Two-Cell Coordinated Transmission Scheme Based on Interference Alignment and MU-MIMO Beamforming

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***Abstract*—We investigate the problem of two-cell multi-user co-channel transmission, wherein both inter-cell interference and intra-cell inter-user interference should be well managed. Interference alignment (IA) is theoretically proved to be a promising technology for managing co-channel interference. It can be used to mitigate inter-cell interference. When multiple users are served by a single cell, advanced multi-user multiple-input multiple output (MU-MIMO) transmission can be used to manage the intra-cell inter-user interference. In this paper, we present an efficient two-cell coordinated linear beamforming method where IA is combined with MU-MIMO to achieve high performance multi-cell cooperative transmission. The effectiveness of the proposed method is verified by numerical evaluations.**

I. Introduction

Inter-cell co-channel interference is a severe problem in fourth-generation (4G) cellular systems, e.g., WiMAX [1] and 3GPP-LTE [2], especially for users located at the cell boundary, i.e., cell-edge users. Advanced interference management methods are desired to mitigate the inter-cell interference and thus improve the cell-edge throughput. One interesting solution, called interference alignment (IA) [3] has been developed recently. The essential idea of this method is to align high-dimensional interference signals to a subspace with smaller dimensions, which is referred to as interference subspace. If the desired signal is transmitted in the subspace that is orthogonal to the interference subspace, the signals will not be affected by the interference. If the dimensions of the total signal space are fixed, reducing the dimensions of the interference subspace means that more resources can be reserved for the desired signal transmission. Although tremendous analytical research on IA has been done and the theoretical gains are significant, the number of feasible solutions for practical implementation is still quite limited. As for the communication within a cell, the base station can serve several users simultaneously. There already exist many multi-user (MU) transmission schemes that address the problem of intra-cell inter-user interference. In this paper, we investigate the problem in a two-cell multi-user scenario where the base stations of two adjacent cells transmit a signal using the same time-frequency resources and each of them serves several users within its own cell. In such a system, both the inter-cell interference and the intra-cell inter-user interference should be well managed.

IA can be implemented along the time, frequency, space domains or jointly across multiple domains. In this paper, we focus on the low complexity method that only utilizes the spatial resources. We assume that both the base station and the mobile stations are equipped with multiple antennas. IA is implemented by appropriately choosing the transmitter and receiver beamforming matrices. Iterative methods were proposed in [3] where the transmit and receive beamforming matrices are alternatively optimized. Such methods have high computational complexity and require many exchanges of information either over the air or through the backhaul link. They are unsuitable for practical deployment. Suh *et. al.* [4] proposed a low complexity beamforming based IA method. A predefined precoding matrix is used to separate the desired signal and the inter-cell interference where the desired signal is transmitted in the column space and the interference is aligned in the null space of the precoding matrix. Although this method has low complexity and low requirements regarding the feedback and other control signaling, it does not achieve the maximum possible degrees of freedom (DoFs), which is a metric that measures the effectiveness of IA. Another method was proposed in [5] where a linear equation set is formulated according to the IA criterion. By solving such an equation set, the transmitter and receiver beamforming matrices can be obtained. With certain antenna configurations, the maximum DoFs can be achieved. In this method, precoding similar to zero forcing (ZF) is applied after IA to orthogonalize all data streams. Such total interference elimination is achieved at the expense of weakening the receive power of the desired signal. Therefore, its performance is limited in the low signal-to-noise-ratio (SNR) region.

In this paper, we focus on the performance in the high SNR region and investigate the case where the noise also clearly affects the transmission. This topic is important because coordinated transmission is typically applied to the cell-edge users who receive not only strong interference from the possible cooperating cells but also a considerable amount of interference from cells that are impossible to cooperate

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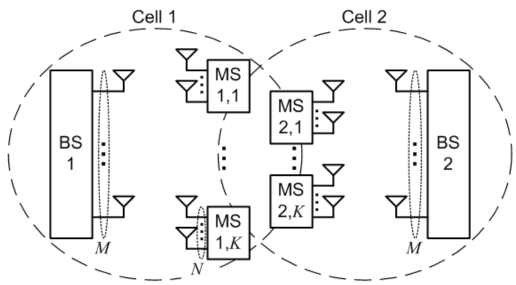

Fig. 1. System model

with. The latter one can only be treated as additional noise. The proposed method combines IA with an advanced MU-MIMO beamforming method. The IA method eliminates the inter-cell interference and the MU-MIMO technology not only manages the intra-cell inter-user interference but also preserves the strength of the desired signal. The performance gain over the existing methods is shown based on numerical simulation results.

The rest of the paper is organized as follows. Section II presents the two-cell multi-user system model. The novel IA and MU-MIMO based coordinated beamforming method is introduced in Section III. The performance is evaluated based on numerical simulations and the results are summarized in Section IV. Finally, Section V concludes the paper.

II. System Model

We study a two-cell multi-user system as illustrated in Figure 1. Each cell serves K users. The base station has M antennas and each user has N antennas. The base station transmits $S \leq \min(\lfloor M/K \rfloor, N)$ parallel data streams to each user. Since we are interested in the scenario where the inter-cell interference causes severe problems, we assume that all users are cell-edge users and specifically each user receives equal average power from its serving base station and from the interfering base station. User data are only available at the serving cell. Therefore, joint transmission by several base stations is not possible. For user k ($k \in \{1, \ldots, K\}$) in cell i ($i \in \{1, 2\}$), the received signal can be expressed as:

$$\begin{aligned} \mathbf{y}_{i,k} = \quad & \mathbf{H}_{i,i,k}\mathbf{P}_{i,k}\mathbf{s}_{i,k} + \sum_{l=1, l\neq k}^{K} \mathbf{H}_{i,i,k}\mathbf{P}_{i,i,l}\mathbf{s}_{i,l} \\ & + \sum_{l=1}^{K} \mathbf{H}_{3-i,i,k}\mathbf{P}_{3-i,l}\mathbf{s}_{3-i,l} + \mathbf{v}_{i,k} \end{aligned} \quad (1)$$

where $\mathbf{H}_{j,i,k} \in \mathcal{C}^{N\times M}$ represents the MIMO channel between base station j and user k in cell i; $\mathbf{s}_{i,k} \in \mathcal{C}^{S\times 1}$ represents the data intended for user k in cell i and $\mathbf{P}_{i,i,k} \in \mathcal{C}^{M\times S}$ is its associated MIMO precoding matrix; $\mathbf{v}_{i,k} \in \mathcal{C}^{N\times 1}$ represents the noise and residual interference from non-cooperating cells at the receiver of user k in cell i. Linear receive beamforming is applied on the receiver side to reconstruct the desired signal, i.e.,

$$\hat{\mathbf{s}}_{i,k} = \mathbf{G}_{i,k}\mathbf{y}_{i,k} \quad (2)$$

where $\mathbf{G}_{i,k} \in \mathcal{C}^{S\times N}$ is the receiver beamforming matrix.

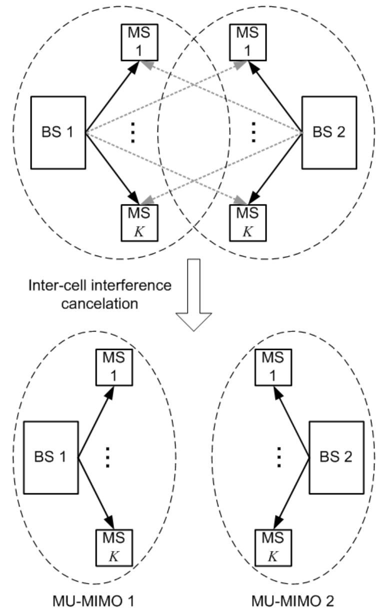

Fig. 2. Two-step interference management

In (1), the first term represents the desired signal, the second term represents the intra-cell inter-user interference and the third term represents the total inter-cell interference. By properly designing the transmitter and receiver beamforming matrices, the interference is efficiently suppressed and the desired signals are well protected. As a result, the system can achieve better sum rate performance. In the next section, we describe a possible solution to such a beamforming design problem.

III. IA and MU-MIMO based 2-cell coordinated beamforming scheme

From the transmission model, i.e. (1), presented in the previous section, we can see that the impairment in the desired signal is caused by inter-cell interference, intra-cell inter-user interference, and noise. In this section, we discuss the methods that suppress the adverse effects of these factors.

To simplify the design, we divide the interference management into two consecutive steps

- Inter-cell interference cancellation
- Intra-cell inter-user interference treatment

Although this kind of artificial separation of the interference management procedure may cause some performance loss, it can simplify the coordinated beamforming design. Figure 2 illustrates the 2-step interference management scheme.

A. Separated inter-cell and intra-cell interfrence management

We impose a cascaded structure for the MIMO linear precoding and decoding matrices. More specifically, we define

MIMO precoding matrix $\mathbf{P}_{i,k}$ to be the product of two matrices, i.e.,

$$\mathbf{P}_{i,k} = \mathbf{P}_i^1 \mathbf{P}_{i,k}^2 \tag{3}$$

where matrix $\mathbf{P}_i^1 \in \mathcal{C}^{M\times R}$ is a common precoding matrix for all mobile stations within cell i, and matrix $\mathbf{P}_{i,k}^2 \in \mathcal{C}^{R\times S}$ is a MS specific precoding matrix. Variable R should satisfy $M > R \geq S$. We use $\mathbf{P}_i^1$ to cancel the inter-cell interference and use $\mathbf{P}_{i,k}^2$ to control the K-user transmission within a cell.

On the receiver side, we define MIMO receiver beamforming matrix $\mathbf{G}_{i,k}$ to be

$$\mathbf{G}_{i,k} = \mathbf{G}_{i,k}^2 \mathbf{G}_{i,k}^1 \tag{4}$$

where matrix $\mathbf{G}_{i,k}^1 \in \mathcal{C}^{Q\times N}$ is applied to cancel the inter-cell interference, and $\mathbf{G}_{i,k}^2 \in \mathcal{C}^{S\times Q}$ is used to reconstruct the S stream user data.

Combining (1), (2), (3), and (4), we obtain:

$$\begin{aligned}\hat{\mathbf{s}}_{i,k} \;=\;& \mathbf{G}_{i,k}^2\mathbf{G}_{i,k}^1\mathbf{H}_{i,i,k}\mathbf{P}_i^1\mathbf{P}_{i,k}^2\mathbf{s}_{i,k} \\ &+ \sum_{l=1,l\neq k}^{K} \mathbf{G}_{i,k}^2\mathbf{G}_{i,k}^1\mathbf{H}_{i,i,k}\mathbf{P}_i^1\mathbf{P}_{i,l}^2\mathbf{s}_{i,l} \\ &+ \sum_{l=1}^{K} \mathbf{G}_{i,k}^2\mathbf{G}_{i,k}^1\mathbf{H}_{3-i,i,k}\mathbf{P}_{3-i}^1\mathbf{P}_{3-i,l}^2\mathbf{s}_{3-i,l} \\ &+ \mathbf{G}_{i,k}^2\mathbf{G}_{i,k}^1\mathbf{v}_{i,k}\end{aligned} \tag{5}$$

To eliminate totally the inter-cell interference, the following equalities should be satisfied

$$\begin{aligned}\mathbf{G}_{j,1}^1\mathbf{H}_{i,j,1}\mathbf{P}_i^1 &= 0 \\ &\vdots \\ \mathbf{G}_{j,K}^1\mathbf{H}_{i,j,K}\mathbf{P}_i^1 &= 0\end{aligned} \tag{6}$$

for all $i \in \{1, 2\}$ and $j = 3 - i$.

To guarantee the existence of $\{\mathbf{G}_{3-i,k}\}_{k=1}^K$ and $\mathbf{P}_i^1$ that satisfy (6), we can choose trivially

$$KS \leq M/2 \tag{7}$$

and

$$M - KS \geq R \geq KS \tag{8}$$

However, such a setting does not fully utilize the available DoFs. So the total number of data streams, i.e., KS is limited by $M/2$. In the following, we introduce an interference alignment method which can support a larger number of total data streams.

B. IA for Multi-cell interference mitigation

1) Basic principle: The essential idea of IA is to align all sources of interference to a subspace and make this subspace orthogonal to the subspace reserved for the desired signal transmission. The dimensions for the interference subspace should be made as small as possible so that more resources can be used for the desired signal transmission. In other words, a larger number of data streams can be transmitted. From (6), we can see that maximally KS streams of inter-cell interference exist. We try to design appropriate receive beamforming matrices $\{\mathbf{G}_{3-i,k}^1\}_{k=1}^K$ to correlate the interfering streams so that all sources of interference are aligned to a low dimensional interference subspace. Let us use Q to denote the dimension of the interference subspace. Obviously, we want the following to hold

$$S \leq Q < KS. \tag{9}$$

To make (6) solvable, the following should be satisfied

$$Q + KS \leq M. \tag{10}$$

Combining (9) and (10), we can see that in the best case, we have

$$S + KS \leq M. \tag{11}$$

Comparing (11) to (7), we can see that the IA method can achieve a much larger number of data transmissions than the trivial solution. In the next section, we give an example of a concrete implementation of the IA based beamforming scheme.

2) Implementation example: Finding the solution to (6) is a non-trivial task. In this section, we present a low-complexity solution.

Let us consider the maximum number of parallel data transmissions. We make Q equal to its minimum value, i.e.,

$$Q = S. \tag{12}$$

In addition, we set

$$R = KS \tag{13}$$

and

$$M = R + Q = KS + S. \tag{14}$$

From (6) we can see that rows of $\mathbf{G}_{3-i,1}^1\mathbf{H}_{i,3-i,1}$ should lie in the null space of $\left(\mathbf{P}_i^1\right)^{\mathrm{T}}$. Let us define $\mathbf{U}_i \in \mathcal{C}^{S\times M}$ with

$$\mathbf{U}_i\mathbf{P}_i^1 = \mathbf{0}. \tag{15}$$

Then the solutions for:

$$\begin{aligned}\mathbf{G}_{3-i,1}^1\mathbf{H}_{i,3-i,1} &= \mathbf{U}_i \\ &\vdots \\ \mathbf{G}_{3-i,K}^1\mathbf{H}_{i,3-i,K} &= \mathbf{U}_i\end{aligned} \tag{16}$$

satisfy the condition in (6).

Now let us use $\mathbf{g}_{3-i,k}^{[l]}$ to denote the l^{th} row of matrix $\mathbf{G}_{3-i,k}^1$ and similarly use $\mathbf{u}_i^{[l]}$ to denote the l^{th} row of matrix $\mathbf{U}_i$. Then for each l, we can obtain the following linear equation group

$$\begin{bmatrix} \mathbf{I} & -\mathbf{H}_{i,3-i,1}^{\mathrm{T}} & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{I} & \mathbf{0} & \cdots & -\mathbf{H}_{i,3-i,K}^{\mathrm{T}} \end{bmatrix} \begin{bmatrix} {\mathbf{u}_i^{[l]}}^{\mathrm{T}} \\ {\mathbf{g}_{3-i,1}^{[l]}}^{\mathrm{T}} \\ \vdots \\ {\mathbf{g}_{3-i,K}^{[l]}}^{\mathrm{T}} \end{bmatrix} = \mathbf{0}, \tag{17}$$

which has $M + KN$ unknowns and MK equations. This equation set should have at least S distinct solutions to satisfy the conditions in (16). To satisfy these, we have

$$M + KN \geq MK + S. \tag{18}$$

Inserting (14) into the above inequality, we obtain

$$N \geq KS. \tag{19}$$

With (14) and (19), we obtain the antenna number, user number and stream number configurations that are suitable for applying IA. In other words, if (14) and (19) are satisfied, we are able to solve (15) and (16) for precoding matrix $\mathbf{P}_i^1$ and decoding matrices $\{\mathbf{G}_{3-i,k}^1\}_{k=1}^K$.

The IA schemes presented in [4] first determine the precoding matrix $\mathbf{P}_i^1$ and solve (15) for $\mathbf{U}_i$. Then they solve (16) for $\{\mathbf{G}_{3-i,k}^1\}_{k=1}^K$. To solve (16), they require that $M = N$. A specific example uses the configuration $M = N = 3$, $K = 2$ and $S = 1$, which satisfy the conditions in (14) and (19). The IA scheme presented in [5] first solves $\{\mathbf{G}_{3-i,k}^1\}_{k=1}^K$ and $\mathbf{U}_i$ in (16) by solving equation set (17). Then the scheme solves (15) for $\mathbf{P}_i^1$. A specific example uses the configuration $M = 3$, $N = 2$, $K = 1$ and $S = 1$. This setting also satisfies the conditions in (14) and (19).

C. MU-MIMO Beamforming

If we manage to obtain precoding matrix $\mathbf{P}_i^1$ and decoding matrices $\{\mathbf{G}_{3-i,k}^1\}_{k=1}^K$ for $i = 1, 2$ which satisfy (6), then the inter-cell interference is totally removed and we can rewrite (5) as

$$\begin{aligned}\hat{\mathbf{s}}_{i,k} &= \mathbf{G}_{i,k}^2\mathbf{G}_{i,k}^1\mathbf{H}_{i,i,k}\mathbf{P}_i^1\mathbf{P}_{i,k}^2\mathbf{s}_{i,k} \qquad (20)\\ &\quad + \sum_{l=1,l\neq k}^{K}\mathbf{G}_{i,k}^2\mathbf{G}_{i,k}^1\mathbf{H}_{i,i,k}\mathbf{P}_i^1\mathbf{P}_{i,l}^2\mathbf{s}_{i,l} + \mathbf{G}_{i,k}^2\mathbf{G}_{i,k}^1\mathbf{v}_{i,k}.\end{aligned}$$

Now, let us define an equivalent channel with

$$\tilde{\mathbf{H}}_{i,k} = \mathbf{G}_{i,k}^1\mathbf{H}_{i,i,k}\mathbf{P}_i^1, \tag{21}$$

and

$$\tilde{\mathbf{v}}_{i,k} = \mathbf{G}_{i,k}^1\mathbf{v}_{i,k}, \tag{22}$$

and apply them to (20) to obtain

$$\begin{aligned}\hat{\mathbf{s}}_{i,k} &= \mathbf{G}_{i,k}^2\tilde{\mathbf{H}}_{i,k}\mathbf{P}_{i,k}^2\mathbf{s}_{i,k} \qquad (23)\\ &\quad + \sum_{l=1,l\neq k}^{K}\mathbf{G}_{i,k}^2\tilde{\mathbf{H}}_{i,k}\mathbf{P}_{i,l}^2\mathbf{s}_{i,l} + \mathbf{G}_{i,k}^2\tilde{\mathbf{v}}_{i,k},\end{aligned}$$

which represents the channel input-output relationship of a standard single-cell MU-MIMO system.

The choice of precoding matrices $\{\mathbf{P}_{i,k}^2\}_{k=1}^K$ and decoding matrices $\{\mathbf{G}_{i,k}^2\}_{k=1}^K$ is independent of the inter-cell IA and thus we can choose any MU-MIMO transmission and reception scheme. Simple methods include ZF or block diagonalization (BD) beamforming methods or MMSE methods. Advanced methods include iterative methods, e.g., iterative weighted MMSE methods. If we abandon the linear precoding/decoding structure, we can also apply non-linear methods, e.g., Dirty Paper Coding (DPC) or Tomlinson-Harashima Precoding (THP).

D. Novelty analysis

In the previous sections, we explained a novel two-cell multi-user precoding scheme. It is designed such that the MIMO precoding/decoding is divided into two steps. The first step utilizes the IA principle to eliminate the inter-cell interference while expending the least amount of resources. The second step utilizes the existing powerful MU-MIMO technologies to implement efficient co-channel multi-user transmission. The IA based methods mentioned in [5] orthogonalize all sources of interference, i.e., inter-cell interference and intra-cell inter-user interference orthogonal, to the desired signal and use the ZF principle to eliminate them. However, the ZF method is not efficient in dealing with noise as it may affect the received power strength of the desired signal. A non-orthogonal method is proposed in [4]. However, iterations are needed to implement that method which not only increases the processing complexity but also requires ping-pong transmissions over the air between the base station and mobile stations in order to update gradually MIMO precoding/decoding matrices. In the proposed scheme, we only orthogonalize the desired signal to the inter-cell interference. Non-orthogonal multi-user transmission is used to achieve the best balance between protecting the power of the desired signal and suppressing the inter-user interference within a cell. The MIMO precoding/decoding matrices are calculated at once at the base station. Even though we apply an iterative method for MU-MIMO precoding, the computation is carried out solely on the base station side. The ping-pong transmissions required by [4] are not necessary in the proposed scheme. The proposed scheme can also be considered as a general framework for two-cell MIMO linear precoding/decoding. If the ZF principle is applied to MU-MIMO transmission, then the resulting MIMO precoder/decoder coincides with the method introduced in [5].

IV. Simulation Results

Numerical simulations are carried out to verify the performance of the proposed two-cell multi-user MIMO precoding/decoding scheme. We select two simulation scenarios that employ settings that are similar to those used in [4] and [5].

The first 2-cell simulation scenario has a (2,3,2,3) configuration, i.e., 2 cooperating base stations with 3 antennas at each base station, and 2 mobile stations per cell with 3 antennas at each mobile station. Such a system configuration is also considered in [4]. We implemented the following in the proposed scheme

- IA based inter-cell interference cancellation and ZF based intra-cell MU-MIMO (IA+ZF MU-MIMO)
- IA based inter-cell interference cancellation and iterative weighted MMSE (WMMSE) based intra-cell MU-MIMO (IA+WMMSE MU-MIMO)

The second method is based on the iterative max-sum-rate methods introduced in [6]. For performance comparison, we also implemented the following reference methods

- IA method introduced in [4] (subspace IA)
- ZF based coordinated beamforming (CB-ZF [7])

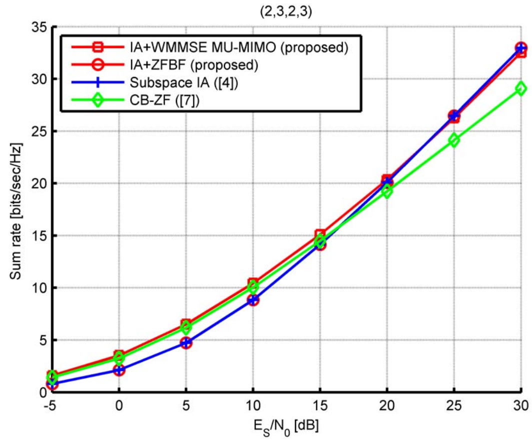

Fig. 3. Sum rate comparison of different schemes with (2,3,2,3) configuration

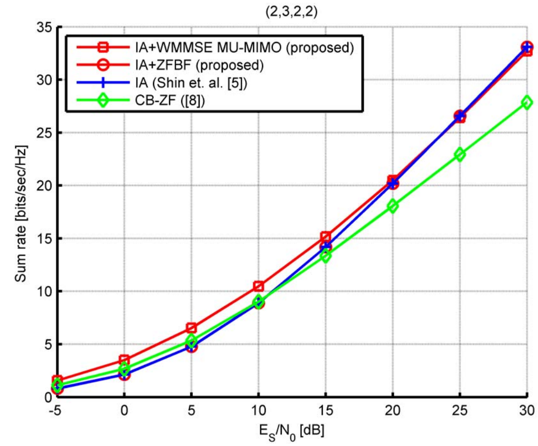

Fig. 4. Sum rate comparison of different schemes with (2,3,2,2) configuration

As analyzed in [7], the coordinated beamforming scheme can only support DoFs equal to 3 transmissions with the (2,3,2,3) configuration. Therefore we use the following configuration for the CB-ZF method in the simulation: base station 1 serves 2 mobile stations and base station 2 only serves 1 mobile station. The sum-rate versus SNR curves achieved by different beamforming schemes are plotted in Figure 3.

Figure 3 shows that the proposed method and the reference method from [4] achieve higher DoFs, i.e. multiplexing gain, than the coordinated beamforming scheme. The IA+ZF MU-MIMO method has the same performance as the subspace IA method since the same design principle, i.e., orthogonalization of the desired signal subspace with all (intra-cell and inter-cell) interference subspaces, is used. The IA+WMMSE MU-MIMO method only orthogonalizes the signal subspace with the inter-cell interference. A better tradeoff between the received signal strength and the residual interference power is achieved by using the advanced MU-MIMO design criteria, i.e., weighted MMSE based iterative sum rate maximization method. It can be seen that the IA+WMMSE MU-MIMO method not only achieves a high DoFs transmission in a high SNR region but also performs well in a low SNR region. In contrast, the subspace IA method performs poorly compared to the coordinated beamforming method in a low SNR region.

The second simulation scenario has a (2,3,2,2) configuration, i.e., 2 base stations each with 3 antennas, and 2 mobile stations in each cell each with 2 antennas. Such a system configuration is also considered in [5]. In this case, the subspace IA method of [4] does not work. So we replace it with the IA method introduced in [5] and notate this method by "IA by Shin *et. al.* in [5]". Again, for the coordinated beamforming scheme, we assume that base station 1 serves 2 mobile stations and base station 2 only serves 1 mobile station. The sum-rate versus SNR curves achieved by different beamforming schemes are plotted in Figure 4.

The simulation results show that the IA based methods achieve higher DoFs than the CB-ZF method. According to the analysis in [5], the IA method by Shin *et al.* reaches the maximum achievable DoFs with the (2,3,2,2) configuration. Therefore, the proposed method also reaches the maximum achievable DoFs. Compared to the subspace IA method, the same DoF transmission is accomplished with one less mobile station antenna. Again, by introducing the advanced MU-MIMO method, the performance is clearly improved in a low SNR region.

V. Conclusions

In this paper, we proposed a general framework for two-cell cooperative transmission. The treatment of interference is divided into two steps: Inter-cell interference elimination and intra-cell inter-user interference management. IA methods are applied in the first step to achieve a high DoFs transmission. ZF based precoding is used to remove totally the inter-cell interference. Advanced MU-MIMO methods can be applied in the second stage to enhance the sum-rate performance. The existing methods, e.g, in [5] can be interpreted as a special implementation of the proposed method. By using advanced MU-MIMO in conjunction with IA, we achieve better performance than the other tested methods. This is evidenced by the numerical evaluation results.

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