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Interference Alignment-based Precoding and User Selection with Limited Feedback in Two-cell Downlink Multi-user MIMO Systems

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Abstract

Interference alignment (IA) is a new approach to address interference in modern multiple-input multiple-out (MIMO) cellular networks in which interference is an important factor that limits the system throughput. System throughput in most IA implementation schemes is significantly improved only with perfect channel state information and in a high signal-to-noise ratio (SNR) region. Designing a simple IA scheme for the system with limited feedback and investigating system performance at a low-to-medium SNR region is important and practical. This paper proposed a precoding and user selection scheme based on partial interference alignment in two-cell downlink multi-user MIMO systems under limited feedback. This scheme aligned inter-cell interference to a predefined direction by designing user's receive antenna combining vectors. A modified singular value decomposition (SVD)-based beamforming method and a corresponding user-selection algorithm were proposed for the system with low rate limited feedback to improve sum rate performance. Simulation results show that the proposed scheme achieves a higher sum rate than traditional schemes without IA. The modified SVD-based beamforming scheme is also superior to the traditional zero-forcing beamforming scheme in low-rate limited feedback systems. The proposed partial IA scheme does not need to collaborate between transmitters and joint design between the transmitter and the users. The scheme can be implemented with low feedback overhead in current MIMO cellular networks.

Keywords: Interference alignment, Limited feedback, User selection, Zero-forcing beamforming

1. Introduction

Multiple-input multiple-output (MIMO) technology in modern wireless cellular systems can provide diversity gain, multiplexing gain, or array gain by using multiple antennas at transmitters and receivers, which significantly improves system throughput. Moreover, the system can obtain multi-user diversity gain and further increase its throughput by simultaneously serving multiple users. Multi-user MIMO transmission may be widely adopted in next-generation cellular networks by using massive MIMO transmission technology [1]. Linear precoding is a commonly used technique in multiple-user MIMO systems to obtain the majority of the system capacity if the transmitter can obtain perfect channel state information (CSI). However, perfect CSI at the transmitter is difficult to satisfy in frequency division duplex (FDD) systems, where CSI is often obtained at the transmitter via limited feedback [2].

The throughput of cellular systems can be dramatically improved by MIMO technology; however, it is significantly limited by interference, which has become a serious problem owing to the dense deployment of small cells, femtocells, and picocells in cellular networks [3]. Interference alignment (IA), a recent emerged theory, provides a new way to decrease inter-cell interference in cellular networks [4]. The purpose of IA is to compress all the interference signals into a small dimension of the transmitted signal space by properly designing the transceiver scheme such that the degrees of freedom (DoF) of the system is maximized. However, the ideal alignment of the interference needs perfect CSI at the transmitter. Thus, designing proper transceiver schemes based on IA for practical systems is an important research topic.

2. Literature Review

A commonly used linear precoding method in downlink multi-user MIMO system, where each user receives only one data stream, is zero-forcing beamforming (ZFBF) [5]. An FDD system uses limited feedback to obtain CSI at the transmitter; its inter-user interference could not be entirely eliminated by ZFBF, and the system sum rate decreases significantly [6]. Nevertheless, the multi-user diversity gain could be obtained when more users participate in the system than those that are simultaneously scheduled by designing a proper user selection algorithm; thus, the sum rate can be improved [7].

The concept of interference alignment was first proposed in [8]. The maximum DoF of the interfering channels can be achieved by aligning interfering signals into a subspace of transmitted signal dimension. IA in MIMO cellular networks has recently received considerable attention. The DoF and the feasibility of IA in different scenarios for a downlink

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multi-user MIMO broadcast channel was investigated in detail [9] [10]. A zero-forcing interference alignment scheme for the downlink cellular systems was proposed in [11]. The per-cell DoF of the system can achieve $K/(K+1)$ in a two-cell scenario, whereas users only need to return CSI to its own cell by aligning inter-cell and inter-user interference in the same subspace. A similar idea with a slightly different method was also proposed [12]. Perfect alignment in the aforementioned two IA schemes can only be achieved in two cell interfering systems with the number of receiving antennas larger than transmitting antennas. An IA scheme was proposed [13] for a two-cell interfering MIMO broadcast channel, where each cell has two users. The interfering signals from another cell to each user are aligned in the same direction by jointly designing users' combining vectors in each cell; the inter-cell and inter-user interferences are then eliminated by designing beamforming vectors at the transmitters. This scheme was extended to the scenario of multiple cells with multiple users in each cell [14]. The number of transmit and receive antennas in the aforementioned two schemes should satisfy special conditions.

The gain of system throughput brought by IA for limited feedback systems that adopt the IA scheme depends on the quantization quality of CSI. System performance with imperfect CSI was investigated in an interfering broadcast channel [15]. An optimal IA scheme [16] was obtained for the two-cell multiple access channel by quantizing the beamforming vector with the criterion of minimizing total residual inter-cell interference. The problem of how to allocate feedback overhead between the users in K user interfering channel when user channels have different path loss and spatial correlations was studied [17].

The implementation of IA in the MIMO cellular network still suffers practical problems, such as complexity and limitation of the scheme and need for high feedback rate of CSI. The present paper investigated the sum rate performance of a two-cell downlink multi-user MIMO system that adopts an IA scheme with low rate feedback when the number of receive antennas is less than the number of transmitters.

The rest of this paper is organized as follows. Section 3 describes the system model, the proposed IA-based precoding scheme, and the corresponding user selection algorithm for the two-cell multi-user downlink MIMO system. Section 4 provides the simulation results and analysis. Section 5 concludes the study.

3. Methodology

3.1 System Model

A two-cell downlink multi-user MIMO system is shown in Fig. 1. The transmitter and the user are equipped with M and N antennas ($M>N$), respectively. Each user receives a single data stream. In each cell, a total of L users exist and the transmitter serves K ($K\le L$) users. The channels between the users and the transmitters are narrow-band Rayleigh flat fading. The two transmitters that send data streams on the same time-frequency resources cause inter-cell interference. The user usually receives the signal and the interference with nearly equal power at the cell edge. Thus, the large-scale fading of the channel is not considered in this scenario. The inter-cell and intra-cell interferences to the users have the same strength. The received signal vector of the user in the ith $(i=1,2)$ cell is

$$\boldsymbol{y}_{i,j}=\boldsymbol{H}_{i,j}\boldsymbol{x}_i+\boldsymbol{G}_{i,j}\boldsymbol{x}_{3-i}+\boldsymbol{n}_{i,j} \tag{1}$$

where $\boldsymbol{H}_{i,j},\boldsymbol{G}_{i,j}\in\mathbf{C}^{N\times M}$ are the direct channel between the user and its transmitter and the cross channel between the user and the interfering transmitter. All the elements of $\boldsymbol{H}_{i,j}$ and $\boldsymbol{G}_{i,j}$ are independent and identically distributed with $\mathcal{CN}(0,1)$. Thus, $\boldsymbol{H}_{i,j}$ and $\boldsymbol{G}_{i,j}$ are fully ranked with the probability of 1. $\boldsymbol{n}_{i,j}$ is additive white Gaussian noise with its covariance matrix $\mathcal{CN}(0,\boldsymbol{I})$. $\boldsymbol{x}_i$ represents the transmitted signal vector, which satisfies

$$\boldsymbol{x}_i=\boldsymbol{F}_i\boldsymbol{d}_i=\sum_{k=1}^{K}\boldsymbol{f}_{i,k}d_{i,k} \tag{2}$$

and its power is constrained by $E\left\{\left\|\boldsymbol{x}_i\right\|^2\right\}=P$, $i=1,2$.

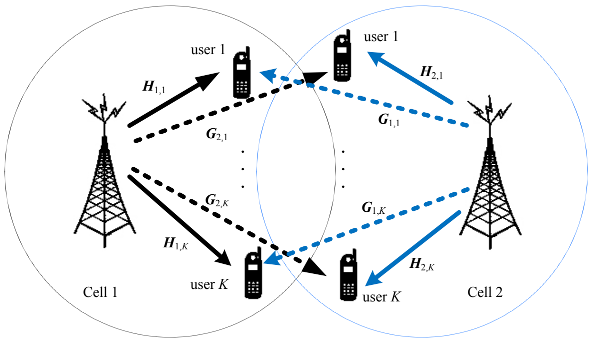

Fig. 1. Two-cell downlink multi-user MIMO system

The transmitter allocates equal power to each user. The average receiving power of each user is $P_k=P/K$. $\boldsymbol{F}_i=\left[\boldsymbol{f}_{i,1}\quad \boldsymbol{f}_{i,K}\right]\in\mathbf{C}^{M\times K}$ is the precoding matrix of cell i , where $\boldsymbol{f}_{i,j}$ is the beamforming vector of user j that satisfies $\left\|\boldsymbol{f}_{i,j}\right\|=1$. $\boldsymbol{d}_i=\left[d_{i,1}\quad d_{i,K}\right]^T$, $(\cdot)^T$ denotes the transpose, and $d_{i,j}$ is the data symbol of user j in cell i . $\boldsymbol{u}_{i,j}\in\mathbf{C}^{N\times 1}$ represents the user's receive antenna combining vector that satisfies $\left\|\boldsymbol{u}_{i,j}\right\|=1$. The received data signal at user j in cell i (i.e., user $[i,j]$) is $(i=1,2;\ j=1,\ ,K)$:

$$\begin{aligned} y_{i,j}&=\boldsymbol{u}_{i,j}^H\boldsymbol{H}_{i,j}\boldsymbol{x}_i+\boldsymbol{u}_{i,j}^H\boldsymbol{G}_{i,j}\boldsymbol{x}_{3-i}+\boldsymbol{n}_{i,j}\\ &=\boldsymbol{u}_{i,j}^H\boldsymbol{H}_{i,j}\sum_{k=1}^{K}\boldsymbol{f}_{i,k}d_{i,k}+\boldsymbol{u}_{i,j}^H\boldsymbol{G}_{i,j}\sum_{k=1}^{K}\boldsymbol{f}_{3-i,k}d_{3-i,k}+\boldsymbol{n}_{i,j} \end{aligned} \tag{3}$$

where $\boldsymbol{n}_{i,j}=\boldsymbol{u}_{i,j}^H\boldsymbol{n}_{i,j}$ and $(\cdot)^H$ is the conjugate transpose.

The sum rate of cell i is $R_i=K\log_2\left(1+\mathrm{SINR}_{i,j}\right)$ if the system simultaneously serves K users. The signal to interference plus noise ratio (SINR) of user $[i,j]$ is

$$\mathrm{SINR}_{i,j} = \frac{\frac{P}{K}\left|\boldsymbol{u}_{i,j}^{H}\boldsymbol{H}_{i,j}\boldsymbol{f}_{i,j}\right|^{2}}{\frac{P}{K}\sum_{\substack{k=1\\k\neq j}}^{K}\left|\boldsymbol{u}_{i,j}^{H}\boldsymbol{H}_{i,j}\boldsymbol{f}_{i,k}\right|^{2} + \frac{P}{K}\sum_{k=1}^{K}\left|\boldsymbol{u}_{i,j}^{H}\boldsymbol{G}_{i,j}\boldsymbol{f}_{3-i,k}\right|^{2} + 1} \tag{4}$$

where $\frac{P}{K}\left|\boldsymbol{u}_{i,j}^{H}\boldsymbol{H}_{i,j}\boldsymbol{f}_{i,j}\right|^{2}$ is the average signal power of the user, $\frac{P}{K}\sum_{\substack{k=1\\k\neq j}}^{K}\left|\boldsymbol{u}_{i,j}^{H}\boldsymbol{H}_{i,j}\boldsymbol{f}_{i,k}\right|^{2}$ is the intra-cell interference within the cell, and $\frac{P}{K}\sum_{k=1}^{K}\left|\boldsymbol{u}_{i,j}^{H}\boldsymbol{G}_{i,j}\boldsymbol{f}_{3-i,k}\right|^{2}$ is the inter-cell interference from the neighboring cell.

3.2 Zero-forcing beamforming and user selection based on interference alignment

3.2.1 Alignment of inter-cell interference

A reference direction $\boldsymbol{v}_{\mathrm{ref}} \in \mathbf{C}^{M\times 1}$ is set in advance to align the interference. The interfering signal is aligned to the reference direction at the user side by properly designing the user's receive antenna combining vector [12].

When the receiver employs more antennas than the transmitter ($N \geq M$), let $\boldsymbol{u}_{i,j} = \left(\boldsymbol{v}_{\mathrm{ref}}^{H}\boldsymbol{G}_{i,j}^{\dagger}\right)^{H}$ and the received data signal of user $[i,j]$ is

$$y_{i,j} = \boldsymbol{v}_{\mathrm{ref}}^{H}\boldsymbol{G}_{i,j}^{\dagger}\boldsymbol{H}_{i,j}\boldsymbol{x}_{i} + \boldsymbol{v}_{\mathrm{ref}}^{H}\boldsymbol{x}_{3-i} + \boldsymbol{n}_{i,j}, \tag{5}$$

where $\boldsymbol{G}_{i,j}^{\dagger} = \left(\boldsymbol{G}_{i,j}^{H}\boldsymbol{G}_{i,j}\right)^{-1}\boldsymbol{G}_{i,j}^{H}$ denotes the left inverse of $\boldsymbol{G}_{i,j}$ that satisfies $\boldsymbol{G}_{i,j}^{\dagger}\boldsymbol{G}_{i,j} = \boldsymbol{I}$. The interfering signal from the neighboring cell $\boldsymbol{x}_{3-i}$ is aligned in the direction of $\boldsymbol{v}_{\mathrm{ref}}$. Otherwise, the left inverse of $\boldsymbol{G}_{i,j}$ does not exist, and the ideal alignment of the interference cannot be obtained. Nevertheless, interference can be closely aligned to $\boldsymbol{v}_{\mathrm{ref}}$ by properly designing $\boldsymbol{u}_{i,j}$. $\boldsymbol{u}_{i,j}$ should satisfy the following condition [12]:

$$\begin{aligned}\boldsymbol{u}_{i,j} &= \arg\min_{\boldsymbol{u}}\left\|\boldsymbol{u}^{H}\boldsymbol{G}_{i,j} - \boldsymbol{v}_{\mathrm{ref}}^{H}\right\| \\ &\text{s.t.} \quad \|\boldsymbol{u}\| = 1 \end{aligned} \quad . \tag{6}$$

Let $\boldsymbol{G} = \left[\boldsymbol{g}_{1}^{H} \quad \boldsymbol{g}_{N}^{H}\right]^{H}$ and $\boldsymbol{u} = \left[u_{1} \quad u_{N}\right]^{H}$ (the subscripts are omitted for convenience), then $\boldsymbol{s} = \boldsymbol{u}^{H}\boldsymbol{G} = u_{1}\boldsymbol{g}_{1} + \quad u_{N}\boldsymbol{g}_{N}$. $\boldsymbol{s}^{H}$ should lie in the direction of the projection of $\boldsymbol{v}_{\mathrm{ref}}$ on the space spanned by the columns of $\boldsymbol{G}^{H}$ to minimize the Euclidean distance between $\boldsymbol{s}$ and $\boldsymbol{v}_{\mathrm{ref}}^{H}$. An example of $N = 2$ is illustrated in Fig. 2. Thus, $\boldsymbol{u}$ can be obtained through the following procedure:

a) The projection of $\boldsymbol{v}_{\mathrm{ref}}$ is computed on the space spanned by $\boldsymbol{g}_{1}^{H}, \quad , \boldsymbol{g}_{N}^{H}$: $\mathrm{Proj}\left(\boldsymbol{v}_{\mathrm{ref}}\right) = \boldsymbol{G}^{H}\left(\boldsymbol{G}\boldsymbol{G}^{H}\right)^{-1}\boldsymbol{G}\boldsymbol{v}_{\mathrm{ref}}$.

b) $\mathrm{Proj}\left(\boldsymbol{v}_{\mathrm{ref}}\right) = a\boldsymbol{s}^{H}$, where a is a scalar. Then, $a\boldsymbol{G}^{H}\boldsymbol{u} = \boldsymbol{G}^{H}\left(\boldsymbol{G}\boldsymbol{G}^{H}\right)^{-1}\boldsymbol{G}\boldsymbol{v}_{\mathrm{ref}}$. The left inverse $\left(\boldsymbol{G}^{H}\right)^{\dagger} = \left(\boldsymbol{G}\boldsymbol{G}^{H}\right)^{-1}\boldsymbol{G}$ exists because $\boldsymbol{G}^{H}$ is assumed as full rank. Multiplying both sides of the previous equation with $\left(\boldsymbol{G}^{H}\right)^{\dagger}$ gives $\boldsymbol{u} = a\left(\boldsymbol{G}\boldsymbol{G}^{H}\right)^{-1}\boldsymbol{G}\boldsymbol{v}_{\mathrm{ref}}$.

c) $\boldsymbol{u}$ is normalized.

The receive antenna combining vector of user $[i,j]$ is given as

$$\boldsymbol{u}_{i,j} = \frac{\left(\boldsymbol{G}_{i,j}\boldsymbol{G}_{i,j}^{H}\right)^{-1}\boldsymbol{G}_{i,j}\boldsymbol{v}_{\mathrm{ref}}}{\left\|\left(\boldsymbol{G}_{i,j}\boldsymbol{G}_{i,j}^{H}\right)^{-1}\boldsymbol{G}_{i,j}\boldsymbol{v}_{\mathrm{ref}}\right\|}. \tag{7}$$

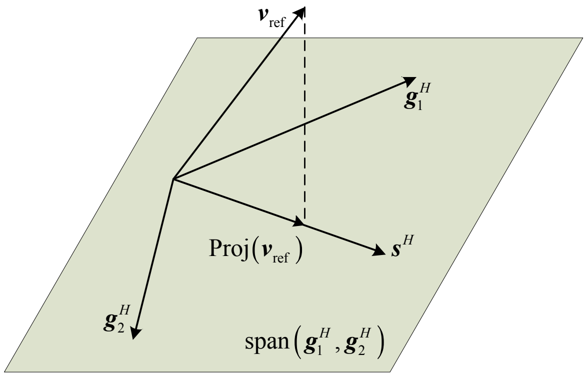

Fig. 2. $\boldsymbol{s}^{H}$ should lie in the direction of the projection of $\boldsymbol{v}_{\mathrm{ref}}$ on the space spanned by the columns of $\boldsymbol{G}^{H}$ ($N = 2$)

The interfering signal from the neighboring cell is aligned in the direction of $\boldsymbol{v}_{\mathrm{ref}}$ by designing the receive antenna combining vector of the user with the aforementioned procedure. The residual interference continues to affect system performance.

After receive combining, the detected symbol of user $[i,j]$ is

$$y_{i,j} = \boldsymbol{u}_{i,j}^{H}\boldsymbol{H}_{i,j}\boldsymbol{x}_{i} + \boldsymbol{u}_{i,j}^{H}\boldsymbol{G}_{i,j}\boldsymbol{x}_{3-i} + \boldsymbol{n}_{i,j} = \boldsymbol{h}_{i,j}^{\mathrm{eq}}\boldsymbol{x}_{i} + \boldsymbol{g}_{i,j}^{\mathrm{eq}}\boldsymbol{x}_{3-i} + \boldsymbol{n}_{i,j} \tag{8}$$

where $\boldsymbol{h}_{i,j}^{\mathrm{eq}}$ and $\boldsymbol{g}_{i,j}^{\mathrm{eq}}$ represent the effective direct channel and cross channel, respectively. The interfering signal is closely aligned onto the direction of $\boldsymbol{v}_{\mathrm{ref}}$; $\boldsymbol{g}_{i.j}^{\mathrm{eq}}$ can be decomposed into two components. One is parallel to $\boldsymbol{v}_{\mathrm{ref}}$ (denoted as $\boldsymbol{g}_{\boldsymbol{v}_{\mathrm{ref}}}^{\mathrm{eq}}$), and the other is vertical to $\boldsymbol{v}_{\mathrm{ref}}$ (denoted as $\boldsymbol{g}_{\perp\boldsymbol{v}_{\mathrm{ref}}}^{\mathrm{eq}}$). Let $\boldsymbol{\beta} = \left(\boldsymbol{g}^{\mathrm{eq}}\right)^{H}$ (the subscript $[i,j]$ is omitted for conciseness), then $\boldsymbol{\beta} = \boldsymbol{\beta}_{\boldsymbol{v}_{\mathrm{ref}}} + \boldsymbol{\beta}_{\perp\boldsymbol{v}_{\mathrm{ref}}}$. Only the component in the direction of $\boldsymbol{\beta}_{\perp\boldsymbol{v}_{\mathrm{ref}}}$ causes interference to the user. $\boldsymbol{\beta}_{\perp\boldsymbol{v}_{\mathrm{ref}}}$ is computed as follows:

$$\boldsymbol{\beta}_{\perp\boldsymbol{v}_{\mathrm{ref}}} = \mathrm{Proj}_{\boldsymbol{v}_{\mathrm{ref}}}\left(\left(\boldsymbol{g}^{\mathrm{eq}}\right)^{H}\right) = \left(\boldsymbol{I} - \frac{\boldsymbol{v}_{\mathrm{ref}}\boldsymbol{v}_{\mathrm{ref}}^{H}}{\left\|\boldsymbol{v}_{\mathrm{ref}}\right\|^{2}}\right)\frac{\left(\boldsymbol{G}^{\dagger}\boldsymbol{G}\right)^{H}\boldsymbol{v}_{\mathrm{ref}}}{\left\|\left(\boldsymbol{G}^{\dagger}\right)^{H}\boldsymbol{v}_{\mathrm{ref}}\right\|} \tag{9}$$

The average power is

$$P_{\mathrm{ICI}} = E\left\{\left|\boldsymbol{\beta}_{\perp\boldsymbol{v}_{\mathrm{ref}}}\boldsymbol{x}_{3-i}\right|^{2}\right\} = \frac{P}{K}\left\|\boldsymbol{\beta}_{\perp\boldsymbol{v}_{\mathrm{ref}}}\right\|^{2} \tag{10}$$

3.2.2 Limited feedback zero-forcing beamforming based on IA

The intra-cell interference can be completely eliminated by ZFBF after aligning most of the inter-cell interference if the transmitter knows the full CSIs of the users. The transmitted signals can only lie within the null space of $\boldsymbol{v}_{\text{ref}}$ to avoid the aligned inter-cell interference [12]. Thus, the precoding matrix $\boldsymbol{F}_i$ of cell i can be obtained as follows:

a) User $[i,j]$ returns its effective direct channel $\boldsymbol{h}_{i,j}^{\text{eq}}$ to its own transmitter.
b) The transmitter constructs the user channel matrix as follows:

$$\boldsymbol{B}_i = \begin{bmatrix} \boldsymbol{h}_{i,1}^{\text{eq}} \\ \\ \boldsymbol{h}_{i,K}^{\text{eq}} \\ \boldsymbol{v}_{\text{ref}} \end{bmatrix} \text{ and computes ZFBF matrix}$$

$$\begin{aligned} \bar{\boldsymbol{F}}_i &= \boldsymbol{B}_i^H \left(\boldsymbol{B}_i \boldsymbol{B}_i^H\right)^{-1} \boldsymbol{\Gamma} \\ &= \boldsymbol{B}_i^H \left(\boldsymbol{B}_i \boldsymbol{B}_i^H\right)^{-1} \begin{bmatrix} \sqrt{\gamma_{i,1}} & & \\ & & \\ & & \sqrt{\gamma_{i,K+1}} \end{bmatrix} \\ &= \begin{bmatrix} \boldsymbol{w}_{i,1} & & \boldsymbol{w}_{i,K} & \boldsymbol{w}_{i,K+1} \end{bmatrix} \begin{bmatrix} \sqrt{\gamma_{i,1}} & & \\ & & \\ & & \sqrt{\gamma_{i,K+1}} \end{bmatrix} \\ &= \begin{bmatrix} \sqrt{\gamma_{i,1}}\boldsymbol{w}_{i,1} & & \sqrt{\gamma_{i,K}}\boldsymbol{w}_{i,K} & \sqrt{\gamma_{i,K+1}}\boldsymbol{w}_{i,K+1} \end{bmatrix} \\ &= \begin{bmatrix} \boldsymbol{f}_{i,1} & & \boldsymbol{f}_{i,K} & \boldsymbol{f}_{i,K+1} \end{bmatrix}, \end{aligned} \tag{11}$$

where $\gamma_{i,k}$ is the power control factor and satisfies $\gamma_{i,k} = \dfrac{1}{\left\|\boldsymbol{w}_{i,k}\right\|^2}$. The precoding matrix $\boldsymbol{F}_i$ takes the first K columns of $\bar{\boldsymbol{F}}_i$. $K+1 \le M$ meets the demand of ZFBF. Therefore, the transmitter can serve $K = M-1$ users at most simultaneously.

The transmitter in practical FDD systems usually obtains CSI by limited feedback method. The precoding matrix is computed according to the estimated user channel. Each user selects a codeword from a codebook $\mathcal{F}$, which is known at both the transmitter and the receiver as the estimated effective channel, according to the following criterion:

$$\hat{\boldsymbol{h}}_{i,j}^{\text{eq}} = \arg\max_{\boldsymbol{c}_m \in \mathcal{F}} \left| \left(\boldsymbol{h}_{i,j}^{\text{eq}}\right) \boldsymbol{c}_m \right|. \tag{12}$$

The transmitter computes the precoding matrix $\hat{\boldsymbol{F}}_i$ using the estimated channels. The intra-cell interference (i.e., the inter-user interference) within a cell is not eliminated completely. The residual intra-cell interference and the residual inter-cell interference decrease the system throughput.

3.2.3 Semi-orthogonal user selection algorithm

When a number of users simultaneously exist in a cell, the system may obtain multi-user diversity gain, and its throughput degradation induced by the limited feedback can be alleviated. Adopting SINR in limited feedback ZFBF systems as the user's channel quality indicator can obtain better performance than other indicators, such as the instantaneous channel gain [7]. This paper adopts SINR as the user selection criterion in a semi-orthogonal algorithm. Here, the specific algorithm is different from the counterpart that was developed for the single-cell system based on two points. First, the user SINR should include the power of the residual inter-cell interference. Second, given that $\boldsymbol{v}_{\text{ref}}$ is set as the direction of the aligned inter-cell interference, all selected user channels should be orthogonal to it. This result can be achieved by viewing $\boldsymbol{v}_{\text{ref}}$ as the channel of a virtual user, which is first selected. Thus, the SINR of user $[i,j]$ is

$$\text{SINR}_{i,j}^{\text{ZF}} = \frac{\dfrac{P}{K}\left\|\boldsymbol{h}_{i,j}^{\text{eq}}\right\|^2 \cos^2\left(\theta_{i,j}+\phi\right)}{\dfrac{P}{K}\left\|\boldsymbol{h}_{i,j}^{\text{eq}}\right\|^2 \sin^2\theta_{i,j} + P_{\text{ICI}} + 1} \tag{13}$$

where $\phi = \cos^{-1}\sqrt{\dfrac{1-(K-1)\varepsilon}{1-(K-2)\varepsilon}(1+\varepsilon)}$, ε is the coefficient that denotes the orthogonality between the selected user channels, and P_{ICI} is the power of the residual inter-cell interference. The corresponding user selection algorithm is described as follows:

a) Candidate user set $\mathcal{T}_0 = \{1, \quad ,L\}$ is initialized. The initial selected user set is $\mathcal{S}_0 = \{\boldsymbol{v}_{\text{ref}}\}$.

b) Users from $\mathcal{T}_0$ are removed if the correlation coefficient between their channels and $\boldsymbol{v}_{\text{ref}}$ are greater than ε, and the candidate user set is updated in the next iteration: $\mathcal{T}_1 = \left\{1 \le l \le L : \left|\hat{\mathbf{h}}_l^{\text{eq}} \mathbf{v}_{\text{ref}}^H\right| \le \varepsilon\right\}$.

c) In i th$(i=1, \quad ,K+1)$ iteration, user $\pi(i)$ is selected with maximum SINR and is added into the selected user set $\mathcal{S}_i \leftarrow \mathcal{S}_{i-1} \cup l_i$, $\mathcal{T}_i \leftarrow \mathcal{T}_{i-1} \setminus \pi(i)$.

d) Users from $\mathcal{T}_i$ are removed if the correlation coefficient between their channels and all selected users are greater than ε, and the candidate user set is formed in the next iteration:

$\mathcal{T}_{i+1} = \left\{1 \le l \le L : \left|\hat{\boldsymbol{h}}_l^{\text{eq}}\left(\hat{\boldsymbol{h}}_{\pi(j)}^{\text{eq}}\right)^H\right| \le \varepsilon,\ 1 \le j \le i\right\}, \quad i = i+1$.

e) If $i > K+1$ or $\mathcal{T}_i = \Phi$, the algorithm is ended. Otherwise, the algorithm returns to c).

3.3 Singular value decomposition (SVD)-based limited feedback precoding and user selection

Limited feedback ZFBF decreases system throughput because of the residual inter-user interference. This paper adopts a modified SVD-based precoding method to alleviate throughput degradation. The SVD-based precoding method exhibited improved performance than ZFBF-based method under low rate feedback [18]. The original method was developed for a single-cell multi-user MIMO system with an MMSE receiving combining vector at the user end. A different scenario is applied. Thus, SINR and the corresponding user selection criterion are different.

If users' precoding vectors are mutually orthogonal, the SINR of each user only depends on its own channel and precoding vector and is irrelative to other users [19]. Thus, the user selects the codeword that maximizes its SINR from the codebook $\mathcal{F}$ as the preferred precoding vector. The user returns its preferred precoding vector and the corresponding

SINR to the transmitter. If more users appear than the scheduled number, the transmitter selects those with maximum SINRs and with mutually orthogonal preferred precoding vectors as the scheduled users. The transmitter constructs new precoding vectors according to the users' preferred precoding vectors and broadcasts to each user. The procedure is shown in Fig. 3 [18].

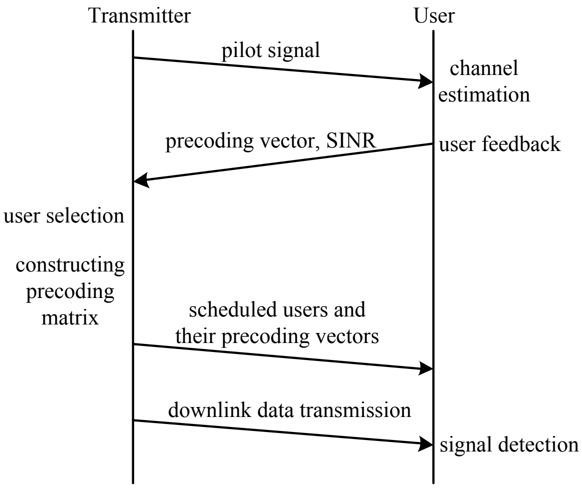

Fig. 3. SVD-based precoding vector design and user selection

3.3.1 Computation of user SINR

Given that all scheduled users' precoding vectors are mutually orthogonal, the SINR of each user only depends on its effective channel, precoding vector, and residual inter-cell interference. When the residual interference power is considered, the SINR of user $[i,j]$ is

$$\mathrm{SINR}_{i,j}^{\mathrm{SVD}} = \frac{\frac{P}{K}\left\|\boldsymbol{h}_{i,j}^{\mathrm{eq}}\right\|^2 a_{i,j}^2}{\frac{P}{K}\left\|\boldsymbol{h}_{i,j}^{\mathrm{eq}}\right\|^2\left(1-a_{i,j}^2\right)+P_{\mathrm{ICI}}+1} \tag{14}$$

where $a_{i,j}^2 = \frac{\left|\left(\boldsymbol{h}_{i,j}^{\mathrm{eq}}\right)^H \boldsymbol{f}_{i,j}\right|^2}{\left\|\boldsymbol{h}_{i,j}^{\mathrm{eq}}\right\|^2}$. Each user selects the codeword $\hat{\boldsymbol{f}}_{i,j} = \arg\max_{\boldsymbol{c}_m \in \mathcal{F}}\left(\mathrm{SINR}_{i,j}^{\mathrm{SVD}}\right)$ as its preferred precoding vector and returns to the transmitter along with the corresponding SINR.

3.3.2 User selection and precoding vector design

The transmitter receives the precoding vectors and SINR values of all users and selects those with maximum SINR values and mutually orthogonal precoding vectors as simultaneously scheduled users. The procedure of the selection algorithm is similar to that of the previous one. The users return their preferred precoding vectors; thus, the estimated effective user channel $\hat{\boldsymbol{h}}_{i,j}^{\mathrm{eq}}$ in the previous algorithm should be replaced by the estimated preferred precoding vector $\hat{\boldsymbol{f}}_{i,j}$. Similar to the previous selection algorithm, all the precoding vectors of scheduled users should be as orthogonal as that of the first scheduled virtual user with channel $\boldsymbol{v}_{\mathrm{ref}}$ to avoid the influence of the interference. The preferred precoding vector of the virtual user can be assumed as the first codeword $\boldsymbol{c}_1$ without generality. The transmitter aggregates all the precoding vectors of scheduled users into a matrix

$$\hat{\boldsymbol{F}}_i = \left[\hat{\boldsymbol{f}}_{i,1} \qquad \hat{\boldsymbol{f}}_{i,K} \quad \boldsymbol{c}_1\right] \tag{15}$$

and computes the SVD of $\hat{\boldsymbol{F}}_i = \boldsymbol{U}\boldsymbol{\Sigma}\boldsymbol{V}^H$. The new precoding matrix is $\boldsymbol{F}_i = \boldsymbol{U}\boldsymbol{V}^H$. The precoding vectors of users take the first $K = M-1$ columns of $\boldsymbol{F}_i$.

4 Analysis and discussion of results

This section verifies the proposed precoding method and user selection algorithm with low-rate limited feedback by computer simulation. The modified SVD based precoding method (IA, SVD) is compared with ZFBF (IA, ZFBF) with regard to the system throughput when the proposed non-ideal IA scheme is adopted. The system throughput when no IA scheme is adopted (i.e., the inter-cell interference is viewed as noise) is also shown for comparison. The combining vector of the user is designed by using quantization based combining (QBC) scheme [20] to improve quantization precision (noIA, QBC).

Each cell has a total of L users. The transmitter of each cell has M antennas, and each user has N antennas. The transmitter can simultaneously serve K users. The number of scheduled users in the systems that adopt the proposed non-ideal IA scheme is $K = M-1$. The number of scheduled users in the system that do not adopt an IA scheme is $K = M$.

Figure 4 compares the system throughput of the three schemes with regard to user SNR when M=4 and N=2 and when feedback rates are $B=4$ and $B=6$, respectively. As shown in Fig. 4, the system sum rate is improved with the proposed non-ideal IA scheme compared with a traditional system where no IA scheme is adopted. Moreover, the throughput of the system with proposed SVD-based precoding is superior to that with ZFBF precoding.

Figure 5 compares the system throughput with regard to the user number when the number of scheduled users is less than the total number of users in the cell. The figure shows that the system throughput can be further improved by user selection.

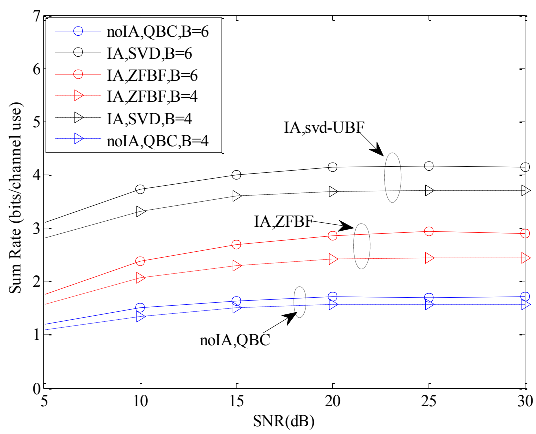

Fig. 4. System throughput with regard to user SNR (L=10, B=4, and B=6)

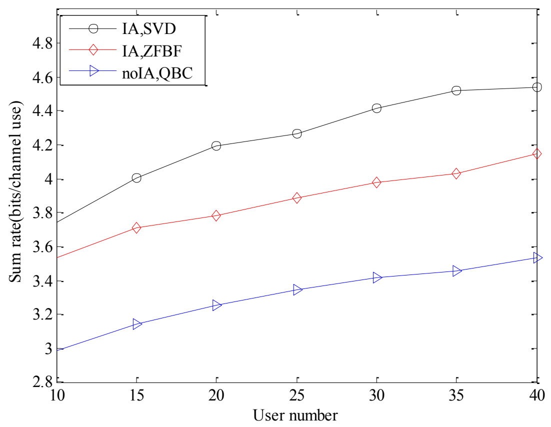

Fig. 5. System throughput with regard to user number L (SNR=15dB and B=4)

5. Conclusions

Designing simple and effective transmission schemes based on IA for practical cellular systems has become a popular research topic. This paper is based on partial interference alignment and proposes a precoding and user selection scheme for two-cell downlink multi-user MIMO systems. The inter-cell interference in the proposed scheme was partially aligned onto a predefined direction by designing users' receive antenna combining vectors, and a modified SVD-based precoding and user selection method was proposed for the system with low-rate limited feedback. The effects of the proposed scheme on improving the system sum rate performance were evaluated by numerical simulations. The main conclusions are drawn as follows:

(1) The proposed partial IA-based precoding scheme does not need coordination between interfering cells and joint design between the transmitter and the users. This scheme is easy to implement with low feedback overhead under the general case when the number of the user antenna is smaller than that of the transmitter.

(2) The simulation results indicate that the system sum rate is significantly degraded by the residual inter-cell and inter-user interference with ZFBF in the case of low-rate limited feedback. This degradation can be alleviated by the proposed SVD-based precoding scheme.

(3) The sum rate can be further improved through a properly designed user selection algorithm when the number of total users in each cell is larger than the simultaneously scheduled users.

The proposed scheme can be easily implemented in current cellular systems. However, the scheme can be adopted only in the two-cell interfering scenario. The generalization to more than two-cell interfering systems remains under consideration.

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