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Low complexity suboptimal decode algorithms for quasi-orthogonal space time block codes

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Abstract: Due to the high complexity of the pairwise decoding algorithm and the poor performance of zero forcing (ZF)/minimum mean square error (MMSE) decoding algorithm, two low-complexity suboptimal decoding algorithms, called pairwise-quasi-ZF and pairwise-quasi-MMSE decoders, are proposed. First, two transmit signals are detected by the quasi-ZF or the quasi-MMSE algorithm at the receiver. Then, the two detected signals as the decoding results are substituted into the two pairwise decoding algorithm expressions to detect the other two transmit signals. The bit error rate (BER) performance of the proposed algorithms is compared with that of the current known decoding algorithms. Also, the number of calculations of ZF, MMSE, quasi-ZF and quasi-MMSE algorithms is compared with each other. Simulation results show that the BER performance of the proposed algorithms is substantially improved in comparison to the quasi-ZF and quasi-MMSE algorithms. The BER performance of the pairwise-quasi-ZF (pairwise-quasi-MMSE) decoder is equivalent to the pairwise-ZF (pairwise-MMSE) decoder, while the computational complexity is significantly reduced.

Key words: quasi-orthogonal space-time block code (QOSTBC); low-complexity decoding; pairwise-quasi-ZF; pairwise-quasi-MMSE; bit error rate (BER)

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Since the space-time code (STC) was proposed in Ref. [1], the design criteria, encoding and decoding, performance analysis and code construction of the STC have been studied[2-4]. As an important branch of the STC, the space-time block code (STBC) has gained much interest due to its linear maximum likelihood decoding complexity[5-7]. However, it is well known that there is no complex orthogonal STBC with rate-one when the number of transmit antennas is larger than two. For the case of more than two transmit antennas, quasi-orthogonal space-time block codes (QOSTBCs) have been proposed instead of orthogonal STBC to gain a high code rate. A family of rate-one complex QOSTBCs was proposed in Ref. [8], and the decoder of the proposed codes works with pairs of transmitted symbols, which is well known as pairwise decoding.

However, the complexity of the pairwise decoding algorithm is high since it increases exponentially. In order to reduce the QOSTBC decoding complexity, many decoding algorithms were proposed[9-13]. The most famous linear low complexity decoding algorithms for QOSTBC are the ZF decoding algorithm and the MMSE decoding algorithm. Two novel rate-one quasi-orthogonal space-time block coding schemes for four antennas were proposed in Ref. [9], and the ZF linear receiver was adopted for the new codes to obtain a lower decoding complexity. Then, the bit error rate (BER) performance of the two kinds of codes proposed in Ref. [9] was compared with the Jafarkhani codes[8]. In Ref. [10], a code selecting algorithm between four transmit antennas QOSTBCs was proposed to improve BER performance and diversity gain without rate loss, and the received signals can be decoded by a simple linear decoder such as the ZF decoder or the MMSE decoder. However, one bit feedback information is required for this algorithm. Although the ZF and the MMSE decoding algorithms have linear complexity, the two algorithms still have a high decoding complexity due to processing the matrix inversion. In order to reduce the complexity, two lower complexity decoding algorithms for the rate-one QOSTBC[11] were proposed in Ref. [12], which are named as quasi-ZF and quasi-MMSE, respectively. The two algorithms do not need the matrix inversion, and they only need to carry out the transpose of matrix operations, so they can effectively reduce the computational complexity of the receiver. However, the ZF algorithm and the MMSE algorithm in Refs. [9 − 10] can reduce the decoding complexity with the cost of a substantial performance loss in comparison to the pairwise decoding algorithm. Combined with the pairwise decoding algorithm and the ZF decoding algorithm, a low-complexity suboptimal decoding algorithm called pairwise-ZF decoding algorithm was proposed in Ref. [13],

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and simulation results show that it can provide a substantially improved tradeoff between the computational complexity and performance in comparison to the well known decoding algorithms such as ZF, MMSE and pairwise decoding.

Two low-complexity suboptimal decoding algorithms, for the second new QOSTBC (Liu's code)[9] according to Ref. [8], called pairwise-quasi-ZF and pairwise-quasi-MMSE, are proposed in this paper, respectively. Unlike the maximum likelihood decoding algorithm, the basic idea of the two algorithms in Ref. [9] is that the receiver first makes use of the quasi-ZF or the quasi-MMSE algorithm to detect two transmit signals, then substitutes the two detected signals as the decoding results into the two pairwise decoding algorithm expressions to detect the other two transmit signals nearly linear. Moreover, we compare the computational complexity and BER performance of the new algorithms with that of the current known decoding algorithms.

1 System Model and Code Construction

Considering a wireless multiple input and single output (MISO) communication system with N transmit antennas and one receiving antenna, and an interval of T symbols during which the channel is constant, the received signal vector is given by

$$\boldsymbol{r} = \boldsymbol{X}\boldsymbol{h} + \boldsymbol{n} \tag{1}$$

where $\boldsymbol{r} = (r_t)^{\mathrm{T}}_{T\times 1}$ is the received signal vector of size $T \times 1$ and whose entries r_t ($t = 1, 2, \ldots, T$) are the received signal at time t. $\boldsymbol{h} = (h_n)^{\mathrm{T}}_{N\times 1}$ is the complex channel vector of size $N \times 1$ and its entries h_n ($n = 1, 2, \ldots, N$) denote the complex path gain from the n-th transmit antenna to the receiver antenna, which are modeled as samples of the independent and identically distributed (i. i. d.) complex Gaussian random variable. The real part and imaginary part of path gain have equal variance 0.5 and zero mean. $\boldsymbol{X}$ is the transmission code matrix of size $T \times N$. $\boldsymbol{n} = (n_t)^{\mathrm{T}}$ is the noise vector of size $T \times 1$, whose entries n_t ($t = 1, 2, \ldots, T$) are the noise samples modeled as the i. i. d. zero-mean complex Gaussian random variable with variance $1/(2\mathrm{SNR})$ per real dimension, where SNR is the signal-to-noise ratio.

In this paper, it is assumed that in one QOSTBC codeword there are $N = 4$ transmit antennas and $T = 4$ transmitted time slots. A quasi-orthogonal space-time block encoder encodes $K = 4$ transmitted symbols x_1, x_2, x_3, x_4 into the transmission matrix $\boldsymbol{X}$ of size 4×4 (The second new QOSTBC coding scheme (NW2)—Liu code[9]), which can be expressed as

$$\boldsymbol{X} = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ x_2 & -x_1 & x_4 & -x_3 \\ x_3^* & -x_4^* & -x_1^* & x_2^* \\ x_4^* & x_3^* & -x_2^* & -x_1^* \end{bmatrix} \tag{2}$$

where the rows and columns of $\boldsymbol{X}$ represent the space and time domains of the QOSTBC, respectively; $(\cdot)^*$ denotes the complex conjugate; x_k ($k = 1, 2, 3, 4$) are the signals which are transmitted by N transmit antennas in $T = 4$ time slots. The rate of matrix $\boldsymbol{X}$ is $R = K/T = 1$.

2 Low-Complexity Suboptimal Decoding Algorithms

This section presents two new low-complexity suboptimal decoding algorithms that provide substantially improved tradeoff between the computational complexity and BER performance in comparison to the current known decoding algorithms. According to the channel model, using the received signals (1) and the transmission code matrix (2), we take advantage of the conjugate of the received signals r_3 and r_4. Hence, we obtain the equivalent received signal,

$$\tilde{\boldsymbol{r}} = \boldsymbol{H}\boldsymbol{x} + \tilde{\boldsymbol{n}} \tag{3}$$

where $\boldsymbol{H}$ is the 4×4 equivalent complex channel matrix.

Assume that the perfect channel state information (CSI) is known at the receiver. It is well known that the traditional decoding algorithm is pairwise decoding for QOSTBC, that is, the pairwise decoder performs joint detection of two independent pairs of transmit symbols (x_1, x_2) and (x_3, x_4). This decoder is a kind of maximum-likelihood (ML) decoder.

$$\hat{\boldsymbol{X}} = \arg\min_{\boldsymbol{X}} \| \boldsymbol{r} - \boldsymbol{X}\boldsymbol{h} \|_{\mathrm{F}}^2 = \arg\min_{\boldsymbol{X}} (\boldsymbol{h}^{\mathrm{H}}\boldsymbol{X}^{\mathrm{H}}\boldsymbol{X}\boldsymbol{h} - \boldsymbol{h}^{\mathrm{H}}\boldsymbol{X}^{\mathrm{H}}\boldsymbol{r} - \boldsymbol{r}^{\mathrm{H}}\boldsymbol{X}\boldsymbol{h}) \tag{4}$$

where $\|\boldsymbol{A}\|$ is the Frobenious norm of matrix $\boldsymbol{A}$ which is defined as $\|\boldsymbol{A}\| = \mathrm{tr}(\boldsymbol{A}^{\mathrm{H}}\boldsymbol{A})$. Here, $\mathrm{tr}(\boldsymbol{A})$ is the trace of matrix $\boldsymbol{A}$; $(\boldsymbol{A})^{\mathrm{H}}$ is the Hermitian transpose of matrix $\boldsymbol{A}$.

So, ML decoding is equivalent to

$$\min_{\boldsymbol{X}} (\boldsymbol{h}^{\mathrm{H}}\boldsymbol{X}^{\mathrm{H}}\boldsymbol{X}\boldsymbol{h} - \boldsymbol{h}^{\mathrm{H}}\boldsymbol{X}^{\mathrm{H}}\boldsymbol{r} - \boldsymbol{r}^{\mathrm{H}}\boldsymbol{X}\boldsymbol{h}) \tag{5}$$

The ML decision metric (5) is calculated as the minimum sum of two terms $f_{12}(x_1, x_2) + f_{34}(x_3, x_4)$, where $f_{12}(x_1, x_2)$ is independent of x_3 and x_4 and $f_{34}(x_3, x_4)$ is independent of x_1 and x_2. Thus, the minimization of (5) is equivalent to minimize these two terms independently.

$$\begin{aligned} f_{12}(x_1, x_2) = {} & (|x_1|^2 + |x_2|^2)\Big(\sum_{m=1}^{4} |h_m|^2\Big) - \\ & 4\mathrm{Im}(x_1^* x_2)\mathrm{Im}(h_1^* h_2 + h_3^* h_4) - \\ & 2\mathrm{Re}[(r_1^* h_1 - r_2^* h_2 - r_3 h_3^* - r_4 h_4^*)x_1 + \\ & (r_2^* h_1 + r_1^* h_2 - r_4 h_3^* + r_3 h_4^*)x_2] \end{aligned} \tag{6}$$

$f_{34}(x_3, x_4)$ is similar to $f_{12}(x_1, x_2)$.

Since the pairwise decoder detects the pair of transmit symbols (x_1, x_2) or (x_3, x_4) simultaneously, the complexity of the pairwise decoding for QOSTBC is exponential. In order to reduce the decoding complexity, two low-complexity suboptimal decoding algorithms called pairwise-quasi-ZF and pairwise-quasi-MMSE are proposed in this paper.

2.1 Pairwise-quasi-ZF decoding algorithm

The traditional ZF decoding algorithm is a linear suboptimal detector. The ZF equalization matrix is $\boldsymbol{W}_{\mathrm{ZF}} = (\boldsymbol{H}^{\mathrm{H}}\boldsymbol{H})^{-1}\boldsymbol{H}^{\mathrm{H}}$. However, the ZF decoding algorithm has high decoding complexity due to the process of the inverse of the matrix in calculating $\boldsymbol{W}_{\mathrm{ZF}}$. So, a new algorithm called quasi-ZF decoding algorithm is proposed[12], which is expressed as

$$\hat{\boldsymbol{r}} = \boldsymbol{W}\tilde{\boldsymbol{r}} \tag{7}$$

where $\boldsymbol{W} = (\boldsymbol{H}^{\mathrm{H}}\boldsymbol{H})^{\mathrm{T}}\boldsymbol{H}^{\mathrm{H}}$. It is known that $f_{12}(x_1, x_2)$ in Eq. (6) is the joint function of x_1 and x_2, which cannot be detected independently of each other. If the decoder knows x_1 through the quasi-ZF decoding algorithm, then $f_{12}(x_1, x_2)$ is only the function of x_2 which can be detected directly.

The decoder detects symbol x_1 by the quasi-ZF decoding algorithm, the estimated value of x_1 is obtained as

$$\begin{aligned}\tilde{x}_1 = &(ah_1^* - bh_2^*)r_1 - (ah_2^* + bh_1^*)r_2 - \\ &(ah_3 + bh_4)r_3^* - (ah_4 - bh_3)r_4^*\end{aligned} \tag{8}$$

where $a = \sum_{m=1}^{4} |h_m|^2$, $b = 2\mathrm{j}\mathrm{Im}(h_1^* h_2 + h_3^* h_4)$, $\mathrm{j} = \sqrt{-1}$ is the imaginary unit and $\mathrm{Im}(\cdot)$ is the imaginary part of a complex number.

So, we obtain the estimate value of symbol x_1. Therefore, instead of minimizing $f_{12}(x_1, x_2)$ for all possible values of x_1 and x_2, we only need to minimize the metric $f_{12}(x_1, x_2)$ for all the values of x_2 since the estimated value of x_1 is known. Eq. (6) is reduced to detect x_2.

$$\begin{aligned}f_2(x_1, x_2) = &(|x_2|^2)\Big(\sum_{m=1}^{4}|h_m|^2\Big) - \\ &4\mathrm{Im}(x_1^* x_2)\mathrm{Im}(h_1^* h_2 + h_3^* h_4) - \\ &2\mathrm{Re}[(r_2^* h_1 + r_1^* h_2 - r_4 h_3^* + r_3 h_4^*)x_2]\end{aligned} \tag{9}$$

Similarly, we can obtain the estimated value of x_3 and x_4.

2.2 Pairwise-quasi-MMSE decoding algorithm

Similarly, a new algorithm called the quasi-MMSE decoding algorithm was proposed in Ref. [12], in which $\boldsymbol{W}_{\mathrm{MMSE}}$ is changed into $\boldsymbol{W}_{\mathrm{MMSE}}^{\mathrm{T}}$, and it can be expressed as

$$\boldsymbol{W}_{\mathrm{MMSE}}^{\mathrm{T}} = \left(\boldsymbol{H}^{\mathrm{H}}\boldsymbol{H} + \frac{\boldsymbol{I}}{\gamma}\right)^{\mathrm{T}}\boldsymbol{H}^{\mathrm{H}} \tag{10}$$

where γ is the input signal-to-noise ratio (SNR), and $\boldsymbol{I}$ is the 4×4 identity matrix. The decoder detects symbol x_1 by the quasi-MMSE decoding algorithm, and the estimated value of x_1 is obtained as

$$\begin{aligned}\tilde{x}_1 = &\left[\left(a + \frac{1}{\gamma}\right)h_1^* - bh_2^*\right]r_1 - \left[\left(a + \frac{1}{\gamma}\right)h_2^* + bh_1^*\right]r_2 - \\ &\left[\left(a + \frac{1}{\gamma}\right)h_3 + bh_4\right]r_3^* - \left[\left(a + \frac{1}{\gamma}\right)h_4 - bh_3\right]r_4^*\end{aligned} \tag{11}$$

So, we can obtain the expected value of symbol x_1. Therefore, instead of minimizing $f_{12}(x_1, x_2)$ for all the possible values of x_1 and x_2, we just need to minimize metric $f_{12}(x_1, x_2)$ for x_2 since the estimated value of x_1 is known. The decoder detects symbols x_3 and x_4 in the same way.

3 Computational Complexity and BER Performance Simulation

3.1 Computational complexity

We compare the computational complexity of the proposed algorithms with those proposed in Refs. [13 - 14]. Since the pairwise decoding algorithm has the same computational complexity, we only compare the computational complexity of the four decoders such as the traditional ZF decoder, the traditional MMSE decoder, the quasi-ZF decoder and the quasi-MMSE decoder, with complexity measured by the number of complex multiplications, complex summations and square-root operations. In traditional ZF, computing $\boldsymbol{H}^{\mathrm{H}}\boldsymbol{H}$ requires $TK(K+1)/2 = 40$ complex multiplications and $(T-1)K(K+1)/2 = 30$ complex summations, the inverse computation $(\boldsymbol{H}^{\mathrm{H}}\boldsymbol{H})^{-1}$ requires $K^3/2 + 3K^2/2 = 56$ complex multiplications and $K^3/2 - K^2/2 = 24$ complex summations and $K = 4$ square-root operations. Multiplying $(\boldsymbol{H}^{\mathrm{H}}\boldsymbol{H})^{-1}$ with $\boldsymbol{H}^{\mathrm{H}}$ requires $K^2 T = 64$ complex multiplications and $KT(K-1) = 48$ complex summations. Thus, the traditional ZF algorithm requires 160 complex multiplications, 102 complex summations and four square-root operations. Similarly, the traditional MMSE algorithm requires 161 complex multiplications, 106 complex summations and four square-root operations. The quasi-ZF algorithm requires 104 complex multiplications and 78 complex summations, and it does not require square-root operations. Also, the quasi-MMSE algorithm requires 105 complex multiplications and 82 complex summations, and it does not require square-root operations.

Tab. 1 summarizes the computational complexity. Tab. 1 shows that the computational complexity of the quasi-ZF algorithm is the lowest, the second lowest is the quasi-MMSE algorithm due to no square-root operations, and the highest is the traditional MMSE algorithm in the four decoding algorithms.

3.2 Simulation results

We consider a wireless communication system with 4-transmit antennas and 1-receiving antenna as a 4×1 system. The wireless channel is assumed to be a quasi-static flat fading so that the path gains are constant over an interval of T and vary from one frame to another. We compare the BER performance of different decoding schemes, including the proposed pairwise-quasi-ZF and pairwise-quasi-MMSE decoding algorithms, the pairwise decoding

Tab. 1 Comparisons of computational complexity of the four algorithms

Complexity	Algorithms			
	ZF	MMSE	Quasi-ZF	Quasi-MMSE
Complex multiplications	160	161	104	105
Complex summations	102	106	78	82
Square-root operations	4	4	0	0

algorithm proposed in Ref. [8], and the quasi-ZF and quasi-MMSE decoding algorithms proposed in Ref. [12] for Liu's code[9]. We consider the BPSK modulations in this paper. Fig. 1 shows the Monte-Carlo simulation results, which displays the BER vs. SNR for the proposed algorithms in this paper and the algorithms proposed in Refs. [8, 12]. We can see that the BER performance of the proposed pairwise-quasi-MMSE decoding algorithm is significantly better than that of the quasi-MMSE decoding algorithm[12], and the proposed pairwise-quasi-ZF decoding algorithm is significantly better than that of the quasi-ZF decoding algorithm[12]. From Fig. 1, we can also see that the BER performance of the proposed pairwise-quasi-MMSE decoding algorithm is better than that of the proposed pairwise-quasi-ZF decoding algorithm, but the computational complexity of the former is slightly higher than that of the latter due to the detection of symbols x_1 and x_3 using the quasi-MMSE algorithm to the pairwise-quasi-MMSE decoding algorithm in consideration of the effects of noise.

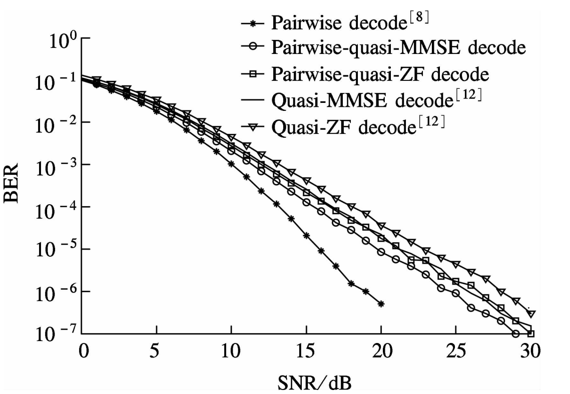

Fig. 1 BER vs. SNR comparison of the proposed algorithm with those proposed in Refs. [8, 12] (4-transmit and 1-receive antennas, BPSK)

Next, we compare the BER performance of the proposed pairwise-quasi-MMSE decoding algorithm with the pairwise-MMSE decoding algorithm proposed in Ref. [14], and compare the proposed pairwise-quasi-ZF decoding algorithm with the pairwise-ZF algorithm proposed in Ref. [13]. Fig. 2 displays the comparison of BER vs. SNR for the Liu code using the four decoding algorithms for the BPSK modulation. From Fig. 2, we can see that the BER performance of the proposed pairwise-quasi-MMSE decoding algorithm is the same as that of the pairwise-MMSE decoding algorithm proposed in Ref. [14]. Similarly, the proposed pairwise-quasi-ZF is the same as that of the pairwise-ZF decoding algorithm proposed in Ref. [13]. However, we observe from Tab. 1 that the computational complexity of the two proposed algorithms are significantly lower than those proposed in Refs. [13 - 14]. This is due to the fact that the quasi-MMSE (quasi-ZF) algorithm does not need matrix inversion and square-root operations, so complexity multiplication and addition operations are significantly reduced.

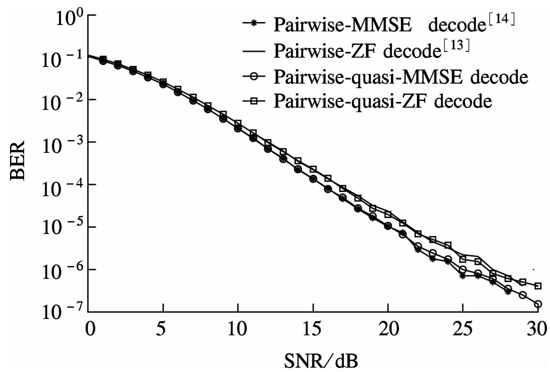

Fig. 2 BER vs. SNR comparison of the proposed algorithm with those proposed in Refs. [13 - 14] (4-transmit and 1-receive antennas, BPSK)

4 Conclusion

Two low-complexity suboptimal decoding algorithms called pairwise-quasi-ZF and pairwise-quasi-MMSE decoders are proposed. Computational complexity analysis and BER performance simulation results show that the proposed algorithms provide a significant BER improvement in comparison to the quasi-ZF and quasi-MMSE algorithms, respectively. The BER performance of the pairwise-quasi-ZF (pairwise-quasi-MMSE) decoder is equivalent to the pairwise-ZF (pairwise-MMSE) decoder, while the computational complexity is significantly reduced. So, the proposed decoding algorithm can provide a substantially improved tradeoff between the computational complexity and performance in comparison to the well known decoding algorithms.

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基于低复杂度次优译码算法的准正交空时分组码

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摘要:针对成对译码算法复杂度高及迫零/最小均方误差算法性能较差等问题,提出了一种 pairwise-quasi-ZF/pairwise-quasi-MMSE 的低复杂度次优译码算法. 利用 quasi-ZF 或 quasi-MMSE 算法计算出部分发射信号的统计判决值,将该判决值作为译码结果代入成对译码算法表达式中,从而计算出剩余部分发射信号的统计判决值并作为译码结果. 比较了所提算法与几种传统译码算法的系统误比特率性能,并比较了 ZF, MMSE,quasi-ZF 和 quasi-MMSE 四种算法的计算量. 仿真结果表明所提算法的 BER 性能与 quasi-ZF 算法和 quasi-MMSE 算法相比有明显改善,与 pairwise-ZF 和 pairwise-MMSE 算法相比 BER 性能相近,计算量却大大降低.

关键词:准正交空时分组码;低复杂度译码;pairwise-quasi-ZF;pairwise-quasi-MMSE;误比特率

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