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A Low-Complexity Antenna Selection Algorithm for Quadrature Spatial Modulation Systems

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Abstract

In this work, an efficient transmit antenna selection approach for the quadrature spatial modulation (QSM) systems is proposed. The conventional Euclidean distance antenna selection (EDAS)-based schemes in QSM have too high computational complexity for practical use. The proposed antenna selection algorithm is based on approximation of the EDAS decision metric employed for QSM. The elimination of imaginary parts in the decision metric enables decoupling of the approximated decision metric, which enormously reduces the complexity. The proposed method is also evaluated via simulations in terms of symbol error rate (SER) performance and compared with the conventional EDAS methods in QSM systems.

Keywords: *Quadrature spatial modulation (QSM), spatial modulation (SM), transmit antenna selection, Euclidean distance antenna selection (EDAS)*

1. Introduction

Spatial modulation (SM) is an attractive multiple input multiple output (MIMO) technique that reduces the system complexity and cost associated with implementation of conventional MIMO communication systems [1] – [3]. This is achieved by activating only one transmit antenna out of N_T transmit antennas per one symbol interval. It results in elimination of inter-channel interference at the receiver and synchronization between transmit antennas. In SM, transmit antennas are exploited as a spatial constellation dimension to convey additional information bits. Thus its overall spectral efficiency can be defined as $\log_2\left(MN_T\right)$, where M is the symbol constellation size. Since SM multiplexing gain is proportional to the base-two logarithm of N_T transmit antennas, a novel transmission technique called quadrature spatial modulation (QSM) has been proposed to enhance the spectral efficiency of SM [4], [5]. In QSM, spatial constellation symbols are transmitted while utilizing both quadrature dimension and in-phase dimension. Consequently, it is possible to transmit $\log_2\left(M N_T^2\right)$ bits during one transmit time.

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Since the SM scheme cannot offer the transmit diversity, some researchers have examined transmit antenna selection techniques to achieve transmit-diversity gains [6] – [9]. In [6], [7], and [8], the Euclidean distance antenna selection (EDAS) criterion to maximize the minimum instantaneous Euclidean distance has been employed to improve the performance of the SM systems. On the other hand, a recent research on transmit antenna selection schemes for QSM systems has been conducted [10]. However, the antenna selection methods presented in [10] require still high computational complexity and thus are limited for practical applications. Motivated by the high complexity of the EDAS-based schemes for QSM, we consider an efficient antenna selection approach to substantially reduce the complexity of optimization. The proposed approximation algorithm is obtained by ignoring the imaginary parts in EDAS decision metric. Thus the decision metric can be decoupled and it results in tremendous reduction of the complexity compared to the EDAS-based scheme with low complexity in [10]. In this work, a trade-off between symbol error rate (SER) performance and computational complexity is investigated. It is shown that the SER performance of the proposed method is better than that of the conventional EDAS approaches for QSM systems with sufficiently large number of receive antennas.

2. System Model

A transmit antenna selection-based QSM scheme is considered in a $N_R \times N_T$ MIMO configuration, where N_T and N_R, respectively, denote the number of transmit and receive antennas. Here $N_S\left(< N_T\right)$ antennas out of N_T transmit antennas are selected. For QSM transmission, $\log_2\left(M N_S^2\right)$ data bits are used. They are partitioned into three groups. The first one contains $\log_2\left(M\right)$ bits, which is mapped into a transmit QAM symbol. The other two ones where each contains $\log_2\left(N_S\right)$ bits are mapped into real and quadrature spatial constellation symbols. The symbol s, which is the transmit symbol from QAM symbol set S, is further divided to its real $\left(s_R\right)$ and imaginary $\left(s_Q\right)$ parts.

Therefore, the $N_S \times 1$ QAM transmit symbol vector $\mathbf{x}$ can be expressed as $\mathbf{x}_R + j\mathbf{x}_Q$, where $\mathbf{x}_R$ and $\mathbf{x}_Q$, respectively, are denoted by $\mathbf{e}_{k_R} s_R$ and $\mathbf{e}_{k_Q} s_Q$, $k_R, k_Q = 1, 2, \cdots, N_S$. Here $\mathbf{e}_{k_R}$ and $\mathbf{e}_{k_Q}$ are $N_S \times 1$ vectors with one non-zero entry at the k_R th and k_Q th locations, respectively. The transmitted vector $\mathbf{x}$ is sent over an $N_R \times N_S$ MIMO wireless channel $\mathbf{H}_S$. The elements of $\mathbf{H}_S$ are independent and identically distributed (i.i.d.) random variables with circularly symmetric complex-valued Gaussian distribution $CN\left(0,1\right)$. It experiences an additive white Gaussian noise (AWGN). The complex AWGN vector with N_R dimension is denoted by $\mathbf{w}$ with i.i.d. entries $w_p \sim CN(0, N_0)$, $p = 1, 2, \cdots, N_R$, where N_0 is the noise variance. Then the $N_R \times 1$ received signal vector $\mathbf{y}$ is given by

$$\mathbf{y} = \left(\mathbf{H}_S \mathbf{x}_R + j\mathbf{H}_S \mathbf{x}_Q\right) + \mathbf{w} \tag{1}$$

where $\mathbf{w} = \left[w_1 \; w_2 \cdots w_{N_R}\right]^T$.

3. Euclidean Distance-Based Antenna Selection for QSM systems

3.1 Euclidean Distance-Based Antenna Selection for QSM systems in [10]

The Euclidean distance-based decision metric for transmit antenna selection in QSM systems involves maximizing the minimum Euclidean distance among all possible transmit symbol vectors and is given by

$$I_{ED} = \arg\max_{I \in \Gamma} \left\{ \min_{\mathbf{x}_1 \neq \mathbf{x}_2 \in X} \left\| \mathbf{H}_I \left(\mathbf{x}_{1R} - \mathbf{x}_{2R} \right) + j\mathbf{H}_I \left(\mathbf{x}_{1Q} - \mathbf{x}_{2Q} \right) \right\|_F^2 \right\} \tag{2}$$

where Γ denotes the set of enumerations of all possible $N_{search} = B_{N_S}^{N_T}$ combinations of selecting N_S antennas from N_T transmit antennas. Here $B_{N_S}^{N_T}$ represents the number of N_S combinations from N_T elements. $\mathbf{H}_I$ is the $N_R \times N_S$ channel gain matrix associated with the I th enumeration of the set Γ and expressed as $\mathbf{H}_I = \left[\mathbf{h}_{(1)}, \mathbf{h}_{(2)}, \cdots, \mathbf{h}_{(N_S)} \right]$. Here $\mathbf{h}_{(t)}$, $t = 1, 2, \cdots, N_S$, is the t th column vector of $\mathbf{H}_I$. X is the set of all possible QSM transmit symbol vectors. Further details on EDAS in QSM systems can be found in [10].

The computation associated with the exhaustive search based on EDAS in QSM systems (called QSM-EDAS-ES) results in huge complexity and it is given by

$$C_{QSM-EDAS-ES} = B_{N_S}^{N_T} \left(B_2^{N_S} + N_S \right) \left(B_2^{N_S} + N_S \right) \left(12 N_R + 2 \right) M^2 \tag{3}$$

The computational complexity analysis is similar to that performed in terms of floating point operations in [8] and [10]. In this work, real multiplications instead of complex multiplications are employed in complexity analysis.

3.2 EDAS for QSM with reduced complexity [10]

To significantly reduce the complexity of QSM-EDAS-ES, an upper triangular $N_T \times N_T$ matrix Σ only once before searching for I_{ED} can be computed for the present. This reduced algorithm is called QSM-EDAS-R and the (m', n') th element of the matrix Σ is calculated by

$$\Sigma_{m',n'} = \min_{\substack{s_{1R} \neq s_{2R} \in \mathrm{Re}(S) \\ m'_R(=m') = n'_R(=n') \\ m'_Q = 1, 2, \cdots, N_T \\ n'_Q = m'_Q, m'_Q + 1, \cdots, N_T}} \mathbf{s}^T \tilde{\mathbf{\Xi}}_{(m',n')} \mathbf{s}, \quad m' = n' \tag{4}$$

$$\Sigma_{m',n'} = \min_{\substack{m'_R(=m') \neq n'_R(=n') \\ m'_Q = 1, 2, \cdots, N_T \\ n'_Q = m'_Q, m'_Q + 1, \cdots, N_T}} \mathbf{s}^T \tilde{\mathbf{\Xi}}_{(m',n')} \mathbf{s}, \quad m' < n' \tag{5}$$

where $\mathbf{s} = \left[s_{1R} \quad s_{1Q} \quad -s_{2R} \quad -s_{2Q} \right]^T$, $\tilde{\mathbf{\Xi}}_{(m',n')} = \mathbf{\Xi}_{(m',n')}^H \mathbf{\Xi}_{(m',n')}$ and

$$\boldsymbol{\Xi}_{(m',n')} = \begin{bmatrix} \mathbf{h}_{m'_R R} & -\mathbf{h}_{m'_Q Q} & \mathbf{h}_{n'_R R} & -\mathbf{h}_{n'_Q Q} \\ \mathbf{h}_{m'_R Q} & \mathbf{h}_{m'_Q R} & \mathbf{h}_{n'_R Q} & \mathbf{h}_{n'_Q R} \end{bmatrix} \tag{6}$$

where $\mathbf{h}_{m'_R R} = \mathrm{Re}\left(\mathbf{h}_{m'_R}\right)$, $\mathbf{h}_{m'_R Q} = \mathrm{Im}\left(\mathbf{h}_{m'_R}\right)$, $\mathbf{h}_{n'_R R} = \mathrm{Re}\left(\mathbf{h}_{n'_R}\right)$, $\mathbf{h}_{n'_R Q} = \mathrm{Im}\left(\mathbf{h}_{n'_R}\right)$, $\mathbf{h}_{m'_Q R} = \mathrm{Re}\left(\mathbf{h}_{m'_Q}\right)$, $\mathbf{h}_{m'_Q Q} = \mathrm{Im}\left(\mathbf{h}_{m'_Q}\right)$, $\mathbf{h}_{n'_Q R} = \mathrm{Re}\left(\mathbf{h}_{n'_Q}\right)$, and $\mathbf{h}_{n'_Q Q} = \mathrm{Im}\left(\mathbf{h}_{n'_Q}\right)$ for $m'_R, m'_Q = 1, 2, \cdots, N_T$, $n'_R = m'_R, m'_R + 1, \cdots, N_T$, $n'_Q = m'_Q, m'_Q + 1, \cdots, N_T$. Here $\mathbf{h}_{t'}$, $t' = 1, 2, \cdots, N_T$, is the t'th column vector of an $N_R \times N_T$ channel matrix $\mathbf{H}$. Then the approximate complexity of QSM-EDAS-R is given by

$$C_{QSM-EDAS-R} = 3N_T^2\left(2N_R - 1\right) + \left(B_2^{N_T} + N_T\right)\left(B_2^{N_T} + N_T\right)51\left(M/2\right) \tag{7}$$

4. Further Complexity Reduction Algorithm for QSM systems

Because the complexity of QSM-EDAS-R is still huge, we propose an approximated method to further reduce its complexity. To do that, (4) and (5) can be rewritten as, respectively,

$$\Sigma_{m',n'} = \min_{\substack{s_{1R} \neq s_{2R} \in \mathrm{Re}(S) \\ m'_R(=m') = n'_R(=n') \\ m'_Q = 1,2,\cdots,N_T \\ n'_Q = m'_Q, m'_Q+1,\cdots,N_T}} \left\{ \left\| Z_R + jZ_Q \right\|_F^2 \right\}, \quad m' = n' \tag{8}$$

$$\Sigma_{m',n'} = \min_{\substack{m'_R(=m') \neq n'_R(=n') \\ m'_Q = 1,2,\cdots,N_T \\ n'_Q = m'_Q, m'_Q+1,\cdots,N_T}} \left\{ \left\| Z_R + jZ_Q \right\|_F^2 \right\}, \quad m' < n' \tag{9}$$

where

$$\left\| Z_R + jZ_Q \right\|_F^2 = \left\| \mathbf{h}_{m'_R} s_{1R} + j\mathbf{h}_{m'_Q} s_{1Q} - \mathbf{h}_{n'_R} s_{2R} - j\mathbf{h}_{n'_Q} s_{2Q} \right\|_F^2 \tag{10}$$

$$Z_R = \begin{bmatrix} \mathbf{h}_{m'_R} & -\mathbf{h}_{n'_R} \end{bmatrix} \begin{bmatrix} s_{1R} \\ s_{2R} \end{bmatrix} \tag{11}$$

$$Z_Q = \begin{bmatrix} \mathbf{h}_{m'_Q} & -\mathbf{h}_{n'_Q} \end{bmatrix} \begin{bmatrix} s_{1Q} \\ s_{2Q} \end{bmatrix} \tag{12}$$

To simplify QSM-EDAS-R, we do not consider two terms, $j\left(Z_R^H Z_Q - Z_Q^H Z_R\right)$, in the expression (10) and thus it results in decoupling Z_R from Z_Q. This decoupling process can significantly reduce the computational complexity of QSM-EDAS-R. Then, by removing $j\left(Z_R^H Z_Q - Z_Q^H Z_R\right)$ in (10), it can be approximately simplified as

$$\| Z_R + jZ_Q \|_F^2 \approx \| Z_R \|_F^2 + \| Z_Q \|_F^2 \tag{13}$$

Note that $\| Z_R \|_F^2 = \| Z_Q \|_F^2$. Thus

$$\begin{aligned} \| Z_R \|_F^2 + \| Z_Q \|_F^2 &= 2\| Z_R \|_F^2 \\ &= 2\| \mathbf{B}_{m'_R n'_R} \mathbf{s}_R \|_F^2 \end{aligned} \tag{14}$$

where

$$\mathbf{B}_{m'_R n'_R} = \begin{bmatrix} \mathbf{h}_{m'_R} & -\mathbf{h}_{n'_R} \end{bmatrix} \tag{15}$$

$$\mathbf{s}_R = \begin{bmatrix} s_{1R} \\ s_{2R} \end{bmatrix} \tag{16}$$

Eventually, (8) and (9) can be simply described as

$$\Sigma_{m',n'} = \min_{\substack{s_{1R} \neq s_{2R} \in \mathrm{Re}(S) \\ m'_R(=m')=n'_R(=n')}} 2\| \mathbf{B}_{m'_R n'_R} \mathbf{s}_R \|_F^2, \quad m' = n' \tag{17}$$

$$\Sigma_{m',n'} = \min_{m'_R(=m') \neq n'_R(=n')} 2\| \mathbf{B}_{m'_R n'_R} \mathbf{s}_R \|_F^2, \quad m' < n' \tag{18}$$

where

$$\begin{aligned} \| \mathbf{B}_{m'_R n'_R} \mathbf{s}_R \|_F^2 &= \mathbf{h}_{m'_R}^H \mathbf{h}_{m'_R} s_{1R}^2 + \mathbf{h}_{n'_R}^H \mathbf{h}_{n'_R} s_{2R}^2 - \mathbf{h}_{m'_R}^H \mathbf{h}_{n'_R} s_{1R} s_{2R} - \mathbf{h}_{n'_R}^H \mathbf{h}_{m'_R} s_{1R} s_{2R} \\ &= \mathbf{h}_{m'_R}^H \mathbf{h}_{m'_R} s_{1R}^2 + \mathbf{h}_{n'_R}^H \mathbf{h}_{n'_R} s_{2R}^2 - 2\,\mathrm{Re}\left\{ \mathbf{h}_{m'_R}^H \mathbf{h}_{n'_R} \right\} s_{1R} s_{2R} \end{aligned} \tag{19}$$

The simplified EDAS algorithm for QSM with further complexity reduction is called QSM-EDAS-S. Then the complexity of QSM-EDAS-S can be computed as

$$C_{QSM-EDAS-S} = 3N_T^2\left(2N_R - 1\right) + \left(B_2^{N_T} + N_T\right)5\left(M/2\right) \tag{20}$$

where the rotational symmetry of angle $\theta_0 = \pi$ in [9] is exploited.

5. Simulation Results

Now we compare the computational complexity of the proposed algorithm with those of QSM-EDAS-ES, QSM-EDAS-R, and the exhaustive search method based on EDAS in SM systems (called SM-EDAS-ES), which are given in Tables 1, 2, and 3. It is noted that the count of real multiplications is included in the complexity. Table 1 gives the number of flops for $N_T = 6$, $N_S = 4$, and $N_R = 2$ with 4-QAM and 16-QAM. In Tables 2 and 3, the other parameters except for $N_R = 4$ and $N_R = 6$, respectively, in the simulation setups employ the same ones as Table 1. From Tables 1, 2, and 3, it is shown that QSM-EDAS-S approximately achieves 84, 47, and 33 times, respectively, smaller complexity than QSM-EDAS-R. Consequently, the proposed QSM-EDAS-S algorithm can reduce the computational complexity significantly compared to the previous antenna selection method for QSM systems such as QSM-EDAS-R. Furthermore, for the purpose of fair comparison with SM-EDAS-ES, the same data rate per channel use is assumed. That is, QSM systems with 4-QAM should be compared with SM systems with 16-QAM as indicated in the highlighted cells of Tables. It is found that the proposed method provides tremendously lower complexity than SM-EDAS-ES.

Table 1. Computational Complexity for $N_T = 6$, $N_S = 4$, $N_R = 2$

	$C_{SM-EDAS-ES}$	$C_{QSM-EDAS-ES}$	$C_{QSM-EDAS-R}$	$C_{QSM-EDAS-S}$
4-QAM	4560	624000	45306	534
16-QAM	72960	9984000	180252	1164

Table 2. Computational Complexity for $N_T = 6$, $N_S = 4$, $N_R = 4$

	$C_{SM-EDAS-ES}$	$C_{QSM-EDAS-ES}$	$C_{QSM-EDAS-R}$	$C_{QSM-EDAS-S}$
4-QAM	9360	1200000	45738	966
16-QAM	149760	19200000	180684	1596

Table 3. Computational Complexity for $N_T = 6$, $N_S = 4$, $N_R = 6$

	$C_{SM-EDAS-ES}$	$C_{QSM-EDAS-ES}$	$C_{QSM-EDAS-R}$	$C_{QSM-EDAS-S}$
4-QAM	14160	1776000	46170	1398
16-QAM	226560	28416000	181116	2028

Performance evaluation of the proposed QSM-EDAS-S algorithm is presented to compare the performances of QSM-EDAS-ES and QSM-EDAS-R. In the simulation results, the SER is depicted as a function of the E_s/N_0 in decibels with E_s denoting the QAM signal symbol energy. Three numbers of receive antennas are also considered, i.e., $N_R = 2$, $N_R = 4$, and $N_R = 6$, which are shown in Figures $1-3$, respectively. The spectral efficiency given by a rate of 6 bits per channel use is assumed in all scenarios. For all simulations, the QSM systems use 4-QAM. A maximum-likelihood detector is employed at the receiver for QSM systems. It jointly estimates the indices of the activated antennas and the symbol transmitted from them. Figure 1 describes the SER performance curves based on Monte Carlo simulations of QSM-EDAS-ES, QSM-EDAS-R, and the proposed QSM-EDAS-S for QSM with $N_T = 6$ and $N_S = 4$. It is seen that

QSM-EDAS-S outperforms the case with no antenna selection in QSM by about 2.5 dB in E_s/N_0 values. It is also shown that it offers slightly better performance than QSM-EDAS-R for a less E_s/N_0 range than 17 dB while worse for a larger region than $E_s/N_0 = 17$ dB. In this case, QSM-EDAS-S experiences considerable performance loss compared with QSM-EDAS-ES, which is due to the ignorance of two terms, $j\left(Z_R^H Z_Q - Z_Q^H Z_R\right)$, in the expression (10). In the Figure 2 and Figure 3, respectively, four and six receive antennas are assumed with the same other parameters as in Figure 1. It is observed in Figure 2 that the performance of QSM-EDAS-S is slightly better than that of QSM-EDAS-R for the given E_s/N_0 values. Figure 3 shows that although QSM-EDAS-S has a significantly lower complexity, it achieves about 0.7 dB better performance than QSM-EDAS-R. The main conclusion that can be drawn by observing Figures 1, 2, and 3 is as follows: The proposed algorithm is more beneficial than QSM-EDAS-R as the number of receive antennas increases.

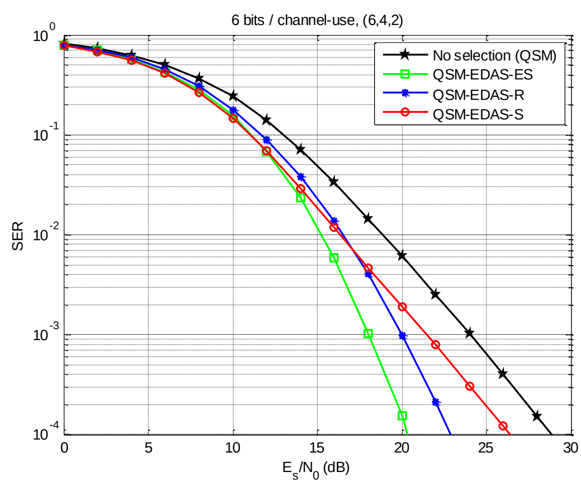

Figure 1. SER performance comparison of QSM-EDAS-ES, QSM-EDAS-R, and QSM-EDAS-S algorithms for $N_T = 6$, $N_S = 4$, and $N_R = 2$

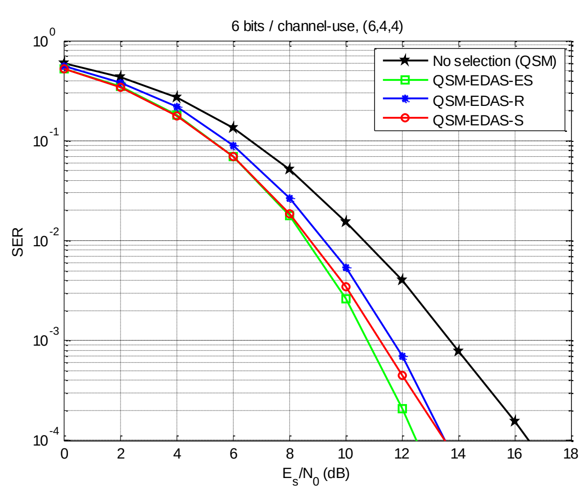

Figure 2. SER performance comparison of QSM-EDAS-ES, QSM-EDAS-R, and QSM-EDAS-S algorithms for $N_T = 6$, $N_S = 4$, and $N_R = 4$

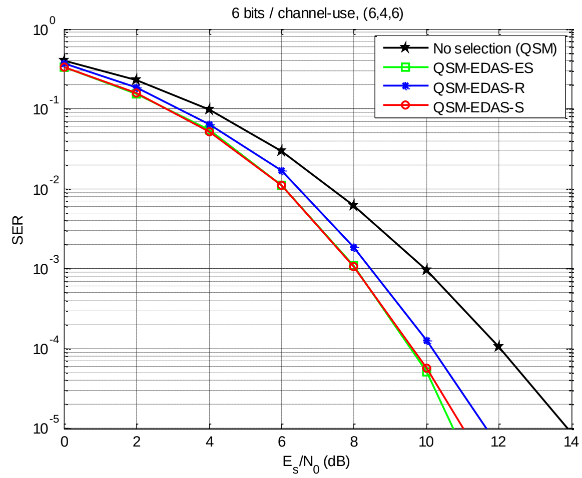

Figure 3. SER performance comparison of QSM-EDAS-ES, QSM-EDAS-R, and QSM-EDAS-S algorithms for $N_T = 6$, $N_S = 4$, and $N_R = 6$

6. Conclusion

In this work, we have proposed a simplified EDAS algorithm through decoupling operation of EDAS to tremendously reduce the complexity. The approximation process has been conducted by removing the imaginary parts of the EDAS-based decision metric. The impacts of this elimination on the SER performance are minor for the given scenario especially with $N_R = 6$. On the other hand, the computational complexity of the proposed algorithm is reduced to about 1/33 ~ 1/84 of the original reduced EDAS algorithm for QSM [10]. Hence the proposed method offers a promising trade-off between SER performance and computational complexity.

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