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# Distributed Quasi-Orthogonal Space-Time Block Code for Four Transmit Antennas with Information Exchange Error Mitigation

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## Abstract

In this paper, we extend the case of information exchange error mitigation for the distributed orthogonal space-time block code (DOSTBC) for two transmit antennas to distributed quasi-orthogonal space-time block code (DQOSTBC) for four transmit antennas. A rate 1 full-diversity DQOSTBC for four transmit antennas is designed. The code matrix changes according to different information exchange error cases, so full diversity is maintained even if not all information exchange is correct. We also perform analysis of the pairwise error probability. The performance analysis indicates that the proposed rate 1 DQOSTBC outperforms rate 1/2 DOSTBC for four transmit antennas at the same transmission rate, which is confirmed by the simulation results.

**Keywords:** Cooperative communications, distributed coding, performance analysis, diversity product, cyclic redundancy check

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This work was supported by the National Science Council, Taiwan under Grant NSC 101-2221-E-027-106, and based on Shih-Han Wang's MS thesis. This work differs from [20] as follows: 1) this paper uses CRC to select coding matrices, and [20] uses a SNR threshold; 2) this paper includes performance analysis (diversity product), and [20] does not; 3) this paper has 4 sources and 1 destination and no intermediate relays, [20] has 4 sources and 1 destination and one intermediate DAF relay.

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## 1. Introduction

The multiple input multiple output (MIMO) technique [1-4] can improve performance in fading channels through space-time processing. Examples include orthogonal space-time block code (OSTBC) and quasi-orthogonal space-time block code (QOSTBC). Because there is no rate 1 OSTBC for more than two transmit antennas, QOSTBC [5][6] is thus proposed. In [5], the QOSTBC with minimum decoding complexity is proposed. This only requires the joint detection of two real symbols. In [6], the QOSTBC for two transmit antennas and three time slots is proposed. It achieves rate 1 and full diversity with low complexity maximum likelihood decoding. However, the cooperative systems involve information exchange errors, so QOSTBC schemes in [5][6], which don't consider information exchange errors, cannot be applied directly

Most mobile phones and wireless sensor network nodes only have a single antenna, and can't use the MIMO technique directly. To solve this problem, in [7], a cooperative system is proposed to share the users' antennas and generate a virtual MIMO system to achieve spatial diversity. The cooperative system can use distributed coding to improve performance further. In distributed coding, the codeword is constructed in a distributed manner [8]. In recent research, many distributed coding schemes are proposed. The distributed space-time block code (DSTBC) is proposed in [9][10]. In [11], a distributed space-time trellis code is proposed.

In the DSTBC scheme, the users exchange information from other users to share their transmit antennas, so STBC can be utilized in a distributed manner. But the distributed coding may result in information exchange errors and thus loss of full diversity. In the previous DSTBC papers, this problem is not considered. Only in [12], a way is proposed to solve the problem of information exchange errors in DSTBC and maintain full diversity. The basic idea is to change the code matrix according to whether each information exchange is correct or not, so the full diversity is maintained even if there are information exchange errors.

The distributed orthogonal space-time block code (DOSTBC) used in [12] is for two transmit antennas only. In [13], it has been shown that no rate 1 OSTBC exists for more than two antennas. In [14], rate 1 quasi-orthogonal space-time codes are designed but only have partial diversity. To achieve full diversity for quasi-orthogonal codes for four transmit antennas, constellation-rotation schemes were proposed in [15] and [16].

In this paper, DOSTBC with information exchange error mitigation for two transmit antennas [12] is extended to distributed quasi-orthogonal space-time block code (DQOSTBC) with information exchange error mitigation for four transmit antennas. The key idea is similar to [12]: to change the code matrix according to whether each information exchange is correct or not, so the full diversity is maintained even if there are information exchange errors. The difference is that the number of cases in the proposed scheme is more than that in [12] because the proposed scheme has more transmit antennas (users). Another contribution, not found in [12], is that the performance in terms of pairwise error probability is analyzed. The analysis in section 5 and simulation results in section 6 both indicate that the proposed DQOSTBC outperforms DOSTBC in terms of BER for the four transmit antennas case at the same transmission rate. In addition, the proposed DQOSTBC also outperforms QOSTBC with errors in information exchange due to loss of diversity.

The rest of this paper is organized as follows. In section 2, the system model of the proposed scheme is discussed. In section 3, a novel DQOSTBC scheme with information exchange error mitigation is proposed. Then, the detection and decoding is discussed in section 4. Performance analysis and simulation results are provided in sections 5 and 6, respectively. Finally, section 7 is the conclusion.

## 2. System Model

As shown in **Fig. 1**, a DSTBC system with four transmit antennas and one receive antenna is considered. The geographically dispersed users first exchange information (data symbols) among them and then transmit synchronously using a distributed space-time coding scheme. The stage of information exchange among users is a communication overhead and is not found in non-distributed space-time coding schemes. In this paper, a cyclic redundancy check (CRC), and additional overhead bits, help to choose one out of 16 cases. Without CRC, case 16 is always used. The full diversity is always maintained in the proposed scheme with and without CRC. However, the proposed scheme with CRC has lower error probability than the proposed scheme without CRC.

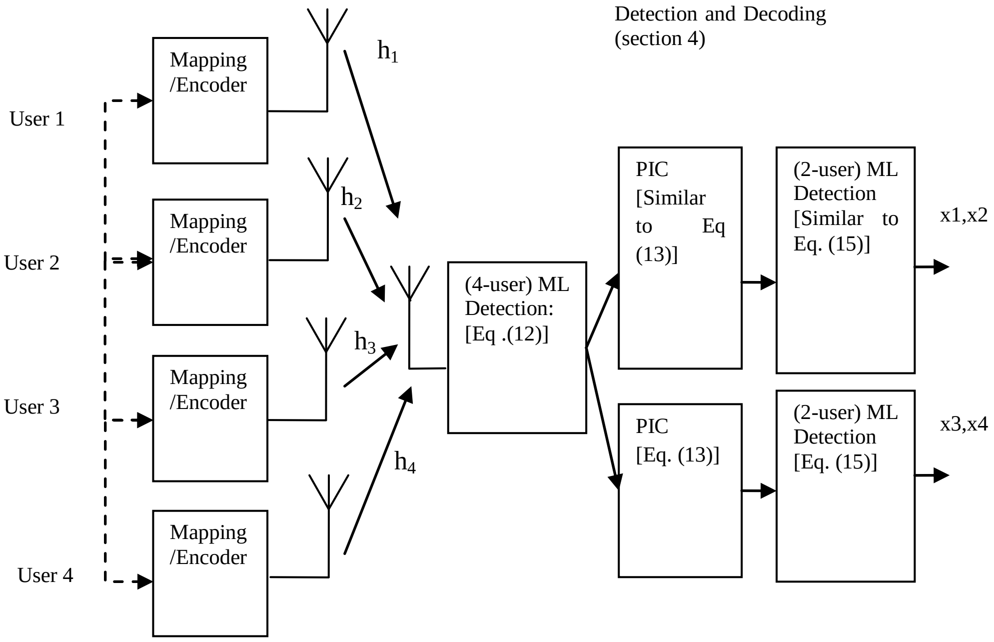

**Fig. 1.** The system model. The dashed arrow: information exchange stage. The detection and decoding has three steps. First, four-user ML in (12) is used. Then, the PIC in (13), where comes from [17], is used. Finally, two-user ML in (15) is used. The steps apply to all cases.

A flat Rayleigh fading channel is assumed and ideal channel state information (CSI) is assumed to be available at the receiver. At the receiver a parallel interference cancellation (PIC) scheme [17] is added. The received vector Y can be written as:

$$\mathbf{Y} = \mathbf{HC}(\mathbf{x}) + \mathbf{N} \tag{1}$$

where N is the AWGN. The rows of the above code matrices C(x) represent the users, and the columns represent the time slots. H is the channel matrix from the users to the destination and is given by:

$$\mathbf{H} = \begin{bmatrix} h_1 & h_2 & h_3 & h_4 \end{bmatrix} \tag{2}$$

where $h_i$ is the channel coefficient from user $i$ to the destination.

The rate 1 QOSTBC for four antennas [14] is given by:

$$\mathbf{C}(\mathbf{x}) = \begin{bmatrix} x_1 & -x_2^* & -x_3^* & x_4 \\ x_2 & x_1^* & -x_4^* & -x_3 \\ x_3 & -x_4^* & x_1^* & -x_2 \\ x_4 & x_3^* & x_2^* & x_1 \end{bmatrix} \tag{3}$$

Let $\mathbf{A}$ be the constellation space. For the elements in (3), $x_1$ and $x_2$ are selected from the constellation space $\mathbf{A}$, $x_3$ and $x_4$ are selected from the constellation space $e^{j\theta}\mathbf{A}$, where $\theta = \pi/4$ [16]. That is, we use the rotational QOSTBC in this paper.

The QOSTBC matrix loses full diversity when information exchange has errors. So we are motivated to propose a novel DQOSTBC matrix for four antennas considering information exchange errors.

## 3. Proposed Full Diversity DQOSTBC for Four Antennas

The received signals of the information exchange between users are given by:

$$R_{mn} = g_{mn} x_m + Z_m \qquad m,n = 1,2,3,4 \;, \tag{4}$$

where $x_m$ is the *m*-th user's data, $R_{mn}$ is the received signal from the *m*-th user to the *n*-th user, $g_{mn}$ is the flat Rayleigh fading channel coefficient between the *m*-th user and the *n*-th user, and $Z_m$ is AWGN with zero mean and $N_0$ variance.

Because each $x_m$, m=1,2,3,4, is detected correctly or in error, there are sixteen cases of the proposed DQOSTBC code matrix $\mathbf{C}(x)$. The full diversity is maintained for every case. If CRC is present, we modify the code matrix and choose the corresponding case based on the received checksum. If CRC is not applied, then we choose the modified code matrix shown in case 16. The reason why case 1 is the best case and case 16 is the worst case is as follows. Case 1 has all decode and forward (DAF) matrix elements and case 16 has 12 amplify and forward (AAF) elements (with power normalization factor β). The more AAF elements, the worse the error probability. Therefore, case 16 is the worst case. The sixteen cases of the novel DQOSTBC are as follows.

Case 1 (best case): $x_1,\ldots,x_4$ are correct:

$$\mathbf{C}(\mathbf{x}) = \begin{bmatrix} x_1 & -x_2^* & -x_3^* & x_4 \\ x_2 & x_1^* & -x_4^* & -x_3 \\ x_3 & -x_4^* & x_1^* & -x_2 \\ x_4 & x_3^* & x_2^* & x_1 \end{bmatrix} \tag{5}$$

Case 2: only $x_1$ is error:

$$\mathbf{C}(\mathbf{x}) = \begin{bmatrix} x_1 & -x_2^* & -x_3^* & x_4 \\ x_2 & \beta_{12}R_{12}^* & -x_4^* & -x_3 \\ x_3 & -x_4^* & \beta_{13}R_{13}^* & -x_2 \\ x_4 & x_3^* & x_2^* & \beta_{14}R_{14} \end{bmatrix} \tag{6}$$

(6) is arrived at because we replace $x_1$ in the 2nd-4th columns by $\beta_{1i}R_{1i}$ , i=2,3,4, respectively. Cases 3-15, which can be derived similarly, are listed in the Appendix A.

Case 16 (worst case): $x_1,\ldots,x_4$ are all in error:

$$\mathbf{C}(\mathbf{x}) = \begin{bmatrix} x_1 & -\beta_{21}R_{21}^* & -\beta_{31}R_{31}^* & \beta_{41}R_{41} \\ x_2 & \beta_{12}R_{12}^* & -\beta_{42}R_{42}^* & -\beta_{32}R_{32} \\ x_3 & -\beta_{43}R_{43}^* & \beta_{13}R_{13}^* & -\beta_{23}R_{23} \\ x_4 & \beta_{34}R_{34}^* & \beta_{24}R_{24}^* & \beta_{14}R_{14} \end{bmatrix} \tag{7}$$

For cases 2-15, each case has variations. For example, consider case 3, where $x_2$ is in error only to one user, say user 3. The code matrix is changed to:

$$\mathbf{C}(\mathbf{x}) = \begin{bmatrix} x_1 & -x_2^* & -x_3^* & x_4 \\ x_2 & x_1^* & -x_4^* & -x_3 \\ x_3 & -x_4^* & x_1^* & -\beta_{23}R_{23} \\ x_4 & x_3^* & x_2^* & x_1 \end{bmatrix} \tag{8}$$

where $\beta_{mn}$ is the power normalization factor given by:

$$\beta_{mn} = \sqrt{\frac{P}{P|g_{mn}|^2 + N_0}} \qquad m,n = 1,2,3,4 \tag{9}$$

,

where $P$ is the users' power constraint.

## 4. Detection and Decoding

As shown in **Fig. 1**, the detection and decoding has three steps. First, four-user ML in (12) is used. Then, the PIC in (13), which comes from [17], is used. Finally, two-user ML in (15) is used. The steps apply to all cases. Case 16 (worst case) is used for illustration purposes. The other cases can be derived similarly.

The received signal vector is as follows:

$$\mathbf{Y}=\begin{bmatrix} y_1\\ y_2\\ y_3\\ y_4\end{bmatrix}=\begin{bmatrix} h_1 & h_2 & h_3 & h_4\end{bmatrix}\begin{bmatrix} x_1 & -\beta_{21}R_{21}^{*} & -\beta_{31}R_{31}^{*} & \beta_{41}R_{41}\\ x_2 & \beta_{12}R_{12}^{*} & -\beta_{42}R_{42}^{*} & -\beta_{32}R_{32}\\ x_3 & -\beta_{43}R_{43}^{*} & \beta_{13}R_{13}^{*} & -\beta_{23}R_{23}\\ x_4 & \beta_{34}R_{34}^{*} & \beta_{24}R_{24}^{*} & \beta_{14}R_{14}\end{bmatrix}+\mathbf{N} \quad (10)$$
,

where **N** is the noise vector.

Then (4) is substituted into (10) and, after some matrix operations, we then get:

$$\tilde{\mathbf{Y}}=\begin{bmatrix} y_1\\ y_2^{*}\\ y_3^{*}\\ y_4\end{bmatrix}=\begin{bmatrix} h_1 & h_2 & h_3 & h_4\\ \beta_{12}g_{12}h_2^{*} & -\beta_{21}g_{21}h_1^{*} & \beta_{34}g_{34}h_4^{*} & -\beta_{43}g_{43}h_3^{*}\\ \beta_{13}g_{13}h_3^{*} & \beta_{24}g_{24}h_4^{*} & -\beta_{31}g_{31}h_1^{*} & -\beta_{42}g_{42}h_2^{*}\\ \beta_{14}g_{14}h_4 & -\beta_{23}g_{23}h_3 & -\beta_{32}g_{32}h_2 & \beta_{41}g_{41}h_4\end{bmatrix}\begin{bmatrix} x_1\\ x_2\\ x_3\\ x_4\end{bmatrix}+\mathbf{N}$$

$$\tilde{\mathbf{Y}}=\tilde{\mathbf{H}}\begin{bmatrix} x_1\\ x_2\\ x_3\\ x_4\end{bmatrix}+\mathbf{N} \quad (11)$$

where $y_k$ is the received signal at the *k*-th time interval, $\tilde{\mathbf{Y}}$ is the received vector, and $\tilde{\mathbf{H}}$ is the equivalent channel matrix. We assume perfect channel state information $\tilde{\mathbf{H}}$ is available.

The first step is (four-user) ML detection, and we get $x_1', x_2', x_3'$ and $x_4'$ by:

$$\begin{bmatrix} x_1'\\ x_2'\\ x_3'\\ x_4'\end{bmatrix}=\arg\min_{x_1,x_2,x_3,x_4}\left\|\tilde{\mathbf{Y}}-\tilde{\mathbf{H}}\begin{bmatrix} x_1\\ x_2\\ x_3\\ x_4\end{bmatrix}\right\|^2 \quad (12)$$

To refine the data detection and get better error probability, we add one-stage of PIC [17] and additional (two-user) ML detection as the second and third steps. The data are regrouped: $x_1', x_2'$ is one group (in one constellation) and $x_3', x_4'$ is the other (in the rotated constellation). To refine the group composed of $x_3$ and $x_4$, for example, we subtract the interference from the other group composed of $x_1$ and $x_2$:

$$\mathbf{Y}_{34} = \mathbf{Y} - \mathbf{H}\begin{bmatrix} x_1^{'} & -x_2^{'*} & 0 & 0 \\ x_2^{'} & x_1^{'*} & 0 & 0 \\ 0 & 0 & x_1^{'*} & -x_2^{'} \\ 0 & 0 & x_2^{'*} & x_1^{'} \end{bmatrix} \tag{13}$$

In (13), $\mathbf{Y}_{34}$ is mainly contributed by $x_3$ and $x_4$. Assume $x_1^{'}$ and $x_2^{'}$ are successfully decoded ( $x_1^{'} = x_1 \quad and \quad x_2^{'} = x_2$ ), then:

$$\mathbf{Y}_{34} = \mathbf{H}\begin{bmatrix} 0 & -\alpha^{*}_{21} & -\beta_{31}R^{*}_{31} & \beta_{41}R_{41} \\ 0 & \alpha^{*}_{12} & -\beta_{42}R^{*}_{42} & -\beta_{32}R_{32} \\ x_3 & -\beta_{43}R^{*}_{43} & \alpha^{*}_{13} & -\alpha_{23} \\ x_4 & \beta_{34}R^{*}_{34} & \alpha^{*}_{24} & \alpha_{14} \end{bmatrix} \tag{14}$$

where $\alpha_{ij} = \beta_{ij}R_{ij} - x_i^{'} \quad i = 1,2, \quad j = 1,2,3,4$. Note that $R_{ij}$ is a noisy version of $x_i$, as shown in (4).

Finally, (two-user) ML detection is applied to get better detection of $x_3$ and $x_4$, the decision metric is:

$$\left\| \mathbf{Y}_{34} - \mathbf{H}\begin{bmatrix} 0 & 0 & -x_3^{*} & x_4 \\ 0 & 0 & -x_4^{*} & -x_3 \\ x_3 & -x_4^{*} & 0 & 0 \\ x_4 & x_3^{*} & 0 & 0 \end{bmatrix} \right\|^2 \tag{15}$$

Similarly, $x_1$ and $x_2$ can be refined in the same way in another PIC block and (two-user) ML detection.

## 5. Performance Analysis

The theoretical analysis of error probability can be obtained by the integral of the diversity product [18]. The diversity product is defined as follows:

$$\lambda = \min_{C \neq C^{'}} \left| \det\left[ \left(\mathbf{C} - \mathbf{C}^{'}\right)\left(\mathbf{C} - \mathbf{C}^{'}\right)^{H} \right] \right|^{1/2N} \tag{16}$$

Then we get [18]:

$$P\left(\mathbf{C} \rightarrow \mathbf{C}^{'}\right) \leq \left(\lambda^{2}\right)^{-NM} \left(\frac{E_{s}}{4N_{0}}\right)^{-NM} , \tag{17}$$

where $N$ is the number of transmit antennas, $M$ is the number of receive antennas, $E_s$ is the average energy of symbols, $\mathbf{C}$ is the transmitted code matrix and $\mathbf{C}^{'}$ is another code matrix.

The significance of the diversity product is that error probability can be obtained by calculating the diversity product λ [18], as shown in (17). In fact, λ is similar to the coding advantage defined in [19].

### 5.1 Diversity Product of DQOSTBC

For illustration purposes, only the diversity product of case 16 without PIC is calculated in this section. The diversity products of cases 1-15 are similar to case 16. The $\mathbf{C}^{'}$ is similar to (7) and given by:

$$\mathbf{C}^{'} = \begin{bmatrix} c_1^{'} & -\beta_{21} g_{21}^{*} c_2^{'*} & -\beta_{31} g_{31}^{*} c_3^{'*} & \beta_{14} g_{14} c_4^{'} \\ c_2^{'} & \beta_{12} g_{12}^{*} c_1^{'*} & -\beta_{42} g_{42}^{*} c_4^{'*} & -\beta_{32} g_{32} c_3^{'} \\ c_3^{'} & -\beta_{43} g_{43}^{*} c_4^{'*} & \beta_{13} g_{13}^{*} c_1^{'*} & -\beta_{23} g_{23} c_2^{'} \\ c_4^{'} & \beta_{34} g_{34}^{*} c_3^{'*} & \beta_{24} g_{24}^{*} c_2^{'*} & \beta_{14} g_{14} c_1^{'} \end{bmatrix} \tag{18}$$

Assume the error matrix of DQOSTBC is:

$$\begin{aligned} (\mathbf{C} - \mathbf{C}^{'}) &= \\ &\begin{bmatrix} x_1 - c_1^{'} & -\beta_{21} g_{21}^{*} (x_2^{*} - c_2^{'*}) & -\beta_{31} g_{31}^{*} (x_3^{*} - c_3^{'*}) & \beta_{41} g_{41} (x_4 - c_4^{'}) \\ x_2 - c_2^{'} & \beta_{12} g_{12}^{*} (x_1^{*} - c_1^{'*}) & -\beta_{42} g_{42}^{*} (x_4^{*} - c_4^{'*}) & -\beta_{32} g_{32} (x_3 - c_3^{'}) \\ x_3 - c_3^{'} & -\beta_{43} g_{43}^{*} (x_4^{*} - c_4^{'*}) & \beta_{13} g_{13}^{*} (x_1^{*} - c_1^{'*}) & -\beta_{23} g_{23} (x_2 - c_2^{'}) \\ x_4 - c_4^{'} & \beta_{34} g_{34}^{*} (x_3^{*} - c_3^{'*}) & \beta_{24} g_{24}^{*} (x_2^{*} - c_2^{'*}) & \beta_{14} g_{14} (x_1 - c_1^{'}) \end{bmatrix} \\ &= \begin{bmatrix} \tilde{c}_{11} & -\tilde{c}_{21}^{\;*} & -\tilde{c}_{31}^{\;*} & \tilde{c}_{41} \\ \tilde{c}_{22} & \tilde{c}_{12}^{\;*} & -\tilde{c}_{42}^{\;*} & -\tilde{c}_{32} \\ \tilde{c}_{33} & -\tilde{c}_{43}^{\;*} & \tilde{c}_{13}^{\;*} & -\tilde{c}_{23} \\ \tilde{c}_{44} & \tilde{c}_{34}^{\;*} & \tilde{c}_{24}^{\;*} & \tilde{c}_{14} \end{bmatrix} , \end{aligned} \tag{19}$$

where:

$$\tilde{c}_i = x_i - c_i^{'} \qquad i = 1,2,3,4$$

$$\tilde{c}_{ij} = \beta_{ij} g_{ij}(x_i - c_i^{'}) \qquad i, j = 1,2,3,4 \quad \text{and} \quad i \neq j \tag{20}$$

Thus:

$$(\mathbf{C}-\mathbf{C}^{'})(\mathbf{C}-\mathbf{C}^{'})^H$$
$$= \begin{bmatrix} \tilde{c}_{11} & -\tilde{c}_{21}^* & -\tilde{c}_{31}^* & \tilde{c}_{41} \\ \tilde{c}_{22} & \tilde{c}_{12}^* & -\tilde{c}_{42}^* & -\tilde{c}_{32} \\ \tilde{c}_{33} & -\tilde{c}_{43}^* & \tilde{c}_{13}^* & -\tilde{c}_{23} \\ \tilde{c}_{44} & \tilde{c}_{34}^* & \tilde{c}_{24}^* & \tilde{c}_{14} \end{bmatrix} \begin{bmatrix} \tilde{c}_{11} & -\tilde{c}_{21}^* & -\tilde{c}_{31}^* & \tilde{c}_{41} \\ \tilde{c}_{22} & \tilde{c}_{12}^* & -\tilde{c}_{42}^* & -\tilde{c}_{32} \\ \tilde{c}_{33} & -\tilde{c}_{43}^* & \tilde{c}_{13}^* & -\tilde{c}_{23} \\ \tilde{c}_{44} & \tilde{c}_{34}^* & \tilde{c}_{24}^* & \tilde{c}_{14} \end{bmatrix}^H \tag{21}$$
$$= \begin{bmatrix} a_1 & b_1 & b_2 & b_3 \\ b_1^* & a_2 & b_4 & b_5 \\ b_2^* & b_4^* & a_3 & b_6 \\ b_3^* & b_5^* & b_6^* & a_4 \end{bmatrix}$$

where:

$$a_i = \sum_{j=1}^{4} \left| \tilde{c}_{ji} \right|^2, \quad i=1,2,3,4$$

$$\begin{aligned} b_1 &= \tilde{c}_{11}\tilde{c}_{22}^* - \tilde{c}_{12}\tilde{c}_{21}^* + \tilde{c}_{42}\tilde{c}_{31}^* - \tilde{c}_{41}\tilde{c}_{32}^* \\ b_2 &= \tilde{c}_{11}\tilde{c}_{33}^* + \tilde{c}_{43}\tilde{c}_{21}^* - \tilde{c}_{13}\tilde{c}_{31}^* - \tilde{c}_{41}\tilde{c}_{23}^* \\ b_3 &= \tilde{c}_{11}\tilde{c}_{44}^* - \tilde{c}_{34}\tilde{c}_{21}^* - \tilde{c}_{24}\tilde{c}_{31}^* + \tilde{c}_{41}\tilde{c}_{14}^* \\ b_4 &= \tilde{c}_{22}\tilde{c}_{33}^* - \tilde{c}_{43}\tilde{c}_{12}^* - \tilde{c}_{13}\tilde{c}_{42}^* + \tilde{c}_{32}\tilde{c}_{23}^* \\ b_5 &= \tilde{c}_{22}\tilde{c}_{44}^* + \tilde{c}_{34}\tilde{c}_{12}^* - \tilde{c}_{24}\tilde{c}_{42}^* - \tilde{c}_{32}\tilde{c}_{14}^* \\ b_6 &= \tilde{c}_{33}\tilde{c}_{44}^* - \tilde{c}_{34}\tilde{c}_{43}^* + \tilde{c}_{24}\tilde{c}_{13}^* - \tilde{c}_{23}\tilde{c}_{14}^* \end{aligned} \tag{22}$$

Then, (21) is substituted into (16) to find the diversity product of DQOSTBC.

### 5.2 Diversity Product of DOSTBC

The diversity product of DOSTBC can be found in a similar way.

The rate 1/2 OSTBC [13] is given by:

$$\begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ -x_2 & x_1 & -x_4 & x_3 \\ -x_3 & x_4 & x_1 & -x_2 \\ -x_4 & -x_3 & x_2 & x_1 \\ x_1^* & x_2^* & x_3^* & x_4^* \\ -x_2^* & x_1^* & -x_4^* & x_3^* \\ -x_3^* & x_4^* & x_1^* & -x_2^* \\ -x_4^* & -x_3^* & x_2^* & x_1^* \end{bmatrix}^T \qquad (23)$$

The information exchange error is also considered and the code matrix is modified in a way similar to (7) in the worst case.

The error matrix of DOSTBC is:

$$\begin{aligned}(\mathbf{C}-\mathbf{C}^{'}) = {} & \begin{bmatrix} x_1-c_1^{'} & x_2-c_2^{'} & x_3-c_3^{'} & x_4-c_4^{'} \\ -\beta_{21}g_{21}(x_2-c_2^{'}) & \beta_{12}g_{12}(x_1-c_1^{'}) & -\beta_{43}g_{43}(x_4-c_4^{'}) & \beta_{34}g_{34}(x_3-c_3^{'}) \\ -\beta_{31}g_{31}(x_3-c_3^{'}) & \beta_{42}g_{42}(x_4-c_4^{'}) & \beta_{13}g_{13}(x_1-c_1^{'}) & -\beta_{24}g_{24}(x_2-c_2^{'}) \\ -\beta_{41}g_{41}(x_4-c_4^{'}) & -\beta_{32}g_{32}(x_3-c_3^{'}) & \beta_{23}g_{23}(x_2-c_2^{'}) & \beta_{14}g_{14}(x_1-c_1^{'}) \\ x_1^*-c_1^{'*} & x_2^*-c_2^{'*} & x_3^*-c_3^{'*} & x_4^*-c_4^{'*} \\ -\beta_{21}g_{21}^*(x_2^*-c_2^{'*}) & \beta_{12}g_{12}^*(x_1^*-c_1^{'*}) & -\beta_{43}g_{43}^*(x_4^*-c_4^{'*}) & \beta_{34}g_{34}^*(x_3^*-c_3^{'*}) \\ -\beta_{31}g_{31}^*(x_3^*-c_3^{'*}) & \beta_{42}g_{42}^*(x_4^*-c_4^{'*}) & \beta_{13}g_{13}^*(x_1^*-c_1^{'*}) & -\beta_{24}g_{24}^*(x_2^*-c_2^{'*}) \\ -\beta_{41}g_{41}^*(R_4^*-c_4^{'*}) & -\beta_{32}g_{32}^*(x_3^*-c_3^{'*}) & \beta_{23}g_{23}^*(x_2^*-c_2^{'*}) & \beta_{14}g_{14}^*(x_1^*-c_1^{'*}) \end{bmatrix}^T \\ = {} & \begin{bmatrix} \tilde{c}_{11} & -\tilde{c}_{21} & -\tilde{c}_{31} & -\tilde{c}_{41} & \tilde{c}_{11}^* & -\tilde{c}_{21}^* & -\tilde{c}_{31}^* & -\tilde{c}_{41}^* \\ \tilde{c}_{22} & \tilde{c}_{12} & \tilde{c}_{42} & -\tilde{c}_{32} & \tilde{c}_{22}^* & \tilde{c}_{12}^* & \tilde{c}_{42}^* & -\tilde{c}_{32}^* \\ \tilde{c}_{33} & -\tilde{c}_{43} & \tilde{c}_{13} & \tilde{c}_{23} & \tilde{c}_{33}^* & -\tilde{c}_{43}^* & \tilde{c}_{13}^* & \tilde{c}_{23}^* \\ \tilde{c}_{44} & \tilde{c}_{34} & -\tilde{c}_{24} & \tilde{c}_{14} & \tilde{c}_{44}^* & \tilde{c}_{34}^* & -\tilde{c}_{24}^* & \tilde{c}_{14}^* \end{bmatrix}\end{aligned} \qquad (24)$$

where:

$$\begin{aligned} &\tilde{c}_{ii} = x_i - c_i^{'} \qquad i = 1,2,3,4 \\ &\tilde{c}_{ij} = \beta_{ij}(R_{ij}^* - c_i^{'*}) \qquad i, j = 1,2,3,4 \quad \text{and} \quad i \neq j \end{aligned} \qquad (25)$$

Thus:

$$(\mathbf{C}-\mathbf{C}^{'})(\mathbf{C}-\mathbf{C}^{'})^{H} = \begin{bmatrix} a_1^{'} & b_1^{'} & b_2^{'} & b_3^{'} \\ b_1^{'} & a_2^{'} & b_4^{'} & b_5^{'} \\ b_2^{'} & b_4^{'} & a_3^{'} & b_6^{'} \\ b_3^{'} & b_5^{'} & b_6^{'} & a_4^{'} \end{bmatrix} \tag{26}$$

where:

$$\begin{aligned}
a_i^{'} &= 2\sum_{j=1}^{4}\left|\tilde{c}_{ji}\right|^2 \quad i=1,2,3,4 \\
b_1^{'} &= \tilde{c}_{11}\tilde{c}_{22}^{*} - \tilde{c}_{21}\tilde{c}_{12}^{*} - \tilde{c}_{31}\tilde{c}_{42}^{*} + \tilde{c}_{41}\tilde{c}_{32}^{*} + \tilde{c}_{22}\tilde{c}_{11}^{*} - \tilde{c}_{12}\tilde{c}_{21}^{*} \\
&\quad - \tilde{c}_{42}\tilde{c}_{31}^{*} + \tilde{c}_{32}\tilde{c}_{41}^{*} \\
b_2^{'} &= \tilde{c}_{11}\tilde{c}_{33}^{*} + \tilde{c}_{21}\tilde{c}_{43}^{*} - \tilde{c}_{31}\tilde{c}_{13}^{*} - \tilde{c}_{41}\tilde{c}_{23}^{*} + \tilde{c}_{33}\tilde{c}_{11}^{*} + \tilde{c}_{43}\tilde{c}_{21}^{*} \\
&\quad - \tilde{c}_{13}\tilde{c}_{31}^{*} - \tilde{c}_{23}\tilde{c}_{41}^{*} \\
b_3^{'} &= \tilde{c}_{11}\tilde{c}_{44}^{*} - \tilde{c}_{21}\tilde{c}_{34}^{*} + \tilde{c}_{31}\tilde{c}_{24}^{*} - \tilde{c}_{41}\tilde{c}_{14}^{*} + \tilde{c}_{44}\tilde{c}_{11}^{*} - \tilde{c}_{34}\tilde{c}_{21}^{*} \\
&\quad + \tilde{c}_{24}\tilde{c}_{31}^{*} - \tilde{c}_{14}\tilde{c}_{41}^{*} \\
b_4^{'} &= \tilde{c}_{22}\tilde{c}_{33}^{*} - \tilde{c}_{12}\tilde{c}_{43}^{*} + \tilde{c}_{42}\tilde{c}_{13}^{*} - \tilde{c}_{32}\tilde{c}_{23}^{*} + \tilde{c}_{33}\tilde{c}_{22}^{*} - \tilde{c}_{43}\tilde{c}_{12}^{*} \\
&\quad + \tilde{c}_{13}\tilde{c}_{42}^{*} - \tilde{c}_{23}\tilde{c}_{32}^{*} \\
b_5^{'} &= \tilde{c}_{22}\tilde{c}_{44}^{*} + \tilde{c}_{12}\tilde{c}_{34}^{*} - \tilde{c}_{42}\tilde{c}_{24}^{*} - \tilde{c}_{32}\tilde{c}_{14}^{*} + \tilde{c}_{44}\tilde{c}_{22}^{*} + \tilde{c}_{34}\tilde{c}_{12}^{*} \\
&\quad - \tilde{c}_{24}\tilde{c}_{42}^{*} - \tilde{c}_{14}\tilde{c}_{32}^{*} \\
b_6^{'} &= \tilde{c}_{33}\tilde{c}_{44}^{*} - \tilde{c}_{43}\tilde{c}_{34}^{*} - \tilde{c}_{13}\tilde{c}_{24}^{*} + \tilde{c}_{23}\tilde{c}_{14}^{*} + \tilde{c}_{44}\tilde{c}_{33}^{*} - \tilde{c}_{34}\tilde{c}_{43}^{*} \\
&\quad - \tilde{c}_{24}\tilde{c}_{13}^{*} + \tilde{c}_{14}\tilde{c}_{23}^{*}
\end{aligned} \tag{27}$$

Then (26) is substituted into (16) and the diversity product of DOSTBC can be found.

Finally, the diversity products of the DOSTBC and DQOSTBC are compared using the above performance analysis result. Equations (16), (21), and (26) are used to calculate the diversity product. The relation of the diversity product between these two is found as follows:

$$\lambda_{DQOSTBC} > \lambda_{DOSTBC} \tag{41}$$

So the performance analysis result indicates that the DQOSTBC outperforms the DOSTBC. In the next section, it will be shown that scenario iii (DQOSTBC) outperforms scenario ii (DOSTBC), which agrees with the performance analysis result.

Equation (17) is only an upper bound of the pairwise error probability, and not an exact average error probability. Therefore comparing the average bit error rate through Monte Carlo simulation is necessary.

## 6. Simulation Results

The simulation environment and channel is as follows. The system has four users and a single destination, as shown in **Fig. 1.** Each user as well as the destination has only one antenna. In other words, DOSTBC and DQOSTBC with four transmit antennas and one receive antenna are compared. The flat Rayleigh fading channels are also assumed.

Four scenarios at the same transmission rate of 2 bits/sec/Hz (the same assumption is in QOSTBC papers [14] [16][17]) are considered in the simulation:

i. QOSTBC with error in information exchange: it uses a rate 1 QOSTBC matrix without information exchange mitigation and QPSK modulation.
ii. DOSTBC: it uses a rate 1/2 OSTBC matrix and 16QAM modulation.
iii. DQOSTBC: it uses a rate 1 QOSTBC matrix and QPSK modulation.
iv. DQOSTBC: it uses a rate 1 QOSTBC matrix and QPSK modulation. At the receiver, we add PIC.

Assuming CRC is not present, we simulate these scenarios with the worst case (case 16). In **Fig. 2**, scenario iv outperforms scenario ii by about 6.5 dB at $10^{-4}$ bit error rate. For scenario iii (scenario iv without PIC), the gain is about 3.5dB.

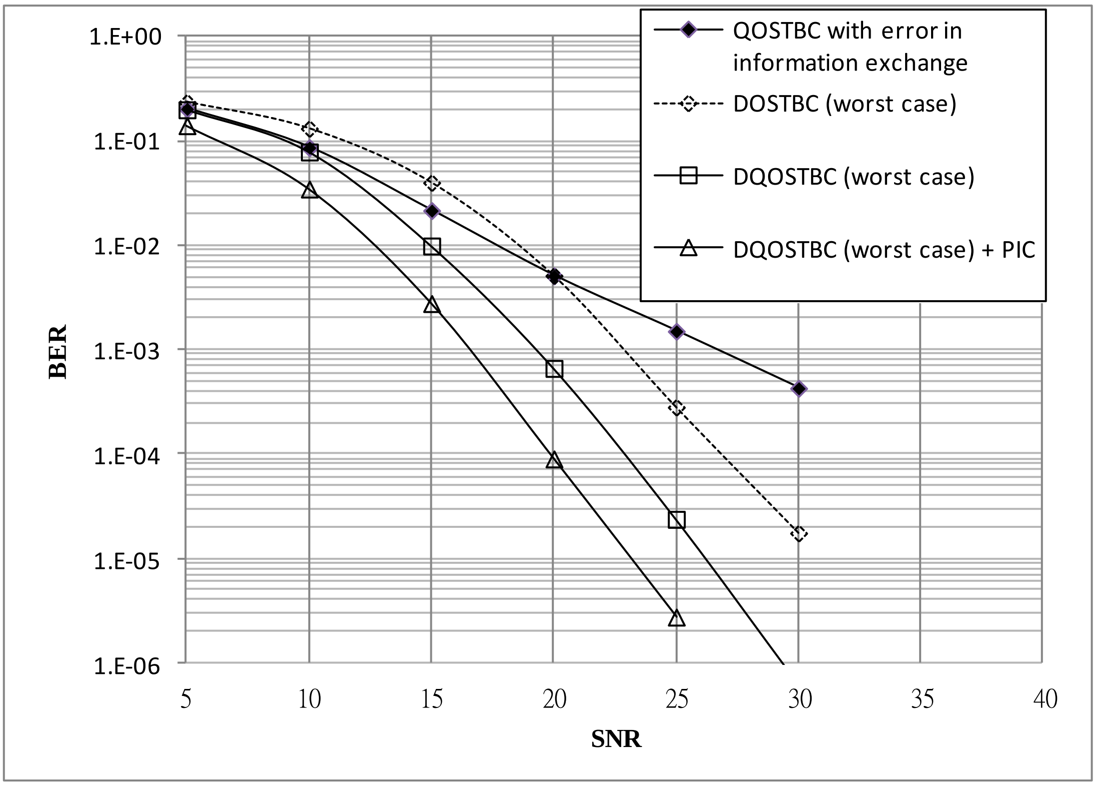

**Fig. 2.** Average bit error rate versus SNR for 2 bits/sec/Hz for the worst case of different distributed coding schemes (without CRC, case 16 is always selected) with four transmit antennas.

Assuming CRC is present, these scenarios with all cases (CRC helps to pick one of 16 cases) are simulated. In **Fig. 3**, scenario iv outperforms scenario ii by about 5.5 dB at $10^{-4}$ bit error rate. For scenario iii (scenario iv without PIC), the gain is about 4.5dB.

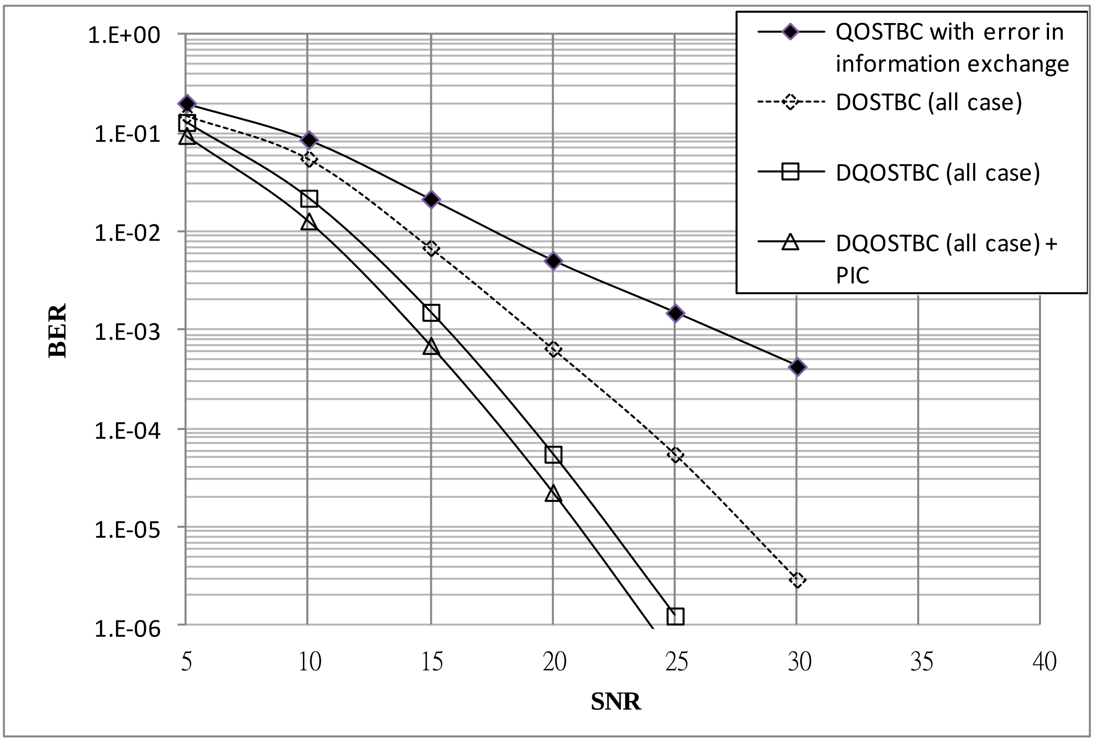

**Fig. 3.** Average bit error rate versus SNR for 2 bits/sec/Hz for all cases of different distributed coding schemes (with CRC, one out of 16 cases is selected) with four transmit antennas.

These scenarios are also simulated with the best case (case 1). In **Fig. 4**, scenario iv outperforms scenario ii by about 3.5 dB at $10^{-4}$ bit error rate. For scenario iii (scenario iv without PIC), the gain is about 3dB.

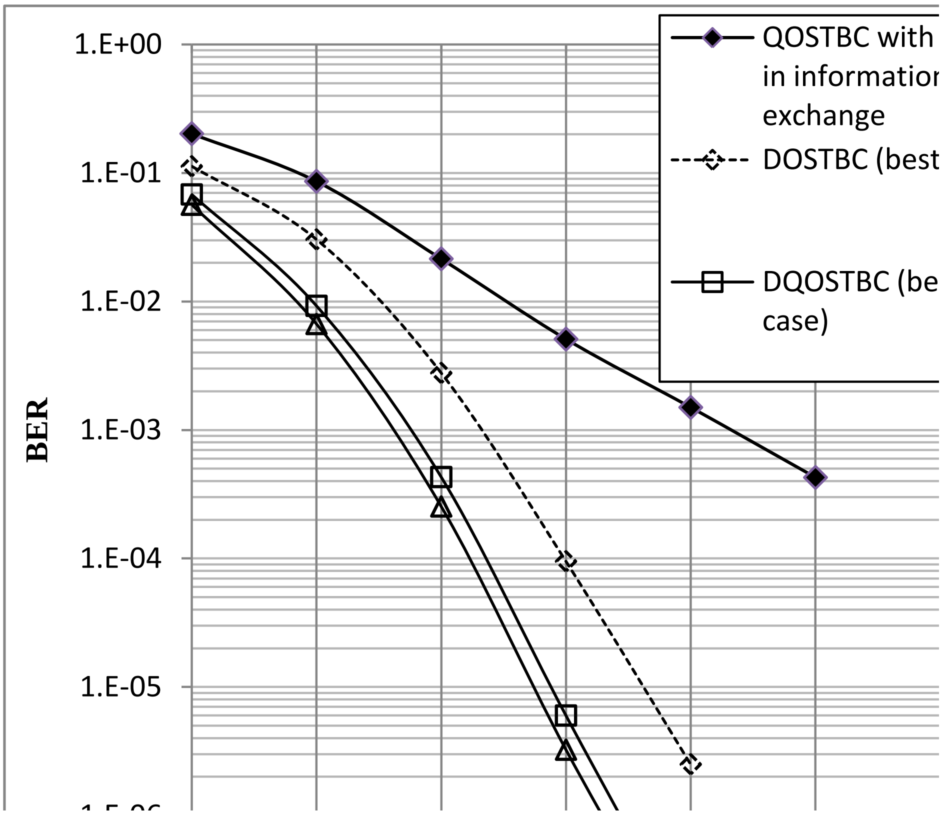

**Fig. 4.** Average bit error rate versus SNR for 2 bits/sec/Hz for the best case of different distributed coding schemes with four transmit antennas.

In **Figs. 2-4**, scenario 1 (a QOSTBC with error in information exchange) is also shown for comparison. It does not change the code matrix according to whether the information exchange is correct or not, so it does not mitigate the information exchange error, and it maintains the same curve in **Figs. 2-4**. From **Figs. 2-4**, we can see that this curve has the worst BER when SNR is higher than 20dB because of loss of full diversity.

Based on (17) in the performance analysis section, scenario iii should have a lower error probability than scenario ii. This agrees with the simulation curves in **Fig. 2**.

To see the efficiency of PIC, we compare scenarios iii and iv in **Figs. 2-4**. For the worst case, all cases, and the best case, the PIC gains 3, 1, and 0.5dB at $10^{-4}$ bit error rate, respectively. We find that the PIC gains most in the worst case (case 16) and little in the best case (case 1). All information exchange is wrong in the worst case, the $\beta_{mn}R_{mn}$ elements in the code matrix contain noise in addition to $x_m$ (see (4)), so additional PIC is most helpful in this case.

## 7. Conclusion

In this paper, a distributed quasi-orthogonal space-time block code (DQOSTBC) focusing on information exchange errors is proposed to achieve full diversity. The analyses are applied on a multi-input multi-output (MIMO) system with four transmit antennas and one receive antenna. The simulation results show that the proposed full rate full diversity DQOSTBC scheme has lower BER than the QOSTBC with error in information exchange (not full diversity). The simulation result and performance analysis also show that the proposed full rate DQOSTBC scheme has lower BER than rate 1/2 DOSTBC at the same transmission rate of 2 bits/sec/Hz.

## Appendix A

Case 3: only $x_2$ is in error:

$$\mathbf{C}(\mathbf{x}) = \begin{bmatrix} x_1 & -\beta_{21}R_{21}^* & -x_3^* & x_4 \\ x_2 & x_1^* & -x_4^* & -x_3 \\ x_3 & -x_4^* & x_1^* & -\beta_{23}R_{23} \\ x_4 & x_3^* & \beta_{24}R_{24}^* & x_1 \end{bmatrix} \tag{A-1}$$

Case 4: only $x_3$ is in error:

$$\mathbf{C}(\mathbf{x}) = \begin{bmatrix} x_1 & -x_2^* & -\beta_{31}R_{31}^* & x_4 \\ x_2 & x_1^* & -x_4^* & -\beta_{32}R_{32} \\ x_3 & -x_4^* & x_1^* & -x_2 \\ x_4 & \beta_{34}R_{34}^* & x_2^* & x_1 \end{bmatrix} \tag{A-2}$$

Case 5: only $x_4$ is in error:

$$\mathbf{C}(\mathbf{x}) = \begin{bmatrix} x_1 & -x_2^* & -x_3^* & \beta_{41}R_{41} \\ x_2 & x_1^* & -\beta_{42}R_{42}^* & -x_3 \\ x_3 & -\beta_{43}R_{43}^* & x_1^* & -x_2 \\ x_4 & x_3^* & x_2^* & x_1 \end{bmatrix} \tag{A-3}$$

Case 6: $x_1$ and $x_2$ are in error:

$$\mathbf{C}(\mathbf{x}) = \begin{bmatrix} x_1 & -\beta_{21}R_{21}^* & -x_3^* & x_4 \\ x_2 & \beta_{12}R_{12}^* & -x_4^* & -x_3 \\ x_3 & -x_4^* & \beta_{13}R_{13}^* & -\beta_{23}R_{23} \\ x_4 & x_3^* & \beta_{24}R_{24}^* & \beta_{14}R_{14} \end{bmatrix} \tag{A-4}$$

Case 7: $x_1$ and $x_3$ are in error:

$$\mathbf{C}(\mathbf{x}) = \begin{bmatrix} x_1 & -x_2^* & -\beta_{31}R_{31}^* & x_4 \\ x_2 & \beta_{12}R_{12}^* & -x_4^* & -\beta_{32}R_{32} \\ x_3 & -x_4^* & \beta_{13}R_{13}^* & -x_2 \\ x_4 & \beta_{34}R_{34}^* & x_2^* & \beta_{14}R_{14} \end{bmatrix} \tag{A-5}$$

Case 8: $x_1$ and $x_4$ are in error:

$$\mathbf{C}(\mathbf{x}) = \begin{bmatrix} x_1 & -x_2^* & -x_3^* & \beta_{41}R_{41} \\ x_2 & \beta_{12}R_{12}^* & -\beta_{42}R_{42}^* & -x_3 \\ x_3 & -\beta_{43}R_{43}^* & \beta_{13}R_{13}^* & -x_2 \\ x_4 & x_3^* & x_2^* & \beta_{14}R_{14} \end{bmatrix} \tag{A-6}$$

Case 9: $x_2$ and $x_3$ are in error:

$$\mathbf{C}(\mathbf{x}) = \begin{bmatrix} x_1 & -\beta_{21}R_{21}^* & -\beta_{31}R_{31}^* & x_4 \\ x_2 & x_1^* & -x_4^* & -\beta_{32}R_{32} \\ x_3 & -x_4^* & x_1^* & -\beta_{23}R_{23} \\ x_4 & \beta_{34}R_{34}^* & \beta_{24}R_{24}^* & x_1 \end{bmatrix} \tag{A-7}$$

Case 10: $x_2$ and $x_4$ are in error:

$$\mathbf{C}(\mathbf{x}) = \begin{bmatrix} x_1 & -\beta_{21}R_{21}^* & -x_3^* & \beta_{41}R_{41} \\ x_2 & x_1^* & -\beta_{42}R_{42}^* & -x_3 \\ x_3 & -\beta_{43}R_{43}^* & x_1^* & -\beta_{23}R_{23} \\ x_4 & x_3^* & \beta_{24}R_{24}^* & x_1 \end{bmatrix} \tag{A-8}$$

Case 11: $x_3$ and $x_4$ are in error:

$$\mathbf{C}(\mathbf{x}) = \begin{bmatrix} x_1 & -x_2^* & -\beta_{31}R_{31}^* & \beta_{41}R_{41} \\ x_2 & x_1^* & -\beta_{42}R_{42}^* & -\beta_{32}R_{32} \\ x_3 & -\beta_{43}R_{43}^* & x_1^* & -x_2 \\ x_4 & \beta_{34}R_{34}^* & x_2^* & x_1 \end{bmatrix} \tag{A-9}$$

Case 12: $x_1$, $x_2$ and $x_3$ are in error:

$$\mathbf{C}(\mathbf{x}) = \begin{bmatrix} x_1 & -\beta_{21}R^*_{21} & -\beta_{31}R^*_{31} & x_4 \\ x_2 & \beta_{12}R^*_{12} & -x_4^* & -\beta_{32}R_{32} \\ x_3 & -x_4^* & \beta_{13}R^*_{13} & -\beta_{23}R_{23} \\ x_4 & \beta_{34}R^*_{34} & \beta_{24}R^*_{24} & \beta_{14}R_{14} \end{bmatrix} \tag{A-10}$$

Case 13: $x_1$, $x_2$ and $x_4$ are in error:

$$\mathbf{C}(\mathbf{x}) = \begin{bmatrix} x_1 & -\beta_{21}R^*_{21} & -x_3^* & \beta_{41}R_{41} \\ x_2 & \beta_{12}R^*_{12} & -\beta_{42}R^*_{42} & -x_3 \\ x_3 & -\beta_{43}R^*_{43} & \beta_{13}R^*_{13} & -\beta_{23}R_{23} \\ x_4 & x_3^* & \beta_{24}R^*_{24} & \beta_{14}R_{14} \end{bmatrix} \tag{A-11}$$

Case 14: $x_1$, $x_3$ and $x_4$ are in error:

$$\mathbf{C}(\mathbf{x}) = \begin{bmatrix} x_1 & -x_2^* & -\beta_{31}R^*_{31} & \beta_{41}R_{41} \\ x_2 & \beta_{12}R^*_{12} & -\beta_{42}R^*_{42} & -\beta_{32}R_{32} \\ x_3 & -\beta_{43}R^*_{43} & \beta_{13}R^*_{13} & -x_2 \\ x_4 & \beta_{34}R^*_{34} & x_2^* & \beta_{14}R_{14} \end{bmatrix} \tag{A-12}$$

Case 15: $x_2$, $x_3$ and $x_4$ are in error:

$$\mathbf{C}(\mathbf{x}) = \begin{bmatrix} x_1 & -\beta_{21}R^*_{21} & -\beta_{31}R^*_{31} & \beta_{41}R_{41} \\ x_2 & x_1^* & -\beta_{42}R^*_{42} & -\beta_{32}R_{32} \\ x_3 & -\beta_{43}R^*_{43} & x_1^* & -\beta_{23}R_{23} \\ x_4 & \beta_{34}R^*_{34} & \beta_{24}R^*_{24} & x_1 \end{bmatrix} \tag{A-13}$$

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