MULTI–USER DOWNLINK PRECODING IN FDD SYSTEMS WITHOUT CHANNEL FEEDBACK

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ABSTRACT

In this contribution we present a new method for multi–user MIMO downlink precoding in Frequency Division Duplex (FDD) systems. In order to avoid channel feedback, we estimate the long term channel statistics (spatial covariance matrix) based on the received uplink data. Afterwards we transform the receive spatial covariance matrix to the downlink frequency and use this data to calculate an equivalent channel. This enables us to use every robust multi–user MIMO precoding technique, e.g., Regularized Block Diagonalization (RBD) for the downlink transmission. Thereby it is possible to use Dominant Eigenmode Transmission or to transmit the data over multiple streams. Therefore a better performance compared to current state of the art methods can be achieved.

1. INTRODUCTION

Multi User – Multiple Input Multiple Output schemes can fulfill the challenging requirements for future communication systems, as higher data rates can be achieved by exploiting the spatial dimension (SDMA – Space Division Multiple Access). For the uplink several multi – user techniques have been proposed in order to distinguish between the signals from different users at the base station. However, similar algorithms are also required for the downlink. Especially in Frequency Division Duplex (FDD) systems it is very challenging to achieve the same performance gains due to the frequency gap. Reasons for this are the uncorrelated fading in the uplink and downlink and the frequency dependent array response. As a consequence, the direct reuse of the uplink antenna weights for the downlink transmission is not sufficient [1].

In order to avoid channel feedback, current state of the art algorithms estimate the second order long term channel statistics on the uplink and transform them to the downlink frequency. For the transformation of the channel statistics several algorithms have been proposed [2]. Afterwards beamforming methods, e.g. the Generalized Eigenmode Beamformer (GEBF) [3] are applied to serve the user on the downlink. However, these beamforming algorithms cannot fully exploit the spatial domain of the channel, as they are restricted to send the signal energy only towards one dominant Direction Of Arrival (DOA) [2]. Therefore these methods cannot send the data over multiple streams on the downlink. Moreover, these beamforming techniques are sensitive against imperfections in the second order channel statistics. Hence they are outperformed by robust multi–user precoding techniques as, e.g., RBD or SMMSE [4, 5].

In order to overcome these problems we propose the following downlink precoding scheme. In the first step, we estimate the second order channel statistics (spatial covariance matrix) based on the received uplink data on the base station. For the transformation of these channel statistics to the downlink frequency we use the Spatial Covariance Matrix Transformation (SCMT). Please note, that any other state of the art algorithm could be used for this transformation. Afterwards, we use the transformed covariance matrix to calculate the equivalent channel for the downlink. This enables us to perform any precoding technique, e.g., RBD [4], and thereby fully exploit the spatial structure of the channel.

This Paper is organized as follows: Section 2 introduces the data model and clarifies how to estimate the receive spatial covariance matrices. Section 3 describes the Spatial Covariance Matrix Transformation [1] and the Generalized Eigenmode Beamformer (GEBF) [3]. In Section 4 we proposed a new downlink precoding scheme and show its performance based in simulations. Finally the conclusions are drawn in Section 5.

To facilitate the distinction between scalars, vectors, and matrices, we use the following notation: scalars are denoted by lower–case italic letters (a, b, ...), vectors by boldface lower–case italic letters (a, b, ...), and matrices by boldface upper–case letters (A, B, ...). This notation is consistently used for lower–order parts of a given structure. For example, the i–th column vector of the matrix A is denoted as a_i. As indices, mainly the letters i, j, k, and n are used. The upper bounds for these indices are given by the upper–case letters I, J, K, and N, unless stated otherwise.

2. DATA MODEL

We assume a Multiple Input Multiple Output (MIMO) system, where K coexisting users are served on the same frequency and time slot. The received signal x_k(t) for the k–th user at the time t is given as

\[ x_k(t) = H_k(t, f) \cdot s_k(t) + n(t) , \tag{1} \]
where \( H_k(t, f) \in \mathbb{C}^{M_R \times M_T} \) is the matrix of time and frequency varying channel coefficients. Furthermore \( M_R \) and \( M_T \) are the number of receive and transmit antennas, respectively. With \( s_k(t) \in \mathbb{C}^{M_R \times 1} \) we denote the vector of transmitted symbols, and \( n(t) \in \mathbb{C}^{M_R \times 1} \) is the noise vector. Please note that the matrix of channel coefficients \( H_k(t, f) \) for the user \( k \) also includes the influences of the antenna arrays at the receiver and the transmitter. The spatial covariance matrix \( R_k(f) \in \mathbb{C}^{M_R \times M_R} \) (second order statistics) at the receiver is defined as

\[
R_k(t, f) = E\{H_k(t, f)H_k^H(t, f)\}, \tag{2}
\]

where \( E\{\cdot\} \) is the expectation operator and \((\cdot)^H\) denotes the Hermitian transpose. An estimate of this matrix on the uplink frequency \( f_u \) can be computed by

\[
\hat{R}_k(f_u) = \frac{1}{T_W} \sum_{n=1}^{T_W} H_k(t_n, f_u)H_k^H(t_n, f_u), \tag{3}
\]

where \( T_W \) is the number of time samples \( t_n \) within a time chunk of the frequency selective channel \( H_k(t, f) \). Therefore we assume that the channel is block-wise stationary along time.

### 3. Spatial Covariance Matrix Transformation and Generalized Eigenmode Beamforming

In order to solve the downlink beamforming problem without channel feedback, we have to estimate the second order statistics of the mobile radio channel \( H_k(t, f_u) \) on the uplink frequency \( f_u \) with the help of equation (3). These covariance matrices can be transformed to the downlink frequency \( f_d \) using the Spatial Covariance Matrix Transformation (SCMT), first presented in [1].

#### 3.1. Spatial Covariance Matrix Transformation

For the transformation of the uplink covariance matrix \( \hat{R}_k(f_u) \) we estimate the azimuthal power spectrum (APS) for each user \( k \) by applying the Minimum Variance Distortionless Response filter (also called Capons beamformer) [6]. The APS for the \( k \)-th user is given by

\[
\hat{P}_k(\theta) = \frac{1}{a^H(\theta, f_u) \cdot R_k^{-1}(f_u) \cdot a(\theta, f_u)}, \tag{4}
\]

where \( a(\theta, f_u) \in \mathbb{C}^{M_R \times 1} \) is the base station array response for the azimuth angle \( \theta \) and the uplink frequency \( f_u \). In order to extract the main Direction Of Arrival (DOA) from the APS \( \hat{P}_k(\theta) \) and to increase the nulling capabilities of beamforming algorithms, an APS - shaping step has been introduced in [1]. This is done by applying a windowing function \( W(\theta) \) to the estimated APS.

\[
\hat{P}_{k,\text{mod}}(\theta) = \hat{P}_k(\theta) \cdot W(\theta). \tag{5}
\]

Assuming that this modified APS is constant over the frequency gap of the FDD system, we can reconstruct the spatial covariance matrix on the downlink frequency \( f_d \) by using

\[
\hat{R}_k(f_d) = \int_{\theta} \hat{P}_{k,\text{mod}}(\theta) \cdot a(\theta, f_d)a^H(\theta, f_d)d\theta. \tag{6}
\]

Here we assume that the signal paths of different azimuthal directions \( \theta \) are uncorrelated. Please note that the SCMT requires the knowledge of the complete base station antenna array manifolds for the uplink and downlink frequency.

#### 3.2. Generalized Eigenmode Beamforming on the Downlink

In order to apply the Generalized Eigenmode Beamformer (GEBF) [3] on the downlink as proposed in [1] we have to estimate the signal covariance matrix \( \hat{R}_k(f_u) \) of the user \( k \) with equation (3). Additionally, we have to calculate the signal plus interference plus noise covariance matrix \( \hat{Q}(f_u) \) on the uplink frequency by using

\[
\hat{Q}(f_u) = \sum_{i=1}^{K} \hat{R}_i(f_u) + \sigma_n^2 \cdot I, \tag{7}
\]

where \( K \) denotes the total number of users, \( \sigma_n^2 \) is the noise variance and \( I \in \mathbb{C}^{M_R \times M_R} \) is the identity matrix. Afterwards, we have to transform these covariance matrices to the downlink frequency \( f_d \) by applying the SCMT from Section 3.1.

\[
\hat{R}_k(f_d) = \text{SCMT}\{\hat{R}_k(f_u), W_R(\theta)\}, \tag{8}
\]

\[
\hat{Q}_k(f_d) = \text{SCMT}\{\hat{Q}(f_u), W_Q(\theta)\}, \tag{9}
\]

where \( \text{SCMT}\{\hat{R}_k(f_u), W_t(\theta)\} \) denotes the Spacial Covariance Matrix Transformation of the matrix \( \hat{R}_k(f_u) \) with the APS shaping window \( W_R(\theta) \). Please note that the downlink beamforming algorithm as proposed in [1] uses a different APS shaping window for the transformation of the latter covariance matrices. For the signal covariance matrix \( \hat{R}_k(f_u) \) a rectangular window with the width 2\( \xi \) centered around the main direction of arrival \( \Theta_{k,\text{dom}} \) for the user \( k \) is used

\[
W_R(\theta) = \text{rect}\{\Theta_{k,\text{dom}} - \xi, \Theta_{k,\text{dom}} + \xi\}, \tag{10}
\]

The interference plus noise covariance matrix \( \hat{Q}_k(f_d) \) for the user \( k \) on the downlink frequency is calculated with the SCMT of the signal plus interference plus noise covariance matrix \( \hat{Q}(f_u) \) using the inverse rectangular window 1 - \( W_R(\theta) \)

\[
W_Q(\theta) = 1 - \text{rect}\{\Theta_{k,\text{dom}} - \xi, \Theta_{k,\text{dom}} + \xi\}. \tag{11}
\]

Then the beamforming vector \( w_k \) for the \( k \)-th user on the downlink is given by

\[
w_k = \arg \max_w \left\{ \frac{\hat{w}^H \cdot \hat{R}_k(f_d) \cdot w}{\hat{w}^H \cdot \hat{Q}_k(f_d) \cdot w} \right\}. \tag{12}
\]

Please notice that this downlink beamforming method requires the knowledge of the parameters \( \Theta_{k,\text{dom}} \) and \( \xi \) of
the APS shaping window. Simulations have shown that the performance of the method is very sensitive against errors in the estimation of these parameters. Due to this the method behaves unstable in practical systems. Furthermore this APS shaping step requires that the signal of the user \( k \) impinges only from one dominant direction of arrival \( \Theta_{k,\text{dom}} \).

### 4. DOWNLINK PRECODING BASED ON THE SCMT

In order to overcome the restrictions (as stated in Section 1) of the current state of the art downlink beamforming methods, we propose the following downlink precoding scheme. In the first step we estimate the uplink covariance matrices \( \hat{\mathbf{R}}_k(\mathbf{f}_d) \) for every user \( k \) by using equation (3). Afterwards, we transform these covariance matrices to the downlink frequency \( \mathbf{f}_d \), e.g., by applying the Spatial Covariance Matrix Transformation as presented in Chapter 3.1.

\[
\hat{\mathbf{R}}_k(\mathbf{f}_d) = \text{SCMT} \left\{ \mathbf{R}_k(\mathbf{f}_d) \right\}.
\]

Please note that we drop the APS shaping step (\( W(\Theta) = 1 \)) for the SCMT, which makes the algorithm much more stable. Based on these downlink covariance matrices we can calculate an equivalent downlink channel \( \bar{\mathbf{H}}_k(\mathbf{f}_d) \) for the \( k \)-th user by applying a singular value decomposition (SVD) to equation (13).

\[
\bar{\mathbf{H}}_k(\mathbf{f}_d) = \mathbf{U}_k \cdot \mathbf{\Sigma}_k \cdot \mathbf{U}_k^H = \mathbf{H}_k(\mathbf{f}_d) \cdot \mathbf{H}_k^H(\mathbf{f}_d).
\]

Here the equivalent downlink channel \( \mathbf{H}_k(\mathbf{f}_d) \in \mathbb{C}^{M_k \times r} \) including \( r \) different streams is given as

\[
\mathbf{H}_k(\mathbf{f}_d) = \begin{bmatrix} \mathbf{u}_{k_1}, \ldots, \mathbf{u}_{k_r} \end{bmatrix} \cdot \text{diag} \left\{ \sqrt{\sigma_1}, \ldots, \sqrt{\sigma_r} \right\},
\]

where \( \mathbf{u}_{k_r} \) denotes the \( r \)-th singular vector and \( \sigma_r \) is the \( r \)-th singular value of the covariance matrix \( \mathbf{R}_k(\mathbf{f}_d) \), respectively. Note that in the case of dominant eigenmode transmission (DET) we get

\[
\mathbf{H}_k(\mathbf{f}_d) = \mathbf{u}_{k_1} \cdot \sqrt{\sigma_1}.
\]

With the help of this equivalent channel we can serve the users via any precoding technique, e.g., Regularized Block Diagonalization [4]. Thus it is possible to fully exploit the spatial dimension of the channel on the downlink frequency.

#### 4.1. Simulations

The simulation environment models a suburban 2 user scenario generated with the IlmProp, cf. [7]. This is a flexible geometry based channel model capable of generating frequency selective time variant multi-user MIMO channels displaying realistic correlation in frequency, time, space, and between users. The simulation scenario is depict in Figure 1. The positions of the User Terminals (UT) are marked with the blue spheres (upper part of the figure), while the position of the Base Station (BS) is marked with the red sphere in the lower part of the figure. Each user terminal is surrounded by a cluster of 20 point like scatterers, highlighted by the small green spheres. The users are moving on the blue trajectories with a speed \( \frac{\mathbf{v}}{2} \). The systems works at a center frequency of 2 GHz with a duplex distance of 120 MHz. Each user has a line of sight, and is equipped with one omnidirectional antenna, while the base station has a 12 – element Uniform Linear Array (ULA).

![IlmProp Geometry with two user terminals (UT) depict by the blue spheres in the upper part of the figure. Each user terminal is surrounded by a cluster of 20 point like scatterers (small green spheres). The base station (BS) is depict by the red sphere in the lower part of the figure. It is equipped with a 12 element Uniform Linear Array (ULA).](image)

The Cumulative Density Functions (CDF) of the reached Signal to Interference and Noise Ratio (SINR) for User 1 are shown. The proposed algorithm clearly outperforms the SCMT based GEBF [1], and almost reaches the optimum SINR.

![Downlink beamforming performance for the SCMT based Generalized Eigenmode Beamformer (GEBF) [1] and the SCMT based RBD downlink precoding as proposed in Section 4. The Cumulative Density Functions (CDF) of the reached Signal to Interference and Noise Ratio (SINR) for User 1 are shown. The proposed algorithm clearly outperforms the SCMT based GEBF, and nearly reaches the optimum performance.](image)

**5. CONCLUSIONS**

In this paper, we have presented a new downlink precoding scheme for FDD systems without channel feedback. It is based on the transformation of the long term channel statis-
tics from the uplink to the downlink frequency via a modified Spatial Covariance Matrix Transformation (SCMT). By introducing the equivalent downlink channel, it is possible to use any multi-user MIMO precoding algorithm (e.g., Regularized Block Diagonalization) to serve the users on the downlink frequency. Thereby we can use Dominant Eigenmode Transmission (DET) or send the signal over multiple streams. Thus we can fully exploit the spatial domain of the channel on the downlink. Furthermore, we can benefit from the performance of robust precoding techniques in the case of imperfect channel state information.

6. REFERENCES


