Performance Evaluation of Decoding Algorithms for Multi-Layered STBC-OFDM systems

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***Abstract*: In this paper, we study and compare the performance of several detection algorithms for high data rate OFDM based systems, such as WLANs. The proposed architecture combines transmit diversity and spatial multiplexing. The single user's data are demultiplexed into layers of information and each layer is encoded independently by a space time block coder. The output is OFDM modulated and transmitted over multiple transmit antennas. At the receiver, after OFDM demodulation, group nulling/ interference cancellation and joint maximum likelihood detection algorithms are employed to detect the transmitted symbols. The performance and tradeoff of the algorithms are compared and evaluated**.

I. INTRODUCTION

New high data rate Wireless LANs (WLANs), such as IEEE 802.11a and Hyperlan2, apply OFDM at the physical layer. This modulation is known to be robust against frequency selective channels (FSC) since it transforms the FSC into several parallel flat fading channels. The WLAN devices are usually large enough to accommodate multiple antennas both at the transmitter and the receiver. Thus, MIMO communication systems are good candidates for increasing data rates and/ or for providing space time diversity. To increase the data rates of WLANs without adding extra bandwidth, [1] proposed a VBLAST-OFDM architecture. This approach will increase the spectral efficiency by a factor of the number of transmit antennas. Also, space time coded OFDM was proposed in [2,3] to mitigate fading through transmit diversity.

Combining V-BLAST and space time block coding (STBC) results in a high data rate architecture with transmit diversity in each layer. It is referred to as multi-layered space time block coded (MLSTBC) system [7]. The idea of this scheme is to demultiplex single user's data into parallel layers of information. Then, each layer is encoded by a space time block coder (STBC). Each code is called a group, because the total number of transmit antennas are divided into groups and each group is assigned to a STBC. This architecture was first introduced in [4], where they used multi-layered space time trellis codes (MLSTTC) with serial nulling and interference cancellation algorithm over flat fading channels. Multi-user STBC system with minimum mean-squared error (MMSE) was studied in [5]. In [7], different decoding algorithms for MLSTBC were compared over flat fading channels. One advantage of using STBC over STTC is that the orthogonal structure and the short code length could be exploited at the receiver which reduces the minimum required number of receive antennas [5]. For the MLSTTC [4,6], the number of receive antennas should be at least equal to the total number of transmit antennas. However, for the MLSTBC, it is equal to the number of groups.

In this paper, we will study the MLSTBC system over frequency selective channels (FSC). To mitigate the effect of FSC, we concatenate MLSTBC with OFDM. This will transform the MIMO FSC into parallel MIMO flat fading channels. The study evaluates the performances and compares several decoders for MLSTBC-OFDM systems.

The remainder of this paper is organized as follow. The system model of MLSTBC-OFDM is briefly described in Section II. Group interference nulling and cancellation algorithms and joint detection algorithms are presented in Section III. In Section IV, the capacity of the various MLSTBC detectors is studied. Simulation results are analyzed in Section V. Finally, conclusions are drawn in Section VI.

II. MLSTBC-OFDM SYSTEM MODEL

The MLSTBC system consists of K parallel space time block encoders which are independent and synchronized. Each encoder consists of N_T antennas and is called a group. Thus, the total number of transmit antennas is $K \cdot N_T$. The receiver has M_R receive antennas. In this section, we will illustrate the system model for two groups (K=2). Extension to higher number of groups is straight forward. Each group uses Alamouti STBC [10] and transmits through two antennas (N_T=2) and the receiver has two antennas (M_R=2) as shown in Figure 1. Note that $M_R \geq K$, which reduces the required number of receive antennas by half compared to V-BLAST with the same total number of transmit antennas. The information symbols are demultiplexed into two layers, where each layer is assigned to a group. Then it is further divided into two OFDM symbols of length L, where L is the number of OFDM subcarriers. Using bold face vector notation, each OFDM symbol is denoted by an $L\times1$ column vector $\mathbf{s}_{ki} = \begin{bmatrix} s_{ki,1} & s_{ki,2} & \cdots & s_{ki,L} \end{bmatrix}^T$, where k refers to the group number and i refers to the OFDM symbol within that group. The output from each encoder over two OFDM symbol periods is the space time matrix:

$$\mathbf{C}_k = \begin{bmatrix} \mathbf{s}_{k1} & \mathbf{s}_{k2} \\ -\mathbf{s}_{k2}^* & \mathbf{s}_{k1}^* \end{bmatrix} \quad (1)$$

After that, each STBC is OFDM modulated before transmission from each antenna. Then, the output is parallel to serial converted and a cyclic prefix (CP) is added to avoid any intersymbol interference (ISI) due to the delay spread of the channel. Figure 2 shows the architecture of a single group and illustrates the STBC-OFDM modulator.

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The MIMO FSC is assumed to be constant over transmission of two OFDM symbols. The receiver is equipped with two receive antennas and the received signals over two periods of OFDM symbols for all subcarriers are:

$$\begin{bmatrix} \mathbf{Y}_1^{t_1} & \mathbf{Y}_1^{t_2} \\ \mathbf{Y}_2^{t_1} & \mathbf{Y}_2^{t_2} \end{bmatrix} = \begin{bmatrix} \mathbf{H}_{11} & \mathbf{H}_{12} & \mathbf{H}_{13} & \mathbf{H}_{14} \\ \mathbf{H}_{21} & \mathbf{H}_{22} & \mathbf{H}_{23} & \mathbf{H}_{24} \end{bmatrix} \begin{bmatrix} \mathbf{s}_{11} & -\mathbf{s}_{12}^* \\ \mathbf{s}_{12} & \mathbf{s}_{11}^* \\ \mathbf{s}_{21} & -\mathbf{s}_{22}^* \\ \mathbf{s}_{22} & \mathbf{s}_{21}^* \end{bmatrix} + \begin{bmatrix} \boldsymbol{\eta}_1^{t_1} & \boldsymbol{\eta}_1^{t_2} \\ \boldsymbol{\eta}_2^{t_1} & \boldsymbol{\eta}_2^{t_2} \end{bmatrix} \quad (2)$$

where $\mathbf{Y}_m^{t_1} = \left[y_{m,1}^{t_1} \quad y_{m,2}^{t_1} \quad \cdots \quad y_{m,L}^{t_1} \right]^T$ is the OFDM received symbol at time t_1 at antenna m. Similarly, $\boldsymbol{\eta}_m^{t_1}$ is the complex AWGN vector of all subcarriers of zero mean and variance $N_0/2$ per dimension. Furthermore, the OFDM channel matrix in the frequency domain between transmit antennas n and receive antenna m is:

$$\mathbf{H}_{mn} = \begin{bmatrix} h_{mn,1} & 0 & \cdots & 0 \\ 0 & h_{mn,2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & h_{mn,L} \end{bmatrix} \quad (3)$$

where $h_{mn,l}$ is the complex Gaussian channel coefficient of the l^{th} subcarrier.

Since the OFDM transforms the FSC into L parallel flat fading channel as apparent in (3), the MLSTBC detection algorithms are applied on each subcarrier. The MLSTBC received signal at the l^{th} subcarrier is:

$$\begin{bmatrix} y_{1,l}^{t_1} & y_{1,l}^{t_2} \\ y_{2,l}^{t_1} & y_{2,l}^{t_2} \end{bmatrix} = \begin{bmatrix} h_{11,l} & h_{12,l} & h_{13,l} & h_{14,l} \\ h_{21,l} & h_{22,l} & h_{23,l} & h_{24,l} \end{bmatrix} \begin{bmatrix} s_{11,l} & -s_{12,l}^* \\ s_{12,l} & s_{11,l}^* \\ s_{21,l} & -s_{22,l}^* \\ s_{22,l} & s_{21,l}^* \end{bmatrix} + \begin{bmatrix} \eta_1^{t_1} & \eta_1^{t_2} \\ \eta_2^{t_1} & \eta_2^{t_2} \end{bmatrix} \quad (4)$$

By exploiting the structure of the STBC, the received signals over two time periods can be rearranged into one vector as:

$$\begin{bmatrix} y_{1,l}^{t_1} \\ y_{2,l}^{t_1} \\ y_{1,l}^{t_2 *} \\ y_{2,l}^{t_2 *} \end{bmatrix} = \begin{bmatrix} h_{11,l} & h_{12,l} & h_{13,l} & h_{14,l} \\ h_{21,l} & h_{22,l} & h_{23,l} & h_{24,l} \\ h_{12,l}^* & -h_{11,l}^* & h_{14,l}^* & -h_{13,l}^* \\ h_{22,l}^* & -h_{21,l}^* & h_{24,l}^* & -h_{23,l}^* \end{bmatrix} \cdot \begin{bmatrix} s_{11,l} \\ s_{12,l} \\ s_{21,l} \\ s_{22,l} \end{bmatrix} + \begin{bmatrix} \eta_{1,l}^{t_1} \\ \eta_{2,l}^{t_1} \\ \eta_{1,l}^{t_2 *} \\ \eta_{2,l}^{t_2 *} \end{bmatrix} \quad (5)$$

$$\begin{aligned} \mathbf{y}_l &= \left[H_{1,l} \quad H_{2,l} \right] \mathbf{s}_l + \boldsymbol{\eta}_l \\ \mathbf{y}_l &= \mathbf{H}_l \mathbf{s}_l + \boldsymbol{\eta}_l \end{aligned} \quad (6)$$

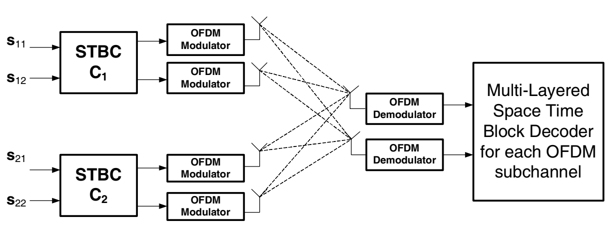

Figure 1: Block diagram of MLSTBC-OFDM.

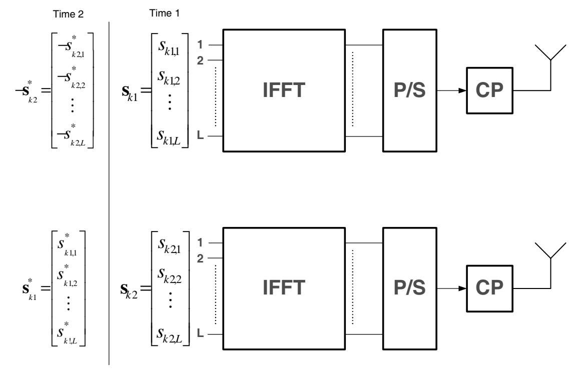

Figure 2: Architecture of a single STBC-OFDM transmitter.

III. MLSTBC Detection Algorithms

Different MLSTBC decoding algorithms [7], which are based on multi-user detection, are applied to each subchannel to detect each layer at the l^{th} subcarrier. They are classified under two categories: group interference nulling/ cancellation (GINC) and maximum likelihood (ML) joint detection.

To briefly illustrate the group interference nulling, assume that we want to null out the first group in (6) and detect the second group, the orthonormal bases $(\boldsymbol{\Theta}_{1,l})$ of the null space of the first group is found then the received vector is projected into this null space by:

$$\tilde{\mathbf{y}}_{2,l} = \boldsymbol{\Theta}_{1,l} \mathbf{y}_l = \tilde{H}_{2,l} \mathbf{s}_{2,l} + \tilde{\boldsymbol{\eta}}_{2,l} \quad (7)$$

This nulling operation is a major source of receive diversity reduction. Then, $\tilde{y}_{2,l}$ is passed to the STBC detector. After that, the contribution of the detected layer is subtracted from the received signal, i.e.,

$$\tilde{\mathbf{y}}_l = \mathbf{y}_l - H_{2,l} \tilde{\mathbf{s}}_{2,l} \quad (8)$$

GINC processing can be applied either serially or in parallel. The serial GINC (SGINC) decodes the strongest layer after nulling all other layers and then the contribution of it is canceled from the received signal and the serial nulling and cancellation is repeated for all other layers. Error propagation and unequal diversity advantages for each group are two disadvantages of SGINC that severely affect its performance [4,7]. The parallel GINC (PGINC) algorithm consists of two stages: parallel nulling followed by parallel interference cancellation and detection of all layers. Since the algorithm does not null out layers in the second stage, it has the potential to achieve full receive diversity for each layer. However, both these GINC algorithms suffer from error propagation. The complexity of these algorithms is $O(K^3)$.

As a ML joint detection algorithm, sphere decoding (SD) [8][9] is applied to MLSTBC to jointly decode the individual layers. The received vector per subcarrier in (6) is passed to the SD. This decoder doesn't suffer from error propagation and provides full receive diversity for all layers. Therefore, the joint detection schemes outperforms the GINC algorithms at a moderate complexity. At high SNR, its average complexity is cubic per layer which is comparable to GINC complexity.

However, at low SNRs, its complexity is O(K^5) [9] and the worst case complexity is exponential.

The transmit diversity advantage of the MLSTBC is the same as the transmit diversity of each STBC, assuming that the MLSTBC uses similar codes. Also, its rate will increase by a factor of K. On the other hand, the receive diversity advantage will depend on the applied decoding algorithm.

IV. Capacity Of MLSTBC System

Group interference nulling and cancellation (GINC) algorithms detect each group separately after nulling interfering groups and canceling previously detected groups. Thus, the received signal vector before detecting the k^{th} group is

$$\mathbf{y}_k = \tilde{\mathbf{H}}_k \mathbf{s}_k + \tilde{\boldsymbol{\eta}}_k \quad (9)$$

where $\tilde{\mathbf{H}}_k$ is the effective channel matrix after nulling.

Since the MLSTBC system is a single user system and assuming equal rate transmission from each layer, an outage will occur if an outage happens in the weakest layer. Therefore, the total capacity will be dominated by the minimum. Thus, the instantaneous capacity of the MLSTBC system is:

$$C_{MLSTBC}^{GNIC} = K \cdot \min_{i=1,2,\ldots,K} \left\{ r_c \log_2 \left(1 + \frac{\rho}{K \cdot N_T} \left\| \tilde{\mathbf{H}}_k \right\|_F^2 \right) \right\} \quad (10)$$

where r_c is the STBC rate, N_T is the number of transmit antennas per group, ρ is the SNR per receive antenna and $\|(\cdot)\|_F^2$ is the squared Frobenius norm (FN).

The joint detector operates on all received signals. Thus, its capacity is:

$$C_{MLSTBC}^{Joint} = \frac{1}{T} \log \left(\det \left[\mathbf{I}_{K \cdot N_T} + \frac{\rho}{K \cdot N_T} \mathbf{H}^H \mathbf{H} \right] \right) \quad (11)$$

where T is the STBC length, which is two for Alamouti code.

In Figure 3, the capacity Complementary CDFs of joint detection and GINC algorithms are estimated via simulation based on (10) and (11). We fixed M_R at eight and N_T per group at two and change K from one to eight. The SNR is fixed at 10dB. This study shows the effect of increasing number of layers while fixing number of receive antennas. Intuition says that the capacity should increase with increasing number of layers and that is true only with joint detection and with PGINC with perfect cancellation, as shown in Figure 3.(a) and (e), respectively. That is due to the fact that these two algorithms provide full receive diversity per layer. On the other hand, after a certain increase in K, we observe a capacity backoff for SGINC and PGINC just after nulling, as shown in Figure 3.(b) and (d), respectively. That is due to the diversity reduction caused by nulling. To explain this, we observe from (10) that the capacity is dominated by the Frobenius norm (FN) of the minimum layer. The weakest layer is usually the first detected layer since it has the lowest receive diversity. For example, the first detected layer when K=4 has a diversity order of 2×5 because the SGINC algorithm uses three antennas to null out three layers and the rest will provide diversity for the first detected layer. At K=8, the algorithm uses seven antennas to null out the seven interfering layers and one antenna is left for the detection of the first layer. Thus, it has a diversity order of 2x1. So initially, the capacity increases with increasing K while the diversity order is high. Then, after a certain point, the reduction in receive diversity will dominate the capacity and a backoff is observed. Also, we observed that this turnover point is highly dependent on the SNR. When the SNR is 10dB, the backoff started after four layers and when SNR=30dB, the turning point is after seven layers.

Furthermore, we showed the effect of ordering on the capacity of SGINC algorithm in Figure 3.(c). We compared between two ordering methods. The first is to order based on the FN of the effective channel matrix after nulling as in (9) and the second is to order based on the FN of the received channel matrix for each layer. The first one performs better but it is more complex, since the algorithm needs to do nulling operation to figure out the best order.

The comparison between the CCDF of the MLSTBC detection algorithms is shown in Figure 3.(f). The joint detection outperforms the GINC and the parallel capacity after cancellation is better than the serial. This difference in performance increases with increasing K.

V. Simulation Results

In this section, the frame error rate (FER) performance of the detection algorithms is evaluated and compared via simulation. We assumed space and time independent frequency selective MIMO channels and that the flat fading coefficients in the frequency domain in (5) are independent. Perfect channel state information is assumed. Also, each layer uses Alamouti full rate code with QPSK modulation. Thus, the rate of each layer is 2bps/Hz and each layer transmits through two antennas and has a transmit diversity of order two. We consider transmission of 4 bps/Hz and 8bps/Hz efficiencies.

Figure 4 and Figure 5 shows the performance of two layered STBC-OFDM (K=2, 4 bps/Hz) at M_R=2 and 4, respectively. The number of receive antennas in Figure 4 is the minimum number required and it is equal to K. The performance of parallel, serial GINC algorithm and SD is shown in these figures. In Figure 4, we depict that the serial and parallel GINC algorithms provide the same diversity since they have the same slope. For SGINC, although each layer has different diversity order, the system performance is dominated by the weakest layer which is usually the first detected layer, as interrupted from (10). Similarly, the PGINC performance is dominated by the weakest layer after parallel nulling stage. Furthermore, ordering for the SGINC provides some gain but doesn't increase the diversity. This gain increase is due to detecting the strongest layer first which has higher FN and that improves the performance of the first layer. For PGINC, the parallel cancellation should theoretically provide full receive diversity and that requires prefect cancellation. However, due to error propagation, this is not visible without using strong outer codes but still parallel cancellation gives a large gain compared to the performance just after parallel nulling. In Figure 4, the gain is around 3dB. The diversity advantage of the GINC algorithm is dominated by the first detected layer which has a diversity order of 2×1. On the other hand, joint detection, using the sphere decoder, provides full receive diversity and doesn't suffer from error propagation. Thus, it performs the best with average cubic complexity per layer at high SNRs. Furthermore, Figure 5 shows the effect of adding more receive antennas on the performance of the detectors. The result shows that the different detection algorithms perform very close to each other at low number of layers and at additional receive diversity. That is because the weakest layer in the GINC algorithms will have a diversity order of 2×3.

The simulation results at four layers (K=4, 8bps/Hz) are shown in Figure 6 and Figure 7. These figures show the performance of the detection algorithms at moderate number of layers. In Figure 6, at M_R=4, the performance of the SGINC with best ordering outperforms the PGINC performance after cancellation by around 2dB. That is because ordering insures that the best layer is detected first which will dominate the performance while the parallel algorithm's performance is dominated by the weakest layer after parallel nulling. Also, in this figure, we show the performance of a hybrid scheme (Serial+Parallel). In this scheme, the SGINC is followed by a parallel cancellation. By doing this, we gained a small improvement but still the diversity order is the same for all GINC algorithms. Furthermore, the performance of the parallel algorithm with perfect cancellation is plotted as a lower bound on the performance and the joint detector achieves this bound. In Figure 7, the performance of the MLSTBC detectors closes up within 1dB when M_R=8. This is because the weakest layer in the GINC algorithm has a diversity order of 2×5, since it needs 3 antennas to null out three layers and the rest are used to detect the first layer.

To sum up the simulation results, the diversity of GINC algorithms is dominated by the weakest layer which has a diversity order of 2×(M_R-K+1). The SGINC with FN ordering after nulling performs better than the parallel because ordering insures that the strongest layer is detected first. Furthermore, the SD algorithm provides each layer with a diversity order of 2×M_R and it performs the best. Also, when extra receive antennas are added at the receiver, the diversity order of the weakest layer increases and all algorithms perform close to each other.

VI. CONCLUSION

In this paper, we have evaluated the performance of multi-layered detection algorithms for multi-layered space time block coded systems over frequency selective MIMO channels. The OFDM modulator transforms the frequency selective MIMO channel into parallel flat fading channels in the frequency domain. The effect of increasing number of layers while fixing number of receive antennas on the MLSTBC capacity was studied. We found that the GINC algorithms experience a capacity backoff due to the nulling operation. Furthermore, the FER performance of the MLSTBC-OFDM scheme was evaluated and compared among the different detection algorithms. The results show that the serial GINC with best ordering outperforms the parallel. The joint detector using the sphere decoder outperforms the GINC since it doesn't suffer from error propagation and provides full receive diversity.

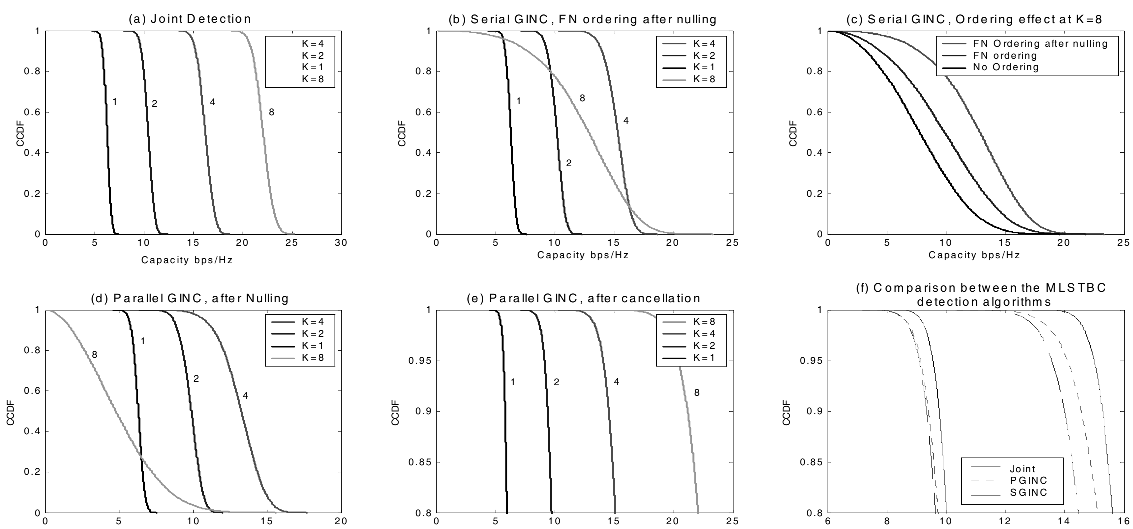

Figure 3: Capacity CCDF of MLSTBC detection algorithms.

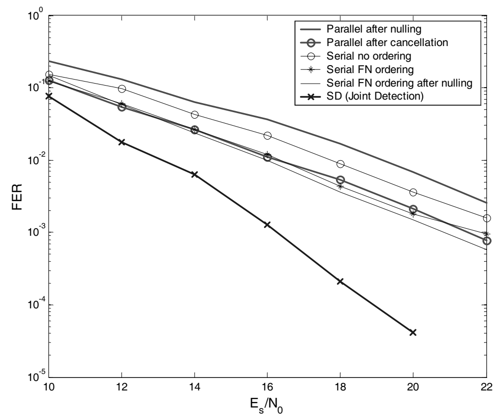

Figure 4: MLSTBC-OFDM at 4bps/Hz, K=2, M_R=2 and N_T=2 antennas per group

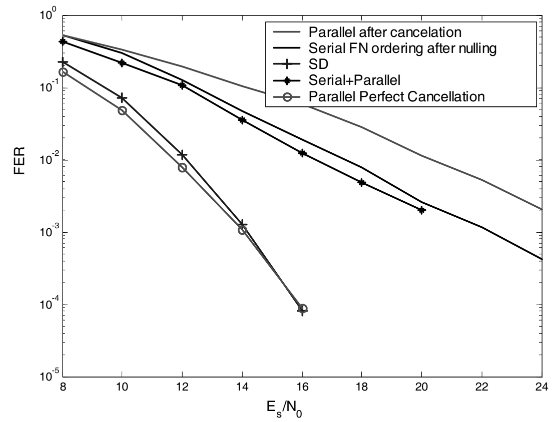

Figure 6: MLSTBC-OFDM at 8bps/Hz, K=4, M_R=4 and N_T=2 antennas per group

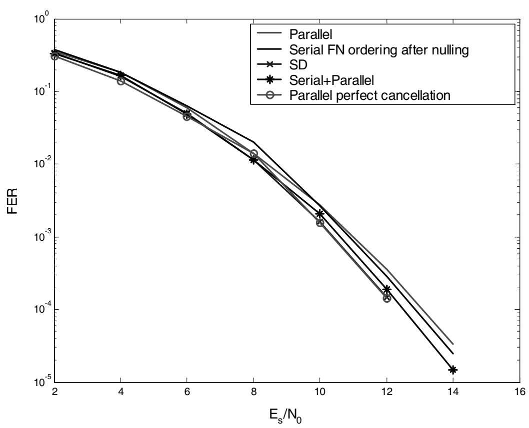

Figure 5: MLSTBC-OFDM at 4bps/Hz, K=2, M_R=4 and N_T=2 antennas per group

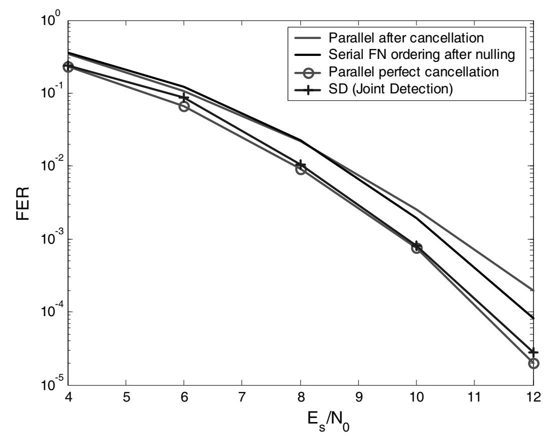

Figure 7: MLSTBC-OFDM at 8bps/Hz. K=4, M_R=8 and N_T=2 antennas per group

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