Improved High-rate Space-Time-Frequency Block Codes

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***Abstract*— High-rate space-time-frequency block codes (STFBC) are promising for achieving high bandwidth efficiency, low overhead and latency. Recently, a class of low-complexity STFBC methods based on two stages of complex diversity coding (CDC) have been proposed, known as double linear dispersion STFC(DLD-STFC). This paper investigates two issues related to the performance improvement of high-rate STFCs. First, it is shown that the two CDC stages of DLD-STFC can be interchanged. Two new diversity concepts for analysis of 3-dimensional DLD-STFC are introduced: per dimension diversity order and per dimension symbol-wise diversity order. A sufficient condition for DLD-STFC to achieve full symbol-wise diversity order is provided despite the existence of two CDC stages. Second, the gain obtainable in combining CDC with forward error correction (FEC) for STFC designs is quantified. Through simulations, it is shown that STFC based on the proper combination of CDC and FEC may outperform a variety of other STFC combinations, especially in spatially correlated channels. Further, the choice of the mapping from FEC to DLD-STFC may significantly impact system performance.**

I. Introduction

Space-time coding (STC) is employed to achieve space and time diversity gains in multiple input multiple output antenna (MIMO) flat-fading channels [1], [2]. However, in frequency-selective channels, STC cannot exploit available frequency dimension diversity in MIMO orthogonal frequency division multiplexing (OFDM) systems. Coding over space, time, and frequency, STFC, is therefore needed to exploit all available diversity across three physical dimensions.

Basically, there are two categories of coding approaches which can exploit diversity. Complex coding may be utilized to exploit diversity over physical dimensions, which we refer to as complex diversity coding (CDC). The second category includes conventional channel coding, including block-based or convolutional forward error correction (FEC).

We are interested in high-rate STFC designs. To distinguish among different existing and newly proposed STFCs discussed in this paper, in terms of different combinations of CDC and FEC, we may categorize high-rate STFCs as follows:

1) concatenation of inner 2-dimensional (2-D) channel codes (e.g. SF FEC or ST FEC) and outer 2-D channel codes (e.g. ST FEC or TF FEC) [3],
2) 3-D channel codes,
3) concatenation of inner channel codes and outer 2-D CDC (e.g. over SF or ST) [4],
4) concatenation of inner 2-D CDC and outer 2-D CDC [5],
5) 3-D CDC [5], [6],
6) concatenation of first-inner channel codes, second-inner 2-D CDC and outer 2-D CDC,
7) concatenation of inner channel codes and outer 3-D CDC.

Previously STFCs of Categories 1, 3, 4, and 5 have been proposed. However, there have been no proposals for STFCs of Categories 2, 6, and 7 to date. Note that STFCs of Category 6 and 7 correspond to STFCs of Category 4 and 5, respectively, with added channel coding. By extending the concept of linear dispersion coding (LDC) [7], high rate STFCs, known as double linear dispersion space-time-frequency-coding (DLD-STFC) are proposed in [5], which may be classified as Category 4.

This paper investigates performance improvement of STFCs in Categories 4 and 6, referred to DLD-STFC based approaches. Two issues are discussed in this paper,

1) investigating the relation of two 2-D CDC for STFCs of Category 4,
2) investigating STFCs of Category 6.

The following notation is used: $(\cdot)^{\mathcal{T}}$ matrix transpose, $[A]_{a,b}$ denote the (a,b) entry (element) of matrix A, $[A]_{:,b}$ denote the b column of matrix A, and $C^{A\times B}$ denotes a complex matrix with dimensions $A \times B$.

II. LDC Encoding

Assume that an uncorrelated data sequence has been modulated using complex-valued source data symbols chosen from an arbitrary, e.g. r-PSK or r-QAM, constellation. A $T \times M$ LDC matrix codeword, $\mathbf{S}_{LDC}$, is transmitted from M transmit channels and occupies T channel uses and encodes Q source data symbols. Denote the LDC codeword matrix as $\mathbf{S}_{LDC} \in C^{T\times M}$, and $\mathbf{A}_q \in C^{T\times M}, \mathbf{B}_q \in C^{T\times M}, q = 1, ..., Q$ are called dispersion matrices.

Just as in [8], we consider the case of $\mathbf{A}_q = \mathbf{B}_q, q = 1, ..., Q$. We have the matrix LDC encoding equation,

$$vec(\mathbf{S}_{LDC}) = \mathbf{G}_{LDC}\mathbf{s}, \tag{1}$$

where $\mathbf{s} = [\ s_1 \ \ \cdots \ \ s_Q\ ]^{\mathcal{T}}$ is the source complex symbol vector, and

$$\mathbf{G}_{LDC} = [vec(\mathbf{A}_1), ..., vec(\mathbf{A}_Q)] \tag{2}$$

is the LDC encoding matrix.

III. MIMO-OFDM SYSTEM MODEL

A MIMO-OFDM system has N_T transmit antennas, N_R receive antennas and a block of N_C OFDM subcarriers per antenna. The channel between the m-th transmit antenna and n-th receive antenna in the k-th OFDM block experiences frequency-selective, temporally flat Rayleigh fading with channel coefficients $\mathbf{h}_{m,n}^{(k)} = \left[h_{m,n(0)}^{(k)}, ..., h_{m,n(L)}^{(k)}\right]^{\mathcal{T}}, m = 1, ..., N_T, n = 1, ..., N_R$, where $L = \max\{L_{m,n}, m = 1, ..., N_T, n = 1, ..., N_R\}$, where $L_{m,n}$ is the frequency-selective channel order of the path between the m-th transmit antenna and the n-th receive antenna.

IV. TWO STAGE COMPLEX DIVERSITY CODING OF DLD-STFC

DLD-STFC [5] is a class of two-stage STFBCs across N_T transmit antennas, N_C subcarriers, and T OFDM blocks. DLD-STFC systems are based on a layered communications structure, which is compatible to non-LDC coded MIMO-OFDM systems. An advantage of DLD-STFC is that the system may obtain 3-D diversity coding performance for source data symbols that are only encoded and decoded through 2-D coding, and the complexity advantage may be significant if non-linear decoding methods, e.g. sphere decoding, are involved. Although [6] claims to have a full diversity STFC design, the 3-D CDC based STFC design in [6] may have high computational complexity.

In this section, we investigate the relationship of the two stages 2-D CDCs of DLD-STFC. We term the originally proposed DLD-STFC as DLD-STFC Type A, which first encodes frequency-time LDC (FT-LDC) and second encodes space-time LDC (ST-LDC) [5]. By exchanging the sequence of the two stages, we propose a modified version of DLD-STFC, termed DLD-STFC Type B, as follows. The corresponding encoding procedure for the i-th STF block of size $T \times N_{F(i)} \times N_T$ within one DLD-STFC Type B block is that

1) First, the source data signals are encoded through per subcarrier ST-LDC, which are performed across space (transmit antennas) and time (OFDM blocks), enabling space and time diversity. The p-th ST matrix codeword is of size $T \times N_T$, where $p = p_{1(i)}, ..., p_{N_{F(i)}}$ are subcarrier indices.
2) Second, all the m-th space index columns of $N_{F(i)}$ ST-LDC codewords are concatenated in sequence to a vector of size $TN_{F(i)} \times 1$, which is further encoded into the m-th FT-LDC codeword of the i-th STF block. FT-LDC are performed across frequency (subcarriers) and time (OFDM blocks), enabling frequency and time diversity. The m-th FT-LDC matrix codeword is of size $T \times N_{F(i)}$. After N_T FT-LDC matrix codewords are created, the i-th STF block is created.

If all subcarriers are used for DLD-STFC and there are in total N_M STF blocks within one DLD-STFC Type B block, the frequency block size relation is $\sum_{i=1}^{N_M} N_{F(i)} = N_C$. The decoding sequence of DLD-STFC Type B is in the reverse order of the encoding procedure.

Note that it is inconvenient to analyze the diversity order of DLD-STFC in general due to the two stages involved. For further analysis, we employ Tirkkonen and Hottinen's concept of symbol-wise diversity order for 2-D codes with dimensions X and Y, $r_{sd(XY)}$ [9], [10]. We extend this concept by introducing a new term, K-symbol-wise diversity order for 2-D codes, $r_d^{(K)}$, for the case that the pair of matrix codewords contain at most K symbol differences, and $r_{d(XY)}^{(K)} = \min \left\{ \begin{array}{l} rank\left(\Phi_{q_1,...,q_K}\right), 1 \le q_i \le Q, \\ q_i \neq q_k, 1 \le \{i,k\} \le K \end{array} \right\}$, where $\mathbf{A}_q, q = 1, ..., Q$ are dispersion matrices, and $\{s_{q_1}, ..., s_{q_K}\}$ and $\{\widetilde{s_{q_1}}, ..., \widetilde{s_{q_K}}\}$ are a pair of distinct source symbol sequences with at least one symbol difference. Note that $r_{sd(XY)} = r_{d(XY)}^{(1)}$.

Further, we introduce two new concepts in 3-D coding: per dimension diversity order and per dimension symbol-wise diversity order. Symbol-wise diversity order is a subset of full diversity order. The importance of symbol-wise diversity for 2-D codes has been explained in [9], [10], and based on similar reasoning, full symbol-wise diversity for 3-D codes is also important, especially in high SNR regions.

Definition 1: A pair of 3-D coded blocks $\mathbf{M}$ *and* $\widetilde{\mathbf{M}}$ *in dimensions* X, Y, *and* Z *are of size* $N_X \times N_Y \times N_Z$. *All possible* $\mathbf{M}$ *and* $\widetilde{\mathbf{M}}$ *comprise the set* $\mathcal{M}$. *Denote* $\mathbf{M}_{(a)}^{(XZ)}$ *and* $\widetilde{\mathbf{M}_{(a)}^{(XZ)}}$ *as a pair of X-Z blocks corresponding to the a-th Y dimension of size* $N_X \times N_Z$ *within* $\mathbf{M}$ *and* $\widetilde{\mathbf{M}}$, *respectively. All possible* $\mathbf{M}_{(a)}^{(XZ)}$ *and* $\widetilde{\mathbf{M}_{(a)}^{(XZ)}}$ *comprise the set* $\mathcal{M}_{(a)}^{(XY)}$. *Denote* $\mathbf{M}_{(b)}^{(YZ)}$ *and* $\widetilde{\mathbf{M}_{(b)}^{(YZ)}}$ *as a pair of Y-Z blocks corresponding to the b-th X dimension of size* $N_Y \times N_Z$ *within* $\mathbf{M}$ *and* $\widetilde{\mathbf{M}}$, *respectively. All possible* $\mathbf{M}_{(a)}^{(XZ)}$ *and* $\widetilde{\mathbf{M}_{(a)}^{(XZ)}}$ *comprise the set* $\mathcal{M}_{(b)}^{(ZX)}$.

Denote per dimension diversity order of Y as $r_{d(Y)}$, *which is defined as*

$$r_{d(Y)} = \max\left\{r_{d(XY)}, r_{d(ZY)},\right\}, \tag{3}$$

where

$$r_{d(XY)} = \min \left\{ \begin{array}{l} rank(\mathbf{M}_{(a)}^{(XY)} - \widetilde{\mathbf{M}_{(a)}^{(XY)}}), \\ a = 1, ..., N_Z, \\ \mathbf{M}_{(a)}^{(XY)} \in \mathcal{M}_{(a)}^{(XY)}, \\ \widetilde{\mathbf{M}_{(a)}^{(XY)}} \in \widetilde{\mathcal{M}_{(a)}^{(XY)}}, \\ \mathbf{M}_{(a)}^{(XY)} \neq \widetilde{\mathbf{M}_{(a)}^{(XY)}}, \\ \widetilde{\mathbf{M}_{(a)}^{(XY)}} \text{within } \mathbf{M} \\ \mathbf{M}_{(a)}^{(XY)} \text{within } \widetilde{\mathbf{M}} \\ \mathbf{M} \in \mathcal{M}, \widetilde{\mathbf{M}} \in \mathcal{M}, \\ \mathbf{M} \neq \widetilde{\mathbf{M}} \end{array} \right\},$$

$r_{d(ZY)}$ *is defined similarly to* $r_{d(XY)}$ ■

Definition 2: For a 3-D code, the definition of the per dimension symbol-wise diversity order of Y *is the same as that of the per dimension diversity order of* Y *except that it is required that the pair of* $\mathbf{M}$ *and* $\widetilde{\mathbf{M}}$ *differs only by a single source symbol difference, which is denoted as* $\left[\mathbf{M} \neq \widetilde{\mathbf{M}}\right]_{sw}$. *Denote per dimension symbol-wise diversity order of* Y *as*

$r_{sd(Y)}$, *which is defined as*

$$r_{sd(Y)} = \max\left\{r_{sd(XY)}, r_{sd(ZY)},\right\}, \quad (4)$$

where $r_{sd(XY)}$ *and* $r_{sd(ZY)}$ *are as in Definition 1, except that* $\left[\mathbf{M} \neq \widetilde{\mathbf{M}}\right]_{sw}$ *instead of* $\left[\mathbf{M} \neq \widetilde{\mathbf{M}}\right]$. ■

The above two concepts quantify the fact that in the case of $N_X < N_Y \leq N_Z$, the dimension Y may reach full per dimension (symbol-wise) diversity order N_Y in the Y-Z plane, although Y cannot reach full per dimension (symbol-wise) diversity order in the X-Y plane.

Definition 3: A 3-D code is called a full symbol-wise diversity code if the per dimension symbol-wise diversity orders of X,Y, *and* Z *satisfy*

$$r_{sd(X)} = N_X,$$

$$r_{sd(Y)} = N_Y,$$

and

$$r_{sd(Z)} = N_Z.$$

■

Note that a full symbol-wise diversity code is achievable only if at least the two largest of N_X, N_Y, and N_Z are equal.

We can show that a properly designed DLD-STFC may achieve full symbol-wise diversity. Let the time dimension be of size T, and space and frequency dimensions be of size either N_X and N_Y, respectively, or, N_Y and N_X, respectively. Without loss of generality, say that dimension X is of size N_X, and dimension Y is of size N_Y. One STF block of size $N_X \times N_Y \times T$ is constructed through a double linear dispersion (DLD) encoding procedure such that the first LDC encoding stage constructs LDCs of size $T \times N_X$ in the X-time planes, and the second LDC encoding stage constructs LDCs of size $T \times N_Y$ in the Y-time planes.

Proposition 1: Assume that a DLD procedure is as described above. Assume that the second LDC encoding stage produces information lossless or rate-one codewords. Assume that all-zero data source elements are allowed for DLD encoding.

1) *In the case of* $N_X < N_Y = T$, *if each of the two-stage LDC encoding procedure enables full diversity in their 2-dimensions, the per dimension diversity orders of* Y *and time dimensions satisfy*

$$r_{d(Time)} = r_{d(Y)} = T = N_Y.$$

2) *Assume that the following conditions are satisfied:*
   a) *Each* Q *source data symbols are encoded into each first stage LDC codeword. The first stage LDC encoding procedure enables full symbol-wise diversity in its 2-dimensions, and the second stage LDC encoding procedure enables full* K*-symbol-wise diversity in its 2-dimensions, where* K *is the maximum number of non-zero symbols of all the* n_X*-th time dimensions after the first stage LDC encoding procedure, where* $n_X = 1, ..., N_X$.
   b) *All the encoding matrices of the second stage LDCs are the same. Denote the dispersion matrices of the second stage LDC as* $\mathbf{A}_q^{(2)}$, *where* $q = 1, ..., N_Y T$. *Denote*

$$\mathbf{J}_{(a,b)} = \left[\left[\mathbf{A}_{(a-1)T+1}^{(2)}\right]_{:,b}, ..., \left[\mathbf{A}_{aT}^{(2)}\right]_{:,b}\right], \quad (5)$$

   where $a = 1, ..., N_Y$ *and* $b = 1, ..., N_Y$. *Square matrix* $\mathbf{J}_{(a,b)}$ *is full rank, i.e. invertible, for any* $a = 1, ..., N_Y$ *and* $b = 1, ..., N_Y$.

   In the cases of both $N_X < N_Y = T$ *and* $N_X = T > N_Y$, *the STF block, constructed using DLD procedure, achieves full symbol-wise diversity order.* ■

The proof of Proposition 1 is omitted due to space limitation, and details may be found in [11]. We remark that

1) Proposition 1 provides a sufficient condition for full symbol-wise diversity. We call the condition (b) the DLD cooperation criterion (DLDCC). When failing to meeting DLDCC, full symbol-wise diversity cannot be guaranteed. Due to the support of DLDCC, the complex diversity coding design in the second LDC stage is more restrictive than that in the first LDC stage. Note that in [5], we have not considered DLDCC as a design criterion.
2) According to Proposition 1, the sequence of ST-LDC and FT-LDC stages can be inter-changed. Properly designed, both DLD-STFC Type A and DLD-STFC Type B are able to achieve full symbol-wise diversity.

V. Complex diversity coding based STFC with FEC

The fundamental differences between complex diversity coding (CDC) and FEC are that

1) CDC improves performance through obtaining better effective communication channels for source data signals while channel codes improve performance through correcting errors;
2) CDC operates in the analog domain, while FEC operates in the digital domain;
3) a system only using CDC cannot guarantee zero bit error rate (BER) even in relatively high SNR regions as the SNR gets large, while a system only using FEC may almost achieve zero BER if SNR is enough high.

We claim that that CDC and FEC are not mutually exclusive techniques. On the contrary, FEC may cooperate with complex diversity coding to achieve better performance. The practical issue is the amount of gain that can be obtained by combining CDC based STFC and FEC. Recalling our STFC classification, DLD-STFC type A (which satisfies DLDCC) with FEC belongs to Category 6.

Due to the multidimensional structure, there are many possible mappings from FEC to STFC, which might influence system performance. For low latency, Reed Solomon (RS) codes are chosen FEC. In the next section, $RS(a, b, c)$ denotes RS codes with a coded RS symbols, b information RS symbols, and c bits per symbol. As shown in Figure 1, we propose to map one $RS(a, b, c)$ codeword to N_K DLD-STFC blocks, and N_a RS symbols are mapped into each of N_G FT-LDC codewords within each DLD-STFC block, where $a = N_a N_G N_K$. We refer to the case of $N_K > 1$ as inter-CDC-STFC FEC, while we refer to the case of $N_K = 1$ as intra-CDC-STFC FEC. Performance comparison of the combination of DLD-STFC with FEC will be given in Section VI-B.

VI. Performance

Perfect channel knowledge (amplitude and phase) is assumed at the receiver but not at the transmitter. The symbol coding rates of all systems are unity. The sizes of all LDC codewords in the ST-LDC and FT-LDC stage of DLD-STFC are $T \times N_T$ and $T \times N_F$, respectively. An evenly spaced LDC subcarrier mapping for the FT-LDC of DLD-STFC is used in simulations.

The frequency selective channel has $(L+1)$ paths exhibiting an exponential power delay profile, and a channel order of $L = 3$ is chosen. Data symbols use QPSK modulation in all simulations. Denote the transmit spatial correlation coefficient for 2×2 MIMO systems by ρ. The signal-to-noise-ratio (SNR) reported in all figures is the average symbol SNR per receive antenna. The matrix channel is assumed to be constant over different integer numbers of OFDM blocks, and i.i.d. between blocks. We term this interval as the channel change interval (CCI).

A. Satisfaction of DLDCC influences the performance of DLD-STFC Type A and Type B

In the previous design of DLD-STFC Type A, FT-LDC and ST-LDC chose Eq. (31) of [7] and uniform linear dispersion codes (U-LDC) [11], respectively, as dispersion matrices, both of which support full symbol-wise diversity in 2-dimensions. Note that original U-LDC design [11] does not support DLDCC, while the square design Eq. (31) of [7] supports DLDCC. Thus the previous design [5] of DLD-STFC Type A does not satisfy DLDCC, and thus does not support full symbol-wise diversity in 3-dimensions. However, our recent results show that by permuting the indices of dispersion matrices from $\{\mathbf{A}_1, ..., \mathbf{A}_Q\}$ to $\{\mathbf{A}_{\sigma(1)}, ..., \mathbf{A}_{\sigma(Q)}\}$, where σ is a special permutation operation, a modified U-LDC is able to support DLDCC. Thus DLD-STFC Type A based on the modified U-LDC may achieve full symbol-wise diversity in 3-dimensions [11]. We conjecture that the modified DLD-STFC Type A may achieve full K-symbol-wise diversity in 3-dimensions for some $K > 1$ with performance close to full diversity performance in 3-dimensions.

Figure 2 shows the Bit Error Rate (BER) vs. SNR performance comparison between DLD-STFC Type A and DLD-STFC Type B with and without satisfaction of DLDCC. It is clear that both DLD-STFC Type A and Type B with satisfaction of DLDCC notably outperform their counterparts without satisfaction of DLDCC. Note that the sensitivity to DLDCC of DLD-STFC Type A is greater than that of DLD-STFC Type B, which might be due to the fact that the size of the frequency dimension of the codes is larger than that of the space dimension of the codes. The performance of DLD-STFC Type A with satisfaction of DLDCC is quite close to that of DLD-STFC Type A with satisfaction of DLDCC. Thus DLD-STFC Type A can achieve similar high diversity performance to DLD-STFC Type B. In the next subsection, we focus on DLD-STFC Type A with satisfaction of DLDCC.

B. Performance comparison of RS codes based STFCs

We would like to compare the performance of Categories 2 and 3. We compare five applications of $RS(8, 6, 4)$ codes to STFCs:

(1): the combination of DLD-STFC with RS codes with parameters $N_a = 2$, $N_G = 4$, and $N_K = 1$;
(2): the combination of DLD-STFC with RS codes with $N_a = 1$, $N_G = 2$, and $N_K = 4$;
(3): the combination of DLD-STFC with RS codes with $N_a = 1$, $N_G = 1$, and $N_K = 8$;
(4): the combination of linear constellation precoding (LCP) [12], [13] based space-frequency codes with RS codes over $T = 8$ OFDM blocks (Category 2);
(5): using single RS codes across space-time-frequency (Category 3).

Figures 3 and 4 show the performance comparison of FEC based STFCs. Note that LCP used in STFC (4) supports maximal diversity gain and coding gains in supported dimensions. It can observed that using the same FEC, STFCs (1), (2), and (3) significantly outperform STFCs (4) and (5) under transmit spatial correlation $\rho = 0$ and $\rho = 0.3$, respectively. Thus, STFCs of Category 6 may be the best choices in terms of BER performance. Note that the performance advantage of STFCs (1), (2), and (3) over STFCs (4) and (5) appears more significant with an increase of transmit spatial correlation. According to Figures 3 and 4, different mappings from FEC to STFC may lead to different BER performances of FEC based DLD-STFCs. Using the same block based FEC, we observe that the larger the number of STFCs that one RS codeword is across, the better the system performance of the STFCs of Category 6. Finally, inter-CDC-STFC FEC systems outperform intra-CDC-STFC FEC systems.

VII. Conclusion

This paper introduces two concepts of diversity order for 3-dimensions, per dimension diversity order and per dimension symbol-wise diversity order. These diversity concepts are used to analyze the relation of two stages of complex diversity coding of DLD-STFC. This paper shows that the two stages of DLD-STFC can be exchanged, and provides a sufficient condition to realize 3-dimensional diversity order for DLD-STFC. This results in notable performance improvement over the originally proposed DLD-STFC codes as shown in simulation results. This paper also investigates the impact of FEC on performance of DLD-STFC, and shows that the mappings from FEC to DLD-STFC need to be properly designed. Finally, this paper shows that STFC based on the combination of DLD-STFC and FEC may significantly outperform STFC based on the combination of LCP SFC and FEC. For instance, in Figure 4, for a 2×2 MIMO system, the STFC using combination of DLD-STFC and FEC with the best FEC mapping obtains a 2.6 dB gain over the STFC using the combination of LCP SFC and FEC at a BER of 10^{-3} and a transmit space channel correlation of 0.3.

This work was supported in part by Natural Sciences and Engineering Council of Canada Grant 41731 as well as in part by Communications and Information Technology Ontario.

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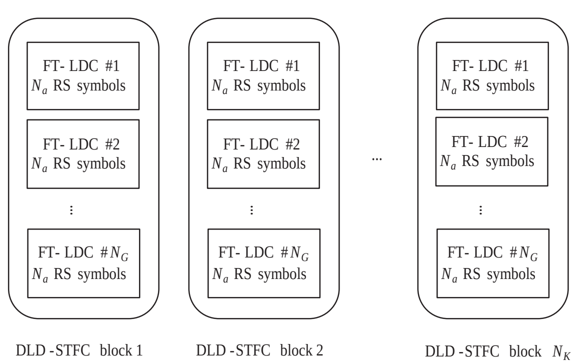

Fig. 1. FEC mapping to DLD-STFC blocks

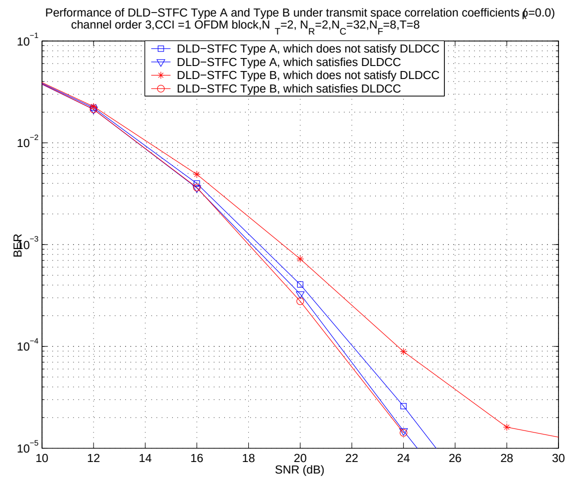

Fig. 2. BER Performance of DLD-STFC are influenced by the satisfaction of DLDCC

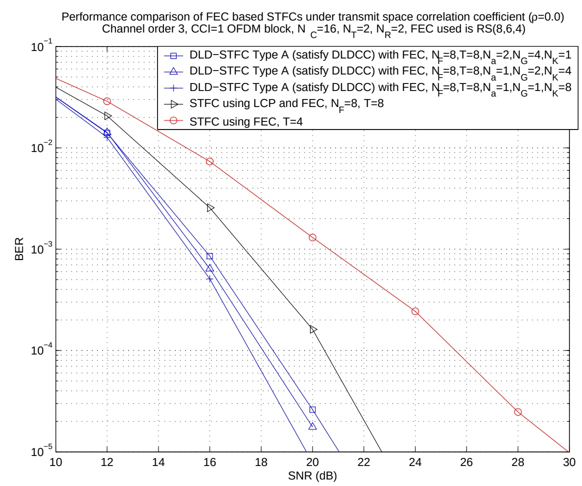

Fig. 3. BER Performance of FEC based STFCs under transmit correlation $\rho = 0$

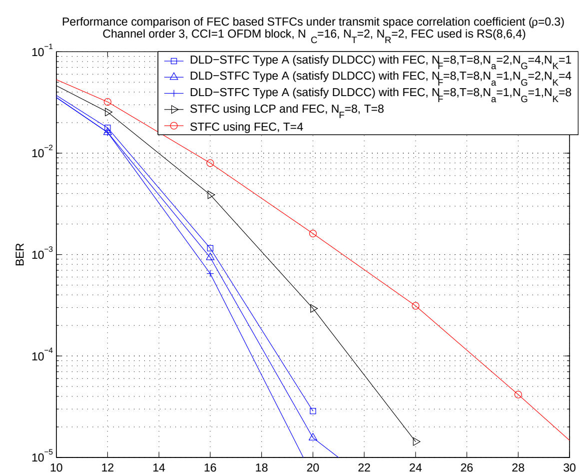

Fig. 4. BER Performance of FEC based STFCs $\rho = 0.3$