NOVEL LINEAR AND NON-LINEAR MULTI-USER MIMO DOWNLINK PRECODING WITH IMPROVED DIVERSITY AND CAPACITY

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ABSTRACT

Space division multiple access (SDMA) promises high gains in the system throughput of wireless multiple antenna systems. If SDMA is used on the downlink of a multi-user multiple-input multiple-output (MIMO) system, either long-term or short-term channel state information has to be available at the base station (BS) to facilitate the joint precoding of the signals intended for the different users. Precoding is used to efficiently eliminate or suppress multi-user interference (MUI). It also allows us to perform most of the complex processing at the BS which leads to a simplification of the mobile terminals. In this paper we introduce two novel precoding techniques (a linear and a non-linear one) that improve the system capacity and the diversity order. The new non-linear precoding technique combines successive minimum-mean-squared error (SMMSE) and Tomlinson-Harashima precoding (THP) to provide a higher capacity and diversity. But it is very sensitive to channel estimation errors. The new linear precoding technique is called regularized block diagonalization (RBD). Although it has a smaller capacity than SMMES THP it achieves a higher diversity order than SMMSE THP. At high data rates it can extract the maximum diversity order of the channel. RBD is less sensitive to channel estimation errors than non-linear techniques and can be also used for precoding with long-term channel state information.

***Index Terms* - MIMO precoding, Tomlinson-Harashima precoding, MMSE precoding.**

1. INTRODUCTION

Multiple-input, multiple-output (MIMO) systems are the key component of the future wireless communication systems, because of their promising improvement in terms of performance and bandwidth efficiency [1], [2], [3], [4], [5]. Multi-user (MU) MIMO systems are especially important since they have the potential to combine the high throughput achievable with MIMO processing with the benefits of space division multiple access (SDMA). In the downlink scenario, a base station (BS) is equipped with multiple antennas and it is simultaneously transmitting to a group of users. Each of these users is also equipped with multiple antennas. In this case, the base station has the ability to coordinate the transmission from all of its antennas. The receiving antennas are associated with different users that are typically unable to coordinate with each other. The BS exploits the channel state information (CSI) available at the transmitter to allow these users to share the same channel and mitigate or ideally completely eliminate multi-user interference (MUI) by linear or non-linear precoding. It is essential to have CSI at the base station since it allows joint processing of all users' signals which results in a significant performance improvement and increased data rates.

The information theoretic results on the sum capacity of the multi-user MIMO downlink system have shown that some kind of Costa or Tomlinson-Harashima precoding (THP) is necessary to attain it, [3], [6], [7], [8], [9]. DPC can achieve the maximum sum rate of the system and provide the maximum diversity order. However, these techniques require the use of a complex sphere-decoder or an approximate closest-point solution, which makes them hard to implement in practice. A simple but practical technique that eliminates a part of the MUI and improves the system diversity is THP. THP is a non-linear precoding technique originally developed for single-input single-output (SISO) multipath channels. THP can be interpreted as moving the feedback part of the decision-feedback equalization (DFE) to the transmitter. It is also applied for the pre-equalization of MUI in MIMO systems [10], where it performs spatial pre-equalization instead of temporal pre-equalization for ISI channels.

All precoding techniques can be classified by the amount of the MUI they allow (as zero or non-zero MUI techniques) and their linearity (as linear and non-linear techniques). Linear precoding techniques require no overhead to provide the mobile the demodulation information, they are less computationally expensive and less sensitive to the channel estimation errors at the transmitter than thir non-linear counterparts.

Block diagonalization (BD) is a linear pre-coding technique for the downlink of MU MIMO systems [11]. It decomposes a MU MIMO downlink channel into multiple parallel independent single-user MIMO downlink channels. The signal of each user is pre-processed at the transmitter using a modulation matrix that lies in the null space of all other users' channel matrices. Thereby, the MUI in the system is efficiently set to zero. BD can be used with any other previously defined single-user MIMO technique [12], as the different users do not interfere with each other. BD is attractive if the users are equipped with more than one antenna. However, the zero MUI constraint can lead to a significant capacity loss when the users' subspaces significantly overlap. Another technique also proposed in [11], named successive optimization (SO), addresses the power minimization and the near-far problem and it can yield better results in some situations but its performance depends on the power allocation and the order in which the users' signals are preprocessed. The zero MUI constraint is relaxed and a certain amount of interference is allowed.

Minimum mean-square-error (MMSE) precoding in combination with THP is proposed in [13]. MMSE balances the MUI in order to improve the performance with respect ot zero frocing tecniques while the THP is used to eliminate a part of the MUI and improves the diversity. However, for two closely spaced antennas, as in the case when the user is equipped with multiple antennas, the inter-stream interference mitigation still causes some performance degradation.

SO THP proposed in [14] combines SO and THP in order to reduce the capacity degradation due to the cancellation of overlapping subspaces of different users and to eliminate the MUI. After the precoding, the resulting equivalent combined channel matrix of all users is again block diagonal. This also facilitates the definition of a new ordering algorithm. Unlike in [6] and [13], this technique allows more than one antenna at the mobile terminals and has no performance degradation due to the cancellation of interference between the signals transmitted to two closely spaced antennas at the same terminal.

In this paper we introduce two novel MU MIMO precoding techniques. The first one combines THP and successive MMSE (SMMSE) proposed [15]. The use of THP precoding results in improved diversity and substantial capacity gains, especially at low SNRs. The second technique is a linear MU MIMO precoding technique that represents a generalization of BD and offers significant improvements over all previously proposed linear precoding techniques. With this technique we can achieve the maximum diversity order with a much lower complexity than with "dirty-paper" codes (DPC).

This paper is organized as follows. In Section 2, we describe the MU downlink channel. In Section 3, we describe the precoding techniques that will be compared and in Section 4, we present the results of the simulations. A short summary follows in the Section 5.

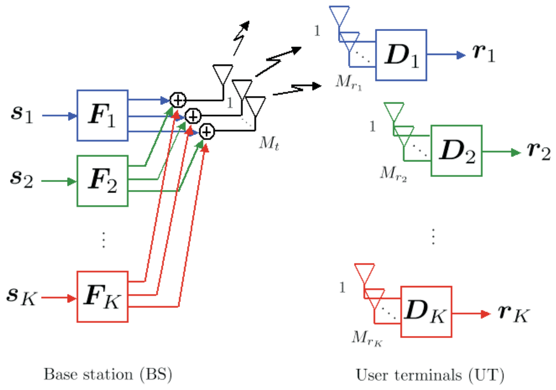

Fig. 1. Block diagram of multi-user MIMO downlink system.

2. SYSTEM MODEL

We consider a MU MIMO downlink channel, where M_T transmit antennas are located at the base station and M_{R_i} receive antennas are located at the i-th mobile station (MS), $i = 1, 2, \ldots, K$. There are K users (user terminals - UTs) in the system. The total number of receive antennas is

$$M_R = \sum_{i=1}^{K} M_{R_i}.$$

A block diagram of such a system is depicted in Fig. 1.

We will use the notation $\{M_{R_1}, \ldots, M_{R_K}\} \times M_T$ to describe the antenna configuration of the system. Let us assume a frequency selective, slow fading channel. Data transmission is performed using OFDM and MIMO processing is implemented in the frequency domain on every subcarrier. The MIMO channel to user i, on the k-th subcarrier is denoted as $\boldsymbol{H}_i^{(k)} \in \mathbb{C}^{M_{R_i} \times M_T}$. Moreover, the combined channel matrix on the k-th subcarrier is given by

$$\boldsymbol{H}^{(k)} = \begin{bmatrix} \boldsymbol{H}_1^{(k)T} & \boldsymbol{H}_2^{(k)T} & \cdots & \boldsymbol{H}_K^{(k)T} \end{bmatrix}^T.$$

3. MULTI-USER PRECODING

For the sake of simplicity we will consider processing only on one subcarrier and omit the indices of subcarriers in the following analysis.

Let us define the precoder matrices as

$$\boldsymbol{F} = \left[\begin{array}{cccc} \boldsymbol{F}_1 & \boldsymbol{F}_2 & \cdots & \boldsymbol{F}_K \end{array}\right] \in \mathbb{C}^{M_T \times r} \tag{1}$$

where $\boldsymbol{F}_i \in \mathbb{C}^{M_T \times r_i}$ is the *i*-th user's precoder matrix. Moreover, $r \leq \min(M_R, M_T)$ is the total number of the transmitted data stream sequences, whereas r_i is the number of data stream sequences transmitted to the *i*-th user. Consider the precoding technique block diagonalization (BD) that was first proposed in [11]. We can find the optimal precoding matrix $\boldsymbol{F}$ such that all MUI is zero by choosing a precoding matrix $\boldsymbol{F}_i$ that lies in the null space of the other users' channel matrices. Thereby, a MU MIMO downlink channel is decomposed into multiple parallel independent SU MIMO channels [16], [12]. However, this kind of approach results in a very poor performance if the subspaces of the users' channel matrices overlap significantly, and has a dimensionality constraint such that the total number of receive antennas has to be less or equal to the number of antennas at the BS, $M_R \leq M_T$. Our goal is to perform MIMO precoding in such a way that the loss due to the multi-user interference mitigation is minimum, to better use multiple antennas at the UTs and that there are no constraints considering the number of antennas at the UTs like in the case of MMSE THP, [13].

We write the precoding matrix in equation (1) as

$$\boldsymbol{F} = \beta \boldsymbol{F}_a \cdot \boldsymbol{F}_b, \tag{2}$$

where

$$\boldsymbol{F}_a = \left[\begin{array}{cccc} \boldsymbol{F}_{a_1} & \boldsymbol{F}_{a_2} & \cdots & \boldsymbol{F}_{a_K} \end{array}\right] \in \mathbb{C}^{M_T \times K M_T},$$

and

$$\boldsymbol{F}_b = \left[\begin{array}{cccc} \boldsymbol{F}_{b_1} & \boldsymbol{0} & \cdots & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{F}_{b_2} & \cdots & \boldsymbol{0} \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{0} & \boldsymbol{0} & \cdots & \boldsymbol{F}_{b_K} \end{array}\right] \in \mathbb{C}^{K M_T \times r},$$

with $\boldsymbol{F}_{a_i} \in \mathbb{C}^{M_T \times M_T}$ and $\boldsymbol{F}_{b_i} \in \mathbb{C}^{M_T \times r_i}$. The parameter β is chosen to set the total transmit power to P_T.

Here, we use an approach similar to the one in [16], where MU MIMO precoding is performed in two steps. In the first step we suppress the MUI using matrices $\boldsymbol{F}_{a_i}$. In case of BD, where we have a zero MUI constraint, the matrices $\boldsymbol{F}_{a_i}$ are chosen such that they lie in the null subspaces of all other users' channel matrices. Then, the matrices $\boldsymbol{F}_{b_i}$ are calculated in the second step based on the desired criterion. For example, these matrices can be obtained by a modal decomposition of the equivalent users' channels after precoding using the matrices $\boldsymbol{F}_{a_i}$ with appropriate power loading. If we want to achieve the maximum information rate we will use water pouring, and if we want to maximize the SNR at the UTs we will transmit only on users' respective dominant eigenmodes.

3.1. Successive MMSE transmit precoding THP (SMMSE THP)

MMSE precoding can improve the system performance by introducing a certain amount of interference especially for users equipped with a single antenna. However, it suffers a performance loss when it attempts to mitigate the interference between two closely spaced antennas as in the case when the user terminal is equipped with more than one receive antenna. SMMSE, proposed in [15], deals with this problem by successively calculating the columns of the precoding matrix $\boldsymbol{F}_{a_i}$ for each of the receive antennas separately. In this way it provides a higher diversity and a higher array gain. Here, the diversity is further improved by combining SMMSE and THP. Block diagram of SMMSE THP system is shown in FIgure 2.

The columns in the precoding matrix $\boldsymbol{F}_{a_i}$, each corresponding to one receive antenna, are calculated successively using SMMSE in the following way. For the *i*-th user, $i = 1, \ldots, K$, and *j*-th receive antenna $j = 1, \ldots, M_{R_i}$ we define the matrix $\bar{\boldsymbol{H}}_i^{(j)}$ as:

$$\bar{\boldsymbol{H}}_i^{(j)} = \left[\begin{array}{c} \boldsymbol{h}_{i,j}^T \\ \boldsymbol{H}_1 \\ \vdots \\ \boldsymbol{H}_{i-1} \\ \boldsymbol{H}_{i+1} \\ \vdots \\ \boldsymbol{H}_K \end{array}\right]$$

where $\boldsymbol{h}_{i,j}^T$ is the *j*-th row of the *i*-th user's channel matrix $\boldsymbol{H}_i$. The corresponding column of the precoding matrix $\boldsymbol{F}_{a_i}$ is equal to the first column of the following matrix:

$$\boldsymbol{F}_{i,j} = \left(\bar{\boldsymbol{H}}_i^{(j)\,H} \bar{\boldsymbol{H}}_i^{(j)} + \alpha \boldsymbol{I}_{M_T}\right)^{-1} \bar{\boldsymbol{H}}_i^{(j)\,H} \tag{3}$$

where $\alpha = M_R \sigma_n^2 / P_T$, P_T is the total transmit power, and σ_n^2 is the variance of a zero mean additive white Gaussian noise. The MSE corresponding to this antenna disregarding the interference from the other antennas colocated at the same UT is equal to:

$$\mathrm{mse}_{i,j} = \left[\left(\bar{\boldsymbol{H}}_i^{(j)} \bar{\boldsymbol{H}}_i^{(j)\,H} + \alpha \boldsymbol{I}_{M_R - M_{M_{R_i}} + 1}\right)^{-1}\right]_{1,1} \tag{4}$$

where the index $1,1$ denotes the matrix element and the total per antenna MSE of the i-th user is:

$$\mathrm{mse}_i = \sum_j \mathrm{mse}_{i,j} \tag{5}$$

From the SVD of $\boldsymbol{H}_i \boldsymbol{F}_{a_i} = \boldsymbol{U}_i \boldsymbol{\Sigma}_i \boldsymbol{V}_i^H$ the matrix $\boldsymbol{F}_{b_i}$ is calculated as $\boldsymbol{F}_{b_i} = \boldsymbol{V}_i \boldsymbol{\Phi}_i$, where $\boldsymbol{\Phi}_i$ is the i-th user's power loading matrix.

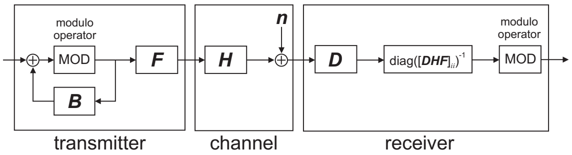

Fig. 2. Block diagram of the SMMSE THP system.

$$
\begin{aligned}
&\boldsymbol{G} = \boldsymbol{H};\\
&\text{for } i = K : 1\\
&\quad \left[\begin{array}{cccccc} \boldsymbol{P}_1, & \dots & \boldsymbol{P}_i, & \mathrm{mse}_1, & \dots & \mathrm{mse}_i \end{array}\right] = \mathrm{SMMSE}\,(\boldsymbol{G})\,;\\
&\quad k_i = \arg\min_{k\in S} \mathrm{mse}_i;\\
&\quad \boldsymbol{F}_i = \boldsymbol{P}_{k_i};\\
&\quad \boldsymbol{D}_i = \boldsymbol{F}_i^H \boldsymbol{H}_i^H \left(\boldsymbol{H}_i \boldsymbol{F}_i \boldsymbol{F}_i^H \boldsymbol{H}_i^H + \sigma_n^2 \boldsymbol{I}_{M_R}\right)^{-1};\\
&\quad \mathrm{S} = \mathrm{S}\backslash\{k_i\};\\
&\quad \boldsymbol{G} = \left[\begin{array}{cccccc} \boldsymbol{H}_1^T & \dots & \boldsymbol{H}_{k_i-1}^T & \boldsymbol{H}_{k_i+1}^T & \dots & \boldsymbol{H}_K^T \end{array}\right]^T;\\
&\text{end};\\
&\boldsymbol{F} = \left[\begin{array}{ccc} \boldsymbol{F}_1 & \dots & \boldsymbol{F}_K \end{array}\right];\\
&\boldsymbol{D} = \left[\begin{array}{ccc} \boldsymbol{D}_1 & & \\ & \ddots & \\ & & \boldsymbol{D}_K \end{array}\right];\\
&\boldsymbol{B} = \text{lower triangular}\left(\boldsymbol{DHF}\cdot \mathrm{diag}\left([\boldsymbol{DHF}]_{ii}^{-1}\right)\right);
\end{aligned}
$$

Table 1. SMMSE THP algorithm.

The combination of SMMSE and THP (SMMSE THP) is performed by successively calculating SMMSE, the reordering of users, and in the end precoding with THP. In every step we use a heuristic approach and minimize the total per antenna MSE of each user. The whole SMMSE THP algorithm is summarized in Table 1.

In Table 1, we use the following notation: SMMSE () is the SMMSE function as explained in previous section, $\boldsymbol{P}_k$ is an auxiliary matrix where we store the precoding matrices generated using SMMSE, $\mathcal{S}$ is a set of indices of the users to be processed, $\boldsymbol{D}_i$ is the i-th user's demodulation matrix and $\boldsymbol{B}$ is the THP feedback matrix. In each step we find the user with the minimum total per antenna MSE and place it as the last one. Afterwards, we form the new combined channel matrix $\boldsymbol{G}$ without this user's channel matrix $\boldsymbol{H}_{k_i}$. We repeat these steps until the combined channel matrix is empty.

3.2. Regularized Block diagonalization (RBD)

Let us define $\widetilde{\boldsymbol{H}}_i$ as

$$\widetilde{\boldsymbol{H}}_i = \left[\begin{array}{cccccc} \boldsymbol{H}_1^T & \cdots & \boldsymbol{H}_{i-1}^T & \boldsymbol{H}_{i+1}^T & \cdots & \boldsymbol{H}_K^T \end{array}\right]^T \quad (6)$$

Then we can rewrite equation (3) as:

$$\boldsymbol{F}_{i,j} = \left(\boldsymbol{h}_{i,j}^* \boldsymbol{h}_{i,j}^T + \widetilde{\boldsymbol{H}}_i^H \widetilde{\boldsymbol{H}}_i + \alpha \boldsymbol{I}_{M_T}\right)^{-1} \bar{\boldsymbol{H}}_i^{(j)\,H} \quad (7)$$

$$= \left(\widetilde{\boldsymbol{H}}_i^H \widetilde{\boldsymbol{H}}_i + \alpha \boldsymbol{I}_{M_T}\right)^{-1} \bar{\boldsymbol{F}}_{i,j} \quad (8)$$

From the previous equation we see that each column in the precoding matrix generated by SMMSE, $\boldsymbol{F}$ can be factored in two matrices where the first one does not depend on the column index. Let us define the SVD of this matrix as:

$$\left(\widetilde{\boldsymbol{H}}_i^H \widetilde{\boldsymbol{H}}_i + \alpha \boldsymbol{I}_{M_T}\right)^{-1} = \widetilde{\boldsymbol{V}}_i \left(\widetilde{\boldsymbol{\Sigma}}_i^2 + \alpha \boldsymbol{I}_{M_T}\right)^{-1} \widetilde{\boldsymbol{V}}_i^H \quad (9)$$

Next, we define the matrix $\boldsymbol{F}_{a_i}$ as:

$$\boldsymbol{F}_{a_i} = \widetilde{\boldsymbol{V}}_i \left(\widetilde{\boldsymbol{\Sigma}}_i^2 + \alpha \boldsymbol{I}_{M_T}\right)^{-1/2} \quad (10)$$

From the equation (10) we see that in this case each user transmits on the eigenmodes of the combined channel matrix of all other users with the power that is inversely proportional to the regularized eigenvalues of the combined channel matrix of all other users in the system. At high SNRs each user transmits only in the null subspace of all other users. The matrix $\boldsymbol{F}_{b_i}$ is then calculated in the same way as for SMMSE, from the SVD of $\boldsymbol{H}_i \boldsymbol{F}_{a_i}$.

4. SIMULATION RESULTS

In this section we compare the performance of systems employing RBD, SMMSE THP, BD, SO THP and TDMA. To do so, we take into account a purely stochastic channel $\boldsymbol{H}_w$ and a frequency selective MIMO channel with the power delay profile as defined by IEEE802.11n - D with non-line of sight conditions [17]. We assume data transmission using OFDM system with $N = 64$ subcarriers, subcarrier spacing of 150 kHz and cyclic prefix $N_{\mathrm{pre}} = 4$ samples long. The data is encoded using a convolutional code rate $1/2$ $(561, 753)_{\mathrm{oct}}$. After coding the data is mapped using QAM and 16 QAM modulation. Coded and modulated symbols are transmitted using $N_c = 48$ subcarriers and $N_{\mathrm{symb}} = 2$ OFDM symbols.

We also consider the antenna correlation at the BS and UTs. Antenna correlation is modeled in the delay domain using the Kronecker model. The channel of each user's l-th path component is modeled as

$$\boldsymbol{H}_i^{(l)} = \boldsymbol{R}_{r_i}^{(l)\,1/2} \boldsymbol{H}_{w_i}^{(l)} \boldsymbol{R}_{t_i}^{(l)\,1/2} \quad (11)$$

where $\boldsymbol{H}_{w_i}^{(l)}$ is a spatially white unit variance flat fading MIMO channel of dimension $M_{R_i} \times M_T$, whereas $\boldsymbol{R}_{r_i}^{(l)}$ and $\boldsymbol{R}_{t_i}^{(l)}$ are receive and transmit covariance matrices with $\mathrm{tr}\left(\boldsymbol{R}_{r_i}^{(l)}\right) = M_{R_i}$ and $\mathrm{tr}\left(\boldsymbol{R}_{t_i}^{(l)}\right) = M_T$.

For the simulations we assume a scenario where the MS is surrounded by a rich scattering environment and the BS/AP antennas are separated by less than the coherence distance. These propagation conditions correspond to a cellular communication systems typically characterized by a low angular spread at the BS/AP. On the other hand, the angular spread at the mobile is often very large and thus low spatial correlation can be achieved with relatively small antenna separation. Hence, we can write

$$\boldsymbol{R}_{r_i}^{(l)} = \boldsymbol{I}_{M_{R_i}}, \ \boldsymbol{R}_{t_i}^{(l)} = \frac{M_T}{\operatorname{tr}\left(\boldsymbol{A}^{(l)*}\boldsymbol{A}^{(l)T}\right)}\boldsymbol{A}^{(l)*}\boldsymbol{A}^{(l)T} \quad (12)$$

and the l-th path of i-th user channel is modeled as

$$\boldsymbol{H}_i^{(l)} = \sqrt{\frac{M_T}{\operatorname{tr}\left(\boldsymbol{A}^{(l)*}\boldsymbol{A}^{(l)T}\right)}}\boldsymbol{H}_{w_i}^{(l)}\boldsymbol{A}^{(l)T} \quad (13)$$

where $\boldsymbol{A}^{(l)} \in \mathbb{C}^{M_T \times N}$ is an array steering matrix containing N array response vectors of the transmitting antenna array corresponding to N directions of departure [18].

In Figure 1 we show the 10 % outage capacity as a function of the ratio of total transmit power P_T and additive white Gaussian noise at the input of every antenna σ_n^2. The capacity is calculated using the results on the capacity of MIMO broadcast channels in [3]. We also present capacity results for a TDMA system as a comparison. By combining SMMSE and THP we substantially improve the capacity of the system. At high SNRs SO THP provides a higher capacity than SMMSE THP but it still has the constraint regarding the number of antennas at the BS and the total number of receive antennas. In the same figure we can see that by increasing the number of antennas at the UTs SMMSE THP performs much better, especially at low SNRs. On the other hand, although RBD has lower capacity than SMMSE THP it provides an improvement compared to BD and SMMSE. RBD outperforms both SMMSE and BD. At different SNRs RBD will adapt and at low SNRs it performs as SMMSE and at high SNRs where the MUI interference is the main factor limiting the capacity it has the same capacity as BD.

The complementary cumulative distribution function (CCDF) of the capacity is shown in Figure 3. By combining THP and SMMSE we improve the system capacity and at the same time remove the constraint regarding the number of transmit and receive antennas that limits the use of BD and SO THP. RBD has a higher array gain and a higher diversity gain compared to BD.

The BER performance of the proposed precoding techniques are shown in Fig. 5. We compare the performance of these techniques with BD and SMMSE. BD is a linear precoding technique that has a zero MUI interference constraint. By introducing MUI, SMMSE provides a higher diversity and array gain than BD. SMMSE THP has a higher diversity gain than SMMSE and outperforms SMMSE at high SNRs. It is an attractive solution for high SNRs and data rates. A more interesting result is that RBD, which is a linear precoding technique, outperforms a non-linear technique like SMMSE THP. In figure 6 we show the BER performance of RBD and the BER curve for a similar "genie aided" system where the users are assumed perfectly orthogonal in order to show the diversity inherent in this type

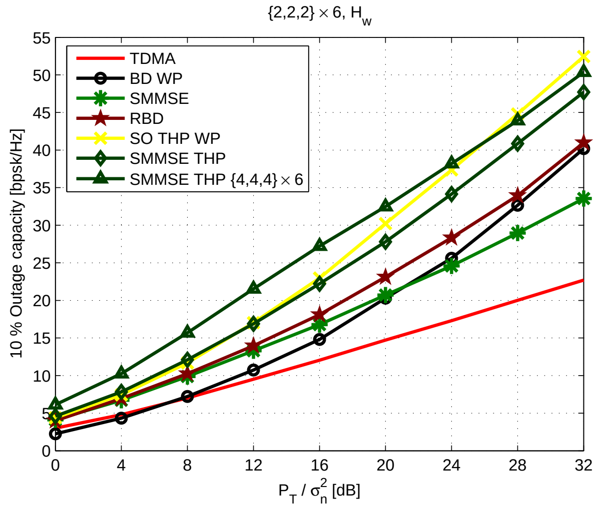

Fig. 3. 10 % outage capacity as a function of receive SNR.

of system. We assume that all users' data in the system are modulated using 16 QAM. As we can see from this figure RBD in this case extracts the full diversity of the system.

5. CONCLUSION

In this paper we have introduced two novel techniques that provide additional gains compared to previously proposed techniques. Depending on the set of constraints, like the size of the overhead or the amount of the MUI allowed, different techniques should be used. Linear techniques are computationally less expensive and generally require no signaling overhead. On the other hand, the non-linear techniques can provide a better performance. SMMSE balances MUI in order to reduce the performance loss due to the overlapping of users' subspaces and has a higher capacity than BD at low SNRs. It extracts higher diversity and array gain than BD or MMSE and has no dimensionality problem regarding the number of antennas at the BS and UTs. By combining SMMSE and THP we substantially improve the capacity of this technique. At high SNRs it has a lower capacity than SO THP. But it can better exploit available antennas at the UTs, and since it has no dimensionality constraints, SMMSE THP is able to provide a higher capacity than SO THP at low SNRs.

The main drawbacks that all non-linear techniques experience are a higher computational complexity, the required signalling overhead and their sensitivity to channel estimation errors. Linear techniques are simpler, less sensitive and could adapt to various CSI quality which makes them more attractive for a practical implementation. BD is a linear technique and can decompose the MU MIMO channel into a set of independent SU MIMO channels. The equivalent

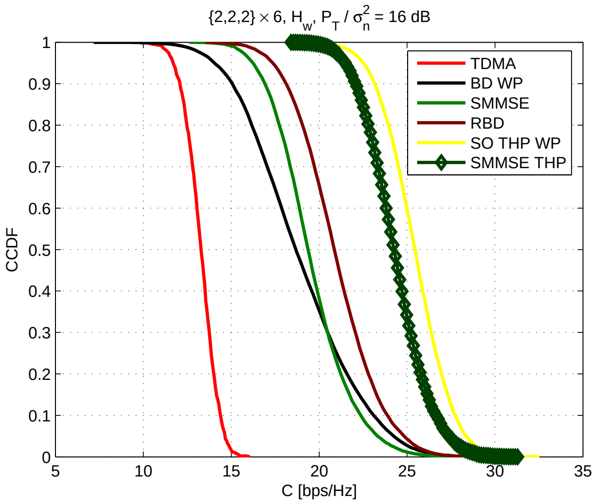

Fig. 4. CCDF of the capacity of the TDMA, BD, SMMSE, RBD, SMSME THP and SO THP system. $\mathrm{SNR} = 16$ dB

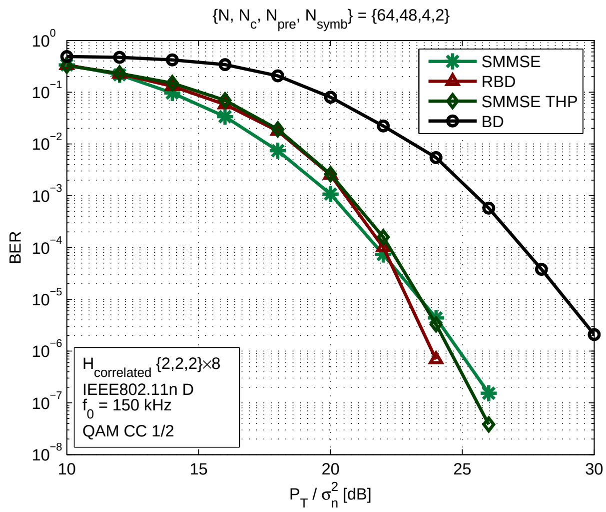

Fig. 5. BER performance comparison of BD, SMMSE, SMMSE THP and RBD in configuration $\{2, 2, 2\} \times 8$.

MU MIMO channel is also block diagonal after SMMSE precoding at high SNRs. Although BD has a higher capacity than SMMSE at high SNRs, SMMSE provides a higher array and diversity gain. By using regularized BD, each user transmits on the eigenmodes of the combined channel of all other users but with the power that is inversely proportional to the regularized eigenvalues of this matrix. The system performance at low SNRs is limited by noise and the user transmits in the null and a part of the signal subspace of all other users, balancing the MUI in order to better use the available subspace. At high SNRs the system performance is limited by MUI and now the user transmits only in the null subspace of all other users. RBD has the same capacity as SMMSE at low SNRs and as BD at high SNRs. Note that RBD provides higher diversity than non-linear SMMSE THP. For high data rates, RBD extracts the full diversity in the system. It can be used short-term (instantaneous) and long-term CSI at the transmitter. Even though SMMSE THP could provide a higher system capacity, RBD is more flexible and more attractive for a practical implementation.

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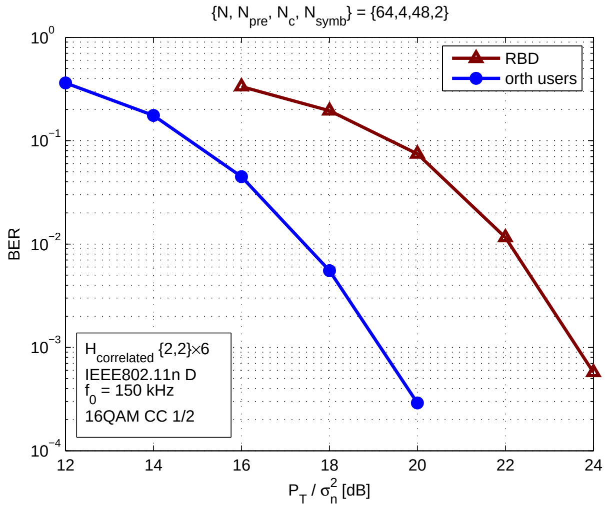

Fig. 6. BER performance comparison of RBD and MU MIMO with orthogonal users in configuration $\{2,2\} \times 6$.

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