# Four Transmit Diversity Schemes for Coded OFDM Systems with Four Transmit Antennas

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*Abstract*— **We compare four open-loop transmit diversity schemes in a coded Orthogonal Frequency Division Multiplexing (OFDM) system with four transmit antennas, namely cyclic shift diversity (CSD), Space-Time Block Code (STBC, Alamouti code is used) with CSD, Quasi-Orthogonal STBC (QO-STBC) and Minimum-Decoding-Complexity QOSTBC (MDC-QOSTBC). We show that in a coded system with low code rate, a scheme with spatial transmit diversity of second order can achieve similar performance to that with spatial transmit diversity of fourth order due to the additional diversity provided by the phase shift diversity with channel coding. In addition, we also compare the decoding complexity and other features of the above four mentioned schemes, such as the requirement for the training signals, hybrid automatic retransmission request (HARQ), etc. The discussions in this paper can be readily applied to many modern wireless communication systems, such as mobile systems beyond 3G, IEEE 802.11 wireless LAN, or IEEE 802.16 WiMAX, that employ more than two transmit antennas and OFDM.**

*Index Terms*— **open loop transmit diversity, coded OFDM, low decoding complexity, quasi-orthogonal design, cyclic shift diversity, cyclic delay diversity, space-time block code**

## I. INTRODUCTION

We consider a multiple-input multiple-output (MIMO) system with four transmit antennas at the base station. Since the wireless channels experience fading, transmit diversity plays an important role, especially when the feedback of the channel state information (CSI) from the mobile to the base station is not possible. Most of the transmit diversity schemes proposed in the literature are for flat fading channels and usually do not consider channel coding. However, in a coded system, additional diversity can be provided through the use of channel coding in a frequency selective fading channel. Hence a different conclusion would be generated under a coded Orthogonal Frequency Division Multiplexing (OFDM) system than the uncoded flat fading channel, and it is the main objective of this paper to investigate transmit diversity for a coded OFDM system with four transmit antennas.

In this paper, we compare four practical transmit diversity schemes in a coded OFDM system. The first scheme is cyclic shift diversity (CSD) [1], also known as cyclic delay diversity (CDD). Since it can be treated as phase diversity in the frequency domain, it does not provide any additional spatial diversity, and its performance relies much on the capability of the channel coding. The second scheme is the combination of Space-Time Block Code (STBC) with CSD [2]. We use the rate-1 orthogonal STBC, namely the Alamouti STBC which is originally designed for two transmit antennas, and combine it with CSD to support four transmit antennas. In this case, it can provide a spatial diversity of two and yet achieve maximum-likelihood detection (MLD) with linear complexity.

As no orthogonal design can achieve full rate when there are four transmit antennas, we consider two rate-1 non-orthogonal STBCs that can provide spatial transmit diversity of order four. They are Quasi-Orthogonal STBC (QO-STBC) [3] and Minimum-Decoding-Complexity QO-STBC (MDC-QOSTBC) [4]. These STBCs are selected as they are "quasi-orthogonal" and hence have a lower decoding complexity than other non-orthogonal STBC schemes for four transmit antennas. The MLD decoding search space for the above mentioned schemes is given in TABLE I.

As shown in TABLE I, for a complex constellation of size-$M$, an orthogonal design only requires a search space of $\sqrt{M}$, while QO-STBC requires a search space of $M^2$ and MDC-QOSTBC requires a search space of $M$. Although MDC-QOSTBC has a slightly higher complexity than the orthogonal design, such complexity is still manageable in practical systems, as it is still single-symbol decodable. And this is the very advantage of MDC-QOSTBC over QO-STBC.

TABLE I
MLD SEARCH SPACE FOR QO-STBC AND MDC-QOSTBC

| | Decoding search space | | |
|---|---|---|---|
| | QO-STBC | MDC-QOSTBC | Alamout, CSD or Alamouti+CSD |
| QPSK | 16 | 4 | 2 |
| 16QAM | 256 | 16 | 4 |
| $M$ points | $M^2$ | $M$ | $\sqrt{M}$ |

The rest of the paper is organized as follows. In Section II, we will first discuss each of the schemes in detail. After that in Section III, we compare the decoding performance of the four transmit diversity schemes in a coded OFDM system. We then discuss on the features and merits of the schemes respectively in Section IV. And finally in Section V, we conclude the paper.

## II. TRANSMIT DVIERSITY IN CODED SYSTEMS

In Figure 1 and Figure 2, we show the transmitter and receiver structure of the coded MIMO-OFDM system that is considered in this paper. The information bits first go through the forward error correction code (FEC), turbo code in this study, and the coded bits are modulated with a selected constellation. The modulation symbols will then go through the MIMO block and be mapped to different spatial streams. After that, the data on each spatial stream are OFDM modulated and transmitted. We would also like to mention that, the MIMO schemes that we implemented in this paper, are in the space-time domain, rather than the space-frequency domain. In other words, the duplication is repeated in the next OFDM symbol rather than the next sub-carrier frequency.

The operations of the OFDM modulation and demodulation are shown in Figure 3. Each spatial stream goes through a serial to parallel (S/P) conversion and the inverse fast Fourier transform (IFFT) to convert the frequency-domain signals into time-domain. The time domain signal then goes through the parallel to serial (P/S) conversion and is appended with a cyclic prefix (CP). The length of the CP has to be longer than the delay spread of the multipath channel in order to preserve the orthogonality among the subcarriers of an OFDM symbol. At the receiver, a reverse process is implemented, i.e. the CP is removed after the timing synchronization is achieved, and FFT operation is performed to convert the time-domain signals into frequency-domain. The MIMO detection is then carried out in the frequency domain for each subcarrier, following which the FEC decoding is implemented.

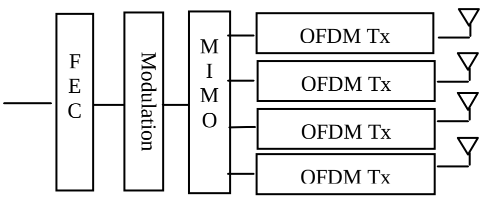


Figure 1 Transmitter structure with 4 transmit antennas

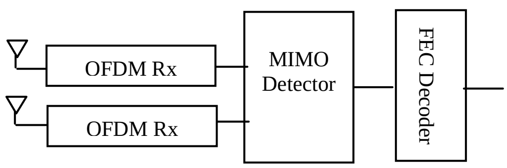


Figure 2 Receiver structure with 2 receive antennas

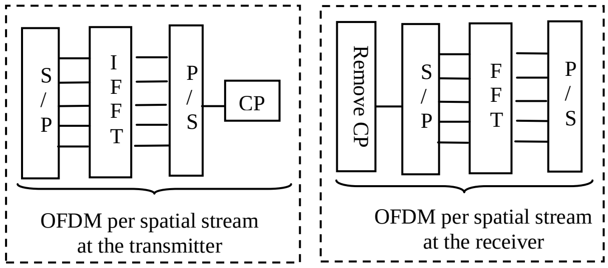


Figure 3 OFDM processing at the transmitter and the receiver

### A. CSD

CSD is a simple form of transmit diversity, more importantly, it can be transparent to the receiver. In other words, the receiver does not need to have the knowledge of the number of transmit antennas and the cyclic shifts used if the traning signals are properly designed. This feature greatly simplifies the decoding process, as it can be treated as a single-transmit-antenna system. The transmit diversity from the multiple antennas in spatial domain is converted to frequency diversity [1]. CSD can be achieved by implementing a phase shift in the frequency domain as shown in Figure 4 That's the reason CSD is also known as phase shift diversity (PSD). Alternatively, CSD can be achieved by implementing a time delay in the time domain, as shown in Figure 5.

The effective channel in frequency domain on the $k^{th}$ subcarrier for a particular receive antenna can be written as:

$$h_{eff}(k) = h_1(k) + h_2(k)e^{j\theta_1 k} + h_3(k)e^{j\theta_2 k} + h_4(k)e^{j\theta_3 k} \quad (1)$$

where $h_1(k)$, $h_2(k)$, $h_3(k)$, and $h_4(k)$ are the effective channels on subcarrier $k$ for the four transmit antennas to a particular receive antenna. Hence by using CSD, the effective channels in the frequency domain has larger frequency diveristy. This additional frequency diversity can be effectively exploited by the channel coding across the subcarriers.

By having the training symbols to go through the same phase shift as the data symbols, the receiver will only see the effective channel as shown in (1), hence the CSD transmit diversity scheme would be transparent to the receiver.

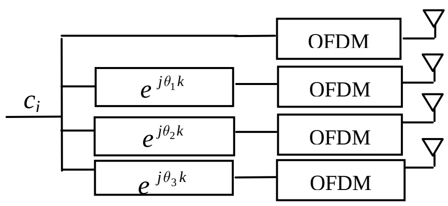


Figure 4 CSD transmitter structure implemented using frequency-domain processing

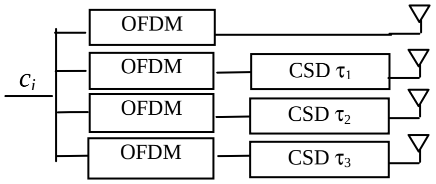


Figure 5 CSD transmitter structure implemented using time-domain processing

### B. Alamouti code + CSD

Alamouti code is a transmit diversity scheme for two transmit antennas [5]. It is a rate-one orthogonal space-time block code, hence it only requires linear processing to achieve MLD. The codeword of the Alamouti code is shown in (2), where the coloumn represents the signals to be transmitted using different antennas and the row represents the signal to be transmitted at different time slots.

$$\mathbf{C} = \begin{bmatrix} c_1 & c_2 \\ -c_2^* & c_1^* \end{bmatrix} \quad (2)$$

Unfortunately, a rate-one orthogonal STBC that requires linear complexity MLD as the Alamouti STBC only exists for two transmit antennas [6]. Similar codes for higher number of transmit antennas would suffer a lower code rate, hence lower spectral efficiency. A simple and straightforward application of Alamouti STBC for four transmit antennas would be the combination of Alamouti STBC with CSD.

As shown in Figure 6, we can duplicate the data symbols onto two parallel streams, and the symbols in one of the stream are being rotated by a phase shift. After that each stream is transmitted on two transmit antennas using Alamouti STBC. The advantage of such transmission is that at the receiver, it only sees two effective transmit antennas, with the following effective channel gain:

$$\begin{aligned} h_{eff,1}(k) &= h_1(k) + h_3(k)e^{j\theta_1 k} \\ h_{eff,1}(k) &= h_2(k) + h_4(k)e^{j\theta_1 k} \end{aligned} \quad (3)$$

By doing so, a spatial diversity of order two has been provided by the Alamouti STBC, and additional frequency diversity will be provided by CSD and the channel coding.

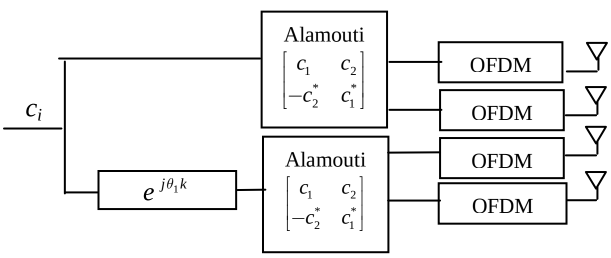


Figure 6 Alamouti + CSD transmitter structure

### C. QO-STBC

To overcome the rate limitation of the orthogonal STBC for four transmit antennas, Quasi-Orthogonal STBC (QO-STBC) has been proposed to provide rate-1 transmit diversity with reduced decoding complexity than non-orthogonal STBC [3][7][8].

The codeword of the QO-STBC [3] is shown below:

$$\mathbf{C} = \begin{bmatrix} c_1 & c_2 & c_3 & c_4 \\ -c_2^* & c_1^* & -c_4^* & c_3^* \\ c_3 & c_4 & c_1 & c_2 \\ -c_4^* & c_3^* & -c_2^* & c_1^* \end{bmatrix} \quad (4)$$

The transmitter structure of QO-STBC OFDM system is shown in Figure 7.

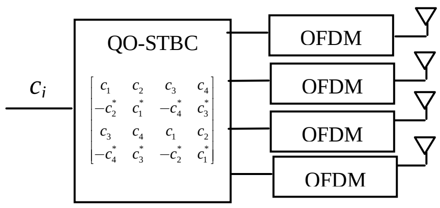


Figure 7 QO-STBC transmitter structure

The MLD of QO-STBC requires a complexity of the joint detection of two complex symbols. Though such complexity is already much lower than other non-orthogonal STBCs, it is sill difficult to implement in a practical system, hence throughout this study, we only use linear minimum mean squred error (LMMSE) receiver for QO-STBC.

The coded performance of QO-STBC in an OFDM system has been reported in [9][10]. However there was no comparsion between the coded performance of QO-STBC with other transmit diversity schemes.

### D. MDC-QOSTBC

In this paper, we also consider a special class of QO-STBC, the minimum-decoding-complexity QO-STBC (MDC-QOSTBC). The advantage of this code is that its MLD only requires joint detection of two real symbols (i.e. one complex symbol), hence for the PSK constellation, it has the same MLD decoding complexity as orthogonal STBC. In an uncoded system, it suffers merely 0.5dB loss in STBC coding gain when compared with QO-STBC, while having a much lower decoding complexity [4][11]. However, the coded performance of MDC-QOSTBC has yet been reported in the literature.

MDC-QOSTBC has a smilar codeword as QO-STBC, just the mapping of the data symbols is different, as shown below:

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

where $x_1 = c_1^R + jc_3^R$, $x_2 = c_2^R + jc_4^R$, $x_3 = -c_1^I + jc_3^I$, $x_4 = -c_2^I + jc_4^I$, and $c_i = c_i^R + jc_i^I$ $(1 \le i \le 4)$ are the transmitted data symbols, while $c_i^R$ and $c_i^I$ are the real and imaginary parts of a complex symbol. Alternatively, we can represent the codeword of a MDC-QOSTBC using the model in [12], as follows:

$$\mathbf{C} = \sum_{i=1}^{K}(c_i^R \mathbf{A}_i + jc_i^I \mathbf{B}_i) \qquad (6)$$

where the matrices $\mathbf{A}_i$ and $\mathbf{B}_i$ are called the "dispersion matrices" and are of size $T \times N_t$, $T$ is the code length and $N_t$ is the number of transmit antennas, and these two values are equal to 4 for MDC-QOSTBC.

The $T \times 1$ received signal, $\boldsymbol{r}_i$, at the $i^{\text{th}}$ received antenna, (where $1 \le i \le N_r$, and $N_r$ is the total number of receive antenna), at each subcarrier can be written as (the subcarrier index is removed for simplicity):

$$\mathbf{r}_i = \mathbf{C}\mathbf{h}_i + \mathbf{n}_i \qquad (7)$$

where $\mathbf{h}_i = \begin{bmatrix} h_{1,i} & h_{2,i} & h_{3,i} & h_{4,i} \end{bmatrix}^T$ are the frequency-domain equivalent channel from the four transmit antennas to the $i^{\text{th}}$ received antenna of a particular subcarrier frequency. By using the model described in [12], we can rewrite the above as:

$$\mathbf{r} = \mathbf{H}_{\mathbf{eq}}\mathbf{c} + \boldsymbol{\eta} \qquad (8)$$

where $\mathbf{r} = \left[ (\mathbf{r}_1^R)^T \ (\mathbf{r}_1^I)^T \ \cdots \ (\mathbf{r}_{N_r}^R)^T \ (\mathbf{r}_{N_r}^I)^T \right]^T$, $\mathbf{c}$ is the real-valued transmitted signals arranged in a column as follows: $\mathbf{c} = \begin{bmatrix} c_1^R & c_1^I & c_2^R & c_2^I & c_3^R & c_3^I & c_4^R & c_4^I \end{bmatrix}^T$, the noise term $\boldsymbol{\eta} = \left[ (\mathbf{n}_1^R)^T \ (\mathbf{n}_1^I)^T \ \cdots \ (\mathbf{n}_{N_r}^R)^T \ (\mathbf{n}_{N_r}^I)^T \right]^T$, and $\mathbf{n}_i$ $(1 \le i \le N_r)$ is $T \times 1$ row vectors which contain the received signal and AWGN noise for the $i^{\text{th}}$ receive antenna respectively, over $T$ symbol periods.

Then $\mathbf{H}_{\mathbf{eq}}$ is the equivalent channel as described in [12] as:

$$\mathbf{H}_{\text{eq}} = \begin{bmatrix} \mathcal{A}_1\underline{\mathbf{h}}_1 & \mathcal{B}_1\underline{\mathbf{h}}_1 & \dots & \mathcal{A}_K\underline{\mathbf{h}}_1 & \mathcal{B}_K\underline{\mathbf{h}}_1 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \mathcal{A}_1\underline{\mathbf{h}}_{N_r} & \mathcal{B}_1\underline{\mathbf{h}}_{N_r} & \dots & \mathcal{A}_K\underline{\mathbf{h}}_{N_r} & \mathcal{B}_K\underline{\mathbf{h}}_{N_r} \end{bmatrix} \qquad (9)$$

where $\mathcal{A}_q = \begin{bmatrix} \mathbf{A}_q^R & -\mathbf{A}_q^I \\ \mathbf{A}_q^I & \mathbf{A}_q^R \end{bmatrix}, \mathcal{B}_q = \begin{bmatrix} -\mathbf{B}_q^I & -\mathbf{B}_q^R \\ \mathbf{B}_q^R & -\mathbf{B}_q^I \end{bmatrix}, \underline{\mathbf{h}}_i = \begin{bmatrix} \mathbf{h}_i^R \\ \mathbf{h}_i^I \end{bmatrix}$.

By applying the linear matched filter $\mathbf{H}_{\mathbf{eq}}^*$ and whitening filter $\mathbf{H}_{\text{w}} = \left(\mathbf{H}_{\mathbf{eq}}^*\mathbf{H}_{\mathbf{eq}}\right)^{-1/2}$ to (7) as described in [13], we get:

$$\begin{aligned} &\mathbf{H}_{\mathbf{w}}\mathbf{H}_{\mathbf{eq}}^*\mathbf{r} \\ &= \mathbf{H}_{\mathbf{w}}\mathbf{H}_{\mathbf{eq}}^*\mathbf{H}_{\mathbf{eq}}\mathbf{c} + \mathbf{H}_{\mathbf{w}}\mathbf{H}_{\mathbf{eq}}^*\boldsymbol{\eta} \\ &= \mathbf{H}_{\mathbf{final}}\mathbf{c} + \tilde{\boldsymbol{\eta}} \end{aligned} \qquad (10)$$

where $\tilde{\mathbf{n}}$ is white noise.

It can be easily shown that $\mathbf{H}_{\mathbf{final}}$ is a block diagonal matrix, with four 2-by-2 sub-matrices. That is, the four transmitted symbols are separated into four orthogonal groups, each of them can be decoded independently. We can represent the first group as follows:

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} c_1^R \\ c_1^I \end{bmatrix} + \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \Rightarrow \mathbf{y} = \mathbf{H}\mathbf{c} + \mathbf{v} \qquad (11)$$

where $v_1$ and $v_2$ are AGWN noise, and $y_1$ and $y_2$ are the output of the matched and whitening filter. So the MLD can be performed symbol-by-symbol independently.

Let's assume that each of the symbols is QPSK, hence the real and imaginary part can only have the value of 1 or -1. The log-likelihood ratio for data bit $b_1$ can be computed as:

$$\begin{aligned} \lambda_{b_1} &= \log \frac{p\left(c_1^R = 1 \mid \mathbf{y}\right)}{p\left(c_1^R = -1 \mid \mathbf{y}\right)} = \log \frac{p\left(\mathbf{y} \mid c_1^R = 1\right) p(c_1^R = 1)}{p\left(\mathbf{y} \mid c_1^R = -1\right) p(c_1^R = -1)} \\ &= \log \frac{p\left(\mathbf{y} \mid c_1^R = 1, c_1^I = 1\right) + p\left(\mathbf{y} \mid c_1^R = 1, c_1^I = -1\right)}{p\left(\mathbf{y} \mid c_1^R = -1, c_1^I = 1\right) + p\left(\mathbf{y} \mid c_1^R = -1, c_1^I = -1\right)} \end{aligned} \qquad (12)$$

if we assume an equal *a priori* probability for bits $c_1^R = 1$, and $c_1^R = -1$. Likewise the soft decision metric for the second bit can be computed accordingly.

## III. Simulation Results

In this section, we present our performance evaluation results of the four transmit diversity schemes. We consider a MIMO system with four transmit and two receive antennas. For error control coding, we employ the turbo codes from the Universal Mobile Telecommunications System (UMTS) standard with feedforward polynomial $1+D+D^3$, and feedback polynomial $1+D^2+D^3$. Information code block length (or frame length) is 594 bits for the rate-1/2 code and 1056 bits for the rate-8/9 code. For decoding, Max-Log-Map with 8 iterations is implemented. We use the TU6 channel and assume that the channel is spatially-uncorrelated and perfectly known at the receiver. The cyclic delay values are [0 64 128 192] respectively for each of the transmit antennas for CSD schemes. There are 512 subcarriers per OFDM symbol. We will compare the following four transmit diversity schemes, all for four transmit antennas:

- CSD
- Alamouti + CSD
- QO-STBC
- MDC-QOSTBC

For MIMO decoding, LMMSE receiver is used with QOSTBC while MLD for the rest of the schemes. We will compare their performance in terms of frame error rate (FER). Usually, FER of $10^{-1}$ is a typical target of practical communication systems.

The simulations results with QPSK modulation are shown in Figure 8 for rate-8/9 and Figure 9 for rate/1/2 turbo code, respectively.

In Figure 8, which is a high code rate case, we observe that:

- MDC-QOSTBC with MLD performs the best.
- Alamouti+CSD performs similar to QO-STBC with LMMSE.
- CSD has the worst performance, and is about 2 dB away from the rest of the schemes.
- All the schemes have similar FER slope, i.e. they achieve similar diversity order.

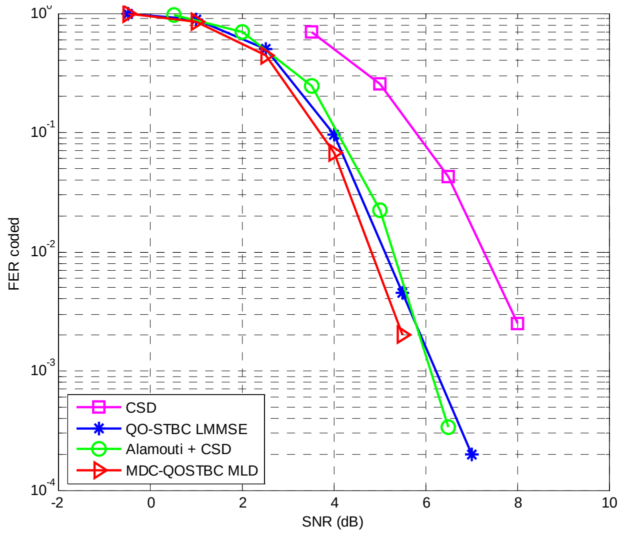


Figure 8 Simulated FER for 4tx-2rx, QPSK with turbo code rate-8/9.

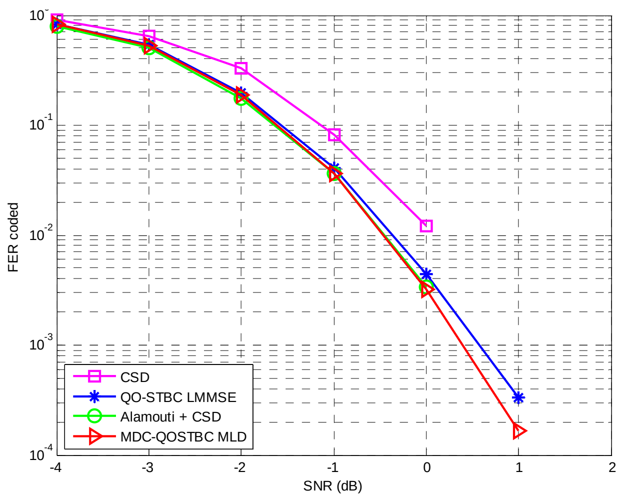


Figure 9 Simulated FER for 4tx-2rx, QPSK with turbo code rate-1/2.

In Figure 9, where a ½ rate code is used, we observe that:

- MDC-QOSTBC and Alamouti+CSD performs the best.
- QO-STBC with LMMSE is slightly worst than MDC-QOSTBC or Alamouti+CSD.
- CSD again has the worst performance, but the gap between CSD and the rest of the schemes is reduced to about 0.5dB (at FER $10^{-1}$ or below).
- Same as high code rate case, all the schemes have similar FER slope, i.e. they achieve similar diversity order.

By comparing the high code rate results in Figure 8 with the low code rate results in Figure 9, we can see that the gap between CSD and the other schemes is larger when the code rate is high. This is because CSD mainly obtains the diversity from the channel coding, hence when the code rate is high (e.g. for the data channel), CSD will perform poorly. However, due to the high diversity obtained for all the scheme (the diversity is collected from spatial and frequency domain), all the schemes have a similar slope.

In addition, it can be seen that in all cases, MDC-QOSTBC performs the best, espeically when the code rate is high. This is mainly because MDC-QOSTBC obtains most of the transmit diversity from its code structure instead of from the channel coding. MDC-QOSTBC with MLD has a better performance than QO-STBC with LMMSE. The low search space feature of MDC-QOSTBC makes MLD possible, and this is the advantage over QO-STBC. Though it is not shown in the figure, MDC-QOSTBC has the same performance as QO-STBC when LMMSE is used [13].

To summarize, in terms of performance, Alamouti+CSD and MDC-QOSTBC are the two best schemes. And MDC-QOSTBC performs the best in all sorts of conditions that we have studied. In the next section, we will discuss additional features of MDC-QOSTBC, and compare it with other CSD-based schemes for their deployment in practicalsystems.

## IV. Additional Features

We will show that MDC-QOSTBC consists of many other schemes as part of its codewords, such as:

- a rate-2 transmit diversity-2 code for four transmit antennas *Double Space Time Transmit Diversity* (DSTTD) [14]

$$\text{DSTTD:} \quad \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ -x_2^* & x_1^* & -x_4^* & x_3^* \end{bmatrix} \tag{13}$$

- a rate-4 *Spatial Multiplexing* (SM) for four transmit antennas [1]

$$\text{SM:} \quad \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \end{bmatrix} \tag{14}$$

- a rate-2 full transmit diversity code for two transmit antennas *crossed-interleaved transmit diversity* (XTD) [15]

$$\text{XTD:} \quad \begin{bmatrix} c_1^R + jc_3^R & -c_2^I + jc_4^I \\ -c_2^R + jc_4^R & -c_1^I - jc_3^I \end{bmatrix} \tag{15}$$

By rewriting the codeword of MDC-QOSTBC in (5) into (16), one can easily notice that all the above schemes together with Alamouti STBC, can be treated as part of the codeword of MDC-QOSTBC:

$$\mathbf{C} = \begin{bmatrix} c_1^R + jc_3^R & c_2^R + jc_4^R & -c_1^I + jc_3^I & -c_2^I + jc_4^I \\ -c_2^R + jc_4^R & c_1^R - jc_3^R & c_2^I + jc_4^I & -c_1^I - jc_3^I \\ -c_1^I + jc_3^I & -c_2^I + jc_4^I & c_1^R + jc_3^R & c_2^R + jc_4^R \\ c_2^I + jc_4^I & -c_1^I - jc_3^I & -c_2^R + jc_4^R & c_1^R - jc_3^R \end{bmatrix} = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ -x_2^* & x_1^* & -x_4^* & x_3^* \\ x_3 & x_4 & x_1 & x_2 \\ -x_4^* & x_3^* & -x_2^* & x_1^* \end{bmatrix} \quad (16)$$

XTD, Alamouti, SM, D-STTD

This feature can be useful in hybrid automatic retransmission request (HARQ) [14] and may lead to simplified receiver design. First of all, in order to achieve maximum throughput, the system can use SM scheme by transmitting the first row of **C**. It the transmission is successful, it leads to a rate-4 throughput. If such transmission is detected in error, the 2nd row of **C** can be transmitted, and the receiver can then combine this received signal with the one received previously and decode them as DSTTD code. By doing so, a rate-2 transmission with transmit diversity of order two can be achieved. If such transmission still has error, the 3rd and 4th row of C can be transmitted, and this is equivalent to transmitting the rate-1 MDC-QOSTBC, and the receiver can then combine all the received signals, and perform a ML decoding. This results in a transmission scheme with transmit diversity of order four, i.e. the maximum spatial transmit diversity that can be achieved. Hence such HARQ scheme has the ability to increase the transmit diversity by lowering the transmission rate, and at the same time, makes full use of the previous transmission rather than discarding them.

Since in many systems, the mandatory transmit antennas is at least two, so it would be nice to have schemes that can be matched to either two or four transmit antennas. It can be noticed that both Alamouti and XTD is a special case for MDC-QOSTBC. By transmitting the first two column of MDC-QOSTBC, it forms a rate-1 Alamouti STBC; by transmitting the first and last column of MDC-QOSTBC, it forms a rate-2 XTD. This suggests possible simplification in the receiver design, as a single form of structure can be used for different setups. In addition, it also posts an interesting direction for antenna selection. For example, either selecting the first two columns or the last two columns, both combinations form an Alamouti STBC. Likewise selecting the middle two columns has the same XTD structure as selecting the first and last columns. We will leave the topic of antenna selection for future study.

By properly designing the reference signaling, CSD and Alamouti+CSD can appear to be transparent to the receiver, i.e. the receiver sees a single stream or two-antenna Alamouti transmission without knowing existence of CSD. Unfortunately, such feature is not available for MDC-QOSTBC.

A summary on the comparisons of CSD, Alamouti+CSD and MDC-QOSTBC is shown in TABLE II. Apparently, each scheme has its own advantages and disadvantages. However, Alamouti+CSD and MDC-QOSTBC appear to be strong competitors, while CSD's performance makes it too weak to be accepted.

TABLE II
COMPARISON BTW DIFFERENT TRANSMIT DIVERSITY SCHEMES

| | CSD | Alamouti + CSD | MDC-QOSTBC |
|---|---|---|---|
| Decoding performance | X | √ | √ |
| Transparent to the receiver (depending on the ref. signal) | √ | √ | X |
| Not sensitive to code rates and channel multipath condition | X | X | √ |
| Others: • Part of the HARQ scheme as described in [14]. • Include other STBC, e.g. XTD as a special case. | X | X | √ |

## V. CONCLUSION

We studied four different transmit diversity schemes for a coded OFDM MIMO system with four transmit antennas, they are CSD, Alamouti+CSD, QO-STBC and MDC-QOSTBC. We first presented their transmitter structure and discussed their decoding complexity. We showed that in a coded OFDM system, a transmit diversity scheme with only spatial transmit diversity of order two can perform as well as a scheme with spatial transmit diversity of order four. This is due to the additional diversity provided by the channel coding. Hence when the channel coding is strong (for example for the case of control channel), Alamouti code with CSD seems to be the best candidate; while when the channel coding is weak (for example for the case of data channel), MDC-QSTBC seems to be the best candidate. In addition, CSD scheme has the advantage of being transparent to the receiver by properly design the reference signal (i.e. pilot), and MDC-QOSTBC has the advantage of being part of an interesting hybrid ARQ.

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