A Novel Uplink MIMO Transmission Scheme in a Multicell Environment

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***Abstract*—Uplink multiple-input multiple-output (MIMO) transmission scheme is developed for time division duplex (TDD) systems in a multicell environment. We propose a precoding scheme that maximizes the total achievable rate and works in the decentralized manner with only locally available channel state information (CSI) at each transmitter. We first establish and solve a decentralized optimization problem for the case of multiple-input single-output (MISO) channels, introducing a new precoding design metric called *signal to generated interference plus noise ratio* (SGINR). By extending the result to general MIMO channels, we propose an SGINR-based precoding scheme where the number of transmit streams is selected adaptively to the surrounding environments. Simulation results confirm that the proposed precoding scheme offers significant throughput enhancement in multicell environments.**

***Index Terms*—Multicell, multiple-input multiple-output (MIMO), generated interference, precoding.**

I. Introduction

THE intercell interference is often one of the most challenging problems in a cellular system, especially for low frequency reuse factor. Fundamentally, there are two different approaches to handling the intercell interference. The first approach is to adopt interference suppression techniques at the receiver. Another approach is to enforce each transmitter to reduce interference to adjacent cells. In this paper, we focus on the latter approach and develop a new multiple-input multiple-output (MIMO) transmission scheme to handle the intercell interference.

Most of works on MIMO have focused on capacity or diversity improvement in a single cell scenario [1]-[4]. Recently, there have been several works on MIMO in a multicell environment [5]-[9]. In [6], an optimal MIMO transmission strategy was studied in a multicell scenario when the channel state information (CSI) is not available at the transmitter. For the case when the CSI is available at the transmitter, a transmit antenna subset selection was proposed in [7], and precoding schemes were proposed in [8] and [9]. The precoding scheme in [8] attempts to maximize the achievable rate of the own cell without accounting for the interference caused to the other cells, and thus fails to maximize the total achievable rate. On the contrary, the precoding scheme in [9] maximizes the sum of the achievable rates of all the cells. However, it may not be suitable to the uplink scenario, since it works in the centralized manner, requiring a lot of feedback and huge signaling overhead among cells.

In this paper, we focus on developing a decentralized uplink transmission scheme that exploits multiple transmit antennas at the mobile station to mitigate the intercell interference in a multicell environment. To the best of our knowledge, this is the first work to develop a decentralized uplink MIMO transmission scheme in a multicell environment. Specifically, we propose a decentralized MIMO precoding scheme. The proposed scheme is designed to determine a precoding matrix considering not only the desired signal power but also the interference to adjacent cells in order to maximize the total achievable rate. We begin with a rather simple case of multiple-input single-output (MISO) channels to establish a decentralized optimization problem. As a result of the optimization, we derive a new precoding design metric called *signal to generated interference plus noise ratio* (SGINR). The precoding vector that maximizes the SGINR at each transmitter is found to satisfy our optimality criterion in the case of MISO channels. By extending the result to general MIMO channels, we propose an SGINR-based precoding scheme, in which the number of transmit streams is adaptively selected to maximize the total achievable rate.

It must be pointed out that the SGINR metric derived in this paper takes the same form as the signal-to-jamming-and-noise ratio (SJNR) metric in [13] and the signal-to-leakage-and-noise ratio (SLNR) metric in [14], both of which were independently developed in the context of precoding for the multiuser broadcast channel in a single cell environment. In particular, the SJNR-based precoding scheme is restricted to transmit only a single stream per user. The SLNR-based precoding scheme allows multiple transmit streams per user, but the number of transmit streams per user must be fixed to a pre-determined value. Unlike the precoding schemes in [13] and [14], the SGINR-based precoding scheme proposed in this paper provides a solution for selecting the number of transmit streams adaptively to the surrounding environments.

In the proposed precoding scheme, each transmitter calculates its precoding matrix or vector with locally available CSI which can be obtained by exploiting the channel reciprocity of time division duplex (TDD) systems. The proposed scheme works in the decentralized manner, and thus eliminates the need for feedback and signaling among cells. Simulation results will be provided to validate the performance im-

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provement of the proposed precoding scheme in multicell environments.

The rest of this paper is organized as follows. Section II describes the system model and formulates an optimization problem. In Section III, we propose a new precoding scheme for MISO channels in a multicell environment. In Section IV, we extend the MISO precoding to general MIMO channels. Simulation results are presented in Section V, and conclusions are drawn in Section VI.

We define here some notation used throughout this paper. We use boldface capital letters and boldface small letters to denote matrices and vectors, respectively, $(\cdot)^T$ and $(\cdot)^H$ to denote transpose and conjugate transpose, respectively, $\det(\cdot)$ to denote determinant of a matrix, $\mathrm{tr}(\cdot)$ to denote trace of a matrix, $(\cdot)^{-1}$ to denote matrix inversion, $\|\cdot\|$ to denote norm of a vector, $\|\cdot\|_F$ to denote Frobenius norm of a matrix, $\mathbf{I}_N$ to denote the $N \times N$ identity matrix, $\mathrm{diag}(a_1, a_2, \cdots, a_N)$ to denote an $N \times N$ diagonal matrix whose diagonal elements are $a_1, a_2, \cdots, a_N$, and $(x)^+$ to denote $\max(x, 0)$.

II. System Model and Problem Formulation

A. System Model

We consider an uplink MIMO system comprised of L cells. It is assumed that a single mobile station (MS) is selected by a user scheduler at the given time and frequency in each cell. The MS and base station (BS) are equipped with N_t transmit antennas and N_r receive antennas, respectively. The i-th transmitter (the MS in the i-th cell) communicates with the i-th receiver (the BS in the i-th cell) by transmitting $N_s^{(i)}$ streams over N_t transmit antennas using an $N_t \times N_s^{(i)}$ linear precoding matrix $\mathbf{W}_i$.

The received signal vector $\mathbf{y}_i$ at the i-th receiver can be expressed as

$$\mathbf{y}_i = \sqrt{\rho_i}\mathbf{H}_{i,i}\mathbf{W}_i\mathbf{x}_i + \sum_{j=1, j\neq i}^{L} \sqrt{\eta_{i,j}}\mathbf{H}_{i,j}\mathbf{W}_j\mathbf{x}_j + \mathbf{n}_i \quad (1)$$

where $\mathbf{H}_{i,j}$ denotes $N_r \times N_t$ channel matrix between the i-th receiver and the j-th transmitter. $\mathbf{x}_i$ denotes $N_s^{(i)} \times 1$ symbol vector transmitted from the i-th transmitter. We assume a flat fading channel in both time and frequency. The elements of $\mathbf{H}_{i,j}$ and $\mathbf{x}_i$ are assumed to be independent and identically distributed (i.i.d.) circularly symmetric complex Gaussian random variables with zero mean and unit variance. $\mathbf{n}_i$ denotes the additive white Gaussian noise (AWGN) vector at the i-th receiver with each element having unit variance. In (1), ρ_i denotes the signal-to-noise ratio (SNR) of the i-th cell, and $\eta_{i,j}$ denotes the interference-to-noise ratio (INR) for the interference that the j-th transmitter causes to the i-th receiver.

We define the *desired channel* $\mathbf{H}_{\mathrm{D}}^{(i)}$ and *interference generating channel* $\mathbf{H}_{\mathrm{GI}}^{(i)}$ at the i-th transmitter as

$$\mathbf{H}_{\mathrm{D}}^{(i)} = \sqrt{\rho_i}\mathbf{H}_{i,i}, \quad (2)$$

$$\mathbf{H}_{\mathrm{GI}}^{(i)} = \begin{bmatrix} \sqrt{\eta_{1,i}}\mathbf{H}_{1,i} \\ \vdots \\ \sqrt{\eta_{i-1,i}}\mathbf{H}_{i-1,i} \\ \sqrt{\eta_{i+1,i}}\mathbf{H}_{i+1,i} \\ \vdots \\ \sqrt{\eta_{L,i}}\mathbf{H}_{L,i} \end{bmatrix}. \quad (3)$$

We assume that the i-th transmitter can obtain $\mathbf{H}_{\mathrm{D}}^{(i)}$ and $\mathbf{H}_{\mathrm{GI}}^{(i)H}\mathbf{H}_{\mathrm{GI}}^{(i)}$ by exploiting the channel reciprocity of TDD systems. In the uplink case, for example, the MS of the i-th cell can estimate $\mathbf{H}_{\mathrm{D}}^{(i)}$ through downlink signal that comes from the i-th BS. Similarly, the MS can determine $\mathbf{H}_{\mathrm{GI}}^{(i)H}\mathbf{H}_{\mathrm{GI}}^{(i)}$ by estimating the covariance matrix of aggregate interference signals that come from adjacent cells during the downlink period. We assume that the estimations of $\mathbf{H}_{\mathrm{D}}^{(i)}$ and $\mathbf{H}_{\mathrm{GI}}^{(i)H}\mathbf{H}_{\mathrm{GI}}^{(i)}$ are perfect, unless otherwise stated.

B. Problem Formulation

From (1), the achievable rate of the i-th cell can be computed as

$$\mathrm{C}^{(i)} = \log_2 \det\left(\mathbf{I}_{N_r} + \mathbf{K}_{\mathrm{D}}^{(i)}(\mathbf{K}_{\mathrm{N}}^{(i)})^{-1}\right), \quad (4)$$

where $\mathbf{K}_{\mathrm{D}}^{(i)}$ denotes the covariance matrix of the desired signal, and $\mathbf{K}_{\mathrm{N}}^{(i)}$ denotes the covariance matrix of the noise plus interference signal at the i-th receiver. These matrices can be expressed as

$$\mathbf{K}_{\mathrm{D}}^{(i)} = \rho_i(\mathbf{H}_{i,i}\mathbf{W}_i)(\mathbf{H}_{i,i}\mathbf{W}_i)^H, \quad (5)$$

$$\mathbf{K}_{\mathrm{N}}^{(i)} = \mathbf{I}_{N_r} + \sum_{j\neq i}\eta_{i,j}(\mathbf{H}_{i,j}\mathbf{W}_j)(\mathbf{H}_{i,j}\mathbf{W}_j)^H. \quad (6)$$

An optimization problem for finding precoding matrices that maximize the achievable rate summed over the L cells can be formulated as

$$\begin{aligned} (\mathbf{W}_{\mathrm{opt}}^{(1)}, \mathbf{W}_{\mathrm{opt}}^{(2)}, \cdots, \mathbf{W}_{\mathrm{opt}}^{(L)}) &= \arg\max_{(\mathbf{W}^{(1)}, \mathbf{W}^{(2)}, \cdots, \mathbf{W}^{(L)})} \sum_{i=1}^{L} C^{(i)} \\ \text{s.t.} \quad \mathrm{tr}(\mathbf{W}^{(i)}\mathbf{W}^{(i)H}) &= 1 \quad \text{for all } i. \end{aligned} \quad (7)$$

Since this is a non-convex problem, it is impossible to find a closed-form solution.

III. Precoding for MISO Channels

In this section, we derive a decentralized precoding scheme for MISO channels where $N_r = N_s^{(i)} = 1$. To further simplify the optimization problem in (7), we first consider a special case of $L = 2$. Then the optimal precoding vectors can be expressed as

$$\begin{aligned}\left(\mathbf{w}_{\text{opt}}^{(1)}, \mathbf{w}_{\text{opt}}^{(2)}\right) &= \underset{(\mathbf{w}^{(1)},\mathbf{w}^{(2)})}{\arg\max} \left(C^{(1)} + C^{(2)}\right)\\ &= \underset{(\mathbf{w}^{(1)},\mathbf{w}^{(2)})}{\arg\max} \left(\log_2(1+\text{SINR}^{(1)}) + \log_2(1+\text{SINR}^{(2)})\right)\\ &= \underset{(\mathbf{w}^{(1)},\mathbf{w}^{(2)})}{\arg\max} \left(\begin{array}{l}\log_2\left(1+\dfrac{||\mathbf{H}_{\text{D}}^{(1)}\mathbf{w}^{(1)}||^2}{1+||\mathbf{H}_{\text{GI}}^{(2)}\mathbf{w}^{(2)}||^2}\right)+\\ \log_2\left(1+\dfrac{||\mathbf{H}_{\text{D}}^{(2)}\mathbf{w}^{(2)}||^2}{1+||\mathbf{H}_{\text{GI}}^{(1)}\mathbf{w}^{(1)}||^2}\right)\end{array}\right)\\ \text{s.t.} \quad & \left\|\mathbf{w}^{(1)}\right\|^2 = \left\|\mathbf{w}^{(2)}\right\|^2 = 1.\end{aligned} \tag{8}$$

We make an approximation $\log_2(1 + \text{SINR}^{(i)}) \approx \log_2(\text{SINR}^{(i)})$, $i = 1, 2$ assuming $\text{SINR}(i) \gg 1$, $i = 1, 2$. Then, (8) can be simplified to

$$\begin{aligned}\left(\mathbf{w}_{\text{opt}}^{(1)}, \mathbf{w}_{\text{opt}}^{(2)}\right) &\approx \underset{(\mathbf{w}^{(1)},\mathbf{w}^{(2)})}{\arg\max} \left(\log_2(\text{SINR}^{(1)}) + \log_2(\text{SINR}^{(2)})\right)\\ &= \underset{(\mathbf{w}^{(1)},\mathbf{w}^{(2)})}{\arg\max} \log_2\left(\frac{||\mathbf{H}_{\text{D}}^{(1)}\mathbf{w}^{(1)}||^2}{1+||\mathbf{H}_{\text{GI}}^{(2)}\mathbf{w}^{(2)}||^2}\right)\left(\frac{||\mathbf{H}_{\text{D}}^{(2)}\mathbf{w}^{(2)}||^2}{1+||\mathbf{H}_{\text{GI}}^{(1)}\mathbf{w}^{(1)}||^2}\right)\\ &= \underset{(\mathbf{w}^{(1)},\mathbf{w}^{(2)})}{\arg\max} \log_2\left(\frac{||\mathbf{H}_{\text{D}}^{(1)}\mathbf{w}^{(1)}||^2}{1+||\mathbf{H}_{\text{GI}}^{(1)}\mathbf{w}^{(1)}||^2}\right)\left(\frac{||\mathbf{H}_{\text{D}}^{(2)}\mathbf{w}^{(2)}||^2}{1+||\mathbf{H}_{\text{GI}}^{(2)}\mathbf{w}^{(2)}||^2}\right)\\ \text{s.t.} \quad & \left\|\mathbf{w}^{(1)}\right\|^2 = \left\|\mathbf{w}^{(2)}\right\|^2 = 1\end{aligned} \tag{9}$$

which can be separated into

$$\begin{aligned}\mathbf{w}_{\text{opt}}^{(i)} &= \underset{\mathbf{w}^{(i)}}{\arg\max} \left(\gamma_{\text{SGINR}}^{(i)}(\mathbf{w}^{(i)})\right), \ i = 1, 2\\ \text{s.t.} \quad & \left\|\mathbf{w}^{(1)}\right\|^2 = \left\|\mathbf{w}^{(2)}\right\|^2 = 1\end{aligned} \tag{10}$$

where $\gamma_{\text{SGINR}}^{(i)}(\mathbf{w}^{(i)})$ is defined as

$$\gamma_{\text{SGINR}}^{(i)}(\mathbf{w}^{(i)}) = \frac{||\mathbf{H}_{\text{D}}^{(i)}\mathbf{w}^{(i)}||^2}{1+||\mathbf{H}_{\text{GI}}^{(i)}\mathbf{w}^{(i)}||^2}. \tag{11}$$

We refer to this metric as signal to *generated interference plus noise ratio (SGINR)* of the i-th transmitter. Note that the numerator of $\gamma_{\text{SGINR}}^{(i)}(\mathbf{w}^{(i)})$ is the desired signal power at the desired receiver, and that the denominator consists of noise and interference to adjacent cells by the i-th transmitter.

We refer to the solution of (10) as the *MAX-SGINR precoding* vector, since it maximizes the SGINR at each transmitter. In order to solve (10), we can rewrite (10) as

$$\begin{aligned}\mathbf{w}_{\text{opt}}^{(i)} &= \underset{\mathbf{w}^{(i)}}{\arg\max} \frac{||\mathbf{H}_{\text{D}}^{(i)}\mathbf{w}^{(i)}||^2}{1+||\mathbf{H}_{\text{GI}}^{(i)}\mathbf{w}^{(i)}||^2}\\ &= \underset{\mathbf{w}^{(i)}}{\arg\max} \frac{\mathbf{w}^{(i)H}\left(\mathbf{H}_{\text{D}}^{(i)H}\mathbf{H}_{\text{D}}^{(i)}\right)\mathbf{w}^{(i)}}{\mathbf{w}^{(i)H}\left(\mathbf{I}_{N_t}+\mathbf{H}_{\text{GI}}^{(i)H}\mathbf{H}_{\text{GI}}^{(i)}\right)\mathbf{w}^{(i)}}\\ \text{s.t.} \quad & \left\|\mathbf{w}^{(1)}\right\|^2 = \left\|\mathbf{w}^{(2)}\right\|^2 = 1\end{aligned} \tag{12}$$

which can be solved using the result of the generalized eigenproblem and the Rayleigh-Ritz theorem [11]. Since $\mathbf{I}_{N_t}+\mathbf{H}_{\text{GI}}^{(i)H}\mathbf{H}_{\text{GI}}^{(i)}$ is always invertible, the solution of (12) is the unit-norm eigenvector associated with the largest eigenvalue of $(\mathbf{I}_{N_t}+\mathbf{H}_{\text{GI}}^{(i)H}\mathbf{H}_{\text{GI}}^{(i)})^{-1}(\mathbf{H}_{\text{D}}^{(i)H}\mathbf{H}_{\text{D}}^{(i)})$. We define the matrix $\mathbf{K}_{\text{SGINR}}^{(i)}$ as

$$\mathbf{K}_{\text{SGINR}}^{(i)} = (\mathbf{I}_{N_t}+\mathbf{H}_{\text{GI}}^{(i)H}\mathbf{H}_{\text{GI}}^{(i)})^{-1}(\mathbf{H}_{\text{D}}^{(i)H}\mathbf{H}_{\text{D}}^{(i)}), \tag{13}$$

and call it the *SGINR-based transmit covariance matrix*. Note that the conventional transmit covariance matrix that does not contain the interference channel is expressed as

$$\mathbf{K}_{\text{SNR}}^{(i)} = \mathbf{H}_{\text{D}}^{(i)H}\mathbf{H}_{\text{D}}^{(i)}. \tag{14}$$

The precoding vector corresponding to the eigenvector associated with the largest eigenvalue of $\mathbf{K}_{\text{SNR}}^{(i)}$, is referred to as the *MAX-SNR precoding* vector. Comparison between (13) and (14) reveals that, unlike the MAX-SNR scheme, the proposed MAX-SGINR scheme reflects the interference channel to adjacent cells as well as the desired channel in determining the precoding vector.

Note that each transmitter can calculate its precoding vector in the decentralized manner with only locally available CSI, $\mathbf{H}_{\text{D}}^{(i)}$ and $\mathbf{H}_{\text{GI}}^{(i)H}\mathbf{H}_{\text{GI}}^{(i)}$. Although the MAX-SGINR precoding scheme has been derived under the scenario of two interfering cells, it can be applied to arbitrary number of cells without any modification: we simply need to account for all $L-1$ interfering cells when constructing the interference generating channel matrix $\mathbf{H}_{\text{GI}}^{(i)}$ in (3). It is also worth mentioning that although we have derived the SGINR criterion from the problem of maximizing the total achievable rate for the interference channel, the problem formulation and solution fall under the principle of dual optimization between multiuser detection and multiuser transmission introduced in [15].

IV. PRECODING FOR MIMO CHANNELS

In this section, we consider MIMO channels where more than one streams can be transmitted, i.e., $N_s^{(i)} \geqslant 1$. In Section IV-A, we extend the MAX-SGINR scheme derived in Section III to MIMO channels, to propose a generalized SGINR-based precoding scheme. In Section IV-B, we briefly discuss two MIMO precoding schemes which were previously proposed for cognitive radios.

A. SGINR-based Precoding

The precoding matrix can be decomposed into two matrices: beamforming matrix and power allocation matrix. To construct a beamforming matrix, we express $\mathbf{K}_{\text{SGINR}}^{(i)}$ in (13) using the eigenvalue decomposition as

$$\begin{aligned}\mathbf{K}_{\text{SGINR}}^{(i)} &= \sum_{k=1}^{N_t} d_{\text{SGINR},k}^{(\text{i})}\mathbf{v}_{\text{SGINR},k}^{(i)}\mathbf{v}_{\text{SGINR},k}^{(i)H}\\ &= \mathbf{V}_{\text{SGINR}}^{(i)}\mathbf{D}_{\text{SGINR}}^{(i)}\mathbf{V}_{\text{SGINR}}^{(i)H}\end{aligned} \tag{15}$$

where $d_{\text{SGINR},k}^{(\text{i})}$ and $\mathbf{v}_{\text{SGINR},k}^{(i)}$ denote the k-th eigenvalue and the k-th unit-norm eigenvector of $\mathbf{K}_{\text{SGINR}}^{(i)}$, respectively. Correspondingly, $\mathbf{V}_{\text{SGINR}}^{(i)}$ and $\mathbf{D}_{\text{SGINR}}^{(i)}$, denote the eigenvector matrix and the diagonal matrix composed of eigenvalues of $\mathbf{K}_{\text{SGINR}}^{(i)}$, respectively. We propose to use $\mathbf{V}_{\text{SGINR}}^{(i)}$ as a beamforming matrix for possibly transmitting up to N_t streams. From the result of the generalized eigenproblem and the Rayleigh-Ritz quotient, we know that $\mathbf{v}^{(i)}_{\text{SGINR},k}$ is related to $d^{(i)}_{\text{SGINR},k}$ as

$$\gamma^{(i)}_{\text{SGINR}}(\mathbf{v}^{(i)}_{\text{SGINR},k}) = d^{(i)}_{\text{SGINR},k} \quad (16)$$

where $\gamma^{(i)}_{\text{SGINR}}(\mathbf{v}^{(i)}_{\text{SGINR},k})$ denotes the SGINR of the stream associated with the beamforming vector $\mathbf{v}^{(i)}_{\text{SGINR},k}$. With the beamforming matrix $\mathbf{V}^{(i)}_{\text{SGINR}}$, the SGINR-based precoding matrix $\mathbf{W}^{(i)}$ can be written as

$$\mathbf{W}^{(i)} = \mathbf{V}^{(i)}_{\text{SGINR}}\mathbf{P}^{(i)1/2} \quad (17)$$

where $\mathbf{P}^{(i)} \triangleq \text{diag}(p^{(i)}_1, p^{(i)}_2, ..., p^{(i)}_{N_t})$ is a power allocation matrix with the constraint $\sum_{k=1}^{N_t} p^{(i)}_k = 1$. The power allocation matrix maximizing the achievable rate can be obtained using a water-filling over the SGINR values. Specifically, the power allocated to the k-th stream is given as

$$p^{(i)}_k = \left(\lambda^{(i)} - \frac{1}{d^{(i)}_{\text{SGINR},k}}\right)^+ \quad (18)$$

where $\lambda^{(i)}$ is chosen to satisfy the power constraint.

The proposed SGINR-based precoding scheme allocates more power to a stream with higher SGINR due to the inherent nature of water-filling algorithm. This is a reasonable policy from the total system perspective, since low SGINR stream will yield low signal power to the desired receiver or cause high level of interference to adjacent cells. It should be noted that the SGINR-based precoding scheme in (17) can be regarded as a generalized version of the MAX-SGINR scheme. The scheme also incorporates an implicit mechanism for selecting the number of transmit streams adaptively to the surrounding environments, so that the interference to adjacent cells as well as the desired signal power is accounted for in determining the number of streams.

B. D-SVD and P-SVD Precoding

For comparison purpose, we briefly discuss two precoding schemes which were previously proposed for cognitive radios in [12]: Direct-channel singular value decomposition (D-SVD) and Projected-channel SVD (P-SVD). In the D-SVD scheme, the precoding matrix is given as

$$\mathbf{W}^{(i)}_{\text{D-SVD}} = \mathbf{V}^{(i)}_{\text{D-SVD}}\mathbf{P}^{(i)1/2}_{\text{D-SVD}} \quad (19)$$

where $\mathbf{V}^{(i)}_{\text{D-SVD}}$ is the matrix composed of right singular vectors of the desired channel $\mathbf{H}^{(i)}_{\text{D}}$, and $\mathbf{P}^{(i)}_{\text{D-SVD}}$ is the power allocation matrix. The power allocation is determined by the water-filling over the SNR of each stream. Note that the D-SVD scheme does not consider the interference generated to adjacent cells.

In the P-SVD scheme, on the other hand, the precoding matrix is given as

$$\mathbf{W}^{(i)}_{\text{P-SVD}} = \mathbf{V}^{(i)}_{\text{NULL}}\mathbf{B}^{(i)}_{\text{P-SVD}}\mathbf{P}^{(i)1/2}_{\text{P-SVD}} \quad (20)$$

where $\mathbf{V}^{(i)}_{\text{NULL}}$ is a nulling matrix such that $\mathbf{H}^{(i)}_{\text{GI}}\mathbf{V}^{(i)}_{\text{NULL}} = \mathbf{0}$, $\mathbf{B}_{\text{P-SVD}}$ is the matrix composed of right singular vectors of $\mathbf{H}^{(i)}_{\text{D}}\mathbf{V}^{(i)}_{\text{NULL}}$, and $\mathbf{P}^{(i)}_{\text{P-SVD}}$ is the water-filling power allocation matrix. Note that the P-SVD scheme generates no interference to adjacent cells. However, in order to use the P-SVD scheme, each transmitter needs to be equipped with transmit antennas as many as the total number of receive antennas in adjacent cells.

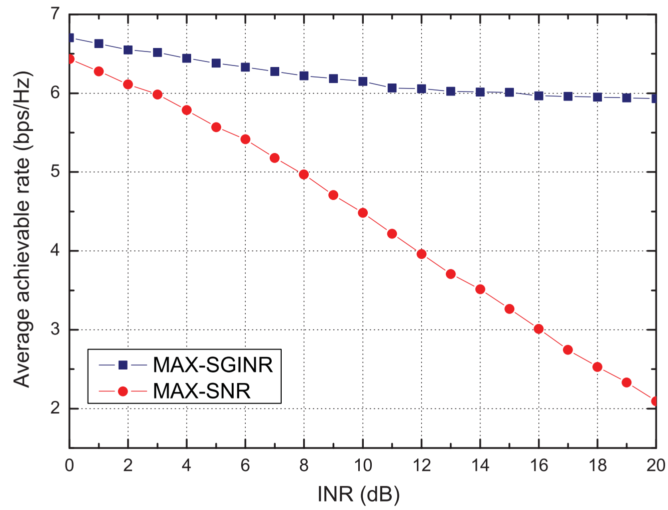

Fig. 1. The average achievable rate vs. INR for L = 2, N_t = 2, N_r = 1, and SNR = 20dB.

There is some interesting relationship between the proposed scheme and the D-SVD/P-SVD scheme. When the INR goes to zero, the proposed scheme is equivalent to the D-SVD. On the contrary, when the INR goes to infinity, the proposed scheme is equivalent to the P-SVD scheme. Proofs are provided in Appendix. In nominal INR regions, the proposed scheme is expected to provide an effective tradeoff between the desired signal and interference generated to adjacent cells.

V. Simulation Results

In this section, we evaluate the performance of the precoding schemes discussed in Sections III-IV using computer simulations. We first consider a symmetric system in Figs. 1-5; in other words, ρ_i and $\eta_{i,j}$ in (1) are assumed to be the same for all i and j.

Fig. 1 shows the average achievable rate per cell vs. INR in a MISO system with $N_t = 2$, $N_r = 1$ for two cells. The SNR is fixed to 20dB. As expected, the proposed MAX-SGINR scheme provides higher achievable rate than the MAX-SNR scheme for all INR regions, and the performance difference becomes larger with INR increasing.

Figs. 2-3 depict the average achievable rate per cell and the average number of transmit streams vs. INR in a two-cell MIMO system with $N_t = N_r = 2$, when SNR = 20dB. The P-SVD scheme is not applicable to this MIMO configuration due to the lack of transmit antennas. It is shown that the proposed SGINR-based precoding scheme outperforms the D-SVD scheme and the SLNR-based multi-stream scheme proposed in [14] in all INR regions. Note that the SLNR-based multi-stream scheme does not provide a solution for selecting the number of transmit streams, for which each MS is assumed to transmit two streams. It is observed in Fig. 3 that the SGINR-based scheme tends to reduce the number of transmit steams as the INR increases, while the number of transmit streams of the other two schemes is independent of

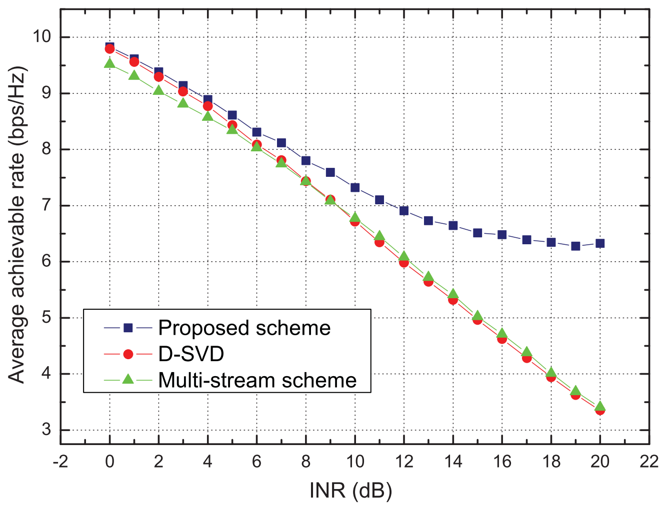

Fig. 2. The average achievable rate vs. INR for L = 2, N_t = 2, N_r = 2, and SNR = 20dB.

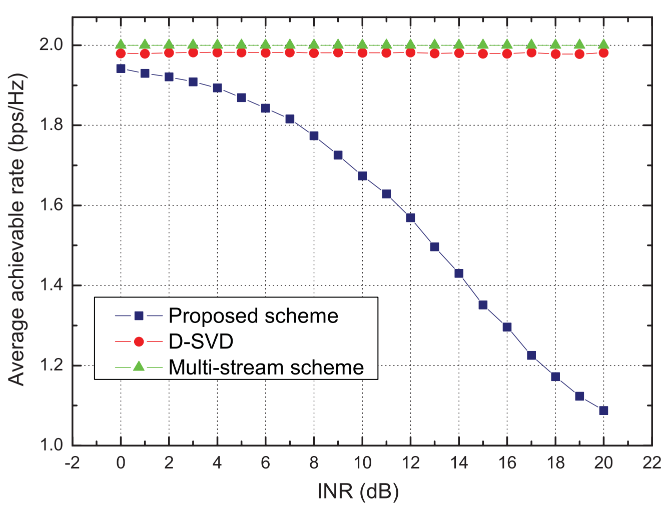

Fig. 3. The average number of transmitted streams vs. INR for L = 2, N_t = 2, N_r = 2, and SNR = 20dB.

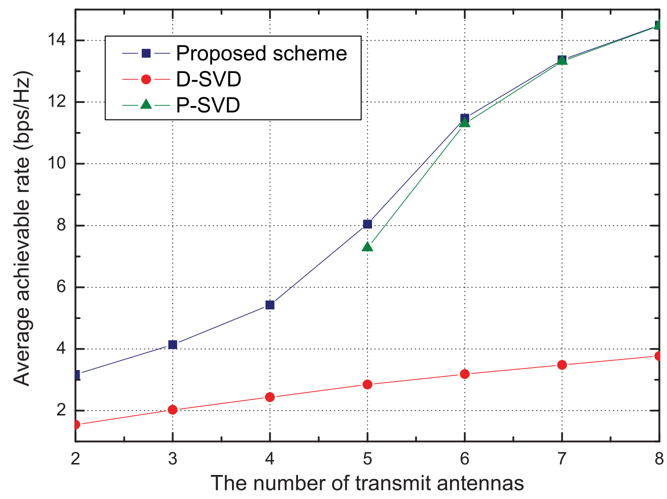

Fig. 4. The average achievable rate vs. N_t for L = 3, N_r = 2, SNR = 20dB, and INR = 20dB.

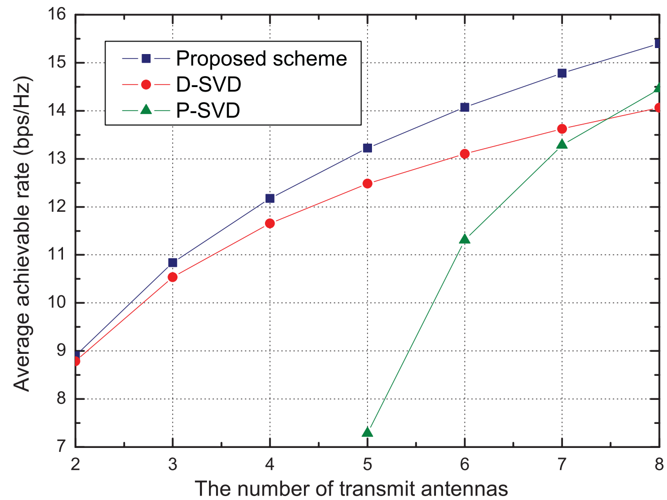

Fig. 5. The average achievable rate vs. N_t for L = 3, N_r = 2, SNR = 20dB, and INR = 0dB

the INR. This behavior of the proposed SGINR-based scheme is consistent with that of the optimal centralized transmission scheme in [9].

Figs. 4-5 depict the average achievable rate per cell vs. the number of transmit antennas in a three-cell MIMO system with $N_r = 2$ at a relatively high INR (20dB) and at a relatively low INR (0dB), respectively. Note that the P-SVD scheme is applicable as long as $N_t \geqslant 5$. It is found that the D-SVD outperforms the P-SVD at the low INR value, whereas the P-SVD outperforms the D-SVD at the high INR value. The proposed SGINR-based scheme is found to always outperform both the D-SVD and P-SVD schemes.

Now we evaluate the performance in a regular hexagonal model with 7 cells. We consider uplink transmission, in which a single mobile station (MS) is selected to be served by a user scheduler at the given time and frequency in each cell. The selected user is assumed to be uniformly distributed over the cell. Each channel between the MS and BS is assumed to experience an independent long-term fading comprised of the path loss and log-normal shadow fading. Correspondingly, ρ_i and $\eta_{i,j}$ in (1) can be expressed as

$$\rho_i = 10^{\frac{S_{i,i}}{10}} (r_{i,i})^{-\alpha} P_i, \ \eta_{i,j} = 10^{\frac{S_{i,j}}{10}} (r_{i,j})^{-\alpha} P_j \qquad (21)$$

where $r_{i,j}$ is the distance between the BS in the i-th cell and the MS in the j-th cell, α is the path loss exponent, and $S_{i,j}$ is a zero-mean Gaussian random variable that stands for the shadow fading. It is assumed that the long-term power control perfectly compensates for the long-term fading so that a given target SNR is satisfied at the BS. In the following simulation, the path loss exponent, log standard deviation of the shadow fading, and the target SNR are set to 3.7, 8dB, and 20dB, respectively.

Fig. 6 shows the achievable rates in the average sense and in the 5% outage sense vs. the number of transmit antennas with $N_r = 2$. It is observed that the proposed scheme provides 33% and 41% improvement over the D-SVD scheme for the case of $N_t = 2$ and $N_t = 4$, respectively, in terms of the average achievable rate. Furthermore, the proposed scheme provides as much as 273% and 321% improvement over the D-SVD scheme for the case of $N_t = 2$ and $N_t = 4$, respectively, in terms of the achievable rate in the 5% outage sense. This result

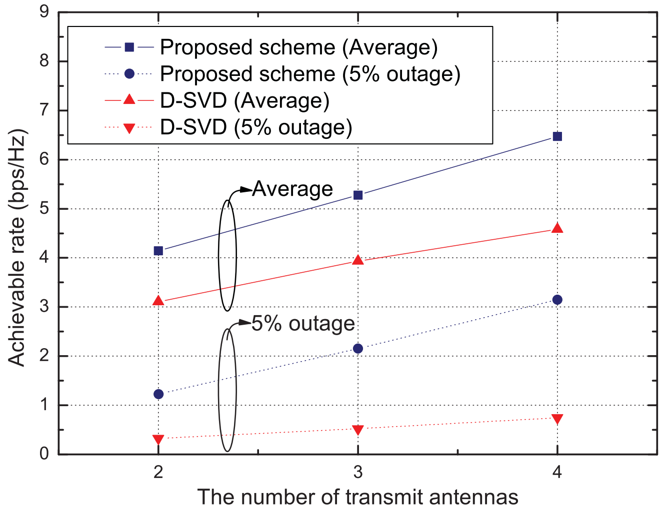

Fig. 6. The achievable rates in the average sense and in the 5% outage sense vs. N_t for 7 hexagonal cells with N_r = 2.

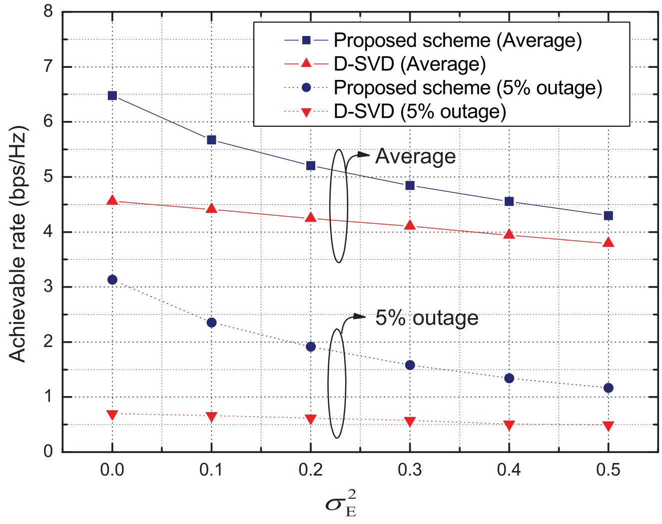

Fig. 7. The achievable rates in the average sense and in the 5% outage sense vs. the MSE σ_E^2 for 7 hexagonal cells with N_t = 4.

demonstrates that the proposed scheme offers more benefits to users near the cell boundary, since it is designed to reduce intercell interference.

We have assumed perfect channel estimation until now. However, estimation errors are unavoidable in practice due to the noise and time-varying nature of the channel. Now we consider the impact of imperfect channel estimation on the precoding performance. We model the estimated channel $\tilde{\mathbf{H}}_{i,j}$ between the i-th receiver and the j-th transmitter as

$$\tilde{\mathbf{H}}_{i,j} = \sqrt{1-\sigma_{\mathrm{E}}^2}\mathbf{H}_{i,j} + \sigma_{\mathrm{E}}\mathbf{H}_w \tag{22}$$

where $\mathbf{H}_w$ is a random matrix with i.i.d. entries of zero mean and unit variance, and σ_{E}^2 denotes the mean square error (MSE) of the channel estimation [16]. Fig. 7 depicts how the achievable rates in the average sense and in the 5% outage sense vary with the MSE σ_{E}^2 for 7 hexagonal cells with $N_t = 4$, when the precoding matrices are determined based on the noisy estimated channel in (22). It is found that the proposed scheme is more sensitive to channel estimation errors than the D-SVD scheme. This is not surprising, because the proposed scheme is affected by the estimation errors on both of the desired channel $\mathbf{H}_{\mathrm{D}}^{(i)}$ and interference channel $\mathbf{H}_{\mathrm{GI}}^{(i)}$, whereas the D-SVD scheme is associated only with $\mathbf{H}_{\mathrm{D}}^{(i)}$. Nonetheless, the proposed scheme still outperforms the D-SVD scheme even when the estimation errors are severe.

VI. Conclusions

In this paper, we have developed an effective MIMO precoding scheme to handle the intercell interference for uplink in a multicell environment. We have formulated an optimization problem for finding a precoding matrix that maximizes the total achievable rate in the decentralized manner. In order to solve the problem, we have introduced a design metric called SGINR for the case of MISO channels. Furthermore, by extending the result of MISO channels, we have proposed an SGINR-based precoding scheme for general MIMO channels. The precoding scheme allows to select the number of transmit streams adaptively to the surrounding environments. Simulation results have shown that the proposed SGINR-based precoding scheme offers significant performance gain over the conventional schemes in terms of the achievable rate. We have also investigated the impact of channel estimation errors on the precoding performance.

Appendix

When the INR goes to zero ($\eta_{i,j} \to 0$): From (13), we have

$$\begin{aligned}\lim_{\eta_{i,j}\to 0}\mathbf{K}_{\mathrm{SGINR}}^{(i)} &= \lim_{\eta_{i,j}\to 0}(\mathbf{I}_{N_t} + \mathbf{H}_{\mathrm{GI}}^{(i)H}\mathbf{H}_{\mathrm{GI}}^{(i)})^{-1}(\mathbf{H}_{\mathrm{D}}^{(i)H}\mathbf{H}_{\mathrm{D}}^{(i)}) \\ &= \mathbf{H}_{\mathrm{D}}^{(i)H}\mathbf{H}_{\mathrm{D}}^{(i)}\end{aligned} \tag{23}$$

which leads to the same precoding matrix as the D-SVD.

When the INR goes to infinity ($\eta_{i,j} \to \infty$): We assume $N_t > N_{\mathrm{GI}}$ so that the P-SVD is feasible, where N_{GI} denotes the number of the whole receive antennas in adjacent cells. The SVD of $\mathbf{H}_{\mathrm{GI}}^{(i)}$ can be written as

$$\begin{aligned}\mathbf{H}_{\mathrm{GI}}^{(i)} &= \mathbf{U}_{\mathrm{GI}}^{(i)}\mathbf{S}_{\mathrm{GI}}^{(i)}\mathbf{V}_{\mathrm{GI}}^{(i)H} \\ &= \mathbf{U}_{\mathrm{GI}}^{(i)}\left[\begin{array}{cccc|c} s_1^{(i)} & 0 & \cdots & 0 & \\ 0 & s_2^{(i)} & \cdots & 0 & \\ \vdots & \vdots & \ddots & \vdots & \mathbf{0}_{N_t\times(N_t-N_{\mathrm{GI}})} \\ 0 & 0 & \cdots & s_{N_{\mathrm{GI}}}^{(i)} & \end{array}\right] \\ &\quad \left[\begin{array}{cc}\bar{\mathbf{V}}_{\mathrm{GI}}^{(i)} & \mathbf{V}_{\mathrm{NULL}}^{(i)}\end{array}\right]^H.\end{aligned} \tag{24}$$

Note that the matrix $\mathbf{V}_{\mathrm{GI}}^{(i)}$ of right singular vectors is composed of two parts:$\bar{\mathbf{V}}_{\mathrm{GI}}^{(i)}$ and $\mathbf{V}_{\mathrm{null}}^{(i)}$. $\bar{\mathbf{V}}_{\mathrm{GI}}^{(i)}$ is an $N_t \times N_{\mathrm{GI}}$ matrix whose column vectors are the right singular vectors corresponding to N_{GI} positive singular values of $\mathbf{H}_{\mathrm{GI}}^{(i)}$, and $\mathbf{V}_{\mathrm{NULL}}^{(i)}$ is an $N_t \times (N_t - N_{\mathrm{GI}})$ nulling matrix. Therefore, as $\eta_{i,j} \to \infty$, $\mathbf{K}_{\mathrm{SGINR}}^{(i)}$ becomes $\mathbf{V}_{\mathrm{NULL}}^{(i)}\mathbf{V}_{\mathrm{NULL}}^{(i)H}\mathbf{H}_{\mathrm{D}}^{(i)H}\mathbf{H}_{\mathrm{D}}^{(i)}$ by (25), which leads to the same precoding matrix as the P-SVD.

$$
\begin{aligned}
\lim_{\eta_{i,j}\to\infty} \mathbf{K}^{(i)}_{\text{SGINR}} &= \lim_{\eta_{i,j}\to\infty} (\mathbf{I}_{N_t} + \mathbf{H}^{(i)H}_{\text{GI}}\mathbf{H}^{(i)}_{\text{GI}})^{-1}(\mathbf{H}^{(i)H}_{\text{D}}\mathbf{H}^{(i)}_{\text{D}}) \\
&= \lim_{\eta_{i,j}\to\infty} \left[\begin{array}{c} \bar{\mathbf{V}}^{(i)}_{\text{GI}} \mathbf{V}^{(i)}_{\text{NULL}} \end{array} \right] \left[\begin{array}{cccc|c} (s^{(i)}_1)^2+1 & 0 & \cdots & 0 & \\ 0 & (s^{(i)}_2)^2+1 & \cdots & 0 & \\ \vdots & \vdots & \ddots & \vdots & \mathbf{0}_{N_{\text{GI}}\times(N_t-N_{\text{GI}})} \\ 0 & 0 & \cdots & (s^{(i)}_{N_{\text{GI}}})^2+1 & \\ & \mathbf{0}_{(N_t-N_{\text{GI}})\times N_i} & & & \mathbf{I}_{(N_t-N_{\text{GI}})\times(N_t-N_{\text{GI}})} \end{array} \right]^{-1} \\
&\quad \left[\begin{array}{cc} \bar{\mathbf{V}}^{(i)}_{\text{GI}} & \mathbf{V}^{(i)}_{\text{NULL}} \end{array} \right]^H (\mathbf{H}^{(i)H}_{\text{D}}\mathbf{H}^{(i)}_{\text{D}}) \\
&= \left[\begin{array}{cc} \bar{\mathbf{V}}^{(i)}_{\text{GI}} & \mathbf{V}^{(i)}_{\text{NULL}} \end{array} \right] \left[\begin{array}{cc} \mathbf{0}_{N_{\text{GI}}\times N_{\text{GI}}} & \mathbf{0}_{N_t\times(N_t-N_{\text{GI}})} \\ \mathbf{0}_{(N_t-N_{\text{GI}})\times N_{\text{GI}}} & \mathbf{I}_{(N_t-N_{\text{GI}})\times(N_t-N_{\text{GI}})} \end{array} \right] \left[\begin{array}{cc} \bar{\mathbf{V}}^{(i)}_{\text{GI}} & \mathbf{V}^{(i)}_{\text{NULL}} \end{array} \right]^H \left(\mathbf{H}^{(i)H}_{\text{D}}\mathbf{H}^{(i)}_{\text{D}}\right) \\
&= \left(\mathbf{V}^{(i)}_{\text{NULL}}\mathbf{V}^{(i)H}_{\text{NULL}}\right)\left(\mathbf{H}^{(i)H}_{\text{D}}\mathbf{H}^{(i)}_{\text{D}}\right) \qquad (25)
\end{aligned}
$$

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