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PCA-Aided Precoding for Correlated MIMO Broadcast Channels

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***Abstract* – In this paper, we propose an efficient precoding solution for a correlated Multi-Input Multi-Output (MIMO) broadcast channels. Indeed, we apply the principal component analysis (PCA) to uncorrelate (whiten) the channel prior to codeword selection. As such, the channel state information at the transmitter (CSIT), picked up through finite-rate feedback, corresponds to the uncorrelated channel version. Thus, the optimality of the approach. The simulation results compared with conventional MIMO precoders for various levels of spatial correlation as well as different receive antenna settings, show that the proposed scheme provides greater system performance enhancement in terms of sum rate.**

Index Terms- MIMO broadcast channel, precoding, correlated channel, principal component analysis.

I. INTRODUCTION

The use of Multi-Input Multi-Output (MIMO) technique has attracted a great interest in the research, since it provides an increase in the spectral efficiency and/or the transmission reliability [1], [2]. These benefits can be, furthermore, improved when the channel state information at the transmitter (CSIT) is available [3]. In the literature, the technique that targets these advantages by exploiting CSIT is referred to precoding. Furthermore, precoder design depends on the level and the kind of CSIT which it is not trivial to have.

For instance, in the frequency division duplexing (FDD) mode, where the broadcast channel and the multiple access channel occupy different frequency bands, the most convenient way to acquire CSIT is to estimate the channel state information at the receiver (CSIR), and from a predefined codebook, the receiver chooses a codeword corresponding to the CSIR. Once done, the receiver feeds back the index of the selected codeword to the transmitter through a low bandwidth feedback channel, hence the precoding with limited feedback [4], [5].

Recently, limited feedback techniques in Multi-User MIMO systems have been introduced in several standards such as IEEE 802.16 e/m [6], [7] and LTE-Advanced [8]. In these systems, the base station (BS) is equipped with an array of antennas, and the mobile stations (MS) may be equipped with one or more antennas, in which the space division multiple access (SDMA) allows for simultaneous communication while sharing the same time-frequency resource via the appropriate utilization of spatial dimensions [9].

The practical issues in Multi-User MIMO systems with limited feedback have been less addressed in the literature. For instance, in realistic wireless communication systems, the closely spaced antenna array, propagation and local scattering environment may exhibit very large correlation properties of the channels [10]. Consequently, some codebooks like Grassmannian line packing (GLP) codebook, designed for independent and identically distributed (i. i. d.) Rayleigh fading channels are very sensitive to this kind of scenario. Although there exist a modified version of these codebooks [11], designed especially for correlated channels. However, the precoding in such context requires additional knowledge of channel covariance. Furthermore, Discrete Fourier Transform (DFT) based codebook does not need the channel statistic, and it is shown a near optimal performance in a highly correlated channel [12], [13]. However, this codebook does not perform well in a fewer correlated or uncorrelated channels. Hence, the use of hybrid codebooks [14]. On the other hand, another solution for the correlated channel consists of creating adaptive codebooks. To this end, the codebooks are adjusted according to the spatial correlation matrix [15], [16], [17], [18], [19]. It is well-known that the adaptive codebook provides a good performance in correlated channels. Nevertheless, it requires knowledge of the covariance matrix at both the BS and the MS. In addition, the search of the adaptive codebook and the matching of the latter at both ends of the wireless links require additional computational complexity, since it is done on-line. In this paper, we propose an efficient precoding approach based on the principal component analysis (PCA). The proposed precoding aims to remove the correlation from the channel before codeword selection process. Moreover, it can be applied for various correlated channels without the feedback of spatial correlation matrix or changing the codebook at each channel realization while assuring a low complexity processing.

The paper is organized as follows; Section II addresses the signal model, while section III discusses the PCA-aided precoding design. The simulation results are provided in section IV. Final a conclusion is drafted in section V.

II. SYSTEM MODEL

A. Multi-User MIMO System with Limited Feedback

We consider a MIMO broadcast channel with one BS, equipped with $N_t > 1$ antennas, and K users (MS) with $N_r \geq 1$ antennas each, as depicted in Fig. 1. At the receiver, the base-band signal for the k^{th} user is given as

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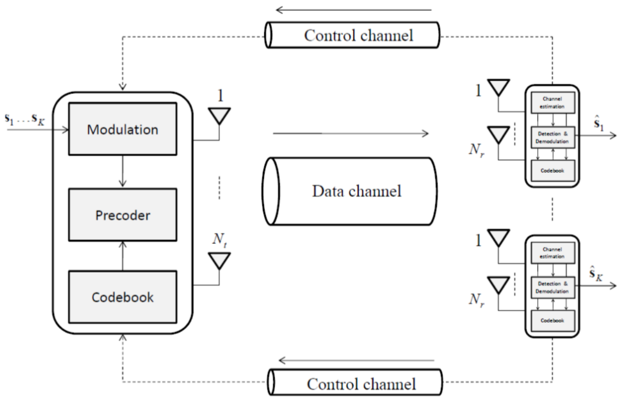

Fig. 1 Broadcast MIMO Channel.

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{x} + \mathbf{n}_k, \qquad k = 1, \cdots, K \tag{1}$$

where $\mathbf{H}_k \in \mathbb{C}^{N_r \times N_t}$ is the k^{th} channel matrix, which is assumed to be correlated fading channel (note that we use a raw vector $\mathbf{h}_k \in \mathbb{C}^{1 \times N_t}$ for a single receiving antenna case). The details on these channels are given a little further. $\mathbf{x} \in \mathbb{C}^{N_t \times 1}$ is the precoded data signal and $\mathbf{n}_k$ denotes the noise terms according to independent complex Gaussian distribution with unit variance.

In this paper, we consider a full knowledge of CSIR at each user. In addition, we assume that there is no cooperation between the users, i.e., there is no information about the channels of other users. However, at the BS, the CSIT comes through the feedback. Thereby, we assume that the control channel is error-free and delay-free.

We consider that a linear precoding is used. In this case, the transmitted signal is a summation of the products formed by the desired signal, s_k and the associated precoding vector, $\mathbf{w}_k \in \mathbb{C}^{N_t \times 1}$. Therefore, the received signal at the k^{th} user can be written as

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{w}_k s_k + \sum_{i \neq k}^{K} \mathbf{H}_k \mathbf{w}_i s_i + \mathbf{n}_k, \tag{2}$$

where the first part of (2) contains the desired data signal for the k^{th} user, while the second part represents the interference caused by the other users, and the last part is the background noise.

The received signal-to-interference and noise ratio (SINR) for the kth user is

$$SINR_k = \frac{\frac{P}{N_t}\left|\mathbf{H}_k^H \mathbf{w}_k\right|_2^2}{\sum_{i \neq k}^{K} \frac{P}{N_t}\left|\mathbf{H}_k^H \mathbf{w}_i\right|_2^2 + 1}, \tag{3}$$

where P represents the total transmit power, which must satisfy the following constraint

$$E\left[\left|\mathbf{W}\mathbf{s}\right|_2^2\right] = Tr\left(\mathbf{W}\mathbf{W}^H\right) \leq P, \tag{4}$$

Where $\mathbf{W} = \left[\mathbf{w}_1, \ \mathbf{w}_2, \ \cdots, \ \mathbf{w}_K\right]$ denotes the precoding matrix, which is formed by the concatenation of the K precoding vectors and $\mathbf{s} = \left[s_1, \ s_2, \ \cdots, \ s_K\right]^T$.

The downlink sum rate is thus given as follows

$$R_{sum} = \sum_{k=1}^{K} \log_2\left(1 + SINR_k\right). \tag{5}$$

In the limited feedback technique, at the receiver, the chosen codeword may represent the quantified version of the channel or the precoder vector, depending on the number of receiver antennas.

For one receive antenna ($\mathbf{h}_k \in \mathbb{C}^{1 \times N_t}$), we adopt the same approach as depicted in [20]. First of all, each user quantizes its own channel to B bits using the Random Vector Quantization (RVQ) codebook, noted C, which consists of 2^B i.i.d. complex Gaussian distribution on the N_t-dimensional unit norm vectors (ie $N_t \times 1$ vectors) $C \triangleq \left\{\mathbf{c}_1, \ \cdots, \ \mathbf{c}_{2^B}\right\}$. It is important to note that, in this study, the common codebook is used in both the transmitter and the receivers.

For the channel quantization, the selection criterion is based on the minimization of the angle between the channel and the codeword of the codebook C.

$$\left\{\tilde{\mathbf{h}}_k \middle| k = 1, \cdots, K\right\} = \arg\min_{j=1,\cdots,2^B} \sin^2\left(\angle\left(\mathbf{h}_k, \mathbf{c}_j\right)\right). \tag{6}$$

The equation (6) can be written as follows

$$\left\{\tilde{\mathbf{h}}_k \middle| k = 1, \cdots, K\right\} = \arg\max_{j=1,\cdots,2^B} \left|\mathbf{h}_k \mathbf{c}_j\right|. \tag{7}$$

After that, the BS is made aware of the quantization decision, $\tilde{\mathbf{h}}_k, k = 1, \cdots, K$, through finite-rate feedback of B bits per user. Based on this information, the BS creates the precoding matrix, $\mathbf{W}$, using Zero-Forcing Beamforming (ZFBF), such as

$$\mathbf{W} = \frac{1}{\left\|\tilde{\mathbf{H}}\right\|_2} \tilde{\mathbf{H}}^{\dagger}, \tag{8}$$

where $\tilde{\mathbf{H}}$ denotes the matrix consisting of the quantization of the channels given by $\tilde{\mathbf{H}} = \left[\tilde{\mathbf{h}}_1, \ \cdots, \ \tilde{\mathbf{h}}_K\right]$ and $\tilde{\mathbf{H}}^{\dagger}$ denotes its pseudo-inverse.

Finally, the BS makes a linear combination of each precoding vector with the associate k^{th} transmitted signal as follows

$$\mathbf{x} = \sum_{k=1}^{K} \mathbf{w}_k s_k. \tag{9}$$

For the multiple receive antennas case ($\mathbf{H}_k \in \mathbb{C}^{N_r \times N_t}$), at each receiver side, we aim to feedback a quantized channel, $\tilde{\mathbf{H}}_k, k = 1, \cdots, K$, which maximizes the receive SNR.

$$\left\{\tilde{\mathbf{H}}_k \middle| k = 1, \cdots, K\right\} = \arg\max_{j=1,\cdots,2^B} \left\|\mathbf{H}_k \mathbf{c}_j\right\|_2^2 \tag{10}$$

After that, each MS sends the selected codeword index to the BS. The latter performs the precoded data signal.

B. Correlated Channel Model

For MIMO systems with N_t transmit antennas and N_r receive antennas, the correlated channel can be modeled as

$$\mathbf{H} = \Sigma_r^{1/2} \mathbf{H}^{(iid)} \Sigma_t^{1/2}, \quad (11)$$

where $\Sigma_r \in \mathbb{C}^{N_r \times N_r}$ and $\Sigma_t \in \mathbb{C}^{N_t \times N_t}$ are the correlation matrices for the receiver and the transmitter antennas, respectively. $\mathbf{H}^{(iid)} \in \mathbb{C}^{N_r \times N_t}$ is the i. i. d. flat fading Rayleigh channel matrix. For the sake of simplicity, we assume that $\Sigma_r = \Sigma_t = \Sigma$ in the case of two transmit antennas and two receive antennas so the correlation matrix is

$$\Sigma = \begin{bmatrix} 1 & \rho \\ \rho & 1 \end{bmatrix}, \quad (12)$$

where ρ represents the correlation coefficient.

III. Principal Component Analysis Aided Precoding Design

In this paper, we propose a low complexity approach to address the problem of the correlated fading in MIMO broadcast channels. The proposed approach is based on the application of PCA model, which is considered as a robust method in data analysis. Indeed, with the use of PCA, the choice of the precoding vectors is done with the consideration of the uncorrelated version of the channel. Therefore, unlike [15], [16], [17], [18], it is not necessary to change the codebook according to the kind of the channel or to estimate the spatial correlation matrix at each channel realization. This makes our proposal a practical solution for MIMO correlated channels.

Moreover, the proposed approach can be applied easily at both single and multiple receive antennas.

A. Single Receive Antenna

For a single receives antenna setup, i.e. $\Sigma_r = 1$. First of all, we proceed by centering the estimated CSIR. Centering or mean subtraction represents an integral part of PCA method. In this step, we remove the mean of each dimension. Therefore, the centered variable has zero mean $\bar{\mathbf{h}}_k$ given by,

$$\bar{\mathbf{h}}_k = \mathbf{h}_k - E[\mathbf{h}_k]. \quad (13)$$

After that, we find the $N_t \times N_t$ covariance matrix as,

$$\mathbf{\Psi}_k = E\left[\bar{\mathbf{h}}_k^H \bar{\mathbf{h}}_k\right]. \quad (14)$$

We then apply a singular value decomposition to $\mathbf{\Psi}_k$

$$\mathbf{\Psi}_k = \mathbf{V}_k \mathbf{\Lambda}_k \mathbf{U}_k^H, \quad (15)$$

where $\mathbf{\Lambda}_k$ is a diagonal matrix containing the singular values of $\mathbf{\Psi}_k$. $\mathbf{V}_k$ and $\mathbf{U}_k$ are the left and the right singular matrices of $\mathbf{\Psi}_k$, respectively.

Finally, unlike Eq. (7), we select the optimal codeword, which corresponds to the quantified version of the uncorrelated channel, noted by $\mathbf{h}_k \mathbf{U}_k$, such as

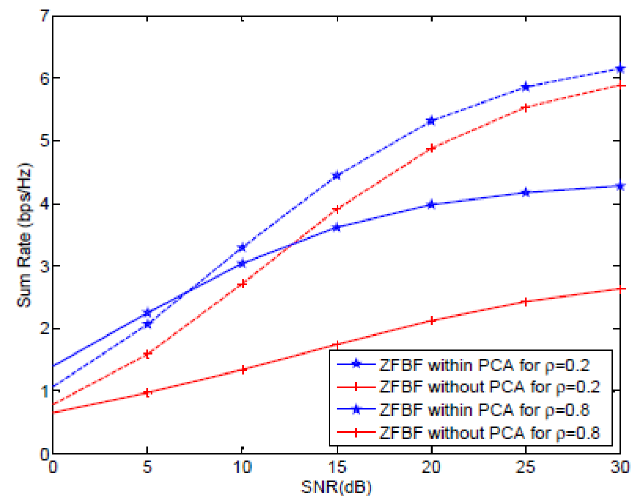

Fig. 2 Sum Rate for MIMO Broadcast channels with N_t=2, N_r=1, K=2, B=4-bit for ZFBF within and without PCA for various levels of spatial correlation, ρ=0.8 (continuous line) and ρ=0.2 (dashed line).

$$\left\{\tilde{\mathbf{h}}_k \middle| k = 1, \cdots, K\right\} = \arg \max_{j=1,\cdots,2^B} \left|\mathbf{h}_k \mathbf{U}_k \mathbf{c}_j\right|. \quad (16)$$

B. Multiple Receive Antennas

A special feature of our proposal is that it can be easily extended to multiple receive antennas scenario. Indeed, the centering and the whiting steps can be done by using Eq. (13), (14) and (15). Unlike Eq. (10), the selected precoding vectors can be obtained from the quantized feedbacks, $\tilde{\mathbf{H}}_k, k = 1, \cdots, K$, given by,

$$\left\{\tilde{\mathbf{H}}_k \middle| k = 1, \cdots, K\right\} = \arg \max_{j=1,\cdots,2^B} \left\|\mathbf{V}_k^H \mathbf{H}_k \mathbf{U}_k \mathbf{c}_j\right\|_2^2, \quad (17)$$

where $\mathbf{V}_k^H \mathbf{H}_k \mathbf{U}_k$ represents the uncorrelated channel.

IV. Performance Results

This section presents the performance evaluation comparing the sum rate achieved with the proposed scheme and the conventional multi-user MIMO precoders.

A. Single Receive Antenna

We consider a MIMO broadcast channel where the BS is equipped with two transmitter antennas by which it is transmitted to two simultaneous users with equal power. Each MS is equipped with one receiver antenna. We also assume that the channel is correlated quasi-static Rayleigh fading.

In order to show the impact of channel correlation on our scheme, we consider different scenarios, in which ρ takes the values of 0.2 and 0.8 for low and high antenna correlation matrix, respectively. The simulations are conducted using RVQ codebook with size of 16.

Fig. 2 shows the sum rate comparison between the proposed PCA-aided method using ZFBF and the conventional ZFBF, as a benchmark [20]. For a low spatial correlated channel, ρ = 0.2, it can be observed from the figure that our proposal performs better than the benchmark [20]. Thus, at 4 bps/Hz, we observe 2.5 dB of SNR gain.

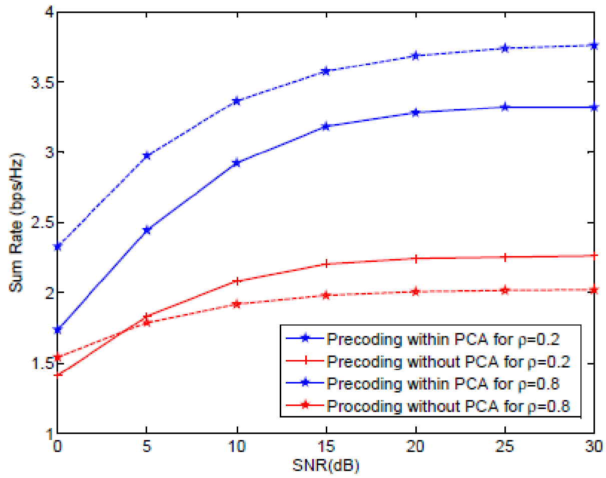

Fig. 3 Sum Rate for MIMO Broadcast channels with N_t=2, N_r=2, K=2, B=4-bit for ZFBF within and without PCA for various levels of spatial correlation, ρ=0.8 (continuous line) and ρ=0.2 (dashed line).

For a high spatial correlated channel, ρ = 0.8, the sum rate achieved with our approach is much higher than the reference method. This is explained by the fact that the channel quantization is applied on already uncorrelated channel. Thus, the optimality of the approach.

B. Multiple Receive Antennas

Now, we consider two receive antennas at each MS. In this context, it should be noted that the two different levels of spatial correlation are applied for both the transmitter and the receiver side, i.e. ρ worth 0.2 and 0.8.

The result in Fig. 3 reinforces our proposal when we use an array of receive antennas in MIMO correlated channel, i.e. both sides of the wireless links are correlated. For a low spatial correlated channel, ρ = 0.2, we observe more than 1 bps/Hz for a high SNR, i.e. when the rates moves towards an upper limit.

For ρ = 0.8, we note that our proposal is still the most efficient. Almost 2 bps/Hz of sum rate gain is observed for a high SNR.

V. Conclusion

In this paper, we proposed an approach that aims at addressing a correlated fading issue in a MIMO broadcast channel. The use of PCA method as a whitening method of the channel matrix is an effective solution, since the selected codeword corresponds to the uncorrelated channel version. In addition, compared to the proposed methods in the literature, our proposal has a low implementation complexity, and it did not need a statistical information about the channel matrix. Moreover, it can be easily extended to multiple receive antennas while performing very well in both the transmitter and the receiver correlation situation. Performance evaluation in terms of sum rate, compared with conventional multi-user MIMO precoders, demonstrates that our approach offers great performance regadless the level of spatial correlation.

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