Flexible Coordinated Beamforming (FlexCoBF) Algorithm for the Downlink of Multi-User MIMO Systems

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***Abstract*—We propose a Flexible Coordinated Beamforming (FlexCoBF) algorithm for the Multi-User MIMO downlink in the case where the total number of receive antennas exceeds the number of transmit antennas at the base station. This case is relevant for many scenarios that have been discussed recently. For instance, for coordinated multipoint (CoMP) transmissions, which play a significant role in LTE to achieve the IMT-Advanced requirements [1], we have to consider users across cell borders jointly and hence a large total number of receive antennas is present. FlexCoBF is significantly more flexible compared to previous approaches, since the linear transmit as well as receive strategies can be chosen arbitrarily. Moreover, we achieve the same sum rate as the best known coordinated beamforming (CBF) algorithm with significantly fewer iterations.**

***Index Terms*—Multi-user MIMO, coordinated beamforming**

I. Introduction

In the multi-user MIMO broadcast channel, a high capacity can be achieved by coordinating the transmissions to multiple users simultaneously. As an optimal transmit strategy, dirty paper coding (DPC) has been shown to achieve the capacity region of Gaussian MIMO broadcast channels in [2]. However, deploying DPC in real systems is impractical due to the prohibitive complexity at both transmitter and receiver. Non-linear precoding [3], [4], as a sub-optimal transmit strategy, is proposed to approach the sum capacity and enhance the link quality. However, non-linear precoding techniques are sensitive to erroneous channel state information (CSI) and still suffer from a high complexity at the transmitter side.

Another alternative sub-optimal transmit strategy is given by linear precoding which is a promising approach due to a lower complexity and an enhanced robustness to erroneous CSI while being able to achieve the same multiplexing gain as DPC. For instance, Zero Forcing (ZF) and Block Diagonalization (BD) [5] are well-known linear precoding techniques. Both ZF and BD enforce zero interference between different users. However, their application is constrained by the dimensionality restriction which states that the total number of receive antennas must be smaller than or equal to the number of transmit antennas. This condition is usually not fulfilled in many scenarios that have been studied recently. For example, the users across cell borders have to be considered jointly for coordinated multipoint (CoMP) transmission [1]. Therefore, a large total number of receive antennas is present. Furthermore, a relay-assisted communication scenario discussed in [6] contains a larger total number of receive antennas than the number of transmit antennas, when the assisting relay simultaneously serves groups of users belonging to different operators.

A related linear precoding technique is Regularized Block Diagonalization (RBD) [7]. RBD has an improved sum rate and diversity order compared to BD and ZF and releases the dimensionality restriction. However, it has been shown that the performance of RBD degrades heavily with an increasing aggregate number of receive antennas [8].

Coordinated beamforming (CBF) algorithms have been proposed to transmit a number of data streams that is smaller than the total number of receive antennas [5], [7], [9], [10], [11]. The methods in [5], [7], [9] compute the transmit-receive beamformers by jointly optimizing the beamforming vectors at the transmitter and the receiver in an iterative fashion. The coordinated transmission strategy in [9] is a low complexity approach, and the sum rate performance is closest to the sum capacity of the MIMO broadcast channel compared to the other CBF algorithms [5], [7]. However, only a single data stream to each user is considered in [9] and the receive beamforming strategy is fixed to maximum ratio combining (MRC) matched filtering. Furthermore, the transmit beamformers are found by a matrix inversion, which imposes further constrains on the dimensionality and is sensitive to the conditioning of the matrix (e.g., it suffers from spatial correlation).

Closed-form expressions for CBF were proposed in [10] and [11], in order to avoid iterative computations while achieving the same sum rate performance as the iterative CBF in [9]. In [10], the transmit beamformers are designed as the generalized eigenvectors of the channel correlation matrices of the users when a MRC matched filter is used at each user side. However, this algorithm is only valid for a two transmit antennas system with two users. In [11], a closed-form coordinated beamforming algorithm for an arbitrary number of transmit antennas was proposed. The coordinated transmit-receive beamformers are directly calculated by using

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a structured joint congruence (STJOCO) transformation. Note that the STJOCO transformation [12] is derived by modifying the LU-based non-orthogonal matrix joint diagonalization. Iterative computations are required to find the sought matrix which is the solution of the defined cost function and related to the coordinated transmit-receive beamformers. The complexity is higher than the coordinated transmission strategy in [9], since a numerical nonlinear convex optimization method (i.e., the Broyden-Fletcher-Goldfarb-Shanno (BFGS) quasi-Newton method with cubic line search) is employed at each iteration for the STJOCO transformation. Furthermore, the receive beamforming strategy is fixed to MRC matched filtering and only the transmission of a single data stream per user is supported.

In this paper, we propose the flexible coordinated beamforming (FlexCoBF) method. The main advantages of FlexCoBF are the following.

- It supports the transmission of multiple data streams to each user.
- FlexCoBF provides freedom in the choice of the linear transmit and receive beamforming strategies.
  - For the transmit beamforming, any existing linear precoding technique can be applied (e.g., ZF, BD, and RBD).
  - The receive beamforming strategy can be chosen flexibly (e.g., MRC or MMSE receivers).
- The sum rate performance of FlexCoBF approaches the sum capacity of the MIMO broadcast channel as the algorithm in [9], while requiring significantly less iterations.

We use upper case and lower case boldface letters to denote matrices $\boldsymbol{A}$ and column vectors $\boldsymbol{a}$, respectively, and $\boldsymbol{A}^{\mathrm{H}}$ indicates the Hermitian transpose of the matrix $\boldsymbol{A}$. The Frobenius norm of the matrix $\boldsymbol{A}$ is represented as $\|\cdot\|_F$.

This paper is organized as follows: In Section II, we introduce the multi-user MIMO downlink system model. In Section III, we first give a short description of the two existing primary CBF algorithms which we compare to our new algorithm. Then, we present details of the FlexCoBF algorithm. The simulation results are shown in Section IV. A short conclusion follows in Section V.

II. System Model

We consider a multi-user MIMO downlink system with a single base station (BS) and K users, where the BS is equipped with M_{T} transmit antennas and the user i has M_{R_i} receive antennas. The total number of receive antennas is denoted by M_{R}, i.e., $M_{\mathrm{R}} = \sum_{i=1}^{K} M_{\mathrm{R}_i}$. In this paper we focus on the case $M_{\mathrm{R}} > M_{\mathrm{T}}$. We represent the flat fading MIMO channel between the BS and the ith user by $\boldsymbol{H}_i \in \mathbb{C}^{M_{\mathrm{R}_i} \times M_{\mathrm{T}}}$. Let $\boldsymbol{x}_i \in \mathbb{C}^{r_i}$ denote the transmitted signal for the ith user and $\boldsymbol{F}_i \in \mathbb{C}^{M_{\mathrm{T}} \times r_i}$ indicate the transmit beamforming matrix of user i. The receiver beamforming matrix for user i is denoted by $\boldsymbol{W}_i \in \mathbb{C}^{M_{\mathrm{R}_i} \times r_i}$. The variable r_i represents the number of data streams to user i. We use the term r to indicate the total number of data streams for all users (i.e., $r = \sum_{i=1}^{K} r_i$) and we have $r \leq M_{\mathrm{T}}$. The ith receiver observes zero mean circularly symmetric complex Gaussian white noise $\boldsymbol{n}_i \in \mathbb{C}^{M_{\mathrm{R}_i}}$ with variance σ_{n}^2. Then, the received signal of the ith user after receiver combining is expressed as

$$\boldsymbol{y}_i = \boldsymbol{W}_i^{\mathrm{H}} \boldsymbol{H}_i \boldsymbol{F}_i \boldsymbol{x}_i + \boldsymbol{W}_i^{\mathrm{H}} \boldsymbol{H}_i \sum_{\ell=1, \ell \neq i}^{K} \boldsymbol{F}_\ell \boldsymbol{x}_\ell + \boldsymbol{W}_i^{\mathrm{H}} \boldsymbol{n}_i. \quad (1)$$

The first term on the right-hand-side (RHS) of equation (1) is the desired signal for user i, and the second term represents the multi-user interference (MUI) at the user i caused by the other users in the system. This MUI can efficiently be mitigated by the coordinated transmission strategy. Figure 1 shows the block diagram of the considered system.

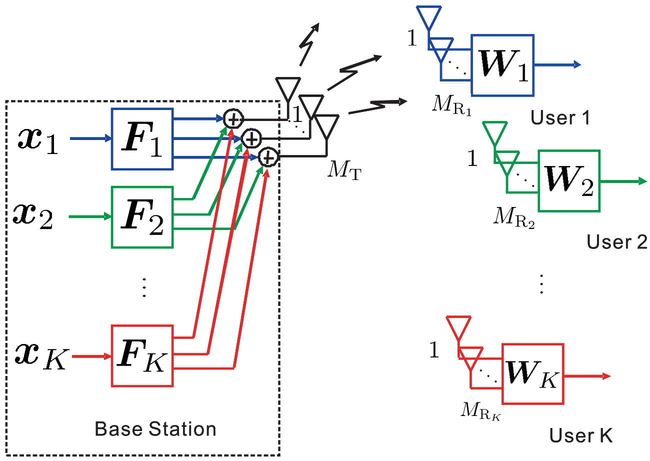

Fig. 1. Block diagram of the multi-user MIMO downlink system.

III. Coordianted Beamforming

Various coordinated beamforming (CBF) algorithms have been proposed in the past years (e.g., [5], [7], [9]). They allow to transmit a smaller number of data streams than the number of receive antennas and mainly compute the transmit-receive beamformers via joint optimization. CBF can solve the dimensionality problem caused by linear precoding techniques (e.g., ZF and BD) in the case that the total number of receive antennas M_{R} is larger than the number of transmit antennas M_{T} at the base station. Iterative computations are employed to find the transmit-receive beamforming weights in order to ensure zero interference on the activated spatial modes. Therefore, the diversity of the channels can be extracted.

At the beginning of this section, we shortly describe two existing CBF algorithms. Then, we propose a new CBF algorithm named flexible coordinated beamforming (FlexCoBF). The FlexCoBF can achieve some promising advantages compared to the previous CBF algorithms.

A. The Previous Coordinated Beamforming Algorithms

A low complexity coordinated beamforming algorithm is proposed in [9]. The transmission of a single data stream to each user is considered, and the receive combining vectors are MRC matched filters, given by $\boldsymbol{w}_i = \boldsymbol{H}_i \boldsymbol{f}_i$ for user i where

$\boldsymbol{f}_i \in \mathbb{C}^{M_{\mathrm{T}} \times 1}$ is the transmit beamforming of the ith user. The equivalent multi-user channel matrix $\boldsymbol{H}_e$ is defined as

$$\boldsymbol{H}_e = \begin{bmatrix} \boldsymbol{w}_1^{\mathrm{H}} \boldsymbol{H}_1 \\ \vdots \\ \boldsymbol{w}_K^{\mathrm{H}} \boldsymbol{H}_K \end{bmatrix} \in \mathbb{C}^{K \times M_{\mathrm{T}}}. \quad (2)$$

This algorithm initializes the receive combining vectors $\boldsymbol{w}_i$ ($i = 1, \ldots, K$) to some random vectors first. Then, with increasing iteration index p the following two steps are repeated until a stopping criterion is satisfied.

- Compute the equivalent multi-user channel matrix $\boldsymbol{H}_e^{(p)}$ at step p.

$$\boldsymbol{H}_e^{(p)} = \begin{bmatrix} \boldsymbol{w}_1^{(p-1)^{\mathrm{H}}} \boldsymbol{H}_1 \\ \vdots \\ \boldsymbol{w}_K^{(p-1)^{\mathrm{H}}} \boldsymbol{H}_K \end{bmatrix},$$

  where

$$\boldsymbol{w}_i^{(p-1)} = \boldsymbol{H}_i \boldsymbol{f}_i^{(p-1)}, \ i = 1, \ldots, K \ .$$

- Compute the transmit beamforming vectors for all users at step p.

$$\boldsymbol{F}^{(p)} = \boldsymbol{H}_e^{(p)^{-1}}, \ \boldsymbol{F}^{(p)} = \left[\boldsymbol{f}_1^{(p)}, \ldots, \boldsymbol{f}_K^{(p)}\right]$$

The changes in the transmit beamformers are tracked. If they are sufficiently small (i.e., $\left\|\boldsymbol{F}^{(p)} - \boldsymbol{F}^{(p-1)}\right\|_F < \epsilon$, where ϵ is an arbitrary small number), the iterative procedure has ended. The CBF algorithm in [9] has a lower complexity compared to most previous CBF algorithms and can achieve a high sum rate which approaches the sum capacity of the MIMO broadcast channel. However, it has the following constraints.

- The receive beamforming strategy is fixed to MRC matched filtering.
- The transmit beamformers are found by a matrix inversion, which imposes a dimensionality constraint stating that the total number of transmitted data streams must be equal to the number of transmit antennas (i.e., $r = M_{\mathrm{T}}$).
- The number of data streams per user is constrained to one.

In [5], coordinated BD was proposed as a sub-optimal CBF algorithm. Unlike the algorithm in [9] which initializes the receive beamforming vectors to some random vectors first and then jointly optimizes the transmit-receive beamformers, coordinated BD only performs two iterative steps. Firstly, it initializes the receive beamformers $\boldsymbol{W}_i \in \mathbb{C}^{M_{\mathrm{R}_i} \times r_i}$ of the ith user as the first r_i columns of the left singular vectors $\boldsymbol{U}_i$, where $\boldsymbol{U}_i$ is obtained by computing the singular value decomposition (SVD) of the channel matrix $\boldsymbol{H}_i$ (i.e., $\boldsymbol{H}_i = \boldsymbol{U}_i \boldsymbol{\Sigma}_i \boldsymbol{V}_i^{\mathrm{H}}$) and r_i is the number of data streams to user i. Then, it computes the equivalent multi-user channel matrix $\boldsymbol{H}_e$, given by

$$\boldsymbol{H}_e = \begin{bmatrix} \boldsymbol{W}_1^{\mathrm{H}} \boldsymbol{H}_1 \\ \vdots \\ \boldsymbol{W}_K^{\mathrm{H}} \boldsymbol{H}_K \end{bmatrix} \in \mathbb{C}^{r \times M_{\mathrm{T}}} \quad (3)$$

and applies the BD algorithm on $\boldsymbol{H}_e$. The coordinated BD algorithm supports multiple data streams per user, but with only two iterations, this algorithm fails to obtain the rich diversity of the channels, since the receive beamformers are not considered together with the optimization. As a result, the sum rate performance is worse than the CBF in [9].

B. Flexible Coordinated Beamforming (FlexCoBF)

The FlexCoBF algorithm is proposed to jointly optimize the transmit-receive beamformers in order to enforce zero MUI at each user and achieve a sum rate close to the sum capacity of the MIMO broadcast channel. To this end, we define an equivalent multi-user channel matrix $\boldsymbol{H}_e \in \mathbb{C}^{r \times M_{\mathrm{T}}}$ and a combined transmit beamforming matrix $\boldsymbol{F} \in \mathbb{C}^{M_{\mathrm{T}} \times r}$ as

$$\boldsymbol{H}_e = \begin{bmatrix} \boldsymbol{W}_1^{\mathrm{H}} \boldsymbol{H}_1 \\ \vdots \\ \boldsymbol{W}_K^{\mathrm{H}} \boldsymbol{H}_K \end{bmatrix} \quad (4)$$

and

$$\boldsymbol{F} = [\boldsymbol{F}_1, \boldsymbol{F}_2, \ldots, \boldsymbol{F}_K], \quad (5)$$

where r denotes the total number of data streams for all users (i.e., $r = \sum_{i=1}^{K} r_i$). Note that r should satisfy $r \leq M_{\mathrm{T}}$. The receive beamforming matrices $\boldsymbol{W}_i$ can be chosen flexibly, e.g., MRC or MMSE receivers. The transmit beamforming matrix $\boldsymbol{F}_i$ is found by applying an arbitrary linear precoding technique on the matrix $\boldsymbol{H}_e$. In this paper, we use ZF, BD, and RBD precoding as examples. The transmit-receive beamformers are updated iteratively until the stopping criterion is satisfied. The FlexCoBF algorithm is summarized as follows.

1) Initialize $\boldsymbol{W}_i^{(0)}$ ($i = 1, \ldots, K$) to some random matrices, the iteration index p to zero, and set the threshold ϵ.
2) Set $p = p + 1$ and compute $\boldsymbol{H}_e^{(p)}$ as

$$\boldsymbol{H}_e^{(p)} = \begin{bmatrix} \boldsymbol{W}_1^{(p-1)^{\mathrm{H}}} \boldsymbol{H}_1 \\ \vdots \\ \boldsymbol{W}_K^{(p-1)^{\mathrm{H}}} \boldsymbol{H}_K \end{bmatrix}$$

3) Apply the desired linear precoding algorithm on the matrix $\boldsymbol{H}_e^{(p)}$ to obtain the transmit beamforming matrices $\boldsymbol{F}_i^{(p)}$ for all users.
4) Compute the receive beamformers for the pth iteration according to the desired strategy using the precoded channel $\boldsymbol{H}_i \boldsymbol{F}_i^{(p)}$. For instance,
   - MRC receiver:

$$\boldsymbol{W}_i^{(p)} = \boldsymbol{H}_i \boldsymbol{F}_i^{(p)}$$

   - MMSE receiver:

$$\boldsymbol{W}_i^{(p)} = (\boldsymbol{H}_i \boldsymbol{F}_i^{(p)} \boldsymbol{F}_i^{(p)^{\mathrm{H}}} \boldsymbol{H}_i^{\mathrm{H}} + \sigma_n^2 \boldsymbol{I}_{M_{\mathrm{R}_i}})^{-1} \boldsymbol{H}_i \boldsymbol{F}_i^{(p)}$$

5) Compute the $\mathrm{MUI}(\boldsymbol{H}_e^{(p)} \boldsymbol{F}^{(p)})$ which is defined as

$$\mathrm{MUI}(\boldsymbol{H}_e^{(p)} \boldsymbol{F}^{(p)}) = \left\| \mathrm{off}(\boldsymbol{H}_e^{(p)} \boldsymbol{F}^{(p)}) \right\|_F^2,$$

   where $\mathrm{off}(\cdot)$ indicates all off-diagonal elements of the matrix $\boldsymbol{H}_e^{(p)} \boldsymbol{F}^{(p)}$. If the $\mathrm{MUI}(\boldsymbol{H}_e^{(p)} \boldsymbol{F}^{(p)}) > \epsilon$, go back to step 2. Otherwise, convergence is achieved and the procedure has ended.

Compared to the previous CBF algorithms, FlexCoBF provides freedom in the choice of the transmit-receive beamforming strategies. The receive beamforming strategy can be chosen flexibly (e.g., MRC or MMSE receivers) and any existing linear precoding techniques (e.g., ZF, BD, and RBD) can be applied as the transmit beamforming strategy. The complexity of the FlexCoBF algorithm mainly depends on the complexity of the chosen transmit beamforming strategy. For example, if ZF precoding is chosen as the transmit beamforming strategy for the FlexCoBF algorithm, we obtain the same low complexity per iteration as the CBF algorithm in [9], while achieving the same sum rate performance as the CBF algorithm in [9] with significantly less iterations. This is demonstrated numerically in the following section.

IV. Simulation Results

In the simulations, we assume that the BS and each user know the channel state information (CSI) perfectly. We assess the sum rate performance and the convergence of the FlexCoBF algorithm in Rayleigh fading channels. Spatial correlation of the channels is considered and the Kronecker model is applied to generate the spatial correlated channel $\boldsymbol{H} \in \mathbb{C}^{M_{\mathrm{R}} \times M_{\mathrm{T}}}$ as

$$\boldsymbol{H} = \boldsymbol{R}_r^{1/2} \boldsymbol{H}_w \boldsymbol{R}_t^{1/2}, \tag{6}$$

where $\boldsymbol{H}_w$ is a spatial white unit variance flat fading MIMO channel of dimension $M_{\mathrm{R}} \times M_{\mathrm{T}}$. The matrices $\boldsymbol{R}_r \in \mathbb{C}^{M_{\mathrm{R}} \times M_{\mathrm{R}}}$ and $\boldsymbol{R}_t \in \mathbb{C}^{M_{\mathrm{T}} \times M_{\mathrm{T}}}$ are the receive and transmit correlation matrices with $\mathrm{tr}(\boldsymbol{R}_r) = M_{\mathrm{R}}$ and $\mathrm{tr}(\boldsymbol{R}_t) = M_{\mathrm{T}}$, respectively. They are defined as

$$\boldsymbol{R}_r = \begin{bmatrix} \rho_r^0 & \rho_r^1 & \cdots & \rho_r^{M_{\mathrm{R}}-1} \\ \rho_r^1 & \rho_r^0 & \cdots & \rho_r^{M_{\mathrm{R}}-2} \\ \vdots & \vdots & \ddots & \vdots \\ \rho_r^{M_{\mathrm{R}}-1} & \rho_r^{M_{\mathrm{R}}-2} & \cdots & \rho_r^0 \end{bmatrix} \tag{7}$$

and

$$\boldsymbol{R}_t = \begin{bmatrix} \rho_t^0 & \rho_t^1 & \cdots & \rho_t^{M_{\mathrm{T}}-1} \\ \rho_t^1 & \rho_t^0 & \cdots & \rho_t^{M_{\mathrm{T}}-2} \\ \vdots & \vdots & \ddots & \vdots \\ \rho_t^{M_{\mathrm{T}}-1} & \rho_t^{M_{\mathrm{T}}-2} & \cdots & \rho_t^0 \end{bmatrix}, \tag{8}$$

where ρ_r and ρ_t $(0 \leq \rho_r, \ \rho_t \leq 1)$ are the correlation coefficients at the receiver and transmitter side, respectively. In the simulations, we assume $\rho_r = \rho_t = \rho$.

The threshold ϵ for the stopping criterion is set to 10^{-5} in all simulations and the maximum number of iterations is limited by 50. The total transmit power P_{T} is equally allocated among users. The received signal-to-noise ratio is defined as $\mathrm{SNR} = P_{\mathrm{T}}/\sigma^2$. In order to compare the proposed FlexCoBF algorithm with the CBF algorithm in [9], we consider the transmission of a single data stream per user first.

In Figures 2, 3, and 4, we assume a MIMO downlink system with three users in uncorrelated Rayleigh fading (i.e., $\rho = 0$).

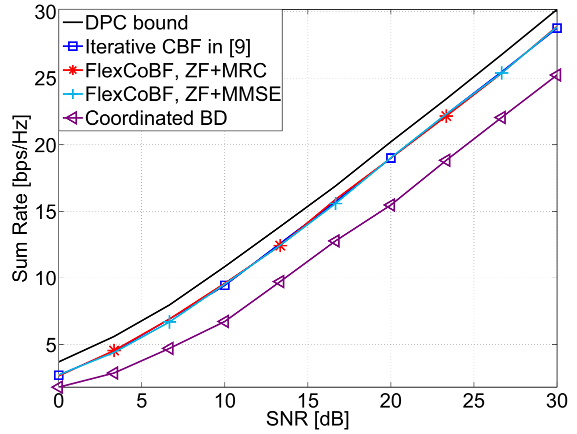

Fig. 2. Achievable sum rate for $M_{\mathrm{T}} = K = 3$ and $M_{\mathrm{R}_i} = 2$.

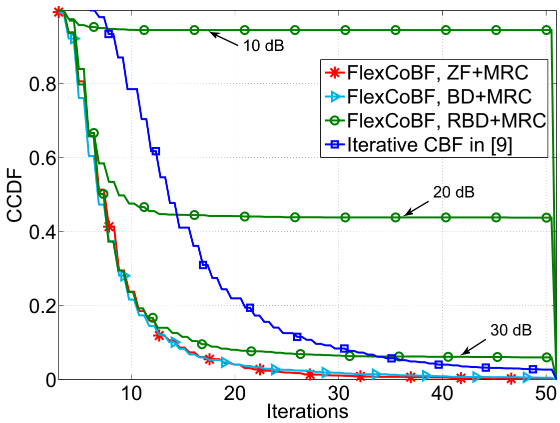

Fig. 3. CCDF of required number of iterations for $M_{\mathrm{T}} = K = 3$ and $M_{\mathrm{R}_i} = 2$

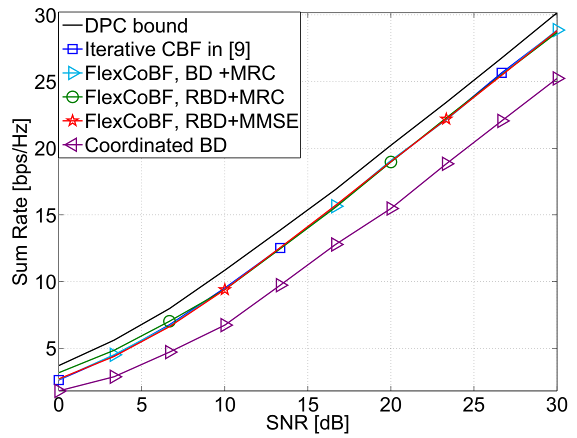

Fig. 4. Achievable sum rate for $M_{\mathrm{T}} = K = 3$ and $M_{\mathrm{R}_i} = 2$.

Each user is equipped with $M_{\mathrm{R}_i} = 2$ receive antennas and the base station has $M_{\mathrm{T}} = 3$ transmit antennas. Figures 2 and 4 show the sum rate performance comparisons among the CBF

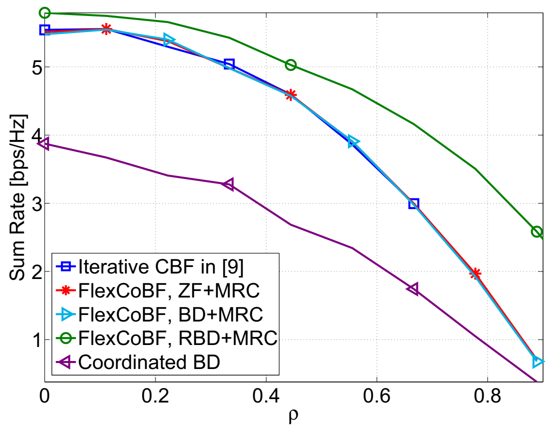

Fig. 5. Achievable sum rate for $M_{\mathrm{T}} = K = 3$ and $M_{\mathrm{R}_i} = 2$ at SNR = 5 dB over ρ.

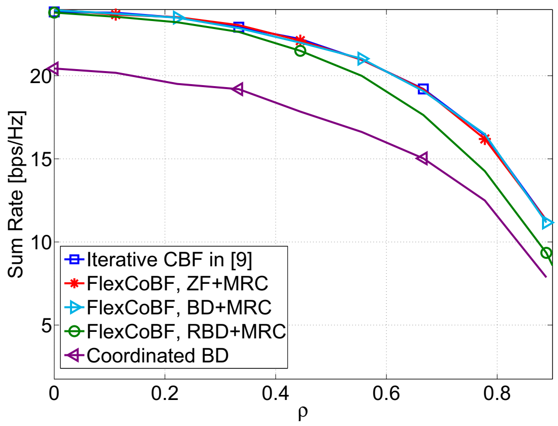

Fig. 6. Achievable sum rate for $M_{\mathrm{T}} = K = 3$ and $M_{\mathrm{R}_i} = 2$ at SNR = 25 dB over ρ.

algorithm in [9], the proposed FlexCoBF algorithm applying different linear precoding techniques (e.g., ZF, BD, and RBD) as the transmit beamforming strategy, and the coordinated BD in [5]. We observe that coordinated BD has the worst sum rate performance due to the missing joint optimization between the transmit and receive beamformers. The FlexCoBF algorithm can achieve a noticeably increased sum rate performance, as the CBF algorithm in [9]. It is noticed that FlexCoBF with RBD precoding as the transmit beamforming strategy and MRC receiver as the receive beamforming strategy can achieve the best sum rate performance at low SNRs.

Figure 3 displays the complementary cumulative distribution function (CCDF) of the required number of iterations. It can be found that FlexCoBF applying ZF precoding as the transmit beamforming strategy has the same low complexity per iteration as the CBF algorithm in [9], while requiring significantly fewer iterations. The complexity of FlexCoBF applying BD and RBD precoding as the transmit beamforming strategies are slightly increased, since the matrix inversion is replaced by the singular value decomposition (SVD) of the matrix. However, FlexCoBF with BD precoding still requires much less iterations compared to the CBF in [9]. The algorithms seem to converge in most cases for FlexCoBF with ZF and BD precoding. Due to the property of the RBD precoding that a small amount of MUI is allowed except for very high SNRs, the CCDF of the required number of iterations of FlexCoBF with RBD precoding as the transmit beamforming strategy is affected by the SNRs. At low SNRs, MUI can only be reduced to a small number which is obviously greater than the assigned threshold $\epsilon = 10^{-5}$. Consequently, the convergence only can be achieved with a threshold which is larger than the assigned threshold $\epsilon = 10^{-5}$.

Figures 5 and 6 shows the effect of the channel spatial correlations on the sum rate performance. The sum rate performance is found to degrade with the increasing spatial correlation coefficient ρ. FlexCoBF with RBD as the transmit beamforming strategy and MRC receivers as the receive beamforming is most robust to the spatial correlation at low SNRs.

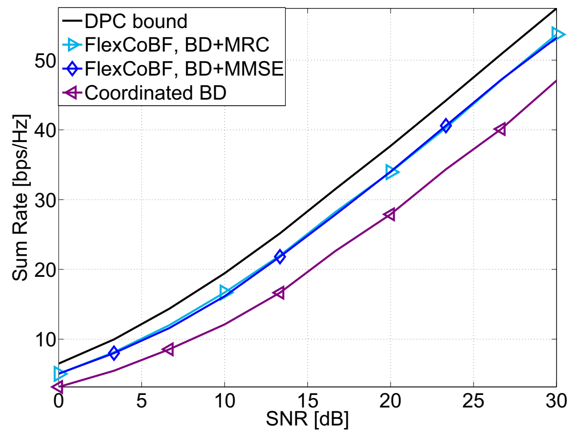

Fig. 7. Achievable sum rate for $M_{\mathrm{T}} = 6$, $K = M_{\mathrm{R}_i} = 3$ and $\rho = 0$. The number of data streams per user is $\{2, 2, 2\}$.

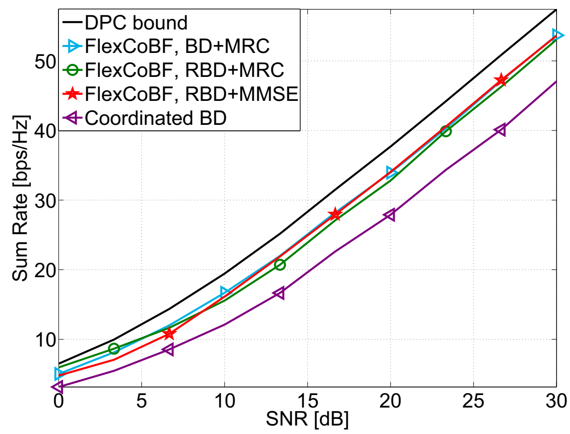

Fig. 8. Achievable sum rate for $M_{\mathrm{T}} = 6$, $K = M_{\mathrm{R}_i} = 3$ and $\rho = 0$. The number of data streams per user is $\{2, 2, 2\}$.

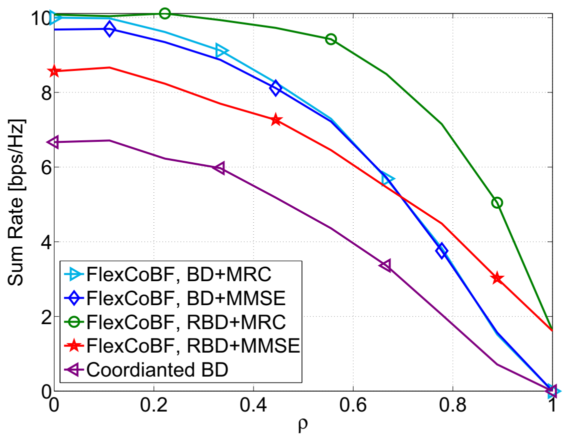

Fig. 9. Achievable sum rate for $M_{\mathrm{T}} = 6$ and $K = M_{\mathrm{R}_i} = 3$ at SNR = 5 dB over ρ. The number of data streams per user is $\{2, 2, 2\}$.

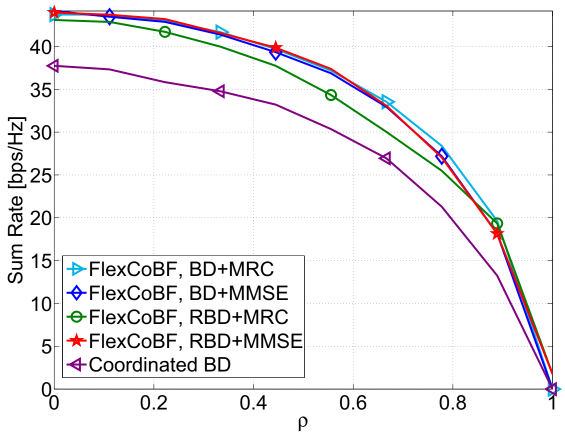

Fig. 10. Achievable sum rate for $M_{\mathrm{T}} = 6$ and $K = M_{\mathrm{R}_i} = 3$ at SNR = 25 dB over ρ. The number of data streams per user is $\{2, 2, 2\}$.

In Figures 7-10, we consider multiple data streams transmission per user. Water filling power allocation is employed among the different data streams of one user. It is observed that the proposed FlexCoBF algorithm has a significantly increased sum rate performance compared to the coordinated BD proposed in [5], when the base station simultaneously transmits multiple data streams to each user in the case where the total number of receive antennas M_{R} exceeds the number of transmit antennas M_{T}. At low SNRs, FlexCoBF with RBD precoding as the transmit beamforming strategy and MRC receiver as the receive beamforming strategy achieves best sum rate performance compared to other methods and is most robust to the spatial correlation.

V. Conclusions

In this paper, we propose the FlexCoBF algorithm for the multi-user MIMO downlink in the case that the total number of receive antennas is greater than the number of transmit antennas. FlexCoBF is designed to jointly optimize the transmit-receive beamforming in an iterative fashion in order to enforce zero MUI at each user. Compared to the previous CBF algorithms, the FlexCoBF provides freedom in the choice of the transmit and receive beamforming strategies. Any existing linear precoding techniques (e.g., ZF, BD, and RBD) can be applied as the transmit beamforming strategy. The receive beamforming strategy can be chosen flexibly between MRC and MMSE receivers. The complexity of the FlexCoBF algorithm is mainly decided by the complexity of the chosen transmit beamforming strategy. If we consider single data stream transmission of each user, which is a reasonable assumption for a real system when the base station intends to simultaneously serve as many users as possible, FlexCoBF with ZF precoding as the transmit beamforming strategy can supply the best sum rate performance with the lowest complexity. If only low SNRs are considered, the best sum rate performance can be achieved by the FlexCoBF algorithm with RBD precoding and MRC receivers as the transmit-receive beamforming strategies, respectively.

Acknowledgments

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