{aligned} \tag{8}$$

$d^2\left(\hat{s_a}, s_j\right)$ is the squared Euclidean distance between $\hat{s_a}$ symbol and s_j. As an added advantage, FQR simplifies the ML decoder in Eq. (8) into

$$d^2\left(\hat{s_a}, s_i\right) \leq d^2\left(\hat{s_a}, s_j\right) \quad \forall i \neq j, a \in \{1, 2\} \tag{9}$$

due to the use of constant amplitude symbol constellation. Next, we present two methods of utilising the sign ambiguity elimination for coding and decoding the Alamouti STBC.

4 Coding and decoding

We propose two methods of coding and decoding. The first method employs the FQR approach for the whole transmitted blocks ensuring all transmitted symbols are positive and have uniform amplitudes. This allows for sign ambiguity elimination scheme to be employed at the receiver. We named this method as first quadrant transmission (FQT).

The second method, named sign preamble transmission (SPT), is done by the use of preamble Alamouti STBC blocks. These blocks contain the sign information of the upcoming symbols in order to allow for correct decoding. Let bit 0 represents positive sign and bit 1 represents negative sign. Each

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preamble block of b bits per symbol is able to store sign information for $b/2$ blocks of Alamouti code. Therefore, the minimum level of PSK that can be used for the preamble is Quadrature PSK (QPSK). Note that the PSK level for preamble blocks and actual symbol blocks need not be the same. With the knowledge of the received symbol signs, Eq. (6) can be generalized into

$$\begin{aligned}
\text{sign of real}\,(y_{11}) &= \text{sgn}\,(R_1 \times real\,(h_{11}) - I_1 \\
&\times imag.\,(h_{11}) + R_2 \times real\,(h_{12}) - I_2 \times imag.\,(h_{12})) \\
\text{sign of imag.}\,(y_{11}) &= \text{sgn}\,(I_1 \times real\,(h_{11}) + R_1 \\
&\times imag.\,(h_{11}) + I_2 \times real\,(h_{12}) + R_2 \times imag.\,(h_{12})) \\
\text{sign of real}\,(y_{21}) &= \text{sgn}\,(R_1 \times real\,(h_{21}) - I_2 \\
&\times imag.\,(h_{21}) + R_2 \times real\,(h_{22}) - I_2 \times imag.\,(h_{22})) \\
\text{sign of imag.}\,(y_{21}) &= \text{sgn}\,(I_1 \times real\,(h_{21}) + R_1 \\
&\times imag.\,(h_{21}) + I_2 \times real\,(h_{22}) + R_2 \times imag.\,(h_{22})) \\
\text{sign of real}\,(y_{12}) &= \text{sgn}\,(-R_2 \times real\,(h_{11}) - I_2 \\
&\times imag.\,(h_{11}) + R_1 \times real\,(h_{12}) + I_1 \times imag.\,(h_{12})) \\
\text{sign of imag.}\,(y_{12}) &= \text{sgn}\,(I_2 \times real\,(h_{11}) - R_2 \\
&\times imag.\,(h_{11}) - I_1 \times real\,(h_{12}) + R_1 \times imag.\,(h_{12})) \\
\text{sign of real}\,(y_{22}) &= \text{sgn}\,(-R_2 \times real\,(h_{21}) - I_2 \\
&\times imag.\,(h_{21}) + R_1 \times real\,(h_{22}) + I_1 \times imag.\,(h_{22})) \\
\text{sign of imag.}\,(y_{21}) &= \text{sgn}\,(I_2 \times real\,(h_{21}) - R_2 \\
&\times imag.\,(h_{21}) - I_1 \times real\,(h_{22}) + R_1 \times imag.\,(h_{22}))
\end{aligned} \tag{10}$$

where R_z and I_z are the signs of real and imaginary components of transmitted symbol, represented by -1 and 1 for negative and positive values respectively. SPT eliminates the need for FQR approach in the transmitted data blocks. However, the preamble block itself must be properly decoded before the signs of the upcoming symbols can be determined. Since the signs of the symbols in the preamble block are unknown, the transmission and reception of these blocks must follow the FQR approach. The use of the preamble blocks leads to loss of data throughput, which can be quantified as $(100/(2^{\mathrm{b}-2}))\%$.

5 Capacity, BER performance and complexity

The upper bound of Alamouti block capacity reduction due to first quadrant restriction is found to be

$$\frac{\dfrac{c}{2}\log\left(1+\dfrac{2E_S}{N_T N_0}\|\mathbf{H}\|_F^2\right)}{c\log\left(1+\dfrac{E_S}{N_T N_0}\|\mathbf{H}\|_F^2\right)} = \frac{1}{2}\left(\frac{\log\left(1+2\mathrm{SNR}\right)}{\log\left(1+\mathrm{SNR}\right)}\right) \tag{11}$$

which is a ratio of real to complex Alamouti block capacity. C is the code rate. N_0 is noise spectral density and E_S is the total transmitted power from N_T transmit antennas. $\|\mathbf{H}\|_F^2$ is the squared Frobenius norm of the channel.

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SNR is the signal-to-noise ratio. The rate of degradation is high at low SNR and low at high SNR. Nevertheless, the percentage of degradation is small at low SNR and approaches 50% at high SNR.

Same simulation settings are used for all schemes for fair comparisons. The BER performance of the proposed methods and the Alamouti schemes are shown in Fig. 1. It is clear that the proposed FQT BPSK and the conventional Alamouti BPSK and QPSK deliver the best performance. The performance of other schemes with very similar BER are represented by a single line for better readability. It can be seen that Alamouti schemes are unusable when decoding is done directly from received signal power unlike the proposed schemes. SPT scheme performance is upper-bounded by its preamble block errors. In the simulation, the preamble blocks employ QPSK. Therefore, SPT BPSK, SPT QPSK and SPT 8PSK deliver similar performance. Note that the QPSK constellations of the SPT preamble are spaced slightly closer than the 8PSK SPT data block constellations due to the first quadrant restrictions in the preamble blocks. SPT preambles and FQT QPSK has the same constellation spacing, hence the same performance. Comparing FQT and SPT, FQT has BER advantage when employing BPSK and is at disadvantage when having PSK levels higher than the SPT preamble

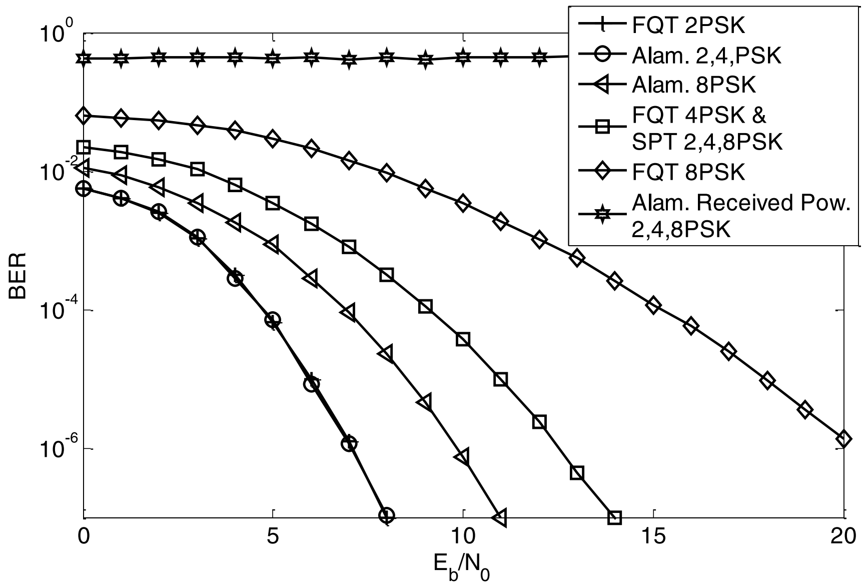

Fig. 1. BER of Alamouti vs. FQT vs. SPT (2 transmit and 2 receive antennas)

Table I. Number of fundamental real operations

Antenna Config.	Operations	Scheme FQT	Scheme SPT
2 Tx.	Add/sub/signum/square root	30	30
1 Rx.	Multiplication	16	32
2 Tx.	Add/sub/signum/square root	56	56
2 Rx.	Multiplication	32	64
2 Tx.	Add/sub/signum/square root	82	82
3 Rx.	Multiplication	48	96

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blocks.

Table I shows the number of theoretical fundamental real operations needed for symbol estimation of one complex Alamouti STBC. FQT has lower complexity compared to SPT due to the latter having more multiplication operations.

6 Conclusions

This letter presents methods for decoding Alamouti STBC from received signal power. It is shown that the proposed schemes are able to decode the signals properly unlike the Alamouti scheme that suffers from very high BER when both are decoded directly from received signal power. Comparisons are also done between the proposed schemes and the conventional Alamouti schemes with full knowledge of the received signal. Even under such situation, the proposed FQT BPSK scheme is able to provide the best performance, on par with Alamouti BPSK and Alamouti QPSK. The proposed schemes can find their use in systems where the received signals are severely distorted but power information is available. Added advantages are high robustness to fast fading and low receiver circuit complexity unlike conventional coherent systems.

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