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IMPROVED INTERFERENCE AWARE PRECODING FOR CELLULAR NETWORK-MIMO SYSTEMS

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ABSTRACT

An interference aware precoding scheme based on limited channel state information at the transmitter (CSIT) is considered for its use in the downlink of a cellular system. The transmitter precoder used is based on an MMSE-ZF criterion in order to maximize the user rate while the interference to other users is reduced. The proposed scheme also exploits the network topology, so that each BS can categorize the users into two groups, according to the level of interference that the BS is introducing in those users. On the receiver end, each user makes use of the whole channel state information at the receiver (CSIR) by employing an MMSE filter. This approach enables a reduction in the complexity of the system, while improving the performance of the whole network.

Index Terms— Multiple-Input Multiple-Output, Interference Aware, Channel State Information, MMSE, ZF

1. INTRODUCTION

Multiple-input multiple-output (MIMO) systems have been proposed as a means to satisfy the increasing demand for high data rates in cellular networks. Several linear precoding schemes have been developed with the aim to maximize the Degrees of Freedom (DoF). Remarkable techniques such as Linear Zero Forcing Beamforming (LZFB) [1], Interference Alignment (IA) [2], or Block Diagonalization (BD) [3] show that an enormous increment of the sum rate is achievable when the channel state information at the transmitter (CSIT) is known.

Unfortunately, providing accurate and instantaneous CSIT requires a large amount of network resources. Feedback channel, high capacity backhaul links among base stations (BS), and phase synchronization are typically required [4]. Furthermore, coordinated transmission among the set of BSs is typically mandatory in order to exploit these techniques in a cellular system. Consequently, attaining the theoretic achievable rates of full CSIT techniques in practice is challenging, if at all possible.

On the other hand, there has been a growing interest in blind transmission schemes. Blind Interference Alignment (BIA) for MISO broadcast channels is presented in [5]. It is shown that a growth in DoF without the need for CSIT is achievable by exploiting channel correlations. In [6], frequency reuse and wireless coding are proposed as solutions to align the interference when CSIT is not available in cellular networks. By exploiting the knowledge of the cellular network topology, it is demonstrated that orthogonal allocation is optimal in many cases. Additionally, [7] shows how under some circumstances treating the interference as noise can be optimal. Therefore, it is expected that precoding based on CSIT will not achieve a great improvement in cellular networks when the users are not heavily limited by interference.

Transmission schemes that do not require coordination among the BS are attractive alternatives for cellular networks, because they represent a trade-off between blind and full CSIT solutions. In [8] an Interference Aware precoder that only requires partial CSIT is presented. Without the need for cooperation, the precoder tries to minimize the mean squared error (MSE) to the user in the current cell, while the interference to the rest of the users is partially suppressed. However, since this precoding scheme does not provide a receive filter at the user side, the achievable rates are limited. [9] proposes a similar scheme, based on a signal and interference leakage MMSE filter at the transmitter, including an MMSE filter at each receiver, which is updated via an iterative algorithm.

In this work an improved interference aware scheme is presented, taking advantage of the knowledge of the network topology and partial CSIT. With the aim to improve the dimensional efficiency of the transmitter precoder, only the users limited by interference are taken into account. Therefore, the precoder calculation considers less users than previous schemes. Additionally, each user exploits full CSIR, which can be easily obtained, to design an MMSE filter that allows for a reduction of other cell interference.

2. SYSTEM MODEL

A MIMO cellular downlink channel that comprises L cells, with one BS each, is considered in this work. Each BS is

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equipped with t antennas, whereas one user equipped with r antennas is served in each cell. Assuming narrow band transmission [1], the total channel matrix $\mathbf{H} \in \mathbb{C}^{Lr \times Lt}$ takes into account the path loss effects and small-scale multipath Rayleigh fading between the L BSs and the set of L users. The received signal at the user in the l-th cell is given by

$$\hat{\mathbf{u}}_l = \mathbf{W}_l^{rx} \left(\mathbf{H}_{ll} \mathbf{W}_l^{tx} \mathbf{u}_l + \sum_{\substack{m=1 \\ m \neq l}}^{L} \mathbf{H}_{lm} \mathbf{W}_m^{tx} \mathbf{u}_m + \mathbf{z}_l \right) \quad (1)$$

where $\hat{\mathbf{u}}_l \in \mathbb{C}^{r \times 1}$ are the received symbols, $\mathbf{u}_l \in \mathbb{C}^{r \times 1}$ are the symbols transmitted from the BS at the l-th cell, $\mathbf{H}_{lm} \in \mathbb{C}^{r \times t}$ is the channel matrix between the BS at the m-th cell and the user in the l-th cell, $\mathbf{W}_l^{tx} \in \mathbb{C}^{t \times r}$ is the transmit precoder at the l-th BS, $\mathbf{W}_l^{rx} \in \mathbb{C}^{r \times r}$ is the receive filter at the user in the l-th cell, and $\mathbf{z}_l \in \mathbb{C}^{r \times 1}$ is the white Gaussian noise at that same receiver, with $\mathbf{z}_l \sim \mathcal{N}(\mathbf{0}, \mathbf{R}_{n,l})$, and $\mathbf{R}_{n,l} = \sigma_l^2 \mathbf{I}_r$ the noise covariance matrix.

It is assumed that the symbols transmitted have a covariance matrix $\mathbb{E}\left\{\mathrm{Tr}(\mathbf{u}\mathbf{u}^H)\right\} = \mathbf{I}_r$, so that the power transmitted by the l-th BS is given by $P_{tx,l} = \mathrm{Tr}(\mathbf{W}_l^{tx} \mathbf{W}_l^{tx\,H})$, and it is constrained to be lower than a maximum power $P_{tx,l} \leq P_{max,l}$.

In the work presented here only partial CSIT is needed, so that at each BS, only its channel to all the users in the system is required. The l-th BS will know, then, the channel matrix

$$\mathbf{H}_l = \begin{bmatrix} \mathbf{H}_{1l} \\ \vdots \\ \mathbf{H}_{ll} \\ \vdots \\ \mathbf{H}_{Ll} \end{bmatrix} \quad (2)$$

so that $\mathbf{H}_l \in \mathbb{C}^{Lr \times t}$. Note that $\mathbf{H}^{[l]}$ is a tall matrix that can be partitioned into three different flows, reordering the submatrices of $\mathbf{H}_l$ without loss of generality, as follows

$$\mathbf{H}_l = \begin{bmatrix} \mathbf{H}_{ll} \\ \mathbf{H}_{I_1,l} \\ \mathbf{H}_{I_2,l} \end{bmatrix} \quad (3)$$

where $\mathbf{H}_{I_1,l} \in \mathbb{C}^{|I_1| r \times t}$ and $\mathbf{H}_{I_2,l} \in \mathbb{C}^{|I_2| r \times t}$ represent the channel matrix from the l-th BS to the users in the subsets I_1 and I_2, and $|\cdot|$ represents the number of users in each subset, and thus $(L-1) = |I_1| + |I_2|$. The reason for this grouping will be detailed in section 3.1.

The signal received by all the users, caused by the transmission from the l-th BS can be expressed as

$$\begin{bmatrix} \hat{\mathbf{u}}_l \\ \hat{\mathbf{u}}_{I_1,l} \\ \hat{\mathbf{u}}_{I_2,l} \end{bmatrix} = \mathbf{W}^{rx} \begin{bmatrix} \mathbf{H}_l l \\ \mathbf{H}_{I_1,l} \\ \mathbf{H}_{I_2,l} \end{bmatrix} \mathbf{W}_l^{tx} \mathbf{u}_l + \begin{bmatrix} \mathbf{z}_l \\ \mathbf{z}_{I_1,l} \\ \mathbf{z}_{I_2,l} \end{bmatrix} \quad (4)$$

[1]The assumption is reasonable even for wideband systems, if OFDM transmission is considered.

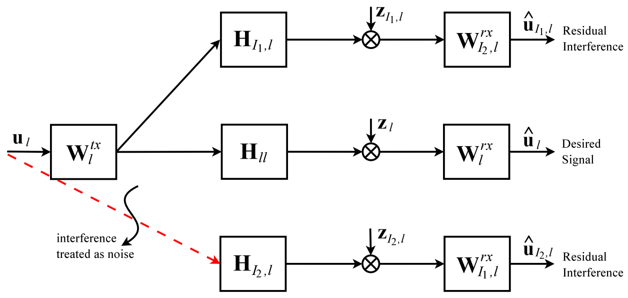

Fig. 1. Improved interference aware scheme for l-th BS.

where

$$\mathbf{W}^{rx} = \mathrm{blkdiag}\Big(\mathbf{W}_l^{rx}, \mathbf{W}_{I_1(1)}^{rx}, \ldots, \mathbf{W}_{I_1(|I_1|)}^{rx}, \mathbf{W}_{I_2(1)}^{rx}, \ldots, \mathbf{W}_{I_2(|I_2|)}^{rx}\Big) \quad (5)$$

is a block diagonal matrix with the receiver filter of each of the users $\mathbf{W}_l^{rx}$. This formulation will be used by the transmitter in order to design the precoding matrix, *cf.* section 3.2.

3. IMPROVED INTERFERENCE AWARENESS

3.1. Topological selection

Since the precoding matrix $\mathbf{W}_l^{tx}$ contains t dimensions to deal with the interference received by the $(L-1)\,r$ receive antennas of the users outside the l-th cell, it can easily be checked from (4) that the interference cannot be totally removed when $t < (L-1)\,r$, which usually is the case in cellular networks [2]. With the aim to maximize the dimensional efficiency of each precoder, the proposed scheme makes a topological processing of the information available at the BS, prior to the computation of the transmit filters.

Based on the Frobenius norm of the channel from the BS to every user in the system, the BS will be able to select those users with the lowest-norm channels. A channel with a low Frobenius norm will mean a user over which the interference that is introduced will not be too high.

In this way, each BS, *e.g.* the l-th BS, ends up with two subsets of users, other than its own: users experiencing a high interference from that BS, in (4) the term $\hat{\mathbf{u}}_{I_1,l}$, and users experiencing a not so important interference from that BS, in (4) the term $\hat{\mathbf{u}}_{I_2,l}$. This can be more easily seen in Fig. 1

In section 3.2, the process to calculate the precoding matrix at a BS is described. The channel matrix that the BS will consider will be just the one corresponding to its own user, and to those users in the group I_1, those with channel matrices $\mathbf{H}_{I_1,l}$ in (4), *i.e.* the channel matrix

[2]The use of cooperation among BSs might enable the use of a higher number of transmit antennas, but in this work no cooperation is studied.

$$\widetilde{\mathbf{H}}_l = \begin{bmatrix} \mathbf{H}_{ll} \\ \mathbf{H}_{I_1,l} \end{bmatrix} \quad (6)$$

3.2. Transmission filter

Based on [8] and [9], the transmission precoder at the l-th BS is obtained by solving the MSE minimization problem

$$\begin{aligned} \underset{\mathbf{W}_l^{tx}}{\text{minimize}} \quad & \mathbb{E}\left\{ \left\| \begin{pmatrix} \mathbf{u}_l \\ \mathbf{0} \end{pmatrix} - \begin{pmatrix} \hat{\mathbf{u}}_l \\ \hat{\mathbf{u}}_{I_1,l} \end{pmatrix} \right\|^2 \right\} \\ \text{subject to} \quad & P_{tx,l} \leq P_{max} \end{aligned} \quad (7)$$

It can be seen that as opposed to the traditional MSE minimization problem, as it will be explained in section 3.3, here not only the signal to the intended user is taken into account, but also the interference introduced in external users is considered. This formulation allows for a solution that is a trade-off between applying a ZF filter in order to cancel the interference to external users and applying an MMSE filter to the intended user.

From [8], the solution to this optimization problem is given by

$$\mathbf{W}_l^{tx} = \beta_l \left(\widetilde{\mathbf{H}}_l \widetilde{\mathbf{W}}_l^{rx} \widetilde{\mathbf{W}}_l^{rx\,H} \widetilde{\mathbf{H}}_l^H + \alpha_l \mathbf{I}_r \right)^{-1} \mathbf{H}_l^H \mathbf{W}_l^{rx\,H} \quad (8)$$

where β_l is a normalization factor that ensures that the power constraint in (7) is met, $\alpha_l = \text{Tr}(\mathbf{W}_l^{rx} \mathbf{W}_l^{rx\,H})/P_{max,l}$, and $\widetilde{\mathbf{W}}_l^{rx}$ is a block diagonal matrix formed with the receiver filter at the intended user and those at all the users in the subset $I_1 = \{I_1(1), \ldots, I_1(|I_1|)\}$

$$\widetilde{\mathbf{W}}_l^{rx} = \text{blkdiag}\left(\mathbf{W}_l^{rx}, \mathbf{W}_{I_1(1)}^{rx}, \ldots, \mathbf{W}_{I_1(|I_1|)}^{rx} \right) \quad (9)$$

3.3. Receiver filter

At the receiver, each user will have complete CSIR, *i.e.* the user at the l-th cell will know the channels $\mathbf{H}_{lm}$ with $m = \{1, \ldots, L\}$. Each user will be listening to the transmission from all the BSs, so that it will be able to estimate this channel with not much difficulty.

With this knowledge, each user will calculate its receiver filter $\mathbf{W}_l^{rx}$ as the well-known MMSE receiver which is given by the expression [9]

$$\mathbf{W}_l^{rx} = \mathbf{W}_l^{tx\,H} \mathbf{H}_{ll}^H \left(\mathbf{H}_{ll} \mathbf{W}_l^{tx} \mathbf{W}_l^{tx\,H} \mathbf{H}_{ll}^H + \mathbf{R}_{I,l} \right)^{-1} \quad (10)$$

where the interference plus noise covariance matrix $\mathbf{R}_{I,l}$ can be calculated from (1) as

$$\mathbf{R}_{I,l} = \sum_{\substack{m=1 \\ m \neq l}}^{L} \mathbf{H}_{lm} \mathbf{W}_m^{tx} \mathbf{W}_m^{tx\,H} \mathbf{H}_{lm}^H + \mathbf{R}_{n,l} \quad (11)$$

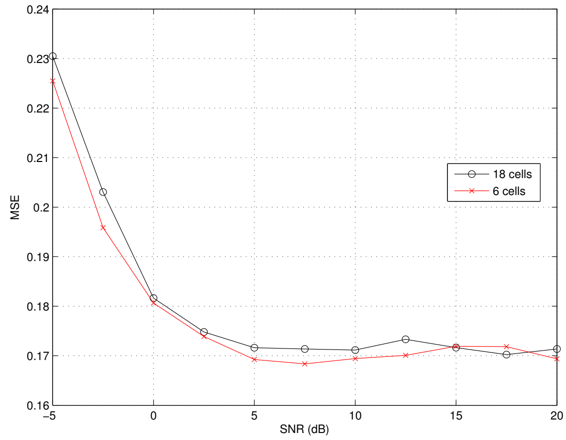

Fig. 2. MSE for a scenario with 8 transmit antennas and 2 receive antennas.

4. RESULTS

The scenario considered for the simulations consist of 19 cells, placed in a hexagonal grid, as two tiers surrounding a central cell. The resuls are calculated for the cell at the center of the scenario, so that no border-effects are observed.

Fig. 2 and 3 show the results of considering all the 18 interfered cells when calculating the precoding matrix at the central cell, and the case of using only the information from the 6 cells where the interference is the strongest. It can be seen how the performance of the network is barely modified even though less users are considered at each BS, which impacts directly in the CSIT estimation and feedback requirements.

The costs associated to channel estimation for a full CSIT transmission and the proposed interference aware schemes are depicted in Fig. 4. Following the cost functions proposed in [10], the overhead costs are

$$\theta_{F-CSIT} = Lt\theta_{csi} + Lt\theta_{fb} + L\theta_{cd} \quad (12)$$
$$\theta_{I-AW} = t\theta_{csi} + t\theta_{fb} + L\theta_{cd} \quad (13)$$

for full CSIT and interference aware, respectively, where θ_{csi} is the ratio of pilots used for estimation to the total number of subcarriers, θ_{fb} is the cost of feedback channel, and θ_{cd} is the cost of coherent detection. Assuming an OFDM system with $N_c = 1024$ subcarriers, 50 frames are sent after CSIT estimation, and a feedback cost of $\theta_{fb} = 0.5\,\%$, Fig. 4 shows the cost associated to channel estimation with respect to the number of BSs deployed in the cellular network when they are equipped with 4 and 8 transmit antennas. It can be seen that the proposed scheme saves a large amount of network resources as the number of BSs increases.

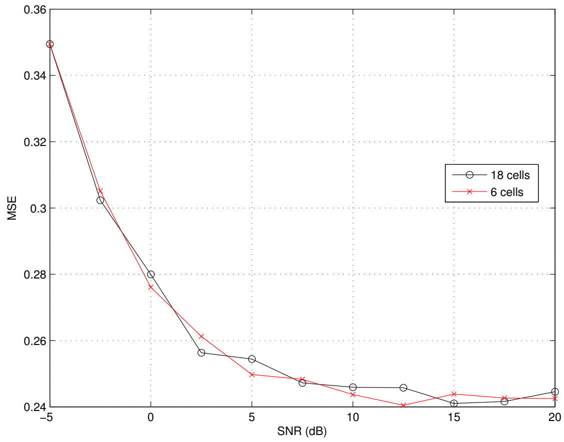

Fig. 3. MSE for a scenario with 4 transmit antennas and 2 receive antennas.

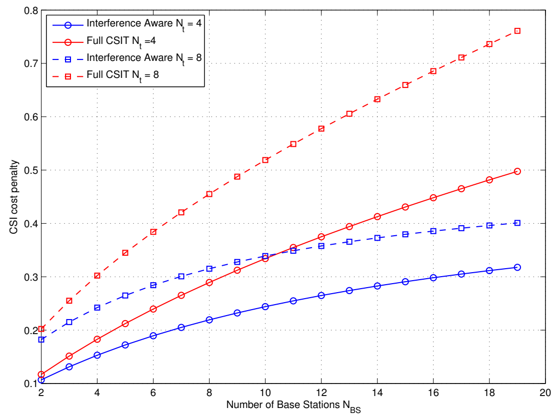

Fig. 4. CSIT and CSIR overheads penalty for full CSIT and interference aware schemes

5. CONCLUSIONS

A topological selection scheme has been proposed in order to reduce the complexity of the interference aware precoding from previous works. As a result, the performance of the network, in terms of MSE, is maintained, and sometimes even improved, while the need for high speed high bandwidth signalling is highly alleviated.

The interference aware system from [8] and [9] already reduced the need for backhaul capacity, with respect to fully cooperative schemes such as ZF and BD, as no user data needs to be exchanged among the BS among the BSss. The topological selection at the BS reduces then the amount of CSIT information that is shared among the BS as well.

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