EFFICIENT MULTI-USER MIMO DOWNLINK PRECODING SCHEMES

Martin Haardt, Veljko Stankovic, and Giovanni Del Galdo

Ilmenau University of Technology
Communications Research Laboratory
P.O. Box 100565, 98684 Ilmenau, Germany
{martin.haardt,veljko.stankovic,giovanni.delgaldo}@tu-ilmenau.de
Phone: +49 (3677) 69-2613, Fax: +49 (3677) 69-1195

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 MIMO system, either long-term or short-term channel state information has to be available at the base station (BS) to faciliate the joint precoding of the signals intended for the different users. Precoding is used to efficiently eliminate or suppress multi-user interference (MUI) via beamforming or by using "dirty-paper" codes. 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 provide an overview of efficient linear and non-linear precoding techniques for multi-user MIMO systems. The performance of these techniques is assessed via simulations on statistical channel models, and on channels generated by the IlmProp, a geometry-based channel model that generates realistic correlations in space, time, and frequency.

1. INTRODUCTION

In recent years, there has been a considerable interest in wireless multiple-input, multiple output (MIMO) communication systems because of their promising improvement in terms of performance and bandwidth efficiency [1], [2], [3], [4], [5]. An important research topic is the study of multi-user (MU) MIMO systems. Such systems 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 beamforming (linear precoding) or by the use of "dirty-paper" codes. 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. All precoding techniques can be classified considering whether they allow MUI (as zero or non-zero MUI techniques) and by their linearity (as linear and non-linear techniques). Linear precoding techniques require no overhead to provide the mobile with the demodulation information and are less computationally expensive than their non-linear counterparts. However, non-linear techniques provide a much higher capacity.

2. LINEAR PRECODING TECHNIQUES

Block diagonalization (BD) is a linear precoding technique for the downlink of MU MIMO systems [6]. It decomposes a MU MIMO downlink channel into multiple parallel orthogonal single-user MIMO 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 is attractive if the users are equipped with more than one antenna. However, the zero MUI constraint can lead to a large capacity loss when the users' subspaces significantly overlap. Another technique also proposed in [6], named successive optimization (SO), addresses the power minimization and near-far problems. 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 pre-processed. The zero MUI constraint is relaxed and a certain amount of interference is allowed.

Minimum mean-square-error (MMSE) precoding improves the system performance by allowing 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, situation always occurring when the user terminal is equipped with more than one receive antenna. In [7] the authors proposed a new algorithm called successive

MMSE (SMMSE) which deals with this problem by successively calculating the columns of the precoding matrix for each of the receive antennas separately. The complexity of this algorithm is only slightly higher than the one of BD but it can provide a higher diversity gain and a larger array gain than BD.

3. NON-LINEAR PRECODING TECHNIQUES

It is well-known that linear equalization suffers from noise enhancement and hence has poor power efficiency in some cases. The same drawback is experienced by linear precoding, which combats noise by boosting the transmit power. This disadvantage of linear equalization at the receiver side can be avoided by decision-feedback equalization (DFE), which is for instance used in V-BLAST [8].

Tomlinson-Harashima precoding (THP) is a non-linear pre-coding technique developed for single-input, single-output (SISO) multipath channels. THP can be interpreted as moving the feedback part of the DFE to the transmitter. Recently it has been also applied for the pre-equalization of MUI in MIMO systems [9], where it performs spatial pre-equalization instead of temporal pre-equalization for ISI channels. Thereby, no error propagation occurs. Hence, the precoding can be performed for the interference-free channel.

MMSE precoding in combination with THP is proposed in [10]. MMSE balances the MUI in order to reduce the performance loss that occurs with zero interfence techniques while THP is used to reduce the MUI and to improve the diversity.

SO THP proposed in [11] combines SO and THP in order to reduce the capacity loss 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 [12] and [10], this technique allows more than one antenna at the mobile terminals and has no performance loss due to the cancellation of interference between the signals transmitted to two closely spaced antennas at the same terminal.

4. SCHEDULING

All precoding techniques suffer from two major drawbacks: They can only spatially multiplex a limited number of users in any given resource slot. Secondly their performance largely degrades when serving spatially correlated users. In a real system it is reasonable to assume that there exist a larger number of users than those a BS can simultaneously transmit to. Therefore, there is a need for a scheduling algorithm, responsible to decide which users are to be spatially

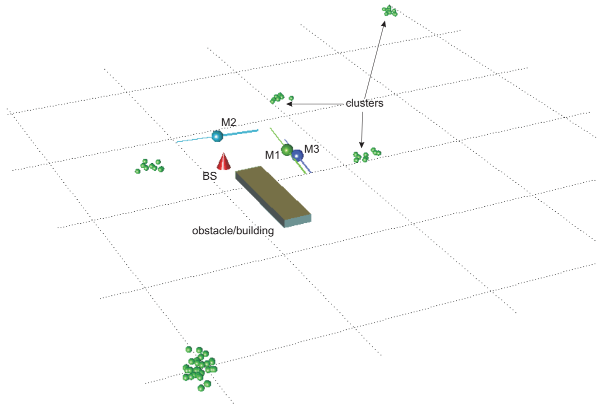

Fig. 1. IlmProp channel model. Three mobiles (M1, M2, and M3) move on linear trajectories around a Base Station (BS). Scattering clusters provide a delay spread of 1 μs.

multiplexed at any given time and frequency. The scheduler should take its decisions avoiding to group spatially correlated users, maximizing the system performance while remaining fair. In fact, for spatially correlated users, the MUI is very large due to the overlapping signal spaces. This of course degrades the performance of non-zero MUI techniques. Forcing the interference to zero, as the zero MUI techniques do, does not help much since it would be inevitable to use unefficient modulation matrices. Therefore, this situation should be avoided by the scheduler. Finally, fairness is very important in a real system since it assures that all users are served. Without it, the scheduler would simply pick the users with the best channels and transmit only to those. These prerequisites render the design of an efficient scheduler a challenging task. Examples of spatial-correlation aware schedulers are the ones presented in [13, 14].

5. SIMULATION ENVIRONMENT

In order to assess the robustness of the algorithms in a realistic scenario we propose simulation results obtained with the help of the IlmProp channel model [15]. The IlmProp, includes a geometrical representation of the environment surrounding the experiment, as depicted in Figure 1. Three users employing a 2-element Uniform Linear Array (ULA) move at approximately 50 km/h around a base station mounting a 4-element ULA. All arrays are characterized by $\frac{\lambda}{2}$ spaced vertical dipole antennas, operating in the 5 GHz band. The mobiles have a Line Of Sight (LOS) component and several scattering clusters around them that provide delay spreads of up to 1 μs. The channels have been computed for 64 subcarriers, separated by 150 kHz, sampled in time with a sampling interval equal to 70 μs. Users 1 and 3 move on a similar trajectory, remaining spatially correlated with one another for the total time of the simulation, while user 2 moves on a different path. The building depicted in Figure 1 obstructs the paths towards one of the far cluster for users 1 and 2 only. In addition to the LOS component and the paths originating from the clusters, the channels has been enriched with a Dense Multipath-Component [16]. The latter is modeled as a complex white noise whose power delay profile exhibits the trend of decaying exponentials as described in [16]. The DMC represents approximately 20 % of the total channel's power.

6. SIMULATION RESULTS

In this section, we will compare the performance of BD, SO THP, and SMMSE precoding. To do so, we take into account a purely stochastic channel $\boldsymbol{H}_{\mathrm{w}}$ and two channels $\boldsymbol{H}_{\mathrm{I}}^{(1)}$ and $\boldsymbol{H}_{\mathrm{I}}^{(2)}$, partly deterministic, generated by the *IlmProp*, a geometry-based channel model for multi-user time variant, frequency selective MIMO systems [15] (http://tu-ilmenau.de/ilmprop). The channel $\boldsymbol{H}_{\mathrm{w}}$ is assumed to be frequency selective with the power delay profile as defined by IEEE802.11n - D with non-line of sight conditions [17]. The IlmProp channels $\boldsymbol{H}_{\mathrm{I}}^{(1)}$ and $\boldsymbol{H}_{\mathrm{I}}^{(2)}$ represent two typical outcomes of a scheduler which is not spatial correlation aware, in the first case, and one where the users' spatial correlation has been considered, for the second channel.

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). We will use the notation $\{M_{R_1}, \ldots, M_{R_K}\} \times M_T$ to describe the antenna configuration of the system. 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 $\mathcal{CN}\left(\mathbf{0}_{M_R \times M_T}, M_R \sigma_e^2 \boldsymbol{I}_{M_T}\right)$. In case of OFDM, we model the channel estimation error on each subcarrier in this way.

The real advantage of SMMSE can be seen from the BER performance shown in Figure 2. By introducing MUI, SMMSE provides a higher diversity and a higher array gain than BD. SO THP does not have the same diversity gain as BD, that can be explained with the influence of the modulo operator used in THP.

Next, we will investigate the influence of scheduling on the performance of the MU MIMO precoding techniques using the IlmProp channel model. In Fig. 3 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. In the next figure we investigate the influence of scheduling on the BER performance of BD

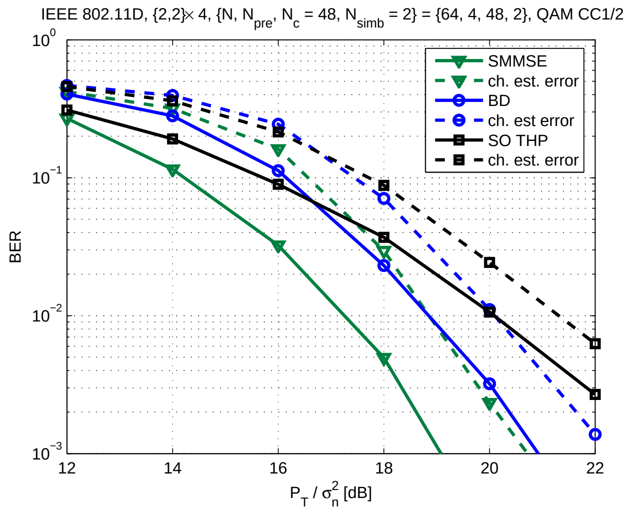

Fig. 2. BER performance comparison of BD, SO THP and SMMSE in configuration $\{2, 2\} \times 4$.

and SMMSE. As it can be seen in these two figures, spatial scheduling has a great impact on the capacity of the system. The capacity gain is about one bps/Hz and the SNR gain is about 2 dB. We also see that SMMSE clearly outperforms BD.

7. CONCLUSION

In this paper we investigate several linear and non-linear precoding techniques suitable for the downlink of MU MIMO systems using the IlmProp channel model with realistic correlations in space, time, and frequency. These precoding techniques represent good candidates for a practical implementation because of the good compromise between performance and complexity. Non-linear techniques like SO THP can theoretically achieve a high capacity. SO THP is especially attractive for users with multiple antennas since it does not experience any capacity loss due to the cancellation of interference between closely spaced antennas at the same mobile terminal. SMMSE also addresses this problem. This technique is a modification of MMSE precoding which optimizes the performance of users equipped with multiple antennas. SMMSE provides the best BER performance regardless of the number of receive antennas per user. The complexity of this technique is also reasonable which makes it a potential candidate for the implementation in future wireless systems. It outperforms other linear techniques (such as BD) and even non-linear techniques like SO THP. Furthermore, the total number of receive antennas at mobile terminals can be greater than the number of transmit antennas at the BS. Moreover, it relies on linear processing and it is less sensitive to channel estimation errors than non-linear techniques.

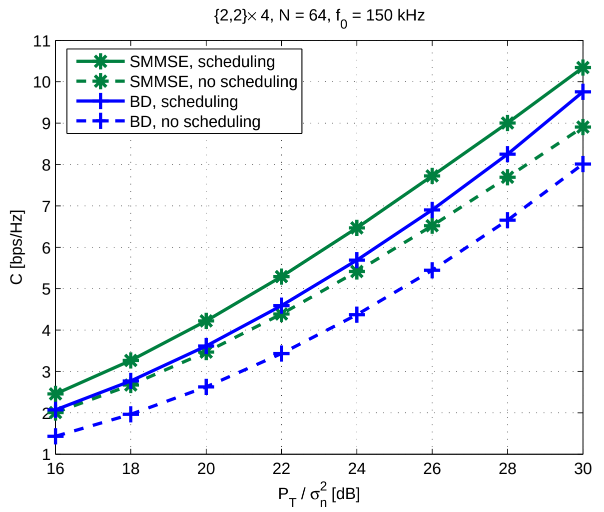

Fig. 3. 10 % outage capacity performamce of BD and SMMSE, with and without schedulling.

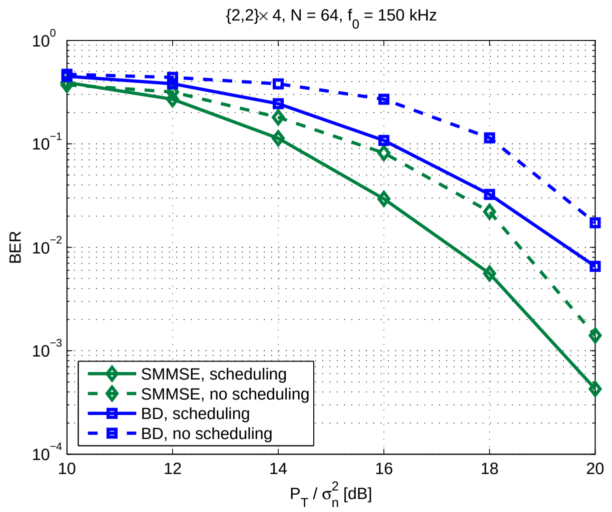

Fig. 4. BER performance comparison of BD and SMMSE in configuration $\{2, 2\} \times 4$, with and without schedulling.

ACKNOWLEDGEMENT

This work has been partially performed in the framework of the IST project IST-2003-507581 WINNER, which is partly funded by the European Union. The authors would like to acknowledge the contributions of their colleagues.

8. REFERENCES

[1] R. W. Heath, M. Airy, and A. J. Paulraj, "Multiuser diversity for MIMO wireless systems with linear receivers," in *Proc. 35th Asilomar Conf. on Signals, Systems, and Computers, Pacific Grove, CA, IEEE Computer Society Press*, November 2001.

[2] Q. H. Spencer, C. B. Peel, A. L. Swindlehurst, and M. Haardt, "An introduction to the multi-user MIMO downlink," *IEEE Communications Magazine*, vol. 42, no. 10, pp. 60–67, October 2004.

[3] S. Vishwanath, N. Jindal, and A. J. Goldsmith, "On the capacity of multiple input multiple output broadcast channels," in *Proc. of the IEEE International Conference on Communications (ICC), New York, NY*, April 2002.

[4] Z. Pan, K. K. Pan, and T. Ng, "MIMO antenna system for multi-user multi-stream orthogonal space time division multiplexing," in *In Proc. of the IEEE International Conference on Communicaions, Anchorage, Alaska*, May 2003.

[5] K. K. Wong, "Adaptive space-division-multiplexing and bit-and-power allocation in multiuser MIMO flat fading broadcast channel," in *Proc. of the IEEE 58th Vehicular Technology Conference, Orlando, FL*, Octoboer 2003.

[6] Q. Spencer and M. Haardt, "Capacity and downlink transmission algorithms for a multi-user MIMO channel," in *Proc. 36th Asilomar Conf. on Signals, Systems, and Computers, Pacific Grove, CA, IEEE Computer Society Press*, November 2002.

[7] V. Stankovic and M. Haardt, "Multi-user MIMO downlink precoding for users with multiple antennas," in *Proc. of the 12-th Meeting of the Wireless World Research Forum (WWRF), Toronto, ON, Canada*, November 2004.

[8] P.W. Wolniansky, G.J Foschini, G.D. Golden, and R.A. Valenzuela, "V-BLAST: An architecture for realizing very high data rates over the rich-scattering wireless channel," in *Proc. ISSSE 98*, September 1998.

[9] G. Cinis and J. Cioffi, "A multi-user precoding scheme achieving crosstalk cancellation with application to DSL systems," in *Proc. Asilomar Conf. on Signals, Systems, and Computers*, November 2000, vol. 2, pp. 1627–1637.

[10] M. Joham, J. Brehmer, and W. Utschick, "MMSE approaches to multiuser spatio-temporal Tomlinson-Harashima precoding," in *Proc. 5th International ITG Conference on Source and Channel Coding (ITG SCC'04)*, January 2004, pp. 387–394.

[11] V. Stankovic and M. Haardt, "Successive optimization Tomlinson-Harashima precoding (SO THP) for multi-user MIMO systems," in *Proc. IEEE Int. Conf. Acoust., Speech, and Signal Processing (ICASSP), Philadelphia, PA, USA*, March 2005.

[12] G. Caire and S. Shamai, "On the achievable throughput of a multi-antenna gaussian broadcast channel," *IEEE Trans. on Inf. Theory.*, vol. 49, no. 7, pp. 1691–1706, July 2003.

[13] M. Fuchs, G. Del Galdo, and M. Haardt, "A novel tree-based scheduling algorithm for the downlink of multi-user MIMO systems with ZF beamforming," in *Proc. IEEE Int. Conf. Acoust., Speech, and Signal Processing (ICASSP), Philadelphia, PA, USA*, March 2005.

[14] G. Del Galdo and M. Haardt, "Comparison of zero-forcing methods for downlink spatial multiplexing in realistic multi-user MIMO channels," in *Proc. IEEE Vehicular Technology Conference 2004-Spring, Milan, Italy*, May 2004.

[15] G. Del Galdo, M. Haardt, and C. Schneider, "Geometry-based channel modelling of MIMO channels in comparison with channel sounder measurements," *Advances in Radio Science - Kleinheubacher Berichte*, 2003.

[16] A. Richter, *Estimation of Radio Channel Parameters: Models and Algorithms*, Ph.D. thesis, Ilmenau University of Technology, 2005.

[17] "IEEE P802.11 Wireless LANs, TGn Channel Models," Tech. Rep. IEEE 802.11-03/940r2, IEEE, January 2004.