Improved diversity on the uplink of multi-user MIMO systems

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***Abstract*— In this paper we analyse the performance of a MIMO receive algorithm that represents a modification of a precoding technique. Thereby we demonstrate the flexibility of these precoding techniques and investigate the possibility of applying the same algorithms at the base station (BS)/access point (AP) for both downlink (DL) and uplink (UL) MIMO processing. Unlike previously reported results where all users in the system are equipped with only one antenna, we investigate a more general case where users can be equipped with an arbitrary number of antennas. By combining one of the previously proposed precoding algorithm and space-time codes we are able to provide an SNR gain of more than 3 dB compared to V-BLAST.**

I. Introduction

Multiple-input multiple-output (MIMO) systems are recognized as a key technology that will achieve high data rates required for the future generation wireless communication systems. MIMO systems are especially beneficial in a multi-user (MU) scenario where they have the potential to combine the high capacity achievable with MIMO processing with the benefits of space division multiple access [1], [2], [3], [4], [5], [6]. Motivated by the need for cheap mobiles with low power consumption, we focus on systems where the computationally demanding signal processing is performed at the base station (BS)/access point (AP). On the downlink (DL) the BS/AP will use any channel state information (CSI) available to mitigate or ideally completely eliminate multi-user interference (MUI) which can lead to significant capacity gains. The user terminal (UT) can estimate either the exact CSI or the equivalent channel. On the uplink (UL) we can identify three possible cases. In the first two cases, the UT has the exact CSI or the information about the equivalent channel and it is transmitting on the dominant eigenmode of one of these. In the third case the UT assumes no CSI, even though it has estimated either the exact CSI or the equivalent channel and it is using space-time block code (STBC) to transmit data.

The information about the equivalent channel is necessary at the receiver in order to perform the optimum reception of data [7]. Therefore, we assume that the UTs estimate the equivalent channel on the downlink (DL). The equivalent channel is equal to the combined network channel after the precoding at the BS/AP. However, on the UL the BS/AP has the possibility to use more powerful techniques so the equivalent channel on the uplink does not have to be the same as on the downlink. Therefore, it is benefitial to assume that mobile terminals have no CSI available which suggests the use of open-loop MIMO techniques on the uplink. The diversity gains of MIMO are more desirable than spatial multiplexing gains if we take into account the limited power available at the UT. Therefore, STBC are the best candidate to be used at the UT.

In [8] the authors propose a MU MIMO precoding technique called successive minimum mean-squared-error (SMMSE) precoding that minimizes the mean-squared-error per receive antenna of each user separately on the downlink. This technique can provide a higher array and diversity gain with perfect CSI at the transmitter than other precoding techniques, especially at low SNRs. In this paper we introduce the multi-user receive filtering technique that is similar to this precoding technique and provides higher diversity gains than V-BLAST [9].

This paper is organized as follows: In Section II, we describe the MU uplink channel and channel estimation errors modeling. In Section III, we present the MU MIMO receive technique that will be investigated and in Section IV, we show the results of the simulations. A short summary follows in Section V.

II. System model

We consider a MU MIMO uplink channel, where M_R receive antennas are located at the BS/AP, and M_{T_i} transmit antennas are located at the i^{th} user terminal, $i = 1, 2, \dots, K$. There are K users (or UTs) in the system. The total number of transmit antennas is $M_T = \sum_{i=1}^{K} M_{T_i}$. A block diagram of such a system is depicted in Figure 1, where $\boldsymbol{s}_i$, $\boldsymbol{r}_i$, $\boldsymbol{F}_i$, and $\boldsymbol{D}_i$ denote the i^{th} user data vector, the received vector, the BS receive matrix, and the UT transmit matrix, respectively.

We will use the notation $M_R \times \{M_{T_1}, \cdots, M_{T_K}\}$ to describe the antenna configuration of the system. In this paper, we assume a flat fading channel. The MIMO channel to user i is denoted as $\boldsymbol{H}_i \in \mathbb{C}^{M_R \times M_{T_i}}$. Moreover, the combined channel matrix of all users is given by

$$\boldsymbol{H} = \begin{bmatrix} \boldsymbol{H}_1 & \boldsymbol{H}_2 & \cdots & \boldsymbol{H}_K \end{bmatrix}.$$

In order to take into account channel estimation errors we use a "nominal-plus-perturbation" model. The estimated combined channel matrix can be represented as

$$\widehat{\boldsymbol{H}} = \boldsymbol{H} + \boldsymbol{E}$$

where $\boldsymbol{H}$ denotes the flat fading combined channel matrix of all users, and $\boldsymbol{E}$ is a complex random Gaussian matrix distributed according to $\mathcal{CN}\big(\boldsymbol{0}_{M_R \times M_T}, M_R \sigma_e^2 \boldsymbol{I}_{M_T}\big)$. In case of OFDM, we model the channel estimation error on each subcarrier in this way.

III. Successive MMSE receive filtering (SMMSE) successive interference cancellation (SIC)

A high throughput on the MU UL can be achieved via an MMSE receiver with successive interference cancellation

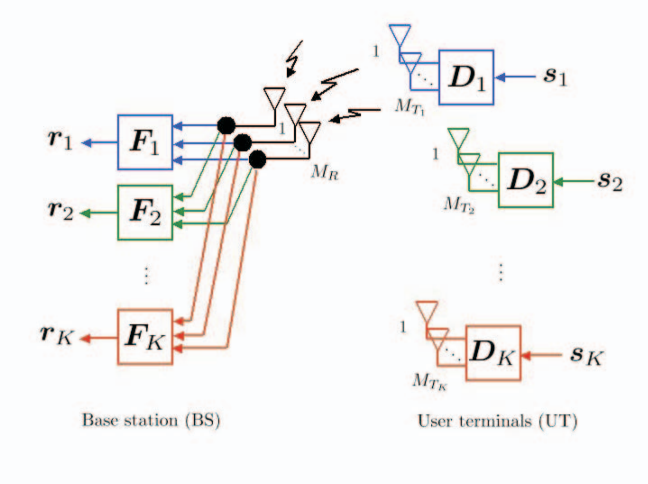

Fig. 1. Block diagram of multi-user MIMO system.

(SIC) [10]. However, this introduces a loss if we try to mitigate the interference between the data streams transmitted from two closely spaced antennas located at the same UT. In order to improve the system performance we can use the same approach as in [8]. In this paper we propose a new algorithm that deals with this problem by successively calculating the rows of the receive matrix for each of the transmit antennas separately. By applying SIC we additionally improve the diversity compared to the DL.

Let us define the receive filter matrix as

$$\boldsymbol{F} = \begin{bmatrix} \boldsymbol{F}_1 \\ \boldsymbol{F}_2 \\ \vdots \\ \boldsymbol{F}_K \end{bmatrix} \in \mathbb{C}^{M_R \times M_T}, \tag{1}$$

where $\boldsymbol{F}_i \in \mathbb{C}^{M_{T_i} \times M_R}$.

The rows in the receive matrix $\boldsymbol{F}_i$, each corresponding to one transmit antenna, are calculated successively. For the i^{th} user, $i = 1, 2, \ldots, K$, and j^{th} transmit antenna $j = 1, 2, \ldots, M_{T_i}$ we define the matrix $\bar{\boldsymbol{H}}_i^{(j)}$ as:

$$\bar{\boldsymbol{H}}_i^{(j)} = \begin{bmatrix} \boldsymbol{h}_{i,j} & \boldsymbol{H}_1 & \cdots & \boldsymbol{H}_{i-1} & \boldsymbol{H}_{i+1} & \cdots & \boldsymbol{H}_K \end{bmatrix} \tag{2}$$

where $\boldsymbol{h}_{i,j}$ is the j^{th} column of the i^{th} user's channel matrix $\boldsymbol{H}_i$. The corresponding row of the receive matrix $\boldsymbol{F}_i$ is equal to the first row of the following matrix:

$$\boldsymbol{F}_{i,j} = \bar{\boldsymbol{H}}_i^{(j)H} \left(\bar{\boldsymbol{H}}_i^{(j)} \bar{\boldsymbol{H}}_i^{(j)H} + \frac{\sigma_n^2}{P_t} \boldsymbol{I}_{M_R} \right)^{-1} \tag{3}$$

where σ_n^2 is the variance of the zero-mean additive white Gaussian noise at the input of one receive antenna and P_t is the transmit power at the output of one transmit antenna. The total transmit power is equal to $P_T = M_T P_t$. The mean-square error (MSE) corresponding to the j^{th} transmit antenna of the i^{th} user is equal to

$$\mathrm{mse}_{i,j} = \sigma_n^2 \left[\left(\bar{\boldsymbol{H}}_i^{(j)} \bar{\boldsymbol{H}}_i^{(j)H} + \frac{\sigma_n^2}{P_t} \boldsymbol{I}_{M_R} \right)^{-1} \right]_{1,1} \tag{4}$$

Let us define the total mean square error of the i^{th} user as

$$\mathrm{mse}_i = \sum_{j=1}^{M_{T_i}} \mathrm{mse}_{i,j} \tag{5}$$

We look for the user with the minimum mse_i, demodulate its data and then subtract the reconstructed signal from the received signal. Afterwards, we form the new combined channel matrix $\widetilde{\boldsymbol{H}}$ without this user's channel matrix and use it instead of $\boldsymbol{H}$ in (2). We repeat these steps until the combined channel matrix is empty.

The resulting matrix after multiplication of the combined network channel matrix $\boldsymbol{H}$ with the receive filter matrix $\boldsymbol{F}$ is lower block diagonal assuming that the users are ordered according to ascending total mse_i. The part below the main block diagonal can be eliminated by successive interference cancellation. Thereby, we transform the uplink channel into a set of parallel single user MIMO channels. The equivalent channel of user i after eliminating the MUI is identified as $\boldsymbol{F}_i \boldsymbol{H}_i$, whose dimension is $M_{T_i} \times M_{T_i}$ and is equivalent to a system with M_{T_i} transmit antennas and M_{T_i} receive antennas. Each of these equivalent single user (SU) MIMO channels has the same properties as a conventional SU MIMO channel and we can apply any other previously defined MIMO technique on it. In this paper we consider two options. One option is to use STBC at the UTs and at the BS to perform space-time decoding. The second option is to generate the matrices $\boldsymbol{D}_i$ also at the BS and then to feed forward them to the UTs. In this case we use dominant eigenmode transmission (DET) in order to extract the maximum diversity and array gain. It is known that DET can provide the same diversity as STBC and an array gain that is equal or greater than STBC [10]. We investigate the gains that result from the increased overhead required to implement DET.

IV. Simulation Results

In this section we compare the performance of SMMSE SIC and V-BLAST with various number of users in the system. The channel $\boldsymbol{H}$ is assumed to be frequency selective with the power delay profile as defined by IEEE802.11n - D with non-line of sight conditions [11]. The channel of the i^{th} user on each subcarrier is modeled as

$$\boldsymbol{H}_i = \boldsymbol{R}_{r_i}^{1/2} \boldsymbol{H}_{w_i} \boldsymbol{R}_{t_i}^{1/2} \tag{6}$$

where $\boldsymbol{H}_{w_i}$ is a spatially white unit variance flat fading MIMO channel of dimension $M_R \times M_{T_i}$, whereas $\boldsymbol{R}_{r_i}$ and $\boldsymbol{R}_{t_i}$ are receive and transmit covariance matrices with $\mathrm{tr}\,(\boldsymbol{R}_{r_i}) = M_R$ and $\mathrm{tr}\,(\boldsymbol{R}_{t_i}) = M_{T_i}$. The correlation matrices on each subcarrier are modeled independently.

In this paper we assume a scenario where the UT 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 user is often very large and thus a low spatial correlation can be achieved with relatively small antenna separation. Hence, we can write

$$\boldsymbol{R}_{t_i} = \boldsymbol{I}_{M_{T_i}}, \quad \boldsymbol{R}_{r_i} = \frac{M_R}{\mathrm{tr}\,(\boldsymbol{A}^* \boldsymbol{A}^T)} \boldsymbol{A}\boldsymbol{A}^H \tag{7}$$

and the channel is modeled as

$$\boldsymbol{H}_i = \sqrt{\frac{M_R}{\mathrm{tr}\,(\boldsymbol{A}^* \boldsymbol{A}^T)}} \boldsymbol{A} \boldsymbol{H}_{w_i} \tag{8}$$

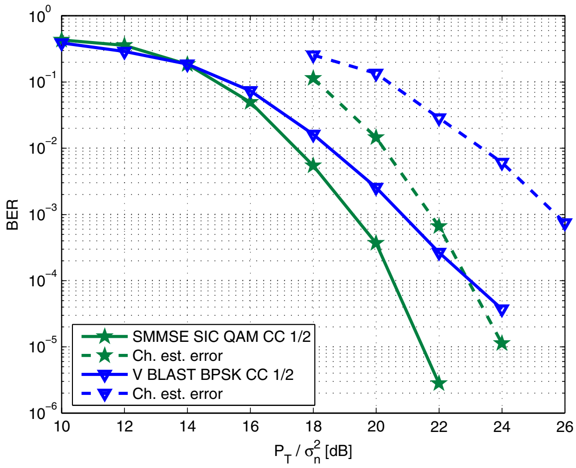

Fig. 2. BER performance of SMMSE SIC Alamouti and V-BLAST as a function of P_T/σ_n^2. System with the configuration $6 \times \{2, 2\}$.

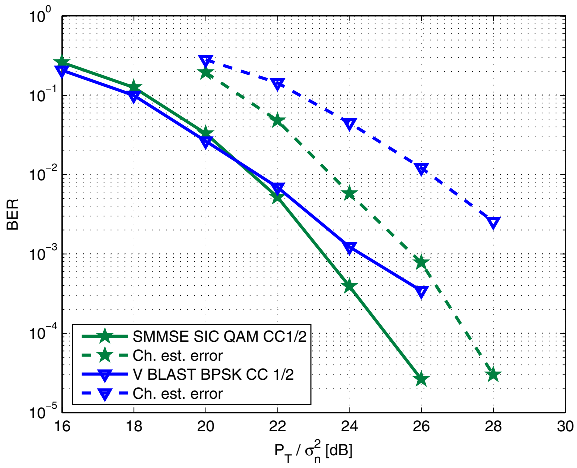

Fig. 3. BER performance of SMMSE SIC Alamouti and V-BLAST as a function of P_T/σ_n^2. System with the configuration $6 \times \{2, 2, 2\}$.

where $\boldsymbol{A} \in \mathbb{C}^{M_R \times L}$ is an array steering matrix containing L array response vectors of the transmitting antenna array corresponding to L directions of departure [12].

The signal-to-noise ratio is defined as P_T/σ_n^2, where P_T is the total transmit power of all users and σ_n is the standard deviation of the additive white Gaussian noise at the input of one receive antenna. We assume that there is no CSI at the UTs and that they either use an Alamouti code in combination with SMMSE SIC or V-BLAST. In our simulations, we assume that the signal at each transmit antenna is modulated using OFDM. The total number of subcarriers is $N = 64$ and the subcarrier spacing is $f_0 = 150$ kHz. The cyclic prefix is 4 samples long. The size of a frequency-time bin used for transmission is 48 subcarriers in the frequency dimension and 2 OFDM symbols in the time dimension. The user data is encoded using a 1/2 rate convolutional code $(561, 753)_{oct}$. Soft decision Viterbi decoding is assumed. After the coding we perform random interleaving. We assume that each user is equipped with two antennas. When the UTs use the Alamouti code, each subcarrier is modulated using QAM modulation. In case of V-BLAST, each subcarrier is modulated using BPSK in order to keep the total data rate in both systems the same.

We assume that the channel estimation error is a zero mean Gaussian random variable with variance equal to the mean-square error (MSE) of the channel estimator. The MSE is proportional to the SNR and is modeled as

$$\sigma_e^2 = \begin{cases} \frac{\sigma_n^2}{P_t G_N} & , \frac{\sigma_n^2}{P_t G_N} > -30 \text{ dB} \\ -30 \text{ dB} & , \frac{\sigma_n^2}{P_t G_N} \leq -30 \text{ dB} \end{cases}$$

where G_N defines the estimator gain and P_t is the power per one antenna per one subcarrier. Hence, the MSE linearly decreases with the SNR. The estimator gain is about $G_N =$ 13 dB, but may vary depending on the number of users, antennas, etc.

First we compare the performance of a V-BLAST system using BPSK modulation and SMMSE SIC system using QAM in a scenario with the configuration $6 \times \{2, 2\}$. In Fig. 3 we compare these two techniques when the system is fully loaded. We assume that there are three users in the system with two antennas each. The system configuration is $6 \times \{2, 2, 2\}$. By combining SMMSE SIC and an Alamouti code we are able to provide an SNR gain of more than 3 dB and improve the system performance by more than an order of magnitude. Also, from these two figures we can see that the V-BLAST system is more sensitive to the channel estimation errors than the system that use the Alamouti code and SMMSE SIC. It can also be seen that the performance of the system decreases as the number of users increases. As the number of users in the system increases the available vector subspace per user decreases resulting in the array and diversity gain reduction. With six antennas at the BS we could multiplex up to 6 users, but the performance of the system would be seriously degraded.

In Figures 4 and 5 we compare the performance of SMMSE SIC when the UTs use an Alamouti code or DET. As it can be seen from the figures, DET provides a better performance but only for higher SNRs and a greater number of UTs in the system. It follows that for moderate load of the system, i.e., number of users, it does not pay off to increase the overhead in order to improve the system performance. The best solution is to use STBCs at the UTs and perform smart scheduling such that the number of users that are spatially multiplexed is not too large [13].

V. Conclusion

In this paper we introduced a receive technique SMMSE SIC for the cancellation of multi-user interference. It performs successive MMSE filtering of every transmit antenna at user terminals separately in order to reduce the performance loss due to the cancellation of the interference between the antennas located at the same terminal. The system diversity is further improved by grouping the signals at the BS/AP corresponding to the same user and by combining them constructively instead of successively canceling the interference among them. Since the BS/AP can apply different processing techniques on the UL and the DL, the user terminals do not have the exact CSI, which implies the use of STBC. By using the STBC at the user terminals, the diversity is further improved compared to V-BLAST, another open-loop MU MIMO technique. In a system, where all users are equipped with multiple antennas, this technique outperforms previously

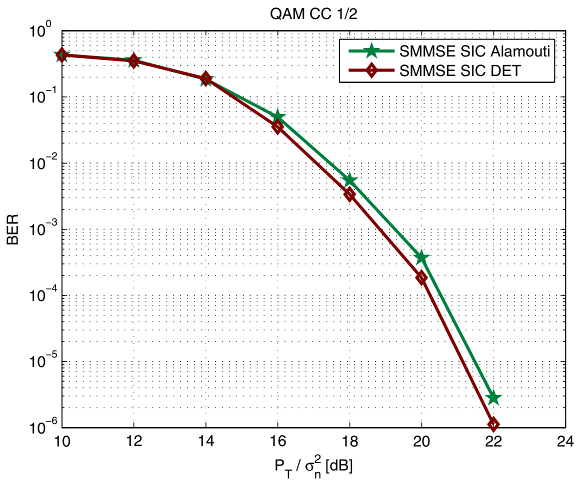

Fig. 4. BER performance of SMMSE SIC Alamouti and SMMSE SIC DET as a function of P_T/σ_n^2. System with the configuration $6 \times \{2, 2\}$.

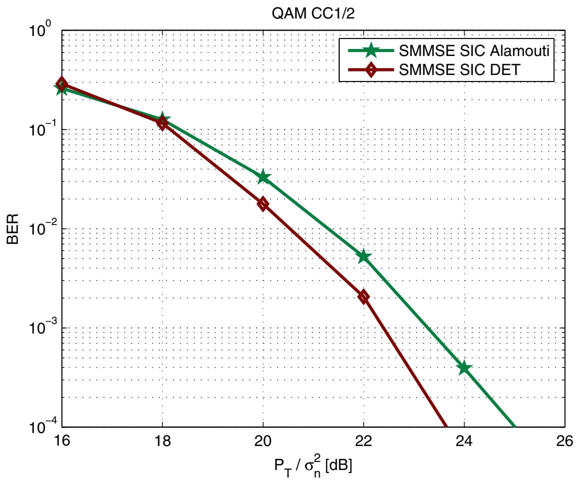

Fig. 5. BER performance of SMMSE SIC Alamouti and SMMSE SIC DET as a function of P_T/σ_n^2. System with the configuration $6 \times \{2, 2, 2\}$.

proposed receive techniques. By combining SMMSE SIC and STBC we have managed to improve the system performance by more than 3 dB. Also, this novel technique is less sensitive to channel estimation errors. As the number of users in the system increases, the diversity gains that we obtain decrease. The system performance can be improved if the user terminal's transmit matrices are also generated at the base station. Dominant eigenmode transmission provides the same diversity gains as STBC but the array gain is greater or equal to the STBCs. However, the gains that dominant eigenmode transmission can provide are not that big compared to the combination of SMMSE SIC and STBC when we take into account the required additional overhead to implement it in a real life system. The best solution is to use the combination of SMMSE SIC and STBC and to schedule the users in such a way that not too many of them are spatially multiplexed. In this case the system performance gains from both - SMMSE SIC and STBC.

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